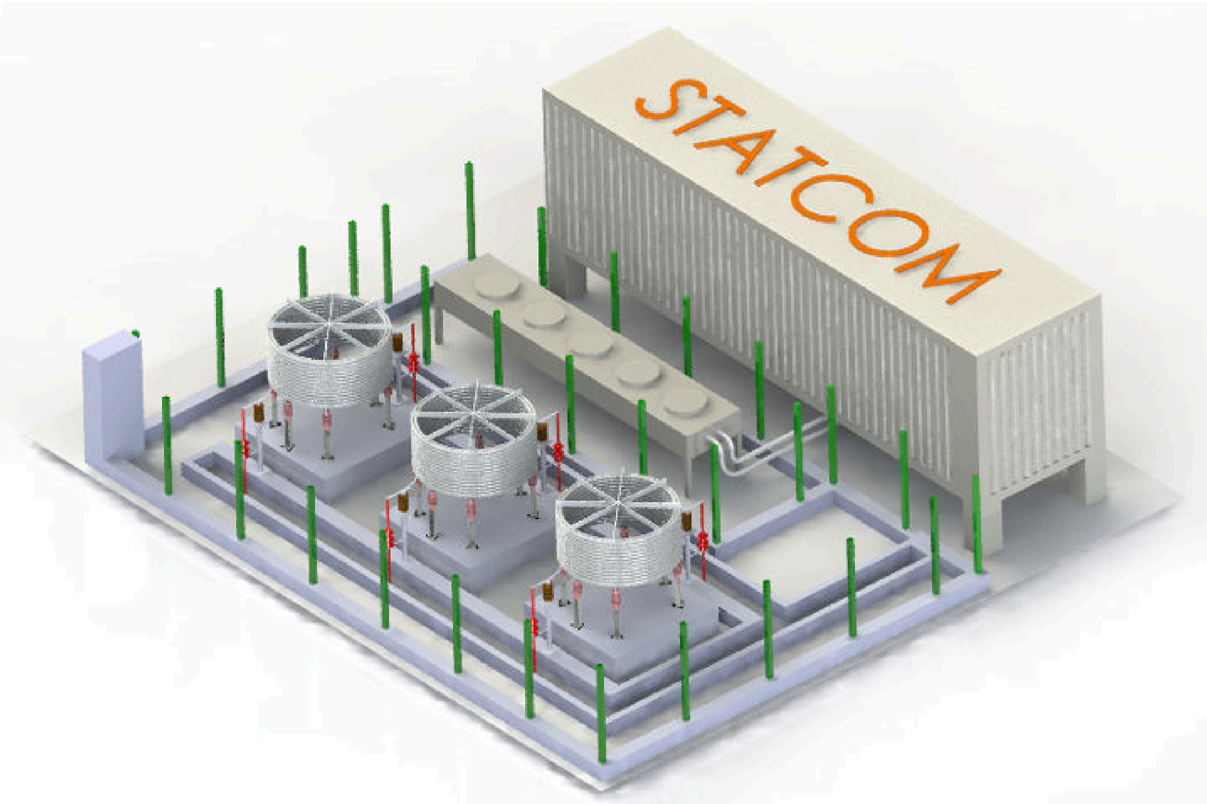
EPRLAB



EPRLAB

Electric Power Research Laboratory, EPRLAB is a high-tech power electronics company that has been specialized on design, manufacturing and implementation of industrial electronic and power systems including Static VAr Compensation (SVC), STATCOM, harmonic filtering and custom design multidisciplinary solutions based on challenging power quality problems.

We utilize our high-tech designs based on continuous research, development and field tests that enables us to achieve highest product reliability while providing innovative solutions for the future leading edge designs.

Serving the power electronics and power quality industry with exceptional expertise and customer satisfaction, EPRLAB continues to be recognized for high-tech engineering, extensive experience, and commitment to excellence.

Keywords of EPRLAB: Power Quality, Renewable Energy, Voltage Regulation, Reactive Power Compensation (RPC), Power Factor Correction (PFC), Flicker Compensation, Harmonic Mitigation, Flexible Alternating Current Transmission System (FACTS).

Products of EPRLAB: Static VAr Compensation (SVC), Static Synchronous Compensator (STATCOM), Multi-level Converter, Voltage Source Converter (VSC), Passive Harmonic Filter (HF), Thyristor Switched Capacitor (TSC), Thyristor Switched Reactor (TSR), Thyristor Controlled Reactor (TCR), RC Snubber, DC Chopper, DC Injection Brake Module, Remote Monitoring and Control System Design.

