UNIT-I

INTRODUCTION TO HVDC

EVOLUTION OF POWER SYSTEMS:

YEAR	HOW COMMERCIAL USE OF ELECTRICITY TOOK PLACE
	The basic discoveries of **GAVLANI, VOLTA, OHM** and **AMPERE** pertained to DC. The first widespread practical application was DC telegraphy by electrochemical batteries and using under- ground return circuits
1870	Commercial use of Electricity when Carbon Arc Lamps were used to illumination of light house and street lighting in series at constant current fed by series wound generators and later carbon filament lamps are used which are operated in parallel at constant voltage supplied current from shunt generators.
1882	First Electric Power System with (steam driven Bipolar DC Generator, Cable, Fuse and Load) by Thomas Alva Edison at Pearl street in New York DC system for 59 customers ,1.5m radius of 110V Underground cable with incandescent lamp load
1884	Electric Motors were developed by Frank Sprague
1886	Limitation of DC became apparent ➢ High losses and voltage drops ➢ Transformation of voltages requirement Development of Transformers and AC Transmission by L. Gaulard and J.D.Gibbs of Paris and France George Westinghouse secured the rights in U.S. William Stanley an associate of Westinghouse developed and tested commercial practical use of Transformers and AC Transmission for 150 lamps at Great Barrington Massachusetts
1888	Nikola Tesla developed Polyphase Systems and had patents of Generators, Motors, Transformers, Transmission lines but these patents were sold to Westinghouse.
1889	First AC Transmission system in North America in Oregon Between Willamette Falls and Portland Single Phase 4KV over 21 Km
1890	Controversial industrial revolution whether the industries need go for DC/AC ➢ Thomas Alva Edison advocated for DC and ➢ Westinghouse advocated for AC
	Earlier Frequencies were used are 25,50,60 and 133Hz European Countries Fixed their values to 60Hz Asian Countries Fixed their values to 50Hz
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1893	First 3-phase line , 2300V , 12km in California . AC was chosen near Niagara falls
1922	165kV
1923	220kV

1935	287kV
1953	330kV
1965	500kV
1966	735kV Hydro Quebec
1969	765kV in USA
1990	1100kV
	Standards are 115 , 138 , 161 , 230KV - HV &
	345 , 500 , 765kV - EHV

VOLTAGE LEVELS:

BASIC ELEMENTS OF ELECTRICAL POWER SYSTEM

YEAR	HOW COMMERCIAL USE OF ELECTRICITY TOOK PLACE
HVDC TRANSMISSION SYSTEMS	
1880-1911	HVDC transmission systems was designed by a French Engineer **Rene Thury** when the AC system is at Infancy. At least 19 Thury systems were installed in Europe by the use of water power most prominent was Mouteirs to Lyons (France) in 1906 57.6KV, 75A, 4.3MW 180Km (4.5Km Underground Cable) ➢ DC series generators were used ➢ Constant Current Control mode of operation ➢ Four water turbines each of 3.6KV 1911- Second plant at La Bridoire rated at 6MW, 150A added in series 1912 –Third located at Bozel 11Km beyond Mouteirs rated at 9MW added raising the total capacity to 193 MW,125KV with 225KM
1920	Transverters (Polyphase transformers commutated by synchronously rotating bus gear) were developed by Two British Engineers W.E Highfield and J.E. Calverly. Functions: ➢ Voltage Transformation ➢ Phase Multiplication ➢ Commutation
1932	Atmospheric arc converters were developed by E.Marx of Braunschweig it is a switching device in which an arc between two water cooled main electrodes
1938	Due to death of Rene Thury all the Thury systems were dismantled
1950	Mercury arc valves were developed
1954	First HVDC Transmission system between Sweden & Gotland Island by Cable

VOLTAGE LEVELS:

MILESTONES OF HVDC:

- Hewitt´s Mercury - Vapour rectifier, which appeared in 1901.
- Experiments with Thyratrons in America and mercury arc valves in Europe before 1940.
- First commercial HVDC transmission, Gotland 1 in Sweden in 1954.
- First solid state semiconductor valves in 1970.
- First microcomputer based control equipment for HVDC in 1979.
- Highest DC transmission voltage (+/- 600 kV) in Itaipú, Brazil, 1984.
- First active DC filters for outstanding filtering performance in 1994.
- First Capacitor Commutated Converter (CCC) in Argentina-Brazil Interconnection, 1998.
- First Voltage Source Converter for transmission in Gotland, Sweden ,1999

COMPARISON OF AC AND D.C TRANSMISSION:

ADVANTAGES OF HVAC

- Voltage transformation.
- Current interruption.
- Easy conversion into mechanical energy to electrical energy and vice-versa.
- Frequency as system-wide control signal.
- Meshed networks.

DISADVANTAGES OF HVAC

- Long distance transmission.
- Difficult to use cables, already at 100km high reactive power consumption.
- Reactive power loss.
- Stability problem.
- Current carrying capacity.
- Skin Effect and Ferranti Effect.
- Power Flow Control.

ADVANTAGES OF HVDC

- More power can be transmitted per conductor per circuit.
- Use of Ground Return Possible.
- Require Less Space compared to AC of the same voltage rating and size.
- Higher Capacity available for cables.
- No skin effect.
- Less Corona and Radio Interference.
- No Stability Problem.
- Asynchronous interconnection possible.
- Lower short circuit fault levels.
- Tie Line Power is easily controlled.
- Cheaper for Bulk Power Transmission.
- Fast Fault Clearing Time.
- No Compensation required for the line.

- **More power can be transmitted per conductor per circuit:**

Let the peak DC voltage $V_m = V_{dc}$

Let the peak AC voltage $V_{ac} = V_m = \sqrt{2}V_{rms}$

For the same insulation Peak DC voltage = Peak AC voltage

$$V_{dc} = \sqrt{2}V_{rms}$$

For the same conductor size, the same current can transmitted with both DC and AC if the skin effect is not considered then

$$I_{dc} = I_{ac}$$

DC power per conductor $P_{dc} = V_{dc}I_{dc}$

AC power per conductor $P_{ac} = V_{ac}I_{ac}\cos\Phi$

The ratio of powers be

$$\frac{P_{dc}}{P_{ac}} = \frac{\sqrt{2}V_{rms}I_{dc}}{V_{ac}I_{ac}\cos\Phi} = \frac{\sqrt{2}V_{rms}I_{dc}}{V_{rms}I_{dc}\cos\Phi} = \frac{\sqrt{2}}{\cos\Phi}$$

Case - I

$$\frac{P_{dc}}{P_{ac}} = \frac{\sqrt{2}}{\cos\Phi} = \frac{1.414}{\cos\Phi}$$

$$\frac{P_{dc}}{P_{ac}} = \sqrt{2} \quad \text{Unity Power Factor}$$

$$P_{dc} = \sqrt{2}P_{ac}$$

Case - II

$$\frac{P_{dc}}{P_{ac}} = \frac{\sqrt{2}}{\cos\Phi} = \frac{1.414}{\cos\Phi}$$

$$\frac{P_{dc}}{P_{ac}} = \frac{\sqrt{2}}{0.8} = 1.7677$$

$$P_{dc} = 1.7677P_{ac} \quad \text{For 0.8 P.F}$$

From the above expressions we can say that more amount of power can be transferred in DC.

In practice, DC transmission is carried out using 2 conductors (+/-) and AC transmission is carried out using either single circuit or double circuit 3Φ transmission using 3 or 6 conductors. In such a case the above ratio for power must be multiplied by 2/3 or by 4/3.

In general, we are interested in transmitting a given quantity of power at a given insulation level, at a given efficiency of transmission.

Let RDC = Resistance of DC line

RAC = resistance of AC line

AAC= Area of cross-section of the conductor of AC

ADC= Area of cross-section of the conductor of DC

For DC

$$\text{DC Current} = \frac{P}{V_m} = \frac{P}{V_{dc}}$$

$$\text{Power Loss } P_L = \left(\frac{P}{V_{dc}}\right)^2 R_{dc} = \left(\frac{P}{V_{dc}}\right)^2 \frac{\rho l}{A_{dc}}$$

For AC

$$\text{AC Current} = \frac{P}{\cos\phi V_{rms}}$$

$$\text{Power Loss } P_L = \left(\frac{P}{\cos\phi V_{rms}}\right)^2 R_{Ac}$$

$$= \left(\frac{P}{\cos\phi V_{rms}}\right)^2 = \frac{\rho l}{A_{ac}} = \left(\frac{P}{\frac{\cos\phi V_m}{\sqrt{2}}}\right)^2 \frac{\rho l}{A_{ac}}$$

$$= \left(\frac{\sqrt{2}P}{\cos\phi V_m}\right)^2 \frac{\rho l}{A_{ac}} = 2\left[\frac{P}{\cos\phi V_m}\right]^2 \frac{\rho l}{A_{ac}}$$

Equating the losses in DC and AC

$$\left(\frac{P}{V_{dc}}\right)^2 \frac{\rho l}{A_{dc}} = 2\left[\frac{P}{\cos\phi V_m}\right]^2 \frac{\rho l}{A_{ac}}$$

$$\left(\frac{P}{V_m}\right)^2 \frac{\rho l}{A_{dc}} = 2\left[\frac{P}{\cos\phi V_m}\right]^2 \frac{\rho l}{A_{ac}}$$

Ratio of the Area is

$$\frac{A_{dc}}{A_{ac}} = \frac{\cos^2\phi}{2} = \frac{0.5 \text{ at a P.F } = \text{Unity}}{0.32 \text{ at a P.F } = 0.8}$$

By this we can say one-half the amount of copper is required for the same power transmission at unity power factor, and less than one-third is required at the power factor of 0.8 lag

- **USE OF GROUND RETURN POSSIBLE:**
  - In the case of HVDC transmission, ground return (especially submarine crossing) may be used, as in the case of a Monopolar DC link.
  - Also the single circuit bipolar DC link is more reliable, than the corresponding AC link, as in the event of a fault on one conductor; the other conductor can continue to operate at reduced power with ground return.
  - For the same length of transmission, the impedance of the ground path is much less for DC than for the corresponding AC because DC spreads over a much larger width and depth.
  - In fact, in the case of DC the ground path resistance is almost entirely dependant on the earth electrode resistance at the two ends of the line, rather than on the line length. However it must be borne in mind that ground return has the following disadvantages. The ground currents cause electrolytic corrosion of buried metals, interfere with the operation of signaling and ships' compasses, and can cause dangerous step and touch potentials

- **SMALLER TOWER SIZE:**

The DC insulation level for the same power transmission is likely to be lower than the corresponding AC level. Also the DC line will only need two conductors whereas three conductors (if not six to obtain the same reliability) are required for AC Thus both electrical and mechanical considerations dictate a smaller tower.

- **HIGHER CAPACITY AVAILABLE FOR CABLES:**
    - In contrast to the overhead line, in the cable breakdown occurs by puncture and not by external flashover. Mainly due to the absence of ionic motion, the working stress of the DC cable insulation may be 3 to 4 times higher than under AC also, the absence of continuous charging current in a DC cable permits higher active power transfer, especially over long lengths.
    - Charging current of the order of 6 A/km for 132 kV). Critical length at 132 kV ≈ 80 km for AC cable. Beyond the critical length no power can be transmitted without series compensation in AC lines. Thus derating which is required in AC cables, thus does not limit the length of transmission in DC.
    - A comparison made between DC and AC for the transmission of about 1550 MVA is as follows. Six number AC 275 kV cables, in two groups of 3 cables in horizontal formation, require a total trench width of 5.2 m, whereas for two number DC ±500 kV cables with the same capacity require only a trench width of about 0.7 m.

- **NO SKIN EFFECT:**
    - Under AC conditions, the current is not uniformly distributed over the cross section of the conductor.
    - The current density is higher in the outer region (skin effect) and result in under utilization of the conductor cross-section.
    - Skin effect under conditions of smooth DC is completely absent and hence there is a uniform current in the conductor, and the conductor metal is better utilized.

- **LESS CORONA AND RADIO INTERFERENCE:**
    - Since corona loss increases with frequency (in fact it is known to be proportional to f+25), for a given conductor diameter and applied voltage, there is much lower corona loss and hence more importantly less radio interference with DC.
    - Due to this bundle conductors become unnecessary and hence give a substantial saving in line costs. (Tests have also shown that bundle conductors would anyway not offer a significant advantage for DC as the lower reactance effect so beneficial for AC is not applicable for DC.)

- **NO STABILITY PROBLEM:**
    - The DC link is an asynchronous link and hence any AC supplied through converters or DC generation do not have to be synchronized with the link.
    - Hence the length of DC link is not governed by stability. In AC links the phase angle between sending end and receiving end should not exceed 30 at full-load for transient stability (maximum theoretical steady state limit is 90).
    - The phase angle change at the natural load of a line is thus 0.6°per 10 km.

- The maximum permissible length without compensation ≈ 30/0.06 = 500 km.
- With compensation, this length can be doubled to 1000 km.

➢ **ASYNCHRONOUS INTERCONNECTION POSSIBLE:**

- With AC links, interconnections between power systems must be synchronous. Thus different frequency systems cannot be interconnected. Such systems can be easily interconnected through HVDC links.
- For different frequency interconnections both convertors can be confined to the same station.
- In addition, different power authorities may need to maintain different tolerances on their supplies, even though nominally of the same frequency. This option is not available with AC With DC there is no such problem.

➢ **LOWER SHORT CIRCUIT FAULT LEVELS:**

- When an AC transmission system is extended, the fault level of the whole system goes up, sometimes necessitating the expensive replacement of circuit breakers with those of higher fault levels.
- This problem can be overcome with HVDC as it does not contribute current to the AC short circuit beyond its rated current.
- In fact it is possible to operate a DC link in "parallel" with an AC link to limit the fault level on an expansion.
- In the event of a fault on the DC line, after a momentary transient due to the discharge of the line capacitance, the current is limited by automatic grid control. Also the DC line does not draw excessive current from the AC system.

➢ **TIE LINE POWER IS EASILY CONTROLLED:**

- In the case of an AC tie line, the power cannot be easily controlled between the two systems.
- With DC tie lines, the control is easily accomplished through grid control.
- In fact even the reversal of the power flow is just as easy.

➢ **RELIABILITY:**

- Energy Availability: $= 100 \quad 1 - \frac{\qquad}{\qquad} \quad \%$

Where equivalent Outage Time= Product of the actual Time and the fraction of the system capacity lost due to the outage.

- Transient Reliability: $= \frac{\qquad}{\qquad}$

Recordable Faults: Faults which cause the one or more AC Bus phase voltage drop below 90% of the rated Voltage.

Disadvantages of HVDC:

- Expensive convertors.
- Huge Reactive power requirement.
- Generation of harmonics.
- Difficulty of circuit breaking.
- Difficulty of voltage transformation.
- Difficulty of high power generation.
- Point to Point Transmission.
- Limited Over load capacity of converters.

- **EXPENSIVE CONVERTORS:**
  - Expensive Convertor Stations are required at each end of a DC transmission link, whereas only transformer stations are required in an AC link.

- **REACTIVE POWER REQUIREMENT:**
  - DC line does not require any amount of reactive power as there is no Inductance effect .
  - Convertors require huge amount of reactive power, both in rectification as well as in inversion for their energy conversion.
  - At each convertor the reactive power consumed may be as much at 50% of the active power rating of the DC link.
  - The reactive power requirement is partly supplied by the filter capacitance, and partly by Synchronous or Static Condensers that need to be installed for the purpose.

- **GENERATION OF HARMONICS:**
  - Convertors generate a lot of harmonics both on the DC side and on the AC side.
  - Filters are used on the AC side to reduce the amount of harmonics transferred to the AC system.
  - On the DC system, smoothing reactors are used. These components add to the cost of the convertor.

- **DIFFICULTY OF CIRCUIT BREAKING:**
  - Due to the absence of a natural current zero with DC, circuit breaking is difficult.
  - This is not a major problem in single HVDC link systems, as circuit breaking can be accomplished by a very rapid absorbing of the energy back into the AC system. (The blocking action of thyristors is faster than the operation of mechanical circuit breakers).
  - However the lack of HVDC circuit breakers hampers multi-terminal operation.

- **DIFFICULTY OF VOLTAGE TRANSFORMATION:**
  - Power is generally used at low voltage, but for reasons of efficiency must be transmitted at high voltage.
  - The absence of the equivalent of DC transformers makes it necessary for voltage transformation to carried out on the AC side of the system and prevents a purely DC system being used.

- **DIFFICULTY OF HIGH POWER GENERATION:**
  - Due to the problems of commutation with DC machines, voltage, speed and size are limited.
  - Thus comparatively lower power can be generated with DC

- **ABSENCE OF OVERLOAD CAPACITY:**
  - Convertors have very little overload capacity unlike transformers and this overload capacity depends on the rating of the Thyristors individually and also the valves.

ECONOMIC COMPARISON:

% COST FOR HVDC COMMISIONING:

TYPES OF HVDC SYSTEMS:

- MONOPOLAR LINK
- BIPOLAR LINK
- HOMOPOLAR LINK
- MTDC LINK

- **MONOPOLAR LONG-DISTANCE TRANSMISSIONS:**
  - Here one Conductor is used only negative(-ve) and the return path is through ground/Sea return.
  - If the Fault occurs on this line the power transferred is Zero.
  - For reducing corona loss negative is preferred
  - If possible instead of ground return metallic return can also be used even if the cost increases.

- **BIPOLAR LONG-DISTANCE TRANSMISSION:**
  - A bipolar is a combination of two poles in such a way that a common low voltage return path, if available, will only carry a small unbalance current during normal operation.
  - This configuration is used if the required transmission capacity exceeds that of a single pole. It is also used if requirement to higher energy availability or lower load rejection power makes it necessary to split the capacity on two poles.
  - During maintenance or outages of one pole, it is still possible to transmit part of the power. More than 50 % of the transmission capacity can be utilized, limited by the actual overload capacity of the remaining pole.
  - The advantages of a bipolar solution over a solution with two monopoles are reduced cost due to one common or no return path and lower losses. The main disadvantage is that unavailability of the return path with adjacent components will affect both poles.

- **HOMOPOLAR DISTANCE TRANSMISSION:**
  - In this type the conductors are two which are negative and operate with he ground return

SYPNOSIS:

The main areas of the Applications based on Economic & Technical Performances:-

- **Long Distance Transmission.**
- **Underground & submarine Cables.**
- **Asynchronous Connection of two power systems with different frequencies.**
- **Control & Stabilize the power system with power flow control**

PRIMARY OBJECTIVES HVDC APPLICATIONS

- **BULK POWER TRANSMISSION**: Transmit Bulk power from one point to another point over long Distances.
- **BACK TO BACK HVDC SYSTEM**: Here rectification and inversion takes place at the same station with very small DC line or No DC line. This is basically used for control power and stabilize the system and also used for connecting 2 power stations at different frequencies.
- **MODULATION OF EXISTING AC/DC SYSTEM**: Parallel connection of AC/DC links where both AC/DC lines run parallel. It is mainly used to modulate power of AC line

COMPONENTS OF HVDC:

- CONVERTERS.
- CONVERTER TRANSFORMERS.
- SMOOTHING REACTORS
- HARMONIC FILTERS
- OVER HEAD LINES
- REACTIVE POWER SOURCES

- EARTH ELECTRODES
- LOCATION OF EARTH ELECTRODE
- CHOICE OF VOLTAGE

- **CONVERTERS:**
  - Heart of the HVDC System.
  - Each HVDC System has 2 converters one at each end.
  - Convertor at sending end act as Rectifier
  - Convertor at Receiving end act as Inverter.
  - For achieving higher voltages and currents thyristors are connected in parallel and series
    - Higher Voltages – Thyristors in Series.
    - Higher Currents – Thyristors in Parallel.
  - Valve: Thyristors in series and parallel.
  - Bridge Converters are Generally used
  - Current rating of the converters can be increased.

    Thyristors in Parallel
    Valves in Parallel
    Bridges in Parallel
    or Some Combinations of above.
  - Voltage rating of the converters can be increased.

    Thyristors in Series
    Valves in Series
    Bridges in Series
    or Some Combinations of above

- **REQUIREMENT OF THE VALVE:**
  - To allow the current flow in one direction (Conduction State) and should not allow the current in other direction (Non Conduction State) i.e the less resistance in one direction and infinite resistance in other direction
  - For an ideal switch forward Direction R = 0.
    - Reverse Direction R = ∞.
  - To withstand high P.I.V (Peak Inverse Voltage) during the Non-Conduction State.
  - To allow a reasonably Short Commutation Margin Angle during the inverter operation.
  - Smooth Control of conduction to Non-Conduction Phases

- **OPERATION MODES:**
  - Depending on the DC Storage Devices
    - Inductor – CSC (Current Source Converter)
    - Capacitor – VSC (Voltage Source Converter)
  - HVDC - CSC
  - FACTS – VSC (SVC, STATCOM, Filters)

S.No	**Current Source Converters**	**Voltage Source Converters**
1.	Inductor on DC side	Capacitor on DC side
2.	Constant Current	Constant Voltage
3.	High loss	Less loss
4.	Fast accurate method	Slow control (Capacitor – sluggish)
5.	Larger & more Expensive (Reactor large)	Small & less Expensive
6.	More Fault tolerant and more reliable	Less Fault tolerant and Less reliable
7.	Simple cost	expensive cost
8.	Not expandable in series	Easily Expandable

CONVERTER VALVE ASSEMBLY

CONVERTER TRANSFORMERS (OLTC):

- The converter transformers transform the voltage of the AC bus bar to the required entry voltage of the converter.
- The 12-pulse converter requires two 3-phase systems which are spaced apart from each other by 30 or 150 electrical degrees. This is achieved by installing a transformer on each network side in the vector groups star – star and star-delta.
- The transformer is an interface between AC side and DC side the main insulation, The converter transformers are equipped with on-load tap-changers in order to therefore, is stressed by both the AC voltage and the direct voltage potential between valve-side winding and ground provide the correct valve voltage
- Generally a bridge converter is of 6-Pulse in nature so the transformer can be 3Φ or three 1Φ transformers.
- But for HVDC a 12 pulse converter is needed so two 6 pulse are connected in series
    - Six 1Φ 2 winding Transformer.
    - Three 1Φ 3 winding Transformer.
    - Two 3Φ Transformer.
- It is not possible to use the winding close to the yoke as the potential of winding connection is determined by conducting Valve.
- When some valves are operating they produce harmonics. So these harmonics pass through the transformer so the winding have to be insulated properly.
- When the valves are in non conduction states they experience PIV and this voltage replicated at the converter transformer so to protect the transformer from this higer voltages they should be properly insulated.
- As the DC currents flow in the windings of the transformer there is problem of saturation
- As the leakage flux of a converter transformer contain high harmonics it produces eddy currents, hysteresis loss and hot spots in the transformer tanks.
- Since under fault the fault current flows through the transformer impedance , so to limit this high current the impedance of the transformer should be high
- Transformer is of the OLTC (On Load Tap Change)

SMOOTHING REACTOR:

- Prevention of intermittent current.
- Limitation of the DC fault currents.
- Prevention of resonance in the DC circuit.
- Reducing harmonic currents including limitation of telephone interference

PREVENTION OF INTERMITTENT CURRENT:

- The intermittent current due to the current ripple can cause high over-voltages in the transformer and the smoothing reactor.
- The smoothing reactor is used to prevent the current interruption at minimum load.

LIMITATION OF THE DC FAULT CURRENT:

- The smoothing reactor can reduce the fault current and its rate of rise for commutation failures and DC line faults.
- This is of primary importance if a long DC cable is used for the transmission. For an overhead line transmission, the current stress in valves is lower than the stress which will occur during valve short circuit

PREVENTION OF RESONANCE IN THE DC CIRCUIT:

- The smoothing reactor is selected to avoid resonance in the DC circuit at low order harmonic frequencies like 100 or 150 Hz.
- This is important to avoid the amplification effect for harmonics originating from the AC system, like negative sequence and transformer saturation.

- **REDUCING HARMONIC CURRENTS INCLUDING LIMITATION OF TELEPHONE INTERFERENCE:**
  - Limitation of interference coming from the DC over-head line is an essential function of the DC filter circuits.
  - However, the smoothing reactor also plays an important role to reduce harmonic currents acting as a series impedance**.**

- **HARMONIC FILTERS:**
  - If the switch is operated there is a harmonic in the system.
  - Generally there are characteristic harmonics and non characteristics harmonics present in the system

    Characteristic harmonics
    AC= np±1: DC=np
    Non-Characteristic harmonics
    DC= np±1: AC=np Where n= integer
    P=Pulse Number
  - Filters provide low impedance path to the ground for one or two particular frequencies
  - They are connected to the converter terminals so that harmonics should not enter AC system and also provide necessary reactive power support for the converter operation.
  - The harmonics which are at greater magnitude are only considered for the filter placements.
  - Filters are used at the bus bar also.
  - filters are required for both at AC side also on the DC side.

- **REACTIVE POWER SOURCES:**
  - Generally consumers does not consume reactive power but to the phase displacement of current drawn by the converters and voltage in the AC system .
  - Reactive power requirement at the converter stations is 50% to 60% of the Real power transferred, which is supplied by the filters , capacitors & synchronous condensers.
  - If the generating station is near to the HVDC generators can also provide necessary reactive power support.
  - Synchronous condensers not only provide reactive power support but also provide AC voltage for Natural Commutation of inverter .
  - These reactive power sources not only should operate in normal condition but also should operate in abnormal conditions as well

EARTH ELECTRODE:

- Under Emergency condition ground Return Path is used.
- Earth Resistivity is generally high in the order of 4000 Ω-m.
- Earth electrode cannot be kept directly on the earth surface.
- Electrodes are to be buried deep in the ground where the resistivity is (3-10Ω-m) to reduce transient over voltages during line faults and also gives low DC electric potential and potential gradient at the surface of the earth

CHOICE OF VOLTAGES:

- For example 1000MW, bipolar
    - $P_{DC} = V_{DC} \times I_{DC}$ Monopole
    - $P_{DC} = 2\, V_{DC} \times I_{DC}$ Bipole
- Conductor sizes depending on the voltages Dog, panther, moose, zebra etc are used.
- Generally for DC the right of way is less when compared to AC

MODERN TRENDS IN HVDC TECHNOLOGY:

- Power Semiconductors & Valves.
- Converter Control.
- Dc Breakers.
- Conversion of Existing AC Lines.
- Operation with weak AC system.
- Active Dc Filters.
- Capacitor Commutated Converters (CCC).
- UHVDC Transmission

POWER SEMICONDUCTORS & VALVES:

- current Rating (overload Capacity)
- Direct Light Triggered Thyristors (LTT).
- Power rating of the devices. By better cooling
- Each Thyristor 8KV, 40mW gate power.
- Gate Turn Off thyristor (GTO) - 6KV & 4KA
- Insulated Gate Bipolar Transistor (IGBT) – ±150KV and 350MVA switching

- **CONVERTER CONTROL:**
  - Microprocessor Based control.
  - Experts in fault detection and Rectification
  - Transducers for measuring Voltages and Currents for protection and control.

- **DC BREAKERS:**
  - High Current Breaking.
  - Development of MTDC.

- **CONVERSION OF EXISTING AC LINES:**
  - ROW (Right of Way).
  - Electromagnetic Interference

- **OPERATION WITH WEAK AC SYSTEM:**
  - Short Circuit Ratio **=** ————————————————

SCR <3- weak AC System
SCR =3- Moderate AC System
SCR >3- Strong AC System

More Reactive power is needed to transmit power or else load rejection is done

- **ACTIVE DC FILTERS**:
  - VSC + Passive Filter
  - Characteristic and Non characteristic Harmonics

- **CAPACITOR COMMUTATED CONVERTERS (CCC):**
  - Capacitors in series with Valve Side Windings of the Converter Transformer
  - Forced Commutation.
  - Reactive Power Support

- **UHVDC TRANSMISSION:**
  - ± 800KV HVDC- ± 500KV
  - Power Transmitted 3000MW / 1500Km

HVDC BIPOLAR/ASYNCHRONOUS LINKS IN INDIA

RIHAND-DELHI 2*750 MW	
CHANDRAPUR-PADGE 2* 750 MW	VINDYACHAL (N-W) – 2*250 MW
TALCHER-KOLAR 2*1000 MW	CHANDRAPUR (W-S)– 2*500 MW
SILERU-BARASORE 100 MW	VIZAG (E-S) - 2*500 MW

HVDC IN INDIA BIPOLAR

HVDC LINK	**CONNECTING REGION**	**CAPACITY (MW)**	**LINE LENGTH (Km)**
Rihand – Dadri	North-North	1500	815
Chandrapur - Padghe	West - West	1500	752
Talcher – Kolar	East – South	2500	1367

HVDC IN INDIA BACK TO BACK

HVDC LINK	CONNECTING REGION	CAPACITY (MW)
Vindyachal	North – West	2 x 250
Chandrapur	West – South	2 x 500
Vizag – I	East – South	500
Sasaram	East – North	500
Vizag – II	East – South	500

REFERENCES

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INTRODUCTION TO FACTS CONCEPTS

➢ TRANSMISSION INTERCONNECTIONS:

- The world’s electric power supply systems are widely interconnected, involving connections inside utilities’ own territories which extend to inter-utility interconnections and then to inter-regional and international connections.
- This is done for economic reasons, to reduce the cost of electricity and to improve reliability of power supply.

➢ NEED OF TRANSMISSION INTERCONNECTIONS:

- Transmission network is to pool power plants and load centers in order to minimize the total power generation capacity and fuel cost.
- Adversity of loads, availability of sources, and fuel price in order to supply electricity to the loads at minimum cost with a required reliability.
- If a power delivery system was made up of radial lines from individual local generators without being part of a grid system, many more generation resources would be needed to serve the load with the same reliability, and the cost of electricity would be much higher.

➢ FLOW OF POWER IN AN AC SYSTEM:

- In AC power systems, given the insignificant electrical storage, the electrical generation and load must balance at all times.
- To some extent, the electrical system is self-regulating. If generation is less than load, the voltage and frequency drop, and thereby the load, goes down to equal the generation minus the transmission losses.
- If voltage is propped up with reactive power support, then the load will go up, and consequently frequency will keep dropping, and the system will collapse. Alternately, if there is inadequate reactive power, the system can have voltage collapse.

POWER FLOW IN PARALLEL PATHS

Consider a very simple case of power flow , through two parallel paths (possibly corridors of several lines) from a surplus generation area, shown as an equivalent generator on the left, to a deficit generation area on the right. Without any control, power flow is based on the inverse of the various transmission line impedances

With HVDC, power flows as ordered by the operator, because with HVDC power electronics converters power is electronically controlled. Also, because power is electronically controlled, the HVDC line can be used to its full thermal capacity if adequate converter capacity is provided. Furthermore, an HVDC line, because of its high-speed control, can also help the parallel ac transmission line to maintain stability.

FACTS Controller can control the power flow as required. Maximum power flow can in fact be limited to its rated limit under contingency conditions when this line is expected to carry more power due to the loss of a parallel line.

POWER FLOW IN A MESHED SYSTEM

Suppose the lines AB, BC, and AC have continuous ratings of 1000 MW, 1250 MW, and 2000MW, respectively, and have emergency ratings of twice those numbers for a sufficient length of time to allow rescheduling of power in case of loss of one of these lines. If one of the generators is generating 2000 MW and the other 1000 MW, a total of 3000MW would be delivered to the load center.

For the impedances shown, the three lines would carry 600, 1600, and 1400 MW, respectively, as shown in Figure (a). Such a situation would overload line Be (loaded at 1600 MW for its continuous rating of 1250 MW), and therefore generation would have to be decreased at B, and increased at A, in order to meet the load without overloading line BC. Power, in short, flows in accordance with transmission line series impedances (which are 90% inductive) that bear no direct relationship to transmission ownership, contracts, thermal limits, or transmission losses.

If, however, a capacitor whose reactance is -5 ohms at the synchronous frequency is inserted in one line Figure (b), it reduces the line's impedance from 10 0hm to 5 0hm, so that power flow through the lines AB, BC, and AC will be 250, 1250, and 1750 MW, respectively. It is clear that if the series capacitor is adjustable, then other power-flow levels may be realized in accordance with the ownership, contract, thermal limitations, transmission losses, and a wide range of load and generation schedules.

Although this capacitor could be modular and mechanically switched, the number of operations would be severely limited by wear on the mechanical components because the line loads vary continuously with load conditions, generation schedules, and line outages. Other complications may arise if the series capacitor is mechanically controlled. A series capacitor in a line may lead to sub-synchronous resonance (typically at 10-50 Hz for a 60 Hz system). This resonance occurs when one of the mechanical resonance frequencies of the shaft of a multiple-turbine generator unit coincides with 60 Hz

Similar results may be obtained by increasing the impedance of one of the lines in the same meshed configuration by inserting a 7 ohm reactor (inductor) in series with line AB [Figure (c)]. Again, a series inductor that is partly mechanically and partly thyristor-controlled, it could serve to adjust the steady-state power flows as well as damp unwanted oscillations

- **LOADING CAPABILITY:**
  - THERMAL CAPABILITY
  - DIELECTRIC CAPABILITY
  - STABILITY CAPABILITY
    - TRANSIENT STABILITY
    - DYNAMIC STABILITY
    - STEADY-STATE STABILITY
  - FREQUENCY COLLAPSE
  - VOLTAGE COLLAPSE
  - SUB-SYNCHRONOUS RESONANCE

- **THERMAL CAPABILITY :**
  - Thermal capability of an overhead line is a function of the ambient temperature, wind conditions, condition of the conductor, and ground clearance.
  - It varies perhaps by a factor of 2 to 1 due to the variable environment and the loading history. The nominal rating of a line is generally decided on a conservative basis, envisioning a statistically worst ambient environment case scenario

- **DIELECTRIC CAPABILITY:**
  - From an insulation point of view, many lines are designed very conservatively. For a given nominal voltage rating, it is often possible to increase normal, operation by +10% voltage (i.e., 500 kV-550 kV) or even higher. Care is then needed to ensure that dynamic and transient overvoltages are within limits. On EHV overhead lines switching surges rather than lightining create more serious transient over voltages
  - Switching surges in DC are lower than 1.7 times normal voltage.

- **STABILITY:**
  The ability of system to regain its original state when it is subjected to any disturbances
  - **TRANSIENT STABILITY:** The ability of system to regain its original state when it is subjected to small and large disturbances
  - **DYNAMIC STABILITY:** The ability of system to regain its original state when it is subjected to small and large disturbances with controller action
  - **STEADY-STATE STABILITY**: The ability of system to regain its original state when it is subjected to small and gradual disturbances

- **FREQUENCY COLLAPSE**: If the frequency of the system falls below a preset value then it is Frequency collapse. It can be eliminated by load shedding

- **VOLTAGE COLLAPSE:** If the voltage of the system falls below a preset value then it is voltage collapse. It can be eliminated by injecting excess amount of reactive power in to the system

- **GRID COLLAPSE:** Both voltage and frequency collapse together account for grid collapse

- **SUB-SYNCHRONOUS RESONANCE**: If the mechanical frequency of the turbine and the electrical frequency of the system are equal then this resonance occurs and these frequencies occur below the synchronous speeds if this Resonance occur the consequence is severe which is torsion stress occurs on the shaft which results in shaft breakage.

➢ REACTIVE POWER AND VOLTAGE REGULATION

On Long EHV AC lines and on shorter AC cables the production and consumption of reactive power by the line itself constitutes a serious problem

Consider a line with series inductance L and shunt capacitance C per unit length and operating at a given voltage V and carrying a current I the line produces a reactive power given by $\mathbf{Q_C = \omega CV^2}$ and consumed reactive power $\mathbf{Q_L = \omega LI^2}$**. The net** reactive power in both should be equal

$$Q_C = Q_L$$

$$\omega CV^2 = \omega LI^2.$$

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In this case the load impedance has a value Z_S known as the **Surge Impedance loading** of the line. This SIL of the Over head line with single conductor is about 400Ωand with bundled conductors about 300Ω that of the cable 15 to 25Ω

The power carried by the line is = = — which also called Natural Loading. It is independent of distance and depends on voltage

➢ POWER FLOW AND DYNAMIC STABILITY CONSIDERATIONS OF A TRANSMISSION INTERCONNECTION:

E_1 and E_2 are the magnitudes of the bus voltages with an angle δ between the two. The line is assumed to have inductive impedance X, and the line resistance and capacitance are ignored. As shown in the phasor diagram the driving voltage drop in the line is the phasor difference EL between the two line voltage phasors, E_1 and E_2• The line current magnitude is given by: $I = E_L/X$, and lags E_L by 90

- Active component of the current flow at E_1 is: $I_{P1} = (E_2 \sin \delta)/X$
- Reactive component of the current flow at E_1 is: $I_{ql} = (E_1 - E_2 \cos \delta)/X$
- Thus, active power at the E_1 end: $P_1 = E_1(E_2/X)\sin\delta$
- Reactive power at the E_1 end: = $E_1 (E_1 - E_2 \cos \delta)/X$
- Active component of the current flow at E_1 is: $I_{P2} = (E_1 \sin \delta)/X$
- Reactive component of the current flow at E_1 is: $Iq_2 = (E_2 – E_1 \cos \delta)/X$
- Thus, active power at the E_1 end: $P_2 = E_2(E_1/X)\sin\delta$
- Reactive power at the E_2 end: = $E_2 (E_2 – E_1 \cos \delta)/X$
- Naturally Powers are equal

➢ RELATIVE IMPORTANCE OF CONTROLLABLE PARAMETERS:

- Control of the line impedance X , When the angle is not large, which is often the case, control of X or the angle substantially provides the control of active power.
- Control of angle which in turn controls the driving voltage, provides a powerful means of controlling the current flow and hence active power flow when the angle is not large.
- Injecting a voltage in series with the line, and perpendicular to the current flow, can increase or decrease the magnitude of current flow. Since the current flow lags the driving voltage by 90 degrees, this means injection of reactive power in series, can provide a powerful means of controlling the line current, and hence the active power when the angle is not large.
- Injecting voltage in series with the line and with any phase angle with respect to the driving voltage can control the magnitude and the phase of the line current. This means that injecting a voltage phasor with variable phase angle can provide a powerful means of precisely controlling the active and reactive power flow. This requires injection of both active and reactive power in series.
- Combination of the line impedance control with a series Controller and voltage regulation with a shunt Controller can also provide a cost-effective means to control both the Active and Reactive Power Flow between the two systems.

➢ FLEXIBILITY OF ELECTRIC POWER TRANSMISSION:

- The ability to accommodate changes in the electric transmission system or operating conditions while maintaining sufficient steady state and transient margins.

➢ FLEXIBLE AC TRANSMISSION SYSTEM (FACTS)

- Alternating Current transmission systems incorporating Power Electronic-based and other Static Controllers to enhance controllability and increase Power Transfer Capability.

➢ FACTS CONTROLLERS:

- A power electronic-based system and other static equipment that provide control of one or more A C transmission system parameters

BASIC TYPES OF FACTS CONTROLLERS:

- SERIES CONTROLLERS
- SHUNT CONTROLLERS
- COMBINED SERIES-SERIES CONTROLLERS
- COMBINED SERIES-SHUNT CONTROLLERS

- **SERIES CONTROLLERS:**
  - The series Controller could be a variable impedance, such as capacitor, reactor, etc., or a power electronics based variable source of main frequency, sub-synchronous and harmonic frequencies (or a combination) to serve the desired need.
  - In principle, all series Controllers inject voltage in series with the line. Even a variable impedance multiplied by the current flow through it, represents an injected series voltage in the line.
  - As long as the voltage is in phase quadrature with the line current, the series Controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

- **SHUNT CONTROLLERS:**
  - As in the case of series Controllers, the shunt Controllers may be variable impedance, variable source, or a combination of these.
  - In principle, all shunt Controllers inject current into the system at the point of connection.
  - Even a variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of current into the line.
  - As long as the injected current is in phase quadrature with the line voltage, the shunt Controller only supplies or consumes variable reactive power.
  - Any other phase relationship will involve handling of real power as well.

- **COMBINED SERIES-SERIES CONTROLLERS:**
  - This could be a combination of separate series controllers, which are controlled in a coordinated manner, in a multiline transmission system. Or it could be a unified Controller, in which series Controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link.
  - The real power transfer capability of the unified series-series Controller, referred to as Interline Power Flow Controller, makes it possible to balance both the real and reactive power flow in the lines and thereby maximize the utilization of the transmission system. Note that the term "**Unified**" here means that the DC terminals of all Controller converters are all connected together for real power transfer

- **COMBINED SERIES-SHUNT CONTROLLERS:**
  - This could be a combination of separate shunt and series Controllers, which are controlled in a coordinated manner or a Unified Power Flow Controller with series and shunt elements.
  - In principle, combined shunt and series Controllers inject current into the system with the shunt part of the Controller and voltage in series in the line with the series part of the Controller. However, when the shunt and series Controllers are unified, there can be a real power exchange between the series and shunt Controllers via the power link

- **SERIES CONNECTED CONTROLLERS:**
  - Static Synchronous Series Compensator (SSSC)
  - Interline Power Flow Controller (IPFC)
  - Thyristor Controlled Series Capacitor (TCSC)
  - Thyristor-Switched Series Capacitor (TSSC)
  - Thyristor-Controlled Series Reactor (TCSR)
  - Thyristor-Switched Series Reactor (TSSR)

- **STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC):**
  - A static synchronous generator operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power**.**

- **INTERLINE POWER FLOW CONTROLLER (IPFC):**
  - It is a combination of two or more Static Synchronous Series Compensators which are coupled via a Common DC link to facilitate bi-directional flow of real power between the AC terminals of the SSSC's, and are controlled to provide independent reactive compensation for the adjustment of real power flow in each line and maintain the desired distribution of reactive power flow among the lines.
  - The IPFC structure may also include a STATCOM, coupled to the IFFC's common DC link, to provide shunt reactive compensation and supply or absorb the overall real power deficit of the combined SSSC's.

- **THYRISTOR CONTROLLED SERIES CAPACITOR (TCSC):**
  - A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor- controlled reactor in order to provide a smoothly variable series capacitive reactance.

- **THYRISTOR-SWITCHED SERIES CAPACITOR (TSSC):**
  - A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-switched reactor to provide a stepwise control of series capacitive reactance.

- **THYRISTOR-CONTROLLED SERIES REACTOR (TCSR):**
  - An inductive reactance compensator which consists of a series reactor shunted by a thyristor controlled reactor in order to provide a smoothly variable series inductive reactance.

- **THYRISTOR-SWITCHED SERIES REACTOR (TSSR):**
  - An inductive reactance compensator which consists of a series reactor shunted by a thyristor-controlled switched reactor in order to provide a stepwise control of series inductive reactance.

- **SHUNT CONNECTED CONTROLLERS:**
  - STATIC SYNCHRONOUS COMPENSATOR (STATCOM)
  - STATIC SYNCHRONOUS GENERATOR (SSG)
  - BATTERY ENERGY STORAGE SYSTEM (BESS)
  - SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES)
  - STATIC VAR COMPENSATOR (SVC)
  - THYRISTOR CONTROLLED REACTOR (TCR)
  - THYRISTOR SWITCHED REACTOR(TSR)
  - THYRISTOR SWITCHED CAPACITOR (TSC)
  - STATIC VAR GENERATOR OR ABSORBER (SVG)
  - STATIC VAR SYSTEM (SVS)
  - THYRISTOR CONTROLLED BRAKING RESISTOR (TCBR)

- **STATIC SYNCHRONOUS COMPENSATOR (STATCOM)**
    - A Static synchronous generator operated as a shunt-connected static VAR compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage.

- **STATIC SYNCHRONOUS GENERATOR (SSG):**
    - A static self- commutated switching power converter supplied from an appropriate electric energy source and operated to produce a set of adjustable multiphase output voltages, which may be coupled to an ac power system for the purpose of exchanging independently controllable real and reactive power.

- **BATTERY ENERGY STORAGE SYSTEM (BESS):**
    - A chemical-based energy storage system using shunt connected, voltage-source converters capable of rapidly adjusting the amount of energy which is supplied to or absorbed from an ac system.

- **SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES):**
    - A Superconducting electromagnetic energy storage device containing electronic converters that rapidly injects and/or absorbs real and/or reactive power or dynamically controls power flow in an ac system.

- **Static VAR Compensator (SVC):**
    - A shunt-connected static VAR generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage).

- **THYRISTOR CONTROLLED REACTOR (TCR):**
  - A shunt-connected, thyristor-controlled inductor whose effective reactance is varied in a continuous manner by partial-conduction control of the thyristor valve.
- **THYRISTOR SWITCHED REACTOR(TSR):**
  - A shunt- connected, thyristor-switched inductor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve.
- **THYRISTOR SWITCHED CAPACITOR (TSC):**
  - A shunt-connected, thyristor-switched capacitor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve.
- **STATIC VAR GENERATOR OR ABSORBER (SVG):**
  - A static electrical device, equipment, or system that is capable of drawing controlled capacitive and/or inductive current from an electrical power system and thereby generating or absorbing reactive power.
  - Generally considered to consist of shunt-connected, thyristor-controlled reactor(s) and/or thyristor-switched capacitors.
- **STATIC VAR SYSTEM (SVS):**
  - A combination of different static and mechanically-switched VAR compensators whose outputs are coordinated.
- **Thyristor Controlled Braking Resistor (TCBR):**
  - A shunt-connected thyristor-switched resistor, which is controlled to aid stabilization of a power system or to minimize power acceleration of a generating unit during a disturbance.
- **COMBINED SHUNT AND SERIES CONNECTED CONTROLLERS:**
  - UNIFIED POWER FLOW CONTROLLER (UPFC)
  - THYRISTOR-CONTROLLED PHASE SHIFTING TRANSFORMER (TCPST)
  - INTERPHASE POWER CONTROLLER (IPC)
- **UNIFIED POWER FLOW CONTROLLER (UPFC):**
  - A combination of static synchronous compensator (STATCOM) and a static series compensator (SSSC) which are coupled via a common de link, to allow bidirectional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM, and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source.

- **THYRISTOR- CONTROLLED PHASE SHIFTING TRANSFORMER (TCPST):**
    - A phase-shifting transformer adjusted by thyristor switches to provide a rapidly variable phase angle.
- **INTERPHASE POWER CONTROLLER (IPC):**
    - A series-connected controller of active and reactive power consisting, in each phase, of inductive and capacitive branches subjected to separately phase-shifted voltages. The active and reactive power can be set independently by adjusting the phase shifts and/or the branch impedances, using mechanical or electronic switches

UNIT-II

ANALYSIS OF RECTIFIER CIRCUITS

- **ASSUMPTIONS AND JUSTIFICATIONS:**
  - AC Source has no impedance and delivers **constant Voltage** of **Sinusoidal** waveform at **constant Frequency**.
  - If polyphase it delivers **Balance Voltages**.
  - Transformers have no leakage Impedances or Exciting Admittances
  - DC load has infinite inductance (DC current is constant and ripple free).
  - Valve is ideal (**zero resistance** during Conduction and **infinite resistance** in Non Conduction state)

DEFINITIONS:

- **VALVE RATING**: It is Volt ampere rating of a valve which is the product of Average Current to Peak Inverse Voltage

- **PEAK INVERSE VOLTAGE(PIV):** It is the peak voltage that occurs across the valve during Non Conduction state

- **TRANSFORMER VA RATING:** It is the product of RMS voltage and RMS currents of either primary or secondary windings.

- **PULSE NUMBER (p):** It is number of pulsations of output DC voltage per one cycle of AC voltage input

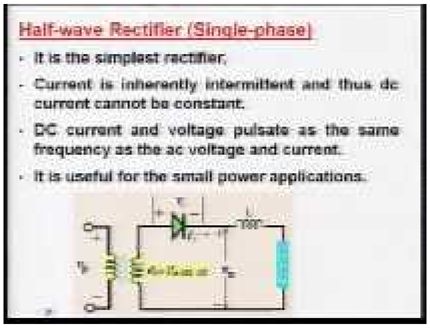
$$\mathbf{p = q * s * r}$$

- **COMMUTATION GROUP(q)**: A group of Valves in which one valve conducts at a time (Neglecting Overlap)

Where s = No of series Valves

r = No of Parallel valves

CONVERTER CIRCUITS



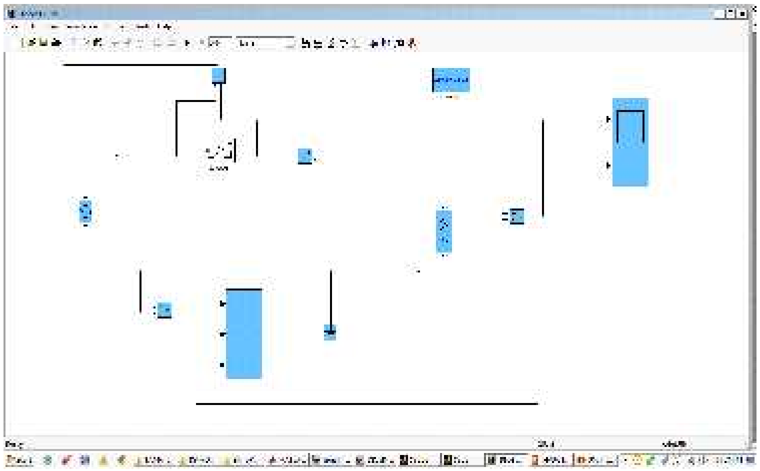
Half-wave Rectifier (Single-phase)

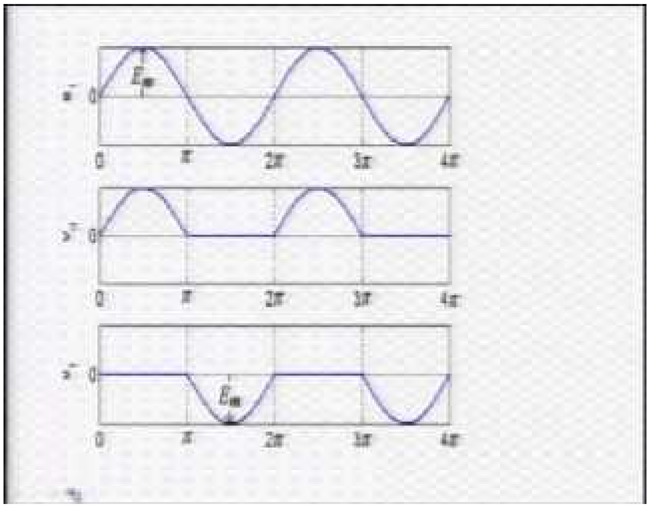
- It is the simplest rectifier.
- Current is inherently intermittent and thus dc current cannot be constant.
- DC current and voltage pulsate as the same frequency as the ac voltage and current.
- It is useful for the small power applications.

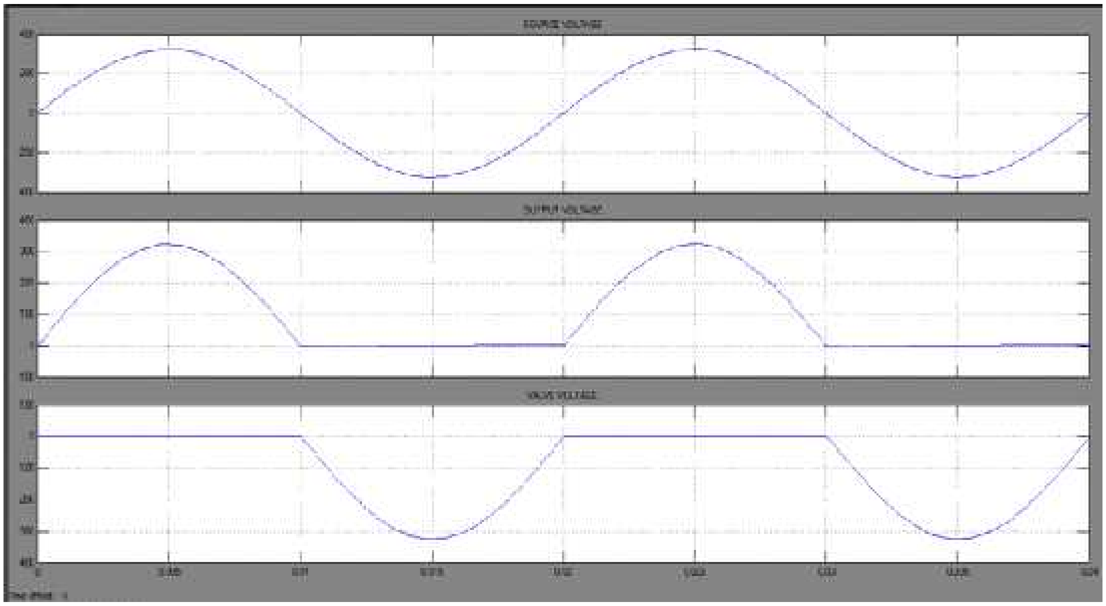
õ= HALF WAVE RECTIFIER:

- It is the simplest rectifier
- Current is inherently intermittent hence DC current cannot be constant.
- DC Voltage and current fluctuate at same frequency as that of AC voltage and currents.

õ= It is used for **Small Power Applications**







Average DC Voltage:

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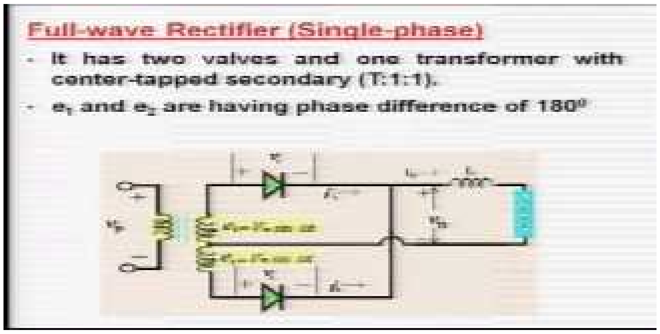
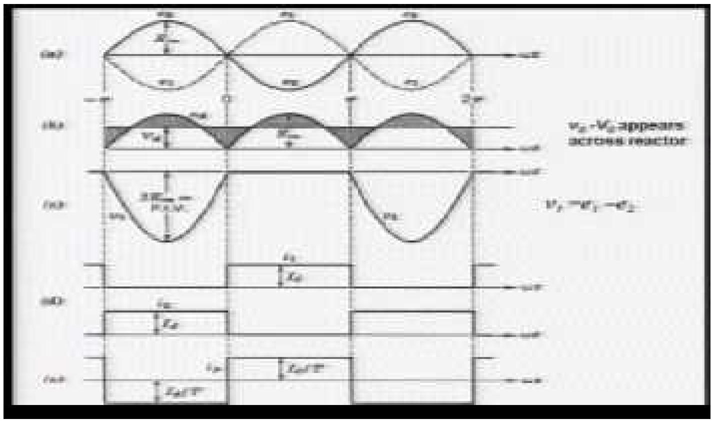
- **PIV = V_m**
- **Pulse number= 1**
- **Average Current = I_d**
- **Valve Rating = $V_m I_d$**
- **One Valve**

FULL WAVE MIDPOINT RECTIFIER:

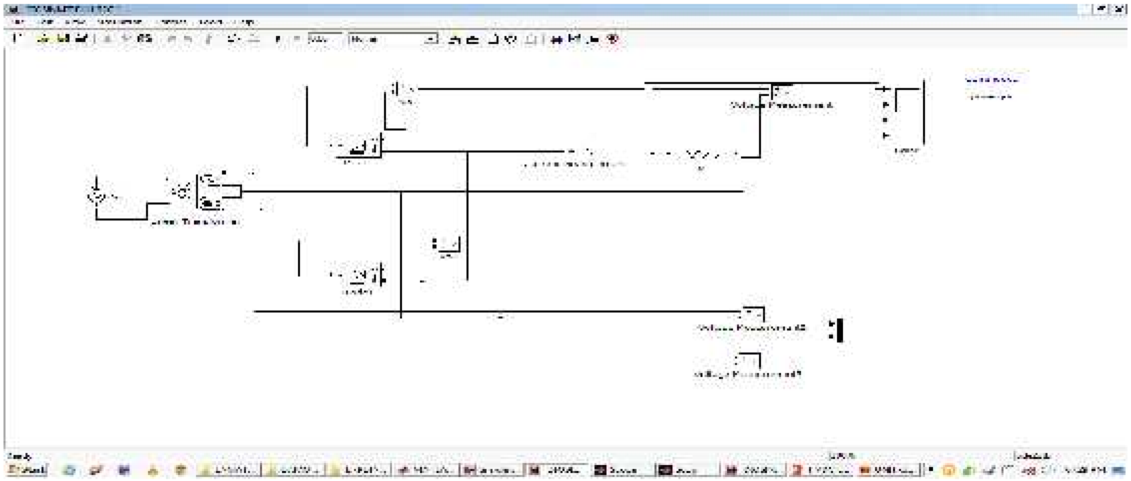
- It has two valves and one transformer with centered tapped secondary (T:1:1).
- The secondary has a phase difference of 180^0
- 

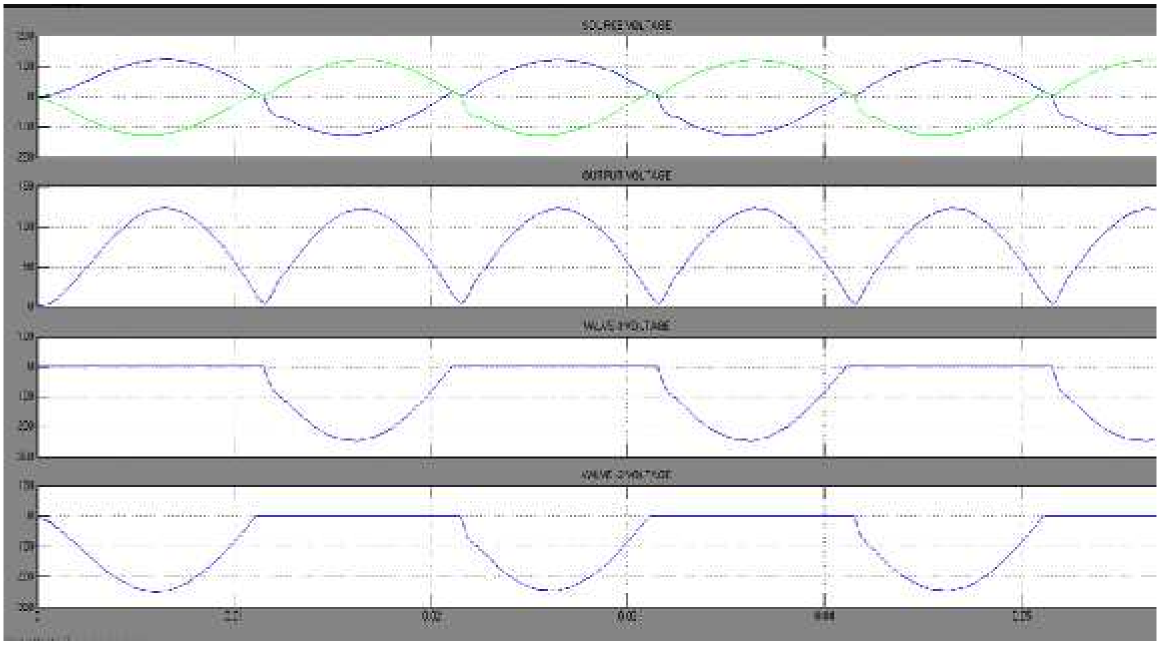
Full-wave Rectifier (Single-phase)

- It has two valves and one transformer with center-tapped secondary (T:1:1).
- e_1 and e_2 are having phase difference of 180^0



TUF is low (50%)





Average DC Voltage:

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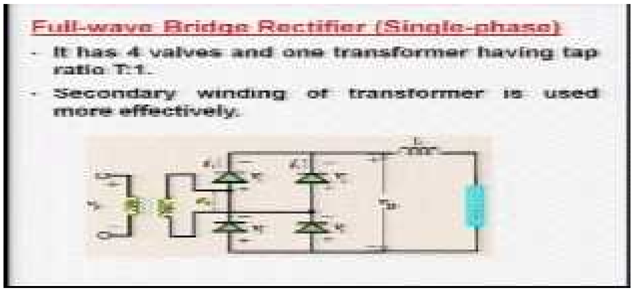
õ- **PIV = 2V$_m$**

- **Pulse Number=2**
- **Average Current = $I_d/2$**
- **Valve Rating = $V_m I_d$**
- **Two valves**

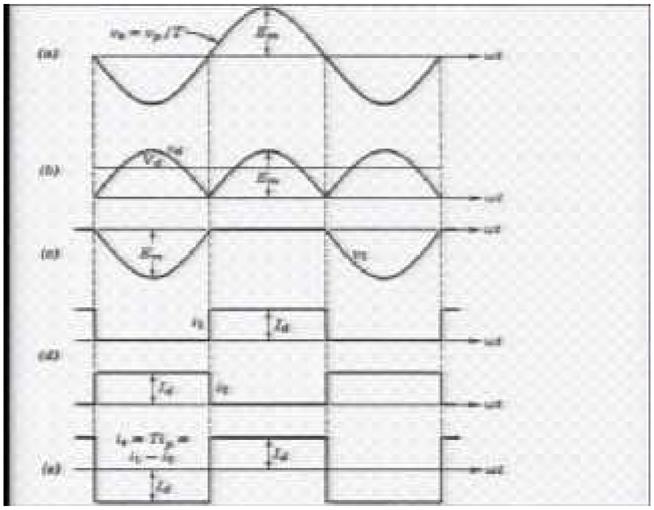
- **FULL WAVE BRIDGE RECTIFIER:**

- It has four valves and one transformer with tap ratio T:1.
- 

  Full-wave Bridge Rectifier (Single-phase)

  - It has 4 valves and one transformer having tap ratio T:1.
  - Secondary winding of transformer is used more effectively.

