EQUIPMENT USED

•DSTATCOM technology is now a mature technology for providing the reactive power compensation, load balancing, and/or neutral current and the harmonic current suppressions in the AC main networks.

•DSTATCOM is also used to regulate the terminal voltage, suppressed voltage flickers and improve the voltage unbalance for the three-phase system, this is the one of the utility.

•Classical technology of using power capacitors and the static VAR compensator using TCR, TSCs has been used to mitigate some of this problems.

•The DSTATCOM technology is considered the best technology to mitigate this current-based power quality problem and thus it is being used frequently in FACTS devices

OBJECTIVES

•Distributed Static Compensator (DSTATCOM) is connected to minimize the Total Harmonics Distortion (THD) and Error Voltage.

•DSTATCOM is used along with inverter for improvement in the power quality of grid connected inverter.

•The purpose of the DSTATCOM is to cancel load harmonics fed to the supply.

•In order to compensate undesirable components of the load current DSTATCOM injects currents into the point of common coupling.

•D-STATCOM has been modeled to provide current compensation with active and dynamic type nonlinear load and D-STATCOM as load compensator is used for power factor improvement.

BASIC STRUCTURE

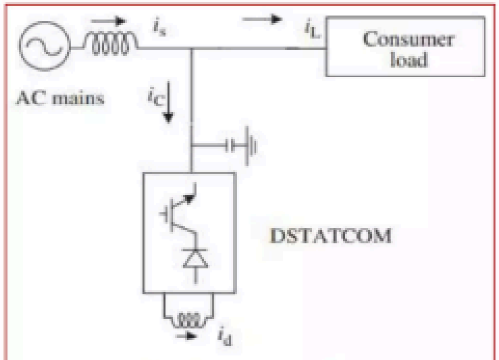


Figure 4.1 A CSC-based DSTATCOM

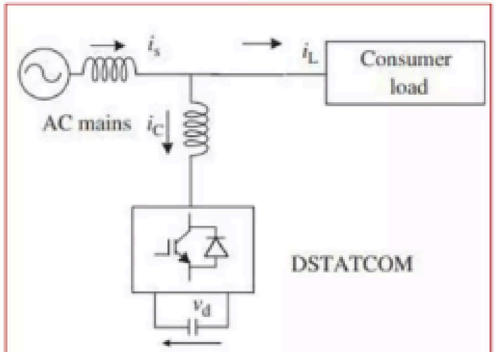


Figure 4.2 A VSC-based DSTATCOM

Explaination of VSC Based DSATCOM :

- DSTATCOM is a controlled reactive source which includes a voltage source converter and a DC link capacitor connected in shunt.
- Capable of generating or absorbing reactive power.
- AC terminals of VSC are connected to the PCC through an inductance which could be a filter inductance or leakage inductance of the coupling transformer.
- DC side of the converter is connected to the capacitor which is reactive energy storage element.
- Capacitor is charged by battery source or recharged by converter itself.
- It is more widely used because it is light, cheap, and expandable to multilevel and multistep versions, to enhance the performance with lower switching frequencies.

CLASSIFICATION

1. *Converter based (Discuss in previous slide)*
   a. CSC based DSTATCOM
   b. VSC based DSTATCOM
2. *Topology based* (DSTATCOMs can also be classified based on the topology, for example, VSCs without transformers, VSCs with non-isolated transformers, and VSCs with isolated transformers)
3. *Supply System based* (This classification of DSTATCOMs is based on the supply and/or the load system, for example, singlephase two-wire, three-phase three-wire, and three-phase four-wire systems)

TOPOLOGY BASED

1. *Three-phase three VSI topology*
2. *Compensator structure which uses a three phase 4 leg VSI*
3. *H-bridge VSI topology with isolation transformer*
4. *Three-Pole Voltage Source Converter with T-Connected Transformer Based DSTATCOM*
5. *NEUTRAL CLAMPED VSI TOPOLOGY*

Operational Principal of DSTATCOM

The DSTATCOM is a shunt connected custom power device connected across the load end of a distribution network. A capacitor, three phase inverter module, AC filter, coupling transformer and a controller are the basic components of it. The voltage source converter (VSI) helps to convert the input DC voltage to an output of three phase of AC voltage with constant frequency. The phase of the thyristor based inverter voltage (Vi) is maintained at a controlling level of distribution system voltage (Vs).

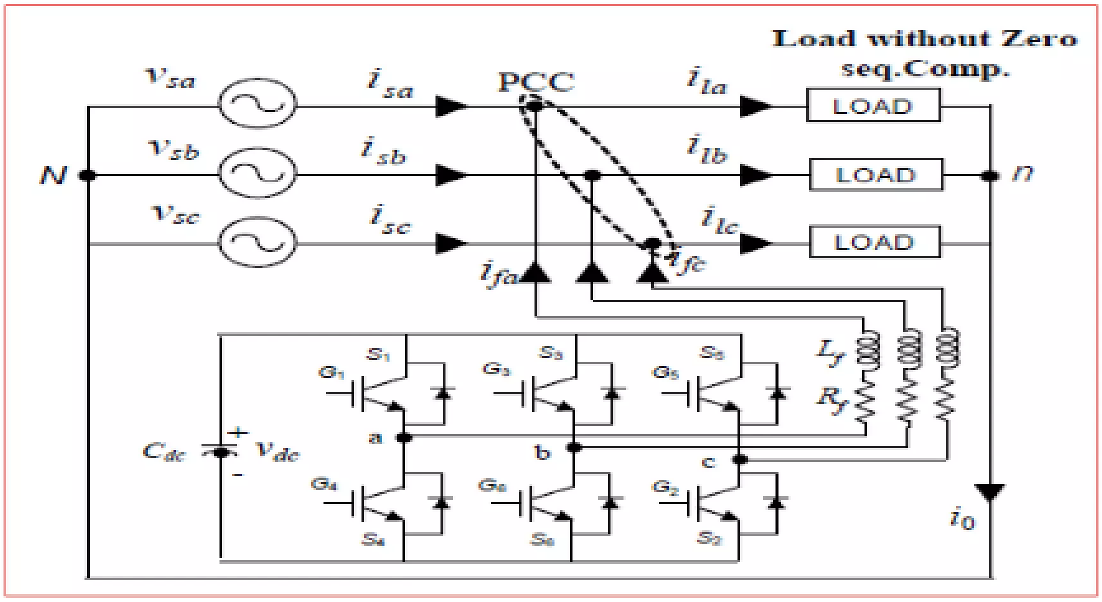
The three basic modes of operation of a D-STATCOM are as follows:

i. When **Vi = Vs**, the reactive power become zero, it indicates that D-STATCOM neither generates nor absorbs any reactive power.

ii. When **Vi > Vs**, it indicates an inductive reactance connected across the terminal of DSTATCOM. It represents inductive mode of operation. The current flows from a DSTATCOM to the AC system through transformer reactance. At this stage, the DSTATCOM generates capacitive reactive power.

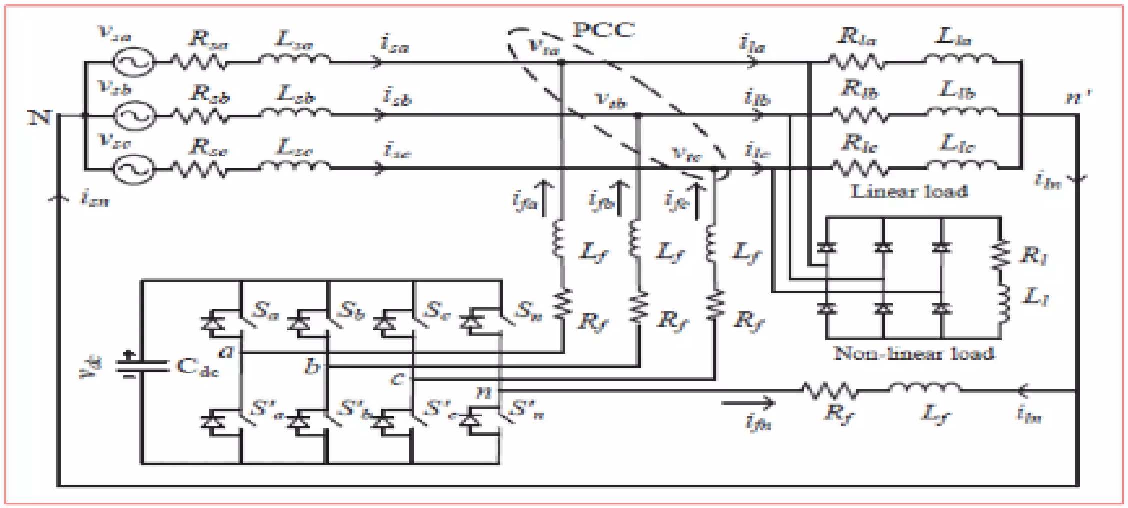
iii. When **Vi < Vs**, it indicates a capacitive reactance connected across it terminals. It represents capacitive mode of operation. The current flows from AC system to DSTATCOM. In this case it absorbs inductive reactive power. Thus, DSTATCOM can either absorb or deliver reactive power to the system.