Services of EPRLAB: Power Quality Analysis, Commissioning, Supervision, Training, Consulting, Engineering, Technical Support, Maintenance.

Please visit http://www.eprlab.com for detailed information on products and solutions.

Send e-mail to info@eprlab.com for any queries, technical questions, and sales information.

Knowledge is POWER

REACTIVE POWER COMPENSATION and FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEMS

1. REACTIVE POWER COMPENSATION

1.1. What is Reactive Power?

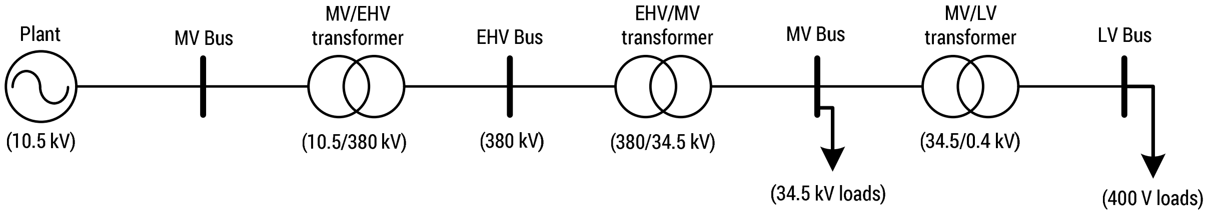
The energy which does not turn into work, but is stored in electric and/or magnetic field is called reactive energy. The amount of this energy in unit time is called reactive power and it is represented in Volt-Ampere reactive (VAr).

In the times when electricity was discovered and started to be used, only dc sources which consist of chemical batteries existed. As time passed, and the use of electricity became widespread, the need for electricity to be produced elsewhere than it is used, urged. With the increasing transmission distances, it is observed that with the increase of loading (current), the voltage drop between these two places got higher. This made the use of dc power very inefficient. Since this drop also meant very high losses in the lines. The reason for this voltage drop is the resistance of the lines, and it became evident that trying to decrease this resistance too much resulted in a very expensive solution, since the conductor diameter had to be increased dramatically.

Since the line resistance value multiplied by the current gives the voltage drop, the other and logical way of decreasing this voltage drop is to decrease the current, as known by almost every engineer today. To draw the same amount of power from the source (or to the load) while decreasing the current, one should increase the voltage magnitude with the same ratio of current decrease. Therefore in the past, the pioneers of transmission tried to increase the dc voltage of source, as much as possible. However, it has always been a problem to have and handle high voltage dc. Moreover, the high voltage should be decreased to low values at the end-user, and again this has been a problem in dc transmission.

While the studies continued, ac form of electricity was discovered, and it suddenly became widely accepted. This was because, the ac form was easily transformable into higher and lower values by means of transformers. Therefore, the basis of our today's electric network was founded on the basis that increasing the voltage before transmitting the energy through long distances, and decreasing it to low values at the end-user is the most economical and feasible way.

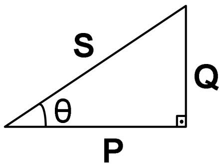
In most of America continent 60 Hz, and in Europe 50 Hz electricity is produced and used. The generation is mainly achieved at voltages between 6.0-15.0 kV. Before going into transmission lines, the voltage level is increase to values such as 154 kV, 220 kV, 400 kV, or etc. An example diagram for such an electrical network is seen in the figure below.



Thanks to increasing to high voltage, the voltage drop (*IxR*) and the power losses (I^2xR) on the lines can be decreased to very low levels. Having all these merits, the use of ac form has some disadvantages. One of these is the inevitable consumption of reactive power.

The energy which transforms into heat, light, potential and motion is defined as work. This energy in unit time is defined as real (active) power in electrical engineering, and is shown in Watts (W). On the other hand, the energy in unit time, which does not turn into work, and which is stored in electrical or magnetic field is called reactive power. The unit of reactive power is Volt-Ampere reactive (VAr). This type of power is produced only as a result of using ac form of electricity. The energy stored in the magnetic field formed by equivalent inductance, and the electric field formed by equivalent capacitance of loads, continuously flows between the source of energy and the place where real power is consumed, without doing work. Therefore, it would be a waste of labor and resources trying to produce this type of energy and transport it.