  TUF = 100%


(a)
E_m
ωt
(b)
E_m
ωt
(c)
E_m
ωt
(d)
i_1
I_d
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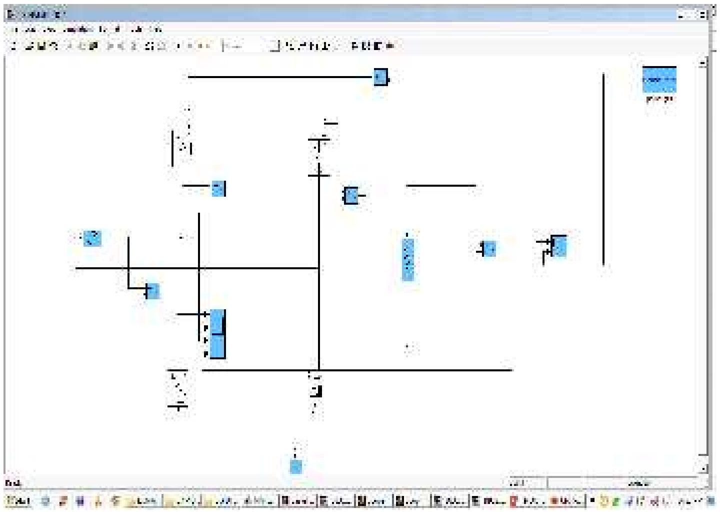
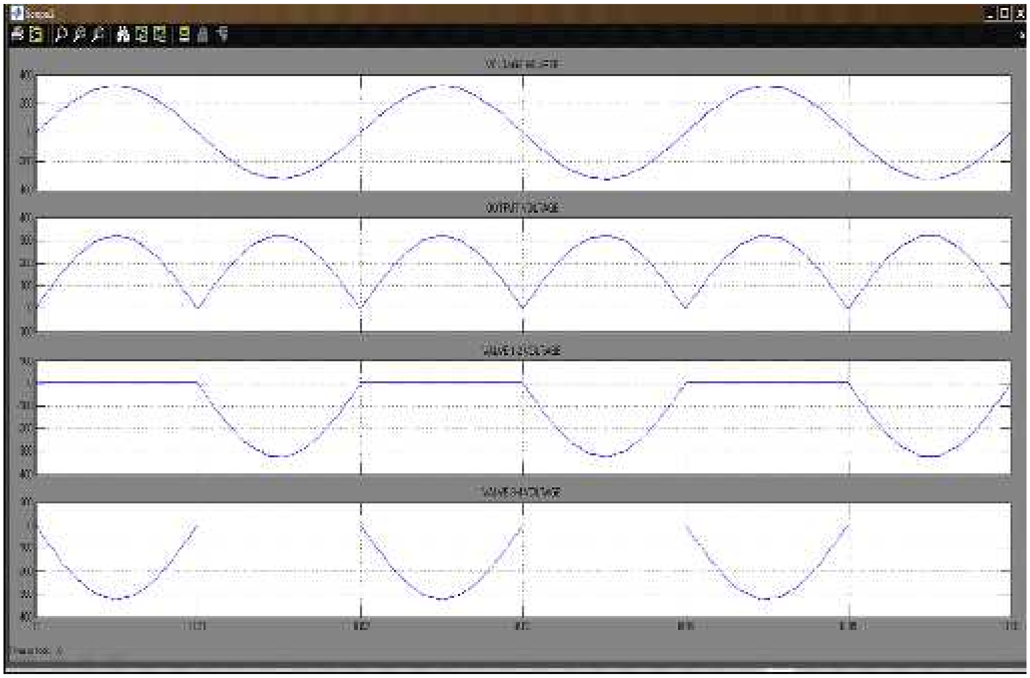
(e)
I_d
I_d
ωt





Average DC Voltage:

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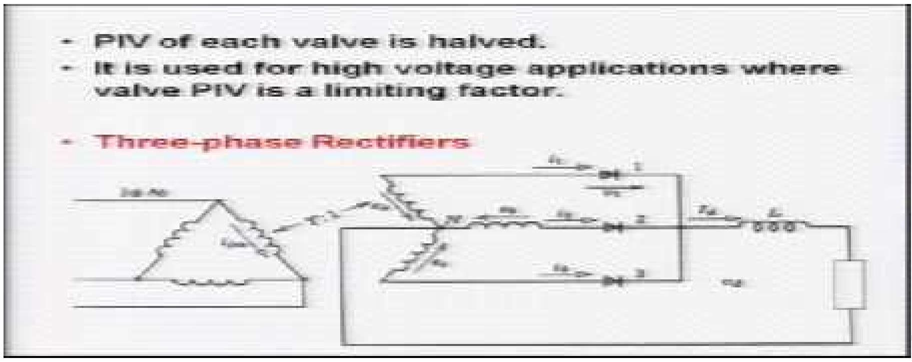
- **PIV = V_m**
- **Pulse Number=2**
- **Average Current = $I_d/2$**
- **Valve Rating = 0.5 V_m I_d**
- **Four Valves**

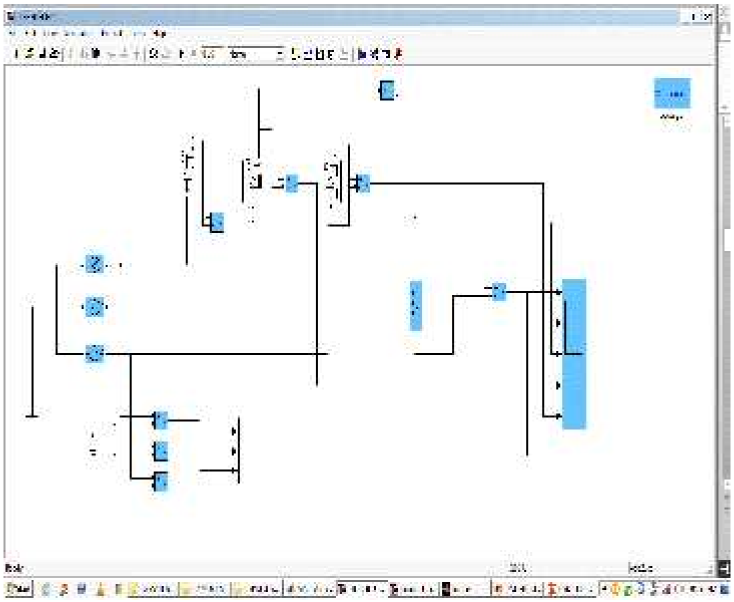
- **PIV is halved**

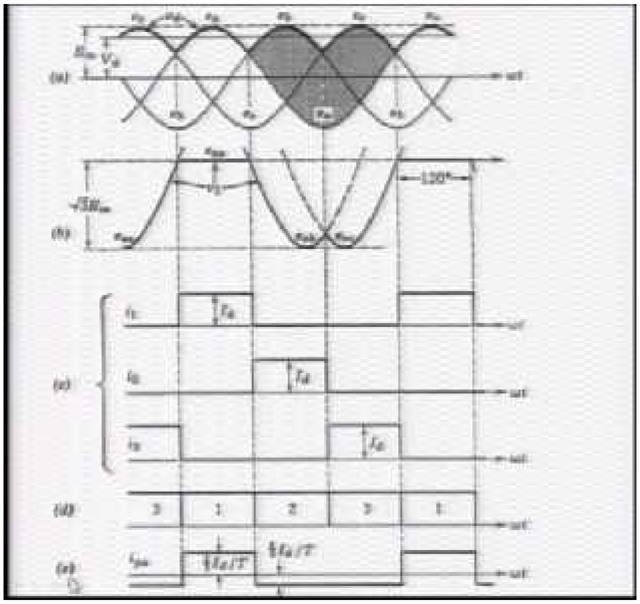
- **It is used for High Power Applications**

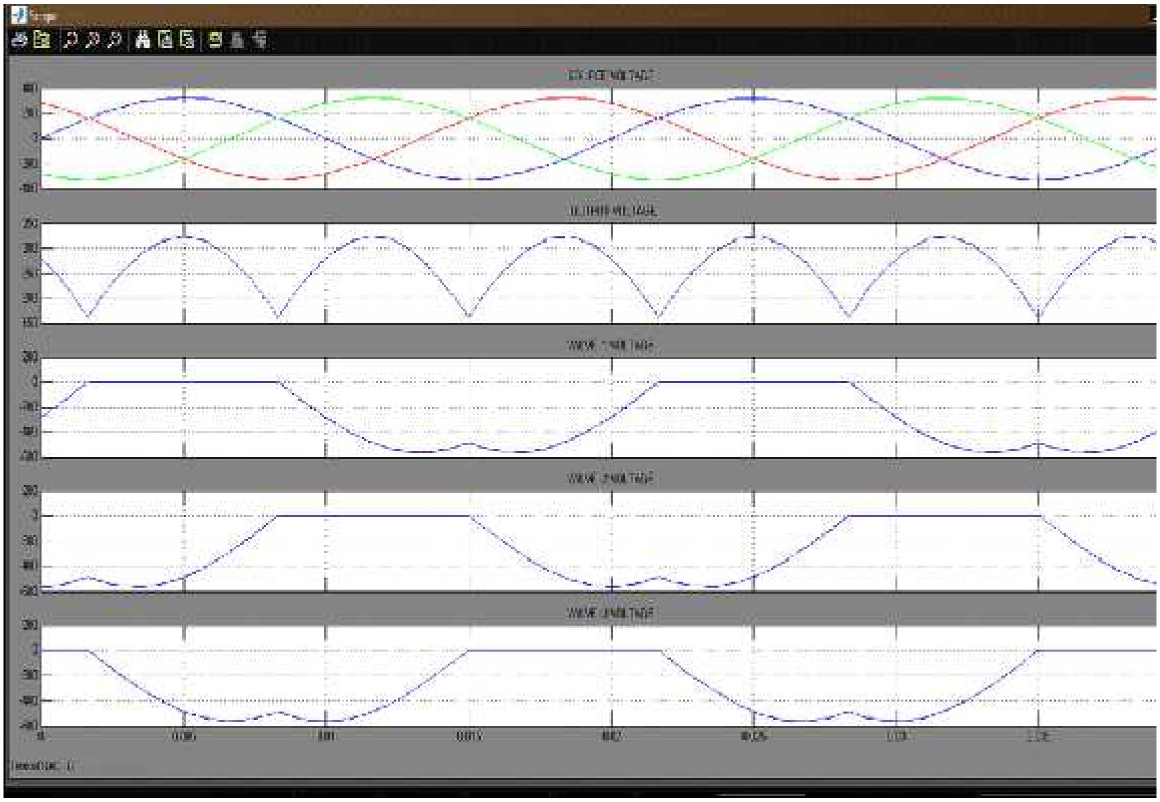


- PIV of each valve is halved.
- It is used for high voltage applications where valve PIV is a limiting factor.
- Three-phase Rectifiers

THREE PHASE ONE WAY RECTIFIER:




(a)
(b)
(c)
(d)
(e)
E_m
V_d
$\sqrt{3}E_m$
120°
I_d
3
1
2
3
1
ωt


SOURCE VOLTAGE
OUTPUT VOLTAGE
VALVE 1 VOLTAGE
VALVE 2 VOLTAGE
VALVE 3 VOLTAGE
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035

Average DC Voltage:

=

- **PIV = V_m**
- **Pulse Number=3**
- **Six Valves**
- **It is used for High Power Applications**

GENERALIZATION: p= q x s x r = 3 x 1 x 1= 3

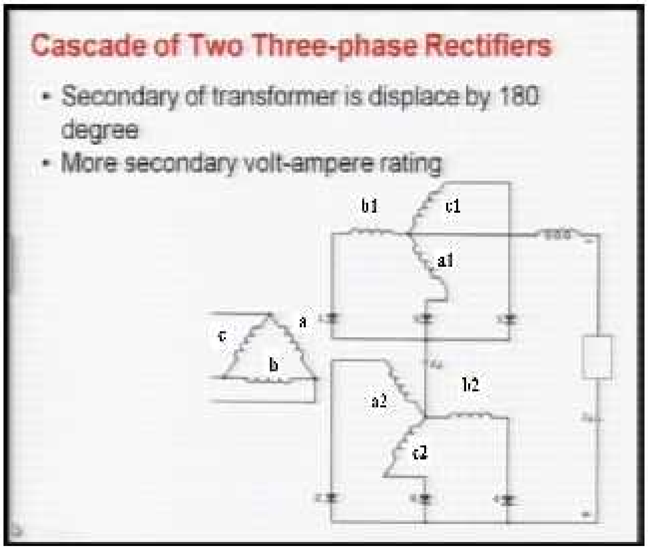
Dc output voltage:

sin(π/q)

If s series valves then

sin(π/q)

- **TOPOLOGIES OF SIX PULSE CONVERTERS:**
  - CASCADE OF TWO THREE PHASE RECTIFIERS
  - PARALLEL CONNECTION WITH INTERPHASE TRANSFORMER
  - SIX PHASE DIAMETRICAL CONNECTION
  - CASCADE OF THREE SINGLE PHASE FULL WAVE RECTIFIERS
  - THREE PHASE TWO WAY RECTIFIER

õ= 

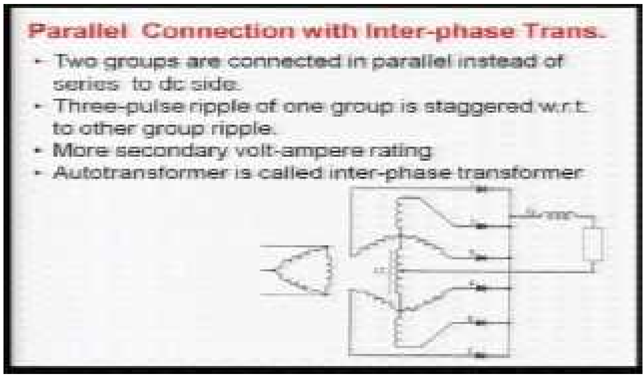
Cascade of Two Three-phase Rectifiers

- Secondary of transformer is displace by 180 degree
- More secondary volt-ampere rating

CASCADE OF TWO THREE PHASE RECTIFIERS:

- Two three phase groups of valves are in series on the DC side.
- Both groups have common cathode.
- Both transformers are connected in star star in $180^{0.}$
- TUF is poor
- Secondary has more VA rating

õ= PARALLEL CONNECTION WITH INTERPHASE TRANSFORMER:

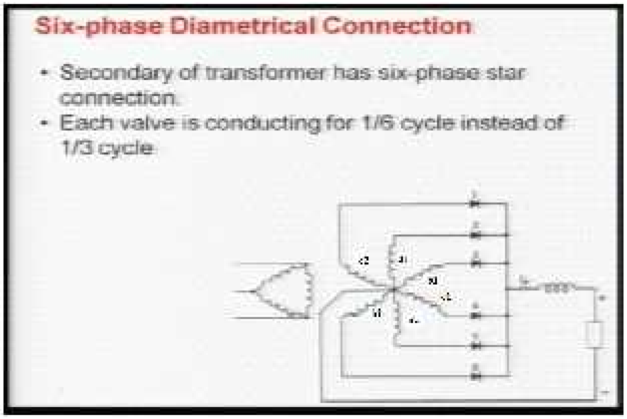


Parallel Connection with Inter-phase Trans.

- Two groups are connected in parallel instead of series to dc side.
- Three-pulse ripple of one group is staggered w.r.t. to other group ripple.
- More secondary volt-ampere rating
- Autotransformer is called inter-phase transformer

- Instead of two valve groups in series now they are connected in parallel.
- They cannot be connected directly in parallel as the pulse ripple is staggered wrt ripple of the other
- One DC pole is connected directly to like pole and other to other pole through a Autotransformer. This Autotransformer is also called Interface transformer.
- Here instantaneous voltages of the centre tap is equal to instantaneous voltages of the two ends of the winding.
- More secondary ampere turns
- This topology is not used for HVDC applications

õ= SIX PHASE DIAMETRICAL CONNECTION:



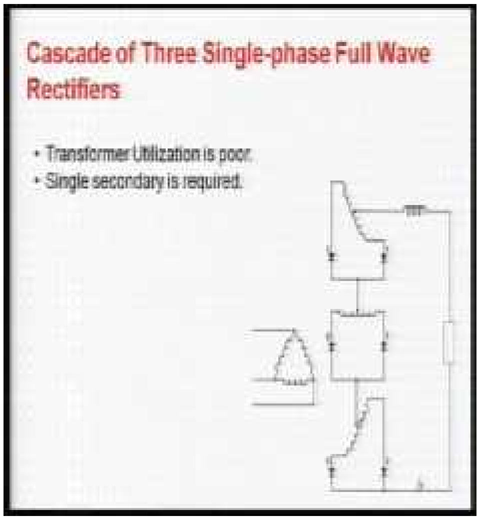
Six-phase Diametrical Connection

- Secondary of transformer has six-phase star connection.
- Each valve is conducting for 1/6 cycle instead of 1/3 cycle

- Instead of interphase transformer all the secondary Y points are solidly connected form a six phase.

- It is made of one centre tapped winding per core instead of two separate winding cores.
- Each valve conducts for 1/6th of the cycle instead of 1/3rd as in the three phase connection.
- TUF is poorer

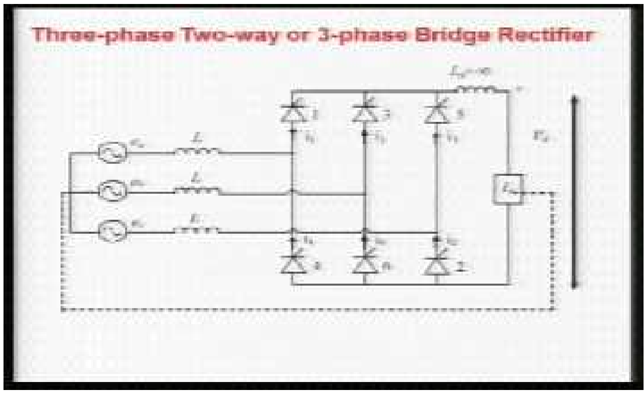
õ= **CASCADE OF THREE SINGLE PHASE FULL WAVE RECTIFIERS:**



Cascade of Three Single-phase Full Wave Rectifiers

- Transformer Utilization is poor.
- Single secondary is required.

- It appears like it gives more DC output voltage wrt PIV but not.
- TUF is poor

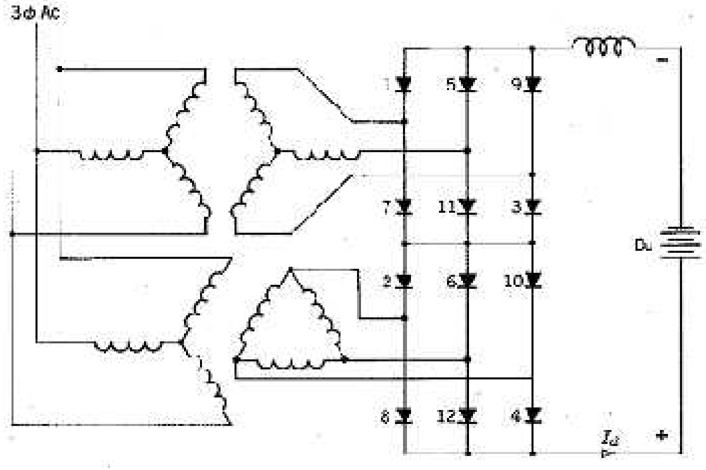
õ= 

Three-phase Two-way or 3-phase Bridge Rectifier

THREE PHASE TWO WAY RECTIFIER:

- In the circuit (3 phase one way), if the three phases are reversed the circuit operates as before but the directions of the DC voltages and currents are reversed.
- In the bridge converter the same transformer is feeding the two one way rectifiers of opposite connections.
- The output voltage is doubled and thus power for the same current but the PIV is same. Thus this circuit is used for high voltage and high power applications.
- No DC current in the transformer windings.
- Pulse number is 6

õ=



TWELVE PULSE CONVERTER:

- Here two six pulse converters are connected in series.
- One converter is connected to phase star – star connection and other in star –delta.
- Y-Y- 6 Pulse + Y-Δ- 6 Pulse= 12 Pulse.
- One converter gives 6 Pulse output and due to phase displacement of 30^0 gives another 6 pulse and total in series which is 12 Pulses

DESIRED FEATURES OF THE CONVERTER CIRCUIT:

õ= High Pulse Number (p).

õ= PIV/V_{d0} should be as low as possible.

- V_{d0}/V should be as high as possible.
- TUF should be near to unity.

õ= **High Pulse Number (p):**

- The converter should have high pulse number if pulse number increases the low order harmonics are eliminated.

õ= **PIV/V_{d0}:**

- This ratio should be as low as possible.
- Cost of the Valve becomes low is the PIV is less.
- The cost of the Valve depends on the valve rating which depends on PIV if PIV is less cost decreases.
- The output voltage of the converter should be as high as possible.

õ= **V_{d0}/E:**

- This ratio should be as high as possible.
- The output voltage of the converter should be as high as possible.
- The input of the converter should be low.
- We expect with less input output should be high.

õ= **TRANSFORMER UTILIZATION FACTOR(TUF):**

- This factor gives us the information how best the transformer material is utilized.
- TUF should be near to unity.

TUF = Transformer Rating/ DC power output

- If q is Even, then the PIV occurs when the valve with a phase displacement of 180^0 is

  conducting and will be equal to **PIV = E_m.**

- If q is odd PIV occurs when the valve with phase displacement of π +(π/q) is

  conducting and will be equal to

$$\mathbf{PIV = 2E_m \cos(\pi/2q)}$$

- The ratio of PIV/V_{d0} is given by

- The ratio of V_{d0}/E is given by

- The current rating of the transformer is given by

From DC current waveform

- The transformer rating will be

- Transformer Utilization Factor is given by

we can say that TUF is a function of q

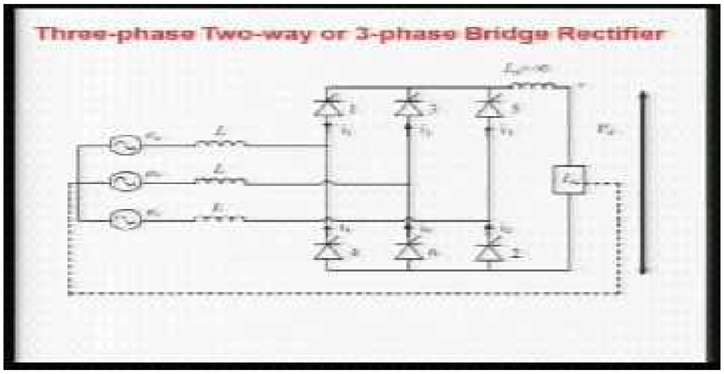
6 Pulse Converter						
S:No	**q**	**r**	**S**	**PIV/V_{d0}**	**V_{d0}/E**	**TUF**
1	2	1	3	1.047	2.700	1.571
2	2	3	1	3.142	0.900	1.571
3	3	1	2	1.047	2.340	1.481
4	3	2	1	2.094	1.169	1.481
5	6	1	1	2.094	1.350	1.814

*From the above table we can pick up S:No: 1 and 3 but TUF is good for S:No: 3

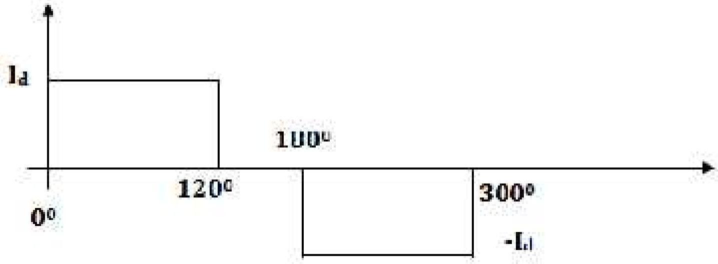
*The configuration which is best suited for **q=3, r=1 and s=2** is nothing but **Bridge Circuit** and it also called "**EUROPEAN GRAETZ CIRCUIT"**

The current rating of the transformer can be further increased by a factor of while decreasing the no of the winding by a factor of 2

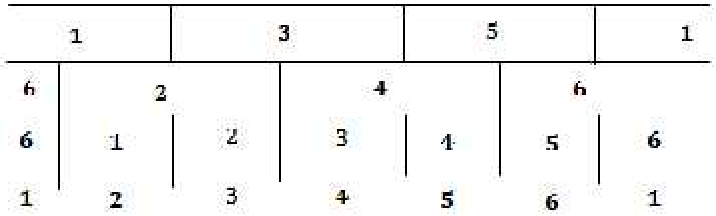
EUROPEAN GRAETZ CIRCUIT:



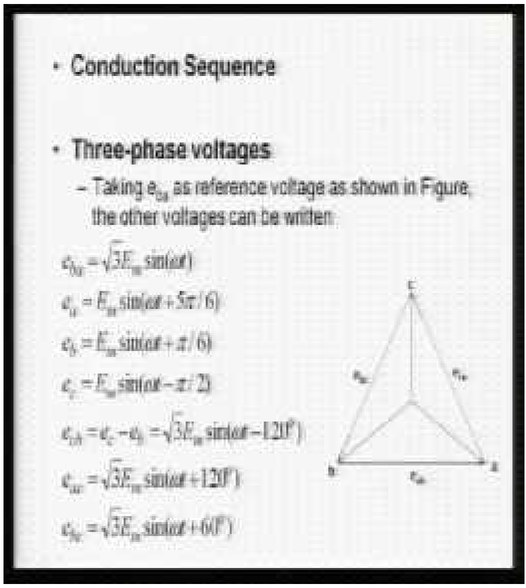
Three-phase Two-way or 3-phase Bridge Rectifier



CONDUCTION SEQUENCE:



- If no overlap at any given instant two devices will be conducting one from upper and one from lower



- Conduction Sequence
- Three-phase voltages
  - Taking e_{ba} as reference voltage as shown in Figure, the other voltages can be written

$$e_{ba} = \sqrt{3}E_m \sin(\omega t)$$
$$e_a = E_m \sin(\omega t + 5\pi/6)$$
$$e_b = E_m \sin(\omega t + \pi/6)$$
$$e_c = E_m \sin(\omega t - \pi/2)$$
$$e_{cb} = e_c - e_b = \sqrt{3}E_m \sin(\omega t - 120^\circ)$$
$$e_{ac} = \sqrt{3}E_m \sin(\omega t + 120^\circ)$$
$$e_{bc} = \sqrt{3}E_m \sin(\omega t + 60^\circ)$$

Here for three phase voltages $\mathbf{e_{ba}}$ is taken as

reference

ASSUMPTION:

- Power sources consisting of balance sinusoidal EMF of constant voltage and frequency with equal lossless inductances.
- The DC current is constant.
- Valves have zero resistances when on an infinite resistance when off.
- Valves are fired with equal intervals of 60^0.
- A valve is fired when there is sufficient forward voltage across it and gate pulse is available

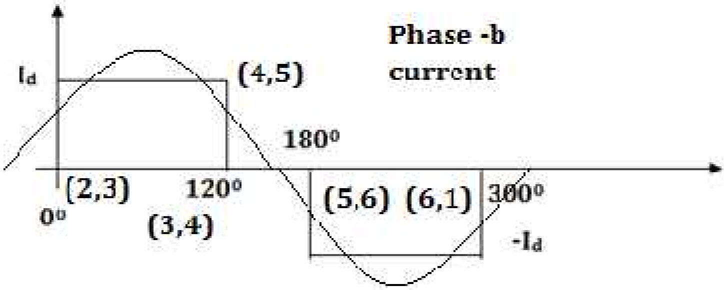
MODE-1:

Average output Voltage with-out overlap : when 1 and 2 are fired at some interval 3 is about to get fired when 3 is fired then one will be off and valve 2 and 3 starts conducting the output voltage is E_{bc}

- For α $< 90^0$ the converter acts as Rectifier = +ve
- For α $> 90^0$ the converter acts as Inverter = - ve
- For α $= 90^0$ = 0

- Although delay angle α can vary from 0 to 180^0 delay angle cannot be less than certain minimum limit (α min = 5^0) in order to ensure the firing of all series connected Thyristors.
- Similarly the upper limit of the delay angle is also restricted due to turnoff of the valve.
- The α value is not allowed to go beyond (180^0 – γ) where γ is the Extinction angle it is also called minimum margin angle which is typically 15^0.
- However in normal operation of the inverter it is not allowed to go below 15^0 the value of the γ will be in between (15^0 - 20^0).

FUNDAMENTAL CURRENT:



Fundamental Peak current:

Where I_1 is the fundamental component of current

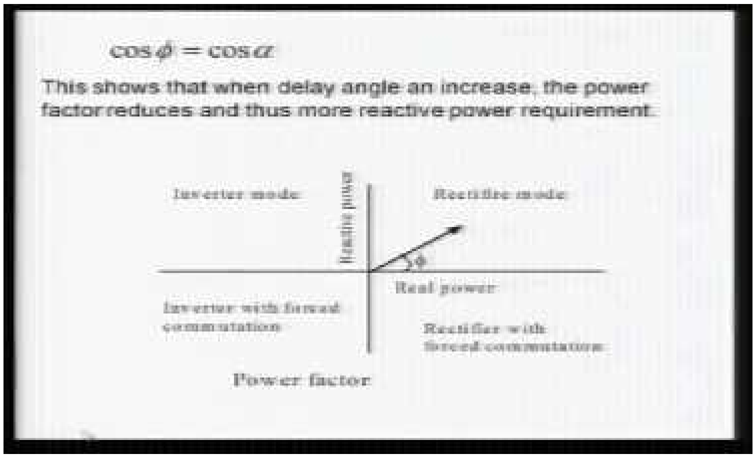
I_h is harmonic current

Total Current = Harmonic current + fundamental current

POWER FACTOR:

Where

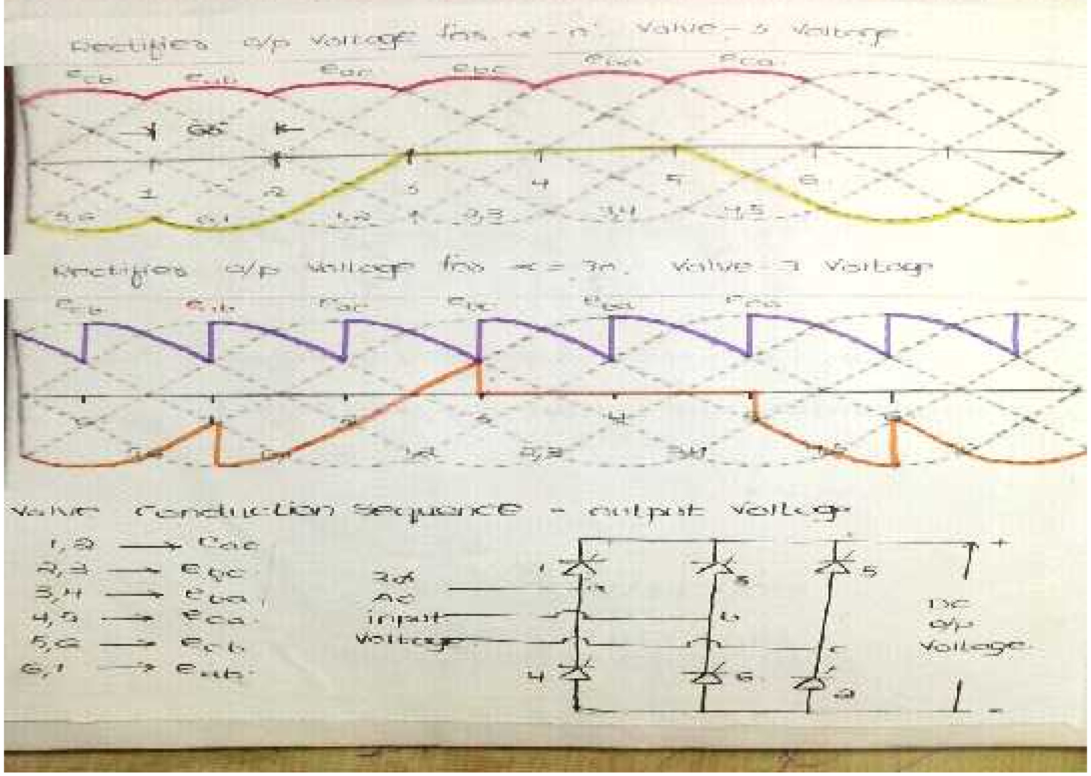
Neglecting the losses



$$\cos\phi = \cos\alpha$$

This shows that when delay angle an increase, the power factor reduces and thus more reactive power requirement.

Power factor

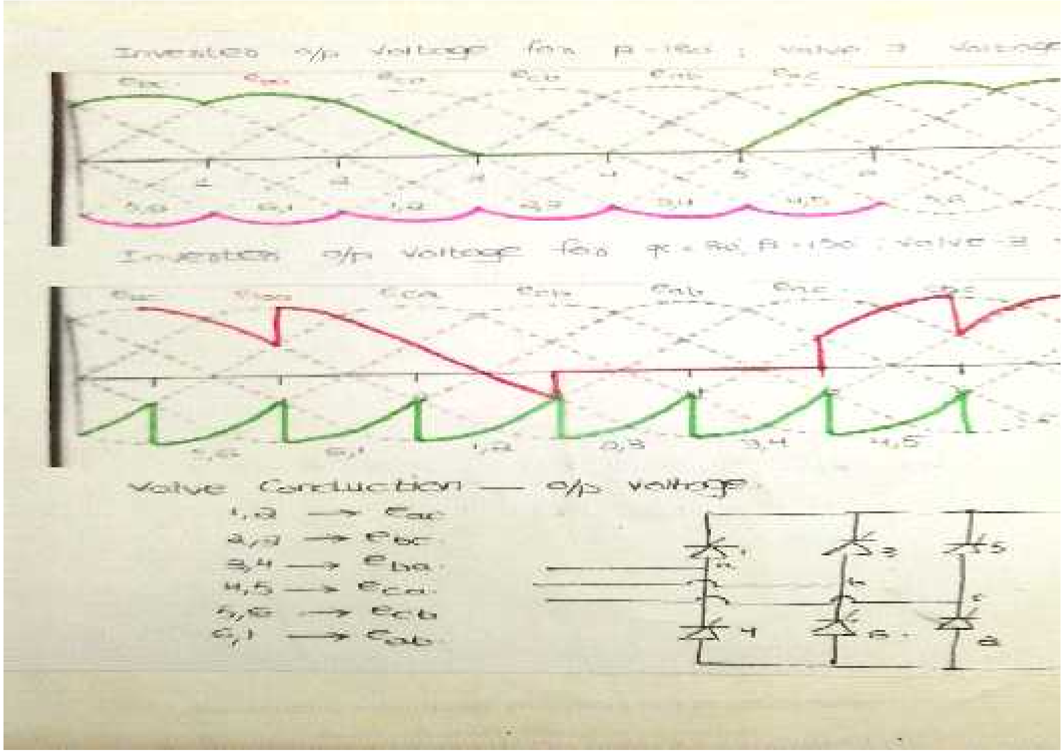


Rectifier o/p voltage for $\alpha = 0^\circ$. Valve & voltage

Rectifier o/p voltage for $\alpha = 30^\circ$. Valve & Voltage

Valve conduction sequence - output voltage

1,2 → e_{ac}
2,3 → e_{bc}
3,4 → e_{ba}
4,5 → e_{ca}
5,6 → e_{cb}
6,1 → e_{ab}



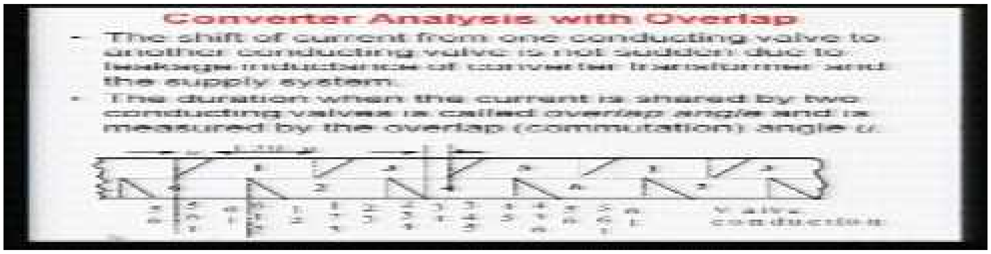
OVERLAP ANGLE (μ):

- The duration when the current is shared by conducting valves in a commutation group is called overlap angle and measured by overlap angle.
- The overlap angle depends on the source inductance the current from one phase to other phase will not be instantaneous there fore depending on the overlap angle the conduction of no of valves will be dependent.

Based on the overlap angle there are three modes of operation

S:No	Mode of operation	Overlap value	No of devices Conducting	Case
1	Mode-1	$\mu = 0$	2	Ideal
2	Mode-2	$\mu < 60^0$	2 to 3	Practical
3	Mode-3	$\mu = 60^0$	3	Practical
4	Mode-4	$\mu > 60^0$	3 to 4	Worst

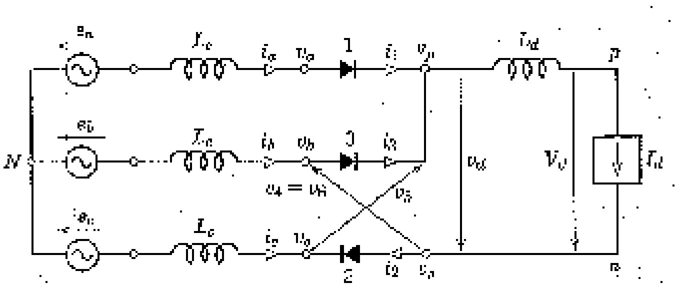
MODE-2: Two To Three Valves Conduction



Converter Analysis with Overlap

- The shift of current from one conducting valve to another conducting valve is not sudden due to leakage inductance of converter transformer and the supply system.
- The duration when the current is shared by two conducting valves is called *overlap angle* and is measured by the overlap (commutation) angle *u*.

Here in mode-2 valve 1 and 2 starts conduction when valve 3 starts due to inductance the current shifts from valve 1 to 3 will not take place instantaneously during the current sharing period valve 1 2 and 3 will be conducting



Applying nodal analysis at node-A

Adding above two equations we get

But we know during commutation $I_1 + I_3 = I_d$

Derivating the above equation we get

Substituting the above relation in the equation we get

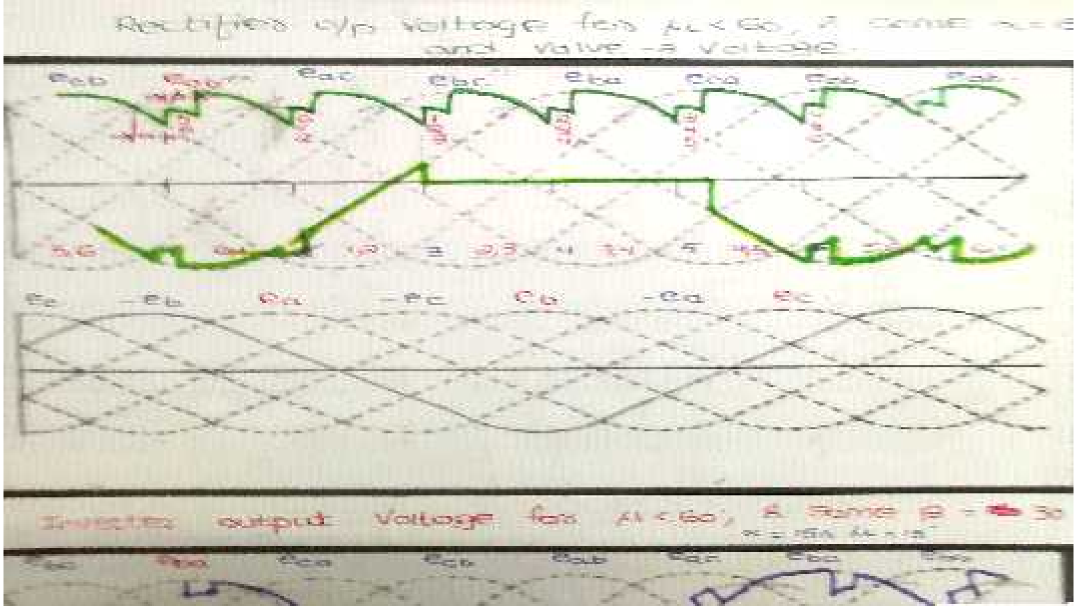
In our Assumption we have

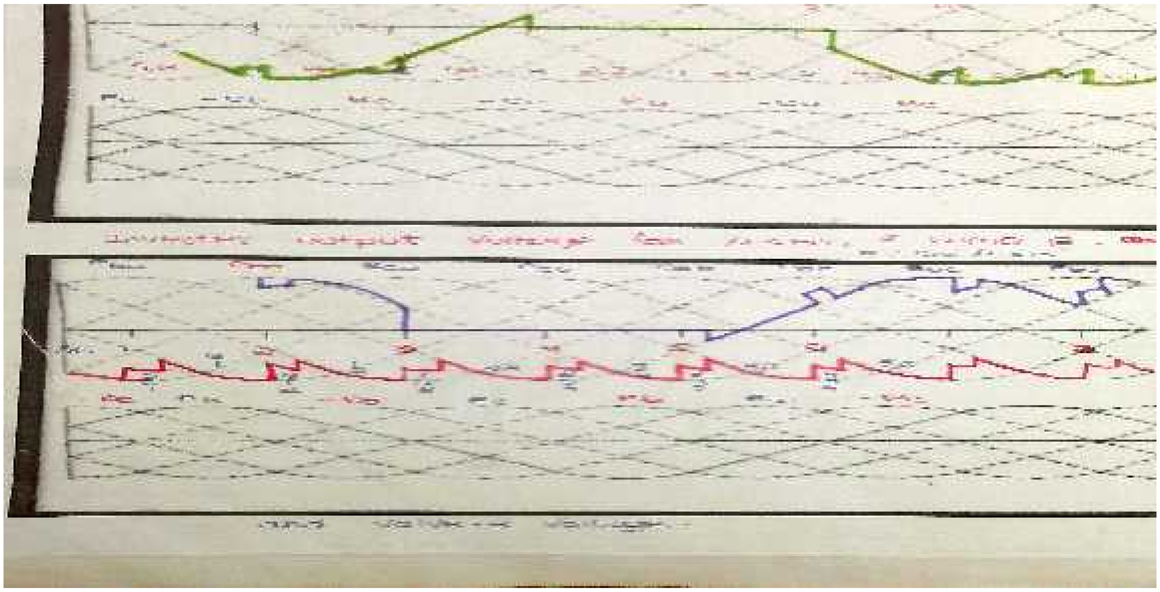
But

Therefore the instantaneous DC output voltage of the bridge is

The Average DC Voltage

OR





PATTERN OF CURRENT SHIFT:

Subtracting above two equations we get

But we know during commutation $I_1 + I_3 = I_d$

Integrating the above equation we get

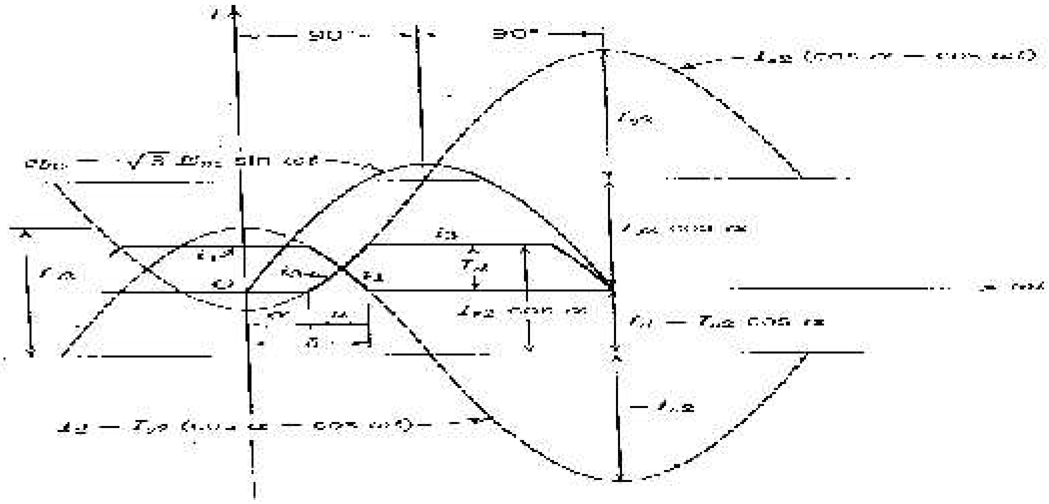
Where A is the Integral Constant in order to find the constant A we have to use initial conditions

At **ωt = α** the instant valve 3 is fired the value of **= 0**

Substituting the value of A in the above

for α ≤ ≤ α+μ

But we know that $I_1 + I_3 = I_d$



EQUIVALENT CIRCUIT OF HVDC:

We know that from the above derivation

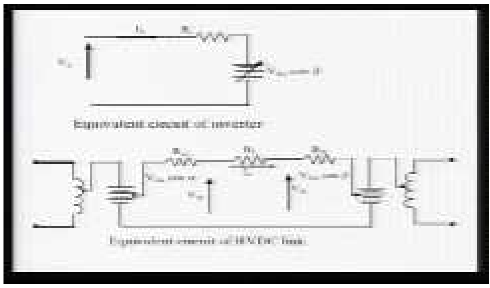
At **$\omega t = \alpha + \mu$** the instant valve 3 is taking care of complete current and Valve-1 is off is fired the value of **$= I_d$**

Substituting in above equation:

Here in the above Equation **α is Controllable** and **μ is not controllable**

Put this cos(α+μ) value in the above output voltage equation then we get

Where R_C is the commutating Reactance



EQUIVALENT CIRCUIT OF RECTIFIER

For Inverter the process is same but the parameters are different in rectifiers we use delay angle α, δ=α+μ for the inverter we use Advance Angle β= π-α and Extinction Angle γ= β-μ

The DC voltage in the Inverter Operation is

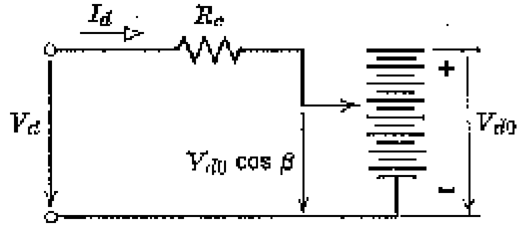
The DC voltage is taken as Negative because inverter uses Opposite Polarity

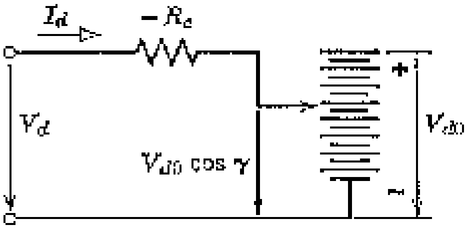
Instead of β if we want to use γ for inverter equation then the equation becomes

From

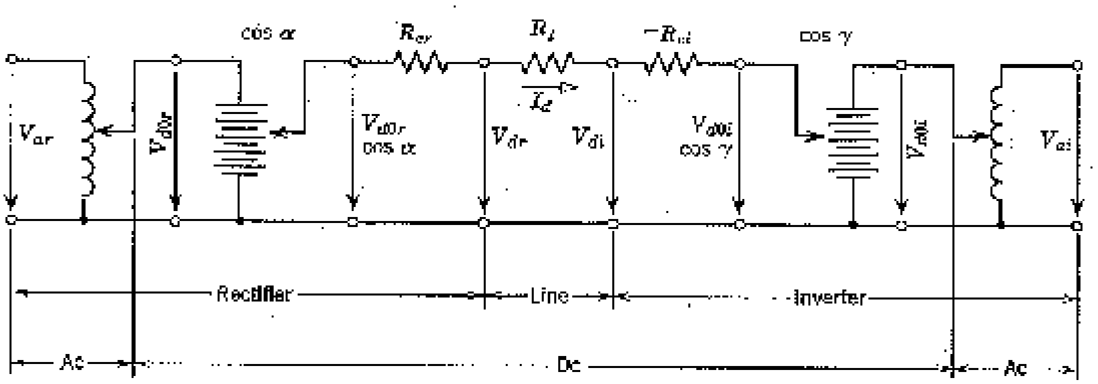
Substituting the above value in

EQUIVALENT CIRCUIT OF INVERTER





OVERALL EQUIVALENT CIRCUIT OF HVDC SYSTEM

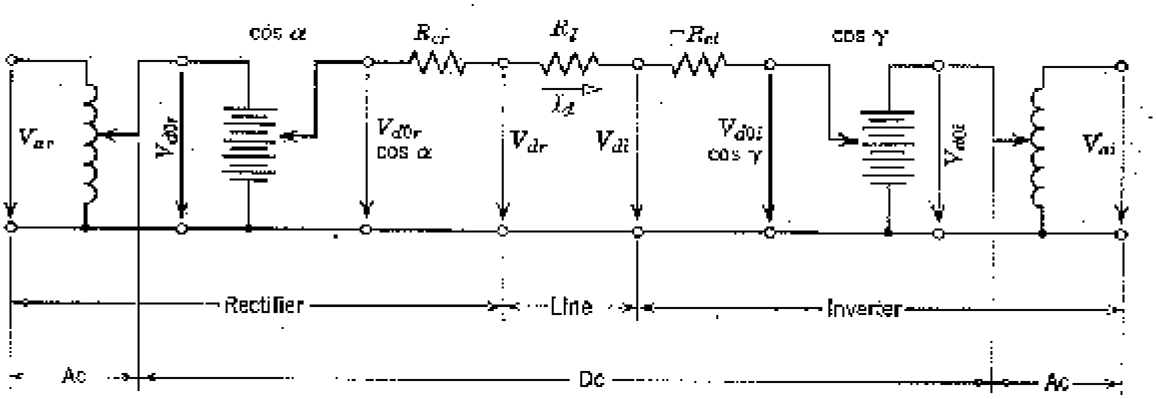


UNIT-III

HVDC CONTROL

Basic means of control:

OVERALL EQUIVALENT CIRCUIT OF HVDC SYSTEM



From the overall equivalent circuit of HVDC system

$$\mathbf{I_d} = \frac{\mathbf{V_d}\ \ c\ \ \alpha - \mathbf{V_d}\ \ c\ \ (\beta/\gamma)}{\mathbf{R_C} + \mathbf{R_L} \pm \mathbf{R_C}}$$

The DC voltage and current in the DC link can be controlled by controlling rectifier voltages and inverter voltages using two methods

- **GRID CONTROL**
- **MANUAL CONTROL**

- **GRID CONTROL:** It is done by varying ignition angle of the valves. It is rapid or instantaneous control

- **MANUAL CONTROL:** It is done changing the taps ratio of the converter transformer. It is slow and done in steps
  Power reversal can be done by changing the polarity of the DC voltage at both ends

BASIS FOR SELECTION OF THE CONTROL:

- Prevention of large fluctuating current due to variations of AC voltages
- Maintaining the DC voltage near to its rated
- Maintaining the power factor at the sending and receiving end as high as possible
- Prevention of various faults in the valves

What is the Need for power factor high?

- To keep the rated power in the converter as high as possible wrt given voltage, current, voltage ratings of the transformer and the valves.
- To reduce the stress on the valve.
- To minimize the losses and the current ratings of the equipment in the AC system to which the converter is connected.
- To minimize the voltage drops as the load increases.
- To minimize the reactive power supplied to the converter

DESIRED FEATURES OF THE CONTROLLER:

- Control system should not be sensitive to normal variations in voltage and frequency of the AC supply system.
- Control should be fast reliable and easy to implement.
- There should be continuous operating range of full Rectification to full Inversion.
- Control should be such that it should require less reactive power.
- Under at steady state conditions the valves should be fired symmetrically.
- Control should be such that it must control the maximum current in the DC link and limit the fluctuations of the current.
- Power should be controlled independently and smoothly which can be done by controlling the current or voltage or both.
- Control should be such that it can be used for protection of the line and the converter

CONSTANT VOLTAGE	CONSTANT CURRENT
Voltage is constant	Current is constant
Current is varied to change power	Voltage is varied to change power
Loads and power sources are connected in parallel in order to turnoff a load or a source respective branch is opened	Loads and power sources are connected in series in order to turn off a load or source it should be bypassed
AC transmission and DC Distribution	Street lighting in DC
DC system the fault current can be greater limited by circuit resistance	Short circuit current is ideally limited by load current and it is twice of the rated current and Accidental open circuits give rise to huge voltages
Power loss is α (power transmitted)^2	Power loss is α full load value

From the overall equivalent circuit of HVDC system

$$I_d = \frac{V_d \cos \alpha - V_d \cos (\beta/\gamma)}{R_c + R_L \pm R_c}$$

$$V_d = \frac{V_d}{2}[\cos(\mu + \alpha) + \cos(\alpha)]$$

We know that

$$\cos(\alpha) = 0.5[\cos(\mu + \alpha) + \cos(\alpha)]$$

$$\cos(\alpha) = 0.5[\cos(\mu + \alpha) + \cos(\gamma)]$$

Therefore for achieving high power factor α for rectifier and γ for inverter should be kept as low as possible

The rectifier has minimum α limit of about 5^0 to ensure adequate voltage across the valves before firing . consequently the rectifier normally operates within in the range of 15^0 and 20^0 so as to leave a room for increasing rectifier voltage to control DC power flow.

In the case of the inverter it is necessary to maintain the a certain minimum Extinction angle to avoid commutation failure. It is important to ensure that commutation is completed with sufficient margin to allow deionization before voltage reverses $\gamma = \beta - \mu$. The minimum margin for this is 15^0 to 50Hz and 18^0 for 60Hz supply.

In order to satisfy basic requirements for better voltage regulation and current regulation it is always be advisable to assign these parameters for the converters. Under normal operations **Rectifier** will take care of the **current** and the **Inverter** will take care of the **voltage**.

Rectifier - Constant Current Control (CC)

Inverter - Constant Extinction Angle Control (CEA)

Let us examine how AC voltages changes reflect in the DC current and which controller has to be exercised to make DC link current at rated value.

$$I_d = \frac{V_{dor}\cos\alpha - V_{doi}\cos(\beta/\gamma)}{R_c + R_L \pm R_c}$$

- **INCREASE IN THE RECTIFIER VOLTAGE:** Current in the DC link will increase to control the current in the rectifier end, controller will increase delay angle α while at the inverter end controller will maintain CEA. Increase in the delay angle worsens the power factor. Generally it is controlled in steps thereafter tap change is done

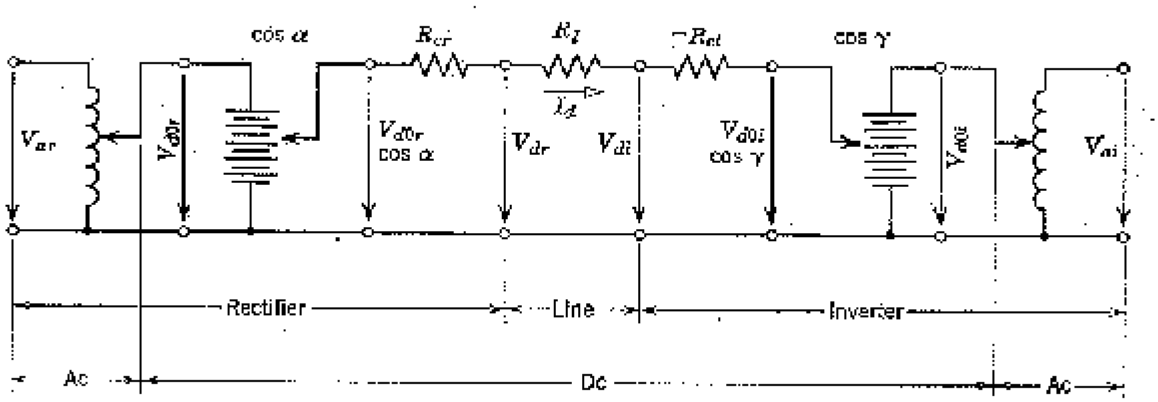
- **INCREASE IN THE INVERTER VOLTAGE** : Current in the DC link will decrease to control the current in the rectifier end, controller will decrease delay angle α up to α_{min} while at the inverter end controller will maintain CEA. decrease in the delay angle improves the power factor. Generally it is controlled in steps thereafter tap change is done

- **DECREASE IN THE RECTIFIER VOLTAGE: :** Current in the DC link will decrease to control the current in the rectifier end, controller will decrease delay angle α up to α_{min} while at the inverter end controller will maintain CEA. decrease in the delay angle improves the power factor. Generally it is controlled in steps thereafter tap change is done. If the further decrease in the rectifier voltage characteristics falls below and CEA characteristics does not intersect then Dc link current will be zero. Therefore inverter also should be equipped with constant current controller

- **DECREASE IN THE INVERTER VOLTAGE**: Current in the DC link will increase to control the current in the rectifier end, controller will increase delay angle α while at the inverter end controller will maintain CEA. Increase in the delay angle worsens the power factor. Generally it is controlled in steps thereafter tap change is done

CHARACTERISTICS OF THE HVDC SYSTEM:

Slope of α, β and γ characteristics



$$\mathbf{V_d = V_d \; c \;\; \alpha - R_C I_d}$$

$$\mathbf{V_d = V_d \; c \;\; (\beta/\gamma) \pm R_C I_d}$$

In this setup we have modeled the rectifier and inverter only missing is the line the resistance of the line we have to include the resistance of the line either with rectifier or with the inverter

Voltage drop across the line = $R_L I_d$

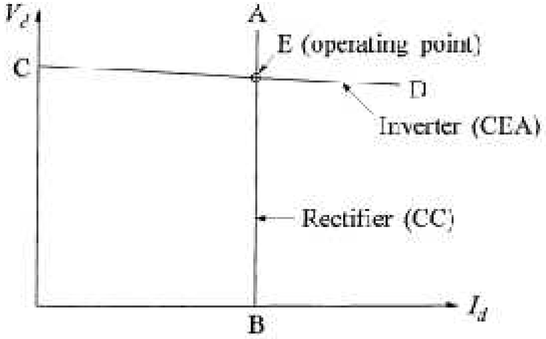
Including the drop along the rectifier we get

$$V_d = V_d \;\; c \;\; \alpha - (R_C + R_L) I_d$$

$$V_d = V_d \;\; c \;\; (\beta) + R_C I_d$$

$$V_d = V_d \;\; c \;\; \gamma - R_C I_d$$

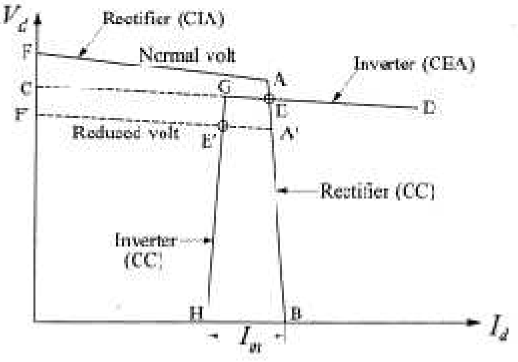
IDEAL CHARACTERISTICS: Rectifier will take care of current so it is a line parallel to Y axis. As Inverter equation with gama is negative slope. The point where rectifier current control and inverter voltage control coincide there exist a operating point which is the power order of the HVDC link



The rectifier characteristics can be shifted horizontally by adjusting the current command or current order. If the measured current is less than the command the regulator advances the firing by decreasing α.