1. Three-phase three VSI topology



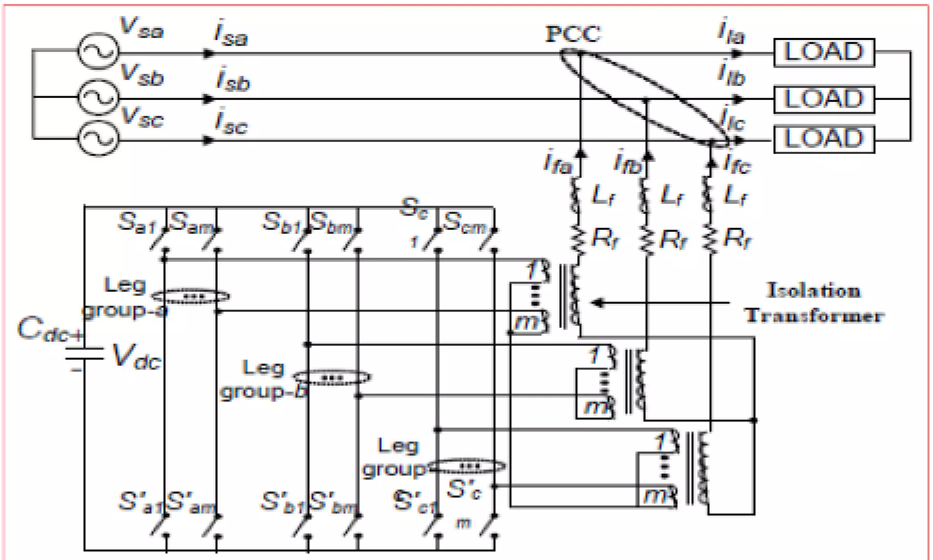
- Each VSI is connected to the power network at the PCC
- *isa, isb & isc* are the source current in phase a, b and c respectively
- *ifa, ifb & ifc* are the reference comparator currents
- If this topology is used, the zero-sequence current in the load cannot be compensated, and it flows in the neutral wire between the system and load.
- The zero-sequence current thus returns to the ac distribution system.
- If load is nonlinear, then the harmonics enter into the ac system, thus degrading the power quality. In this topology, the generations of the three compensator currents are not independent.
- Hence, this scheme is not suitable for a three-phase four-wire distribution system with loads containing zero-sequence currents.

2. Compensator structure which uses a three phase 4 leg VSI



- Three-phase four-leg VSI topology is suitable for the elimination of dc as well as zero-sequence components from the source currents.
- Three of its legs are connected to three phases, and the fourth leg is connected to the neutral through an interface reactor.
- The fourth leg used for compensation of zero - sequence currents and triplen harmonics present in the load
- Reference current for the fourth leg is the negative sum of the three-phase load currents.
- This nullifies the effect of dc components in the load currents
- When a compensator is working, the zero-sequence current containing switching frequency components are routed between the load and compensator neutral.

3. H-bridge VSI topology with isolation transformer



- Each VSI is connected to the power network at the PCC through a transformer
- The purpose of isolation transformer is to provide isolation between the inverter legs and to prevent the dc storage capacitor from being shorted by switches in different inverter legs.
- Due to the presence of isolation transformers, this topology, however, is not suitable for compensation of the load currents containing dc components.
- The dc current will saturate the transformers causing heating and increased losses thereby reducing the life of transformers.

Advantages-

- Three H-bridge based DSTATCOM is able to eliminate the harmonics form source current and makes it sinusoidal, balances the phases and reactive power compensation.

4. Three-Pole Voltage Source Converter with T-Connected Transformer Based DSTATCOM

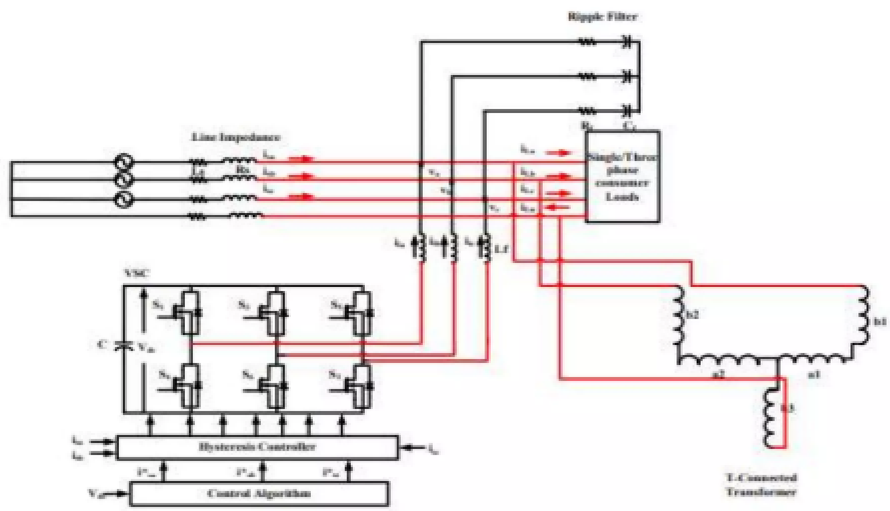


Fig. 3 Three-pole voltage source converter with T-connected transformer based DSTATCOM.

•Fig.3 represents the three-pole voltage source converter with T-connected transformer-based DSTATCOM.

•T-connected transformer is used for neutral current compensation by providing a path for current in the neutral wire and reduces the rating of voltage source converter.

• Three-phase fourwire (3P4W) VSC is interfaced through the compensating impedances in parallel to the load.

• Tconnected transformer is constructed using two single phase isolated transformer connected in T-shape.

• Three pole VSC is configured by 6-IGBT switches and an anti-parallel diode.

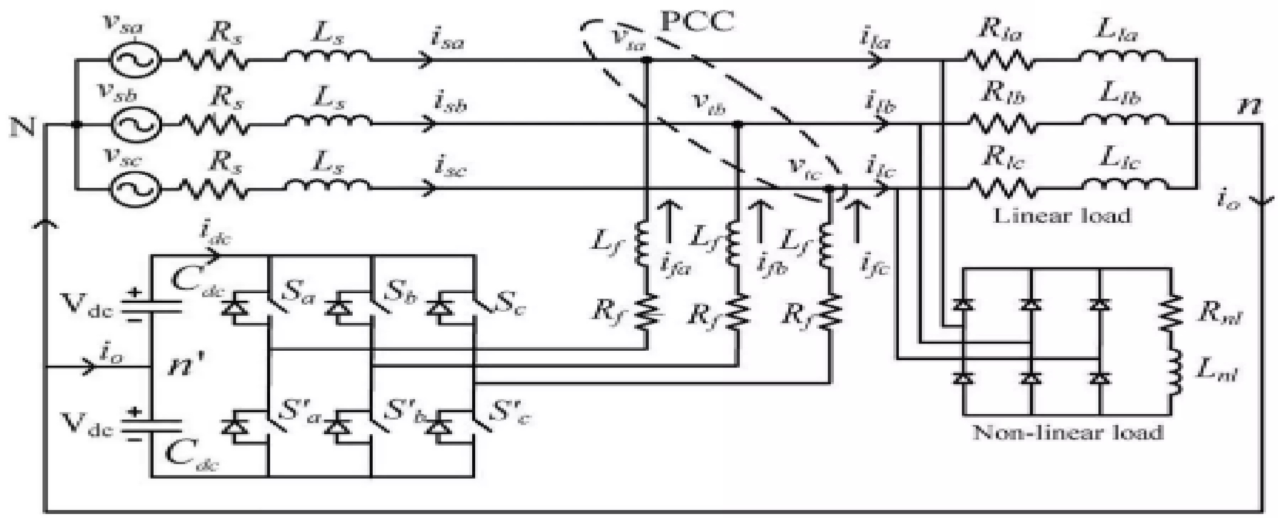
Advantages-

•Perfor-mance of DSTATCOM it is seen that three-pole voltage source converter with a T-connected transformer is able to eliminate the harmonics from the source current, reactive power compensation and balance the phases.