In electrical engineering, a power triangle is defined by real power and reactive power, as seen in the figure below. This triangle definition is for fundamental frequency only (50 or 60 Hz), where P represents active power (W), Q represents reactive power (VAr), and S represents apparent power (VA). The power factor (*pf*) is defined as the ratio of P to S, and it is the cosine of the angle between S and P, θ. The power factor gets values from 0 to 1 for inductive loads, whereas it is between 0 and -1 for capacitive loads.



As can be inferred from the power triangle, for the same value of P, if Q increases, than the magnitude of S will increase, which means that the amount of current should be higher for the same voltage. This means that if the reactive power would be produced in the plants and transported all the way to the customers, the lines would be loaded unnecessarily due to I^2xR losses, and the real power transfer capacity of the lines would be taken down. However, if the angle θ seen in the triangle was zero, in other words, if the power factor was unity, the apparent power would consist of real power only, and the unnecessary loading and inefficient utilization of the transformers would be avoided.

Due to the reasons stated above, both at transmission and distribution stage, keeping the reactive power at minimum, and by this way devoting the system almost totally to the flow of real power is a wise idea. In present day, this is the reason why the power system operators apply sanctions for reactive power consumption. If the reactive power consumption limits are violated, the customer is forced to pay a penalty for it.

For Turkey, as per the first episode of the first item of "Elektrik İletim Sistemi Arz Güvenilirliği ve Kalitesi Yönetmeliği" which was published in Official Journal on 10th of November, 2004 with number 25639, and as per the regulation published again in Official Journal on the 11th episode and the first item of this episode on 9th of January, 2007 with number 26398:

Any industrial customer's consumption ratio of inductive reactive power to active power and capacitive reactive power to active power should not go above 20% and 15%, respectively, for a reconciliated period (usually one month).

The ratios given above correspond to power factor being 0.98 at the inductive region and 0.989 at the capacitive region. Although the ratios may vary, most of the countries worldwide apply similar measures to discourage consumption of reactive power.

Almost all of the industrial loads are of inductive type. The reason is that the machines used (induction motors, welding machines, compressors, etc.) all have series inductances and resistances in their equivalent circuit representations. These loads demand reactive power, and they must be compensated.

1.2. What is Reactive Power Compensation (RPC), and why is it important?

It is not necessary for the reactive power consumed by the loads to be produced in the power plants. This power can be produced right at the place where it is needed, by using correct equipment in series or parallel with the load. In other words, if a correctly rated capacitive load is connected in parallel with an inductive load, the reactive power will flow only through these two, and it will not be reflected to the grid. Similar is true when the load is capacitive and the compensator is inductive. The two loads will compensate for each other's reactive power. This is called reactive power compensation (RPC). It should be best to represent the importance of RPC with examples.

Assume that there is a load drawing 4 kW and 3kVAr powers from a 3-phase 400 V ac grid. The current for this load can be calculated as 7.22 A. However, if the load was compensated according to *pf*=0.98, as an example, the current will decrease down to 5.89 A. In terms of line and/or transformer losses, this current decrease will correspond to a drop of 33% power losses. Similarly, RPC is also important for voltage regulation. As an example:

Assume that the source is rated at 34.5 kV, with a short circuit power capacity of 100 MVA, and there is a transformer between the source and load, with the ratings of 34.5/0.4 kV, 1.6 MVA, and

u_k=%6.5. If the load draws 1.5 MVA with a lagging (inductive) power factor of 0.81, the current into the load would be calculated as 2074.4 A, and the voltage on the load as 383.4 V. However, if RPC is made with *pf*=0.98, then the load current will decrease down to 1765.2 A, and the load voltage would stay at 394.7 V. This means that the 4.3% voltage regulation will be improved to 1.3%.

1.3. RPC Methods

1.3.1. Selection of RPC Points

RPC being made as closest as possible to the point where reactive power needed is the best solution, theoretically. However, this may not be an optimum solution in practice. In industry, there may be more than one distribution or step-down transformer fed from distribution voltage around 34.5kV, for a single factory or foundation. For such cases, if the loads are not very far from each other, it may be better to compensate from the secondary sides (0.4kV-6.6kV for example) of each transformer for the total load. However, in some cases the lines going from the transformer secondary to separate loads may cover a long range. For these, it may be better to compensate each load individually in order to decrease losses and voltage drops in the cables. If the aim is to avoid any reactive energy penalty only, then RPC can be made only at the MV side, where the energy meter is connected.