The inverter characteristics can be raised or lowered by means of the transformer tap changer. When the tap is moved the CEA regulator quickly restores the desired gama. As a result the DC current changes which is then quickly restored by current regulator of the rectifier.

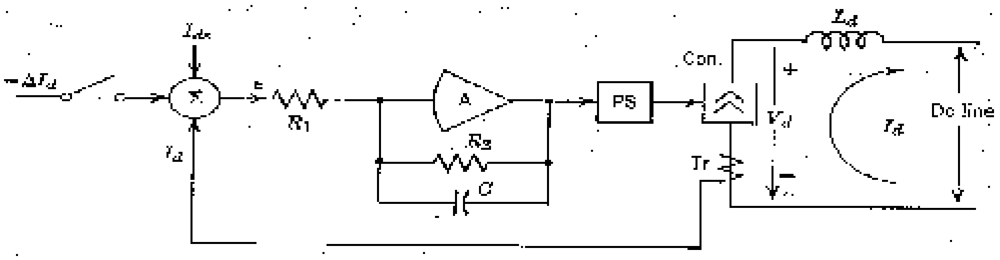
ACTUAL CHARACTERISTICS:

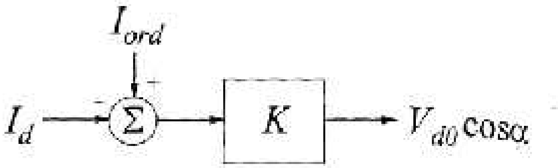


- The rectifier maintains constant current in the DC link by changing α however α cannot be less than α_{min}. Once α_{min}. is hit no further increase in voltage is possible. This is called Constant Ignition Angle Control(CIA)

- In practice as current controller will have a proportional controller it has high negative slope due to finite gain of the controller

CONSTANT CURRENT CONTROLLER:





I_{ord} = current order

With the current regulator gain K

$$V_d\ \ c\ \ \alpha = K(I_o - I_d)$$

$$V_d\ \ c\ \ \alpha = V_d + R_c I_d$$

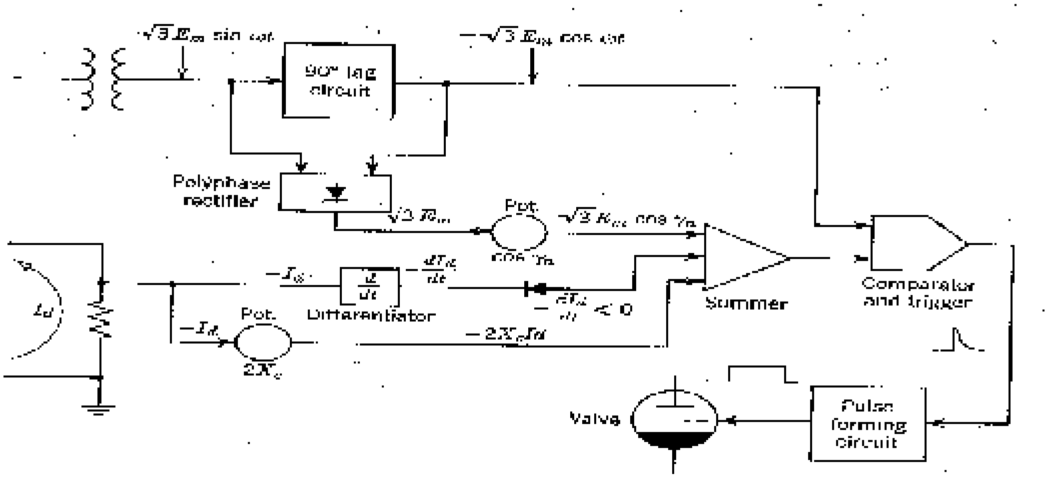
There fore

$$V_d = KI_o - (K + R_c)I_d)$$

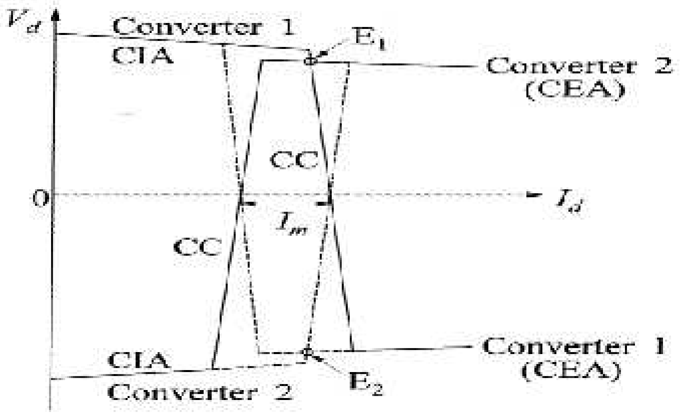
CONSTANT CURRENT CONTROL INVOLVES THE FOLLOWING:

- Measurement of the DC current.
- Comparison of I_d with the set value I_{ds} or I_{ord} (called as Reference/Current Order /Current Command).
- Amplification to the differences called error.
- Application of the output signal of the amplifier to the phase shift circuit that alters the ignition angle α of the valves in the proper direction for reducing the error.

CONSTANT EXTINCTION ANGLE CONTROL:



COMBINED RECTIFIER AND INVERTER CHARACTERISTICS:

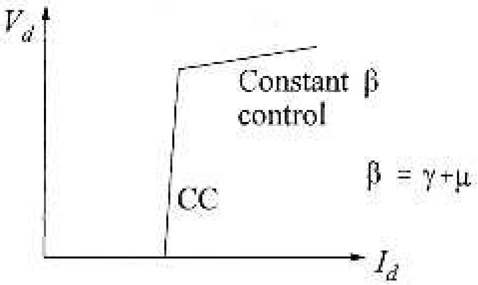


Power reversal can be done by changing the current settings of the converter and inverter which is shown in the dotted line above

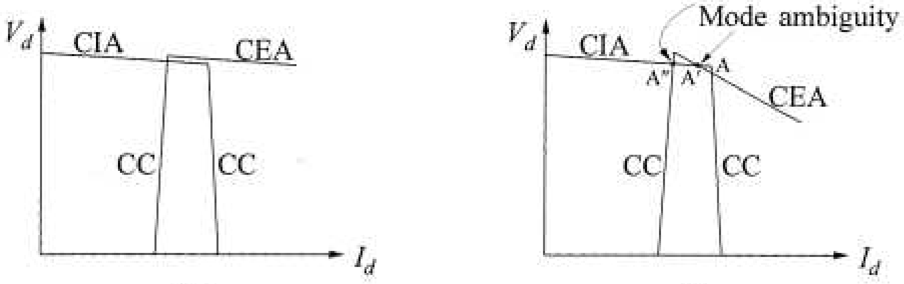
ALTERNATIVE CONTROL STRATEGIES FOR INVERTER:

DC VOLTAGE CONTROL MODE: instead of regulating by fixing γ a closed loop may be used so as to maintain the constant voltage at desired point on the DC line. It ensures that the voltage is constant

CONSTANT β CONTROL: In the inverter equation if there is beta there will be a positive slope. At low load beta gives additional security against commutation failure. However for heavy currents and large overlap gama is used

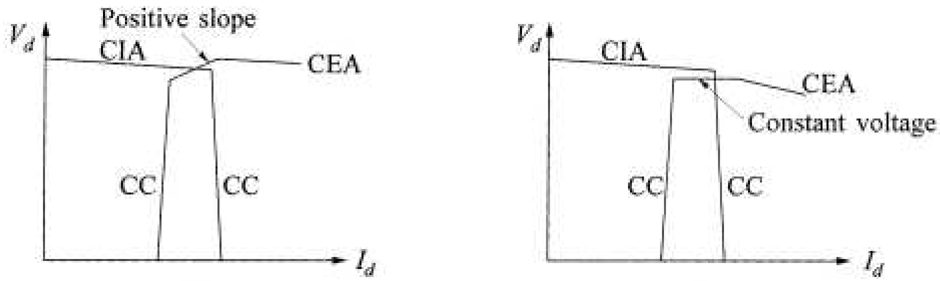


For stabilization and ambiguity reasons also



(a) (b)

Figure 10.33 Regions of mode ambiguity



(a) (b)

TAP CHANGE CONTROL: Tap changing control is done to maintain the firing angles in the desired range. Normally rectifier which takes care of the current backed up by tap change and also inverter CEA also backed up by tap change.

They are changed in fixed steps from minimum to maximum. Tap changes are prevented during transients. Hunting is avoided by having dead band wider than step size.

CURRENT LIMITS

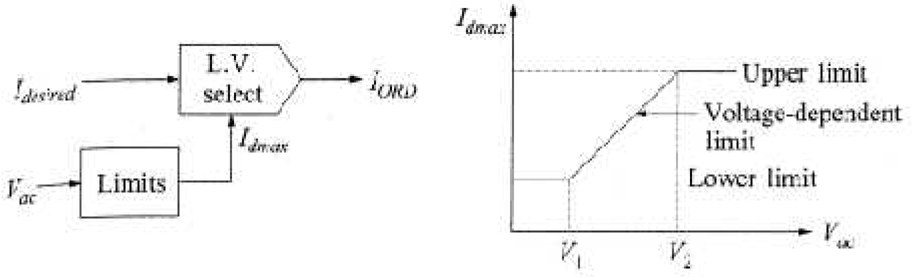
- **MAXIMUM CURRENT LIMITS:** The maximum short time current is usually limited to 1.2 to 1.3 times the normal full load current to avoid thermal damage to the valves.

- **MINIMUM CURRENT LIMIT**: As the load current is discontinuous high voltages may occur in the transformer windings and this can be avoided by high Dc reactor on the DC side

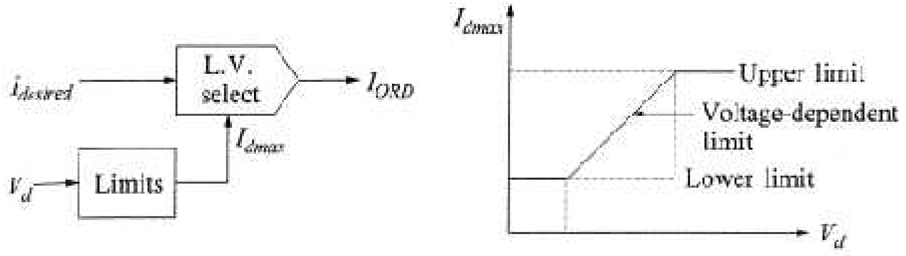
- **VOLTAGE DEPENDENT CURRENT ORDER LIMIT(VDCOL):** under low voltage condition it may not be desirable to maintain DC current or power for the following reasons

  When voltage at one converter falls more than 30%, the reactive power demand of the remote converter increase and this may have adverse effects on the AC system. A higher alpha or Gama is necessary to control the current in the link which increase the reactive power demand at the converter. If the Ac system voltage is reduced substantially the amount of reactive power is reduced

  At reduced voltages there is also chance of commutation failure and voltage instability

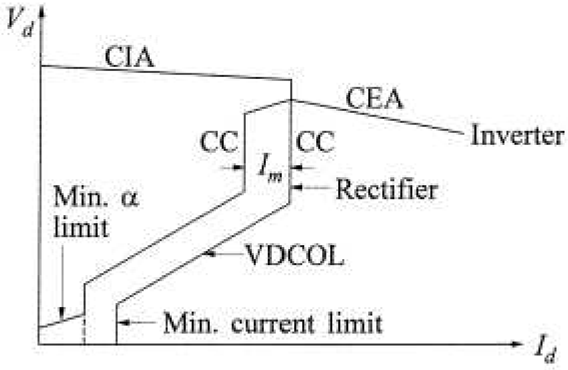


(a) Current limit as a function of alternating voltage



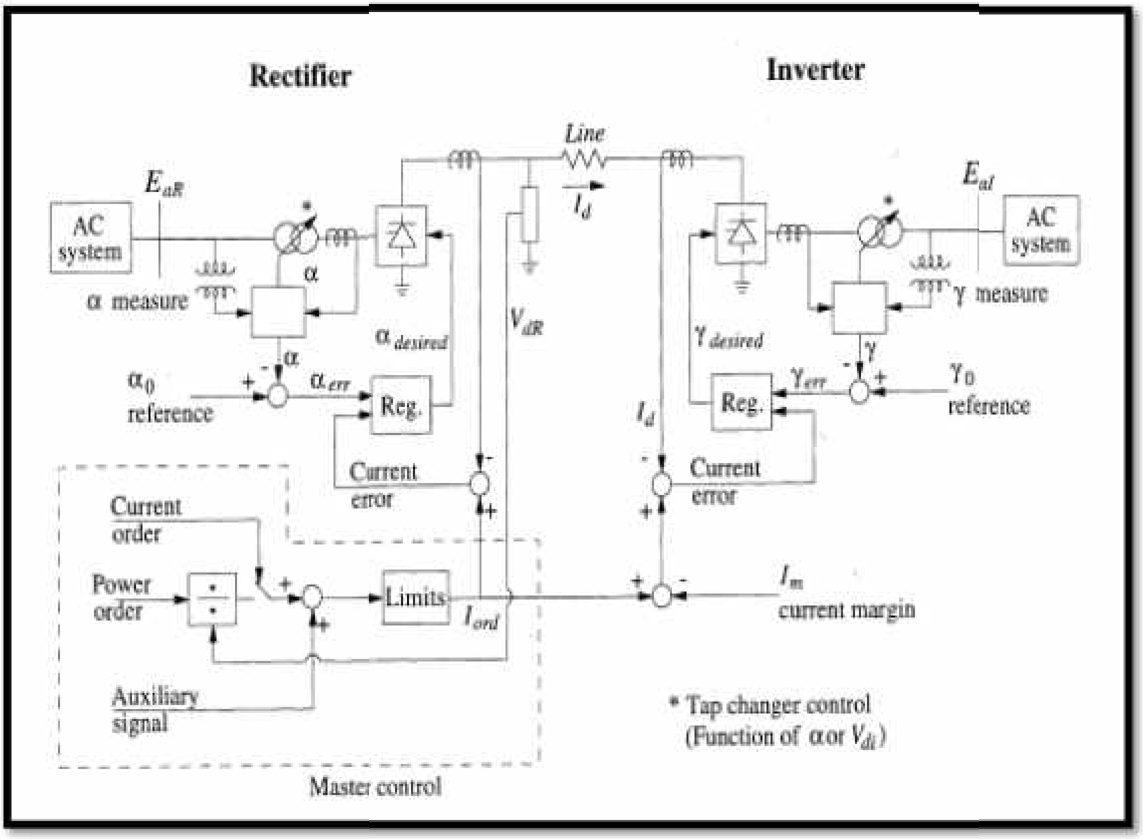
(b) Current limit as a function of direct voltage

VDCOL CONTROL



MINIMUM FIRING ANGLE CONTROL: power transferred in the DC line is mainly due to manipulation of the current order. These signals are to be sent to the converter via telecommunication. If this link fails there is a chance that a inverter can change to rectifier which results in power reversal. To prevent that the inverter control is provided with minimum delay angle control

POWER CONTROL: Usually the HVDC link is required to transmit scheduled power. In such an application the corresponding current order is found out from the power order/ DC Voltage measured



CONTROL HIERARCHY:

Generally two bridges with star- star and star delta connected transformers are considered for 12 pulse bridge unit.

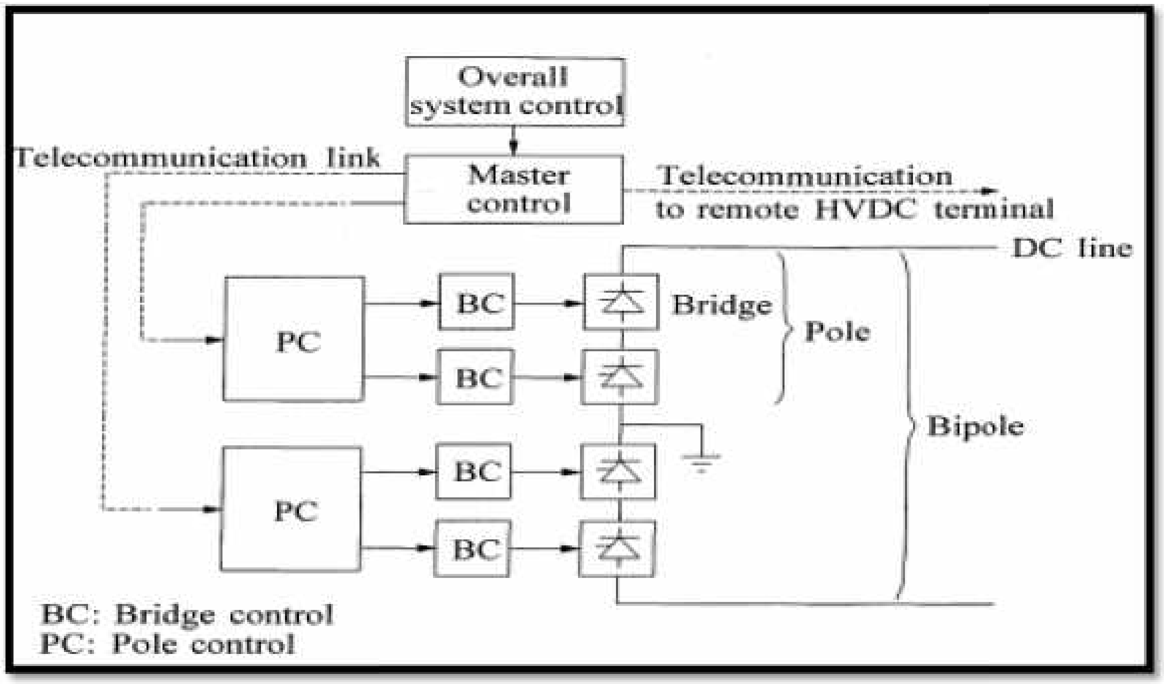
The control scheme is divided into four levels

- **BRIDGE OR CONVERTER LEVEL**
- **POLE CONTROL**
- **MASTER CONTROL**
- **OVERALL CONTROL**

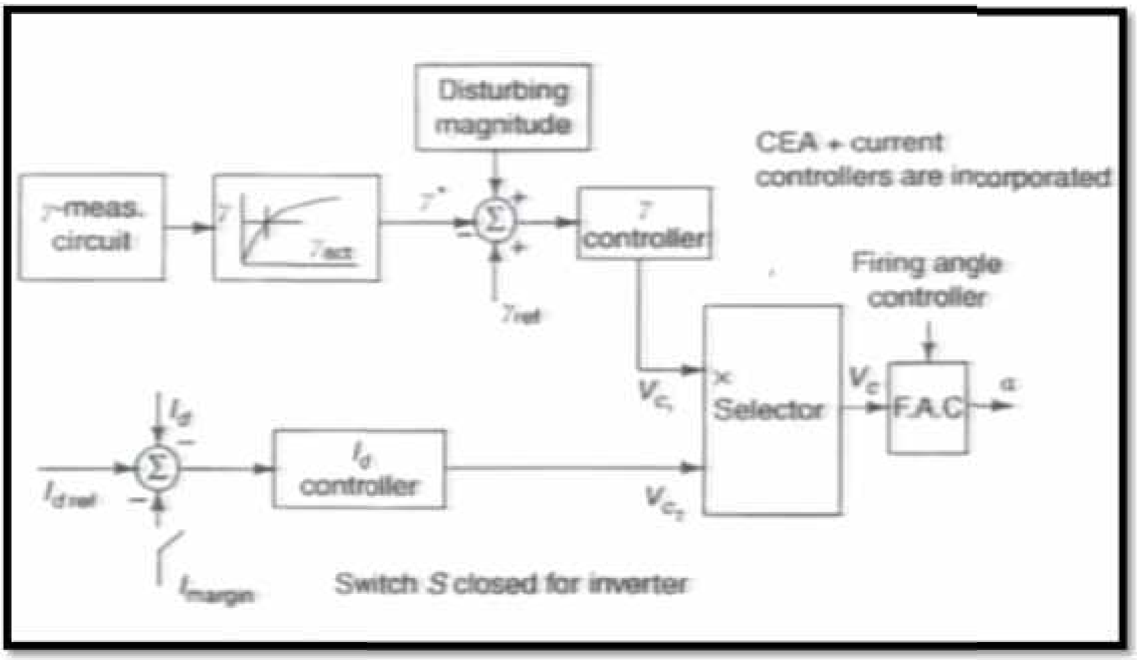
- **BRIDGE OR CONVERTER LEVEL:**
  - It determines the firing instants of the valves within a bridge and defines α_{min} and γ_{min} limits.
  - This has the fast response in the hierarchy.

- **POLE CONTROL:**
  - It coordinates the control of bridges in a pole.
  - The conversion of the current order to the firing angle order, tap changer control and some protection control sequence are handled in pole control.
  - It also handles starting, stopping and de-blocking and balancing of the bridge

- **MASTER CONTROL:**
  - It determines the current order and provides coordinated current order signals to all poles.
  - It interprets the broader demands for controlling the HVDC system by providing the interface between the pole control and overall system control
  - This includes power flow scheduling determined by control centre and AC system stabilization



BRIDGE/VALVE GROUP CONTROL:



FIRING ANGLE CONTROL: The manner which mode you operate the HVDC system either in CIA,CC and CEA only need is how we generate firing pulses.

There are two methods in which firing pulses can be generated

- **INDIVIDUAL PHASE CONTROL (IPC).**
- **EQUIDISTANT PULSE CONTROL (EPC).**

- **INDIVIDUAL PHASE CONTROL (IPC):**
    - Here firing angles are calculated individually for every phase with their commutation voltages.
    - Six phase delay circuits are required
    - Six zero crossing circuits are required

In this IPC there are two methods

- **COSINE CONTROL**
- **LINEAR CONTROL**

➢ **COSINE CONTROL:** There are several versions of this method.

- Pulses are generated at the zero crossing of control voltage V_C–and the line voltage AC.
- The control voltage is nothing but error produced from the current

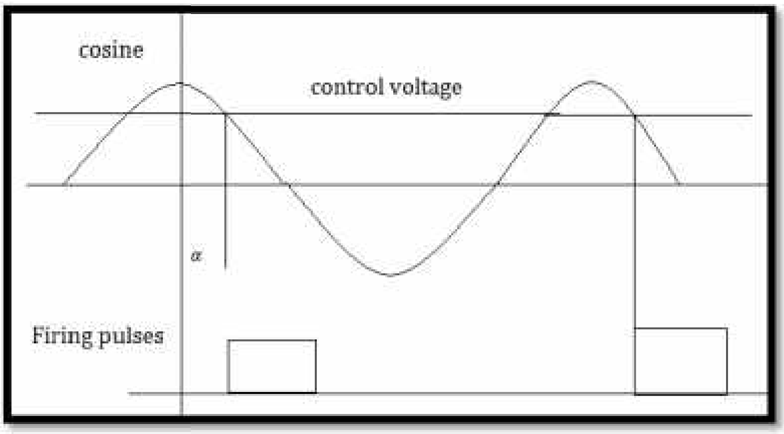
$$V_C = V_m \mathrm{c} \quad \alpha$$

$$V_d = V_d \ \mathrm{c} \quad \alpha$$

$$\alpha = \mathrm{c} \quad ^{-1}(\frac{V_C}{V_m})$$

$$V_d = V_d \ \mathrm{c} \quad \alpha = KV_C$$

- This control system results in a linear transfer characteristic.
- The output voltage independent on the change of the input AC voltage.
- However near alpha at zero it is sensitive to control voltage and leads to high accuracy

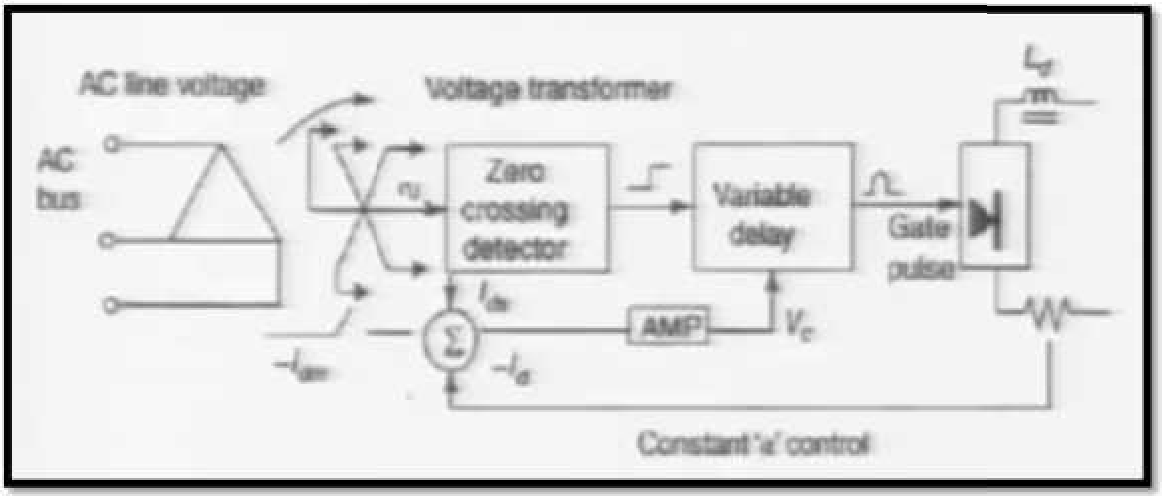


- **LINEAR CONTROL:**
    - Pulses are generated at the zero crossing of control voltage V_C and the line voltage AC.

$$\alpha = K_1 V_C$$

$$V_d = V_d \ c \quad \alpha = K_1 V_C$$

    - This makes linear transfer characteristics non linear but accuracy is $\pm 1^0$



ADVANTAGES OF IPC:

- The output voltage will be high

DISADVANTAGES OF IPC:

- Harmonic instability with less SCR.
- Non characteristics harmonics introduction in the system.
- Parallel resonance with filter impedance and system impedance

- **EQUIDISTANT PULSE CONTROL (EPC):** Here pulses are generated in the steady state at a equal intervals of 1/Pf. Through the ring counter

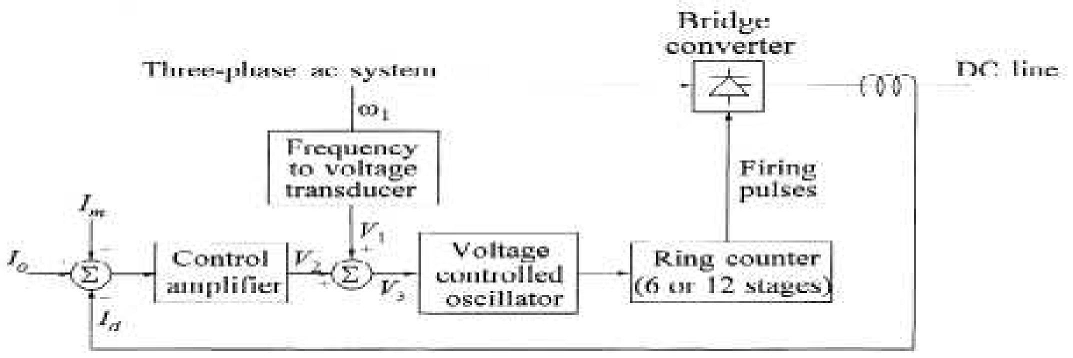
It consists of three variations of the EPC scheme

- **PULSE FREQUENCY CONTROL (PFC)**
- **PULSE PEROID CONTROL (PPC)**
- **PULSE PHASE CONTROL (PPC)**

❖ **PULSE FREQUENCY CONTROL (PFC):**

- The basic components of the system are Voltage Controlled Oscillator (VCO) and a ring counter. The VCO delivers pulses at a frequency directly proportional to the input control voltage.

- The train of pulses is fed to a ring counter which has six or twelve stages.
- One stage is on at a time with the pulse train output of the VCO changing the on stage of the ring counter.
- As each stage turns on it produces a short output pulse once per cycle.
- Over one cycle a complete set of 6 or 12 output pulses are produced by the ring counter at equal intervals**.**
- These pulses are transferred to the firing pulse generator to the appropriate valves of the converter bridge



- Under steady state conditions V_2=0 and the voltage V_1 is proportional to the AC line frequency ω_1.
- This generates pulses at the line frequency and constant firing delay angles α.
- If there is a change in the current order , margin settings or line frequency., a change in V_3 occurs which in turn results in change in the frequency of the firing pulses.
- A change in the firing delay angle results from the time integral of the differences between the line and firing pulse frequencies.
- It is apparent that this equidistant pulse control firing scheme is based on pulse frequency control.

❖ **PULSE PHASE CONTROL (PPC):** In this scheme a step change in control signals causes a spacing of the only pulse to change these results in a shift of phase only.

ADVANTAGES:

- Equal delay for all the devices.
- Non characteristics harmonics are not introduced

DISADVANTAGES:

- Less DC output voltage than IPC

HARMONICS AND FILTERS

8-1 SUMMARY

Converters generate harmonic voltages and currents on both ac and dc sides. A converter of pulse number p generates harmonics principally of orders

$$h = pq \tag{1}$$

on the dc side and

$$h = pq \pm 1 \tag{2}$$

on the ac side, q being any integer. Most HV dc converters have pulse number 6 or 12 and thus produce harmonics of the orders given in Table 1. The amplitudes of the harmonics decrease with increasing order: the ac harmonic current of order h is less than I_1/h, where I_1 is the amplitude of the fundamental current.

Table 1. Orders of Characteristic Harmonics

Pulse No.	DC Side	AC Side
p	pq	$pq \pm 1$
6	0, 6, 12, 18, 24, . . .	1, 5, 7, 11, 13, 17, 19, 23, 25 . . .
12	0, 12, 24, . . .	1, 11, 13, 23, 25 . . .

Unless measures are taken to limit the amplitude of the harmonics entering the ac network and the dc line, some of the following undesirable effects may occur: overheating of capacitors and generators, instability of the converter control, and interference with telecommunication systems, especially noise on telephone lines. These effects may not be confined to the vicinity of the converter station but may be propagated over great distances. The most difficult of these to eliminate is telephone interference.

The principal means of diminishing the harmonic output of converters are (a) increase of the pulse number and (b) installation of filters. High pulse numbers have been used in some converters, but it is the general opinion that for HV dc converters the use of filters is more economical than increase of the pulse number beyond 12. Filters are nearly always used on the ac side of converters. Ac filters serve the dual purpose of diminishing ac harmonics and supplying reactive power at fundamental frequency. On the dc side, the dc reactor diminishes harmonics, and, in many converters, especially those connected to dc cables, no additional filtering is required on the dc side. Dc filters are required, however, on some overhead dc lines.

8-2 CHARACTERISTIC HARMONICS

Definitions and Assumptions

The *pulse number* of a converter is the number of nonsimultaneous commutations per cycle of fundamental alternating voltage.

The *order of a harmonic* is the ratio of its frequency to the fundamental (lowest) frequency of a periodic wave. The order of harmonics on the dc side of a converter, however, is defined with respect to the fundamental frequency on the ac side.

Characteristic harmonics are those of orders given by Eqs. (1) and (2) in Section 8-1.

Noncharacteristic harmonics are those of other orders.

Assumptions. The following assumptions are made as bases for deriving the orders, magnitudes, and phases of the characteristic harmonics of a six-pulse converter:

1. The alternating voltages are three-phase, sinusoidal, balanced, and of positive sequence.
2. The direct current is absolutely constant, that is, without ripple. Such current would be the consequence of having a dc reactor of infinite inductance.
3. The valves are ignited at equal time intervals of one-sixth cycle, that is, at constant delay angle α measured from the zeros of the respective commutating voltages. By assumption 1, these zeros are equally spaced in time.
4. The commutation inductances are equal in the three phases.

Deductions from the Foregoing Assumptions

From assumptions 1 and 2 immediately follow deductions 1 and 2, respectively:

1. The alternating voltage has no harmonics except the first (the fundamental).
2. The direct current has no harmonics.

There can be higher harmonic currents on the ac side and harmonic voltages on the dc side, however, and deductions are made concerning these. Because of assumptions 1, 3, and 4:

3. The overlap angle is the same for every commutation.
4. The ripple of the direct voltage has a period of one-sixth that of the alternating voltage.
5. Hence the harmonics of the direct voltage are of order 6 and its multiples 12, 18, 24, etc.
6. The alternating currents of the three phases have the same wave shape but are displaced by one-third cycle in time (120° of the fundamental).
7. The alternating currents have positive and negative parts of the same shape except that one is inverted; that is, $F(\theta + 180°) = -F(\theta)$.
8. As a result of deduction 7, there are no even harmonics in the alternating current.
9. As a result of deduction 6 and the fact that the phase difference for the hth harmonic is h times that for the fundamental, the ac harmonics have the following phase sequences:

Sequence	Orders (h)
Zero (0)	0, 3, 6, 9, 12, 15, 18, 21, 24, ..., $3q$
Positive (1)	1, 4, 7, 10, 13, 16, 19, 22, 25, ..., $3q + 1$
Negative (2)	2, 5, 8, 11, 14, 17, 20, 23, 26, ..., $3q - 1$

Harmonic analysis of the wave shape of the alternating current shows that

10. No characteristic harmonics of order $3q$ (triple harmonics) can exist.

Final Conclusions on Orders of Characteristic Harmonics. By deduction 5, the direct voltage has only harmonics of orders that are multiples of 6, that is, of orders $6q$, where q is an integer.

By deductions 8 and 10, the alternating currents have only odd harmonics of orders not multiples of 3. Those of orders $6q + 1$ have positive sequence, and those of orders $6q - 1$ have negative sequence.

AC Harmonics at No Overlap

The wave shapes of alternating voltages and currents conforming to the assumptions made are shown in Figure 1. The current waves drawn in solid lines are for any ignition delay angle α but no overlap. The broken curved

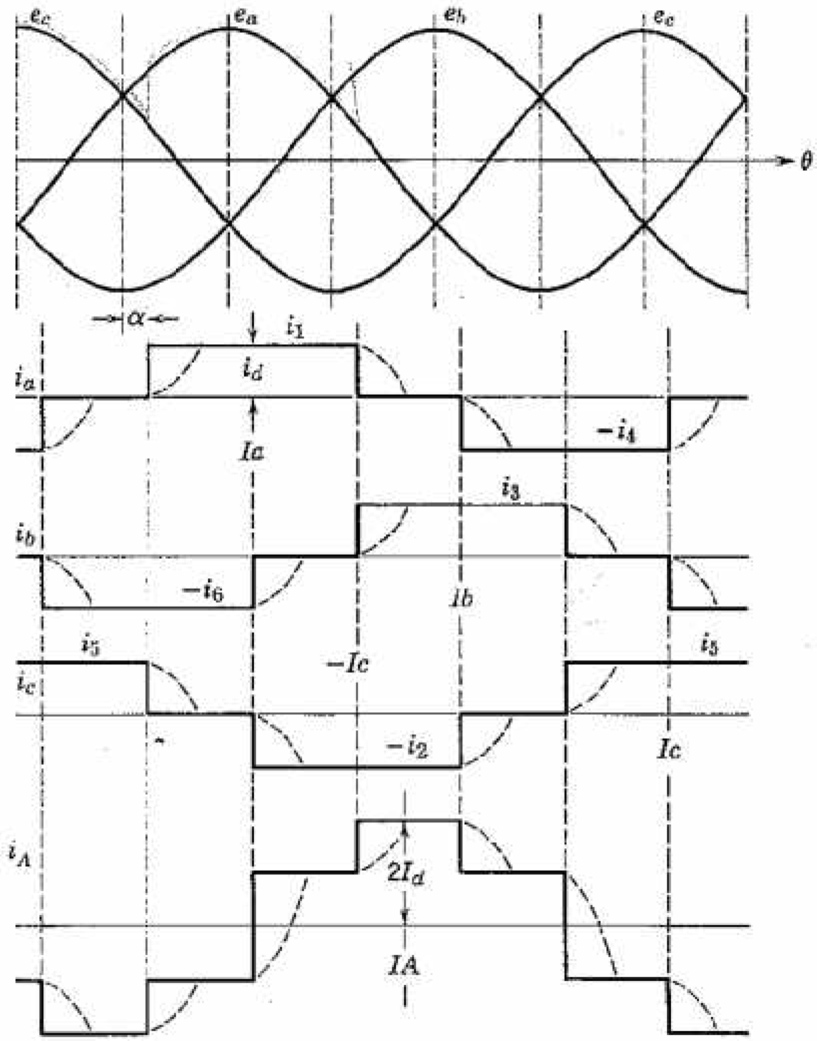


Fig. 1. Wave forms in a six-pulse bridge: line-to-neutral voltages e_a, e_b, e_c and line currents i_a, i_b, i_c with YY-connected transformer; also line current I_A with ΔY-connected transformer.

lines show qualitatively how overlap would modify the fronts and tails of the current pulses.

Valve Currents and Line Currents on Valve Side. The line-current wave forms at no overlap are a series of equally spaced rectangular pulses, alternately positive and negative. Fourier analysis of such a wave shape, for finding the characteristic alternating-current harmonics in this limiting case, is very simple; it also serves to illustrate several features of these harmonics. However, let us take an even simpler starting point: the analysis of a train of positive rectangular pulses of unit height and arbitrary width w radians, that is, of duration w/ω sec (see Figure 2). These pulses might represent the current through one valve.

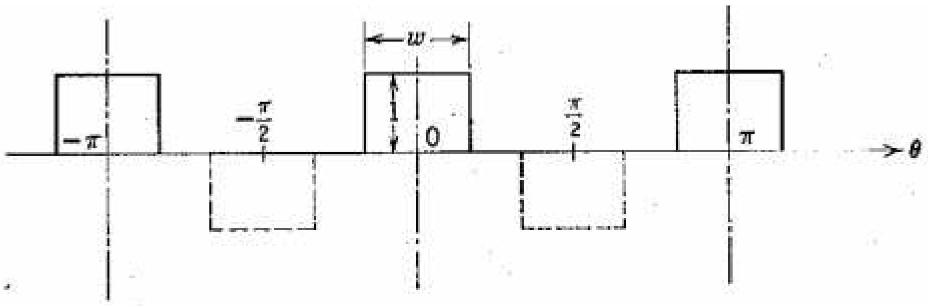


Fig. 2. Trains of positive and negative rectangular pulses of arbitrary width *w*.

The general trigonometric form of the Fourier series is

$$F(\theta) = \frac{A_0}{2} + \sum_{h=1}^{\infty} (A_h \cos h\theta + B_h \sin h\theta) \tag{3}$$

where

$$A_0 = \frac{1}{\pi}\int_0^{2\pi} F(\theta)\, d(\theta) \tag{4}$$

$$A_h = \frac{1}{\pi}\int_0^{2\pi} F(\theta) \cos h\theta \, d\theta \tag{5}$$

$$B_h = \frac{1}{\pi}\int_0^{2\pi} F(\theta) \sin h\theta \, d\theta \tag{6}$$

The limits of integration in Eqs. (4), (5), and (6) can be taken more generally as σ and $\sigma + 2\pi$, where σ is any angle. $A_0/2$ is the average value of the function F; A_h and B_h are rectangular components of the hth harmonic. The corresponding phasor is

$$A_h - jB_h = C_h\underline{/\phi_h} \tag{7}$$

where

$$C_h = \sqrt{A_h^2 + B_h^2} = \text{crest value}$$

and

$$\phi_h = \tan^{-1} \frac{-B_h}{A_h}$$

If, in the analysis of the wave shown in Figure 2, the origin of θ is taken at the center of a pulse, $F(\theta)$ is an "even" function, and $B_h = 0$ for all h; that is, the series has only cosine terms. Their amplitudes are found by Eq. (5) thus:

$$\begin{aligned} A_h &= \frac{1}{\pi}\int_{-\pi}^{\pi} F(\theta)\cos h\theta\, d\theta = \frac{1}{\pi}\int_{-w/2}^{+w/2} \cos h\theta \, d\theta \\ &= \frac{1}{\pi h}\left[\sin\frac{hw}{2} - \sin\left(-\frac{hw}{2}\right)\right] = \frac{2}{\pi h}\sin\frac{hw}{2} \end{aligned} \tag{8}$$

Also

$$\frac{A_0}{2} = \frac{1}{2\pi} \int_{-w/2}^{+w/2} d\theta = \frac{w}{2\pi} \tag{9}$$

The series is therefore

$$F_1(\theta) = \frac{2}{\pi}\left(\frac{w}{4} + \sin\frac{w}{2}\cos\theta + \frac{1}{2}\sin\frac{2w}{2}\cos 2\theta \right.$$
$$\left. + \frac{1}{3}\sin\frac{3w}{2}\cos 3\theta + \frac{1}{4}\sin\frac{4w}{2}\cos 4\theta + \cdots\right) \tag{10}$$

In general, this series has a constant term and cosine terms of every harmonic frequency. For certain pulse widths, however, certain cosine terms vanish. This occurs if

$$\frac{hw}{2} = q\pi \qquad \text{or} \qquad w = \frac{2q\pi}{h} \tag{11}$$

For example, the pulses of valve current in the three-phase bridge current have width

$$w = \frac{2\pi}{3}$$

so that if $h = 3, 6, 9, \ldots, 3q$, $\sin (hw/2) = \sin q\pi = 0$. Then the series lacks the third harmonic and its multiples, called triple harmonics for brevity.

Now, if we consider the negative pulses only, shown by broken lines in Figure 2, we get

$$F_2(\theta) = \frac{2}{\pi}\left(-\frac{w}{4} + \sin\frac{w}{2}\cos\theta - \frac{1}{2}\sin\frac{2w}{2}\cos 2\theta \right.$$
$$\left. + \frac{1}{3}\sin\frac{3w}{2}\cos 3\theta - \frac{1}{4}\sin\frac{4w}{2}\cos 4\theta + \cdots\right) \tag{12}$$

This result can be obtained in at least two ways: (a) by putting the new function into Eqs. (4), (5), (6) and performing the indicated operations or (b) by appropriate changes in series 10. These changes are the following: (1) Shift the pulse π radians; this shifts the fundamental component π rad and shifts the higher harmonics by $\pm h\pi$ rad. If h is even, $\cos (\theta \pm h\pi) = \cos \theta$; but if h is odd, $\cos (\theta \pm h\pi) = -\cos \theta$. Hence the signs of all odd harmonics are changed. (2) Invert the pulse. This changes the sign of every term. The net result is to change the signs of all even-order terms, including the constant term.

Next, let us analyze the train of alternately positive and negative rectangular pulses. Its Fourier series is

$$F_3 = F_1 + F_2 = \frac{4}{\pi}\left(\sin\frac{w}{2}\cos\theta + \frac{1}{3}\sin\frac{3w}{2}\cos 3\theta + \frac{1}{5}\sin\frac{5w}{2}\cos 5\theta + \cdots\right) \tag{13}$$

The constant term and all even harmonics have vanished.

Let us now put $w = 2\pi/3$ and change the height to I_d. For increments of 2 in h, the arguments of the sines increase in increments of $2\pi/3$ rad. For odd h the sines are all $\pm\sqrt{3}/2$, except for triple harmonics, which are zero. The series is

$$i_a = \frac{2\sqrt{3}}{\pi}\cdot I_d\left(\cos\theta - \frac{1}{5}\cos 5\theta + \frac{1}{7}\cos 7\theta - \frac{1}{11}\cos 11\theta + \frac{1}{13}\cos 13\theta - \frac{1}{17}\cos 17\theta + \frac{1}{19}\cos 19\theta - \cdots\right) \tag{14}$$

This contains only harmonics of orders $6q \pm 1$, as predicted earlier. The crest value of the fundamental-frequency current is

$$I_{10m} = \frac{2\sqrt{3}}{\pi} I_d = 1.103 I_d \tag{15}$$

and its effective or rms value is

$$I_{10} = \frac{I_{10m}}{\sqrt{2}} = \frac{\sqrt{6}}{\pi} I_d = 0.780 I_d \tag{16}$$

The effective value of the hth harmonic is

$$I_{h0} = \frac{I_{10}}{h} \tag{17}$$

Series 14 represents the ac line current of phase a on the valve side of the transformer (Figure 1) if the origin of θ is taken at the center of the positive pulse (axis Ia). The currents i_b and i_c in the other two phases have the same wave shape as i_a but are displaced 120° ($= 2\pi/3$ rad) behind and before i_a, respectively. Their Fourier series, if written for $\theta = 0$ at axes Ib and Ic, respectively, are the same as that for i_a written with respect to axis Ia. Likewise, these series are independent of the ignition delay angle α. If any wave is shifted forward by an angle ϕ, measured for the fundamental period, the hth harmonic is shifted by $h\phi$ measured for the shorter harmonic period, being shifted forward if of positive sequence and backward if of negative sequence.

Line Currents on Network Side of Six-pulse Group. If the transformers are connected YY or ΔΔ and have ratios 1 : 1, the line currents on the network side have the same wave shape, hence the same harmonics, as those on the valve side. If, however, the transformers are connected YΔ or ΔY, the wave shape on the network side is different from that on the valve side.

Let the transformers be connected in Y on the valve side and in Δ on the network side, and let the ratio of each individual transformer be 1:1. Then the currents in the delta-connected windings are the same as those in the corresponding Y-connected windings. Each line current on the delta side is the difference of two delta currents; for instance,

$$i_A = i_b - i_c \tag{18}$$

Line current i_A at the bottom of Figure 1 is constructed graphically from the two waves above it. Let us find its Fourier series with respect to $\theta = 0$ at the center of its positive part (axis *IA*). With respect to this same axis, i_b is retarded 30° and $-i_c$ is advanced 30°. Table 2 shows the magnitude and phase of each harmonic component of these three current waves.

If, instead of the ratio of individual transformers being 1:1, the bank ratio is made 1:1, then the factor $\sqrt{3}$ is removed from every entry in the last column of the table, and the Fourier series becomes

$$i_A = 1.103 I_d(\cos\theta + \tfrac{1}{5}\cos 5\theta - \tfrac{1}{7}\cos 7\theta - \tfrac{1}{11}\cos 11\theta + \tfrac{1}{13}\cos 13\theta + \tfrac{1}{17}\cos 17\theta - \tfrac{1}{19}\cos 19\theta - \cdots) \tag{19}$$

It differs from Eq. (14) only in the signs of the terms representing the fifth, seventh, seventeenth, nineteenth, etc., harmonics. Although all the harmonics in Eqs. (14) and (19) are equal in amplitude, the two series represent different wave shapes because of the difference in signs (or in phase) or certain orders of harmonics.

Alternating Line Currents on Network Side of 12-pulse Converter. A 12-pulse group in a HV dc converter is composed of two 6-pulse groups fed from sets of valve-side transformer windings having a phase difference of 30° (or 90°) between the fundamental voltages. Since α is normally the same for both 6-pulse groups, the fundamental valve-side currents have the same phase difference as the voltages, and the fundamental network-side currents are in phase with one another. The no-load voltage ratios between the network-side windings and each of the two sets of valve-side windings are equal; hence the fundamental network-side currents are also equal.

The resultant network-side current of the two groups is then given by the sum of Eqs. (14) and (19). To keep the power rating of the 12-pulse converter equal to that of a 6-pulse converter, however, both the direct voltage and the alternating current of each of the two bridges of the 12-pulse converter should be half of the corresponding quantities of the comparable one-bridge 6-pulse converter. Half of the sum of Eqs. (14) and (19) is

$$i_{12} = 1.103 I_d \left(\cos\theta - \tfrac{1}{11}\cos 11\theta + \tfrac{1}{13}\cos 13\theta - \tfrac{1}{23}\cos 23\theta + \tfrac{1}{25}\cos 25\theta - \cdots\right) \quad (20)$$

This contains only harmonics of orders $12q \pm 1$. Currents of orders 5, 7, 17, 19, etc., circulate between the two banks of transformers, but do not enter the ac line. If there are two valve windings and one network winding on each transformer, these harmonics appear only in the valve windings. In practice, such harmonics in the two 6-pulse groups are not always exactly equal in magnitude nor exactly in phase opposition; hence their cancellation is incomplete, and they appear to some degree in the network-side line currents. They are *uncharacteristic harmonics* in a 12-pulse converter.

Figure 3 shows the wave shapes of current in each component 6-pulse group and in the 12-pulse group. The fundamental waves are shown in broken lines.

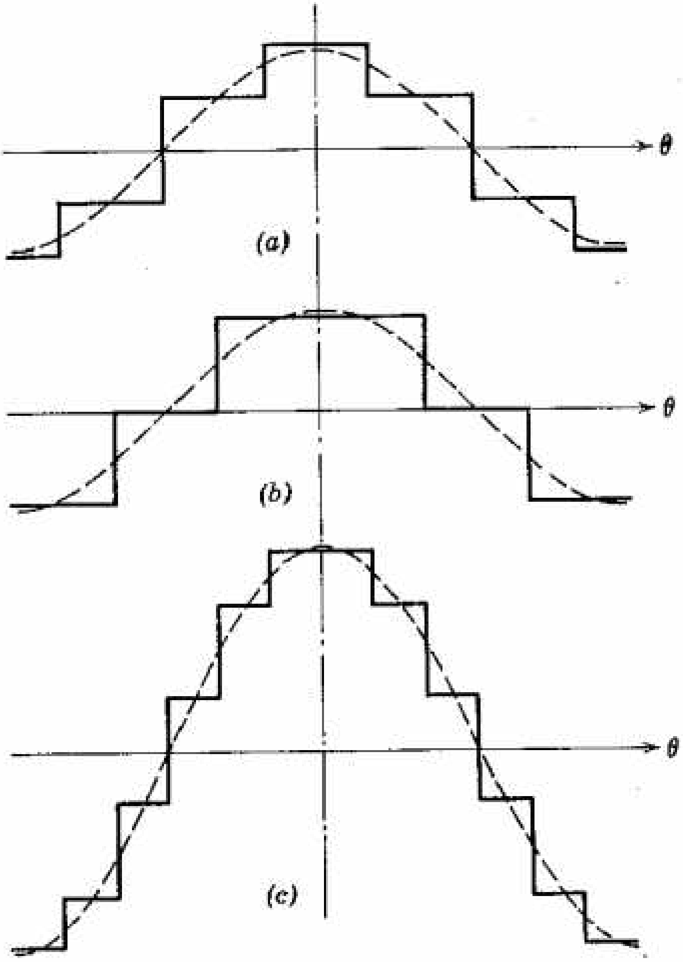


Fig. 3. Alternating line currents of a two-bridge 12-pulse converter with no overlap: (*a*) current of six-pulse bridge with YΔ-connected transformer; (*b*) current of six-pulse bridge with YY-connected transformer; (*c*) total current.

AC Harmonics at Overlap

In Figure 1 the wave shapes for positive overlap appear as better approximations to sine waves than do the wave shapes for no overlap. Hence we make the qualitative deduction that the effect of overlap is to decrease the amplitudes of the harmonics.

Quantitative results are computed from the following formulas. They are valid only for characteristic orders h. For overlap not exceeding 60°, the complex rms value, with phase referred to the respective commutation voltage E is

$$\mathbf{I}_h = K_1\mathbf{F}_1(\alpha, \delta, h) \qquad \text{amperes} \tag{21}$$

where

$$K_1 = \frac{3}{2\pi h}\left(\frac{E}{X}\right) = \frac{\sqrt{6}I_{s2}}{2\pi h} \qquad \text{amperes} \tag{22}$$

and

$$\mathbf{F}_1 = \frac{\underline{/-(h+1)\alpha} - \underline{/-(h+1)\delta}}{h+1} - \frac{\underline{/-(h-1)\alpha} - \underline{/-(h-1)\delta}}{h-1} \tag{23}$$

Sometimes it is convenient to express the harmonic as a fraction of one of the following currents:

$I_{s2} = \sqrt{3/2}E/X$ = crest value of ac component of current in line-to-line short circuit on valve side.

$I_{\text{base}} = (\sqrt{6}/\pi)I_{s2}$ = rms fundamental alternating current corresponding to $I_d = I_{s2}$ with no overlap.

I_{10} = rms fundamental alternating current with no overlap.

$I_{h0} = I_{10}/h$ = rms harmonic current with no overlap.

I_d = direct current.

The results are as follows:

$$\frac{\mathbf{I}_h}{I_{s2}} = K_2\mathbf{F}_1 \tag{24}$$

where

$$K_2 = \frac{\sqrt{6}}{2\pi h} \tag{25}$$

$$\frac{\mathbf{I}_h}{I_{\text{base}}} = K_3\mathbf{F}_1 \quad \text{per unit} \tag{26}$$

where

$$K_3 = \frac{1}{2h} \tag{27}$$

$$\frac{\mathbf{I}_h}{I_{10}} = K_4\mathbf{F}_1 \tag{28}$$

where

$$K_4 = \frac{1}{2hD} = \frac{K_3}{D} \tag{29}$$

$$\frac{\mathbf{I}_h}{I_{h0}} = K_5\mathbf{F}_1 \tag{30}$$

where

$$K_5 = \frac{1}{2D} \tag{31}$$

$$\frac{\mathbf{I}_h}{I_d} = K_6\mathbf{F}_1 \tag{32}$$

where

$$K_6 = \frac{\sqrt{6}}{2\pi hD} \tag{33}$$

where

$$D = \cos\alpha - \cos\delta = 2\sin\frac{\alpha+\delta}{2}\sin\frac{u}{2} = I'_d \tag{34}$$

Usually only the magnitude of a harmonic is wanted, the phase being of no interest. Convenient formulas for computation are the following:

$$I_h = 2K_1F_2(\alpha, u, h) \qquad \text{amperes} \tag{35}$$

$$\frac{I_h}{I_{s2}} = 2K_2F_2 = \frac{\sqrt{6}F_2}{h} \tag{36}$$

$$\frac{I_h}{I_{\text{base}}} = 2K_3F_2 = \frac{F_2}{h} \tag{37}$$

$$\frac{I_h}{I_{10}} = 2K_4F_2 = \frac{F_2}{hD} \tag{38}$$

$$\frac{I_h}{I_{h0}} = 2K_5F_2 = \frac{F_2}{D} \tag{39}$$

$$\frac{I_h}{I_d} = 2K_6F_2 = \frac{\sqrt{6}F_2}{hD} \tag{40}$$

where

$$F_2 = \left(\left\{ \frac{\sin[(h-1)u/2]}{h-1} \right\}^2 + \left\{ \frac{\sin[(h+1)u/2]}{h+1} \right\}^2 \right.$$
$$\left. - 2 \left\{ \frac{\sin[(h-1)u/2]}{h-1} \right\} \left\{ \frac{\sin[(h+1)u/2]}{h+1} \right\} \cos(2\alpha + u) \right)^{1/2} \qquad (41)$$

The last equation has the same form as the law of cosines for the length of one side of a triangle in terms of the lengths of the other two sides and the included angle.

Computed results for I_h/I_{10} versus u are plotted in Figures 4 to 11. Results for $I_h' = I_h/I_{\text{base}}$ versus I_d' at the usual value of α or γ, 15°, are plotted in Figure 12.

Overlap Greater than 60°. In the region bounded by $60° < u < 120°$, $\alpha > 30°$, and $\delta < 150°$, Eqs. (21) to (41) apply if α is replaced by α' and δ by δ', where, as before (Eq. (20) of Chapter 4),

$$\alpha' = \alpha - 30° \qquad \delta' = \delta + 30° \qquad u' = u + 60° \qquad (42)$$

Direct-voltage Harmonics

A formula for complex values of the harmonics of the direct voltage is the following:

$$\frac{\mathbf{V}_{dh}}{V_{d0}} = \tfrac{1}{2}\mathbf{F}_3(\alpha, \delta, h) \qquad (43)$$

and a formula for the rms values is

$$\frac{V_{dh}}{V_{d0}} = F_4(\alpha, u, h) \qquad (44)$$

where

$$\mathbf{F}_3 = \frac{\underline{/(h+1)\alpha} + \underline{/(h+1)\delta}}{h+1} - \frac{\underline{/(h-1)\alpha} + \underline{/(h-1)\delta}}{h-1}$$
$$= \frac{\underline{/(h+1)\alpha}(1 + \underline{/(h+1)u})}{h+1} - \frac{\underline{/(h-1)\delta}(1 + \underline{/(h-1)u})}{h-1} \qquad (45)$$

$$F_4 = \left[\left(\frac{\cos[(h-1)u/2]}{h-1} \right)^2 + \left(\frac{\cos[(h+1)u/2]}{h+1} \right)^2 \right.$$
$$\left. - 2 \left(\frac{\cos[(h-1)u/2]}{h-1} \right) \left(\frac{\cos[(h+1)u/2]}{h+1} \right) \cos(2\alpha + u) \right]^{1/2} \qquad (46)$$

8-3 UNCHARACTERISTIC HARMONICS

The conditions postulated in the foregoing analysis of characteristic harmonics of a converter are never exactly fulfilled in practice. Consequently, not only are the harmonics of characteristic orders slightly changed from their theoretical magnitudes and phases, resulting in small components of opposite phase sequence from their characteristic sequences, but also—and this is more important—harmonics of uncharacteristic orders are produced. Indeed, a converter is likely to produce harmonics of all orders and some dc component on the valve winding of the transformers.