•The T-connected transformer is designed for integrating the DSTATCOM by its secondary winding.

• The transformer also reduces the rating of the switch as we can see from the figure that there is no increment of THD even it uses less number of the switches.

5. NEUTRAL CLAMPED VSI TOPOLOGY



•This topology requires two dc storage devices.
•Each leg of the VSI can be controlled independently.
•Tracking is smooth with less number of switches when compared to other VSI topologies.
•vsa , vsb , and vsc are source voltages of phases a, b, and c respectively.
•Similarly vta , vtb , and vtc are the terminal voltages at the PCC.
•The source currents in three phases are represented by isa , isb , and isc and load currents are represented by ila , ilb , and ilc .
•The shunt active filter currents are denoted by ifa, ifb, if c, and io represents the current in the neutral leg.
•Ls and Rs represent the feeder inductance and resistance, respectively.
•The interfacing inductance and resistance are represented by Lf and Rf respectively.
•The dc-link capacitors and voltages across them are represented by Cdc1 = Cdc2 = Cdc and Vdc1 = Vdc2 = Vdc , respectively.
•The current through the dc link is represented by the idc.

Advantages-
•Requires single dc source.
•Does not require auxiliary capacitors .

Disadvantages-
•Unequal power distribution among switches
•Balancing problems while delivering real power above 3-levels .
•Requires a large number of diodes which is a quadratic function of the number of levels.
•The diodes reverse recovery time can become problematic for high switching frequencies

KEY POINTS

•Distribution Static Compensator is an important device in correcting power factor, maintaining constant distribution voltage, and mitigating harmonics in a distribution network.
•In power distribution networks, reactive power is the main cause of increasing distribution system losses and various power quality problems.
•Conventionally, Static Var Compensators (SVCs) have been used in conjunction with passive filters at the distribution level for reactive power compensation and mitigation of power quality problems
•Thus, a controller which continuously monitors the load voltages and currents to determine the right amount of compensation required by the system and the less response time should be a viable alternative.
•Distribution Static Compensator (DSTATCOM) has the capacity to overcome by providing precise control and fast response during transient and steady state.
•At the transmission level, STATCOM handles only fundamental reactive power and provides voltage support, while a DSTATCOM is employed at the distribution level or at the load end for dynamic compensation.
•Additionally, a DSTATCOM can also behave as a shunt active filter to eliminate unbalance or distortions in the source current or the supply voltage.
•Since a DSTATCOM is such a multifunctional device, the main objective of any control algorithm should be to make it flexible and easy to implement, in addition to exploiting its multi functionality to the maximum

Control Strategies for Distribution Static Compensator for Power Quality Improvement.

CONTROL STRATEGIES

Satisfactory performance, fast response, flexible and easy implementation are the main objectives of any compensation strategy. The control strategies of a DSTATCOM are mainly implemented in the following steps:

1. Measurements of system variables and signal Conditioning.
2. Extraction of reference compensating signals.
3. Generation of firing angles for switching devices.

•The generation of proper pulse width modulation (PWM) firing is the most important part of DSTATCOM control and it has a great impact on its compensation objectives, transient as well as steady state performance.
•Since a DSTATCOM shares many concepts with that of a STATCOM at the transmission level, a few control techniques have been directly implemented to a DSTATCOM, incorporating PWM switching, rather than fundamental frequency switching (FFS) methods

A DSTATCOM for power factor correction and harmonic mitigation is based on:

1. *Phase shift control*

2. *Indirect decoupled current control*

3. *Regulation of AC bus and DC link voltage*

The performance of DSTATCOM with different control schemes have been studied through digital simulations for common system parameters.

1. Phase Shift Control

• In this method, the compensation is achieved by the measuring of the rms voltage at the load point, whereas no reactive power measurements are required. Sinusoidal PWM technique is used with constant switching frequency.

•The error signal obtained by comparing the measured system rms voltage and the reference voltage is fed to a proportional integral (PI) controller, which generates the angle for deciding the necessary phase shift between the output voltage of the VSC and the AC terminal voltage.

•This angle is summed with the phase angle of the balanced supply voltages, assumed to be equally spaced at 120 degrees, to produce the desired synchronizing signal required to operate the PWM generator. In this scheme, the DC voltage is maintained constant, using a separate battery source.

Disadvantages

Though this strategy is easy to implement, is robust and can provide partial reactive power compensation without harmonic suppression, it has the following major disadvantages:

1.The controller does not use a self supporting DC bus and thus requires a very large DC source to pre charge the capacitor.

2.Balanced source supply as rms voltage is assumed and the supply phase angle are calculated over the fundamental only.

3. No harmonic suppression and partial compensation is achieved in case of nonlinear loads.

2. Indirect Decoupled Current Control

1.This scheme is based on the governing equations of advanced static var compensator.It requires the measurement of instantaneous values of three phase line voltages and current.

2.The control scheme is based on the transformation of the three phase system to a synchronously rotating frame, using Park's transformation.

3. Subsequently, when the d axis is made to lie on the space vector of the system voltage, its quadrature component (vq) becomes zero.

4. The compensation is achieved by the control of id and iq .This is an indirect current control method, where current error compensation is achieved indirectly through voltage modulation, in order to incorporate simple open loop sine PWM modulators, so that fixed switching frequency is achieved.

5.Using the definition of the instantaneous reactive power theory for a balanced three phase three wire system, the real (p) and the reactive power (q) injected into the system by the DSTATCOM can be expressed under the dqO reference frame as

•p = vdid + vqiq

•vqid – vdiq = q

•since vq = 0, id and iq completely describe the instantaneous value of real and reactive powers produced by the DSTATCOM, when the system voltage remains constant.

Disadvantages

The disadvantages of this scheme are:
1.Phase Locked Loop gives erroneous results in case of distorted mains and is applicable for only three phase systems.
2. It requires intensive computation, including complex transformations, making the operation complex.
3. Harmonic suppression is significantly achieved, but not below the IEEE-519 standards.
4. Bandwidth is restricted due to the use of sine PWM generator.
5.During transient condition, the supply current shoots to a very high value.

2. Regulation of AC Bus and DC Link Voltage

•Three phase AC supply voltages and DC link voltage are sensed and fed to two PI controllers, the outputs of which decide the amplitude of reactive and active current to be generated by the DSTATCOM.
•Next figure shows the block diagram of the implemented scheme.
•Multiplication of these amplitudes with the in phase and quadrature voltage unit vectors yields the respective component of the reference currents.

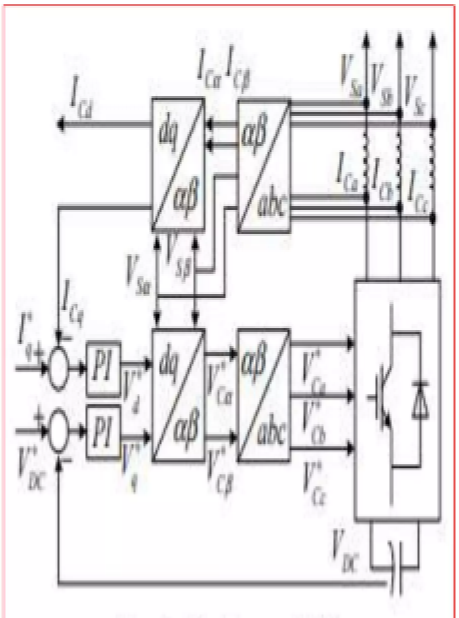


Figure 5. Block diagram of VOC

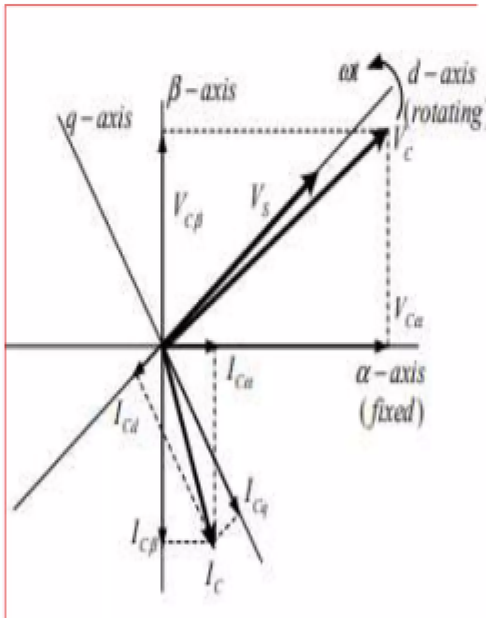


Figure 4. Vector diagram of VOC

Advantages

The advantages of this scheme are:

1.The derivation of switching signals uses a hysteresis controller, which is robust and simple, with fast dynamic response and automatic current limiting capability.