1.3.2. RPC Techniques

RPC is achieved mainly by connecting a compensator with the reverse sign of reactive power of load, in parallel with it. Since most of the industrial loads are inductive, RPC is usually made by connecting parallel capacitors (or harmonic filters). However, RPC is not limited with passive circuit elements only. Synchronous condensers, STATCOMs and active filters may also be used as compensators. These mainly act as voltage sources. On the other hand, passive circuit components can be controlled to have variable reactive power with the help of semiconductors as in Thyristor Controlled Reactor (TCR), Thyristor Switched Capacitor (TSC), and etc. Moreover, RPC is not only achieved by parallel connection of compensator. A series compensation in the lines can also be made. Thyristor switched series capacitor (TSSC) is an example to this. Please refer to *FACTS Section* for details.

None of the RPC devices should be overrated, since it may cause the power factor to go below the limit in the other quadrant of P-Q curve, which means paying reactive energy penalty again. The most common RPC techniques can be listed as follows:

- Conventional compensation with shunt capacitors (may be switched with contactors or breakers)
- Harmonic Filter, HF (tuned or detuned)

- Thyristor Switched Capacitor, TSC (with plain capacitors or HFs)
- Thyristor Switched Reactor, TSR
- Thyristor Controlled Reactor, TCR
- Static VAr Compensator, SVC (a combination of HFs, TCRs and TSCs)
- Synchronous Condenser (An unloaded synchronous generator)
- Static Synchronous Compensator, STATCOM
- Active Power Filter, APF
- Series Capacitor (connected in series with the line to decrease the effective line reactance)
- Thyristor Switched Series Capacitor, TSSC

Please refer to *FACTS Section* for details of semiconductor based systems, and to *PQ and HF.pdf* for details on passive harmonic filtering and Active Power Filter (APF).

2. FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEMS (FACTS)

2.1. What is FACTS?

FACTS is the abbreviation for Flexible Alternative Current Transmission Systems. It is used for the systems that enhances reliability, stability, capacity and power quality and reduces power losses of electricity network. FACTS devices are semiconductor based complex power quality enhancement systems. Due to semiconductor (Thyristor, GTO, IGCT IGBT, MOSFET, etc.) action, they respond very quickly (on the order of milliseconds) to changing loads, and to disturbances in the grid.

2.2. Types of FACTS Devices

FACTS devices can be classified into four groups as a) shunt compensation, b) series compensation, c) combined compensation, and d) high voltage dc transmission.

a) <u>Shunt compensation</u>

- Thyristor Switched Capacitor, TSC
- Thyristor Controlled Reactor, TCR
- Thyristor Switched Reactor, TSR
- Static VAr Compensator, SVC
- Static Synchronous Compensator, STATCOM
- Active Power Filter, APF

b) <u>Series compensation</u>

- Thyristor Switched Series Capacitor, TSSC
- Thyristor Controlled Series Capacitor, TCSC
- Gate Turnoff Thyristor (GTO) Controlled Series Capacitor, GCSC

- Static Synchronous Series Compensator, SSSC
- Dynamic Voltage Restorer, DVR
- Phase Angle Regulator, PAR

c) Combined compensation

- Unified Power Flow Controller, UPFC
- Interline Power Flow Controller, IPFC

d) HVDC transmission

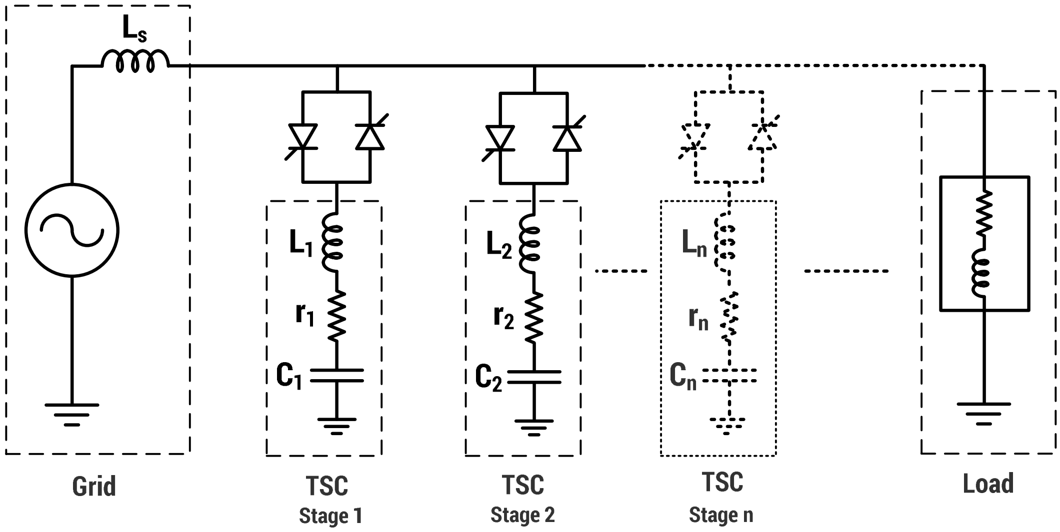
- Line Commutated Converter, LCC
- VSC Based (MMC)