The harmonics of low uncharacteristic orders are normally much smaller than those of adjacent characteristic harmonics in the converter itself. Filters are usually provided for the low characteristic orders, however, and on the network (or line) side of the filters, the uncharacteristic harmonics may be of about the same magnitudes as those of the characteristic harmonics. For high orders, the magnitudes of both characteristic and uncharacteristic harmonics are small and approximately the same, even before filtering. For the high-order characteristic harmonics, the equations presented in Section 8-2 cannot be depended on for accurate results. The magnitudes of these harmonics and of all the noncharacteristic harmonics can be found only by measurement.

Causes

The ignition delay angle of a rectifier is usually measured from a zero of the commutating voltage. If the three-phase alternating voltages are unbalanced, their zeros are not equally spaced, and, consequently, the valves are not fired at equal time intervals. Probably, even with balanced voltages, there is some "jitter" in the electronic circuitry of the current regulator that produces uncharacteristic harmonics. The variation of firing angles from their normal values is usually cited as 1 or 2°. Reeve and Krishnayya[58] state, however, that on the Cross Channel link the variation was ±3° for rectifier operation and ±1.5° for inversion.

It was shown in Section 5-11 that the combination of high gain and short time constant in the current regulator would cause alternate early and late ignitions. As a result, harmonics of orders $3q$ are produced in the direct voltage, and harmonics of orders $3q \pm 1$ in the alternating currents. These orders are uncharacteristic if q is an odd integer. For example, a third harmonic and its odd multiples appear in the direct voltage, and even harmonics appear in the alternating currents.

Inverters normally operate on C.E.A. control, and unbalanced three-phase voltages can again lead to unequally timed firing. The C.E.A. control has no feedback. As a rule, inverters on C.E.A. control produce smaller uncharacteristic harmonics than does a rectifier on C.C. control.

Another suggested cause of uncharacteristic ac harmonics is interaction of characteristic-harmonic and fundamental currents in nonlinear elements of the power system.[14,29] The theory of modulation shows that such interaction produces sum and difference frequencies, which, in the case in question, are uncharacteristic. This cause appears to be unimportant, because the principal nonlinear elements of a power system are transformers, in which only the small exciting current is affected by the nonlinear relation between current and flux. Of course, transformers do generate harmonics, but there is no evidence that these interact significantly with converters. The same could be said for corona, which is also a shunt nonlinear element.

Amplification of Uncharacteristic Harmonics. Several HV dc terminals on going into service experienced trouble from a low-order uncharacteristic harmonic of large amplitude causing improper operation, and even instability, of the C.C. control. At Lydd[42] it was the third harmonic; at Benmore, the ninth.[52] Analyses of these troubles have led to the following explanation:[55,56,58] The addition of harmonics to the fundamental three-phase voltage waves shifts the times of voltage zeros from the zeros of the fundamental waves alone. These shifts of zeros cause unequally spaced firings of valves, which, in turn, generate uncharacteristic ac harmonics. If any of these current harmonics meets a high impedance, significant voltage harmonics of like orders are produced. It may happen that one of these uncharacteristic alternating-voltage harmonics has the same harmonic order and phase sequence and nearly the same phase as one of the voltage harmonics assumed at the beginning of this explanation. That particular harmonic is amplified by positive feedback.

If the loop gain is high enough, a harmonic oscillation of increasing amplitude is produced: this is instability.

Consequences

Uncharacteristic harmonics (1) increase telephone interference, because it is not feasible to provide adequate filtering of each order of them, and (2) in some instances cause instability of C.C. control, as explained above.

Suppression or Diminution

In the instances of control instability cited above, a three-phase HV ac filter bank was provided for the offending harmonic (third or ninth). Such a filter provides a low shunt impedance at the frequency of the offending harmonic, with the result that a given current of this frequency produces less voltage of the same frequency, and thus the loop gain is reduced to a degree that gives but little amplification of this harmonic; consequently the control becomes stable.

This method is expensive. A modification of the control system, which operates at a low level of power, would be less expensive. For example, filters to block the offending harmonic could be placed in the three-phase low-voltage circuit that provides a replica of the commutating voltages to the control system. No reason is apparent why a shunt filter in this location could introduce any different transfer function into the loop from what a similar filter placed in the HV circuit would.

A better control system is isochronous control such as the phase-locked oscillator described by Ainsworth.[57] This generates a series of equally timed firing pulses that is locked to the correct average delay angle by the current regulator, actuated by the difference between the set and measured values of direct current. This, or an equivalent scheme, for getting equally timed firing of valves should be used if it is desired to diminish uncharacteristic harmonics as much as possible.

Relation of Uncharacteristic Harmonics to Errors in Ignition Angles

Even AC Harmonics. Suppose that, as previously discussed, the ignition times of valves in a six-pulse bridge are alternately late and early. To be more specific, assume that the odd-numbered valves, constituting one half bridge, are ignited early by an angle ε, while the even-numbered valves, constituting the other half bridge, are ignited late by the same angle. The wave shapes of the alternating currents consist of alternate positive and negative pulses of unaltered duration 120°, but the intervals between a positive pulse and the following negative pulse are increased by 2ε from the normal value.

On pages 297 to 300, the Fourier series for trains of positive only, and of negative only, rectangular pulses were derived, and it was shown that, with the correct relationship between the two trains, the odd harmonics are doubled but the even harmonics vanish. The same relationship holds for the nonrectangular pulses observed where there is overlap. In the event of relative displacement 2ε between the two trains, the resultant harmonics can be found by vector addition, with the odd harmonics separated by $2h\varepsilon$ instead of zero and the even harmonics separated by $\pi - 2h\varepsilon$ instead of by π. The sums are respectively 2 cos $h\varepsilon$ and 2 sin $h\varepsilon$ times the respective harmonics of one train. For small $h\varepsilon$ the decrease of magnitude of the odd harmonics is negligible; the even harmonics except those of order $6q$, which do not appear in the individual trains, increase from zero to a nonzero value, which we proceed to estimate.

The ratio of an even harmonic of order h to the fundamental wave at small overlap is

$$\frac{I_h}{I_1} = \frac{2 \sin h\varepsilon}{2h \cos \varepsilon} = \frac{h\varepsilon - \frac{1}{6}(h\varepsilon)^3 + \frac{1}{120}(h\varepsilon)^5 - \cdots}{h[1 - \frac{1}{2}(h\varepsilon)^2 + \frac{1}{24}(h\varepsilon)^4 - \cdots]}$$

$$\cong \varepsilon[1 + \tfrac{1}{3}(h\varepsilon)^2 + \tfrac{2}{15}(h\varepsilon)^4 + \cdots] \cong \varepsilon \qquad \text{radians} \tag{47}$$

For $\varepsilon = 1^\circ$, corresponding to 2° relative shift between the positive and negative pulses, the second and fourth harmonics are each approximately $1/57.3 = 0.0174$ per unit $= 1.74\%$ of the fundamental current. This value is further decreased by overlap.

Triple AC Harmonics. It was shown in Section 8-2 by Eq. (11) that a train of rectangular pulses of normal width (120°) has no triple harmonics. If, however, the pulse width is longer or shorter than normal, triple harmonics are generated. Again let us estimate the magnitude of such harmonics as a function of the angular ignition error. Suppose that the ignitions of two valves connected to the same phase are late by ε and that the other four valves of the bridge ignite on time. Then the alternating current of that phase consists of positive and negative pulses both of which are shorter than normal by ε. The current of the phase leading that one has pulses longer than normal by ε, and the current of the remaining phase has pulses of normal length. Assume zero overlap, so that the series of Eqs. (10) and (12) are applicable. In each of these series and in their sum, the ratio of odd harmonic to fundamental is

$$\frac{I_h}{I_1} = \frac{\sin(hw/2)}{h \sin(w/2)} \tag{48}$$

Now put $w = 2\pi/3 \pm \varepsilon$ and $h = 3q$. Then

$$\frac{I_h}{I_1} = \frac{\sin(q\pi \pm 1.5q\varepsilon)}{3q \sin(\pi/3 \pm \varepsilon/2)}$$

$$= \frac{\sin q\pi \cos 1.5q\varepsilon \pm \cos q\pi \sin 1.5q\varepsilon}{3q[\sin(\pi/3)\cos(\varepsilon/2) \pm \cos(\pi/3)\sin(\varepsilon/2)]}$$

$$= \frac{\sin 1.5q\varepsilon}{3q[(\sqrt{3}/2)\cos(\varepsilon/2) \pm \frac{1}{2}\sin(\varepsilon/2)]} \tag{49}$$

For small ε, $\cos(\varepsilon/2) \cong 1$, $\sin(\varepsilon/2) \cong 0$, $\sin 1.5q\varepsilon \cong 1.5q\varepsilon$, and

$$\frac{I_3}{I_1} \cong \frac{1.5q\varepsilon}{3q\sqrt{3}/2} = \frac{\varepsilon}{\sqrt{3}} = 0.577\varepsilon \tag{50}$$

For $\varepsilon = 1° = 0.0174$ rad, $I_3/I_1 = 0.01 = 1\%$.

Magnitudes of Uncharacteristic Harmonics Found in Field Tests

Measurements of harmonics from the converter at Lydd (at the English end of the Cross Channel link) were made with the filters disconnected, giving the results shown in Table 4. They were obtained by Fourier analyses of oscillograms.

Table 4. Harmonic Currents Measured on AC Side of Converter at Lydd[39,49]
To an arbitrary scale

Order of Harmonic	Converter Blocked	100-A DC 12-pulse Operation	400-A DC 6-pulse Operation
2	2.0	29.7	25.9
3	2.1	9.3	10.2
4	0.3	10.9	21.6
5	6.0	26.4	92.5*
6	1.3	9.2	6.2
7	4.0	16.2	66.5*
8	0.8	31.7	44.3
9	0.1	57.8	23.8
10	0.5	22.3	43.6
11	2.0	119.6*	75.3*
12	0.6	67.9	3.8
13	1.0	21.5*	19.2*
14	0.3	28.4	15.0
15	0.2	17.9	4.4
16	0.04	18.4	11.1
17	0.2	13.4	7.5*
18	0.3	10.4	3.4
19	0.08	8.6	5.4*
20	0.1	11.7	4.9

* Characteristic harmonics.

8-4 TROUBLES CAUSED BY HARMONICS[38]

List of Troubles

Troubles in the Converter and on the AC Power System

1. Extra losses and heating in machines and capacitors
2. Overvoltages due to resonance
3. Interference with ripple control systems
4. Inaccuracy or instability of the constant-current control of converters

Troubles on the Telecommunication Systems

5. Noise on voice-frequency telephone lines

Noise on telephone lines is the most difficult trouble to eliminate and forms the subject of most of the rest of this chapter. There are reasons for concern, however, over the effects of harmonics on the power system itself. Item 4 was discussed in Section 8-3, page 318. Items 1, 2, and 3 are briefly discussed below.

Extra Losses and Heating in Machines[7,38,50]

Harmonic currents in induction and synchronous machines cause additional losses in, and heating of, these machines. These effects are chiefly attributable to the harmonics of low orders, which can have large magnitudes. Low-resistance damper windings serve to shield the rotor iron from harmonic fluxes that would overheat it, and the heating of the damper windings is small. Damper windings are used on salient-pole synchronous machines but not on round-rotor synchronous machines.

Large harmonics in induction motors reduce the torque available from them at rated speed and cause parasitic torques at lower speeds that can prevent a motor that is being started from attaining its rated speed.

There have been proposals for feeding rectifiers from generators isolated from the rest of the ac system, and this is done at Volgograd. Among the advantages claimed are that the provision of ample damper windings on the generators would cost less than the provision of ac harmonic filters and that the generators could be allowed to vary in speed more than generators usually do in an interconnected ac system with no concern about detuning of these filters. Studies of this possibility on the Nelson River project[59] showed, however, that filtering was more economical than building the generators to carry the harmonic currents continuously. An additional complication was that, because the project would be built by stages, additional generating plants being connected to the rectifiers at each stage, there was no assurance that the harmonics would divide among all these plants in any definite ratio without putting undue restrictions on the design of the future generators, ac lines, etc.

Although filters are provided at the rectifier station, the frequency generated by the plants connected to this station is subject to large variations during system disturbances. The filters are then out of tune, and a greater part of the harmonic current output of the rectifiers passes through the generators, which, however, were designed, at small additional cost, to withstand the temporary additional heating caused by these increased harmonic currents.

Measurements of losses caused by harmonics in a cylindrical-rotor synchronous generator of normal design, loaded by nonlinear reactors were reported by Easton.[50] Measurements of harmonic impedances of a 27.5-MVA generator were reported by Gardiner.[51a]

Extra Losses and Heating in Capacitors

The increase of losses in capacitors due to harmonics is[9,24]

$$\sum_{h=2}^{\infty} C(\tan\delta)\omega_h V_h^2 \tag{51}$$

where $C =$ capacitance

$\tan\delta =$ loss factor

$\omega_h = 2\pi$ times frequency of hth harmonic

$V_h =$ rms voltage of hth harmonic

The dielectric stress is proportional to the crest voltage, which may be either raised or lowered by the harmonic voltages.

The total reactive power, including fundamental and harmonics,

$$Q = \sum_{h=1}^{\infty} Q_h \tag{52}$$

should not exceed the rated reactive power of the capacitor.

Overvoltages from Resonance

The following method may be used to estimate the possibility of resonance between a large shunt capacitor bank on the power system and the rest of the system at a harmonic frequency.[48]

Let Q_s equal short-circuit power of power system at point where capacitor bank is connected, Q_C equal rating of capacitor bank and h equal order of harmonic at which resonance may occur. Then

$$h = \left(\frac{Q_s}{Q_C}\right)^{1/2} \tag{53}$$

Trouble from such resonance is most likely at a frequency close to a harmonic frequency for which no filter is provided. For example, third-harmonic resonance could occur if $Q_C \cong 0.1 Q_s$. Such resonance could have several undesirable effects: (a) overheating of the capacitors, (b) overvoltage at the capacitor bank, and (c) instability of the constant-current regulator of a converter.

Interference with Ripple Control Systems[47]

Some electric-power utilities sell electric energy at especially low rates for off-peak loads, such as water heaters, and control the hours during which such loads can be connected by transmitting audiofrequency tones, in the range of 290 to 1650 Hz, from substations over power-distribution circuits to customers' premises to control contactors in series with such loads. Similar control is used for street lighting by some utilities. The receiving devices for the control signals are broadly tuned and can accept harmonics from high-power converters, which may cause undesired operation of the contactors or prevent desired ones.

The remedies are adequate filtering of ac harmonics or decreasing the susceptibility of the ripple control system to harmonics.

8-5 DEFINITIONS OF WAVE DISTORTION OR RIPPLE

A complete description of a periodic current or voltage wave that is neither constant nor sinusoidal would require either an oscillogram or a list of the harmonics present, together with their phases and magnitudes, or, at least, their magnitudes.

For some purposes, such as filter design, it is convenient to have a more concise expression—a single number—serving as an index of the degree of departure of the wave from its ideal shape. Several such indices have been defined.

Total RMS Harmonics

For alternating current, this quantity is

$$H_1 = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} = \frac{\sqrt{I^2 - I_1^2}}{I_1} \qquad \text{per unit} \tag{54}$$

and for direct current it is

$$H_2 = \frac{\sqrt{\sum_{h=1}^{\infty} I_h^2}}{I_d} = \frac{\sqrt{I^2 - I_d^2}}{I_d} \qquad \text{per unit} \tag{55}$$

where I = effective (rms) current
I_d = average direct current
I_1 = rms fundamental current
I_h = rms harmonic current of order h

Similar expressions hold for voltages.

Because the harmonics are squared, the largest ones, that is, the lower orders, dominate the result.

Wasserab[32] calls these indices *Welligkeit* (waviness).

Deviation from a Sine Wave (or a Constant)

For alternating current, it is

$$H_3 = \frac{|i - i_1|_{\max}}{I_{1m}} \quad \text{per unit} \tag{56}$$

and for direct current

$$H_4 = \frac{|i - I_d|_{\max}}{I_d} \quad \text{per unit} \tag{57}$$

where i = instantaneous current
i_1 = instantaneous value of fundamental current wave
I_{1m} = crest value of fundamental wave
I_d = average direct current

In words, the index is the maximum difference of ordinates of the wave in question and of the corresponding fundamental wave or average value. The result depends on the phase position of the harmonics. All harmonics have equal weights.

A closely related index is the *peak-to-peak value of ripple* of direct current or voltage. The maximum positive and negative deviations are taken separately, and their difference is found. Again, it is usually divided by the average value:

$$H_5 = \frac{i_{\max} - i_{\min}}{I_d} \quad \text{per unit} \tag{58}$$

Maximum Theoretical Deviation from a Sine Wave

In many cases the magnitudes of harmonics are known or calculated, but their phase angles are not known. For this reason, it is usually more practical to assume that the crests of all the harmonics occur simultaneously at least once per cycle. The index thus modified is the arithmetical sum of the crest values of all the harmonics divided by the crest value of the fundamental wave. Of course, rms values can be used instead of crest values in both numerator and denominator, giving

$$H_6 = \frac{\sum_{h=2}^{\infty} I_h}{I_1} \tag{59}$$

This index weighs all harmonics equally. It is not used for dc quantities. In practice, we can neglect harmonic orders above the twenty-fifth with very little error.

Psophometric and C-message Weightings

We now come to a group of wave-form indices in which the various frequencies or harmonic orders are weighted according to their effectiveness in interfering with telephone conversations. The sensitivity of the human ear, the response of the telephone receiver, and the coupling between power and telephone circuits all vary with frequency, and these variations can be taken into account by appropriate weighting factors.

Two systems of weighting are in wide use: (a) that of the Bell Telephone System (B.T.S.) and the Edison Electric Institute (E.E.I.) is used in the United States and Canada; (b) another system promulgated by the International Consultative Commission on Telephone and Telegraph Systems (C.C.I.T.T.) is used in Europe. (The C.C.I.T.T. resulted from a merger of C.C.I.F. and C.C.I.T. in 1956.)

One set of weighting factors of each system, based on the sensitivity of the ear and the response of telephone equipment, applies only to currents and voltages on the telephone circuit. This is called *C-message weighting* by B.T.S. and E.E.I., and *psophometric weighting* by C.C.I.T.T. These weights are shown in Tables 5 and 6 and in Figure 18. In both systems maximum weight occurs at 1000 Hz. In the C.C.I.T.T. system, weight 1000 (0 dB) occurs at 800 Hz; in the B.T.S.-E.E.I. system, unit weight occurs at 1000 Hz.

In both systems, the weights have been revised from time to time to reflect the increasing bandwidth and higher standards of quality of telephone transmission. The C-message weighting was adopted in 1960, when it superseded the earlier F1A weighting, which had already superseded the 144-line weighting in 1941. The psophometric weighting presented here is from the 1963 edition of C.C.I.T.T. Directives.[35]

Other sets of weighting factors pertaining to the coupling between power and telephone lines and to the interfering effect of currents and voltages on power systems are described next.

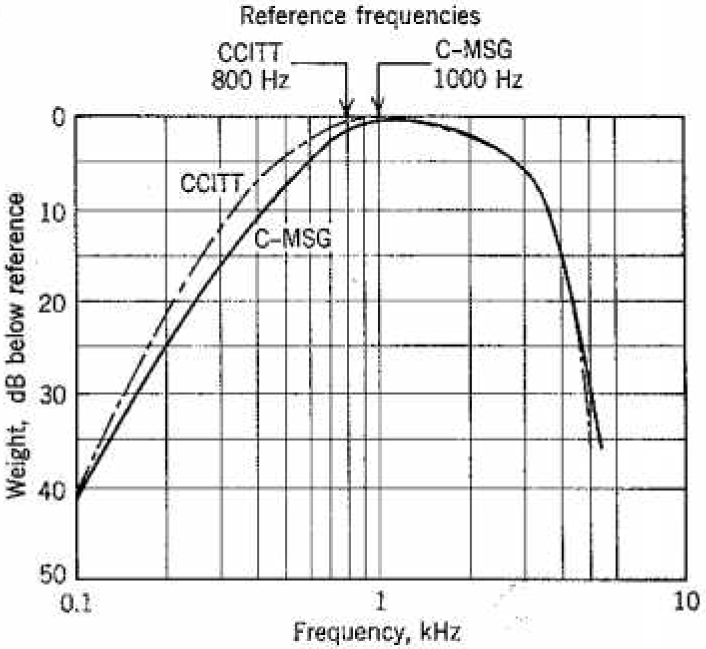


Fig. 18. Comparison of B.T.S. C-message and C.C.I.T.T. weights.

Coupling Factors

In both the B.T.S.-E.E.I. and C.C.I.T.T. systems, the coupling between a power circuit and a telephone circuit is assumed to be directly proportional to frequency. The coupling is taken by convention as 5000 units at 1000 Hz in the B.T.S.-E.E.I. system and as 1 unit at 800 Hz in the C.C.I.T.T. system. Change in coupling as a function of separation or length of circuits is not included in these factors.

Telephone Influence Factor (TIF) and Telephone Harmonic Form Factor

These factors give an approximation to the effect of wave shape of current or voltage of a power line on telephone noise, excluding the magnitude of power-system current or voltage and the geometrical aspects of coupling. Each of these factors is a root-sum-square combination of the products of coupling factors and weighting factors for each frequency. In the B.T.S.-E.E.I. system the result is called *telephone influence factor* (abbreviated TIF), and is defined by

$$\mathrm{TIF} = \frac{\left[\sum_{f=0}^{\infty} (k_f p_f V_f)^2\right]^{1/2}}{V} \qquad (60)$$

Table 6. C.C.I.T.T.[35] **Psophometric Weights ($1000p_f$) and Telephone Interference Weights fp_f**

h	f (Hz)	$1000p_f$	dB	fp_f	h	f (Hz)	$1000p_f$	dB	fp_f
1	50	0.71	−63.0	0.000044	20	1000	1122	+1.0	1.40
2	100	8.91	−41.0	0.00111	24	1200	1000	0.0	1.50
3	150	35.5	−29.0	0.00665	30	1500	861	−1.3	1.62
4	200	89.1	−21.0	0.0223	40	2000	708	−3.0	1.77
6	300	295	−10.6	0.111	50	2500	617	−4.2	1.93
8	400	484	−6.3	0.242	60	3000	525	−5.6	1.97
10	500	661	−3.6	0.413	70	3500	376	−8.5	1.65
12	600	794	−2.0	0.595	80	4000	178	−15.0	0.89
16	800	1000	0.0	1.000	100	5000	15.9	−36.0	0.10

where

$$k_f = 5000(f/1000) = 5f \tag{61}$$

$$p_f = \text{C-message weighting} \tag{62}$$

$$V_f = \text{rms voltage of frequency } f \text{ on power line}$$

$$V = \sqrt{\textstyle\sum V_f^2} = \text{rms voltage, unweighted} \tag{63}$$

In the C.C.I.T.T. system the result is called *telephone harmonic form factor* (T.H.F.F.) and is defined by a similar expression with

$$k_f = \frac{f}{800} \tag{64}$$

$$p_f = \frac{\text{psophometric weighting}}{1000} \tag{65}$$

Generally the sums are for a finite number of discrete frequencies, which include the power frequency (50 or 60 Hz) and its multiples.

C-message-weighted or Psophometrically Weighted Voltage on the Telephone Circuit

These quantities are either longitudinal or transverse voltages on the telephone circuit weighted psophometrically or by C-message weights (see page 327). They also are root-sum-square combinations of the noise effect of discrete frequencies produced in the telephone by other sources than the speaker's voice. Our attention is limited to voltages induced by a power line.

In the B.T.S.-E.E.I. system, the quantity is called *C-message weighted voltage*. In the C.C.I.T.T. system, the longitudinal induced voltage is called *psophometrically weighted voltage*, and the resulting transverse voltage is called *psophometric voltage*:

$$V_\psi = \sqrt{\sum (p_f V_f)^2} \tag{66}$$

where V_f is the rms longitudinal or transverse voltage of frequency f on the telephone line.

I·T Product, kV·T Product, Equivalent Disturbing Voltage, and Equivalent Disturbing Current

These are weighted currents or voltages in the power systems. In the B.T.S.-E.E.I. system, the *I·T product* is a root-sum-square combination of products of currents (in amperes) of various frequencies, each multiplied by the corresponding TIF:

$$\mathrm{I \cdot T} = \sqrt{\sum (T_f I_f)^2} = I \cdot (\mathrm{TIF}) \tag{67}$$

where I_f = rms current of frequency f
T_f = corresponding single-frequency TIF

The *kV·T product* is a similar combination of power-line voltages (in kV). In the C.C.I.T.T. system, the *disturbing current* or *voltage* is similarly defined. In the use of either system, the power-line current or voltage must be specified as either balanced, that is, positive and negative sequence, or unbalanced, that is, zero sequence.

Analogous quantities on the two systems are tabulated in Table 7.

Table 7. Corresponding Quantities in B.T.S.-E.E.I. and C.C.I.T.T. Systems

B.T.S.-E.E.I.	C.C.I.T.T.
C-message weighting	Psophometric weighting
Telephone influence factor (TIF)	Telephone harmonic form factor (THFF)
C-message-weighted voltage:	
Longitudinal	Psophometrically weighted voltage
Transverse	Psophometric voltage
I·T product	Equivalent disturbing current
kV·T product	Equivalent disturbing voltage

8-6 MEANS OF REDUCING HARMONICS

Increased Pulse Number

In low voltage high-current rectifiers, high pulse numbers have sometimes been used, ranging from 24 to 108. This means of reducing harmonics is very effective as long as all valves are in service, but it requires complicated transformer connections. In HV high-current converters for dc transmission, problems of insulation of the converter transformers to withstand high alternating voltages in combination with high direct voltages dictate simple transformer connections. A pulse number of 12 is easily obtained with simple connections of two six-pulse valve groups, as we have seen, and 24 pulses can be obtained with four six-pulse groups by use of a phase-shifting transformer bank in conjunction with two 12-pulse converters. The required phase shift is 15°. Two ways of obtaining it are shown in Figure 19.

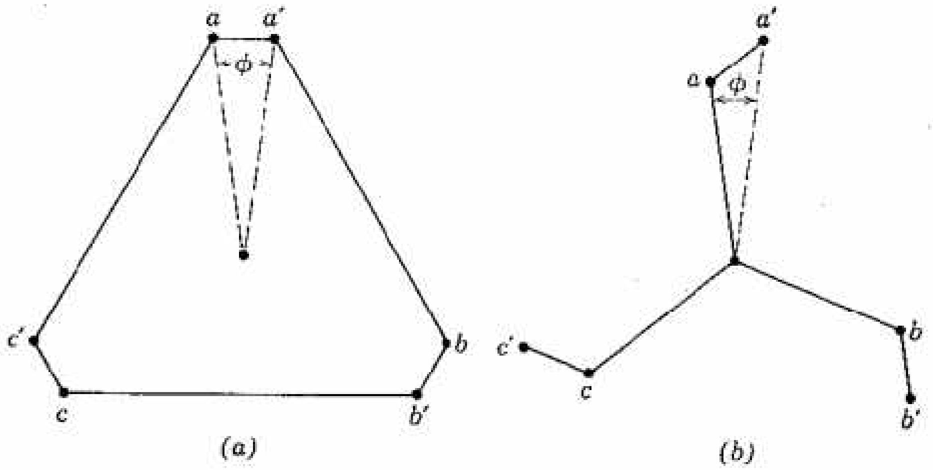


Fig. 19. Voltage vector diagrams of autotransformers for shifting three-phase voltages by angle ϕ (drawn for $\phi = 15°$): (*a*) ring; (*b*) zigzag.

The effectiveness of 12- or 24-pulse converters in reducing harmonics is somewhat decreased when one valve group is out of service. Consider, for example, a converter with four valve groups. If two groups have one transformer connection and the other two groups have a different connection, giving a 30° phase difference, then, with all groups in service, the ac harmonics consist of the 12-pulse harmonics of four groups; but, with only three groups in service, there are the 12-pulse harmonics of three groups and the six-pulse harmonics* of one group. If all groups were connected alike, the harmonic output with three groups in service would consist of both the 12-pulse and six-pulse harmonics of three groups. Obviously, the 12-pulse converter has some advantage over the six-pulse converter even when one bridge is out of service though less than when all are in service.

Filters

Any necessary reduction in harmonic output of the converter beyond that accomplished by increase of pulse number must be done by harmonic filters. Most experts on HV dc transmission feel that it is more economical to use a 12-pulse converter with filters than to use a converter of higher pulse number with the permissible reduction in filters. Therefore, the emphasis in the rest of this chapter is on design of adequate harmonic filters.

Filters are almost always needed on the ac side of the converter and, sometimes, on the dc side also. The ac filters serve two purposes simultaneously: supplying reactive power of fundamental frequency in addition to reducing harmonics. Hence the part of the cost of filters chargeable to the need for reducing harmonics is usually near to the cost of the filter inductors, the filter capacitors being required for supply of reactive power. Thus we are led to the concept of the *minimum filter*, which is required for harmonic reduction only in installations where the reactive power required by the converter can be supplied by the ac system without reinforcing the latter. A filter costing more than the minimum filter not only supplies additional reactive power but also generally gives better filtering. Care should be taken, however, that not too much reactive power is supplied during operation of the dc link at light load.

In addition to the ac harmonic filter at the converter stations, such filters could also be placed in any sections of transmission line giving rise to especially bad telephone noise. This is seldom, if ever, done, because it is usually cheaper to modify or relocate the telephone line.

8-7 TELEPHONE INTERFERENCE

General

The frequencies used in commercial voice transmission range from 200 to 3500 Hz. In this range lie many harmonics of the power-system frequency which are usually of small magnitude but which, because of the high TIF weightings and the great difference between the power levels at which power circuits and telephone circuits operate, may, nevertheless, result in perceptible —or even unacceptable—telephone noise. The power on a voice-frequency telephone circuit is from 10^{-3} to 10^{-5} W. By contrast, that on a power distribution circuit is 10^3 to 10^5 W, and on a major transmission line is 10^7 to 10^9 W.

History

The subject of inductive coordination of power and telephone circuits has been thoroughly studied by both power-system and telephone engineers for the last 50 yr or more. In the United States those studies have been made principally by the B.T.S. and E.E.I.; in Europe, by the C.C.I.F. (now the C.C.I.T.T.) and by governmental power and telephone authorities. Improvements in the quality of telephone service during this period have resulted in a decrease of the tolerable psophometric voltage. Rectifiers in industrial and railway service are not new, but the converters for HV dc transmission have now attained much higher power ratings than those.

Coupling, Electric and Magnetic

Coupling between power circuits and telephone circuits is through both electric and magnetic fields. Unless the spacing between the two circuits is close, however—for example, if both circuits are on the same poles—the magnetic coupling predominates, and the electric coupling is negligible. The magnetic coupling may be expressed as a *mutual impedance*, that is, as the voltage induced in the telephone circuit per ampere of current in the power circuit.

Spacing. The coupling between two circuits having parallel conductors increases with increased spacing between conductors of the same circuit and decreases with increased distance between circuits.

Length. The coupling between parallel circuits is directly proportional to the common length, known as the length of exposure.

Metallic and Ground-return Circuits. If the ground were a perfect conductor, there would be no electric field or varying magnetic field in the ground, and the fields above the surface of the ground caused by overhead conductors carrying currents and charges would be the same as that caused by the actual conductors and their *image conductors* with the ground removed. On the assumption that the surface of the ground is a horizontal plane, each image conductor is a fictitious conductor like the corresponding real conductor, located directly below the latter as far below the surface as the real conductor is above it and carrying current and charge equal in magnitude but opposite in direction to those in the real conductor.

If the ground has finite and uniform conductivity, the foregoing statements are still substantially true with respect to the electric field. The magnetic field, however, can now penetrate the earth, and its effect on self- and mutual inductances is as if the image conductors were lowered to a greater depth below the surface of the ground. The *equivalent depth of ground return* is proportional to the *skin depth*; both of these depths vary inversely as the square root of the frequency and of the conductivity.

If the ground is nonuniform, the foregoing is still true qualitatively.

Because the distance between the overhead conductors of a ground-return circuit and their image conductors are much greater than the distances between conductors of a metallic circuit and because the two conductors of a ground-return circuit are in a vertical plane, the coupling between two ground-return circuits is very much greater than the coupling between two metallic circuits separated by the same distance as the ground-return circuits.

Although ground-return circuits were used for dc telegraphy and voice telephony when these arts were new, they are seldom if every used now because of the severe problems of noise and cross talk. Power circuits are also all metallic except for some HV dc lines, because the power loss and telephone interference from ground-return ac circuits are both high. It would, therefore, appear that the coupling to be calculated is that between a metallic power circuit and a metallic telephone circuit. But, on the contrary, the practice is to calculate the coupling between a ground-return power circuit and an open-ended ground-return telephone circuit. In other words, one calculates the *longitudinal voltage* induced in the telephone circuit by *residual current* in the power circuit. The reasons for this practice are now given.

Unbalances. The currents in a metallic three-phase power circuit are nominally balanced. In telephone parlance *balanced currents* have a sum that is zero. In power-system parlance, the phase currents have positive- and negative-sequence components but no zero-sequence components. In practice, the line-to-ground fundamental-frequency voltages of the power system are almost entirely of positive sequence. The impedances of the three phases, however, are not perfectly balanced because of the inequality of interphase spacing and the lack or infrequency of transpositions. Consequently, some zero-sequence current exists. The power circuit is usually grounded at the source end, and some are multigrounded. At least, there are shunt capacitances to complete the zero-sequence path. The balance of a power circuit seems to be poorer for the higher harmonics than for fundamental currents.

The *residual current*, which, in a three-phase circuit, is $3I_0$, generally induces both longitudinal and transverse voltages in a parallel telephone circuit. If the power and telephone circuits are well separated, however (say, 0.5 km or more) and if the two wires of the telephone circuit are close together and frequently transposed, the induced transverse voltage is negligible, but the induced longitudinal voltage is much greater. This induced longitudinal voltage, however, would still produce no noise in the telephone circuit if the latter were perfectly balanced; but small unbalances in the telephone circuit give rise to unbalanced currents, accompanied by a *transverse voltage.*

Unbalances on the telephone circuit may consist of any unequal series impedances or shunt impedances to ground; for example, ringers connected from one wire to ground and slight differences in resistance of wires or of their capacitances or leakage to ground.

To sum up, the following series of events causes balanced voltages in metallic power systems to produce transverse noise voltage in metallic telephone circuits:

Balanced voltage on power circuit, through
Unbalance of power circuit, causes
Residual current on power circuit, which, through
Coupling between two ground-return circuits, induces
Longitudinal voltage in telephone circuit, which, through
Unbalance of telephone circuit, causes
Transverse voltage in telephone circuit

Shielding (Screening). Passive ground-return circuits between the power and telephone circuits or near to either of them can affect the coupling and the balance. Among such circuits are ground wires on open power lines and metallic sheaths on power cables and on telephone cables, all of which are multigrounded. Their usual effect is to decrease the coupling. Any parallel circuits, however, that are unsymmetrically located with respect to the power circuit and near it also increase the unbalance of the latter. Either the screening effect or the unbalancing effect may predominate. Other parallel, energized power lines can have both of these effects and also be an additional source of telephone influence. For underground cable circuits, the earth has a screening effect, and for submarine cables, the water has an even greater effect.

The *screening factor* is the ratio of the induced telephone noise with the screening to that without the screening.

Frequency. The coupling increases with frequency. For circuits having fixed current paths, the inductive mutual reactance is directly proportional to frequency. Because the equivalent depth of ground return decreases with increasing frequency, however, the coupling between two ground-return circuits increases more slowly than as the first power of the frequency.

The coupling is usually calculated at 1000 Hz (B.T.S.-E.E.I.) or at 800 Hz (C.C.I.T.T.). Then the variation of coupling with frequency is calculated as a separate factor. As previously noted, in the calculation of TIF, the coupling is assumed to vary in direct proportion to the frequency, which is an approximation.

The mutual impedance between two ground return circuits is usually computed by Carson's formula,[1] which assumes a homogeneous earth and parallel conductors. Krakowski[54] has extended Carson's work to crossing conductors. Riordan and Sunde[4,11] have extended this work to a two-layer earth, that is, to surface layer of one resistivity separated by a horizontal plane from an infinite volume having a different resistivity.

If the separation between power and telephone circuits is much greater than that between conductors of the same circuit, the conductors of each circuit may be replaced by one equivalent conductor at the center of gravity of the several conductors. The coupling between widely separated ground-return circuits increases with the resistivity of the ground.

Unbalance of Telephone Circuit

The *balance factor* of a telephone pair is the ratio of the longitudinal voltage induced in the telephone pair by current in a power circuit to the transverse voltage resulting from unbalance of the telephone circuit. For a subscriber loop in modern cable, a typical value of this factor is said to be 316, or 50 dB.[40] An open-wire circuit would be more poorly balanced and thus have a lower balance factor.

Unbalance of Power Circuit

A common configuration of the three conductors of a three-phase transmission line is for them to be in a horizontal or vertical plane with equal spacing between adjacent conductors. Transpositions are rarely used. If such a line carries balanced (positive-sequence) currents, the zero-sequence voltage drop is approximately one-thirtieth of the positive-sequence voltage drop, corresponding to 30 dB.

If the conductors have a triangular configuration, the balance is better, being theoretically perfect for an equilateral triangle. Transpositions, when used, help to balance the line for the fundamental. For the high harmonics, the number of transposition cycles per wavelength is usually too small to be effective. Ground wires on the power line usually improve the balance slightly, but the ground wires most commonly used have a much higher resistance than do the main conductors; hence, their effect is small.

Direct-current overhead lines of the usual configuration are inherently well balanced.

8-8 HARMONIC FILTERS

Purposes

The ac harmonic filters serve two purposes: (1) to reduce the harmonic voltages and currents in the ac power network to acceptable levels and (2) to provide all or part of the reactive power consumed by the converter, the remainder being supplied by shunt capacitor banks, by synchronous condensers, or by the ac power system. The dc harmonic filters serve only to reduce harmonics on the dc line.

Types

The filters at a converter station may be classified by their location, their manner of connection to the main circuit, their sharpness of tuning, and the number and frequencies of their resonances.

Location. Filters are located on both ac and dc sides of converters. Filters on the ac side may be connected either on the primary (network) side of the converter transformers or on the tertiary winding if one is provided for this purpose. Filters are never connected to the secondary (valve side) windings.

Since the tertiary windings, if provided, have a lower voltage than the primary windings, the filters are insulated for lower power-frequency and surge voltage and, therefore, cost less. The tertiary windings, however, add to the cost of the transformers. These windings usually have a high leakage reactance, which inherently forms a common branch in series with all the shunt filters and complicates the computation of possible resonances between the filters and the ac network.

Series or Shunt. Harmonics may be (a) impeded in passing from the converter to the power network or line by a high series impedance, (b) diverted by a low shunt impedance, or (c) both. Figure 20 illustrates the first two kinds. Each is a dual of the other.

The series filter must carry the full current of the main circuit and must be insulated throughout for full voltage to ground. The shunt filter can be grounded at one end and carries only the harmonic current for which it is tuned plus a fundamental current much smaller than that of the main circuit. Hence, a shunt filter is much cheaper than a series filter of equal effectiveness.

Ac shunt filters have another advantage over series filters in that at fundamental frequency the former supplies needed reactive power but the latter consumes it.

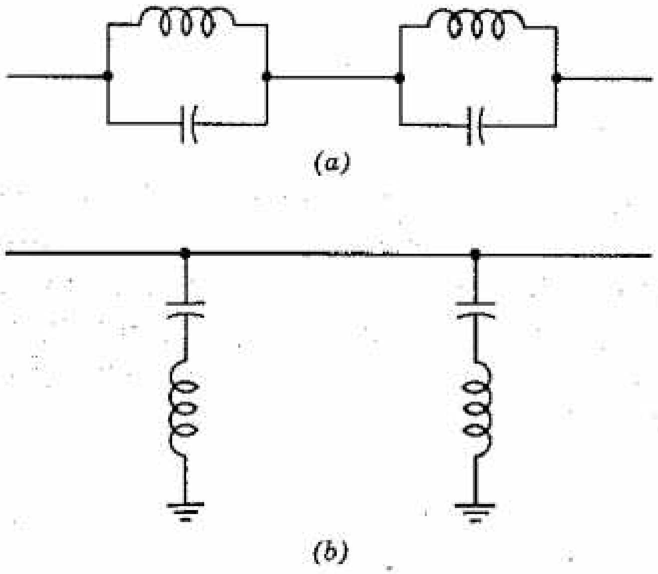


Fig. 20. (*a*) Series filter and (*b*) shunt filter.

For these two reasons shunt filters are used exclusively on the ac side. On the dc side, the dc reactor, which is obviously a series element, constitutes all or part of the dc filters. It must withstand high direct voltage to ground and high direct current. It serves several additional functions (Section 7-2), however, that require series connection. The remainder of the dc filters (if used) consists of shunt branches.

Ac filters could be Δ-connected, but this connection offers no advantage; therefore, the Y connection with grounded neutral is used.

Sharpness of Tuning. Two kinds are used: (a) the *tuned filter* (high Q filter), which is sharply tuned to one or two of the lower harmonic frequencies, such as the fifth and seventh, and (b) the *damped filter* (low Q filter), which, if shunt-connected, offers a low impedance over a broad band of frequencies embracing, for example, the seventeenth and higher harmonics. The second kind is also called a *high-pass filter*. Figures 21 and 22 show typical circuit diagrams and characteristics of the two types. They are analyzed under "Design of Tuned Filter," page 355, and "Design of High-pass Damped Filters," page 375, respectively.

Cost of Filters

The capital cost of ac filters is in the range of 5 to 15% of the cost of the terminal equipment.* This is high enough to justify careful design from the standpoint of economy as well as adequacy. The cost of losses should also be taken into consideration. The cost of filters may be partly charged to reactive-

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* For example, the cost of the filters of the New Zealand scheme was said to be 12%.[52]

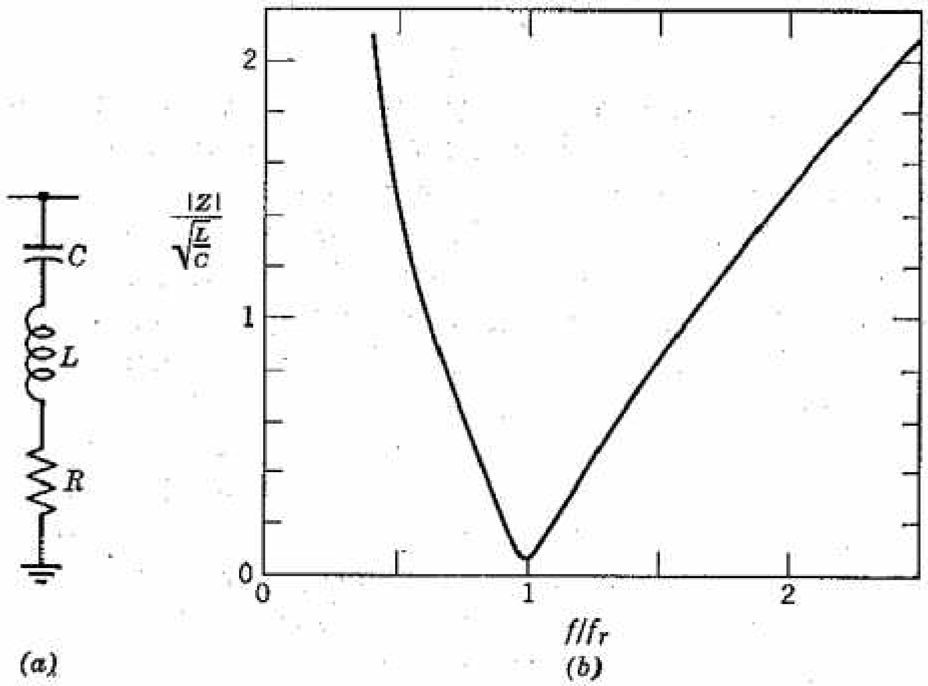


Fig. 21. Single-tuned shunt filter: (*a*) circuit; (*b*) impedance versus frequency.

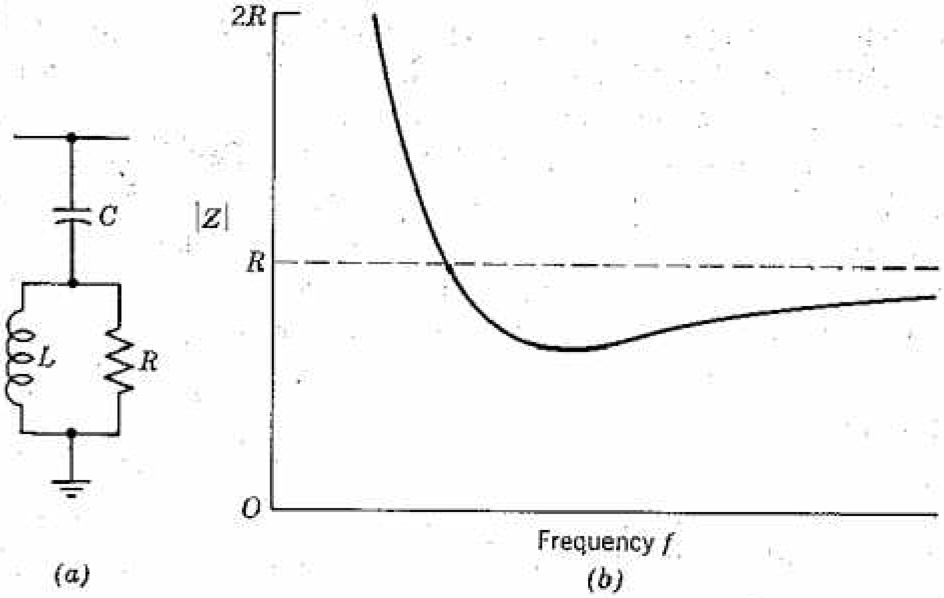


Fig. 22. Second-order damped shunt filter: (*a*) circuit; (*b*) impedance versus frequency.

power supply and partly to filtering though there is no logical basis of the division.

A *minimum filter* is one that adequately suppresses harmonics at the least cost and supplies some reactive power but perhaps not all that is required.

A *minimum-cost-filter* is defined under "Minimum-cost Tuned Filter," page 368. It may or may not give adequate filtering.

About 60% of the capital cost of the filters is that of the capacitors. Hence, substantial savings are possible by judicious choice of kind of capacitor.

Criteria for Adequacy of AC Filters

Ideally, the criterion should be the absence of all detrimental effects from harmonics, including telephone interference, which is the most difficult effect to eliminate entirely. This criterion is impractical from both technical and economic standpoints. From the technical standpoint of filter design, the distribution of harmonics throughout the ac network is too difficult to determine in advance. From the economic standpoint, the reduction of telephone interference can generally be accomplished more economically by taking some of the measures in the telephone system and others in the power system.

The practical criterion would be an acceptable level of harmonics at the converter terminals, expressed in terms of harmonic current, of harmonic voltage, or of both. The filter designer would prefer a criterion based on harmonic voltage at the converter terminals because he can more readily guarantee staying within a reasonable voltage limit than a reasonable current limit despite changes in the network impedance seen from the converter terminals.

Unfortunately, there is no general agreement on the acceptable limit of either harmonic current or harmonic voltage. Presently, we can look only at the limits that have been proposed or attained.

Stumpf[40] stated that, from the experience of the Bell Telephone System with industrial rectifiers, an I · T product greater than 25 kA would be likely to cause severe interference problems; one less than 5 kA would be unlikely to cause any interference problems.

Several others have proposed limits for harmonic voltage.

1. Ainsworth[41] has suggested the following limits:
   - *a.* Maximum theoretical deviation from a sine wave (H6, Section 8-5, page 327) is not to exceed 3 to 5%.
   - *b.* Telephone harmonic form factor (THFF, Section 8-5, page 328) is not to exceed 1 or 2%.
2. Iliceto[38] reported that, for the Sardinian project,
   - *a.* H6 had been specified as 4% (a value said to be satisfactory for turbogenerators, induction motors, and fluorescent lamps) and
   - *b.* Maximum THFF as 1%.
3. The values proposed by C.E.G.B. for the Kingsnorth scheme are the the following[44]:
   - *a.* Limit every single characteristic-harmonic voltage to 1%. This should be calculated with the most unfavorable network impedance within the chosen impedence bounds (Figure 28).

   b. Limit the arithmetic sum of the characteristic harmonic voltages of orders 5 to 25 to 2.5% with any one harmonic as in (*a*) and the rest from the most unfavorable impedance locus.

4. Filters for the New Zealand scheme[47] were designed so that each characteristic harmonic would be less than 0.7%.

Effect of Network Impedance on Filtering

The converter approximates a constant-voltage harmonic source on the dc side and a constant-current harmonic source on the ac side. More accurately, the converter is a low-impedance harmonic source on the dc side and a high-impedance harmonic source on the ac side. We now consider, on the ac side, the effect of filter impedance and network impedance on the harmonic voltage V_h at the converter terminals and on the harmonic current I_{hn} entering the network.

Figure 23 shows an equivalent circuit for the purpose. The harmonic current I_{hc} generated in the converter is assumed to be known. It splits between two paths, the shunt filter and the network. The harmonic voltage across this parallel circuit depends on the impedance of these two branches in parallel. Let

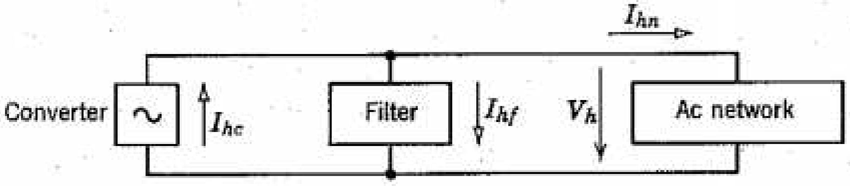


Fig. 23. Circuit for computation of harmonic currents and voltages on the ac side of a converter.

$\mathbf{Z}_{hf}$ = impedance of filter to harmonic of order h
$\mathbf{Z}_{hn}$ = impedance of network to harmonic of order h

$$\mathbf{Y}_{hf} = \frac{1}{\mathbf{Z}_{hf}} \quad \text{and} \quad \mathbf{Y}_{hn} = \frac{1}{\mathbf{Z}_{hn}}$$

Then the harmonic voltage is

$$\mathbf{V}_h = \frac{\mathbf{Z}_{hf}\mathbf{Z}_{hn}\mathbf{I}_{hc}}{\mathbf{Z}_{hf} + \mathbf{Z}_{hn}} = \frac{\mathbf{I}_{hc}}{\mathbf{Y}_{hf} + \mathbf{Y}_{hn}} \tag{69}$$

and the harmonic currents in the network and filter, respectively, are

$$\mathbf{I}_{hn} = \frac{\mathbf{V}_h}{\mathbf{Z}_{hn}} = \frac{\mathbf{Z}_{hf}\mathbf{I}_{hc}}{\mathbf{Z}_{hf} + \mathbf{Z}_{hn}} = \frac{\mathbf{Y}_{hn}\mathbf{I}_{hc}}{\mathbf{Y}_{hf} + \mathbf{Y}_{hn}} \tag{70}$$

$$\mathbf{I}_{hf} = \frac{\mathbf{V}_h}{\mathbf{Z}_{hf}} = \frac{\mathbf{Z}_{hn}\mathbf{I}_{hc}}{\mathbf{Z}_{hf} + \mathbf{Z}_{hn}} = \frac{\mathbf{Y}_{hf}\mathbf{I}_{hc}}{\mathbf{Y}_{hf} + \mathbf{Y}_{hn}} \tag{71}$$

Since the impedance of the network to harmonics is subject to change and is seldom accurately known, the effect of some extreme assumptions is investigated:

1. If the network impedance were nil to all harmonics, there would be $\mathbf{V}_h = 0$ and $\mathbf{I}_{hn} = \mathbf{I}_{hc}$. Shunt filters would have no effect. All the harmonic current generated by the converter would enter the network. Filtering would appear perfect if judged by voltage but bad if judged by current. This assumption of $\mathbf{Z}_{hn} = 0$ is unrealistic. If it were approximately true, filters with series elements would be required.
2. If the network impedance were infinite, all the harmonic current generated by the converter would pass through the filter. There would be $\mathbf{I}_{hn} = 0$, $\mathbf{I}_{hf} = \mathbf{I}_{hc}$, and $\mathbf{V}_h = \mathbf{Z}_{hf}\mathbf{I}_{hc}$. Filtering would be perfect if judged by current and could be good if judged by voltage, for the design of suitable filters would present no great problem. This assumption of $\mathbf{Z}_{hn} = \infty$, although obviously untrue, might give reasonable results as regards harmonic voltages.
3. There is, however, a more pessimistic assumption: that the network and filter are in parallel resonance. The resulting impedance would be a high resistance; and $\mathbf{V}_h$, $\mathbf{I}_{hn}$, and $\mathbf{I}_{hf}$ would all be high. Indeed, the harmonic network current and voltage could be increased by the presence of the filter. The filtering could be bad, whether judged by current or voltage or both. Moreover, the filter could be overloaded; that is, its elements would be subjected to both high harmonic current and high harmonic voltage.

Since tuned filters are customarily provided for the low characteristic harmonics and since the impedance of such a filter at the frequency to which it is tuned is a low resistance, severe parallel resonance of filter and network to such a harmonic is unlikely unless the filter passband is too narrow and unless either the system frequency is abnormal or the filter is detuned. Such resonance is likewise unlikely at the higher frequencies for which the high-pass damped filter provides a low impedance and high power factor. It is more likely to occur at a low uncharacteristic harmonic. It is unlikely to occur at more than one harmonic frequency at the same time although, because of changes in the network, it could occur at another harmonic frequency at another time.

The severity of resonance depends on the amount of damping due to losses both in the filters and in the network. Therefore, some knowledge of the response of the network to harmonics is desirable.

Impedance of the AC Network

The impedance of the ac network seen from the converter terminals, as a function of frequency, may be either measured or calculated. Both methods offer certain difficulties.

Measurement. Measurements must be made with the power system alive at high voltage. Since the ac network contains other sources of harmonics, measurements of network impedance at harmonic frequencies require a high-power source of harmonics. An adjustable-speed motor-generator set may be used for generating a single frequency, adjustable, perhaps, from 180 to 1200 Hz. Alternatively, a rectifier short-circuited on the dc side can be used to generate all its characteristic harmonics simultaneously. Either source may be single-phase and may be connected to the ac network through a step-up transformer. For greatest usefulness, the complex impedance must be measured, not merely the scalar value.

Measurements apply only to conditions at the time of measurement and not to future conditions under which a converter may operate. Nevertheless, measurements give some useful information that cannot be obtained by computation. Results of measurements are discussed later.

Calculation. Calculation can be done by either a model (network analyzer) or a digital computer. Calculations can be made for light and heavy loads, outages of lines or equipment, and planned future conditions. The principal uncertainties are due to inadequate knowledge of the circuit parameters at harmonic frequencies and to the effect of unbalances of the circuits.

The following are some suggestions for details of the power-system representation:

Represent only the positive-sequence network.

Overhead lines may be represented by one equivalent π section, whose branches are corrected for each frequency, or, alternatively, by several nominal π circuits in tandem.

Transformers may be represented by a fixed leakage inductance in series with a resistance that is a function of frequency. Their capacitances are neglected.

Generators are represented by an inductance equal to between 0.8 and 0.9 of their subtransient inductances.

Loads may be represented by resistances in series with the transformer inductances.

In the use of a network analyzer, it is more feasible to use a constant-frequency source and to readjust the circuit impedances for each harmonic than to use an adjustable-frequency source with a fixed network.

Examples and Conclusions. Three loci of network impedance in the complex impedance plane for the 220-kV Italian mainland network at the San Dalmazio terminal of the Sardinia dc link are given in Figures 24, 25, and 26.

These loci were measured on a model. They illustrate several points:

1. Alternation of resonance (low resistance) and antiresonance (high resistance) as the frequency increases.

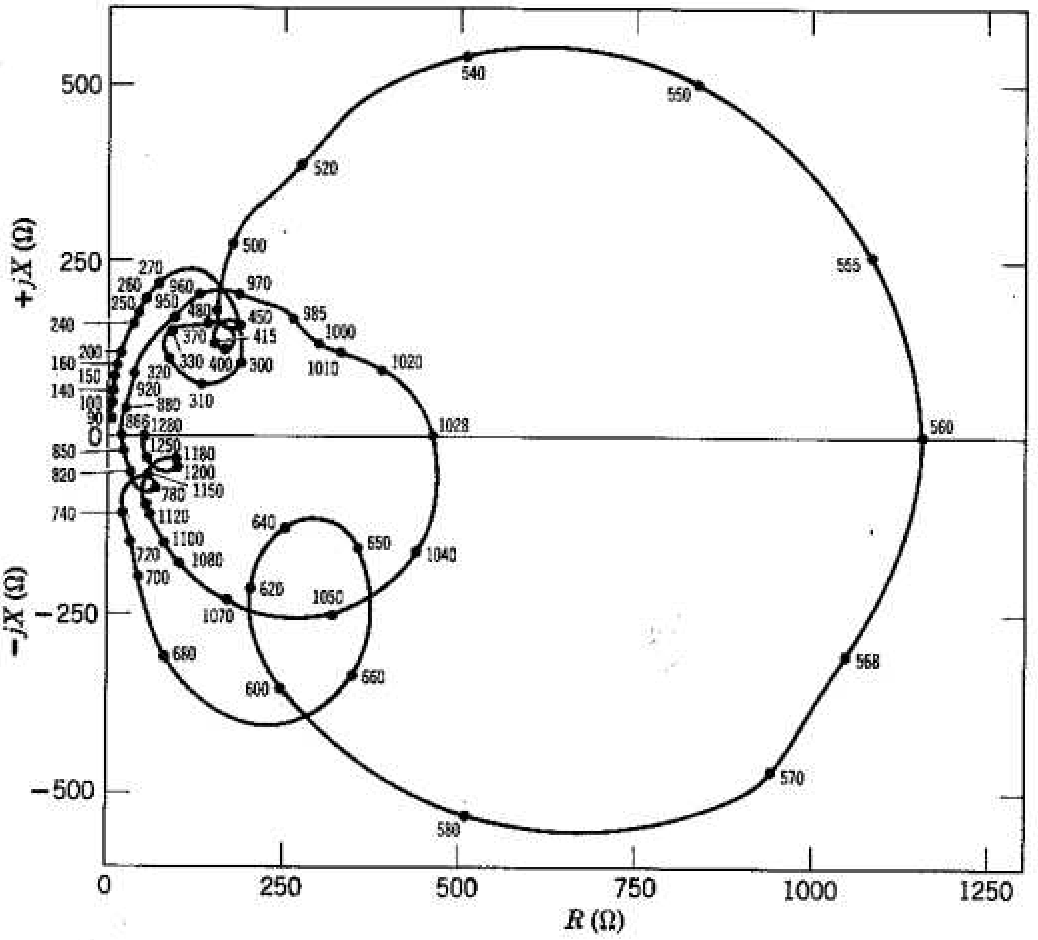


Fig. 26. Calculated impedance of 220-kV network at minimum load with two lines disconnected. (From Ref. 38 by permission.)