2.The algorithm is flexible and can be easily modified for improved voltage regulation, harmonic suppression and load balancing.

3. The inherent property to provide self supporting dc bus does not require complex abc_dqO transformations.

4. The THD in case of nonlinear loads is well below the IEEE-519 standard limits.

Advantages of DSTATCOM

1.) DSTATCOM is used in voltage regulation in distribution line.

2.) It is also used to improve power factor as unity.

3.) It is also used to mitigate harmonics in distribution system.

4.) DSTATCOM can be also used for load balancing.

Disadvantages of DSTATCOM

1.) The consumption of reactive energy will be important.

2.) In transmission lines the voltage drop can be big but their distance would matter.

Application of DSTATCOM

Siemens has commissioned **400 kV Synchronous Compensator** (STATCOM) solutions at Power Grid Corporation of India's (PGCIL) substation in Rourkela, Odisha. The state-of-the-art STATCOM solution provides optimal grid stabilization technology. The project was designed, delivered and commissioned in 22 months. The STATCOM solution equipment was manufactured locally at Siemens Goa plant.

STATCOM, with a dynamic swing range of 600MVAr and 250MVAr mechanically switched components, regulates the transmission variations automatically according to the grid conditions, thus leading to availability of reliable and uninterrupted power to the consumers in the associated network.

This is the first STATCOM order commissioned by Siemens and is the latest chapter in the long and successful Flexible AC Transmission Systems (FACTS) journey in India. Siemens together with PGCIL, have always been trendsetters in India for FACTS. It started in 2003 when Siemens delivered several Fixed Series Capacitors (FSC), the first Thyristor Controlled Series Capacitor (TCSC) in India followed in 2004. The largest Indian Static Var Compensator (SVC) project has also been commissioned by Siemens in 2017.

STATIC SYNCHRONUS SERIES COMPENSATOR

Applications:

Power Flow Control
Series Compensation
Voltage Regulation of Long Transmission System
Economic Operation
Voltage Stability Enhancement
Harmonic SSR Torsional Mode Damping by Detuning Resonance Conditions

Applications:

The SSSC has been applied to different power system studies to improve the system performance.

A static synchronous Series Compensator operated without an external energy source as Reactive Power with output voltage.

SSSC controls the electric power flow by increasing or decreasing the overall reactive voltage drop across the transmission line.

The SSSC FACTS device can provide either capacitive or inductive injected voltage compensation.

If SSSC-AC injected voltage, (Vs), lags the line current IL by 90º, a capacitive series voltage compensation is obtained in the transmission line .

if leads IL by 90º, an inductive series compensation is achieved.

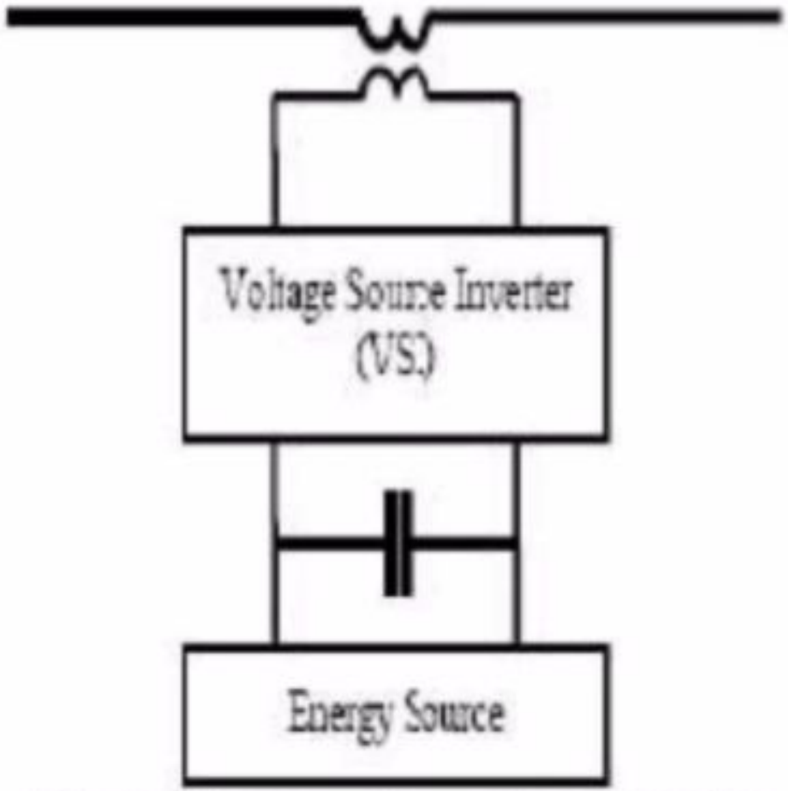
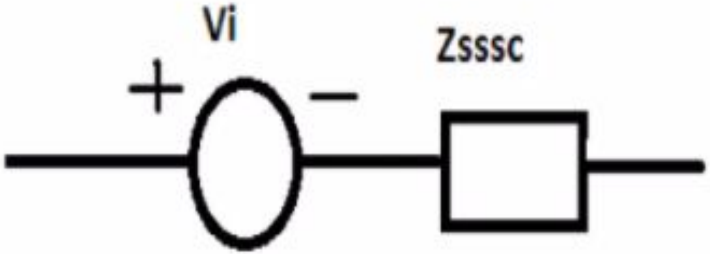
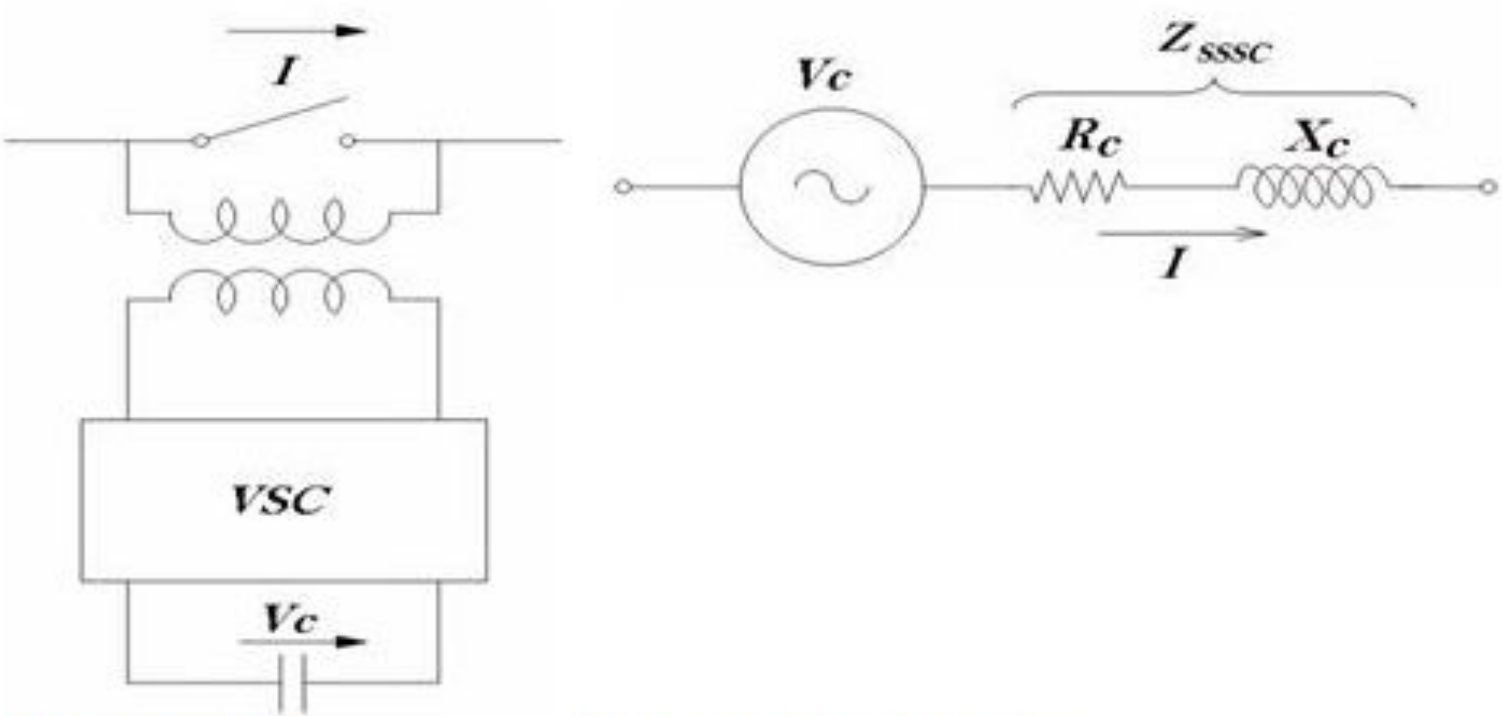