Except for TSSC, the series and combined compensation FACTS devices are not commonly used. The most commonly used FACTS devices are of shunt type, such as SVC and STATCOM. As can be seen in the answer of Frequently Asked Questions (FAQ), Q21, most of the FACTS devices are used as RPC systems.

2.2.1. Shunt Compensation

Thyristor Switched Capacitor, TSC

It is used for the cases when the load is of inductive type. The operating principle can be defined simply as taking capacitive banks (or harmonic filters) with suitable reactive power rating into and out of operation by the help of back-to-back connected thyristors. The bank or harmonic filter, switched by these thyristors can be in either fully operation, or out of operation. Because in TSC, the thyristors angles cannot be changed to vary the reactance connected to the bus, since this will result in current and voltage transients. Therefore, most of the time TSCs are connected in parallel, in order to meet the reactive power demand for a time-varying load. See the figure below for an example application circuit schematic.



The advantages of TSC over conventional compensation (breaker or contactor switched compensation) are:

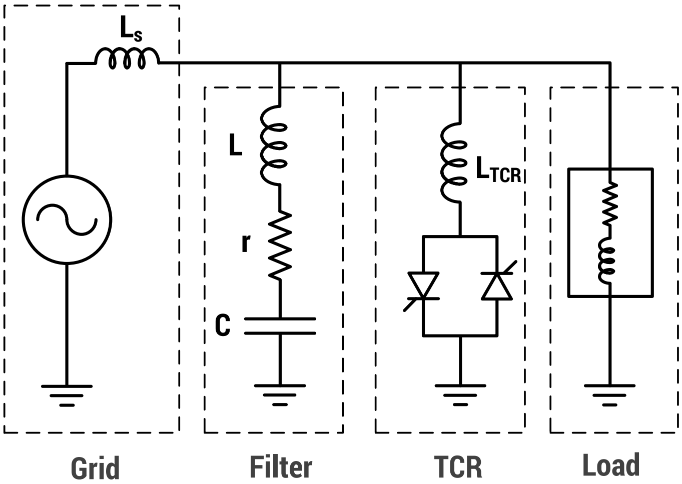
- No mechanical contacts
- Very fast operation due to semiconductor action
- Reliability and long life

Thyristor Controlled Reactor, TCR

In order to provide variable reactive power to the grid, TCRs are used. TCR consists of reactors in series with back-to-back connected thyristors. By changing the triggering angle of these thyristors, the current passing through the reactors may be varied between rated value and zero.

Most of the time, TCRs are used in parallel with harmonic filters, and/or TSCs. Then, the total system is named a Static VAr Compensator (SVC). This is because, TCR may provide inductive power, however most of the industrial loads need capacitive power. Therefore, fixed capacitive power (HF or TSC) and a variable inductive power (TCR) are used together to adjust the reactive power output of an SVC, mostly in capacitive region.

The branches of TCR are usually configured in delta connection. By this way, unbalanced loads can be independently compensated, and an unbalanced grid voltage may be improved. See the figure below for an example SVC single line diagram.



Thyristor Switched Reactor, TSR

TSR is same with TCR as regards its power circuit. However, its thyristors are triggered in either fully conductive or non-conductive mode. In other words, the triggering angles of the thyristors are not varied. Therefore the reactive power output of a TSR is not variable. This means simpler control electronics and algorithm, therefore in some cases TSR may be preferred.