AC Filter Design—General Remarks

Aims are (a) to achieve adequate harmonic reduction and (b) to supply the required reactive power at fundamental frequency, (c) achieving both at minimum cost.

Composition. The ac filters in each phase usually comprise:

1. Tuned filters for several (2 to 8) lower harmonics
2. A damped filter for higher harmonics
3. Switchable shunt capacitors

The lower characteristic harmonics have the largest current magnitudes and, therefore, require filters that have low impedances at and near the frequencies of these harmonics. It is more economical to use a separate tuned branch for each of these harmonics than to provide a wide-band filter of sufficiently low impedance.

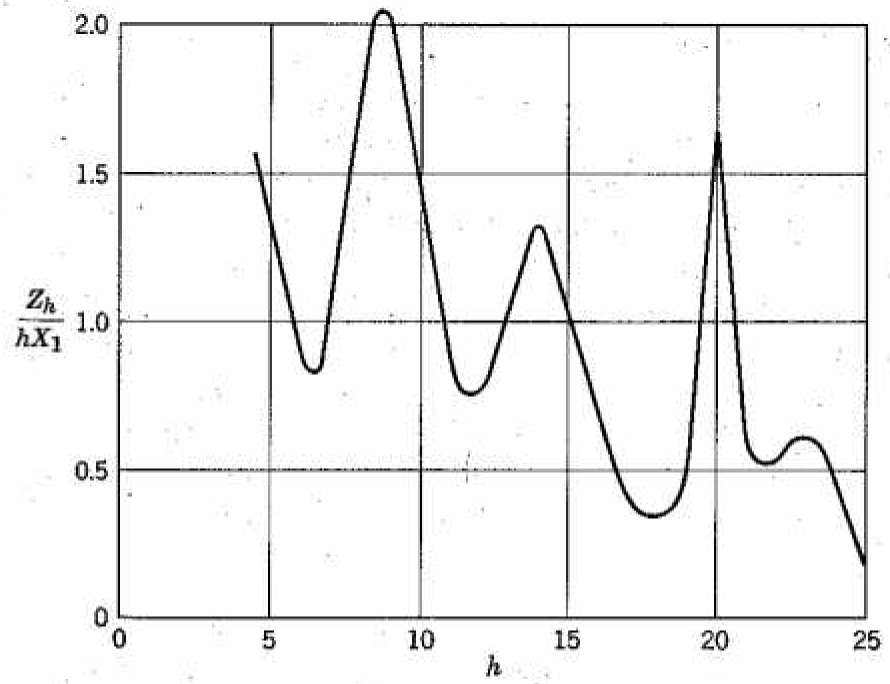


Fig. 27. Measured harmonic impedance of the 132-kV 50-Hz system at Lydd. (From Ref. 49 by permission.)

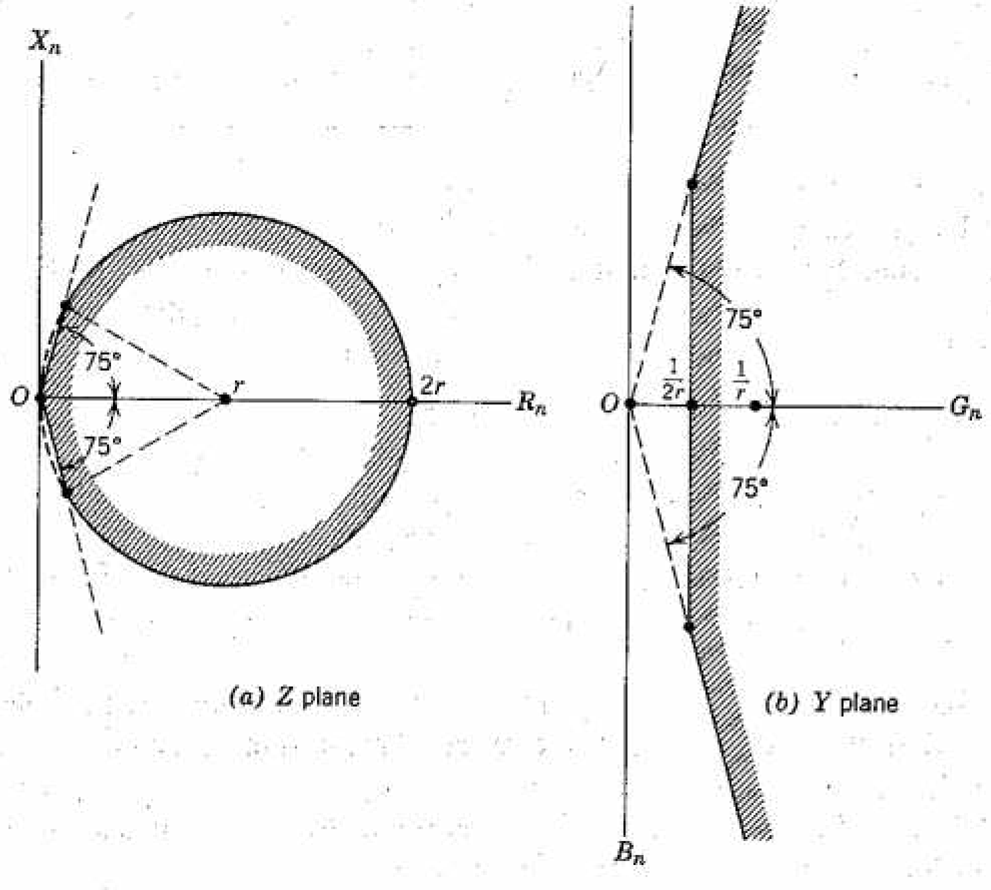


Fig. 28. Bounds of loci of (*a*) impedance and (*b*) admittance to harmonics in an ac network.

The higher harmonics have smaller magnitudes, and the frequency ratio of successive harmonics approaches unity. A great many tuned filters would be required, and their passbands would overlap anyhow. A damped high-pass filter is more economical for these higher harmonics.

The number of tuned filter arms varies from one dc link to another, the commonest number being four. Logically, the combination of tuned arms and high-pass arms should be the cheapest one that satisfies the filtering requirements. Provision of tuned filters for the seventeenth and nineteenth harmonics may depend on the number of bridges in the converter.

The relative magnitudes of characteristic harmonics of 2- and 4-bridge 12-pulse converters are shown in Table 8 for all bridges in service and for one bridge out of service. Filters for the fifth, seventh, seventeenth, and nineteenth harmonics are needed only when a bridge is out of service.

Table 8

Number of Bridges	Harmonic Current of Order h in Per-unit of Full-Load Fundamental Current								
	$h = 1$	5	7	11	13	17	19	23	25
2/2 or 4/4	1.000	0	0	0.091	0.077	0	0	0.044	0.040
3/4	0.750	0.050	0.036	0.068	0.058	0.015	0.013	0.033	0.030
1/2	0.500	0.100	0.071	0.046	0.038	0.029	0.026	0.022	0.020

Shunt capacitors are used mainly for varying the reactive power when the load on the converter changes. They also improve the filtering of high harmonics.

Size. The size of a filter is defined as the reactive power that the filter supplies at fundamental frequency. It is substantially equal to the fundamental reactive power supplied by the capacitors. The total size of all the branches of a filter, including shunt capacitors, is determined by the reactive-power requirement of the converter station and by how much of this requirement can be supplied by the ac network and by synchronous condensers, if any.

The size of individual arms depends on filtering requirements, but seldom is it less than the size for minimum cost (see "Minimum-cost Tuned Filter," page 368).

The design of tuned filters involves selection of their size and sharpness of tuning (Q), and is discussed immediately below.

The design of high-pass damped filters involves selection of their size, sharpness of tuning, and resonant frequency; it is discussed beginning on page 375.

Design of Tuned Filters

Single-tuned Filters. A single-tuned filter is a series RLC circuit (Figure 21) tuned to the frequency of one harmonic (generally a low characteristic harmonic). Its impedance is given by

$$\mathbf{Z}_f = R + j\left(\omega L - \frac{1}{\omega C}\right) \tag{72}$$

At its resonant frequency, its impedance is a low resistance R. Its passband is commonly regarded as bounded by frequencies at which $|\mathbf{Z}_f| = \sqrt{2}R$. At these frequencies the net reactance equals the resistance, and the impedance angle is ±45°.

Let the quantities ω, R, L, C in Eq. (72) be replaced by the following:

$$\omega_n = \frac{1}{\sqrt{LC}} = \text{tuned angular frequency (rad/sec)} \tag{73}$$

$$\delta = \frac{\omega - \omega_n}{\omega_n} = \text{deviation (per unit) of frequency from tuned frequency} \tag{74}$$

$$X_0 = \omega_n L = \frac{1}{\omega_n C} = \sqrt{\frac{L}{C}} = \text{reactance of inductor or capacitor (ohms) when } \omega = \omega_n \tag{75}$$

$$Q = \frac{X_0}{R} = \text{quality factor of inductor or sharpness of tuning of filter (dimensionless)} \tag{76}$$

From these,

$$\omega = \omega_n(1 + \delta) \tag{77}$$

$$C = \frac{1}{\omega_n X_0} = \frac{1}{\omega_n R Q} \tag{78}$$

$$L = \frac{X_0}{\omega_n} = \frac{RQ}{\omega_n} \tag{79}$$

Substitution of Eqs. (77), (78), (79) into Eq. (72) gives

$$\mathbf{Z}_f = R\left(1 + jQ\delta\frac{2 + \delta}{1 + \delta}\right) \tag{80}$$

For the small frequency deviations ($\delta \ll 1$) in which we are now interested, the impedance is given very nearly and more simply by

$$\mathbf{Z}_f \cong R(1 + j2\delta Q) = X_0\left(\frac{1}{Q} + j2\delta\right) \tag{81}$$

$$|\mathbf{Z}_f| \cong R\sqrt{1 + 4\delta^2 Q^2} = X_0\sqrt{Q^{-2} + 4\delta^2} \tag{82}$$

The admittance, conductance, and susceptance under like conditions are

$$\mathbf{Y}_f \cong \frac{1}{R(1+j2\delta Q)} = \frac{1-j2\delta Q}{R(1+4\delta^2 Q^2)} = \frac{Q-j2\delta Q^2}{X_0(1+4\delta^2 Q^2)} \tag{83}$$

$$|\mathbf{Y}_f| \cong \frac{1}{R\sqrt{1+4\delta^2 Q^2}} = \frac{Q}{X_0\sqrt{1+4\delta^2 Q^2}} \tag{84}$$

$$G_f \cong \frac{1}{R(1+4\delta^2 Q^2)} = \frac{Q}{X_0(1+4\delta^2 Q^2)} \tag{85}$$

$$B_f \cong \frac{2\delta Q}{R(1+4\delta^2 Q^2)} = \frac{2\delta Q^2}{X_0(1+4\delta^2 Q^2)} \tag{86}$$

Inductive susceptance is positive; capacitive, negative.

Frequency Deviation (Detuning). In practice a filter is not always tuned exactly to the frequency of the harmonic that it is intended to suppress.

1. The power-system frequency may change, thus causing the harmonic frequency to change proportionally.
2. The inductance of the inductor and the capacitance of the capacitor may change. Of these two, the capacitance changes more because of aging and change of temperature due to ambient temperature and self-heating (see "Capacitors," page 365).
3. The initial tuning may be off because of finite size of tuning steps.

A change of L or C of 2% causes the same detuning as a change of system frequency of 1%. The total *detuning* or *equivalent frequency deviation* is, consistent with Eq. (74),

$$\delta = \frac{\Delta_f}{f_n} + \frac{1}{2}\left(\frac{\Delta L}{L_n} + \frac{\Delta C}{C_n}\right) \tag{87}$$

In subsequent analysis, δ is assumed to be wholly attributable to Δf.

Graphs of Impedance. Figure 29 shows three curves of filter impedance $|\mathbf{Z}_f|$ versus frequency deviation δ. Curves A and B are for the same R; they have the same minimum impedance. Curves B and C are for the same X_0; they have the same asymptotes D (corresponding to $R = 0$). The equation of the asymptotes is $|X_f| = \pm 2X_0|\delta|$. Curves A and C are for the same Q; they have the same passband **PB**. From Eq. (81) the edges of the passband are at $\delta = \pm 1/2Q$, and the width of the passband is $1/Q$.

From these curves it is apparent that the impedance of the filter at its resonant frequency can be decreased by decreasing R. In order to keep the impedance low over a frequency band bounded by the points of maximum

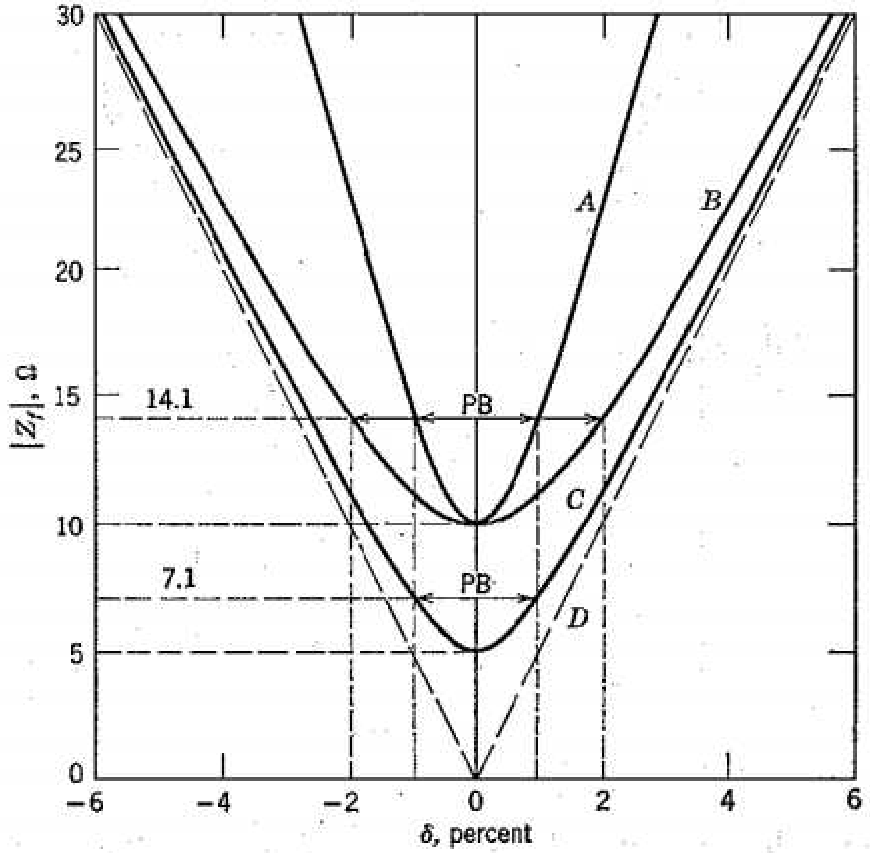


Fig. 29. Impedance of tuned filter as function of frequency deviation. Curve *D* consists of the asymptotes of curves *B* and *C*.

Curve	*R* (Ω)	X_0 (Ω)	*Q*	Passband (PB)
A	10	500	50	2%
B	10	250	25	4%
C	5	250	50	2%

expected frequency deviation, however, it may be necessary to decrease X_0 also, thereby decreasing Q.

Figure 30 has a generalized dimensionless impedance curve with coordinates $y = |\mathbf{Z}_f|\,Q/X_0$ versus $x = Q\delta$. In these coordinates, the minimum impedance is 1, the width of the passband is 1, and the asymptotes are $y = \pm 2|x|$. The curve is a hyperbola, given by $y^2 = 4x^2 + 1$.

Minimization of Harmonic Voltage V_h (see "Effect of Network Impedance on Filtering," page 347) requires minimization not of the filter impedance $\mathbf{Z}_{hf}$ alone but of the impedance $\mathbf{Z}_h$ resulting from the parallel combination of filter impedance $\mathbf{Z}_{hf}$ and the impedance $\mathbf{Z}_{hn}$ of the ac network—(Eq. 69) and Figure 23):

$$V_h = |\mathbf{V}_h| = |\mathbf{Z}_h|\,\mathbf{I}_{hc} = \frac{|\mathbf{I}_{hc}|}{|\mathbf{Y}_h|} = \frac{|\mathbf{I}_{hc}|}{|\mathbf{Y}_{hf} + \mathbf{Y}_{hn}|} \tag{88}$$

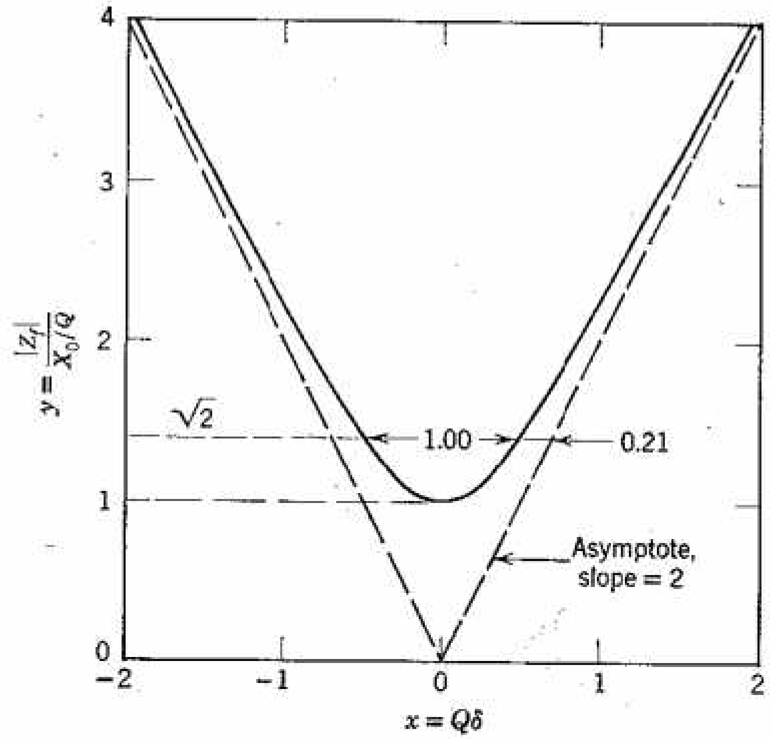


Fig. 30. Generalized impedance curve of tuned filter.

The variables that are not under the control of the filter designer are chosen pessimistically; that is, so as to give the highest V_h. Then the variables that are under his control are chosen optimally to give acceptable V_h. The variables for which pessimistic values are assumed are the frequency deviation δ and the network impedance $\mathbf{Z}_{hn}$. Harmonic voltage is shown to increase with δ; hence, the pessimistic value of δ is the greatest value that is expected to persist: δ_m. The network impedance is taken as the worst value within reasonable limits (see "Impedance of the AC Network," page 348). The variables that the designer can vary, within reasonable limits, are the Q and the "size" of the filter. There is an optimum value of Q that gives minimum harmonic voltage for the assumed network conditions, and this value, denoted by Q_o should be used. It is independent of filter size. Then size is chosen for acceptable harmonic voltage and for the desired amount of reactive power. Since Q_o depends on the assumptions about the network impedance, several cases must be examined.[41]

Case 1. Infinite Network Impedance. In this case the resultant impedance is merely that of the filter: $\mathbf{Z}_h = \mathbf{Z}_{hf}$. By substitution of Eq. (82) for $|\mathbf{Z}_f|$ into Eq. (88), the harmonic voltage is given as

$$V_h = |\mathbf{Z}_{hf}| I_{hc} = I_{hc} X_0 (Q^{-2} + 4\delta_m^2)^{1/2} \tag{89}$$

For given X_0 and δ_m, V_h is minimized by making

$$Q = Q_o = \infty \tag{90}$$

The harmonic voltage is then

$$V_h = 2\delta_m X_0 I_{hc} \tag{91}$$

In practice there is a maximum Q for which a coil of given inductance can be built to operate at a given frequency, and economy dictates a somewhat lower Q. If the harmonic voltage is unacceptably high at this Q, it becomes necessary to decrease X_0 by increasing the size of the filter.

The assumption of infinite network impedance is optimistic and unrealistic, because it rules out the possibility of resonance between the network and the filter, which increases the harmonic voltage.

Case 2. Purely Reactive Network. We now pass to consider the most pessimistic assumption about the network. Equation (88), with admittances expressed in terms of their components, becomes

$$V_h = \frac{I_{hc}}{\sqrt{(G_{hf} + G_{hn})^2 + (B_{hf} + B_{hn})^2}} \tag{92}$$

In the present case we may put $G_{hn} = 0$ and also, on the assumption of resonance, $B_{hf} + B_{hn} = 0$. Then, simply,

$$V_h = \frac{I_{hc}}{G_{hf}} \tag{93}$$

and substitution of Eq. (85) for G_{hf}, with $\delta = \delta_m$, gives

$$V_h = X_0 I_{hc}(Q^{-1} + 4\delta_m^2 Q) \tag{94}$$

This is minimized if

$$Q = Q_0 = \frac{1}{2\delta_m} \tag{95}$$

giving the harmonic voltage as

$$V_h = 4\delta_m X_0 I_{hc} \tag{96}$$

which is twice the value—Eq. (91)—obtained in case 1.

The present case is unduly pessimistic, because every power network has some conductance that decreases the voltage at parallel resonance.

Case 3. Network with Limited Impedance Angle. Let the network impedance angle ϕ be limited to values between $\pm\phi_m$, where $0 < \phi_m < 90°$. It is shown that the highest harmonic voltage occurs if $\phi = \phi_m$ and has opposite sign from that of δ. Since no limit was placed on $|\mathbf{Y}_{hn}|$, we must find and use the value that minimizes $|\mathbf{Y}_h|$ and, hence, maximizes V_h. Here a graphical analysis is informative.

As before, the greatest value of δ, δ_m, must be assumed, and optimum Q must be found, this being the value that maximizes $|\mathbf{Y}_h|$.

Figure 31*a* shows the locus of filter impedance—Eq. (81)—

$$\mathbf{Z}_{hf} = X_0(Q^{-1} + j2\delta_m),$$

with fixed $X_f = 2\delta_m X_0$ and variable $R_f = X_0/Q$ as a horizontal line in the **Z** plane. In the **Y** plane (part *b* of the figure) this line, inverted, becomes a semicircle of diameter $1/(2\delta_m X_0)$ tangent to the G axis at the origin. Points on the semicircular locus in the **Y** plane, corresponding to points on the rectilinear locus in the **Z** plane for the same values of Q, are found by drawing radial lines from the origin of each plot with equal but opposite slopes; for example, the points for $Q = 1/(2\delta_m)$ lie on lines of slope ±1 (angle ±45°). Vectors from the origins to points on the loci represent filter impedance and admittance, $\mathbf{Z}_{hf}$ and $\mathbf{Y}_{hf}$, respectively.

In Figure 31*b* vector $\mathbf{Y}_{hf}$ is tentatively taken as that for $Q = 1/(2\delta_m)$, and a tentative vector $\mathbf{Y}_{hn}$ is added to it to give $\mathbf{Y}_h$. The terminal points of $\mathbf{Y}_{hn}$ and

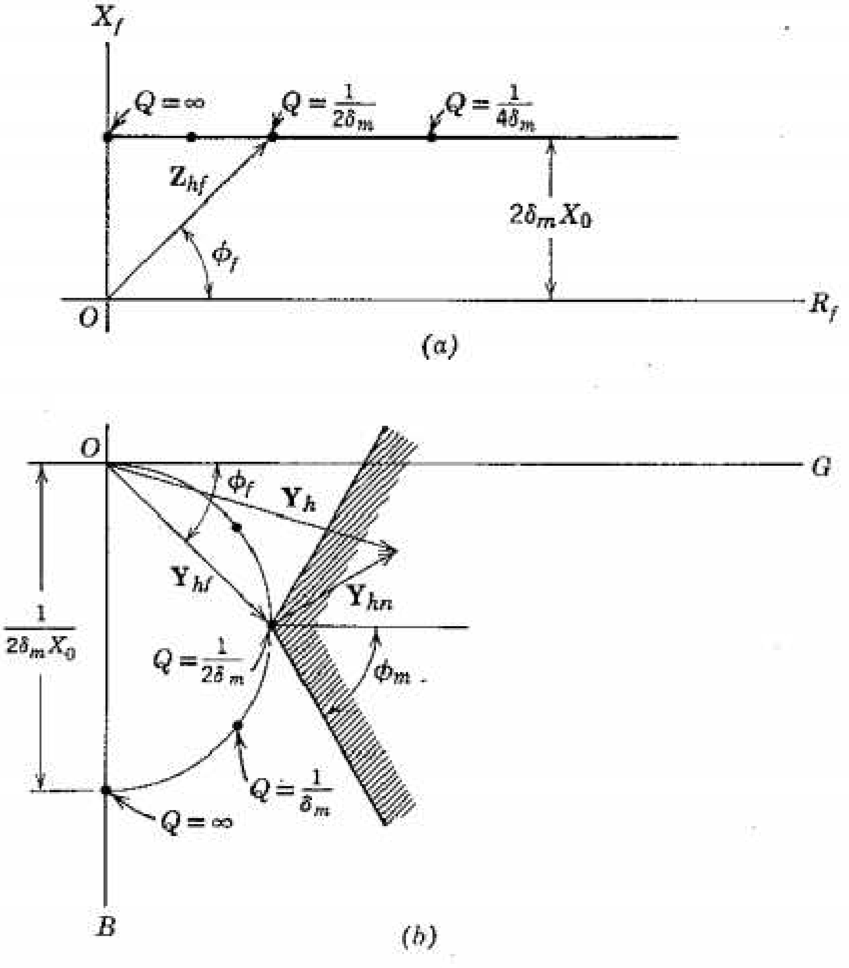


Fig. 31. Loci of (*a*) filter impedance $\mathbf{Z}_{hf}$ and (*b*) filter admittance $\mathbf{Y}_{hf}$ with constant X and varying R and Q; (*b*) also shows tentative choices of $\mathbf{Y}_{hf}$ and $\mathbf{Y}_{hn}$.

$\mathbf{Y}_h$ must lie within or on the boundary of the shaded area, drawn there for $\phi_m = 60°$. It is readily seen that the tentative choice of vectors does not give minimum $\mathbf{Y}_h$. For the assumed $\mathbf{Y}_{hf}$ the shortest vector $\mathbf{Y}_h$ is perpendicular to the boundary and terminates on the boundary above the vertex. Furthermore, it may be seen that the tentative choice of $\mathbf{Y}_{hf}$ is not that which maximizes $\mathbf{Y}_h$ with respect to Q. The proper $\mathbf{Y}_{hf}$ is that which ends on the semicircle at a point where the boundary at angle $+\phi_m$ is tangent to the semicircle.

In Figure 32 the vectors are redrawn so that $\mathbf{Y}_{hf}$ maximizes $\mathbf{Y}_h$, and $\mathbf{Y}_{hn}$ minimizes it.

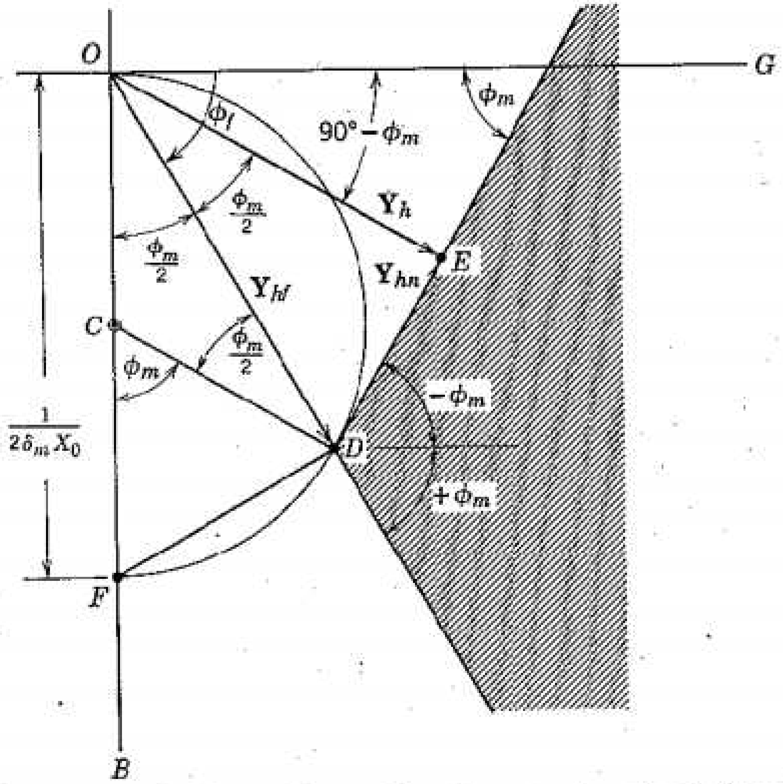


Fig. 32. Construction for finding optimum Q and worst network admittance $\mathbf{Y}_{hn}$. Drawn for $\phi_m = 60°$.

The truth of the statement made earlier, that $|\phi| = \phi_m$ and that the sign of ϕ is opposite to the sign of δ, is proved by the vector diagram, drawn for positive $\delta = \delta_m$ and for negative $\phi = \phi_m$. (Remember that ϕ was defined as an impedance angle and that $-\phi$ is the corresponding admittance angle.) In addition, the effect of varying δ may be shown. Decrease of δ increases the diameter of the semicircular locus of $\mathbf{Y}_{hf}$, thereby increasing $\mathbf{Y}_h$ and decreasing V_h. Hence $|\delta| = \delta_m$ is more pessimistic than $|\delta| < \delta_m$. Negative δ turns the figures upside down.

Formulas for optimum Q and for the corresponding $\mathbf{Y}_{hf}$, $\mathbf{Y}_{hn}$, and $\mathbf{Y}_h$ can be derived by trigonometry, starting with the known diameter of the semicircle, the known angle ϕ_m, and other angles related to ϕ_m. Triangle

OCD is isosceles, with the two smaller angles $\angle COD = \angle CDO = \phi_m/2$. In right triangle ODF, $OD = OF \cos(\phi_m/2)$; hence

$$|\mathbf{Y}_{hf}| = \frac{\cos(\phi_m/2)}{2\delta_m X_0} \tag{97}$$

In right triangle OED, $OE = OD \cos(\phi_m/2)$ and $DE = OD \sin(\phi_m/2)$.

$$|\mathbf{Y}_h| = |\mathbf{Y}_{hf}| \cos\frac{\phi_m}{2} = \frac{\cos^2(\phi_m/2)}{2\delta_m X_0} = \frac{\cos\phi_m + 1}{4\delta_m X_0} \tag{98}$$

and
$$|\mathbf{Y}_{hn}| = |\mathbf{Y}_{hf}| \sin\frac{\phi_m}{2} = \frac{\cos(\phi_m/2)\sin(\phi_m/2)}{2\delta_m X_0} = \frac{\sin\phi_m}{4\delta_m X_0} \tag{99}$$

$$\mathbf{Y}_{hf} = |\mathbf{Y}_{hf}| \; \underline{/-90^\circ + \phi_m/2} \tag{100}$$

$$\mathbf{Y}_h = |\mathbf{Y}_h| \; \underline{/-90^\circ + \phi_m} \tag{101}$$

$$\mathbf{Y}_{hn} = |\mathbf{Y}_{hn}| \; \underline{/+\phi_m} \tag{102}$$

The value of Q corresponding to the chosen $\mathbf{Y}_{hf}$ is found from Figure 31*a*:

$$\tan\phi_f = \frac{X_f}{R_f} = \frac{2\delta_m X_0}{X_0/Q} = 2\delta_m Q \tag{103}$$

and from Figure 31*b*,

$$\tan\phi_f = \cot(\phi_m/2)$$

Equating the last terms of the two equations for $\tan\phi_f$, we find the optimum value of Q to be

$$Q_o = \frac{\cot(\phi_m/2)}{2\delta_m} = \frac{\cos\phi_m + 1}{2\delta_m \sin\phi_m} \tag{104}$$

The corresponding harmonic voltage is

$$V_h = \frac{I_{hc}}{|\mathbf{Y}_h|} = \frac{4\delta_m X_0 I_{hc}}{\cos\phi_m + 1} \tag{105}$$

Table 9 shows the effect of limiting the impedance angle of the network to

Table 9

ϕ_m	0	15°	30°	45°	60°	75°	80°	85°	90°
$\delta_m Q_o$	∞	3.80	1.87	1.21	0.87	0.65	0.60	0.55	0.50
$V_h/\delta_m X_0 I_{hc}$	2.00	2.03	2.14	2.35	2.67	3.17	3.41	3.68	4.00

$\pm\phi_m$ on the optimum Q of the filter and on the maximum guaranteed harmonic voltage V_h. In particular, limitation to ±75° reduces the harmonic voltage for a given size of filter, or the size of filter for a given harmonic voltage by about 21% from Case 2 (purely reactive network, $\phi_m = 90°$).

Typical values of Q in practice range from 30 to 60 with series resistors.

Double-tuned Filters. One double-tuned filter (the circuit of which is shown in Figure 33*b*) is substantially equivalent, near the resonant frequencies, to two single-tuned filters in parallel (Figure 33*a*); for example, those tuned to the fifth and seventh harmonics. The equations for the parameters of the double-tuned filter are given by Ainsworth.[41]

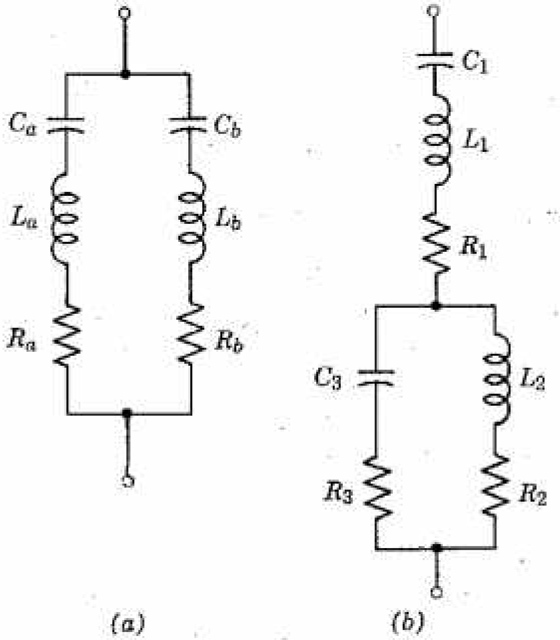


Fig. 33. Transformation from (*a*) two single-tuned filters to (*b*) double-tuned filter.

The advantages of a double-tuned filter over two single-tuned filters are the following:

1. Its power loss at fundamental frequency is less.
2. One inductor, instead of two, is subjected to full impulse voltage.

Such filters are used at both terminals of the Cross Channel link.[42] The impedance of that at the French terminal is given in Figure 34*a* and *b*. Its parameters are

$R_1 = 4.2\ \Omega$
$R_2 = 1.656\ \Omega$
$R_3 = 2.11\ \Omega$

$C_1 = 1.51\ \mu F$
$C_3 = 12.08\ \mu F$
$L_1 = 208$ mH
$L_2 = 24$ mH

Filter Components and Their Ratings

Capacitors. Capacitors account for the major part of the cost of filters. They are composed of standard units—typically rated at 100 or 150 kvar, 8 to 14.4 kV, at 50 or 60 Hz—connected in series and parallel for obtaining the desired overall voltage and kvar ratings.

Each unit consists of several rolls made of alternate layers of aluminum foil and sheets of insulation, tightly enclosed in a sheet-steel box filled with an insulating liquid. The solid insulation consists of either (a) several sheets of special paper impregnated with the liquid or (b) a sandwich of one sheet of such paper placed between two sheets of thermoplastic material. There is also an unavoidable thin film of liquid between the solid insulation and the metal foil; the thickness of the film depends on the pressure with which the rolls are formed. Three kinds of liquid impregnants are in use: (a) mineral oil, (b) trichlordiphenyl, and (c) pentachlordiphenyl. The last two are generically called *askarels*. Thus the dielectric properties depend on those of the paper, the impregnant, and the plastic (if used) and on the amounts used of each. The density of the paper can be varied, ranging from 0.8 to 1.2 g/cm^3, and the paper may be impregnated with any one of the three liquids. Of these, trichlordiphenyl is the most used at present, having superseded pentachlordiphenyl, which has a higher freezing point, a lower dielectric strength, and a lower dielectric constant.

Two of the most important properties of the capacitors are (a) temperature coefficient of capacitance and (b) reactive power per unit of volume. The latter is usually proportional to the dielectric constant and the square of the maximum safe voltage gradient. Other important properties are (c) power loss, (d) reliability (or life), and (e) cost. Approximate values of some of these properties are listed in Table 10 for various dielectric materials. These values should be interpreted as indicative rather than exact, because they vary with the density of the paper, the thickness of the liquid film, the temperature at which they are measured, quality control of the materials, etc.

A very low temperature coefficient of capacitance is desirable for tuned filters in order to avoid detuning caused by change of capacitance with ambient temperature or with self-heating of the capacitors; but this property is unimportant for damped filters or for power-factor capacitors. Capacitors filled with mineral oil can have either positive or negative temperature coefficients, depending on paper density or film thickness, and, by proper design, can be made to have essentially zero coefficient. In the past such capacitors have been used for tuned filters almost to the exclusion of other kinds. Low temperature coefficient is obtainable also by use of high-density paper impregnated with pentachlordiphenyl. Both of these kinds, however, are substantially more bulky and expensive than those of equal rating having a dielectric of plastic and paper impregnated with trichlordiphenyl. The latter

Table 10. **Typical Properties of Capacitors for Power Systems partly based on Ref. 46**

Solid Dielectric	Paper Density (g/cm³)	Impregnant	Temperature Coefficient of Capacitance (10^{-6} per deg C)	Overall Dielectric Constant at 20°C	Dissipation Factor (%)	Relative kvar per Unit Volume
Paper	1.0	Mineral oil	+250	3.6	0.17	41
Paper	1.2	Mineral oil	+400	4.2	0.19	39
Paper	0.8	Pentachlordiphenyl	...	...	0.20	87
Paper	1.0	Pentachlordiphenyl	−460	5.2	0.28	59
Paper	1.2	Pentachlordiphenyl	−50	5.4	...	...
Paper	0.8	Trichlordiphenyl	−750	5.5	0.20	100
Paper	1.0	Trichlordiphenyl	−500	5.5	0.28	66
Paper	1.2	Trichlordiphenyl	−100	5.5	...	...
Plastic and paper	...	Trichlordiphenyl	−710	3.1	0.10	150 200

is acceptable for use not only as power-factor capacitors and in high-pass filters but also in automatically tuned filters (page 372).

Capacitors obtain their high reactive power per unit volume by having low losses and operating at very high voltage stress. For this reason, prolonged operation at moderate overvoltage must be avoided to prevent thermal destruction of the dielectric; and even very brief operation at high overvoltage must be avoided to prevent destructive ionization of the dielectric.

The required reactive-power rating of a capacitor is calculated as the sum of the reactive powers at each of the frequencies to which it is subjected.

Inductors. These are built with nonmagnetic cores. The inductance usually has a fixed value. The Q at the predominant harmonic frequency may be selected for lowest cost and is usually between 50 and 150. If lower Q is desired, a series resistor is used. The cost of the inductor depends mainly on the maximum rms current and the insulation level for withstanding switching surges. The required insulation level may be greatly reduced, with attendant savings in cost, by protecting the inductor by connecting a lightning arrester of suitable rating in parallel with the inductor.

Arrangement. The most economical sequence of the components of a tuned filter, from ground to line, is R, L, C.

Conditions Under Which Required Ratings of Filter Components Are Determined. For preventing damage to the filter components, their ratings must be based on the most severe conditions to which they may be exposed; for example, one should assume the following:

1. Highest power-frequency alternating voltage, say, 10% above nominal or normal voltage.
2. Higher effective frequency deviation than that assumed in determining adequacy of filtering, say, ±5%.
3. Highest harmonic current, caused by resonance of the respective filter branch with the network and the other filter branches. Logically, harmonic currents from other sources than the converter in question should be assumed; however, experience has shown that, with high-power converters, the harmonics from other sources can be neglected.

Tuning

The manufacturing tolerances of inductors and capacitors are 2 to 3%. Final tuning of the tuned filters must be done after installation. The capacitance can be varied in small enough steps by changing the number of units in parallel in the tier next to ground.

The most convenient indicator is a harmonic phase-angle meter, which measures the phase difference between the harmonic voltage across the entire filter and the harmonic current through it. Such instruments have been installed in the converter stations at Sakuma, New Zealand, and Konti-Skan.[48]

The converter current should be at least 0.8 of rated current. The fifth, sixth, and seventh-harmonic filters (also seventeenth, eighteenth, and nineteenth, if used) should be tuned while the converter is in six-pulse operation. The eleventh, twelfth, and thirteenth-harmonic filters should be tuned during 12-pulse operation.

Operation with One Tuned Branch of Filter Out of Service

Such operation may become necessary or, at least, desirable when it is necessary to repair a filter component or substitute a spare component. The possibility of resonance between the remainder of the filter and the power system at the frequency for which the disconnected branch is tuned should be assessed. If this possibility appears unlikely, the converter may be operated with this branch disconnected while the harmonic voltage of this frequency is measured to determine its acceptability. Perhaps it will be necessary to run the converter at reduced load in order to make this harmonic voltage acceptable.

Minimum-cost Tuned Filter

The cost of a filter tuned for a particular harmonic varies with the size of the filter in the manner shown in Figure 35, and is least at a particular size.

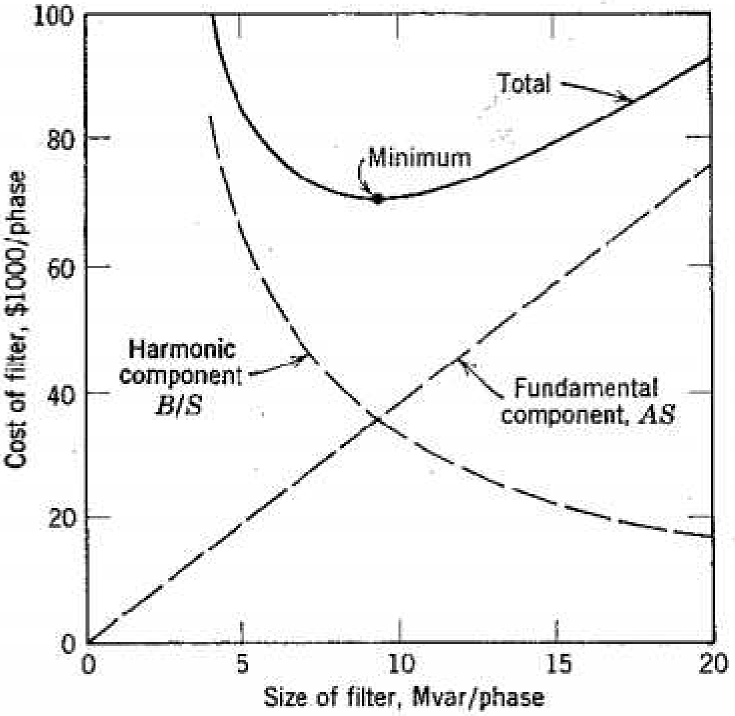


Fig. 35. Cost of filter versus its size, illustrated for fifth-harmonic filter for 600-MW 4-bridge 12-pulse converter.

The shape of the curve is attributable to the presence of two components of cost, one of which is directly proportional to size and the other, inversely proportional to size:

$$K = AS + BS^{-1} \tag{106}$$

where K = cost (k\$)
S = size (Mvar)
A, B = constants (k\$/Mvar and k\$ $\cdot$ Mvar, respectively)

A filter capacitor is subjected to currents and voltages of two frequencies—the fundamental power-system frequency and the harmonic frequency (of order h) for which the filter is tuned. The *rating* of the capacitor, in Mvar, must be the largest sum of the fundamental-frequency reactive power and the harmonic reactive power for which the filter is designed. Other harmonics in a tuned filter are negligible. The *cost* of the capacitor is assumed to be directly proportional to its rating. The *size* of the filter, by definition, is the reactive power of the capacitor at fundamental frequency only.

The fundamental-frequency source is essentially a constant-voltage source; the harmonic source is essentially a constant-current source. Therefore, the fundamental-frequency reactive power of the capacitor is directly proportional to its size; the harmonic reactive power is inversely proportional. The capacitor rating is

$$P_{rC} = V_1^2\omega_1 C + \frac{I_{hf}^2}{h\omega_1 C} = S + \frac{V_1^2 I_{hf}^2}{hS} \qquad \text{megavars} \tag{107}$$

where $C =$ capacitance (F)
$\omega_1 = 2\pi \times$ fundamental frequency
$V_1 =$ fundamental voltage (kV)
$I_{hf} =$ harmonic current of order h (kA)
$S =$ size of capacitor (Mvar)

The rating of the inductor may be assumed to depend similarly on the sum of the fundamental and harmonic reactive powers:

$$P_{rL} = \frac{S}{h^2} + \frac{V_1^2 I_{hf}^2}{hS} \tag{108}$$

The uncertainty of this assumption is considerably offset by the facts that the fundamental reactive power of the inductor is much less than its harmonic reactive power and that the total reactive power and cost of the inductor are smaller than those of the capacitor. The cost of the inductor is greatly affected by its insulation level, but this component of cost should be independent of filter size.

Neglecting the cost of the resistor, the total cost of the filter is

$$K = P_{rC}U_C + P_{rL}U_L \tag{109}$$

where U_C and U_L are the unit costs of capacitor and inductor, respectively. Substitution of the values of P_{rC} and P_{rL} from Eqs. (107) and (108) gives

$$K = S\left(U_C + \frac{U_L}{h^2}\right) + \frac{V_1^2 I_{hf}^2}{hS}(U_C + U_L) = AS + BS^{-1} \tag{110}$$

The size for minimum cost is found by equating the derivative dK/dS to zero:

$$\frac{dK}{dS} = A - BS^{-2} = 0 \tag{111}$$

whence

$$S_{\min} = \left(\frac{B}{A}\right)^{1/2} \tag{112}$$

and substitution of this value of S into the equation for cost gives the minimum cost as

$$K_{\min} = 2\sqrt{AB} \tag{113}$$

EXAMPLE 1

Find the minimum-cost fifth-harmonic filter for a bipolar four-bridge 12-pulse converter rated 1.00 kA, ±300 kV on the dc side. The filters are to be connected to the 235-kV 60-Hz three-phase line. The fifth-harmonic filter is to be designed for the operation of the converter with one bridge out of service. Assume the unit cost of capacitors to be \$3.50/kvar and that of inductors \$8.00/kvar. At full load with all bridges in service, $\alpha = 15°$, $u = 25°$, and $\cos\phi = 0.866$. The limiting network impedance angle may be taken as 75°.

SOLUTION

The rated power of the converter is

$$P_n = V_{dn} I_{dn} = 600 \times 1.00 = 600 \text{ MW}$$

The full-load fundamental alternating line current is

$$I_{L1} = \frac{P_{dn}}{3V_1 \cos\phi} = \frac{600}{3(235/\sqrt{3})0.866} = 1.70 \text{ kA} = 1700 \text{ A}$$

The fifth-harmonic current from one bridge of the converter is approximately $1700/(5 \times 4) = 85.0$ A, but a more accurate value, allowing for ignition delay and overlap, is $0.165 \times 1700/4 = 70.2$ A. From Eq. (98), we find that the harmonic current in the filter is larger than that from the converter by a factor $|\mathbf{Y}_{hf}|/|\mathbf{Y}_h| = \sec\ (\phi_m/2) = \sec\ 37.5° = 1.26$; it is, therefore $1.26 \times 70.2 = 88.5$ A.

$$A = U_C + \frac{U_L}{h^2} = 3.50 + \frac{8.00}{(5)^2} = 3.82 \text{ \$/kvar}$$

$$= 3820 \text{ \$/Mvar}$$

$$B = \frac{V_1^2 I_{hf}^2 (U_C + U_L)}{h} = \frac{(235/\sqrt{3})^2 (88.5 \times 10^{-3})^2\ 11{,}500}{5}$$

$$= 3.32 \times 10^5\ \$ \cdot \text{Mvar}$$

$$S_{\min} = \left(\frac{B}{A}\right)^{1/2} = \left(\frac{3.32 \times 10^5}{3.82 \times 10^3}\right)^{1/2} = 9.32 \text{ Mvar per phase}$$

is the size for minimum cost.

The corresponding cost is

$$K_{\min} = 2\sqrt{AB} = 2\sqrt{3.82 \times 10^3 \times 3.32 \times 10^5}$$

$$= \$71{,}200 \text{ per phase}$$

For any size S the cost is

$$K = \$3820S + \frac{\$332{,}000}{S}$$

The result is plotted in Figure 35.

Capacitance of the minimum-cost filter is

$$C = \frac{S_{\min}}{\omega_1 V_1^2} = \frac{9.32}{377 \times (235/\sqrt{3})^2} = 1.34 \times 10^{-6}\text{ F} = 1.34\ \mu\text{F}$$

Its inductance is

$$L = \frac{1}{C(h\omega_1)^2} = \frac{10^6}{1.34(5 \times 377)^2} = 0.210 \text{ H}$$

Optimum Q for $\phi_m = 75°$ is $0.65/\delta_m$. If δ_m is taken as 0.02, $Q_o = 0.65/0.02 = 32.5$, and the resistance of the filter is

$$R = \frac{X_0}{Q_o} = \frac{1}{Q_o}\left(\frac{L}{C}\right)^{1/2} = \frac{1}{32.5}\left(\frac{0.210}{1.34 \times 10^{-6}}\right)^{1/2} = \frac{395}{32.5} = 12.2\ \Omega$$

The fifth harmonic voltage is (by Table 9)

$$V_5 = 3.17\delta_m X_0 I_5 = 3.17 \times 0.02 \times 395 \times 88.5 = 2220 \text{ V}$$

$$= 2.22 \text{ kV}$$

This is 1.64% of the fundamental line-to-ground voltage V_1 and is greater than the usually acceptable value of 1%. For decreasing it to 1%, the size of the filter would have to be 1.64 times as great as that calculated, or 15.3 Mvar per phase. The increase of cost (Figure 35) would be moderate, \$10,000/\$71,200 = 14%.

From the curve in Figure 35 it is seen, on the one hand, that the cost of the filter increases sharply with a decrease of size below that for minimum cost and, on the other hand, that the cost increases more slowly with an increase of size above that for minimum cost. Moreover, the quality of filtering increases with size. Thus, it is reasonable to assume that a filter smaller than that for minimum cost is almost never used and that ones greater than that for minimum cost are often used.

The foregoing example points to one reason why six-pulse operation of a large converter is undesirable. The fifth-harmonic filter for full six-pulse operation would be four times as great as that designed for one bridge of four out of service. Its three-phase size would be $3 \times 4 \times 15.3 = 184$ Mvar. Since the full-load reactive power consumed by the converter is $P \tan \phi = 600 \times 0.577 = 346$ Mvar, the fifth harmonic filter would supply 185/346 = 53% of the reactive power required. The seventh-harmonic filter, designed on the same basis, would supply 27%; and the two filters together would supply 80% of the full-load reactive requirement. The whole bank of filters would supply too much reactive power, especially at light load.

Automatically Tuned Filters[43]

It was shown earlier ("Design of Tuned Filters," page 355) that for each tuned filter branch there is an optimum value of Q, depending on the assumed values of maximum frequency deviation δ_m and maximum network impedance angle ϕ_m. Of these two variables, δ_m is the one that has the greater effect on Q, for Q varies inversely as δ_m. Thus high δ_m requires low Q, which increases the continual power-frequency losses and which either impairs the filtering by increasing the harmonic voltage or requires a greater capacitance and, consequently, greater cost for maintaining the same quality of filtering. Only partially offsetting this increase of cost is the fact that low Q decreases the harmonic current at resonance and thus decreases the reactive-power rating of a of a given capacitance.

One can get cheaper or better filtering by limiting the equivalent maximum frequency deviation. A large part of this equivalent deviation is caused by variation of capacitance with temperature. This part of the deviation can be limited by using capacitors with low temperature coefficient of capacitance, but this feature increases the cost of the capacitors.

Two methods have been proposed for limiting the equivalent frequency deviation.

One of these maintains the average temperature of the capacitors nearly constant by cooling them with air currents from a fan controlled thermostatically or by capacitance measurement. The other method varies either the inductance or capacitance by small steps so as to maintain the frequency deviation at small values—ideally at zero.

The capacitance can be varied by switching a variable number of capacitor units in parallel in the tier nearest to ground potential. The inductance can be varied by the use of a tapped coil and tap-changing mechanism or by a variometer (a fixed coil in series with a movable coil so that the coupling between the two coils is variable). A range of ±5% is usually adequate.

One proposed method of control measures the harmonic-frequency reactive power of the entire branch and decreases L (or C) whenever this exceeds a preset value or increases L (or C) whenever it is less than another preset value. In other words, there is an on-off servomechanism with a dead zone.[43]

The advantages of the automatically tuned filter over a fixed filter are that, for equally good filtering:

1. A capacitor of lower rating may be used.
2. The capacitor may be of a kind that has a high temperature coefficient of capacitance but also has a high reactive-power rating per unit of volume and per unit of cost.
3. Since it has a higher Q, the power loss is smaller.

Advantages 1 and 2 reduce the cost of the capacitor, which is the most expensive component of the filter. Advantage 3 reduces the cost of the resistor and the cost of the system losses. These cost savings are offset partially by the cost of the tuning control.

In some cases, advantage 1 cannot be realized because the filter must supply a large amount of reactive power at fundamental frequency. In such cases, however, advantages 2 and 3 are still realizable, and, in addition, the quality of filtering is improved.

Filter design follows the procedure already outlined for fixed tuned filters except that a smaller δ_m is specified, which depends on the accuracy of the automatic tuning.

Figure 36 compares the reactive-power rating of the capacitor of an automatically tuned filter for $\delta_m = 0.01$ to that of a fixed-tuned filter having the same filtering performance, that is, the same harmonic voltage at maximum frequency deviation.

EXAMPLE 2

Calculate the rating of the capacitor required for the fifth-harmonic filter bank of Example 1 (a) if the filter has fixed tuning and if the maximum estimated detuning varies from 1 to 5%; and (b) if the filter is automatically tuned so as to limit the detuning to 1%. In both cases the fifth-harmonic voltage is to be limited to 1% of the fundamental voltage, and the maximum angle of the network impedance at 300 Hz is assumed to be 85°.

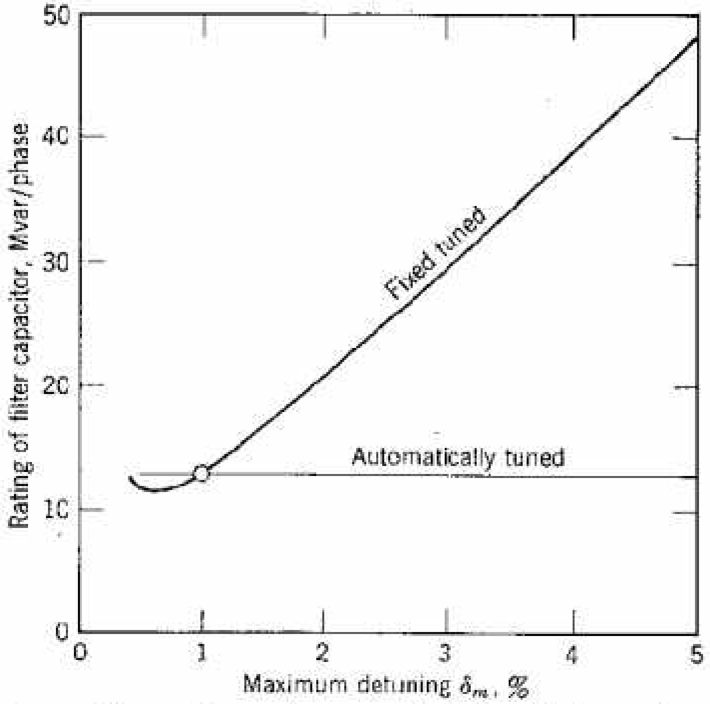


Fig. 36. Comparison of capacitor ratings required for fixed-tuned and automatically tuned filters.

SOLUTION, Part a

From Example 1, the fundamental line-to-ground voltage on the filters is $V_1 = 235/\sqrt{3} = 135.5$ kV. The fifth harmonic voltage should not exceed 1% of this, or $V_5 = 1355$ V. The fifth-harmonic current put out by the converter is 70.2 A, and the fifth-harmonic current in the filter is $I_5 = 70.2 \sec(\phi_m/2) = 70.2 \sec 42.5° = 70.2/0.737 = 95.5$ A. By Eq. (105),

$$X_0 = \frac{V_5(\cos\phi_m + 1)}{4\delta_m I_5} = \frac{1355 \times 1.087}{4\delta_m \times 95.5} = \frac{3.86}{\delta_m} \qquad \text{ohms}$$

The capacitance of the capacitor of the filter is

$$C = \frac{1}{\omega_5 X_0} = \frac{1}{5\omega_1 X_0}$$

The fundamental-frequency reactive power ("size") of the filter is

$$P_{rC1} = V_1^2\omega_1 C = \frac{V_1^2\omega_1}{5\omega_1 X_0} = \frac{V_1^2}{5X_0} = \frac{V_1^2\delta_m}{5 \times 3.86} = \frac{(135.5)^2\delta_m}{19.3}$$

$$= 950\delta_m \text{ Mvar}$$

The harmonic-frequency reactive power is

$$P_{rC5} = I_5^2 X_0 = (95.5)^2 \times \frac{3.86}{\delta_m} = \frac{3.52 \times 10^4}{\delta_m} \qquad \text{vars}$$

and the capacitor rating should be

$$P_{rC} = P_{rC1} + P_{rC5} = 950\delta_m + \frac{0.0352}{\delta_m} \quad \text{Mvar}$$

The result is plotted in Figure 36.

SOLUTION, Part b

This is the same as the result of part a for $\delta_m = 0.01$.

Design of High-pass Damped Filters

Figure 37 shows three kinds. The first-order filter, a series *RC* circuit, requires a large capacitor and has excessive power loss at fundamental frequency. The second- or third-order filter is used. Both are built with low Q, 0.7 to 1.4, and have capacitive reactance at fundamental frequency and low, predominantly resistive, impedance over a wide band of higher frequencies. See Figures 38 to 43. The resonant frequency can be chosen near the first pair of characteristic harmonics for which tuned filters are not provided.

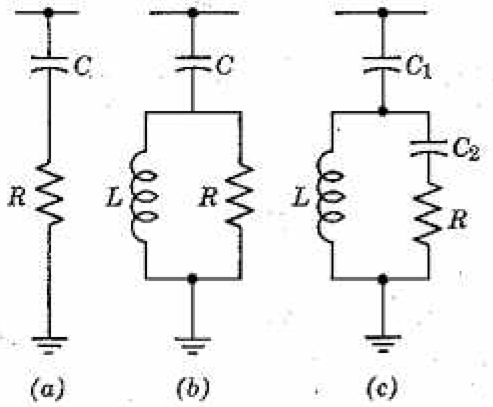


Fig. 37. High-pass damped filters: (*a*) first order, (*b*) second order, (*c*) third order.