Fig. 1. Basic configuration of SSSC



Equivqlent circuit of sssc



(a) *Schematic* **(b)** *Equivalent circuit*

Figure 1. *Principal of SSSC*

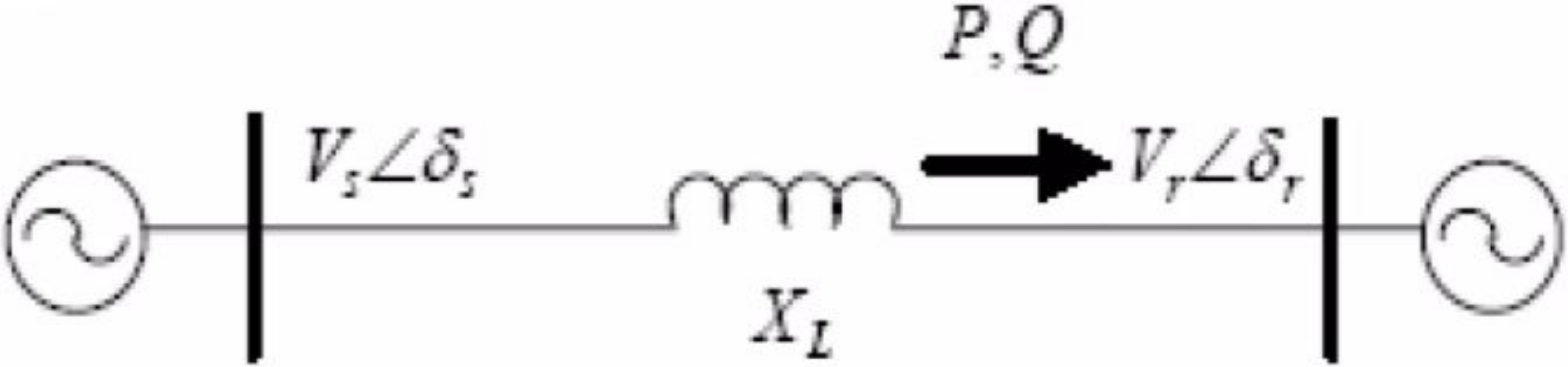
The Structure of SSSCs

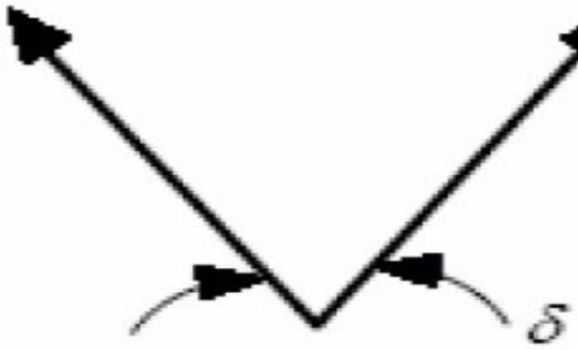
The key element of an SSSC is the power electronic converter, usually a DC-AC converter or inverter. The converter can be either a voltage source converter or a current source converter.

In commonly employed voltage source converter-based SSSCs, the converter is switched to supply a required voltage to the power system. The voltage from the converter is injected in series to the line using an injection transformer. Even though the SSSC is duly insulated from the ground, the injection transformer is a source of insulation for the power electronic converter in an SSSC. The transformer primary is rated at the maximum voltage that the converter can supply.

Usually, the transformer is a step-up transformer, and injects more voltage in series to the power system, thereby reducing the voltage rating of the converter and the DC energy source, if present. The transformer carries the full line current, including the fault current. If there is a short circuit current or line fault, the SSSC is disconnected from the power system to protect the converter.

Figure 1 shows a single line diagram of a simple Transmission line with an inductive transmission reactance, XL, connecting a sending-end (S.E.) voltage source, , and a receiving end (R.E.) voltage source, respectively.





$$P = \frac{V_S V_r}{X_L} \sin \delta$$

$$Q = \frac{V_S V_r}{X_L} (1 - \cos \delta)$$

$$P = \frac{V_s V_r}{X_L} \sin(\delta_s - \delta_r) = \frac{V^2}{X_L} \sin \delta \qquad \text{(i)}$$

$$Q = \frac{V_s V_r}{X_L} (1 - \cos(\delta_s - \delta_r)) = \frac{V^2}{X_L} (1 - \cos \delta) \qquad \text{(ii)}$$

$$\delta = \delta_S - \delta_r \qquad \text{(iii)}$$

$$V_S = V_r = V \qquad \text{(iv)}$$

expression of power flow given in eq.1 and eq. 2 become :

$$P_q = \frac{V^2}{Xeff}\sin\delta = \frac{V^2}{X_L(1-\frac{X_q}{X_L})}\sin\delta$$

$$Q_q = \frac{V^2}{X_{eff}}(1-\cos\delta) = \frac{V^2}{X_L(1-\frac{X_q}{X_L})}(1-\cos\delta)$$

Where Xeff is the effective total transmission line reactance between its sending and Receiving power system ends, including the equivalent "variable reactance" inserted by the equivalent injected voltage (Vs) (Buck or Boost) by the SSSC-FACTS Compensator.

Characteristics of SSSCs

SSSCs can be used for reactive power as well as real power compensation. SSSCs generate reactive power by producing the compensating voltage. They can be used to supply voltage either 90° lagging or leading the line current. When the SSSC injects voltage that leads the line current, it is equivalent to a capacitive reactance connected in series with the power line, and it increases the line current as well as the power flow. When the injected voltage lags behind the line current, it is similar to an inductive reactance connected in series to the line, causing the line current and power flow to decrease.

An SSSC can be considered a variable impedance type series compensator, as it indirectly varies the line resistance and line reactance by injecting real power and reactive power, respectively. Whenever the voltage injected is not in quadrature with the line current, the SSSC compensates for real power. A DC energy source is required in SSSCs for real power supply—this can be a battery, photovoltaic module, or fuel cell. A DC-link capacitor is connected in parallel to the DC power source to keep the DC voltage constant and to increase the quality of current flowing towards the power electronic converter.

The Static Synchronous Series Compensator:

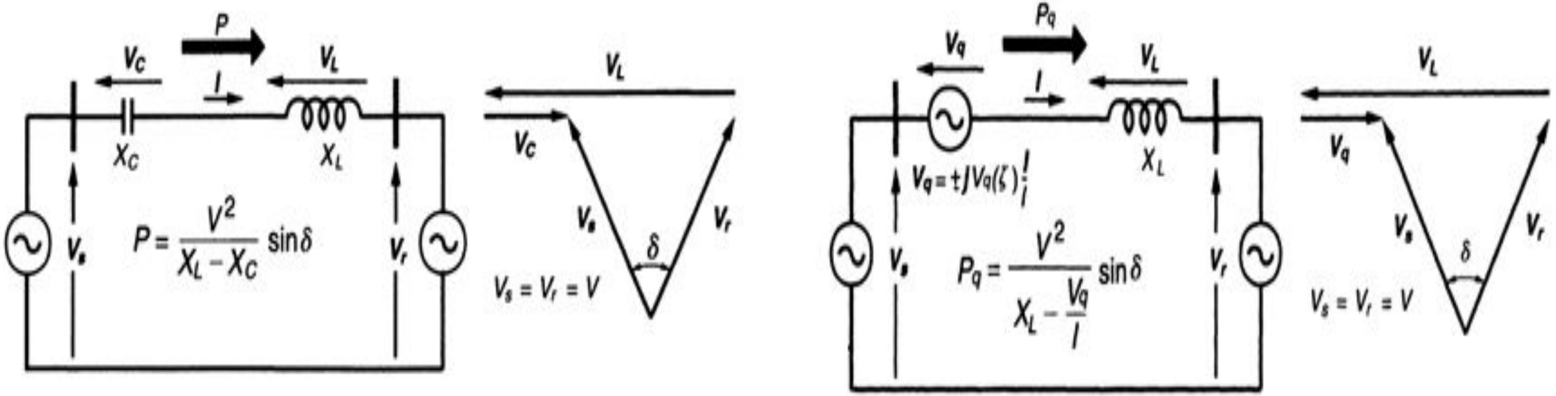


Fig: 1 Basic two-machine system with a series capacitor compensated line and associated phasor diagram & Fig 2: Basic two-machine system as in Fig 1 but with synchronous voltage source replacing the series capacitor.