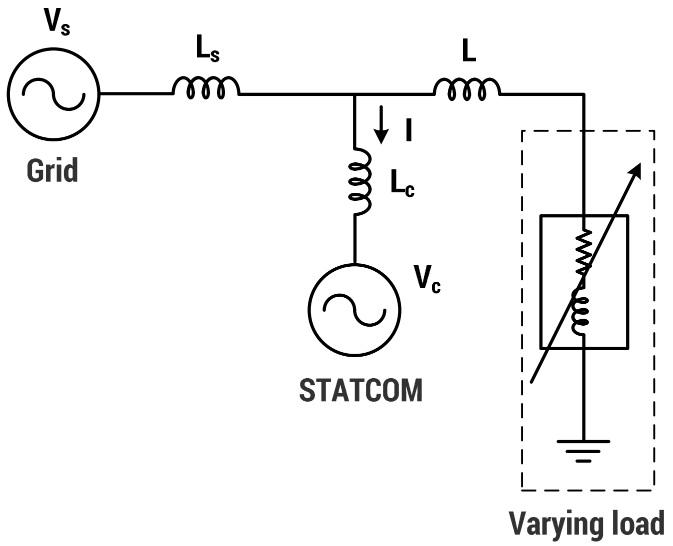
Static VAr Compensator, SVC

As described in TCR, SVC is the combination of TCR and HFs and or TSCs. They are used as reactive power compensators, voltage regulators, flicker compensators, stability improvers, etc. SVCs are the most commonly used type of FACTS devices.

Static Synchronous Compensator, STATCOM

The static (semiconductor based) version of a synchronous condenser is called a STATCOM. It is based on a voltage or current source based converter. A STATCOM is used mainly for RPC purposes. Basically, since a STATCOM is connected to the grid via a coupling reactor and/or coupling transformer, it behaves in capacitive mode and injects reactive power when its voltage magnitude is higher than the grid's. On the contrary, it behaves in inductive mode and draws reactive power when its voltage magnitude is lower than the grid's.

The phase angle between the STATCOM's voltage and the grid's gets a very small value. This angle is nonzero, in order to compensate for the losses in STATCOM systems. A sample single line diagram for a STATCOM is seen in the figure below.



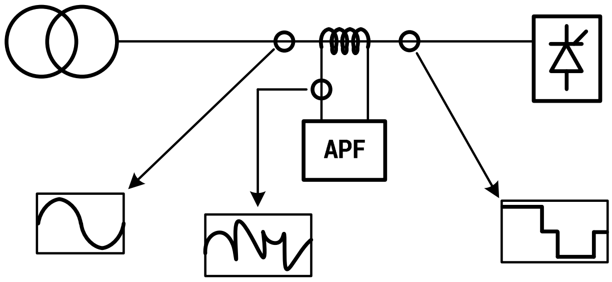
Active Power Filter, APF

The main idea in an active power filter (APF) is to form one or more harmonic current components, with 180° phase difference with the load's harmonics. By this way, the harmonic currents coming from the load would be cancelled with the harmonic currents formed by APF. Therefore, the grid would not be affected by those harmonics. APFs are composed of inductive, capacitive and resistive elements as well as semiconductor devices (mostly IGBTs and MOSFETs). Working as a controlled voltage or current source, they can filter the desired currents with changing magnitudes at specific frequency intervals. The basic working principle of an APF may be seen in the figure below.

The advantages of APFs can be listed as follows:

- They can filter out almost all of a specific harmonic

- Their filtering performance does not degrade due to ageing.
- They can filter out more than one harmonic, i.e. they can filter out all components in a specified frequency interval; these include interharmonics also.
- They can make RPC also, even in both capacitive and inductive regions



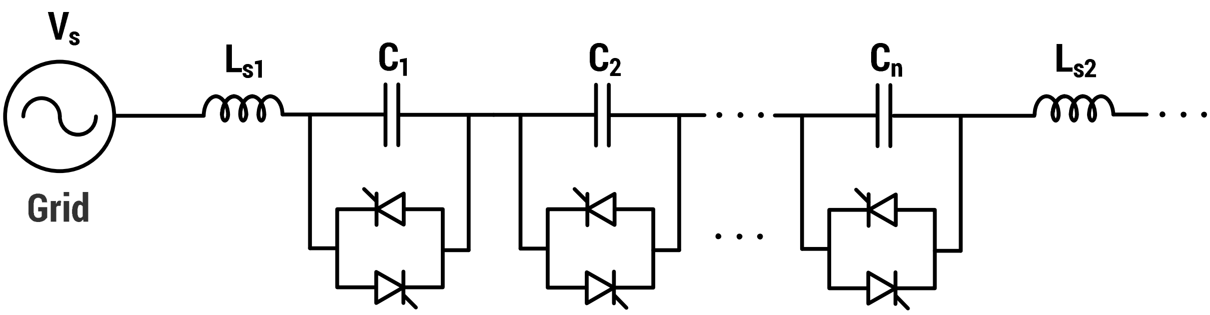
The main disadvantages of APF are having complex control and circuitry, and being expensive.