Impedance. The impedance of the second-order filter is

$$\mathbf{Z}_{2\text{nd}} = \frac{1}{j\omega C} + \left(\frac{1}{R} + \frac{1}{j\omega L}\right)^{-1} \tag{114}$$

and that of the third-order filter with two equal capacitors is

$$\mathbf{Z}_{3\text{rd}} = \frac{1}{j\omega C_1} + \left(\frac{1}{R + 1/j\omega C_2} + \frac{1}{j\omega L}\right)^{-1} \tag{115}$$

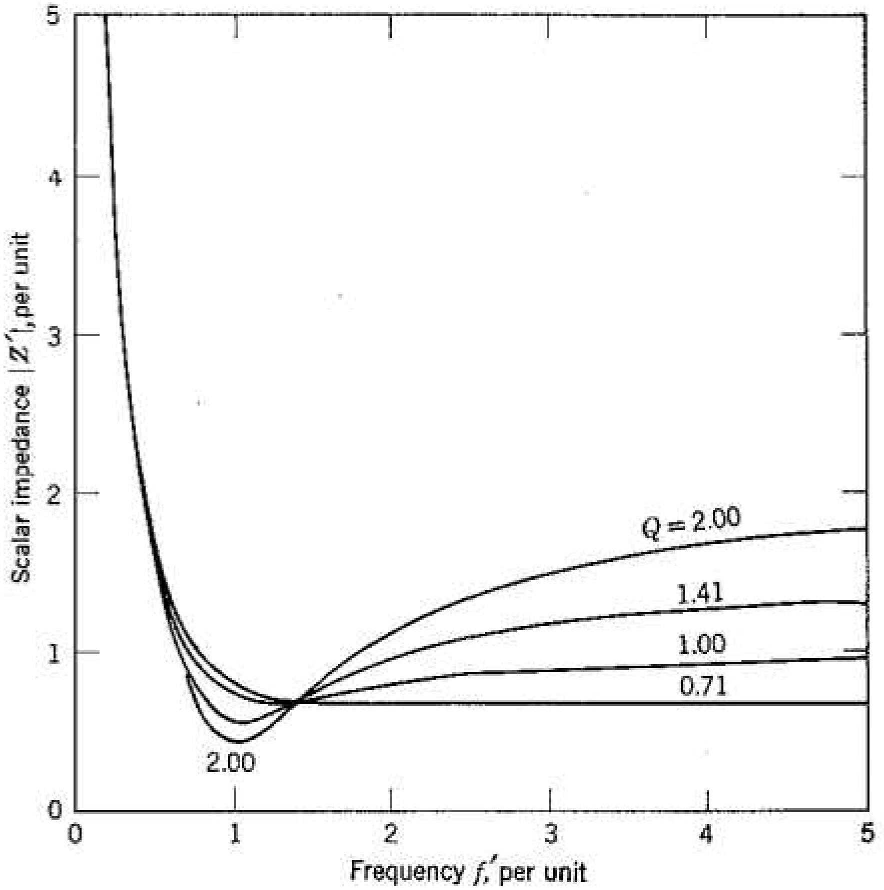


Fig. 38. Scalar impedance of second-order high-pass filters. Per-unit f' and Z' are defined by Eqs. (116) to (120).

For the sake of generality, let the following dimensionless variables be introduced:

$$\omega_n = \frac{1}{\sqrt{LC}} \tag{116}$$

$$f' = \frac{\omega}{\omega_n} = \frac{f}{f_n} \tag{117}$$

$$X_0 = \left(\frac{L}{C}\right)^{1/2} \tag{118}$$

$$Q = \frac{R}{X_0} \tag{119}$$

$$\mathbf{Z}' = \frac{\mathbf{Z}}{X_0} \tag{120}$$

These definitions are consistent with those used in connection with the tuned filter—Eqs. (73) and (75)—except that Q is defined as the reciprocal of the Q

Supply of Reactive Power by AC Filters and Shunt Capacitors

The maximum amounts of reactive power that can be accepted by and drawn from the ac network should be determined from such considerations as voltage regulation at the converter terminals and reactive-power capability of nearby generating stations. The range of this reactive power should be compared with the range of reactive power drawn by the converter between minimum and maximum loads. If the latter range does not exceed the former, it can be fitted into the former by addition of fixed shunt reactances. If the latter range exceeds the former, some of the shunt reactances must be switchable and must be switched as the load on the converter varies.

The shunt reactances must at least comprise the minimum size of filter that satisfies the requirement for satisfactory suppression of ac harmonics during the worst operating condition with respect to generation of harmonics. The filter, as already stated, presents capacitive reactance at power frequency, and thus supplies at least part of the reactive power required by the converter. The rest can be drawn from the ac network or supplied by making the filter larger or by adding shunt capacitors.

If switchable shunt reactances are required, the alternatives are the following:

1. A subdivided filter; that is, two or more duplicate filters.
2. Switchable high-pass filters in addition to those required for minimum satisfactory filtering.
3. Switchable shunt capacitors.

In theory, situations could arise in which shunt inductors would be required, but have not yet been used on existing dc links.

A larger filter than minimum is less costly than a minimum filter plus shunt capacitors and gives better filtering. If switchable elements are required, a filter plus switchable shunt capacitors is cheaper than switchable filters.

The switchable shunt reactances can be switched so as to maintain either net reactive power or alternating voltage within specified limits.

An alternative to switchable shunt reactance is a *synchronous condenser.* A condenser is more expensive than shunt capacitors but has several advantages:

1. It can absorb reactive power as well as supply it.
2. It has smooth control of reactive power or voltage instead of a few large steps.
3. It provides more stability of the alternating voltage.

Synchronous condensers have been installed at several of the existing dc links at the terminal that has no considerable nearby generating plant. They are usually connected to low-voltage tertiary windings of the converter transformers.

UNIT-IV

SHUNT COMPENSATION

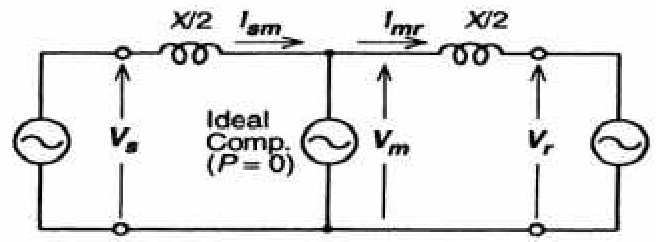
OBJECTIVES OF SHUNT COMPENSATION:

- Change the natural electrical characteristics of the transmission line to make it more compatible with the prevailing load demand.
- Thus, shunt connected, fixed or mechanically switched reactors are applied to minimize line overvoltage under light load conditions, and shunt connected, fixed or mechanically switched capacitors are applied to maintain voltage levels under heavy load conditions.
- The ultimate objective of applying reactive shunt compensation in a transmission system is to increase the transmittable power

MIDPOINT VOLTAGE REGULATION FOR LINE SEGMENTATION:

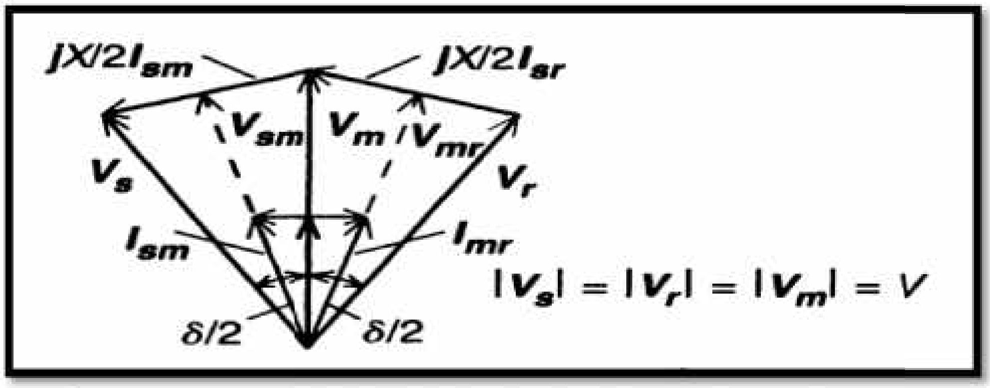
- VAR compensation is thus used for voltage regulation at the midpoint (or some intermediate) to segment the transmission line and at the end of the (radial) line to prevent voltage instability, as well as for dynamic voltage control to increase transient stability and "damp power oscillations

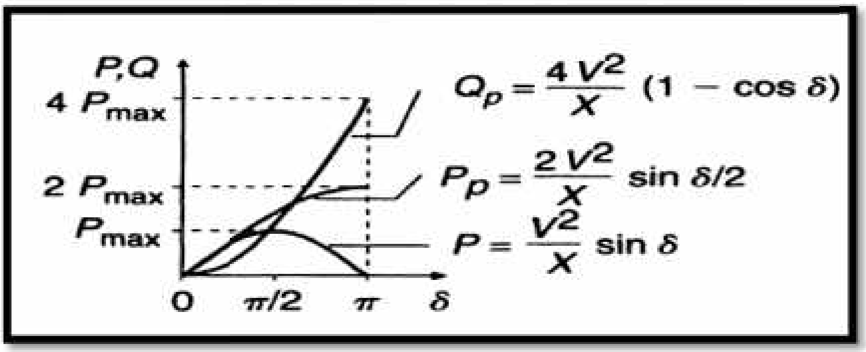
- Consider the simple two-machine (two-bus) transmission model in which an ideal var compensator is shunt connected at the midpoint of the transmission line,. For simplicity, the line is represented by the series line inductance. The compensator is represented by a sinusoidal ac voltage source (of the fundamental frequency), in-phase with the midpoint voltage, V_m and with an amplitude identical to that of the sending and receiving-end voltages ($V_m = V_s = V_r = V$)



The midpoint compensator in effect segments the transmission line into two independent parts: The first segment, with an impedance of X/2, carries power from the sending end to the midpoint, and the second segment, also with an impedance of X/2, carries power from the midpoint to the receiving end.

The midpoint VAR compensator exchanges only reactive power with the transmission line in this process. For the lossless system assumed, the real power is the same at each terminal (sending end, midpoint, and receiving end) of the line.





The corresponding equations are

$$V_s \;=\; V_m \;= V\cos\frac{\delta}{4}$$

$$I_s \;=\; I_m \;= I = \frac{4V}{X}\sin\frac{\delta}{4}$$

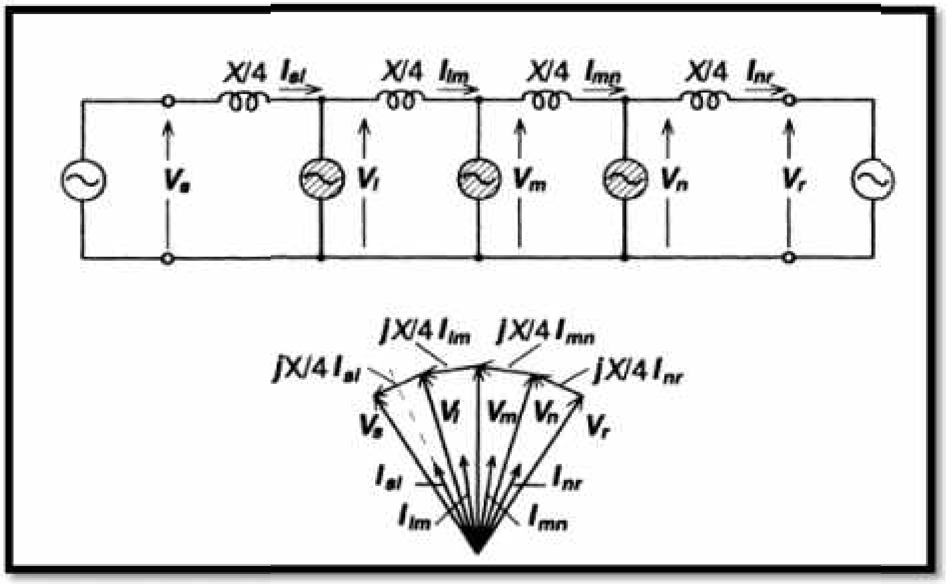
The transmitted power is

$$P = \; V_s \quad I_s \;=\; V_m \;\; I_m \;= VI\cos\frac{\delta}{4} = \;\frac{2V^2}{X}\;\sin\frac{\delta}{2}$$

$$Q = \; V_s \quad I_s \;=\; V_m \;\; I_m \;= VI\sin\tfrac{\delta}{4} = \tfrac{4V^2}{X}\;(1-\cos\tfrac{\delta}{2})$$

It can be observed that the midpoint shunt compensation can significantly increase the transmittable power (doubling its maximum value) at the expense of a rapidly increasing reactive power demand on the midpoint compensator (and also on the end-generators).

The midpoint of the transmission line is the best location for the compensator. This is because the voltage sag along the uncompensated transmission line is the largest at the midpoint. Also, the compensation at the midpoint breaks the transmission line into two equal segments for each of which the maximum transmittable power is the same. For unequal segments, the transmittable power of the longer segment would clearly determine the overall transmission limit. The same can be used for longer length of the lines.



END OF LINE VOLTAGE SUPPORT TO PREVENT VOLTAGE INSTABILITY:

A simple radial system with feeder line reactance of *X* and load impedance Z, together with the normalized terminal voltage *V*, versus power *P* plot at various load power factors, ranging from 0.8 lag and 0.9 lead.

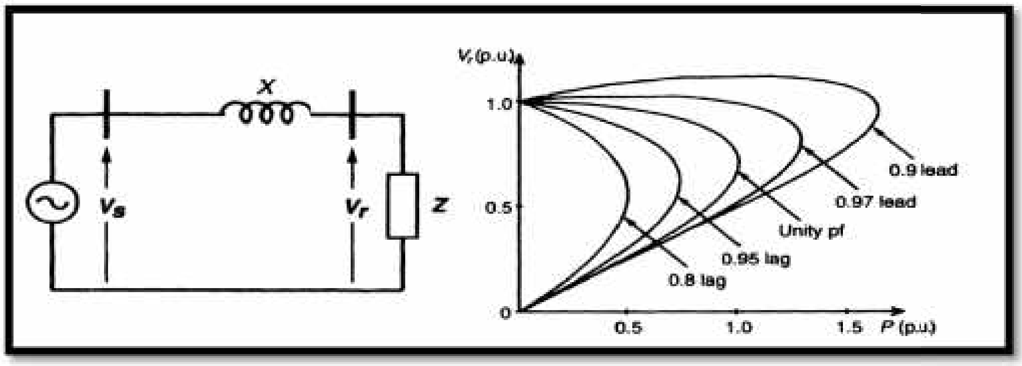
The "nose-point" at each plot given for a specific power factor represents the voltage instability corresponding to that system condition. It should be noted that the voltage stability limit decreases with inductive loads and increases with capacitive loads. The shunt reactive compensation can effectively increase the voltage stability limit by supplying the reactive load and regulating the terminal voltage ($V - V_r = 0$).

It is evident that for a radial line, the end of the line, where the largest voltage variation is experienced, is the best location for the compensator. (Recall that, by contrast, the midpoint is the most effective location for the line interconnecting two ac system buses.)

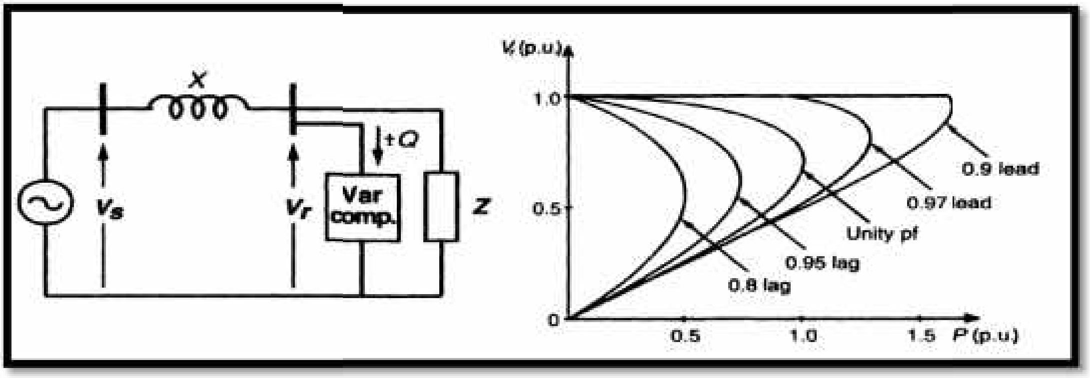
Reactive shunt compensation is often used in practical applications to regulate the voltage at a given bus against load variations, or to provide voltage support for the load when, due to generation or line outages, the capacity of the sending-end system becomes impaired.

when a large load area is supplied from two or more generation plants with independent transmission lines. (This frequently happens when the locally generated power becomes inadequate to supply a growing load area and additional power is imported over a separate transmission link.) The loss of one of the power sources could suddenly increase the load demand on the remaining part of the system, causing severe voltage depression that could result in an ultimate voltage collapse.

WITHOUT COMPENSATION:



WITH COMPENSATION:

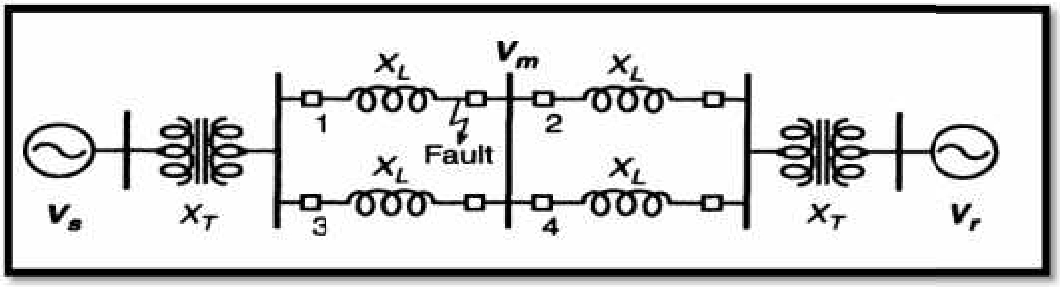


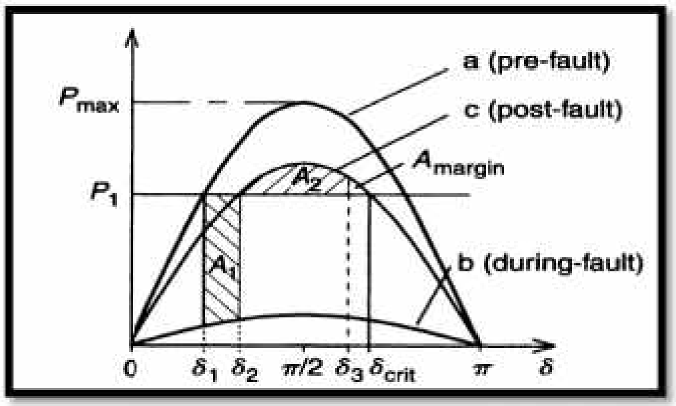
IMPROVEMENT OF TRANSIENT STABILITY:

Shunt compensation will be able to change the power flow in the system during and following dynamic disturbances so as to increase the transient stability limit and provide effective power oscillation damping.

The potential effectiveness of shunt (as well as other compensation and flow control techniques) on transient stability improvement can be conveniently evaluated by the **EQUAL AREA CRITERION.**

Assume that the complete system is characterized by the P versus δ curve "a" and is operating at angle δ_1 to transmit power P_1 when a fault occurs at line segment "1."

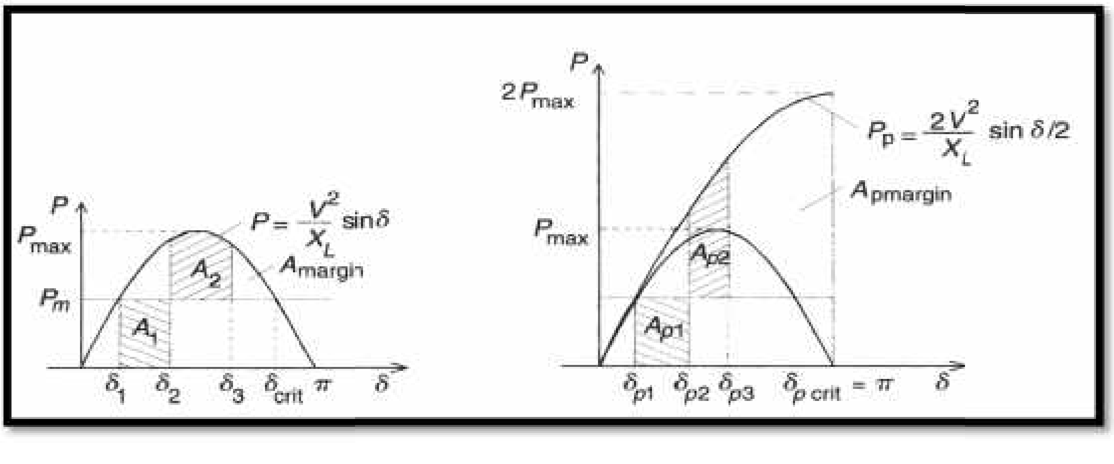




During the fault the system is characterized by the P versus δ curve "b" and thus, over this period, the transmitted electric power decreases significantly while mechanical input power to the sending-end generator remains substantially constant corresponding to P_1. As a result, the generator accelerates and the transmission angle increases from δ_1 to δ_2 at which the protective breakers disconnect the faulted line segment "1" and the sending-end generator 'absorbs accelerating energy, represented by area "A_1."

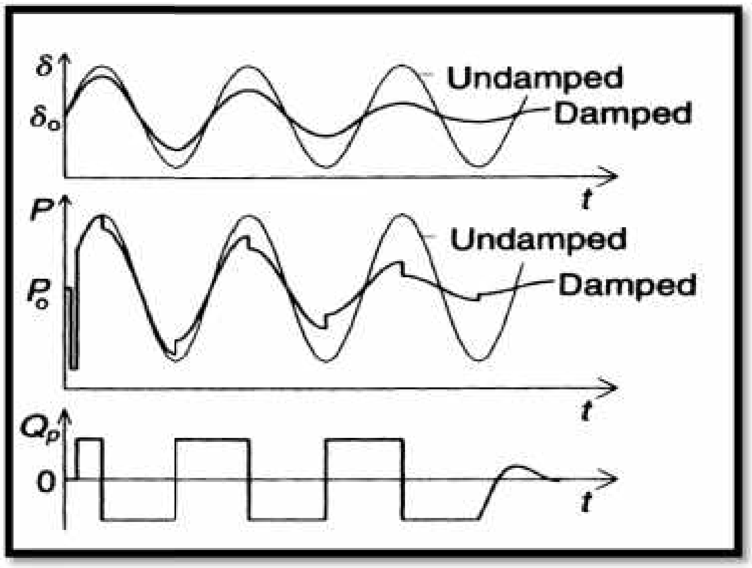
After fault clearing, without line segment "1" the degraded system is characterized by the P versus δ curve "c." At angle δ_2 on curve "c" the transmitted power exceeds the mechanical input power P_1 and the sending end generator starts to decelerate; however, angle δ further increases due to the kinetic energy stored in the machine. The maximum angle reached at δ_3, where the decelerating energy, represented by area "A_2, " becomes equal to the accelerating energy represented by area "A_1". The limit of transient stability is reached at $\delta_3 = \delta_{\text{critical}}$, beyond which the decelerating energy would not balance the accelerating energy and synchronism between the sending end and receiving end could not be restored. The area "A_{margin}," between δ_3 and δ_{critical} represent the transient stability margin of the system.

From the above general discussion it is evident that the transient stability, at a given power transmission level and fault clearing time, is determined by the P versus δ characteristic of the post-fault system. Since appropriately controlled shunt compensation can provide effective voltage support, it can increase the transmission capability of the post-fault system and thereby enhance transient stability.



POWER OSCILLATION DAMPING:

- In the case of an under-damped power system, any minor disturbance can cause the machine angle to oscillate around its steady-state value at the natural frequency of the total electromechanical system.
- The angle oscillation, of course, results in a corresponding power oscillation around the steady-state power transmitted. The lack of sufficient damping can be a major problem in some power systems and, in some cases, it may be the limiting factor for the transmittable power.
- That is, when the rotationally oscillating generator accelerates and angle δ increases ($d\delta/dt>0$), the electric power transmitted must be increased to compensate for the excess mechanical input power. Conversely, when the generator decelerates and angle δ decreases ($d\delta/dt<0$), the electric power must be decreased to balance the insufficient mechanical input power. (The mechanical input power is assumed to be essentially constant in the time frame of an oscillation cycle.)



SUMMARY OF COMPENSATOR REQUIREMENTS:

- The compensator must stay in synchronous operation with the AC system at the compensated bus under all operating conditions including major disturbances. Should the bus voltage be lost temporarily due to nearby faults, the compensator must be able to recapture synchronism immediately at fault clearing.
- The compensator must be able to regulate the bus voltage for voltage support and improved transient stability, or control it for power oscillation damping and transient stability enhancement, on a priority basis as system conditions may require.
- For a transmission line connecting two systems, the best location for Var compensation is in the middle, whereas for a radial feed to a load the best location is at the load end.

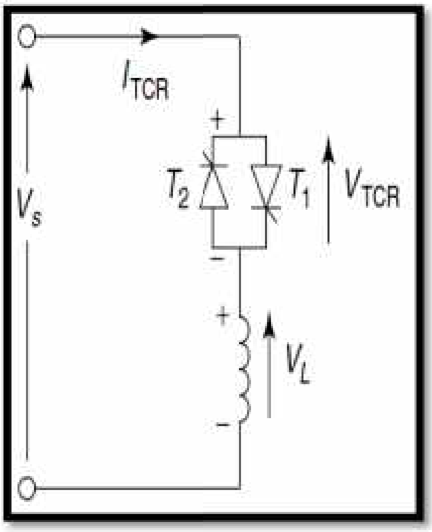
METHODS OF CONTROLLABLE VAR GENERATION:

- **VARIABLE IMPEDANCE TYPE STATIC VAR GENERATORS:**
  - THYRISTOR CONTROLLED/ SWITCHED REACTOR (TCR/TSR)
  - THYRISTOR SWITCHED CAPACITOR (TSC)
  - FIXED CAPACITOR- THYRISTOR CONTROLLED REACTOR (FC-TCR).
  - THYRISTOR SWITCHED CAPACITOR-THYRISTOR CONTROLLED REACTOR

- **SWITCHING CONVERTER TYPE VAR GENERATORS:**
  - STATIC CONDENSOR & STATIC COMPENSTOR (STATCON & STATCOM)

- **HYBRID VAR GENERATORS:**
  - SWITCHING CONVERTER WITH TSC AND TCR

THYRISTOR-CONTROLLED REACTOR (TCR):

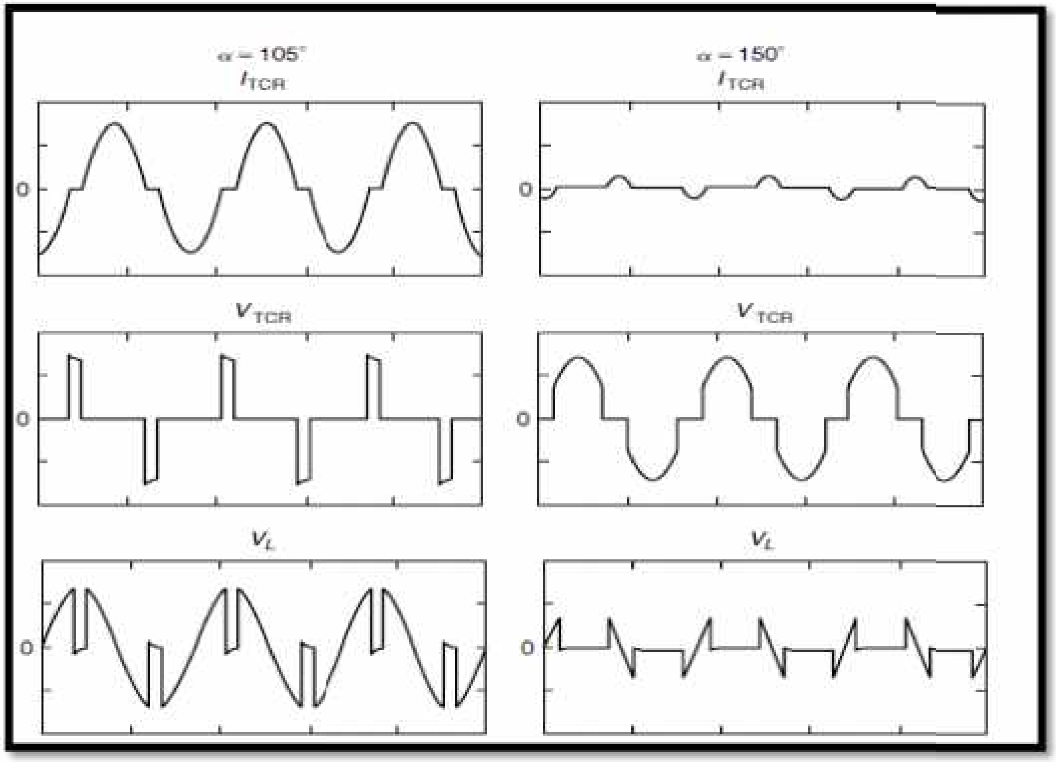


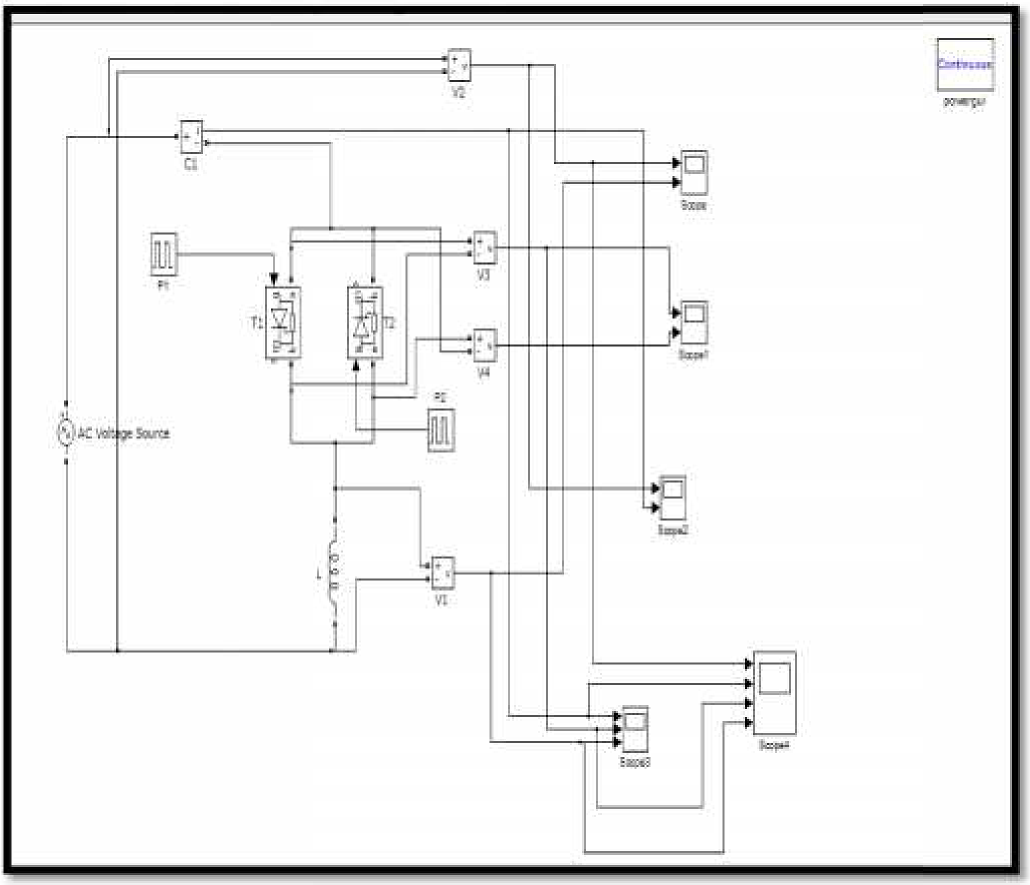
A basic single-phase Thyristor-Controlled Reactor (TCR) comprises an anti-parallel–connected pair of thyristor valves, T_1 and T_2, in series with a linear air-core reactor. The anti-parallel–connected thyristor pair acts like a bidirectional switch, with thyristor valve T_1 conducting in positive half-cycles and thyristor valve T_2 conducting in negative half-cycles of the supply voltage. The firing angle of the thyristors is measured from the zero crossing of the voltage appearing across its terminals.

The controllable range of the TCR firing angle, α extends from 90^0 to 180^0. A firing angle of 90^0 results in full thyristor conduction with a continuous sinusoidal current flow in the TCR. As the firing angle is varied from 90^0 to close to 180^0, the current flows in the form of discontinuous pulses symmetrically located in the positive and negative half-cycles.

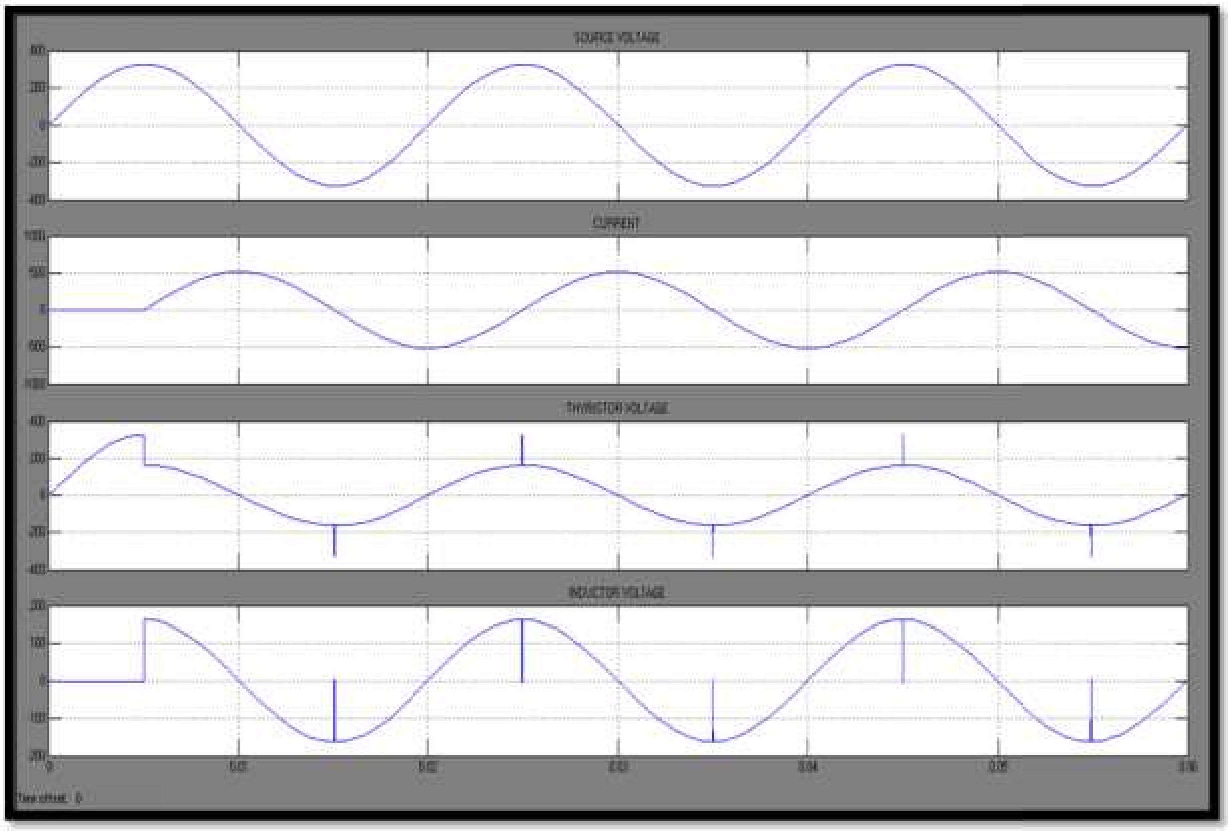
Once the thyristor valves are fired, the cessation of current occurs at its natural zero crossing, a process known as the **Line Commutation**. The current reduces to zero for a firing angle of 180^0. Thyristor firing at angles below 90^0 introduces dc components in the current, disturbing the symmetrical operation of the two anti-parallel valve branches.

A characteristic of the line-commutation process with which the TCR operates is that once the valve conduction has commenced, any change in the firing angle can only be implemented in the next half-cycle, leading to the so-called thyristor dead time.

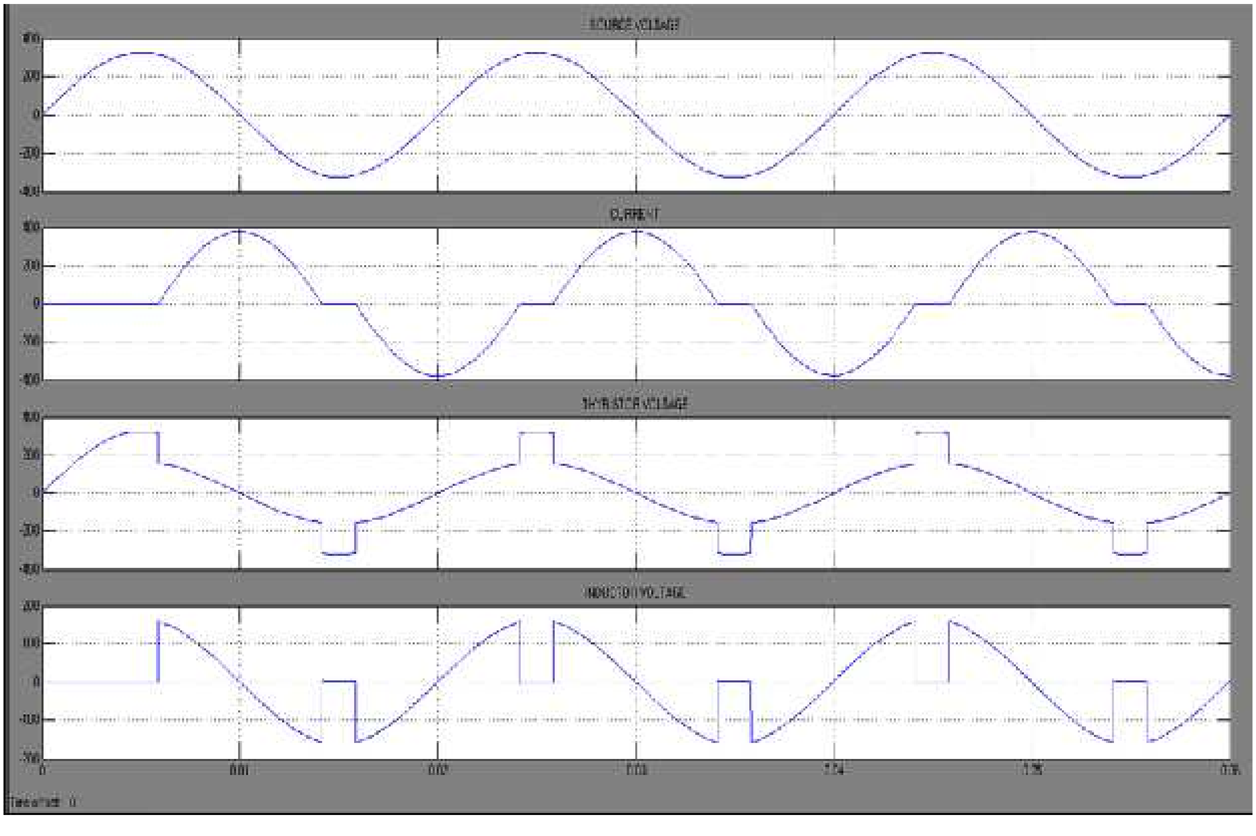

α = 105°
I_{TCR}
0
V_{TCR}
0
V_L
0
α = 150°
I_{TCR}
0
V_{TCR}
0
V_L
0


V2
Continuous
powergui
C1
Scope
P1
T1
T2
V3
Scope1
V4
P2
AC Voltage Source
Scope2
L
V1
Scope3
Scope4

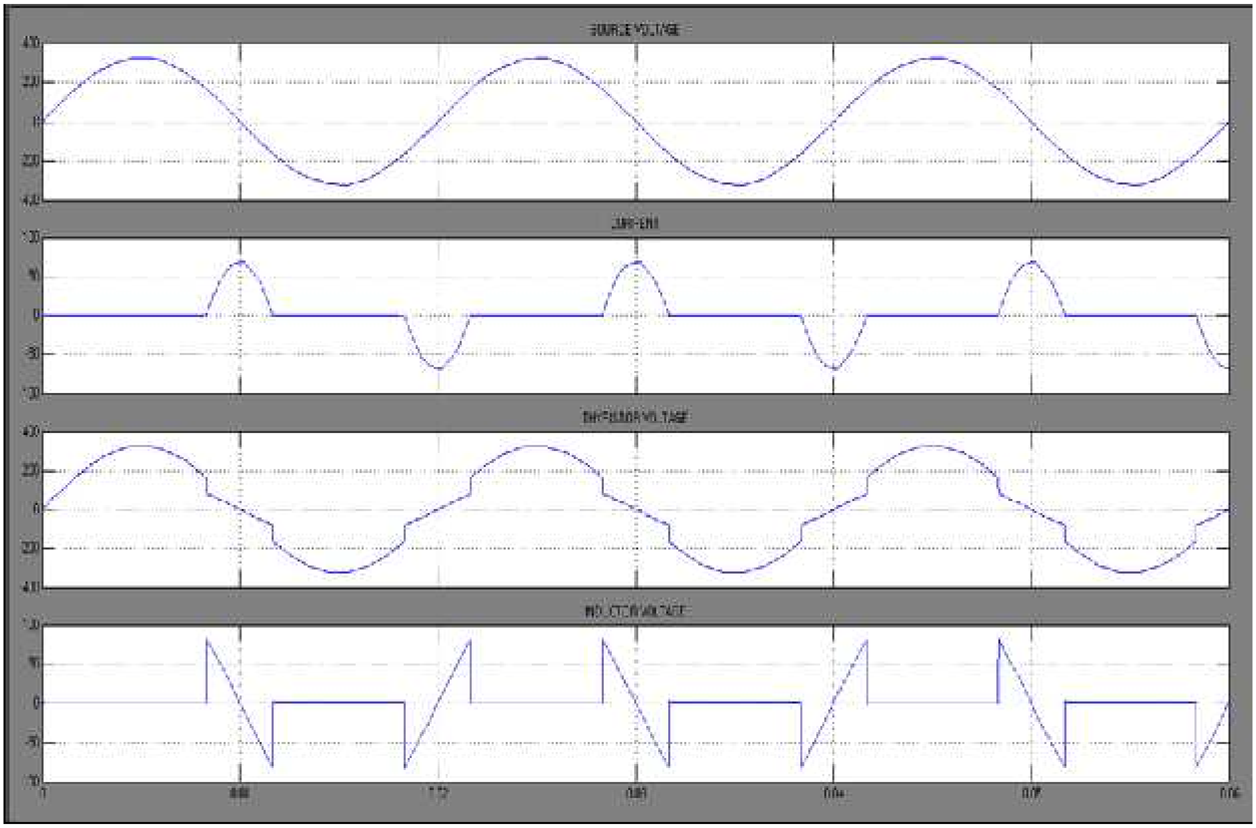
FOR FIRING ANGLE α =90°



FOR FIRING ANGLE α =105°



FOR FIRING ANGLE α =150°



Let the source voltage is

$$V_s(t) = V \sin \omega t$$

Where V= peak voltage of the applied voltage and ω = Angular Frequency

The TCR current is given by

$$L\frac{di}{dt} - V_s(t) = 0$$

where L is the inductance of the TCR

$$i(t) = \frac{1}{L}\int V_s(t)dt + C$$

Where C is integration constant

$$i(t) = -\frac{V}{\omega L}\cos \omega t + C$$

For finding C use initial conditions i(ωt = α) = i(t)= 0

$$i(t) = -\frac{V}{\omega L}(\cos \alpha - \cos \omega t)$$

Where α is the firing angle measured from positive going zero crossing of the applied voltage

Fourier analysis is used to derive the fundamental component of the TCR current $I_1(\alpha)$, which, in general, is given as

$$I_1(\alpha) = a_1 \cos \omega t + b_1 \sin \omega t$$

Where $b_1 = 0$ because of the odd symmetry, that is, f (x) = f (-x) Also, no even harmonics are generated because of the half-wave symmetry, that is,

$$F(x+T/2) = -f(x)$$

The coefficient

$$a_1 = \frac{4}{\pi} \int_0^{T/2} f(x) \cos \frac{2\pi}{T} \, d$$

$$I_1(\alpha) = \frac{V}{\omega L}\left(1 - \frac{2\alpha}{\pi} - \frac{1}{\pi}\sin 2\alpha\right)$$

$$I_1(\alpha) = VB_T \quad (\alpha)$$

Where

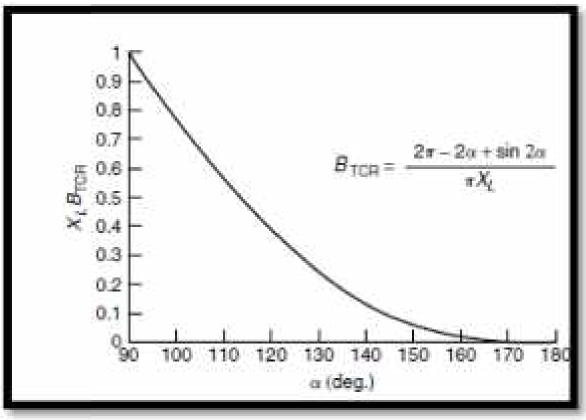
$$B_T \quad (\alpha) = B_m \quad \left(1 - \frac{2\alpha}{\pi} - \frac{1}{\pi}\sin 2\alpha\right)$$

$$B_{max} = 1/\omega L$$

The firing angle α is related to the conduction angle σ, as follows

$$\sigma + \frac{\alpha}{2} = \pi$$

$$I_1(\sigma) = VB_m \quad \left(\frac{\sigma - \sin \sigma}{\pi}\right)$$



$$I_1(\sigma) = VB_T \quad (\sigma)$$

$$B_T \quad (\sigma) = B_m \quad \left(\frac{\sigma - \sin \sigma}{\pi}\right)$$

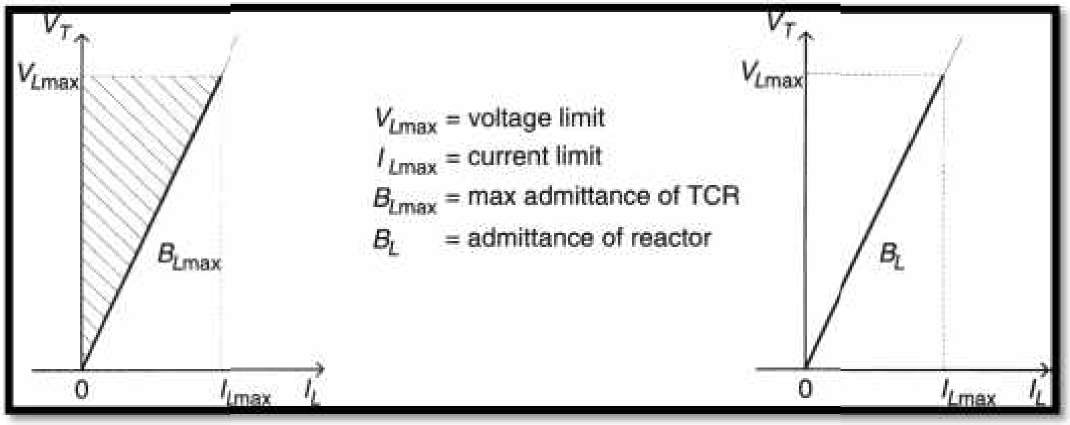
The TCR thus acts like a variable susceptance. Variation of the firing angle changes the susceptance and, consequently, the fundamental-current component, which leads to a variation of reactive power absorbed by the reactor because the applied ac voltage is constant. However, as the firing angle is increased beyond 90^0, the current becomes non sinusoidal, and harmonics are generated. If the two thyristors are fired symmetrically in the positive and negative half-cycles, then only odd-order harmonics are produced.

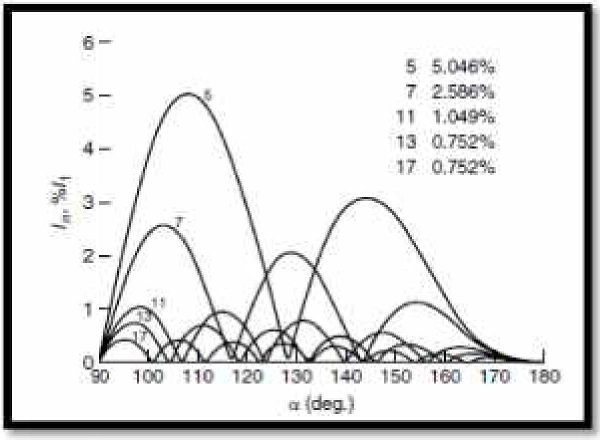
The harmonics can be deduced through a Fourier analysis of higher-frequency components. The rms value of the *n*th-order harmonic is expressed as a function of α in the following equation

$$I_n(\alpha) = \frac{V}{\omega}\frac{2}{\pi}\left\{-2\frac{\cos\alpha}{n}\sin n\alpha + \frac{\sin(n-1)\alpha}{n-1} + \frac{\sin(n+1)\alpha}{n+1}\right\}$$

$$I_n(\alpha) = \frac{V}{\omega}\frac{4}{\pi}\left\{\frac{\sin\alpha\cos(n\alpha) - n\cos\alpha\sin(n\alpha)}{n(n^2-1)}\right\}$$

Where n= 2K+1 and K= 1,2,3……….





THYRISTOR-SWITCHED REACTOR:

- The TSR is a special case of a TCR in which the variable firing-angle control option is not exercised. Instead, the device is operated in two states only: either fully on or fully off.
- If the thyristor valves are fired exactly at the voltage peaks corresponding to $\alpha = 90°$ for the forward-thyristor valve T_1 and $\alpha = 270°$ (90 + 180) for the reverse-thyristor valve T_2, The maximum inductive current flows in the TCR as if the thyristor switches were replaced by short circuits. However, if no firing pulses are issued to the thyristors, the TSR will remain in a blocked-off state, and no current can flow.
- The TSR ensures a very rapid availability of rated inductive reactive power to the system. When a large magnitude of controlled reactive power, Q, is required, a part of Q is usually assigned to a small TSR of rating, say, Q/2; the rest is realized by means of a TCR also of a reduced rating Q/2. This arrangement results in substantially decreased losses and harmonic content as compared to a single TCR of rating Q.

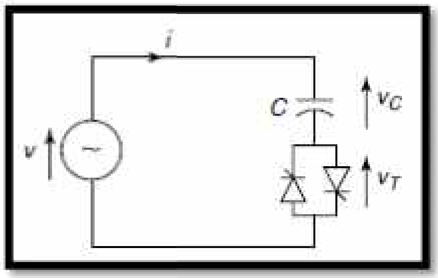
THYRISTOR-SWITCHED CAPACITOR (TSC):

The circuit consists of a capacitor in series with a bidirectional thyristor switch. It is supplied from an ideal ac voltage source with neither resistance nor reactance present in the circuit.

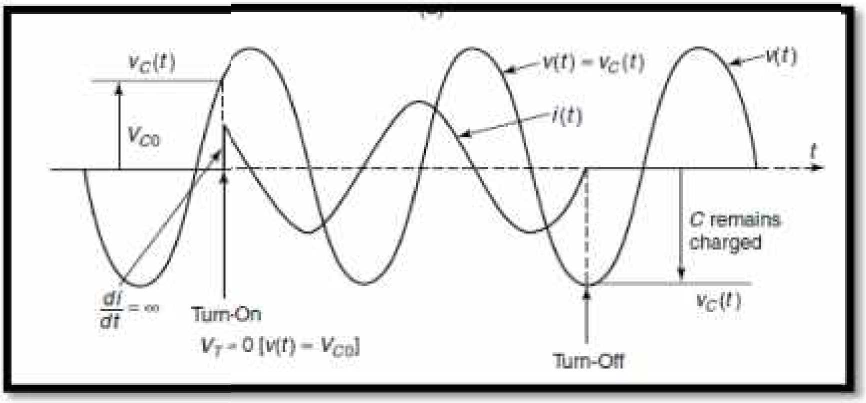
The analysis of the current transients after closing the switch brings forth two cases:

SWITCHING A CAPACITOR TO A VOLTAGE SOURCE:

Case-1: The capacitor voltage is not equal to the supply voltage when the thyristors are fired. Immediately after closing the switch, a current of infinite magnitude flows and charges the capacitor to the supply voltage in an infinitely short time. The switch realized by thyristors cannot withstand this stress and would fail.



Case-2: The capacitor voltage is equal to the supply voltage when the thyristors are fired, the analysis shows that the current will jump immediately to the value of the steady-state current. The steady state condition is reached in an infinitely short time. Although the magnitude of the current does not exceed the steady-state values, the thyristors have an upper limit of di/dt values that they can withstand during the firing process. Here, di/dt is infinite, and the thyristor switch will again fail.

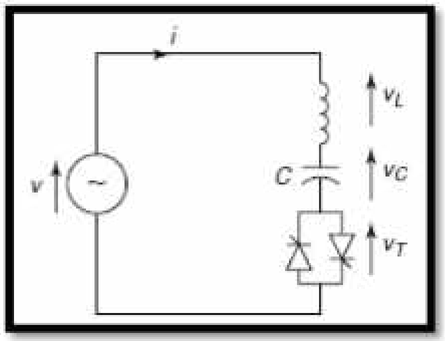


Switching a Series Connection of a Capacitor and Reactor:

To overcome the problems discussed in the preceding list, a small damping reactor is added in series with the capacitor
Let the source voltage be

$$V_s(t) = V \sin \omega_0 t$$

Where ω_0 is the system nominal frequency.
The analysis of the current after closing the thyristor switch at $t = 0$ leads to the following results



$$i(t) = I_{A} \cos(\omega_0 t + \alpha) - nB_C \left(V_{C0} - \frac{n^2}{n^2 - 1} V \sin\alpha\right) . \sin \omega_n t - I_{A} \cos\alpha \cos \omega_n t$$

where the natural frequency is

$$\omega_n = n\omega_0 = \frac{1}{\sqrt{LC}} = \sqrt{\frac{X_C}{X_L}}$$

$$I_{A} = V \left[\frac{B_L B_C}{B_C + B_L}\right]$$

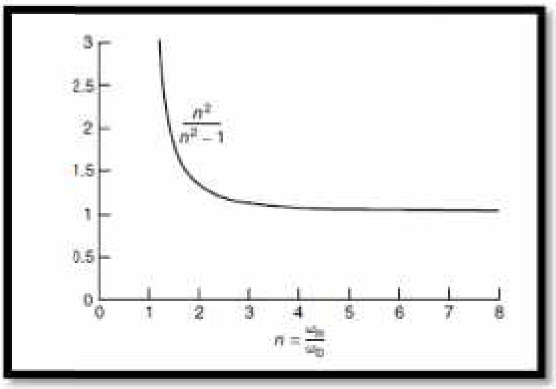
Here, V_{C0} is initial capacitor voltage at t =0. It is well-worth discussing this result in some detail. Note that no damping is considered in the circuit.

The Term Involving Fundamental Frequency(ω_0):

This term represents the steady-state solution. As expected, the current leads the voltage by 90^0. The current magnitude, I_{AC}, as obtained in the foregoing equation, can be alternatively expressed as

$$I_A = V B_C \left[\frac{n^2}{n^2 - 1}\right]$$

A magnification in current by a factor of $n^2/(n^2 - 1)$ is seen as compared to the case without reactor. The same magnification factor is also inherent in the magnitude of the capacitor voltage.



Voltage across the capacitor(peak) is

$$V_C = I X_C = V \left[\frac{n^2}{n^2 - 1}\right]$$

The TSC branch can be disconnected ("switched out") at any current zero by prior removal of the gate drive to the thyristor valve. At the current zero crossing, the capacitor voltage is at its peak value. The disconnected capacitor stays charged to this voltage and, consequently, the voltage across the non conducting thyristor valve varies between zero and the peak-to-peak value of the applied ac voltage

If the voltage across the disconnected capacitor remained unchanged, the TSC bank could be switched in again, without any transient, at the appropriate peak of the applied ac voltage.

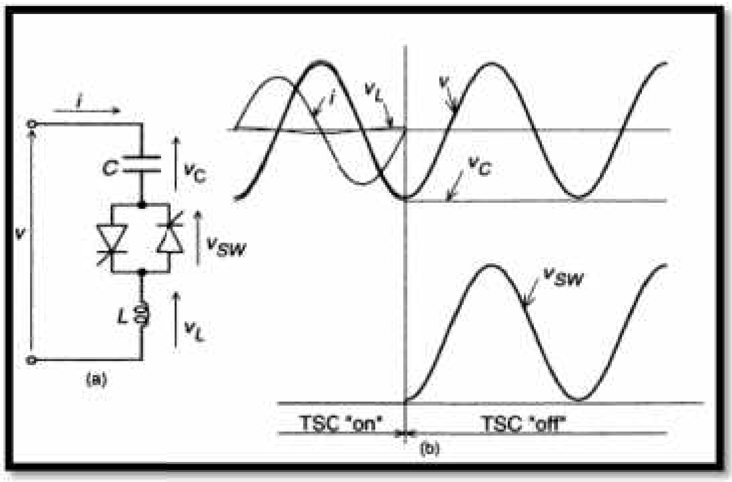
Normally, the capacitor bank is discharged after disconnection. Thus, the reconnection of the capacitor may have to be executed at some residual capacitor voltage between zero and V $n^2/(n^2 - 1)$. This can be accomplished with the minimum possible transient disturbance if the thyristor valve is turned on at those instants at which the capacitor residual voltage and the applied ac voltage are equal, that is, when the voltage across the thyristor valve is zero.

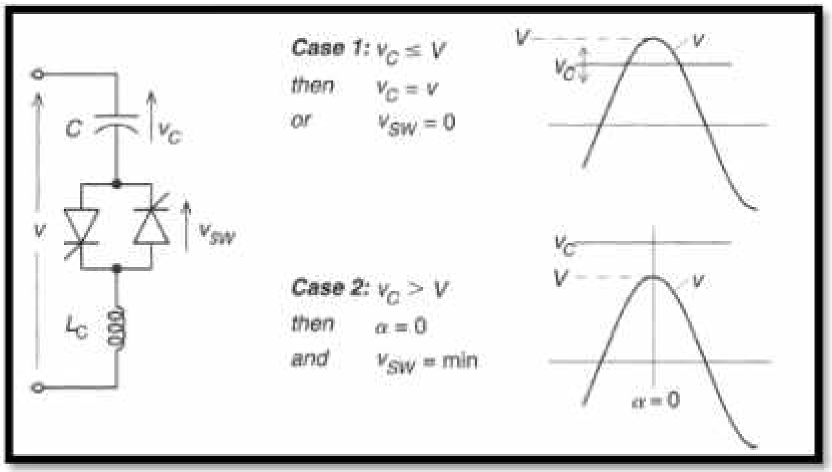
These transients are caused by the nonzero dv/dt at the instant of switching, which, without the series reactor, would result in an instantaneous current of $i_C = C dv/dt$ in the capacitor. (This current represents the instantaneous value of the steady-state capacitor current at the time of the switching.)