The Advantages of SSSCs

Compared to other FACTS controllers, SSSCs are superior due to the following advantages:

1. They eliminate bulky passive components such as capacitors and inductors.
2. They can supply or absorb reactive power. The ability to offer inductive and capacitive operating modes symmetrically is also a benefit.
3. When connected with a DC power source on the DC side of an SSSC, they can exchange real power to the power system.

Causes of Power Quality issues in Power Systems:
Because of a number of single-phase loads in the distribution system, especially domestic, residential, and commercial in small power ratings and traction, transportation, rural distribution systems, and so on in medium power ratings, there have been additional problems of load unbalancing and excessive neutral current causing increased losses, voltage imbalance and derating of the distribution system.

Moreover, switching in many electrical loads causes switching transients and inrush currents resulting in various voltage-based power quality problems such as surges, spikes, sags, voltage fluctuations, voltage imbalance, and so on.

These power quality problems affect other loads and system components such as protection systems.

Some of these nonlinear loads are as follows,

- Fluorescent lighting and other vapor lamps with electronic ballasts
- Switched mode power supplies
- Computers, copiers, and television sets
- Printer, scanners, and fax machines
- High-frequency welding machines
- Fans with electronic regulators
- Microwave ovens and induction heating devices
- Xerox machines and medical equipment
- Variable frequency-based HVAC (heating ventilation and air-conditioning) systems
- Battery chargers and fuel cells
- Electric traction
- Arc furnaces
- Cycloconverters
- Adjustable speed drives
- Static slip energy recovery schemes of wound rotor induction motors
- Wind and solar power generation
- Static VAR compensators (SVCs)
- HVDC transmission systems
- Magnet power supplies
- Plasma power supplies
- Static field excitation systems.

These types of nonlinear loads draw harmonic currents and reactive power components of the current from the single-phase AC mains.
Some of them have harmonic currents, reactive power components of the current, and unbalanced currents in the three-phase threewire supply system.

Mitigation of Voltage Swells:

Over voltages are extremely transient phenomena occurring for only fractions of a second, but which can never less have a negative effect on electronic equipment and can even result in their total failure.

Although damage due to over voltage primarily occurs in industry and large community and office complexes, the losses suffered in the private sector due to damaged TV equipment and personal computers have also reached considerable levels.

The basic principles of over voltage protection of load equipments are,
Limit the voltage across sensitive insulation
Divert the surge current away from the load
Block the surge current entering into the load
Bonding of equipment with ground
Prevent surge current flowing between grounds
Design a low pass filter using limiting and blocking principle

1.OVER VOLTAGES mitigation devices:

Over voltage: 10% above the nominal voltage for a period of time greater than 1 min.

Some of the equipment used to counter overvoltages are:

i. Line Voltage drop Compensator (LDC)
ii. Phase modifying equipment, such as Static Capacitor and Shunt Reactor
iii. Step Voltage Regulator (SVR) or Transformer with on-load tap changer.
iv. Thyristor Voltage Regulator (TVR)
v. Static VAr Compensator (SVC)
vi. STATic synchronous COMpensator (STATCOM)
vii. Dynamic Voltage Restorer (DVR) using Storage Devices
viii. Power Conditioning System (PCS) with function to suppress rise in grid voltage
ix. Passive Filter or LC Filter
x. Active Filter
xi. Sodium-sulfur (NaS) Battery
xii. Batteries or Supercapacitors Energy Storage

Unfortunately, many of the counter measures listed above have their own disadvantages. Thyristor Voltage Regulator (TVR) has disadvantages of long term reliability when installed on a pole.

Cost is a bottleneck in Static VAr Compensator (SVC) technology and Static Synchronous Compensator (STATCOM). Line voltage Drop Compensator (LDC) has a problem of overvoltage suppression. Step Voltage Regulator (SVR) has the disadvantage of low response time.

Harmonics:

Harmonics are distortions in the AC waveform. These distortions are caused by loads on the electrical system that use the electrical power at a different frequency than the fundamental 50 or 60 Hz.

Harmonic voltages and currents in an electric power system are a result of non-linear electric loads. Harmonic frequencies in the power grid are a frequent cause of power quality problems. Harmonics in power systems result in increased heating in the equipment and conductors, misfiring in variable speed drives, and torque pulsations in motors. A harmonic of a wave is a component frequency of the signal that is an integer multiple of the fundamental frequency, i.e. if the fundamental frequency is f, the harmonics have frequencies 2f, 3f, 4f, . . . etc. The harmonics have the property that they are all periodic at the fundamental frequency; therefore the sum of harmonics is also periodic at that frequency. Harmonic frequencies are equally spaced by the width of the fundamental frequency and can be found by repeatedly adding that frequency. For example, if the fundamental frequency (first harmonic) is 25 Hz, the frequencies of the next harmonics are: 50 Hz (2nd harmonic), 75 Hz (3rd harmonic), 100 Hz (4th harmonic) etc.

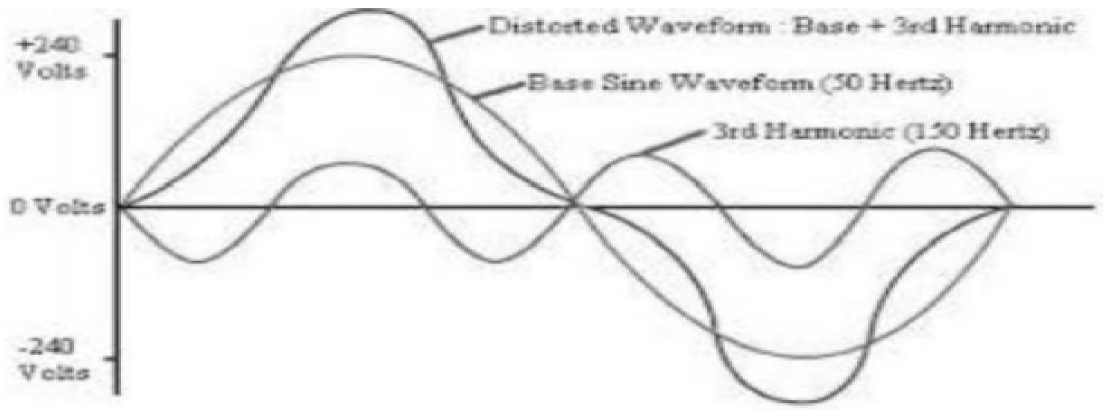


Fig. 4.1 Fundamental Harmonic Frequency

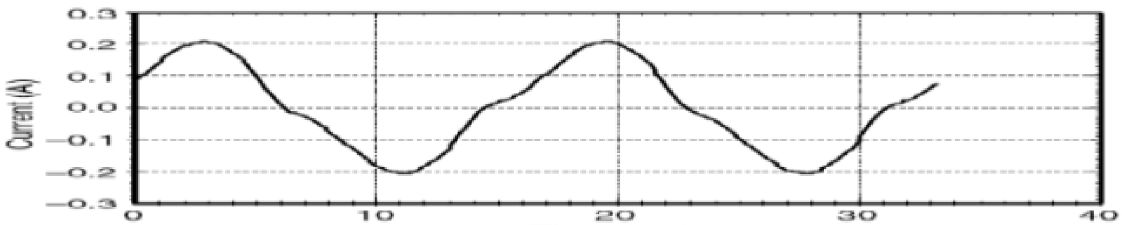
Harmonic Sources from Commercial Loads:

Commercial facilities such as,

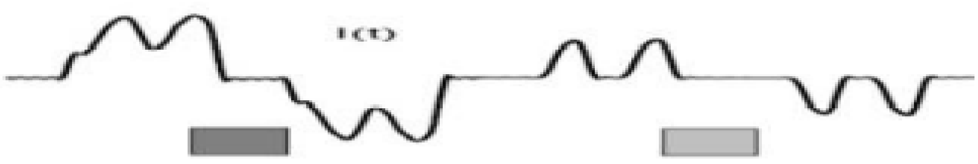
1. office complexes,
2. department stores,
3. hospitals, and
4. Internet data centers are dominated with high-efficiency fluorescent lighting with electronic ballasts,
5. adjustable-speed drives for the heating, ventilation, and air conditioning (HVAC) loads,
6. elevator drives, and
7. sensitive electronic equipment supplied by single-phase switchmode power supplies.
8. The application of power factor correction capacitors can potentially magnify harmonic currents from the nonlinear loads, giving rise to resonance conditions within the facility.