2.2.2. Series Compensation

Thyristor Switched Series Capacitor, TSSC

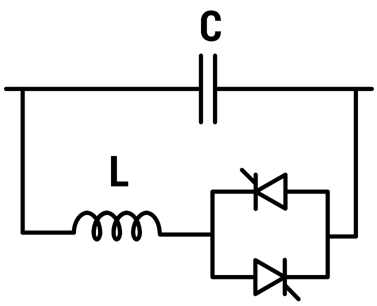
In order to decrease the effective reactance of especially long transmission lines, series capacitors are sometimes installed in appropriate places. This is an application which increases the power transfer capacity of a line directly. However, decreasing the reactance too much, may result in fault current becoming too high. Rather than fixed installation of series capacitors, TSSCs are usually preferred in transmission lines. In parallel with the installed capacitor, back-to-back thyristors are installed. By taking these thyristors into conduction, the series capacitor may be bypassed.

TSSCs are sometimes used in stages. This is because, the triggering angle of the thyristors may not be varied to change the effective capacitance, in order not to create huge transients. Therefore, variable capacitance effect is formed in a discrete way by using stages. A sample single line diagram of a TSSC application is given below.



Thyristor Controlled Series Capacitor, TCSC

A TCSC consists of a series capacitor bank, shunted by a back-to-back thyristor in series with a reactor. By changing the triggering angles of the thyristors, the effective parallel reactance is changed. The aim is again same with fixed series capacitor, and TSSC. Single line diagram of a TCSC is given below. Since the reactance may be varied by changing the triggering angles of the thyristors, stages are not needed as in the case of TSSC.



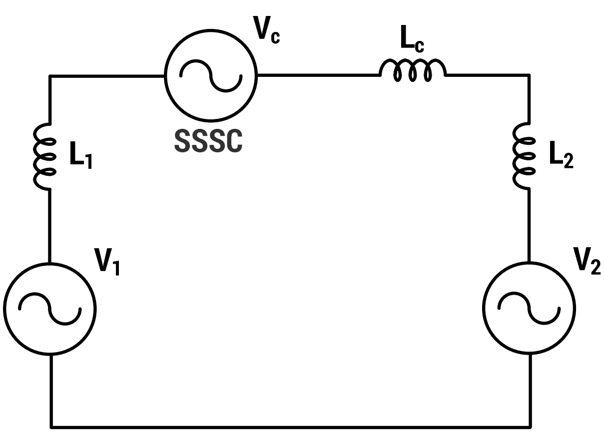
Gate Turnoff Thyristor (GTO) Controlled Series Capacitor, GCSC

GCSC is very similar to TSSC, with the difference being in the thyristors. The thyristors used in GCSC have turn-off capability for nonzero currents. Some examples for such thyristors are GTOs and IGCTs.

The current through the capacitor in a GCSC has the same waveform as the current in TCR branches. GCSC mainly provides a variable series capacitance, instead of a variable reactance.

Static Synchronous Series Compensator, SSSC

An SSSC is basically the series version of a STATCOM. It is connected in series with the line. Its output voltage is in quadrature with the line current, and it can be controlled independently of this current. The purpose is the increase or decrease the overall reactive voltage drop across the line and hence controlling the transmitted power. An SSSC may include battery energy storage systems to enhance the dynamic behavior of a power system by active power support, by increasing or decreasing the overall resistive voltage drop among the line during faults. The circuit diagram of an SSSC is given below.



Dynamic Voltage Restorer, DVR

A DVR has the same single line diagram and operating characteristics with an SSSC. However, SSSC has a 3-phase converter to act like a voltage source, whereas a DVR has 3 independent single phase converters. In this way, a DVR can compensate every phase independently. The dc link of the voltage source converter of a DVR are either of battery energy storage type, or they are fed from the ac source. Therefore, a DVR can provide active power for prolonged durations, even when one of the phases in the source side is lost.