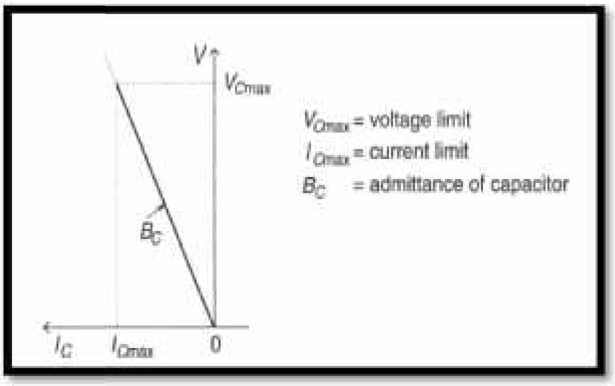
The interaction between the capacitor and the current (and di/dt) limiting reactor, with the damping resistor, produces the oscillatory transients visible on the current and voltage waveforms. (Note that the switching transient is greater for the fully discharged than for the partially discharged capacitor because the dv/dt of the applied (sinusoidal) voltage has its maximum at the zero crossing point.

Case-1: If the residual capacitor voltage is lower than the peak ac voltage (Vc < V), then the correct instant of switching is when the instantaneous ac voltage becomes equal to the capacitor voltage

Case-2 : If the residual capacitor voltage is equal to or higher than the peak ac voltage (Vc > V), then the correct switching is at the peak of the ac voltage at which the thyristor valve voltage is minimum.







FIXED CAPACITOR, THYRISTOR-CONTROLLED REACTOR (FC-TCR):

A basic var generator arrangement using a fixed (permanently connected) capacitor with a thyristor-controlled reactor (FC-TCR) .The current in the reactor is varied by the previously discussed method of firing delay angle control.

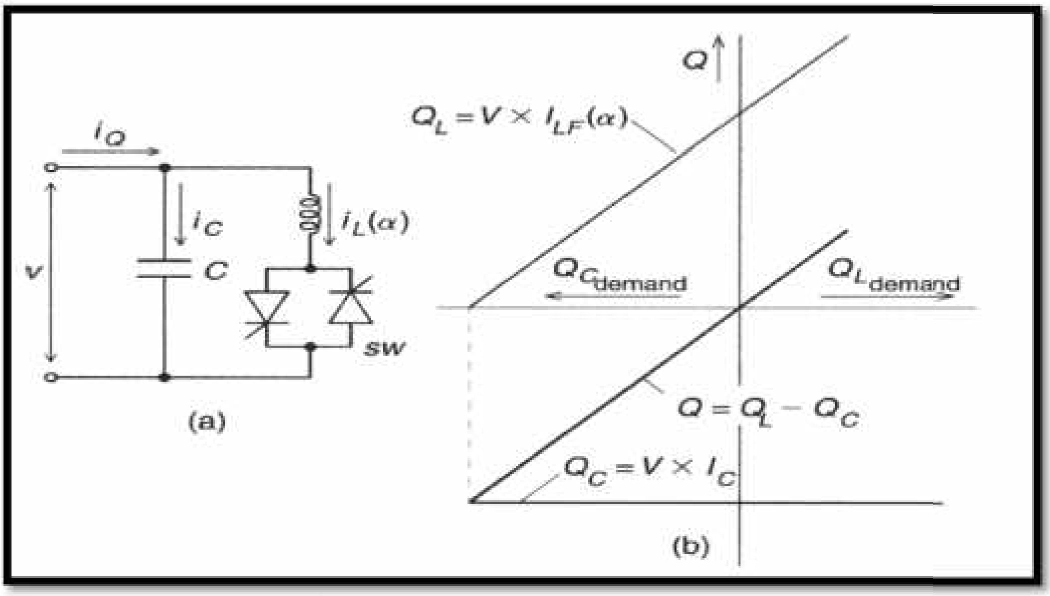
The fixed capacitor in practice is usually substituted, fully or partially, by a filter network that has the necessary capacitive impedance at the fundamental frequency to generate the reactive power required, but it provides low impedance at selected frequencies to shunt the dominant harmonics produced by the TCR.

The fixed capacitor, thyristor-controlled reactor type var generator may be considered essentially to consist of a variable reactor (controlled by delay angle a) and a fixed capacitor

As seen, the constant capacitive var generation (Q_C) of the fixed capacitor is opposed by the variable var absorption (Q_L) of the thyristor-controlled reactor, to yield the total var output (Q) required.

At the maximum capacitive var output, the thyristor-controlled reactor is off ($\alpha = 90°$). To decrease the capacitive output, the current in the reactor is increased by decreasing delay angle α. At zero var output, the capacitive and inductive currents become equal and thus the capacitive and inductive vars cancel out. With a further decrease of angle α (assuming that the rating of the reactor is greater than that of the capacitor), the inductive current becomes larger than the capacitive current, resulting in a net inductive var output.

At zero delay angle, the thyristor-controlled reactor conducts current over the full 180 degree interval, resulting in maximum inductive var output that is equal to the difference between the vars generated by the capacitor and those absorbed by the fully conducting reactor.



CONTROL OF THE THYRISTOR-CONTROLLED REACTOR IN THE FC-TCR:

One function is synchronous timing. This function is usually provided by a phase locked loop circuit that runs in synchronism with the ac system voltage and generates appropriate timing pulses with respect to the peak of that voltage.

In a different approach, the ac voltage itself may be used for timing. However, this seemingly simple approach presents difficult problems during system faults and major disturbances when the voltage exhibits wild fluctuations and large distortion.

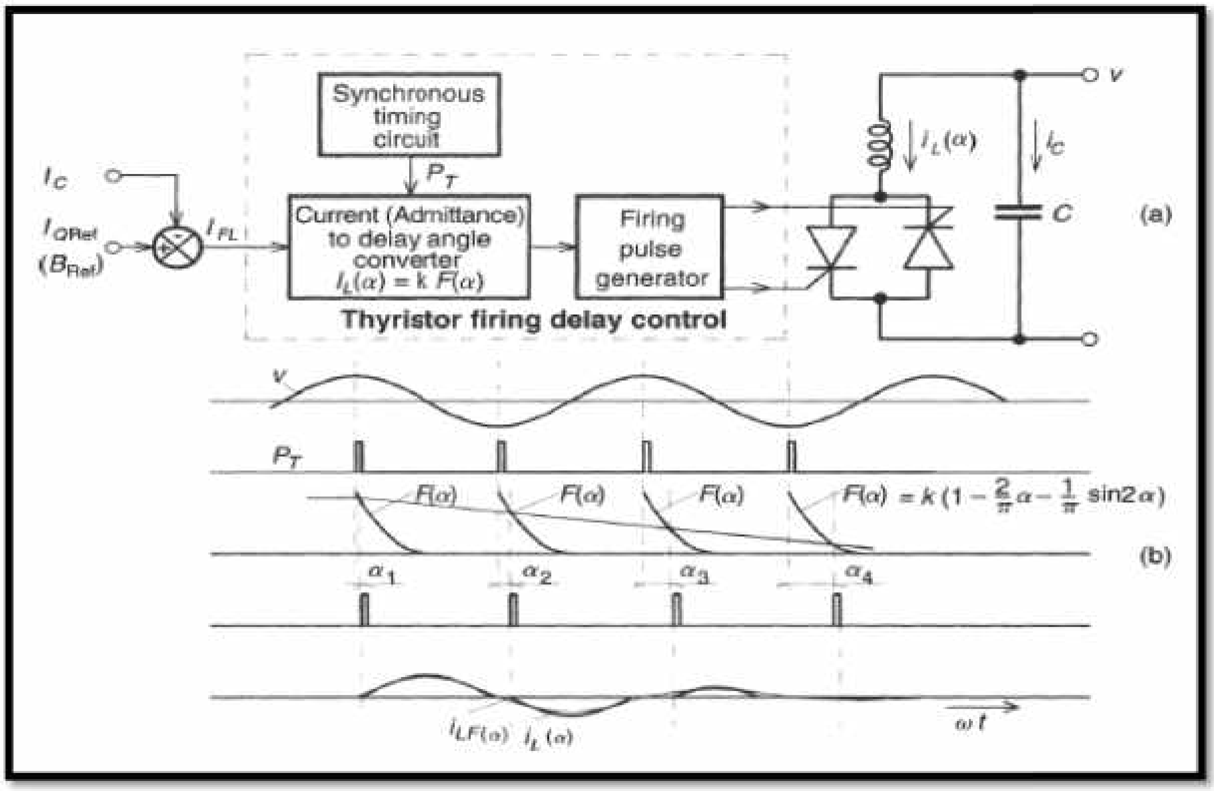
The second function is the reactive current (or admittance) to firing angle conversion. This can be provided by a real time circuit implementation of the mathematical relationship between the amplitude of the fundamental TCR current $I_{LF}(\alpha)$ and the delay angle α. Several circuit approaches are possible. One is an analog function generator producing in each half-cycle a scaled electrical signal that represents the $I_{LF}(\alpha)$ versus a relationship.

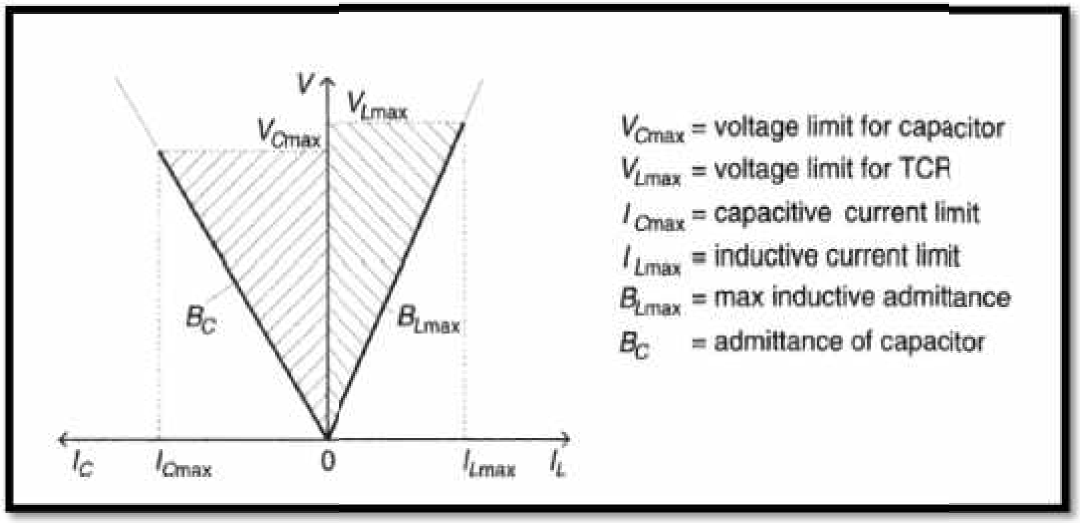
An other is a digital "look-up table" for the normalized $I_{LF}(\alpha)$ versus α function which is read at regular intervals (e.g., at each degree) starting from $\alpha = 0$ (peak of the voltage) until the requested value is found, at which instant a firing pulse is initiated.

A third approach is to use a microprocessor and compute, prior to the earliest firing Angle ($\alpha = 0$), the delay angle corresponding to the required $I_{LF}(\alpha)$. The actual firing instant is then determined simply by a timing circuit (e.g., a counter) "measuring" α from the peak of the voltage.

The third function is the computation of the required fundamental reactor current I_{LF} from the requested total output current I_Q (sum of the fixed capacitor and the TCR currents) defined by the amplitude reference input I_{QRef} to the var generator control. This is simply done by subtracting the (scaled) amplitude of the capacitor current, l_C from l_{QRef} (Positive polarity for l_{QRef} means inductive output current, and negative polarity means capacitive output current.).

The fourth function is the thyristor firing pulse generation. This is accomplished by the firing pulse generator (or gate drive) circuit which produces the necessary gate current pulse for the thyristors to turn on in response to the output signal provided by the reactive current to firing angle converter. The gate drive circuits are sometimes at ground potential with magnetic coupling to the thyristor gates; more often, however, they are at the (high) potential level of the thyristors. In the latter case, in order to provide sufficient insulation between the ground level control and the gate drive circuits, the gating information is usually transmitted via optical fibers ("light pipes").





The V-I operating area of the FC-TCRvar generator is defined by the maximum attainable capacitive and inductive admittances and by the voltage and current ratings of the major power components (capacitor, reactor, and thyristor valve). The ratings of the power components are derived from application requirements.

The dynamic performance (e.g., the frequency band) of the var generator is limited by the firing angle delay control, which results in a time lag or transport lag with respect to the input reference signal. The actual transfer function of the FC-TCR type var generator can be expressed with the transport lag in the following form:

$$\mathbf{G(S) = Ke^{-T_d s}}$$

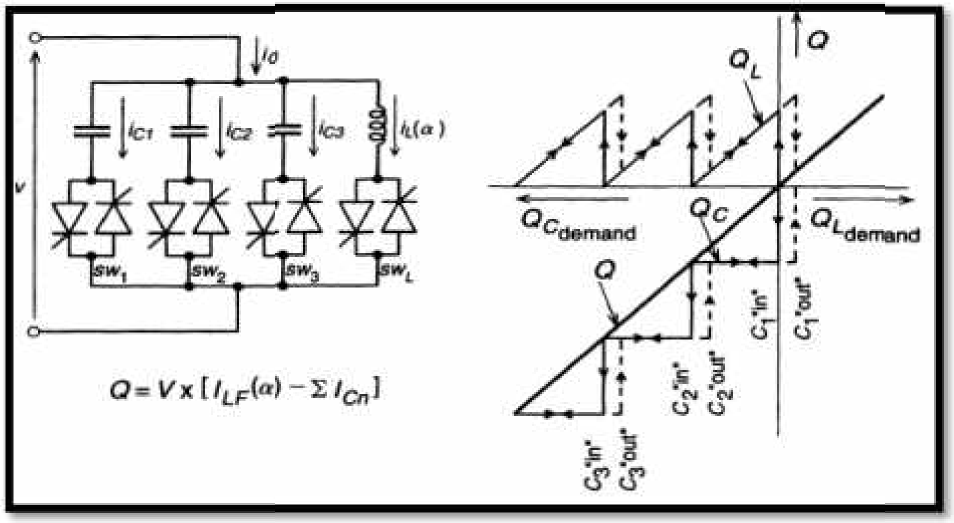
Where S is Laplace operator , K is gain constant, T_d is time lag and firing angle α

THYRISTOR-SWITCHED CAPACITOR-THYRISTOR-CONTROLLED REACTOR (TSC-TSR):

A basic single-phase TSC-TCR arrangement is shown. For a given capacitive output range, it typically consists of n TSC branches and one TCR. The number of branches n, is determined by practical considerations that include the operating voltage level, maximum var output, current rating of the thyristor valves, bus work and installation cost, etc. Of course, the inductive range also can be expanded to any maximum rating by employing additional TCR branches.

The total capacitive output range is divided into n intervals. In the first interval, the output of the var generator is controllable in the zero to Q_{Cmax}/n range, where Q_{Cmax} is the total rating provided by all TSC branches.

In this interval, one capacitor bank is switched in (by firing, for example, thyristor valve S_{W1},) and, simultaneously, the current in the TCR is set by the appropriate firing delay angle so that the sum of the var output of the TSC (negative) and that of the TCR (positive) equals the capacitive output required**.**



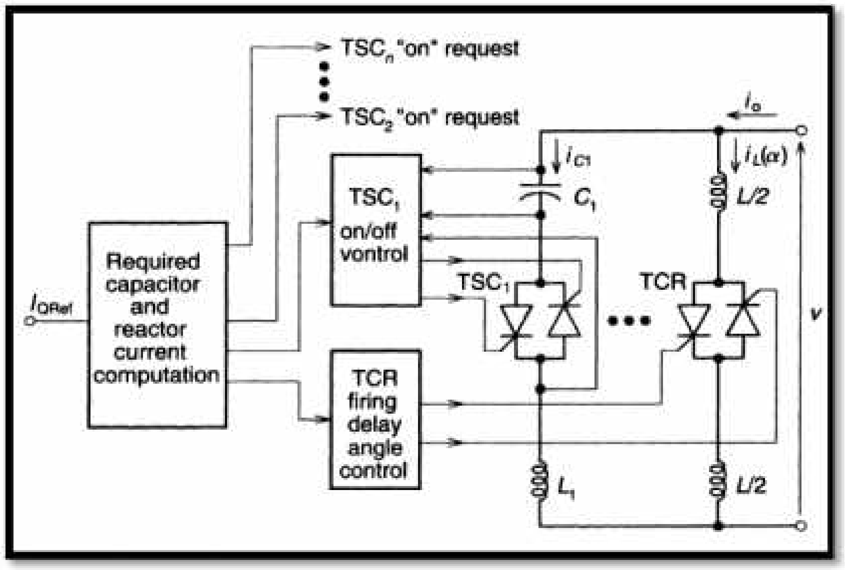
In the second, third, ..., and nth intervals, the output is controllable in the Q_{Cmax}/n to $2Q_{Cmax}/n$, $2Q_{cmax}/n$ to $3Q_{Cmax}/n$, ..., and $(n - 1)Q_{cmax}/n$ to Q_{Cmax} range by switching in the second, third, ..., and nth capacitor bank and using the TCR to absorb the surplus capacitive vars.

By being able to switch the capacitor banks in and out within one cycle of the applied ac voltage, the maximum surplus capacitive var in the total output range can be restricted to that produced by one capacitor bank, and thus, theoretically, the TCR should have the same var rating as the TSC. However, to ensure that the switching conditions at the endpoints of the intervals are not indeterminate, the var rating of the TCR has to be somewhat larger in practice than that of one TSC in order to provide enough overlap (hysteresis) between the "switching in" and "switching out" var levels.

As seen, the capacitive var output, Q_C, is changed in a step-like manner by the TSC's to approximate the var demand with a net capacitive var surplus, and the relatively small inductive var output of the TCR, Q_L, is used to cancel the surplus capacitive vars.

A functional control scheme for the TSC-TCR type var generator. It provides three major functions:

1. Determines the number of TSC branches needed to be switched in to approximate the required capacitive output current (with a positive surplus), and computes the amplitude of the inductive current needed to cancel the surplus capacitive current.
2. Controls the switching of the TSC branches in a "transient-free" manner.
3. Varies the current in the TCR by firing delay angle control.

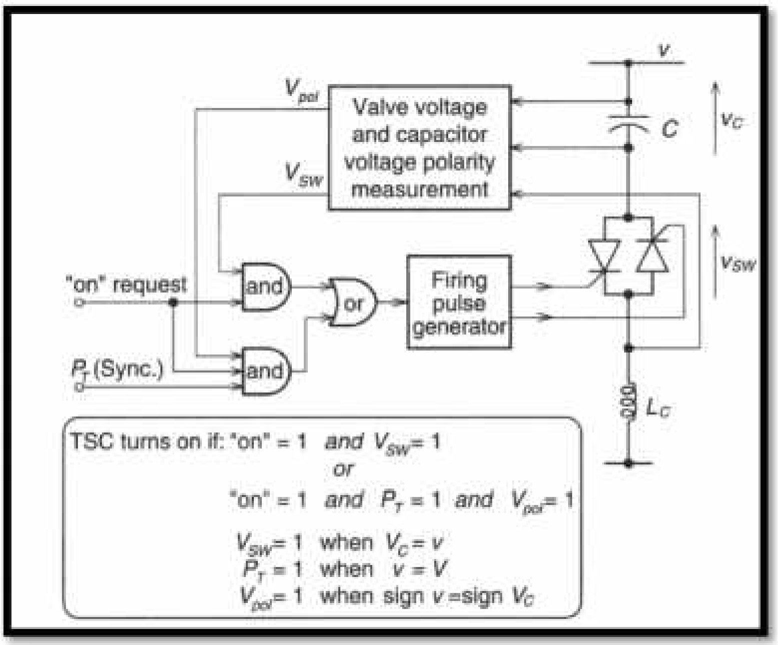


The input current reference I_{QRef} representing the magnitude of the requested output current is divided by the (scaled) amplitude I_C of the current that a TSC branch would draw at the given amplitude V of the ac voltage. The result, rounded to the next higher integer, gives the number of capacitor banks needed. The difference in magnitude between the sum of the activated capacitor currents, $\sum I_L$ and the reference current, I_{QRef} gives the amplitude, I_{LF} of the fundamental reactor current required.

The basic logic for the second function (switching of the TSC branches). This follows the two simple rules for "transient-free" switching. That is, either switch the capacitor bank when the voltage across the thyristor valve becomes zero or when the thyristor valve voltage is at a minimum. (The first condition can be met if the capacitor residual voltage is less than the peak ac voltage and the latter condition is satisfied at those peaks of the ac voltage which has the same polarity as the residual voltage of the capacitor.)

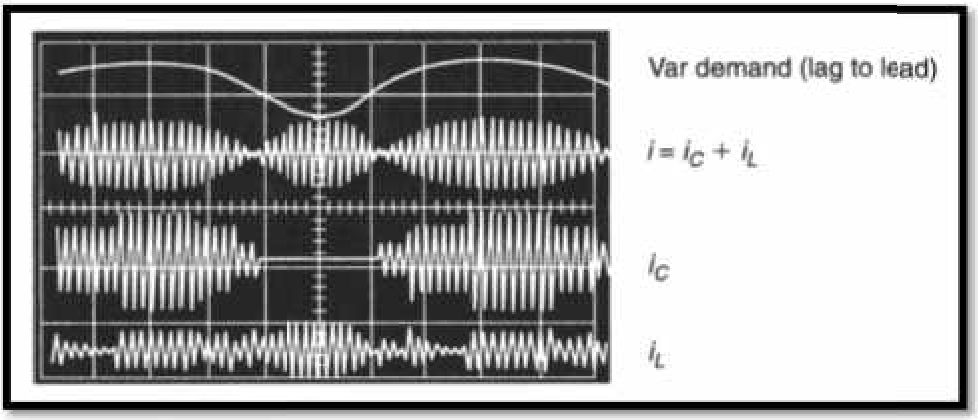
The actual firing pulse generation for the thyristors in the TSC valve is similar to that used for the TCR with the exception that a continuous gate drive is usually provided to maintain continuity in conduction when the current is transferred from one thyristor string carrying current of one polarity (e.g., positive) to the other string carrying current of opposite polarity (e.g., negative).

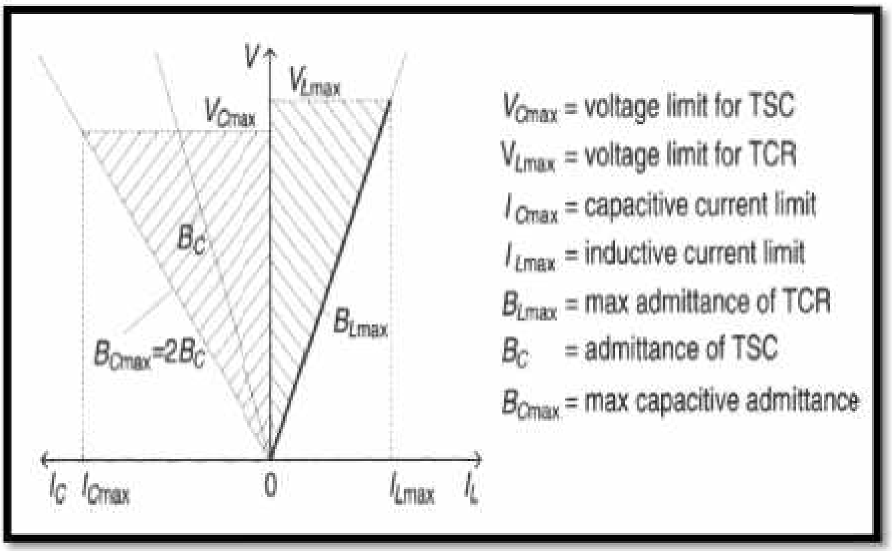
The third function (TCR firing delay angle control) is identical to that used in the fixed-capacitor, thyristor-controlled reactor scheme. The reactive current reference signal I_{QRef}, the total output current the current $i_Q = i_C + i_L$ drawn by the thyristor switched capacitor banks, and the current i_L drawn by the thyristor-controlled reactor.



TSC turns on if: "on" = 1 *and* V_{SW} = 1
or
"on" = 1 *and* P_T = 1 *and* V_{pol} = 1

V_{SW} = 1 when $V_C = v$
P_T = 1 when $v = V$
V_{pol} = 1 when sign v = sign V_C





V_{Cmax} = voltage limit for TSC
V_{Lmax} = voltage limit for TCR
I_{Cmax} = capacitive current limit
I_{Lmax} = inductive current limit
B_{Lmax} = max admittance of TCR
B_C = admittance of TSC
B_{Cmax} = max capacitive admittance

SWITCHING CONVERTER TYPE VAR GENERATORS:

Static var generators discussed in the previous section generate or absorb controllable reactive power (var) by synchronously switching capacitor and reactor banks "in" and "out" of the network.

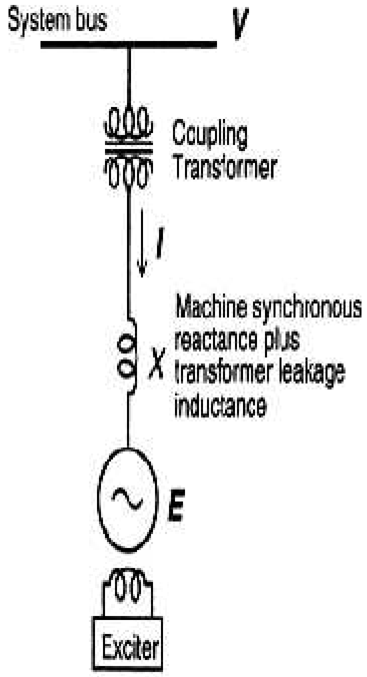
The aim of this approach is to produce a variable reactive shunt impedance that can be adjusted (continuously or in a step-like manner) to meet the compensation requirements of the transmission network. The possibility of generating controllable reactive power directly, without the use of ac capacitors or reactors, by various switching power converters was disclosed by Gyugyi in 1976.

These (dc to ac or ac to ac) converters are operated as voltage and current sources and they produce reactive power essentially without reactive energy storage components by circulating alternating current among the phases of the ac system.

Synchronous machine whose reactive power output is varied by excitation control. Like the mechanically powered machine, they can also exchange real power with the ac system if supplied from an appropriate, usually dc energy source. Because of these similarities with a rotating synchronous generator, they are termed **Static Synchronous Generators (SSGs)**. When an SSG is operated without an energy source, and with appropriate controls to function as a shunt-connected reactive compensator, it is termed, analogously to the rotating **Synchronous Compensator (condenser), a Static Synchronous Compensator (Condenser) STATCOM STATCON.**

BASIC OPERATING PRINCIPLES:

The basic principle of reactive power generation by a voltage-sourced converter is akin to that of the conventional rotating synchronous machine. For purely reactive power flow, the three-phase induced electromotive forces (EMF's) E_a, E_b and E_c of the synchronous rotating machine are in phase with the system voltages, V_a, V_b, and V_c. The reactive current I drawn by the synchronous compensator is determined by the magnitude of the system voltage V, that of the internal voltage E, and the total circuit reactance (synchronous machine reactance plus transformer leakage reactance plus system short circuit reactance X).



$$I = \frac{V - E}{X}$$

The corresponding reactive power Q exchanged can be expressed as follows

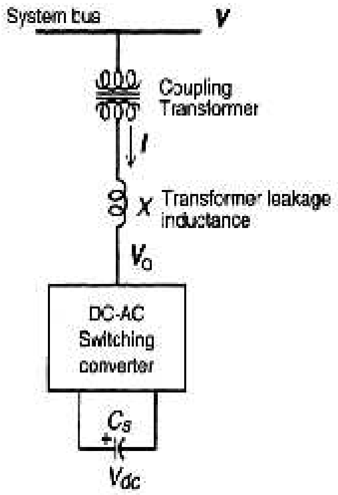
$$Q = \frac{1 - \frac{E}{V}}{X} V^2$$

By controlling the excitation of the machine, and hence the amplitude E of its internal voltage relative to the amplitude V of the system voltage, the reactive power flow can be controlled. Increasing E above V (i.e., operating over-excited) results in a leading current, that is, the machine is "seen" as a capacitor by the ac system.

Decreasing E below V (i.e., operating under-excited) produces a lagging current, that is, the machine is "seen" as a reactor (inductor) by the ac system. Under either operating condition a small amount of real power of course flows from the ac system to the machine to supply its mechanical and electrical losses.

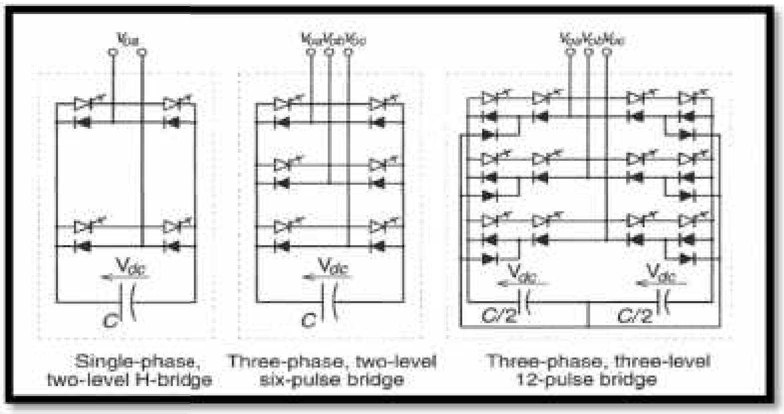
Note that if the excitation of the machine is controlled so that the corresponding reactive output maintains or varies a specific parameter of the ac system (e.g., bus voltage), then the machine (rotating var generator) functions as a rotating synchronous compensator (condenser).

The basic voltage-sourced converter scheme for reactive power generation is shown in the form of a single-line diagram. From a dc input voltage source, provided by the charged capacitor C the converter produces a set of controllable three-phase output voltages with the frequency of the ac power system. Each output voltage is in phase with, and coupled to the corresponding ac system voltage via a relatively small (0.1-0.15 p.u.) tie reactance (which in practice is provided by the per phase leakage inductance of the coupling transformer).



By varying the amplitude of the output voltages produced, the reactive power exchange between the converter and the ac system can be controlled in a manner similar to that of the rotating synchronous machine. That is, if the amplitude of the output voltage is increased above that of the ac system voltage, then the current flows through the tie reactance from the converter to the ac system, and the converter generates reactive (capacitive) power for the ac system.

If the amplitude of the output voltage is decreased below that of the ac system, then the reactive current flows from the ac system to the converter, and the converter absorbs reactive (inductive) power. If the amplitude of the output voltage is equal to that of the ac system voltage, the reactive power exchange is zero.



Single-phase, two-level H-bridge

Three-phase, two-level six-pulse bridge

Three-phase, three-level 12-pulse bridge

Since the converter supplies only reactive output power (its output voltages are controlled to be in phase with the ac system voltages), the real input power provided by the de source (charged capacitor) must be zero (as the total instantaneous power on the ac side is also zero).

Furthermore, since reactive power at zero frequency (at the dc capacitor) by definition is zero, the de capacitor plays no part in the reactive power generation. In other words, the converter simply interconnects the three ac terminals in such a way that the reactive output currents can flow freely between them. Viewing this from the terminals of the ac system, one could say that the converter establishes a circulating current flow among the phases with zero net instantaneous power exchange.

BASIC CONTROL APPROACHES:

A static (var) generator converter comprises a large number of gate controlled semiconductor power switches (GTO thyristors). The gating commands for these devices are generated by the internal converter control (which is part of the var generator proper) in response to the demand for reactive and/or real power reference signal(s).

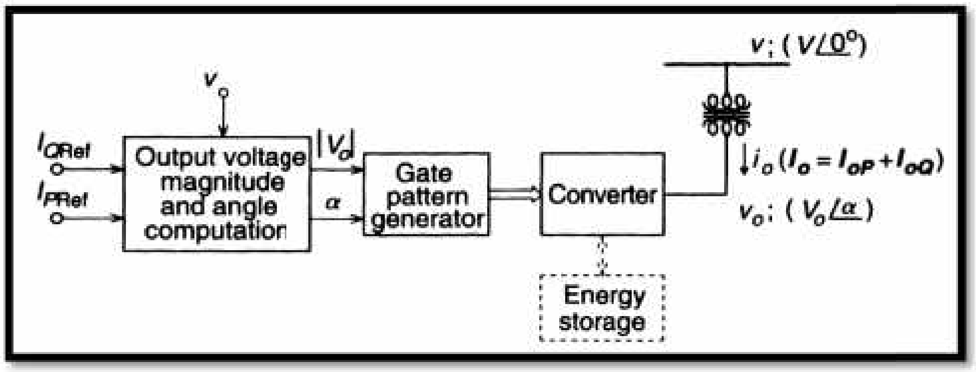
The reference signals are provided by the external or system control, from operator instructions and system variables, which determine the functional operation of the STATCOM.

The internal control is an integral part of the converter. Its main function is to operate the converter power switches so as to generate a fundamental output voltage waveform with the demanded magnitude and phase angle in synchronism with the ac system. In this way the power converter with the internal control can be viewed as a sinusoidal, synchronous voltage source behind a tie reactor (provided by the leakage inductance of the coupling transformer), the amplitude and phase angle of which are controlled by the external (STATCOM system) control via appropriate reference signal(s).
The main function of the internal control, as stated above, is to operate the converter power switches so as to produce a synchronous output voltage waveform that forces the reactive (and real) power exchange required for compensation.

The internal control achieves this by computing the magnitude and phase angle of the required output voltage from I_{QRef} and I_{PRef} provided by the external control and generating a set of coordinated timing waveforms ("gating pattern"), which determines the on and off periods of each switch in the converter corresponding to the wanted output voltage. These timing waveforms have a defined phase relationship between them, determined by the converter pulse number, the method used for constructing the output voltage waveform, and the required angular phase relationship between the three outputs (normally 120 degrees).

The magnitude and angle of the output voltage are those internal parameters which determine the real and reactive current the converter draws from, and thereby the real and reactive power it exchanges with the ac system.

If the converter is restricted for reactive power exchange, i.e., it is strictly operated as a static var generator, then the reference input to the internal control is the required reactive current. From this the internal control derives the necessary magnitude and angle for the converter output voltage to establish the required dc voltage on the dc capacitor since the magnitude of the ac output voltage is directly proportional to the dc capacitor voltage. Because of this proportionality, the reactive output current, as one approach, can be controlled indirectly via controlling the dc capacitor voltage (which in turn is controlled by the angle of the output voltage) or, as another approach, directly by the internal voltage control mechanism (e.g., PWM) of the converter in which case the de voltage is kept constant (by the control of the angle)



There are two basic approaches to output voltage, and thus to var control

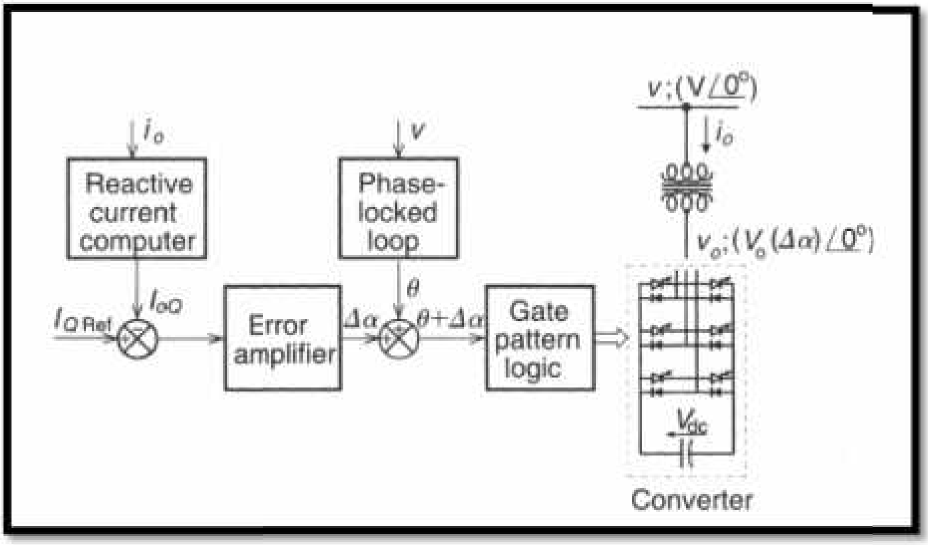
1. Indirect output voltage control
2. Direct" output voltage control

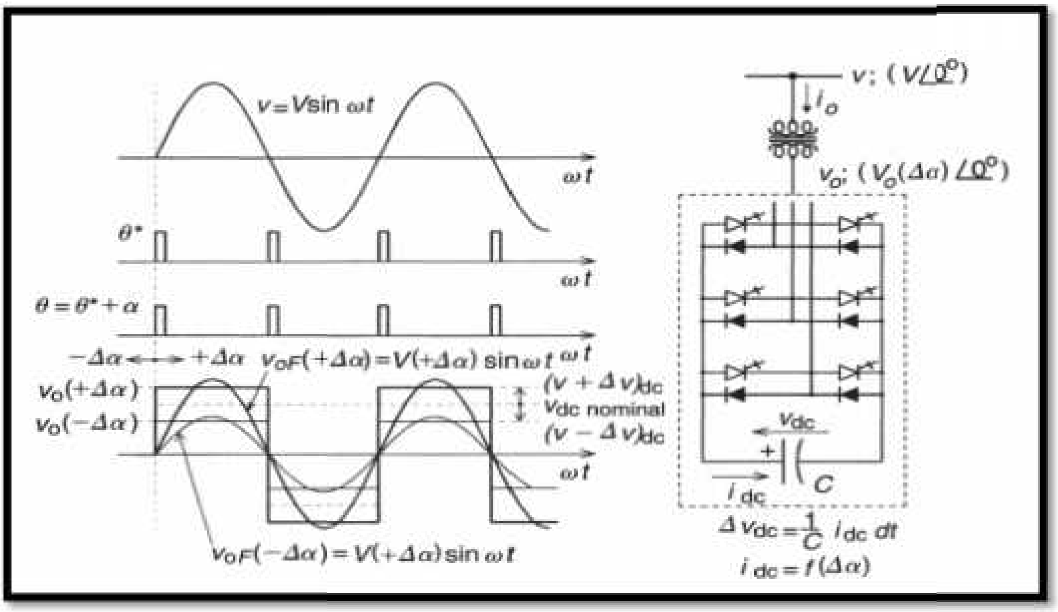
Block diagram of the internal control for purely reactive compensation, based on the indirect approach of dc capacitor voltage control:

The inputs to the internal control are: the ac system bus voltage v, the output current of the converter i_0 reference, and the reactive current I_{QRef}. Voltage v operates a phase-locked loop that provides the basic synchronizing signal, angle θ.

The output current, i_0 ' is decomposed "into its reactive and real components, and the magnitude of the reactive current component, I_{0Q} to the reactive current reference, I_{QRef} is compared. The error thus obtained provides, after suitable amplification, angle α, which defines the necessary phase shift between the output voltage of the converter and the ac system voltage needed for charging (or discharging) the storage capacitor to the dc voltage level required.

Accordingly, angle α is summed to θ to provide angle $\theta + \alpha$, which represents the desired synchronizing signal for the converter to satisfy the reactive current reference. Angle $\theta + \alpha$ operates the gate pattern logic (which may be a digital look-up table) that provides the individual gate drive logic signals to operate the converter power switches.



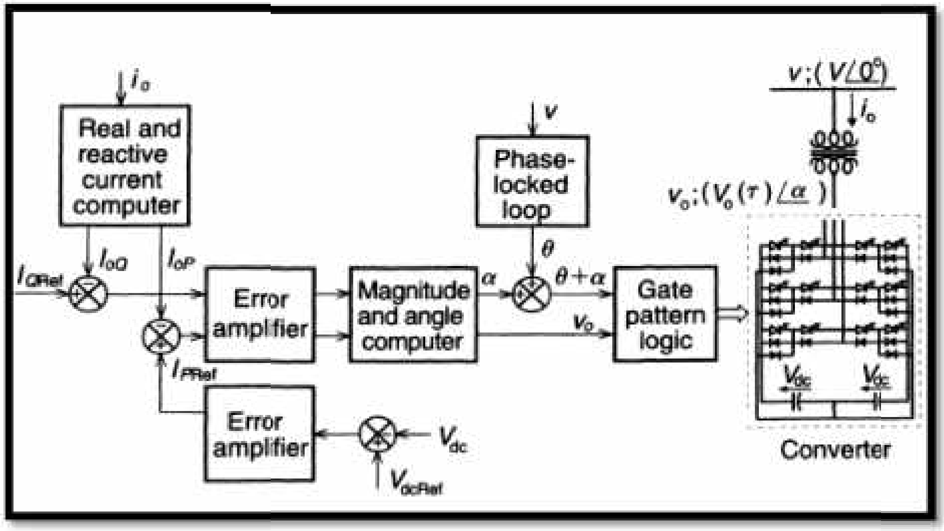


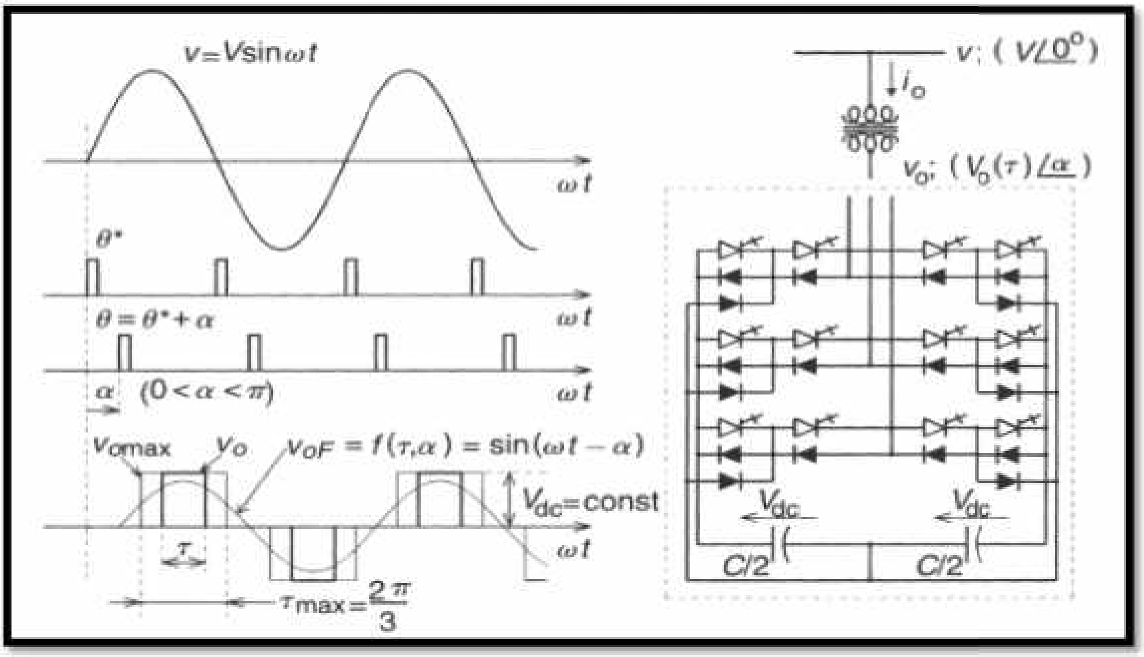
Block diagram of the internal control for a converter with direct internal voltage control capability, such as the three-level converter:

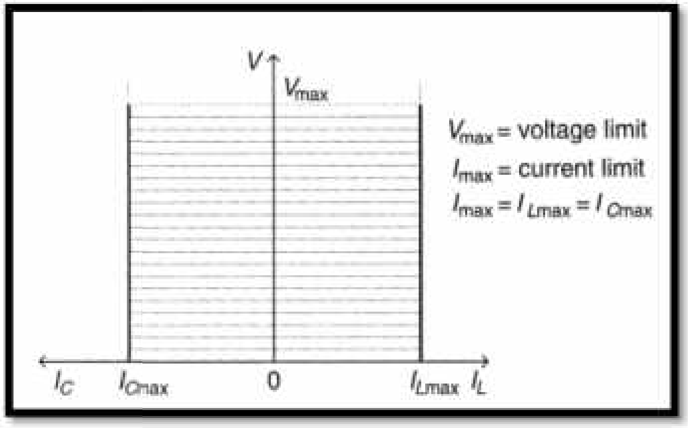
The input signals are again the bus voltage, v, the converter output current, i_0 , and the reactive current reference, I_{QRef}, plus the dc voltage reference V_{dc} .This dc voltage reference determines the real power the converter must absorb from the ac system in order to supply its internal losses.

The converter output current is decomposed into reactive and real current components. These components are compared to the external reactive current reference (determined from compensation requirements) and the internal real current reference derived from the dc voltage regulation loop. After suitable amplification, the real and reactive current error signals are converted into the magnitude and angle of the wanted converter output voltage, from which the appropriate gate drive signals, in proper relationship with the phase-locked loop provided phase reference, are derived.

Note that this internal control scheme could operate the converter with a dc power supply or energy storage as a static synchronous generator. In this case the internal real current reference would be summed to an externally provided real current reference that would indicate the desired real power exchange (either positive or negative) with the ac system. The combined internal and external real current references (for converter losses and active power compensation), together with the prevailing reactive current demand, would determine the magnitude and angle of the output voltage generated, and thus the real and reactive power exchanged with the ac system.



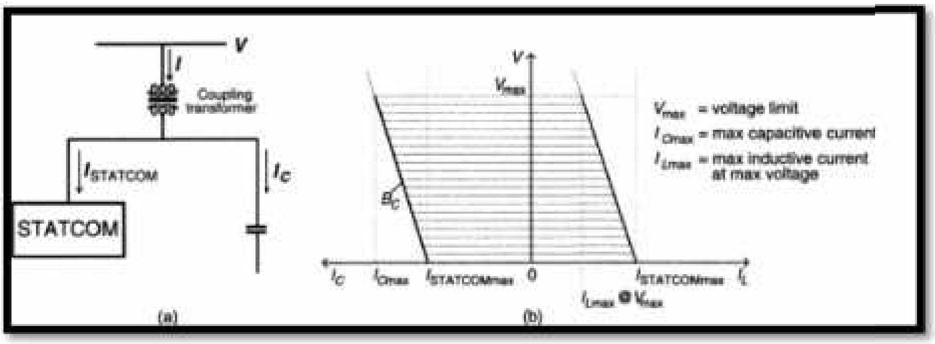


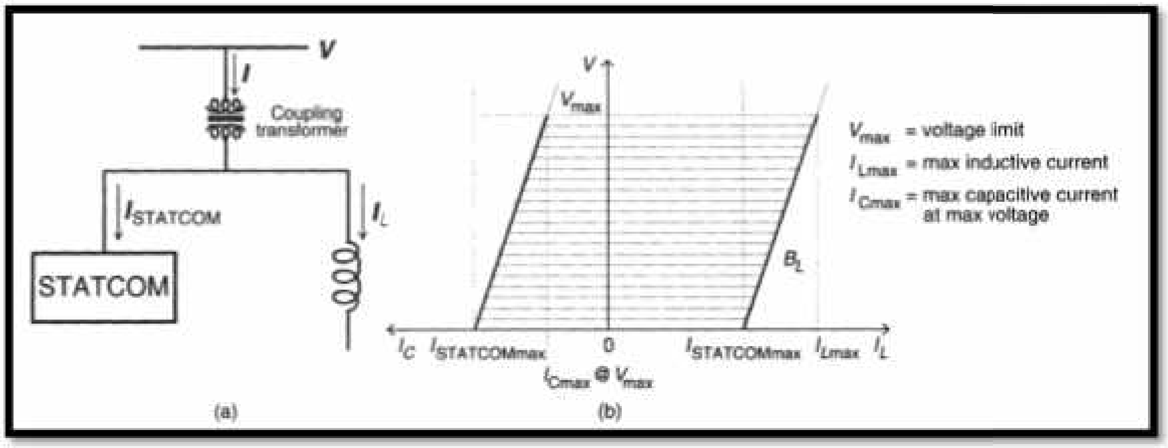


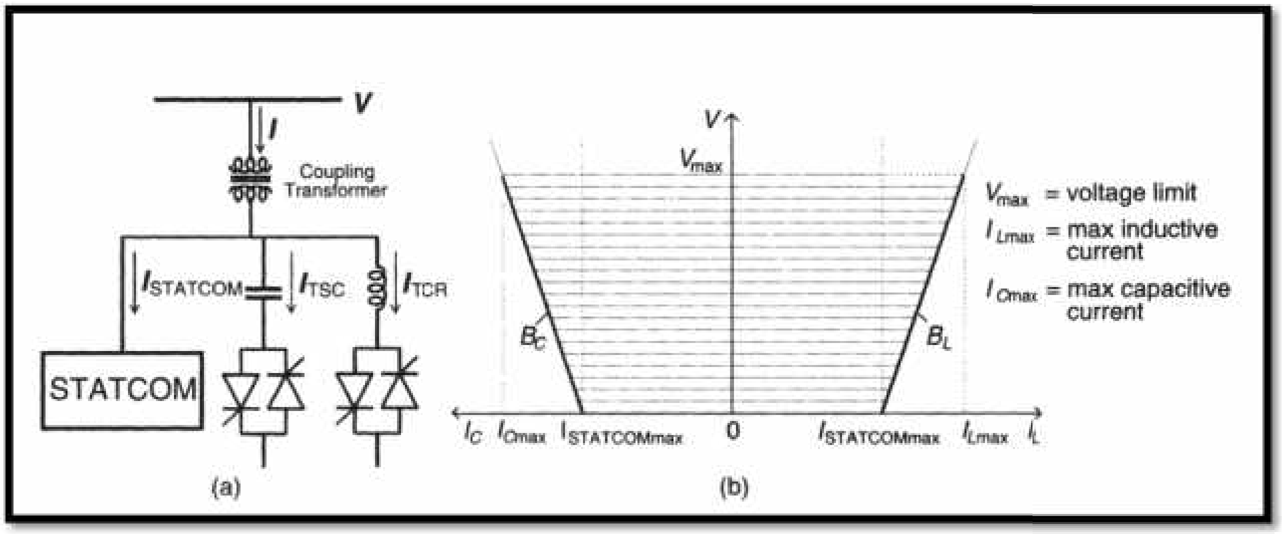
HYBRID VAR GENERATORS:

SWITCHING CONVERTER WITH TSC AND TCR:

The converter-based var generator can generate or absorb the same amount of maximum reactive power; in other words, it has the same control range for capacitive and inductive var output. However, many applications may call for a different var generation and absorption range. This can simply be achieved by combining the converter with either fixed and/or thyristor-switched capacitors and/or reactors.







Compiled by

P.Pawan Puthra

UNIT-V

SERIES COMPENSATION

OBJECTIVES OF SERIES COMPENSATION:

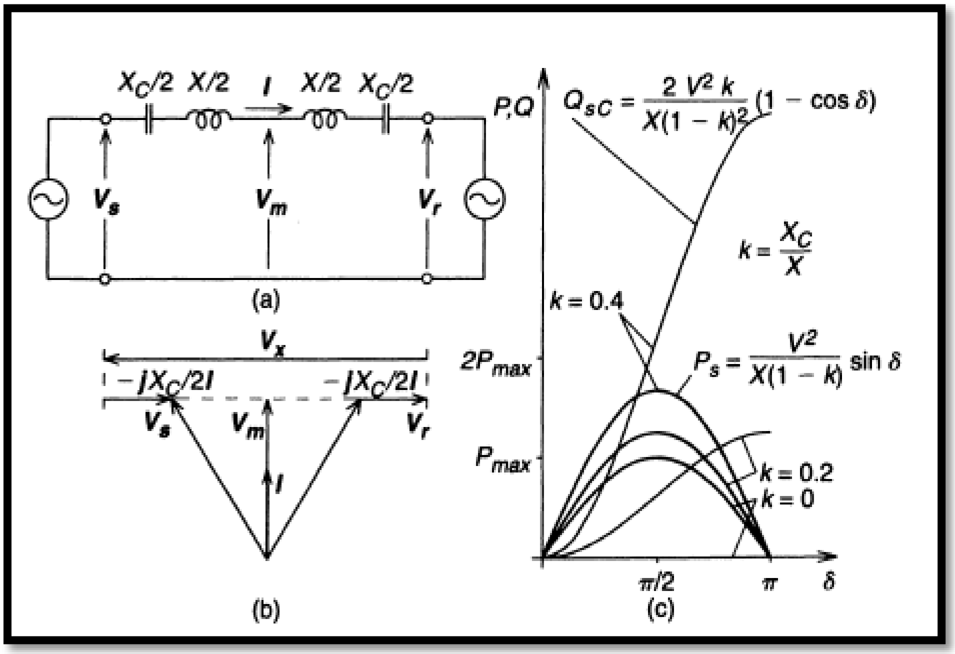
The effect of series compensation on the basic factors, determining attainable

- MAXIMAL POWER TRANSMISSION,
- STEADY-STATE POWER TRANSMISSION
- LIMIT, TRANSIENT STABILITY,
- VOLTAGE STABILITY
- POWER OSCILLATION DAMPING

CONCEPT OF SERIES CAPACITIVE COMPENSATION:

The basic idea behind series capacitive compensation is to decrease the overall effective series transmission impedance from the sending end to the receiving end, i.e., X in the $P = (V^2/X) \sin \delta$ relationship characterizing the power transmission over a single line.

Consider the simple two-machine model, with a series capacitor compensated line, which, for convenience, is assumed to be composed of two identical segments. Note that for the same end voltages the magnitude of the total voltage across the series line inductance, $V_x = 2V_{X/2}$ is increased by the magnitude of the opposite voltage, V_c developed across the series capacitor and this results from an increase in the line current.



Effective transmission impedance with the series capacitive compensation is

$$X_{eff} = X - X_C$$

$$X_{eff} = (1 - K)X$$

where K is the degree of series compensation,

$$K = \frac{X_C}{X}$$

Assuming the voltages $V_S = V_r = V$

The current in the compensated line is

$$I = \frac{2V}{(1-K)X} \sin\frac{\delta}{2}$$

Real Power Transmitted is

$$P = V_m I = \frac{V^2}{(1-K)X} \sin\delta$$

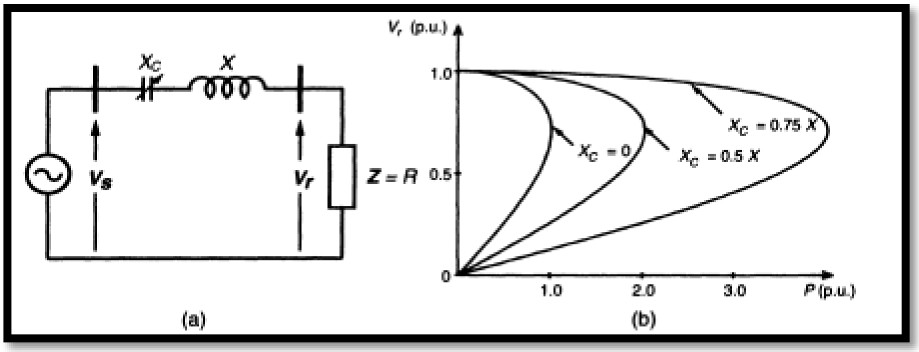
Reactive power supplied by the series capacitor is

$$Q_C = I^2 X_C = \frac{2V^2}{(1-K)^2 X} (1 - \cos\delta)$$

VOLTAGE STABILITY:

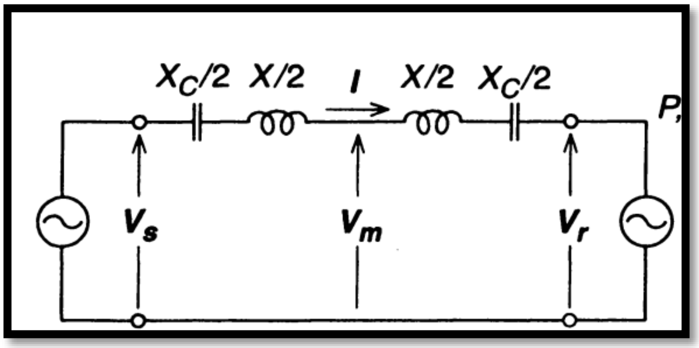
Series capacitive compensation can also be used to reduce the series reactive impedance to minimize the receiving-end voltage variation and the possibility of voltage collapse.

A simple radial system with feeder line reactance X, series compensating reactance Xc, and load impedance Z is shown . The "nose point" at each plot given for a specific compensation level represents the corresponding voltage instability where the same radial system with a reactive shunt compensator, supporting the end voltage, is shown. Clearly, both shunt and series capacitive compensation can effectively increase the voltage stability limit. Shunt compensation does it by supplying the reactive load demand and regulating the terminal voltage. Series capacitive compensation does it.



IMPROVEMENT OF TRANSIENT STABILITY:

The powerful capability of series line compensation to control the transmitted power can be utilized much more effectively to increase the transient stability limit and to provide power oscillation damping. The equal area criterion, to investigate the capability of the ideal shunt compensator to improve the transient stability, is used again here to assess the relative increase of the transient stability margin attainable by series capacitive compensation.

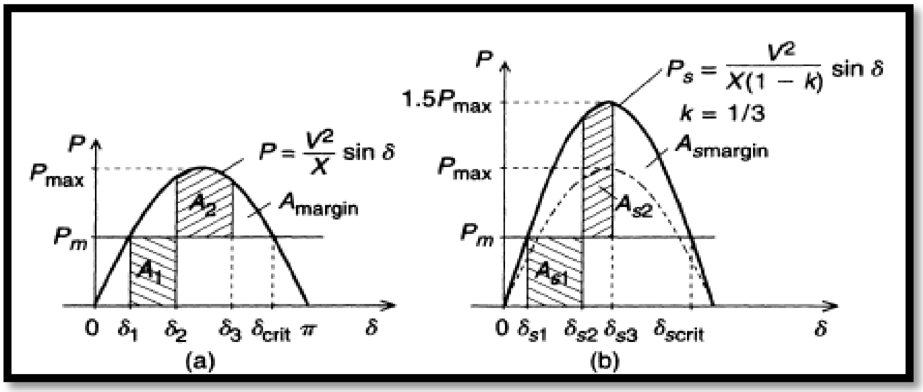


Consider the simple system with the series compensated line shown. As for the shunt compensated system shown, it is, for convenience, also assumed for the series compensated case that the pre-fault and post-fault systems remain the same.

Suppose that the system, with and without series capacitive compensation, transmits the same power P_m. Assume that both the uncompensated and the series compensated systems are subjected to the same fault for the same period of time.

The dynamic behavior of these systems is illustrated in as seen, prior to the fault both of them transmit power P_m at angles δ_1 and δ_{s1}, respectively. During the fault, the transmitted electric power becomes zero While the mechanical input power to the generators remains constant, P_m. Therefore, the sending-end generator accelerates from the steady-state angles δ_1 and δ_{s1} to δ_2 and δ_{s2} respectively, when the fault clears.