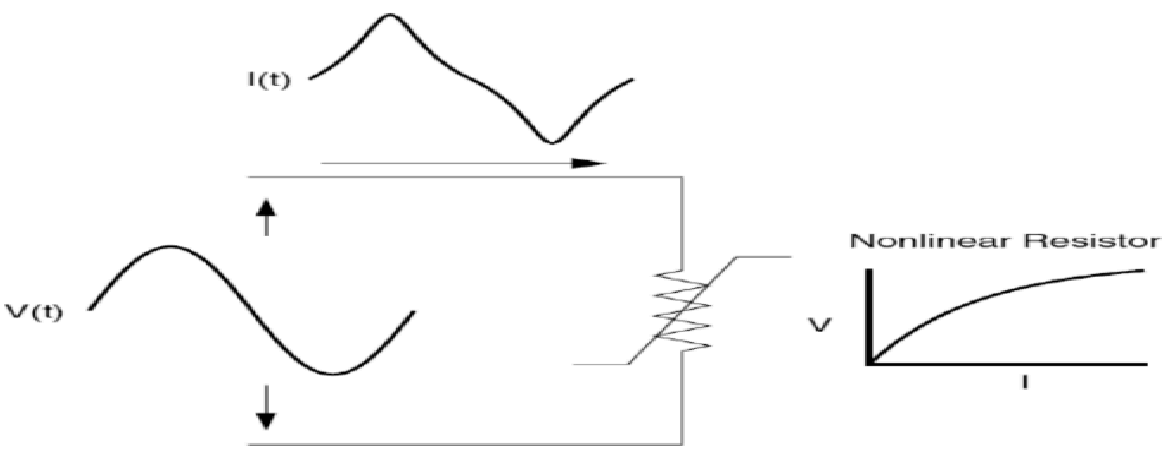
Wave shapes of few loads:

Fluorescent lamp

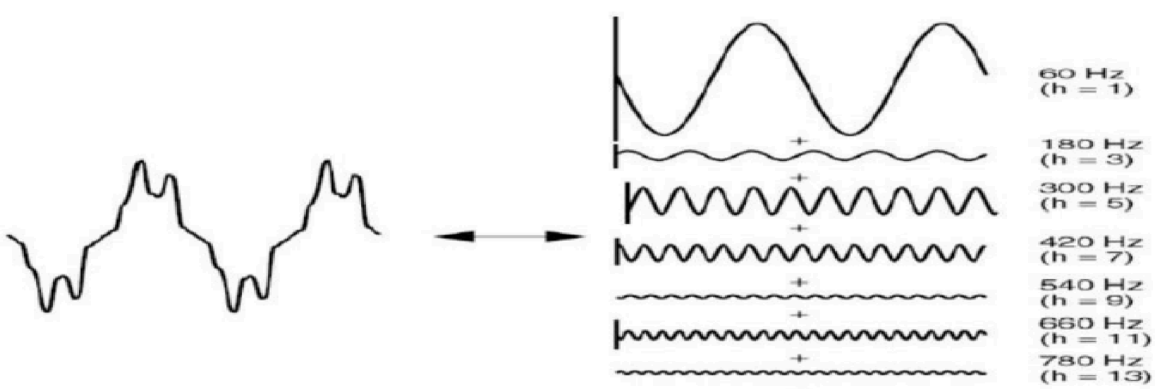


Effect of PWM ASD speed on ac current harmonics





Current distortion caused by nonlinear resistance



Fourier series representation of a distorted waveform

Effects of Harmonics:

Harmonics in electrical systems result in waveform distortion.

They are periodic disturbances in voltage and current.

Any non sinusoidal periodic waveform can be considered as a combination of sine waveform of certain frequency, amplitude and phase angle.

Generally these are individual multiples of fundamental frequency. Hence 3rd order frequency has got frequency of 150 Hz and the 5 th order harmonic has 250 frequency and so on.

The amplitude and phase angle of individual components will vary depending on the nature of the distorted waveform.

THD is defined as the ratio of the root mean square value of the harmonic content to the root mean square value of the fundamental quantity, expressed as percent of the fundamental.

It is measured by the effective value of harmonic distortion.

The total harmonic value of distortion (THD) is the value used to describe the characteristics of a distorted waveform.

The THD is a measure of how badly the waveform is distorted from pure sinusoidal which has a THD is 0%.

IEEE standard 519 recommends that for most systems, the THD of the bus voltage should be less than 5% with a maximum of 3% with any individual components.

Harmonic Indices:

The two most commonly used indices for measuring the harmonic content of a waveform are the total harmonic distortion and the total demand distortion.

Both are measures of the effective value of a waveform and may be applied to either voltage or current.

1. **THD:**

   Total Harmonic Distortion:

   The THD is a measure of the effective value of the harmonic components of a distorted waveform.

   That is, it is the potential heating value of the harmonics relative to the fundamental. This index can be calculated for either voltage or current,

$$THD = \frac{\sqrt{\sum_{h>1}^{h_{max}} M_h^2}}{M_1}$$

Where Mh is the RMS value of harmonic component h of the quantity M.

Benefits of THD:

The THD is a very useful quantity for many applications,

It can provide a good idea of how much extra heat will be realized when a distorted voltage is applied across a resistive load.

It can give an indication of the additional losses caused by the current flowing through a conductor.

Limitations of THD:

It is not a good indicator of the voltage stress within a capacitor because that is related to the peak value of the voltage waveform, not its heating value.

2. **TDD:**

Total demand distortion is the calculated harmonic current distortion in an electrical system against the full load demand. It can be mathematically expressed as,

$$TDD = \frac{\sqrt{\sum_{h=2}^{h_{max}} I_h^2}}{I_L}$$

Devices for controlling Harmonic Distortion: Active and Passive Filters connected in series and parallel and some FACTS devices.

IEEE and IEC standards It should be emphasized that the philosophy behind this standard seeks to limit the harmonic injection from individual customers so that they do not create unacceptable voltage distortion under normal system characteristics and to limit the overall harmonic distortion in the voltage supplied by the utility. The voltage and current distortion limits should be used as system design values for the worst case of normal operating conditions lasting more than 1 hour. For shorter periods, such as during start-ups, the limits may be exceeded by 50 percent. This standard divides the responsibility for limiting harmonics between both end users and the utility. End users will be responsible for limiting the harmonic current injections, while the utility will be primarily responsible for limiting voltage distortion in the supply system

IEC Standards on Harmonics:
The International Electro technical Commission (IEC), currently with headquarters in Geneva, Switzerland, has defined a category of electromagnetic compatibility (EMC) standards that deal with power quality issues.
The term electromagnetic compatibility includes concerns for both radiated and conducted interference with end-use equipment.
The IEC standards are broken down into six parts,

Part 1: General These standards deal with general considerations such as introduction, fundamental principles, rationale, definitions, and terminologies. They can also describe the application and interpretation of fundamental definitions and terms. Their designation number is IEC 61000-1-x.

Part 2: Environment These standards define characteristics of the environment where equipment will be applied, the classification of such an environment, and its compatibility levels. Their designation number is IEC 61000-2-x.

Part 3: Limits These standards define the permissible levels of emissions that can be generated by equipment connected to the environment. They set numerical emission limits and also immunity limits. Their designation number is IEC 61000-3-x.

Part 4: Testing and measurement techniques These standards provide detailed guidelines for measurement equipment and test procedures to ensure compliance with the other parts of the standards. Their designation number is IEC 61000-4-x.

Part 5: Installation and mitigation guidelines These standards provide guidelines in application of equipment such as ear thing and cabling of electrical and electronic systems for ensuring electromagnetic compatibility among electrical and electronic apparatus or systems. They also describe protection concepts for civil facilities against the high-altitude electromagnetic pulse (HEMP) due to high altitude nuclear explosions. They are designated with IEC 61000-5- x.

Part 6: Miscellaneous These standards are generic standards defining immunity and emission levels required for equipment in general categories or for specific types of equipment.