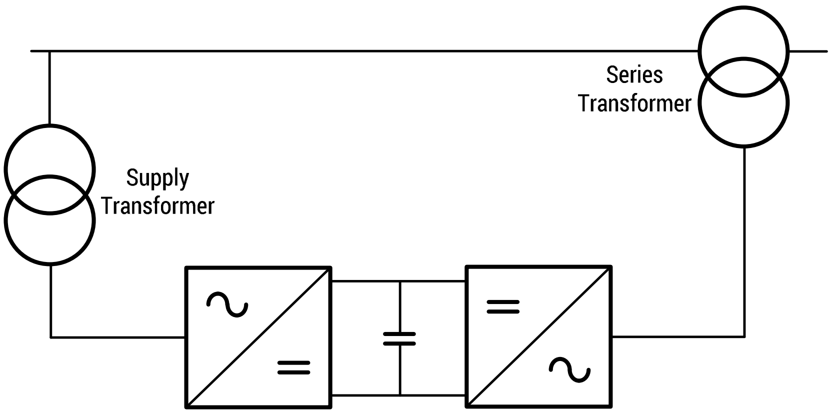
Phase Angle Regulator, PAR

PARs can be considered as ac voltage sources with controllable amplitude and phase angle. Although they cannot supply or dissipate reactive power, they can exchange active power with the system. They are connected in series with the line to provide power oscillation damping and to improve voltage regulation during overloads and voltage sags.

2.2.4. Combined Compensation

Unified Power Flow Controller, UPFC

A UPFC is a combination of a STATCOM and a SSSC which are coupled through the same dc link. It allows bidirectional active power flow, and it provides active and reactive series line compensation without the need for an external energy source. UPFC can control line voltage, impedance and angle or the active and reactive power flow, and it also can provide shunt reactive compensation. The single line diagram of a UPFC is seen below.



Interline Power Flow Controller, IPFC

IPFC consists of two or more SSSCs which are coupled through the same dc link. By this means, active power flow between the ac terminals of SSSCs is made possible. The SSSCs are controlled to provide independent RPC for adjusting active power flow in each line, and distribute the reactive power among lines in the desired way. An IPFC may also include a STATCOM coupled to the same dc link to make shunt RPC and to provide or absorb the deficient or surplus active power due to the SSSCs.

2.2.5. High Voltage Direct Current (HVDC) Transmission

The discovery of semiconductor devices made possible the high voltage transmission of direct current electricity. Dc transmission has the advantage of no reactive power loss. Especially for underwater and underground cables, the high value of cable capacitance is a big obstacle decreasing the power transfer capacity. Moreover, the energy trade between two countries may be achieved through HVDC conversion (sometimes without transmission), without the need for meeting the harsh criteria for a synchronous connection.

Using thyristors or IGBTs, mainly two different converter based HVDC transmission topologies exist.

Line Commutated Converter, LCC

LCCs are formed with semiconductor switches that can only be turned on, namely thyristors or diodes. Most of the HVDC systems that are in operation today are based on LCCs. In an LCC, the dc current cannot change direction. In order to provide power reversal, the polarity of dc voltage should be changed at both stations. On the dc side, the current is almost constant. On the ac side, LCC behaves as a current source and injects both grid-frequency and harmonic currents into the grid. Basic configuration for an LCC is a 6-pulse bridge. 12-pulse bridges are also used in order to eliminate 5^{th} and 7^{th} harmonics.

LCC based HVDC systems require a strong grid, and need both reactive power compensation and harmonic filtering at their ac sides.

VSC Based (MMC)

Voltage source converter based HVDC topologies usually use Modular Multilevel Converters (MMC). The converters may also be of lower level orders, but these are not feasible due to limited switching frequency for high power IGBTs. Without switching at rather high frequencies, low-level converters inject harmonics into the system and these would need filtering as in the case of LCCs.

These converters employ semiconductor switches that can also be turned off. In these converters, the dc link voltage is kept constant. By varying the voltage magnitude and angle formed at the ac terminals of the MMC, the real power absorbed and reactive power compensation amount can be controlled. The real power is controlled from one side only, since the other converter's real power will equal the first converter's real power supply minus the losses. However, both converters may provide inductive or capacitive reactive powers independently.

MMC based HVDC systems do not require a strong grid and do not need any reactive power compensation or harmonic filtering at their ac sides. They are also capable of conducting current in both sides.