The accelerating energies are represented by areas A_1 and A_{s1} After fault clearing, the transmitted electric power exceeds the mechanical input power and therefore the sending-end machine decelerates. However, the accumulated kinetic energy further increases until a balance between the accelerating and decelerating energies, represented by areas A_1 , A_{s1} and A_2 , A_{s2} respectively is reached at the maximum angular swings, δ_3 and δ_{s3}



The areas between the P and δ curve and the constant P_m line over the interval defined by the angles δ_3 and $\delta_{critical}$ and δs_3 and $\delta s_{critical}$ respectively. Transient margin stability represented by Amargin and Asmargin.

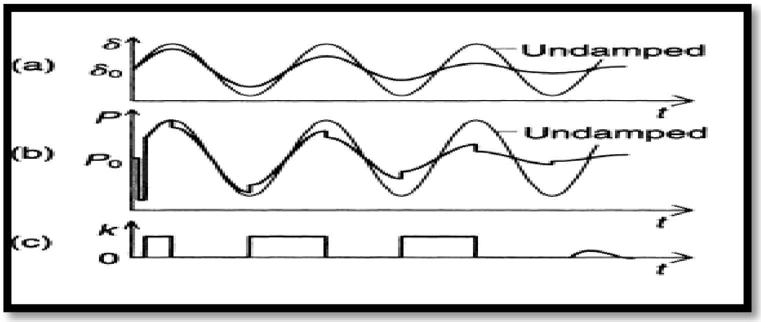
Comparison clearly shows a substantial increase in the transient stability margin the series capacitive compensation can provide by partial cancellation of the series impedance of the transmission line.

The increase of transient stability margin is proportional to the degree of series compensation. Theoretically this increase becomes unlimited for an ideal reactive line as the compensation approaches 100%. However, practical series capacitive compensation does not usually exceed 75% for a number of reasons, including load balancing with parallel paths, high fault current, and the possible difficulties of power flow control. Often the compensation is limited to less than 30% due to subsynchronous concerns.

POWER OSCILLATION DAMPING:

Controlled series compensation can be applied effectively to damp power oscillations, for power oscillation damping it is necessary to vary the applied compensation so as to counteract the accelerating and decelerating swings of the disturbed machine(s). That is, when the rotationally oscillating generator accelerates and angle δ increases ($d\delta/dt > 0$), the electric power transmitted must be increased to compensate for the excess mechanical input power. Conversely, when the generator decelerates and angle δ decreases ($d\delta/dt < 0$), the electric power must be decreased to balance the insufficient mechanical input power.

As seen, k is maximum when $d\delta/dt > 0$, and it is zero when $d\delta/dt < 0$. With maximum k, the effective line impedance is minimum (or, alternatively, the voltage across the actual line impedance is maximum) and consequently, the electric power transmitted over the line is maximum. When k is zero, the effective line impedance is maximum (or, alternatively, the voltage across the actual line impedance is minimum) and the power transmitted is minimum. The illustration shows that k is controlled in a "bang-bang" manner (output of the series compensator is varied between the minimum and maximum values). Indeed, this type of control is the most effective for damping large oscillations. However, damping relatively small power oscillations, particularly with a relatively large series compensator, continuous variation of k, in sympathy with the generator angle or power, may be a better alternative.



SUBSYNCHRONOUS OSCILLATION DAMPING:

Sustained oscillation below the fundamental system frequency can be caused by series capacitive compensation. The phenomenon, referred to as **SUBSYNCHRONOUS RESONANCE (SSR),** was observed as early as 1937, but it received serious attention only in the 1970s, after two turbine-generator shaft failures occurred at the Mojave Generating Station in southern Nevada.

Theoretical investigations showed that interaction between a series capacitor-compensated transmission line, oscillating at the natural (subharmonic) resonant frequency, and the mechanical system of a turbine-generator set in torsional mechanical oscillation can result in negative damping with the consequent mutual reinforcement of the electrical and mechanical oscillations. The phenomenon of subsynchronous resonance can be briefly described as follows:

A capacitor in series with the total circuit inductance of the transmission line (including the appropriate generator and transformer leakage inductive) forms a series resonant circuit with the natural frequency of $f_e = \frac{1}{2\pi\sqrt{LC}} = f\sqrt{\frac{X_C}{X}}$ where X_c is the reactance of the series capacitor and X is the total reactance of the line at the fundamental power system frequency f. Since the degree of series compensation k = X_c/X is usually in the 25 to 75% range, the electrical resonant frequency f_e; is less than the power frequency f, i.e., f_e is a sub harmonic frequency.

If the electrical circuit is brought into oscillation (by some network disturbance) then the sub harmonic component of the line current results in a corresponding sub harmonic field in the machine which, as it rotates backwards relative to the main field (since t. < f), produces an alternating torque on the rotor at the difference frequency of $f - f_e$.

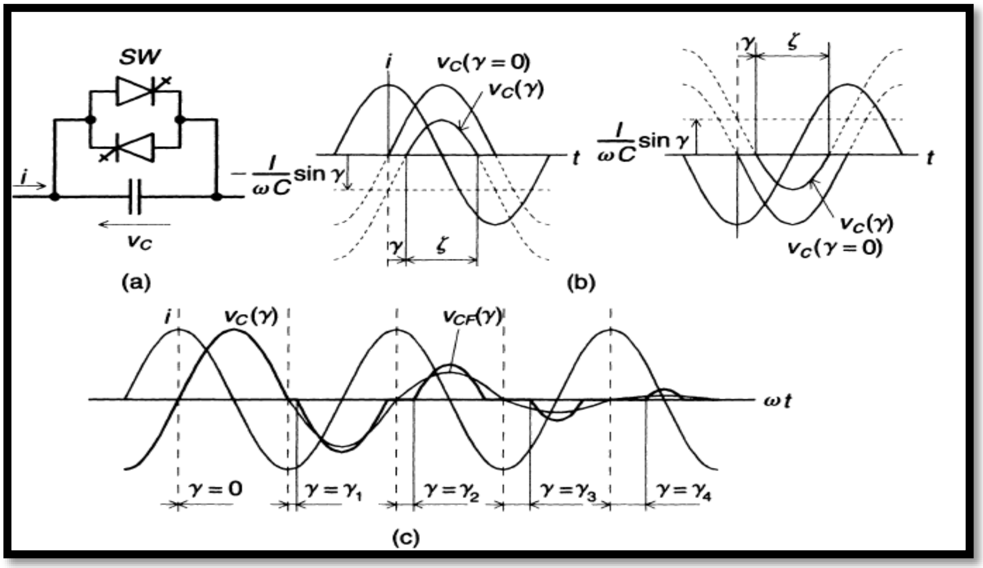
If this difference frequency coincides with one of the torsional resonances of the turbine-generator set, mechanical torsional oscillation is excited, which, in turn, further excites the electrical resonance. This condition is defined as subsynchronous resonance. (Of course, this process could also start in the reverse sense: a shock could start a torsional oscillation which, under the condition of subsynchronous resonance, would be reinforced by the response of the electrical network.)

METHODS OF CONTROLLABLE VAR GENERATION

- ➢ **VARIABLE IMPEDANCE TYPE STATIC VAR GENERATORS:**
    - **GTO THYRISTOR-CONTROLLED SERIES CAPACITOR (GCSC)**
    - **THYRISTOR-CONTROLLED SERIES CAPACITOR (TCSC)**
    - **THYRISTOR-SWITCHED SERIES CAPACITOR (TSSC)**
- ➢ **SWITCHING CONVERTER TYPE VAR GENERATORS**
    - ➢ **STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC)**

GTO THYRISTOR-CONTROLLED SERIES CAPACITOR (GCSC):

An elementary GTO Thyristor-Controlled Series Capacitor, proposed by Karady with others in 1992, is shown. It consists of a fixed capacitor in parallel with a GTO thyristor (or equivalent) valve (or switch) that has the capability to turn on and off upon command.



The objective of the GCSC scheme shown is to control the ac voltage V_c across the capacitor at a given line current i. Evidently, when the GTO valve, SW, is closed, the voltage across the capacitor .is zero, and when the valve is open, it is maximum. For controlling the capacitor voltage, the closing and opening of the valve is carried out in each half-cycle in synchronism with the ac system frequency.

The GTO valve is stipulated to close automatically (through appropriate control action) whenever the capacitor voltage crosses zero. (Recall that the thyristor valve of the TCR opens automatically whenever the current crosses zero.) However, the turn-off instant of the valve in each half-cycle is controlled by a (turn-off) delay angle γ ($0 \le \gamma \le \pi/2$), with respect to the peak of the line current. where the line current i, and the capacitor voltage $V_C(\gamma)$ are shown at $\gamma = 0$ (valve open) and at an arbitrary turn-off delay angle γ for a positive and a negative half-cycle.

When the valve sw is opened at the crest of the (constant) line current ($\gamma = 0$), the resultant capacitor voltage V_c will be the same as that obtained in steady state with a permanently open switch. When the opening of the valve is delayed by the angle γ with respect to the crest of the line current, the capacitor voltage can be expressed with a defined line current, as follows

$$i(t) = I\cos\omega t$$

$$V_C(t) = \frac{1}{C}\int_{\gamma}^{\omega t} i(t)dt = \frac{I}{\omega C}(\sin\omega t - \sin\gamma)$$

Since the valve opens at γ and stipulated to close at the first voltage zero, is valid for the interval $\gamma \le \omega t \le \pi - \gamma$. For subsequent positive half-cycle intervals the same expression remains valid. For subsequent negative half-cycle intervals, the sign of the terms becomes opposite.

It is evident that the magnitude of the capacitor voltage can be varied continuously by this method of turn-off delay angle control from maximum ($\gamma = 0$) to zero ($\gamma = \pi/2$) , where the capacitor voltage $V_c(\gamma)$, together with its fundamental component $V_{CF}(y)$, are shown at, various tum-off delay angles, /'. Note, however, that the adjustment of the capacitor voltage, similar to the adjustment of the TCR current, is discrete and can take place only once in each half-cycle.

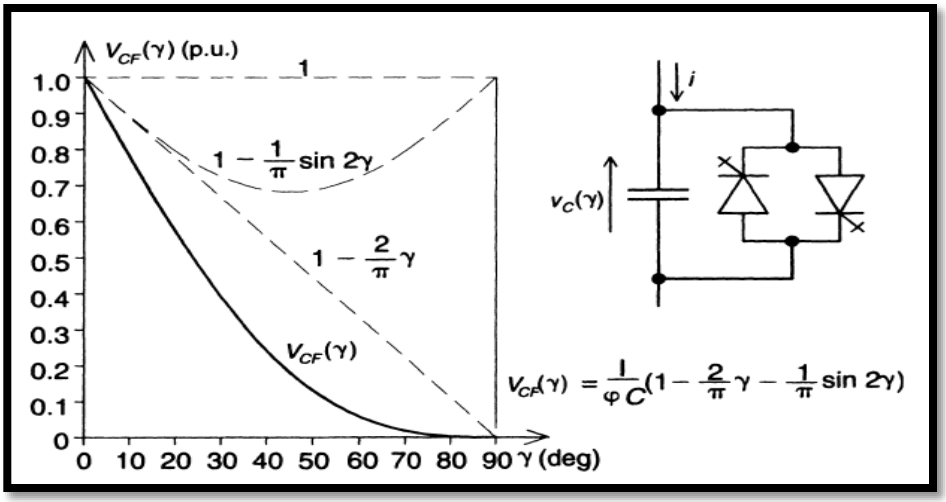
The amplitude of the capacitor voltage is given by

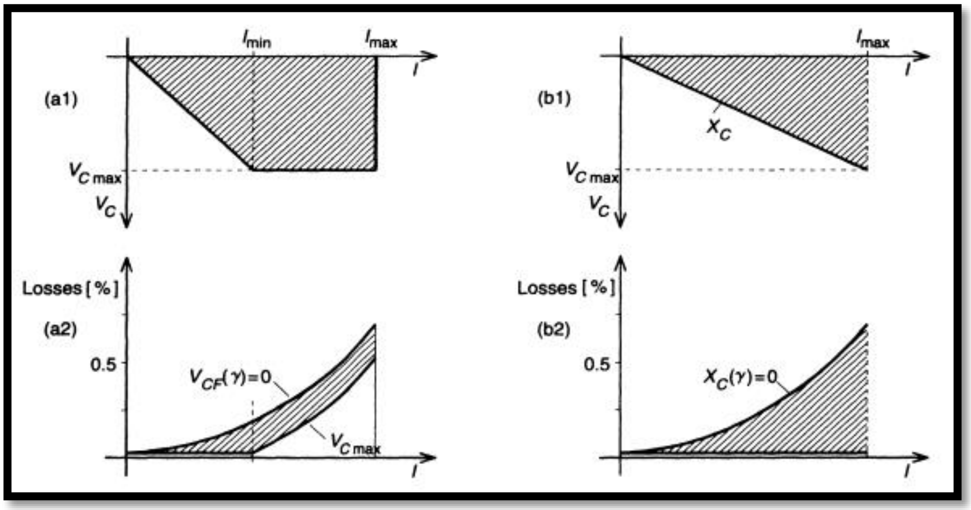
$$V_{CF}(\gamma) = \frac{I}{\omega C}\left(1 - \frac{2\gamma}{\pi} - \frac{1}{\pi}\sin 2\gamma\right)$$

where I is the amplitude of the line current, C is the capacitance of the GTO thyristor controlled capacitor, and ω is the angular frequency of the ac system.

On the basis of the GCSC, varying the fundamental capacitor voltage at a fixed line current, could be considered as a variable capacitive impedance. Indeed, an effective capacitive impedance can be found for a given value of angle γ Of, in other words, an effective capacitive impedance, X_c, as a function of γ, for the GCSC can be defined.

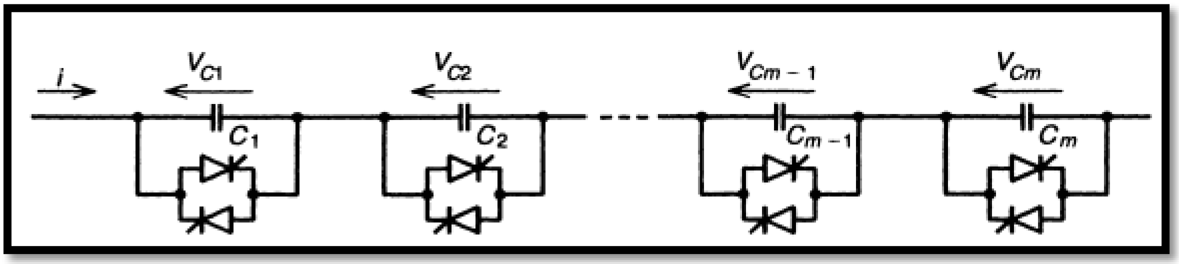
$$X_C(\gamma) = \frac{1}{\omega C}\left(1 - \frac{2\gamma}{\pi} - \frac{1}{\pi}\sin 2\gamma\right)$$





THYRISTOR-SWITCHED SERIES CAPACITOR (TSSC):

The basic circuit arrangement of the thyristor-switched series capacitor is shown. It consists of a number of capacitors, each shunted by an appropriately rated bypass valve composed of a string of reverse parallel connected thyristors, in series.



Its operation is different due to the imposed switching restrictions of the conventional thyristor valve. The operating principle of the TSSC is straightforward: the degree of series compensation is controlled in a step-like manner by increasing or decreasing the number of series capacitors inserted.

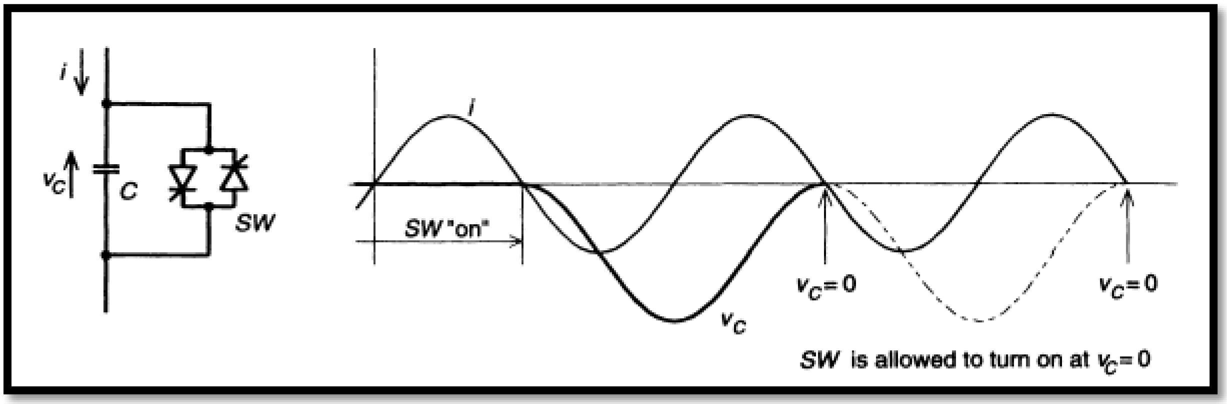
A capacitor is inserted by turning off, and it is bypassed by turning on the corresponding thyristor valve. A thyristor valve commutates "naturally," that is, it turns off when the current crosses zero. Thus a capacitor can be inserted into the line by the thyristor valve only at the zero crossings of the line current.

Since the insertion takes place at line current zero, a full half-cycle of the line current will charge the capacitor from zero to maximum and the successive, opposite polarity half-cycle of the line current will discharge it from this maximum to zero, as.

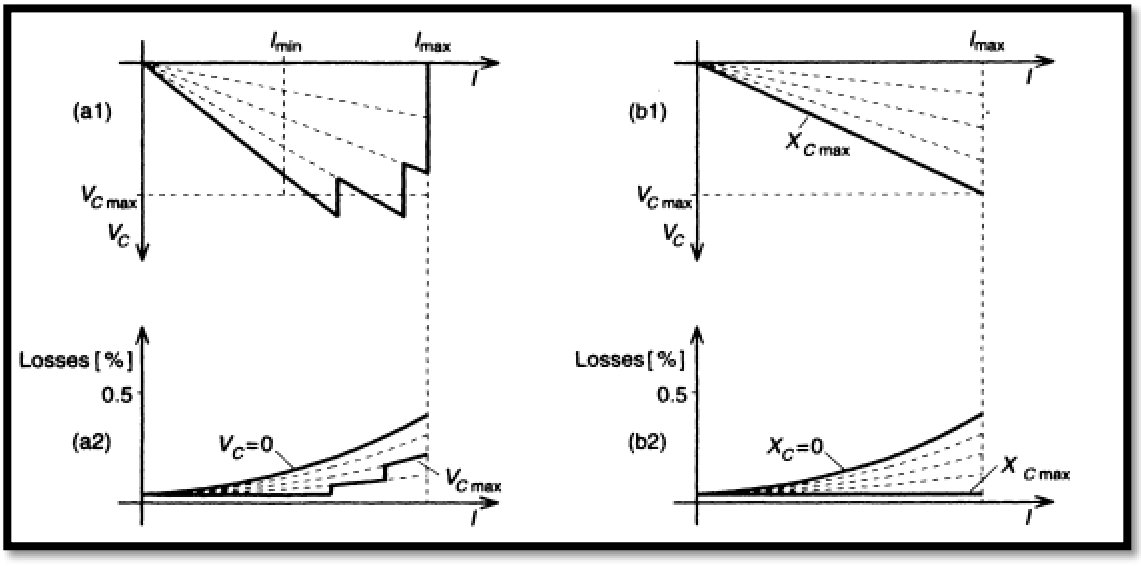
The capacitor insertion at line current zero, necessitated by the switching limitation of the thyristor valve, results in a de offset voltage which is equal to the amplitude of the ac capacitor voltage. In order to minimize the initial surge current in the valve, and the corresponding circuit transient, the thyristor valve should be turned on for bypass only when the capacitor voltage is zero. With the prevailing de offset, this requirement can cause a delay of up to one full cycle, which would set the theoretical limit for the attainable response time of the TSSC.

The basic V-I characteristic of the TSSC with four series connected compensator modules operated to control the compensating voltage is shown. For this compensating mode the reactance of the capacitor banks is chosen so as to produce, on the average, the rated compensating voltage, $V_{Cmax} = 4X_C\ I_{min}$ in the face of decreasing line current over a defined interval $I_{min} \leq I \leq I_{max}$.

As the current I_{min} is increased toward I_{max} the capacitor banks are progressively bypassed by the related thyristor valves to reduce the overall capacitive reactance in a step-like manner and thereby maintain the compensating voltage with increasing line current.



In the impedance compensation mode, the TSSC is applied to maintain the maximum rated compensating reactance at any line current up to the rated maximum. In this compensation mode the capacitive impedance is chosen so as to provide the maximum series compensation at rated current, $4X_C = V_{cmax}/I_{max}$, that the TSSC can vary in a step-like manner by bypassing one or more capacitor banks. The loss versus line current characteristic for this compensation mode is shown for zero compensating impedance (all capacitor banks are bypassed by the thyristor valves) and for maximum compensating impedance (all thyristor valves are off and all capacitors are inserted).



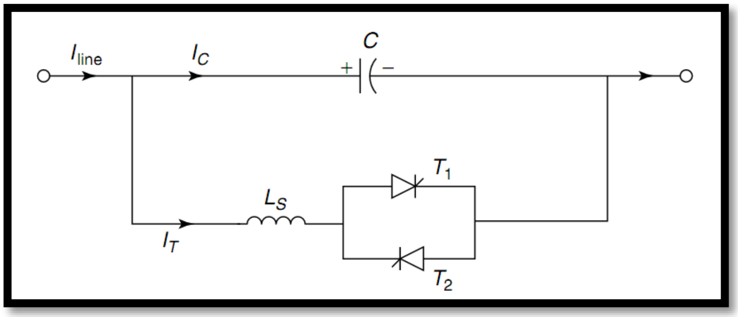
THYRISTOR-CONTROLLED SERIES CAPACITOR (TCSC):

ADVANTAGES OF TCSC:

Use of thyristor control in series capacitors potentially offers the following little-mentioned advantages:

1. Rapid, continuous control of the transmission-line series-compensation level.
2. Dynamic control of power flow in selected transmission lines within the network to enable optimal power-flow conditions and prevent the loop flow of power.
3. Damping of the power swings from local and inter-area oscillations.
4. Suppression of subsynchronous oscillations. At subsynchronous frequencies, the TCSC presents an inherently resistive–inductive reactance. The subsynchronous oscillations cannot be sustained in this situation and consequently get damped.
5. Decreasing dc-offset voltages. The dc-offset voltages, invariably resulting from the insertion of series capacitors, can be made to decay very quickly (within a few cycles) from the firing control of the TCSC thyristors.
6. Enhanced level of protection for series capacitors. A fast bypass of the series capacitors can be achieved through thyristor control when large over voltages develop across capacitors following faults. Likewise, the capacitors can be quickly reinserted by thyristor action after fault clearing to aid in system stabilization.
7. Voltage support. The TCSC, in conjunction with series capacitors, can generate reactive power that increases with line loading, thereby aiding the regulation of local network voltages and, in addition, the alleviation of any voltage instability.
8. Reduction of the short-circuit current. During events of high short-circuit current, the TCSC can switch from the controllable-capacitance to the controllable-inductance mode, thereby restricting the short-circuit currents.

The basic conceptual TCSC module comprises a series capacitor, C, in parallel with a thyristor-controlled reactor, L



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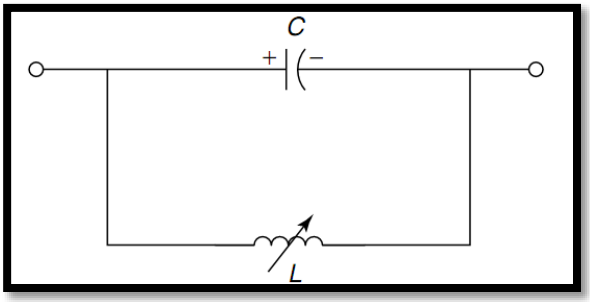
BASIC PRINCIPLE:

A TCSC is a series-controlled capacitive reactance that can provide continuous control of power on the ac line over a wide range. From the system viewpoint, the principle of variable-series compensation is simply to increase the fundamental-frequency voltage across an fixed capacitor (FC) in a series compensated line through appropriate variation of the firing angle, α. This enhanced voltage changes the effective value of the series-capacitive reactance.



The impedance of the LC network is given by

$$Z_{eq} = \frac{X_C\, X_L}{X_C + X_L}$$

If ωL > 1/ωC, the the reactance of the FC is less than that of the parallel-connected variable reactor and that this combination provides a variable-capacitive reactance are both implied. Moreover, this inductor increases the equivalent-capacitive reactance of the LC combination above that of the FC.

If ωC - 1/ωL = 0 a resonance develops that results in an infinite-capacitive impedance an obviously unacceptable condition.

If, however, ωL < 1/ωC, the LC combination provides inductance above the value of the fixed inductor. This situation corresponds to the inductive-vernier mode of the TCSC operation.

In the variable-capacitance mode of the TCSC, as the inductive reactance of the variable inductor is increased, the equivalent-capacitive reactance is gradually decreased. The minimum equivalent-capacitive reactance is obtained for extremely large inductive reactance or when the variable inductor is open-circuited, in which the value is equal to the reactance of the FC itself. The behavior of the TCSC is similar to that of the parallel LC combination.

The difference is that the LC-combination analysis is based on the presence of pure sinusoidal voltage and current in the circuit, whereas in the TCSC, because of the voltage and current in the FC and thyristor-controlled reactor (TCR) are not sinusoidal because of thyristor switchings.

MODES OF TCSC OPERATION:

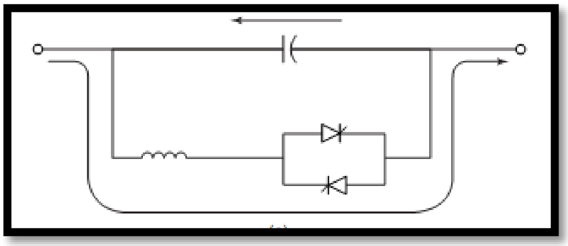
- **BYPASSED-THYRISTOR MODE**
- **BLOCKED-THYRISTOR MODE**
- **PARTIALLY CONDUCTING THYRISTOR, OR VERNIER, MODE**

BYPASSED-THYRISTOR MODE:

In this bypassed mode, the thyristors are made to fully conduct with a conduction angle of 180^0. Gate pulses are applied as soon as the voltage across the thyristors reaches zero and becomes positive, resulting in a continuous sinusoidal of flow current through the thyristor valves.

The TCSC module behaves like a parallel capacitor–inductor combination. However, the net current through the module is inductive, for the susceptance of the reactor is chosen to be greater than that of the capacitor. Also known as the thyristor-switched-reactor (TSR) mode, the bypassed thyristor mode is distinct from the bypassed-breaker mode, in which the circuit breaker provided across the series capacitor is closed to remove the capacitor or the TCSC module in the event of TCSC faults or transient over voltages across the TCSC.

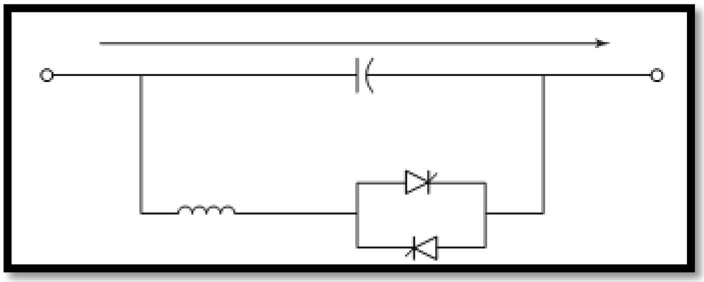
This mode is employed for control purposes and also for initiating certain protective functions. Whenever a TCSC module is bypassed from the violation of the current limit, a finite-time delay, T_{Delay} , must elapse before the module can be reinserted after the line current falls below the specified limit.



BLOCKED-THYRISTOR MODE:

In this mode, also known as the waiting mode, the firing pulses to the thyristor valves are blocked. If the thyristors are conducting and a blocking command is given, the thyristors turn off as soon as the current through them reaches a zero crossing.

The TCSC module is thus reduced to a fixed-series capacitor, and the net TCSC reactance is capacitive. In this mode, the dc-offset voltages of the capacitors are monitored and quickly discharged using a dc-offset control without causing any harm to the transmission-system transformers.



PARTIALLY CONDUCTING THYRISTOR, OR VERNIER, MODE:

This mode allows the TCSC to behave either as a continuously controllable capacitive reactance or as a continuously controllable inductive reactance. It is achieved by varying the thyristor-pair firing angle in an appropriate range.

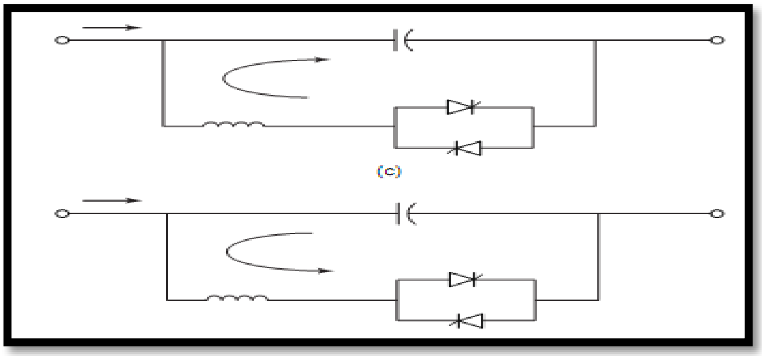
However, a smooth transition from the capacitive to inductive mode is not permitted because of the resonant region between the two modes.

A variant of this mode is the capacitive-vernier-control mode, in which the thyristors are fired when the capacitor voltage and capacitor current have opposite polarity

This condition causes a TCR current that has a direction opposite that of the capacitor current, thereby resulting in a loop-current flow in the TCSC controller. The loop current increases the voltage across the FC, effectively enhancing the equivalent-capacitive reactance and the series-compensation level for the same value of line current.

To preclude resonance, the firing angle α of the forward-facing thyristor, as measured from the positive reaching a zero crossing of the capacitor voltage, is constrained in the range of $\alpha_{min} \le \alpha \le \alpha_{max}$. This constraint provides a continuous vernier control of the TCSC module reactance. The loop current increases as α is decreased from 180^0 to α_{min}. . The maximum TCSC reactance permissible with $\alpha = \alpha_{min}$. is typically two-and-a-half to three times the capacitor reactance at fundamental frequency.

Another variant is the inductive-vernier mode, in which the TCSC can be operated by having a high level of thyristor conduction. In this mode, the direction of the circulating current is reversed and the controller presents a net inductive impedance

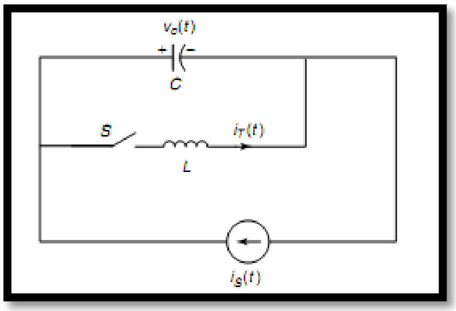


Based on the three modes of thyristor-valve operation, two variants of the TCSC emerge:

- Thyristor-switched series capacitor (TSSC), which permits a discrete control of the capacitive reactance.
- Thyristor-controlled series capacitor (TCSC), which offers a continuous control of capacitive or inductive reactance. (The TSSC, however, is more commonly employed.)

ANALYSIS OF THE TCSC:

The analysis of TCSC operation in the vernier-control mode is performed based on the simplified TCSC circuit. Transmission-line current is assumed to be the independent-input variable and is modeled as an external current source, $i_S(t)$. It is further assumed that the line current is sinusoidal, as derived from actual measurements demonstrating that very few harmonics exist in the line current. However, the analysis presented in the following text may be erroneous to the extent that the line current deviates from a purely sinusoidal nature.



The current through the fixed-series capacitor, C, is expressed as

$$C\frac{dV_C}{dt} = i_S(t) - i_T(t).u$$

The switching variable u = 1 when the thyristor valves are conducting, that is, when the switch S is closed. On the other hand, u = 0 when the thyristors are blocked, that is, when switch S is open.

The thyristor-valve current, $i_T(t)$, is then described by

$$L\frac{di_T}{dt} = V_C.u$$

Let the line current, $i_S(t)$, be represented by

$$i_S(t) = I_m \cos \omega t$$

Equations above can be solved with the knowledge of the instants of switching. In equidistant firing-pulse control, for balanced TCSC operation, the thyristors are switched on twice in each cycle of line current at instants t_1 and t_3, given by

$$t_1 = -\frac{\beta}{\omega} \text{ and } t_3 = \frac{(\pi - \beta)}{\omega}$$

where β is the angle of advance (before the forward voltage becomes zero). Or

$$\beta = \pi - \alpha \qquad 0 \le \beta \le \beta_{max}$$

The firing angle α is generated using a reference signal that can be in phase with the capacitor voltage. The thyristor switch S turns off at the instants t_2 and t_4 , defined as

$$t_2 = t_1 + \frac{\sigma}{\omega} \text{ and } t_4 = t_3 + \frac{\sigma}{\omega}$$

where σ is the conduction angle, which is assumed to be the same in both the positive and the negative cycle of conduction. Also,

$$\sigma = 2\beta$$

Solving TCSC equations results in steady state thyristor currents

$$\mathrm{i_T(t)} = \frac{\mathrm{k}^2}{\mathrm{k}^2 - 2}\left\{\cos\omega\mathrm{t} - \frac{\cos\beta}{\cos\mathrm{k}\,\beta}\cos\omega_\mathrm{r}\,\mathrm{t}\right\}$$

Where

$$\omega_\mathrm{r} = \frac{1}{\sqrt{\mathrm{LC}}}$$

$$\mathrm{k} = \frac{\omega_\mathrm{r}}{\omega} = \sqrt{\frac{1}{\omega\mathrm{L}}\frac{1}{\omega\mathrm{C}}} = \sqrt{\frac{\mathrm{X_C}}{\mathrm{X_L}}}$$

and X_C is the nominal reactance of the FC only.
The steady-state capacitor voltage at the instant ωt = -β

$$\mathrm{V_{C1}} = \mathrm{Im}\,\frac{\mathrm{X_C}}{\mathrm{k}^2 - 1}\,(\sin\beta - \mathrm{k}\cos\beta\,\mathrm{tank}\beta)$$

At ωt = β, $i_T = 0$, and the capacitor voltage is given by

$$\mathrm{v_c}\,(\omega\mathrm{t} = \beta) = \mathrm{v_{c2}} = -\mathrm{v_{c1}}$$

The capacitor voltage is finally obtained as

$$\mathrm{V_C(t)} = \mathrm{Im}\,\frac{\mathrm{X_C}}{\mathrm{k}^2 - 1}\left(-\sin\omega\mathrm{t} + \mathrm{k}\frac{\cos\beta}{\cos\mathrm{k}\beta}\sin\omega_\mathrm{r}\,\mathrm{t}\right)$$

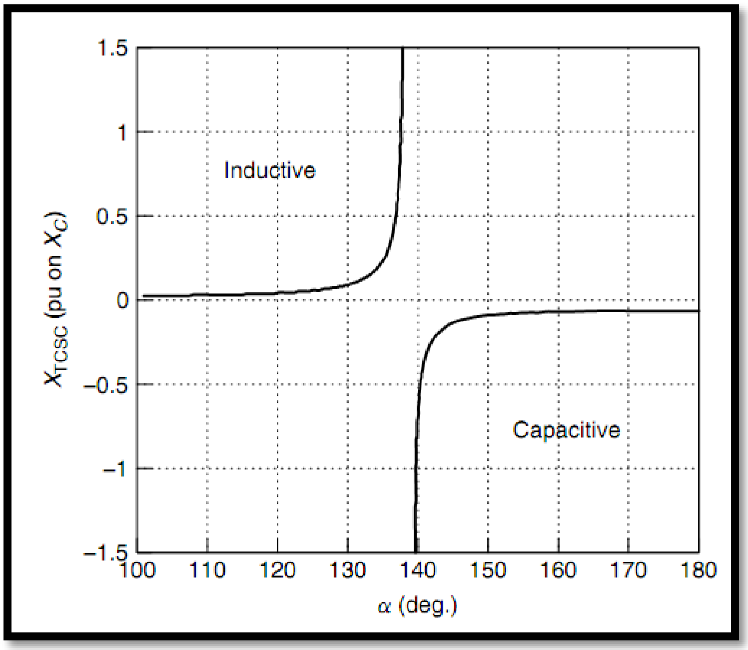
$$\mathrm{V_C(t)} = \mathrm{V_{C2}} + \mathrm{Im}\,\mathrm{X_C}\,(\sin\omega\mathrm{t} - \sin\beta)$$

Because the non sinusoidal capacitor voltage, v_c , has odd symmetry about the axis ωt = 0, the fundamental component, V_{CF} is obtained as

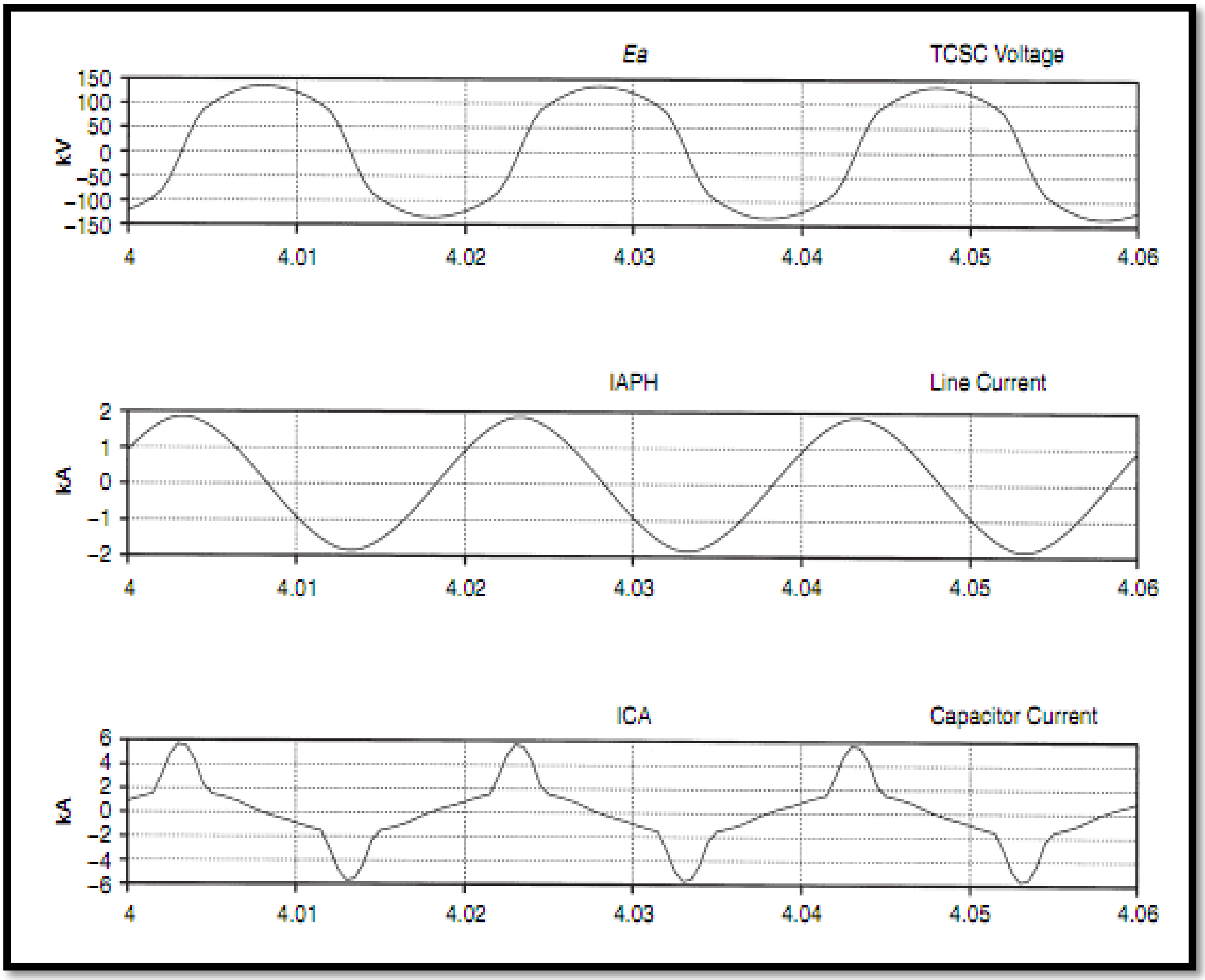
$$V_{CF} = \frac{4}{\pi}\int_0^{\pi/2} V_C(t)\sin\omega t\, d(\omega t)$$

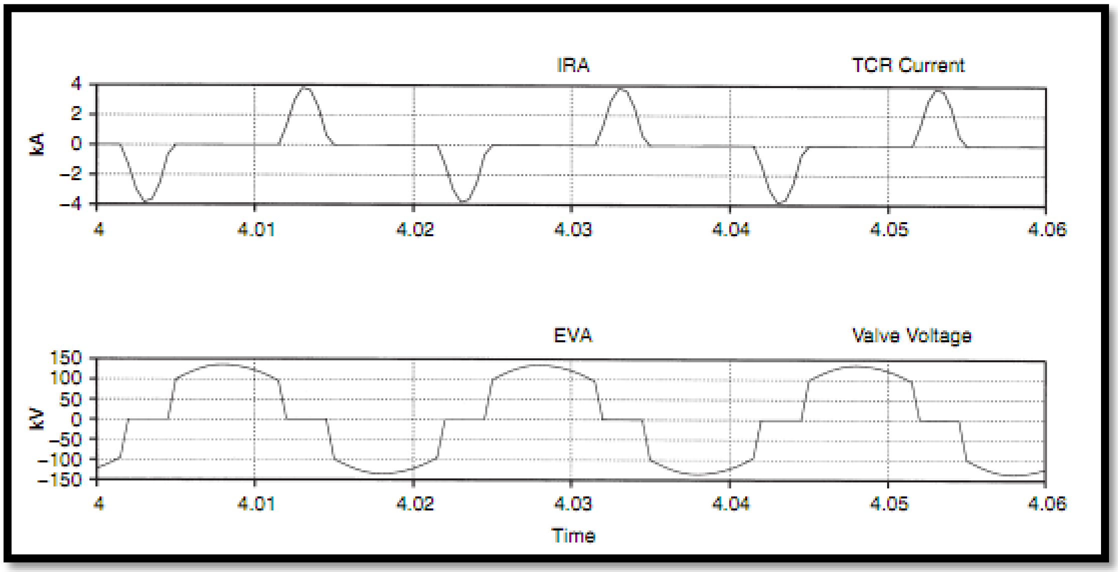
$$X_{TCSC} = \frac{V_{CF}}{I_m}$$

$$X_{TCSC} = \frac{V_{CF}}{I_m} = X_C - \frac{{X_C}^2}{(X_C - X_L)}\frac{2\beta + sin2\beta}{\pi} + \frac{4{X_C}^2}{(X_C - X_L)}\frac{cos^2\beta}{k^2 - 1}\frac{k\tan k\beta - \tan\beta}{\pi}$$

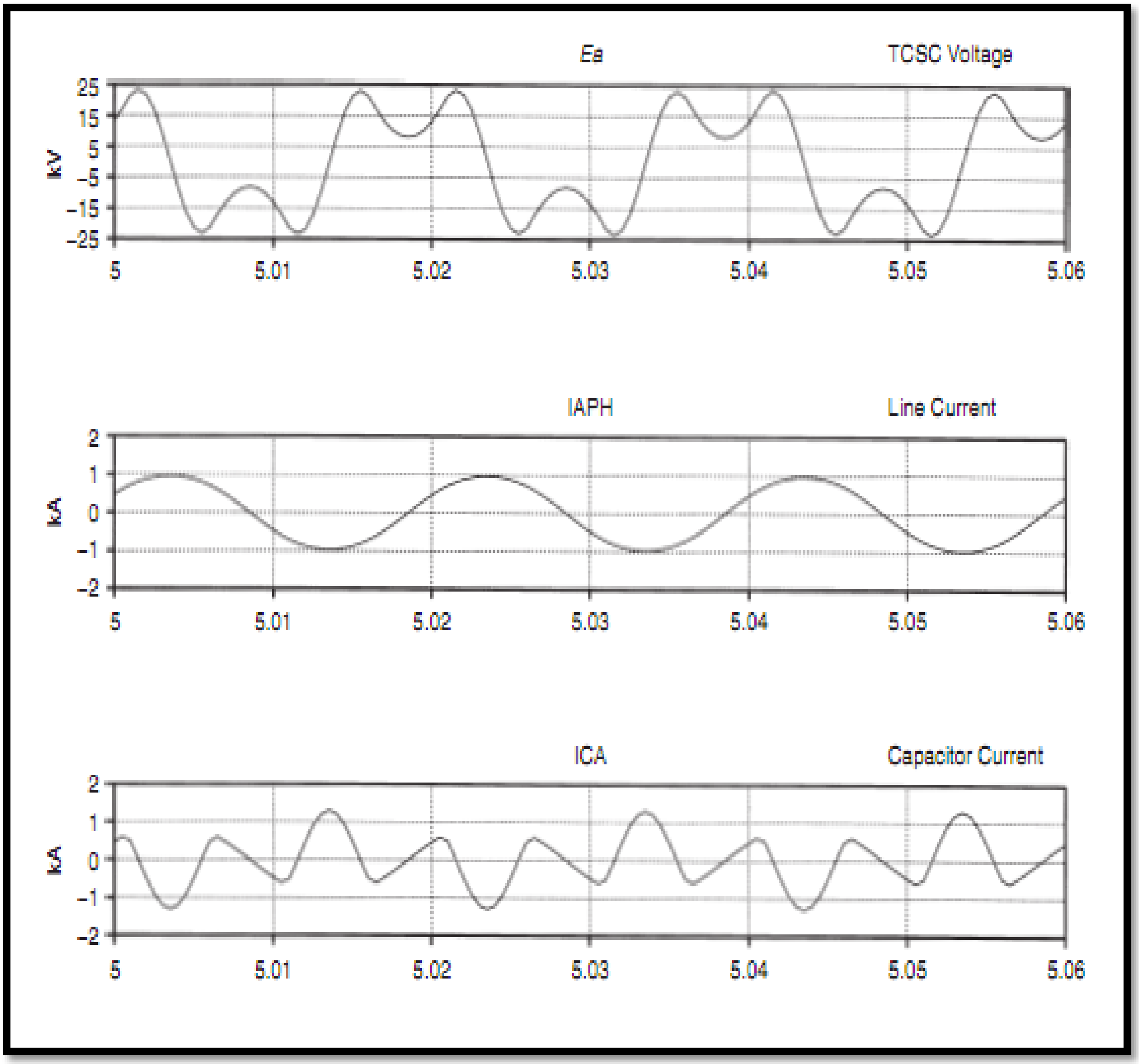


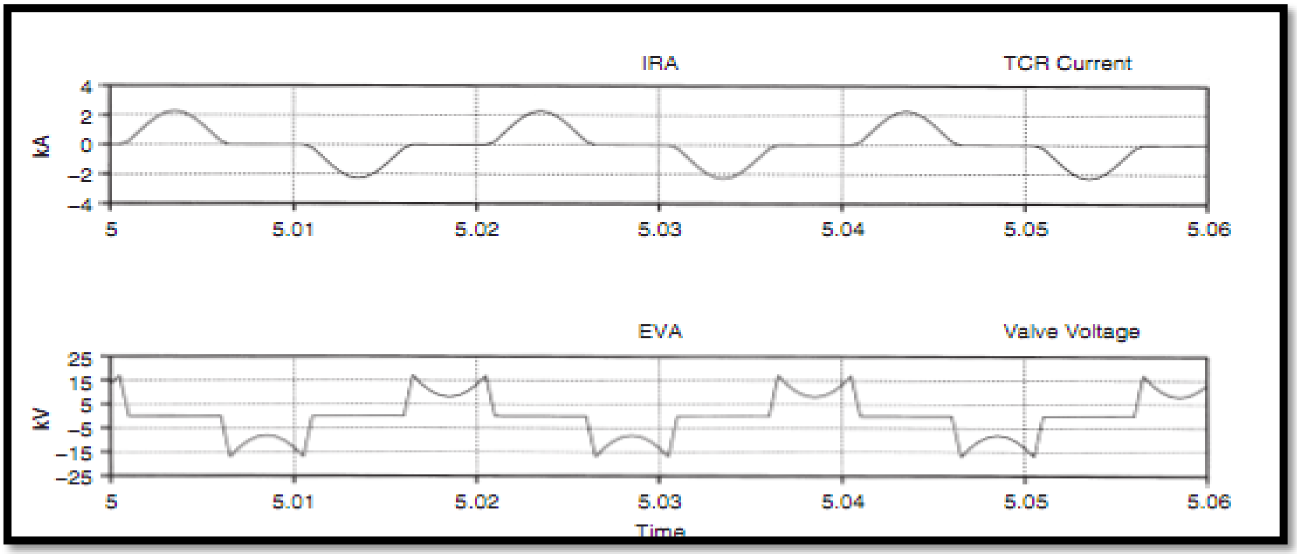
CAPACITIVE MODE FOR α = 150^0





INDUCTIVE MODE FOR $\alpha = 130^0$





BASIC OPERATING CONTROL SCHEMES FOR GCSC, TSSC, AND TCSC:

The function of the operating or "internal" control of the variable impedance type compensators is to provide appropriate gate drive for the thyristor valve to produce the compensating voltage or impedance defined by a reference.

The internal control operates the power circuit of the series compensator, enabling it to function in a self-sufficient manner as a variable reactive impedance. Thus, the power circuit of the series compensator together with the internal control can be viewed as a "black box" impedance amplifier, the output of which can be varied from the input with a low power reference signal.

The reference to the internal control is provided by the "external" or system control, whose function it is to operate the controllable reactive impedance so as to accomplish specified compensation objectives of the transmission line. Thus the external control receives a line impedance, current, power, or angle reference and, within measured system variables, derives the operating reference for the internal control.

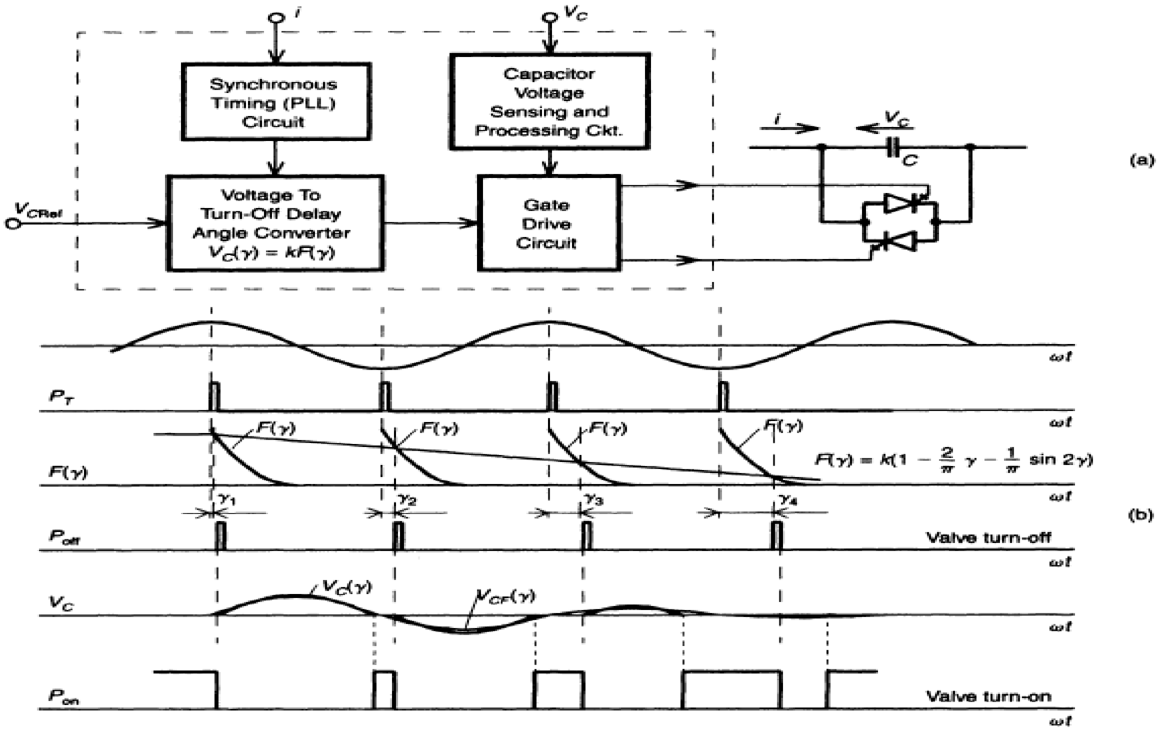
Structurally the internal controls for the three variable impedance type compensators (GCSC, TCSC, TSSC) could be similar. Succinctly, their function is simply to define the conduction and/or the blocking intervals of the valve in relation to the fundamental (power frequency) component of the line current.

This requires the execution of three basic functions:

- synchronization to the line current,
- turn-on or turn-off delay angle computation, and
- gate (firing) signal generation.

These functions obviously can be implemented by different circuit approaches, with differing advantages and disadvantages. In the following, three possible internal control schemes are functionally discussed: one for the GCSC, and the other two for the TCSC power circuit arrangements. Either of the TCSC schemes could be adapted for the TSSC if subsynchronous resonance would be an application concern.

INTERNAL CONTROL SCHEME FOR THE GCSC:



- The first function is synchronous timing, provided by a phase-locked loop circuit that runs in synchronism with the line current.
- The second function is the reactive voltage or impedance to tum-off delay angle conversion according to the relationship respectively.
- The third function is the determination of the instant of valve turn-on when the capacitor voltage becomes zero. (This function may also include the maintenance of a minimum on time at voltage zero crossings to ensure immunity to subsynchronous resonance.)
- The fourth function is the generation of suitable turn-off and turn-on pulses for the GTO valve.

The basic GCSC (power circuit plus internal control) can be considered as a controllable series capacitor which, in response to the transmission line current, will reproduce (within a given frequency band and specified rating) the compensating impedance (or voltage) defined by the reference input.

The dynamic performance of the GCSC is similar to that of the TCR, both having a maximum transport lag of one half of a cycle.

INTERNAL CONTROL SCHEME FOR THE TCSC:

The main consideration for the structure of the internal control operating the power circuit of the TCSC is to ensure immunity to subsynchronous resonance. Present approaches follow two basic control philosophies. One is to operate the basic phase locked-loop (PLL) from the fundamental component of the line current.

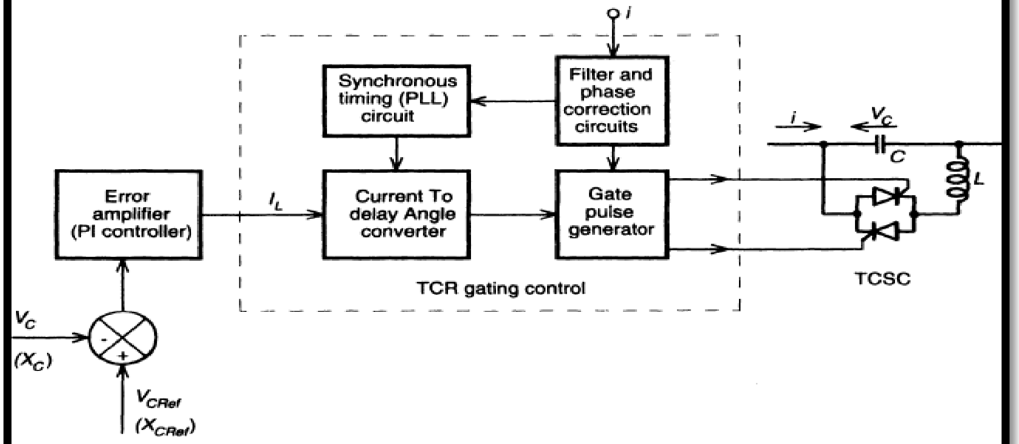


Figure 6.27 A functional internal control scheme for the TCSC based on the synchronization to the fundamental component of the line current.

In order to achieve this, it is necessary to provide substantial filtering to remove the super- and, in particular, the subsynchronous components from the line current and, at the same time, maintain correct phase relationship for proper synchronization. A possible internal control scheme of this type is shown.

In this arrangement the conventional technique of converting the demanded TCR current into the corresponding delay angle, which is measured from the peak (or, with a fixed 90 degree shift, from the zero crossing) of the fundamental line current, is used.

The reference for the demanded TCR current is;, usually provided by a regulation loop of the external control, which compares the actual capacitive Impedance or compensating voltage to the reference given for the desired system operation.

The second approach also employs a PLL, synchronized to the line current, for the generation of the basic timing reference. However, in this method the actual zero crossing of the capacitor voltage is estimated from the prevailing capacitor voltage and line current by an angle correction circuit.

The delay angle is then determined from the desired angle and the estimated correction angle so as to make the TCR conduction symmetrical with respect to the expected zero crossing.

The desired delay angle in this scheme can be adjusted by a closed-loop controlled phase shift of the basic time reference provided by the PLL circuit. The delay angle of the TCR, and thus the compensating capacitive voltage, as in the previous case, is controlled overall by a regulation loop of the external control in order to meet system operating requirements. This regulation loop is relatively slow, with a bandwidth just sufficient to meet compensation requirements (power flow adjustment, power oscillation damping, etc.). Thus, from the stand point of the angle correction circuit, which by comparison is very fast (correction takes place in each half cycle), the output of the phase shifter is almost a steady state reference.

Although control circuit performances are usually heavily dependent on the actual implementation, the second approach is theoretically more likely to provide faster response for those applications requiring such response.

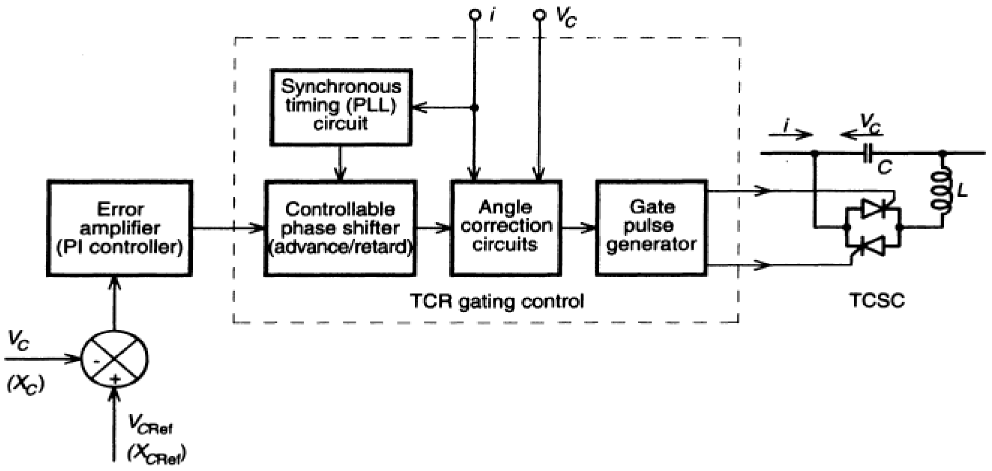


Figure 6.28 A functional internal control scheme for the TCSC based on the prediction of the capacitor voltage zero crossings.