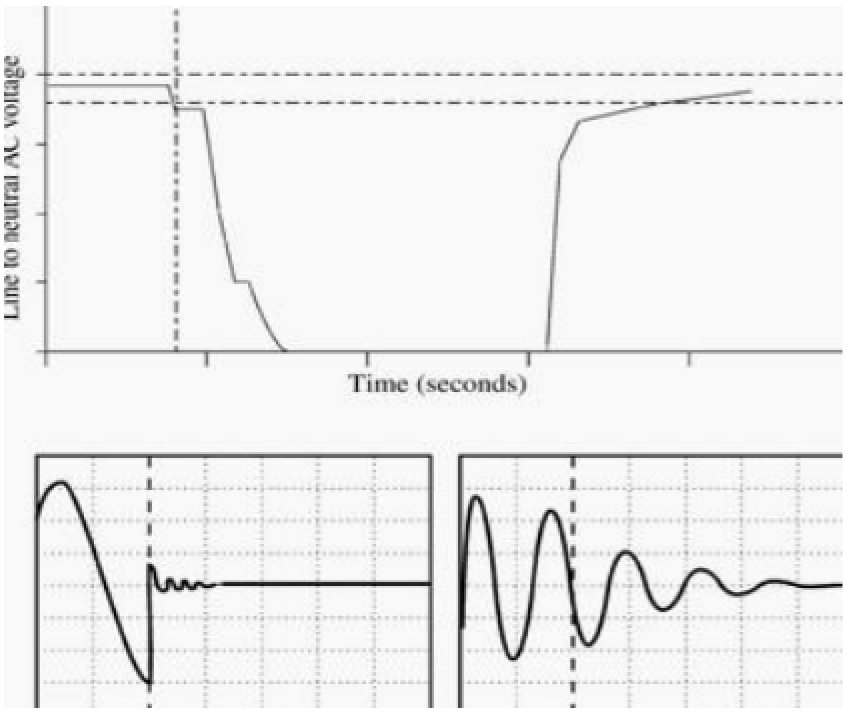
Note: x, defines the year.

Short Answer Questions

1. Define harmonics?
2. Give at least two IEC standards for EMC.
3. Define harmonic indices?
4. Mention the devices for controlling harmonic distortion?
5. Give the IEC standard to define harmonics.
6. What is the crest factor?
7. What kind of equipment is needed to measure distorted waveforms?
8. Define TDD.
9. Define THD.
10. What is the reason for the existence of harmonic distortion?
11. What is voltage and current distortion?
12. Define inter harmonics.
13. Give at least two IEEE standards for harmonics.
14. What is the classification of active harmonic conditioner?

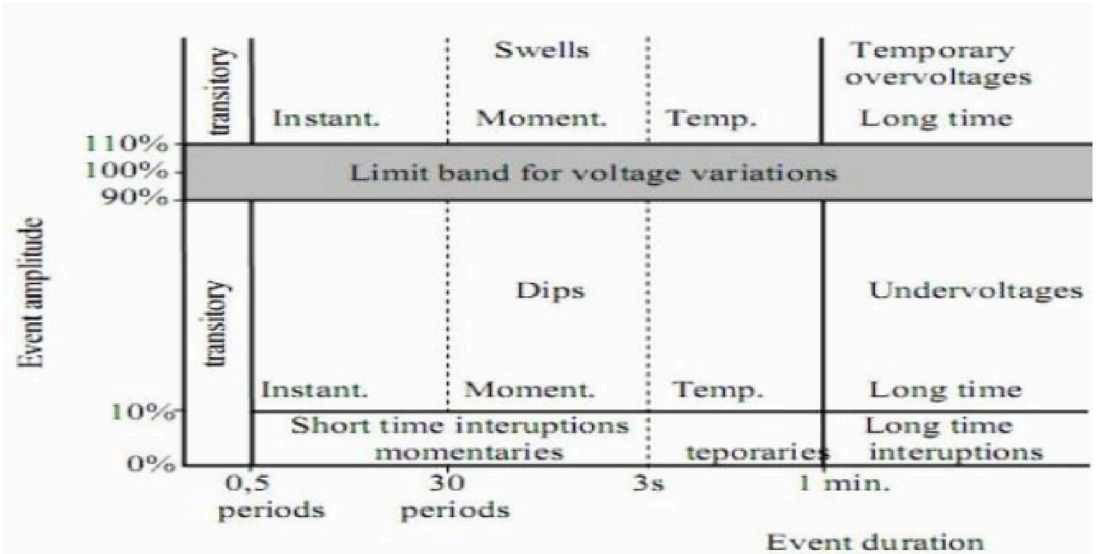
Interruptions:

Short duration variations – Interruption The complete loss of voltage on one or more phase conductors for a time less than 1 min.They are measured and described by their duration since the voltage magnitude is always less than 10% of nominal.



Types of Short Duration interruption:
Momentary Interruption < 1 min , <0.1 pu
Temporary Interruption < 1 min , <0.1 pu

Long duration variations – Sustained interruption The complete loss of voltage on one or more phase conductors for a time greater than 1 min.



Consequences of short interruptions are similar to the effects of voltage sags. Interruptions may cause the following (but not limited to):

- Stoppage of sensitive equipment (i.e. computers, PLC, ASD)
- Unnecessary tripping of protective devices
- Loss of data
- Malfunction of data processing equipment.

-Sustained Interruption is defined by IEEE 1159 as the decrease in the voltage supply level to zero for more than one (1) minute.

Source: Utility or facility

Symptoms: Equipment Shutdown

Occurrence: Less than 2 interruptions/year in the US

Protection: Uninterruptible Power Supply (UPS), Self-generation, Energy storage

<u>Voltage sag(Dip):</u>

Voltage sags are considered the most common power quality problem.
These can be caused by the utility or by customer loads.
When sourced from the utility, they are most commonly caused by faults on the distribution system.
These sags will be from 3 to 30 cycles and can be single or three phase.

A voltage sag or voltage dip is a short duration reduction in RMS voltage which can be caused by a short circuit, overload or starting of electric motors.

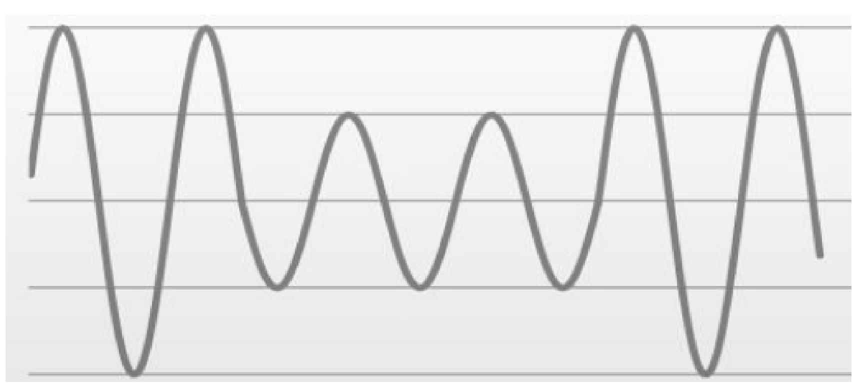
Voltage sag happens when the RMS voltage decreases between 10 and 90 percent of nominal voltage for one-half cycle to one minute.
Some references define the duration of sag for a period of 0.5 cycles to a few seconds, and longer duration of low voltage would be called “sustained sag".

There are several factors which cause voltage sag to happen: Since the electric motors draw more current when they are starting than when they are running at their rated speed, starting an electric motor can be a reason of voltage sag.

When a line-to-ground fault occurs, there will be voltage sag until the protective switch gear operates. Some accidents in power lines such as lightning or falling an object can be a cause of line-to-ground fault and voltage sag as a result.
Sudden load changes or excessive loads can cause voltage sag.

Depending on the transformer connections, transformers energizing could be another reason for happening voltage sags.

Voltage sags can arrive from the utility but most are caused by in-building equipment. In residential homes, we usually see voltage sags when the refrigerator, air-conditioner or furnace fan starts up.



Sources of Sags;

A sudden increase in load results in a corresponding sudden drop in voltage. Any sudden increase in load, if large enough, will cause a voltage sag in,

Motors

Faults cause the voltage sag.

Switching operation

Mitigation of Voltage Sags

Different mitigation methods are,

Dynamic voltage restorer

Active series Compensators

Distribution static compensator (DSTATCOM)

Solid state transfer switch (SSTS)

Static UPS with energy storage

Backup storage energy supply (BSES)

Ferro resonant transformer

Flywheel and Motor Generator set

Static VAR Compensator (SVC)

Short Answer Questions

1. List the sources of sag and interruptions.
2. Mention the methods to improve voltage sags in utility system.
3. Define the depth of the voltage dip.
4. Define the duration of the voltage dip.
5. Explain the area of vulnerability.
6. What are the factors affecting equipment sensitivity to the voltage sag?
7. What are the three categories of equipment sensitivity?
8. What is the use of estimation of voltage sag?
9. List the devices used to reduce the voltage sag.
10. Mention the types of compensations.