

Reactive power compensation for transmission and distribution systems

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With growing demand and constrained and weak power systems in Southern Africa, we need to find the means to improve the power transmission capability within acceptable power quality limits. Reactive power compensation (RPC) offers the most economic means to do so.

In this article, we consider the theory of reactive power compensation, shunt and series capacitor banks and flexible AC transmission systems (FACTS) as option for optimising transmission and distribution systems.

RPC theory

The beer mug analogy is useful to understand the theory of reactive power compensation. If the mug capacity is the apparent power (kVA) that we can transmit through a system, then the foam is the reactive power (kvar) and the beer is the real power (kW). Power factor = beer (kW) divided by mug capacity (kVA) or the efficiency that we can achieve of beer volume to mug capacity.

If we use capacitors to provide the foam (kvar) when we drink the beer, then we free up mug capacity so you don't have to buy a bigger mug and/or so you can pay less for your beer. Most loads and delivery apparatus (e.g., lines and transformers) are inductive in nature and operate at a lagging power factor. They need the reactive power component, but that's not to say, that we need to constrain the power system by transmitting the reactive power through the system.

The benefits of reactive power compensation in the transmission and distribution system include:

- Voltage improvement
- Increase power flow capacity
- Release system capacity
- Reduced losses

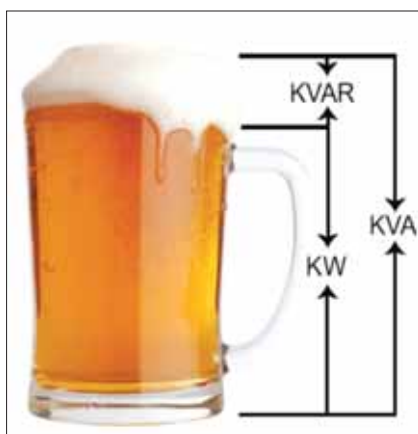


Fig. 1: Beer mug analogy.

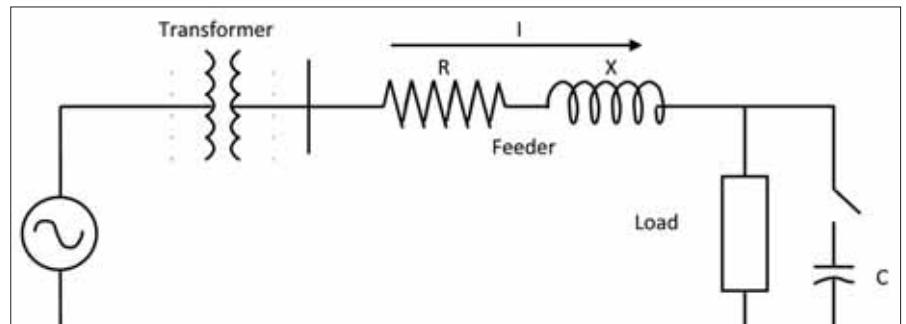


Fig. 2: Volt drop in transmission system.

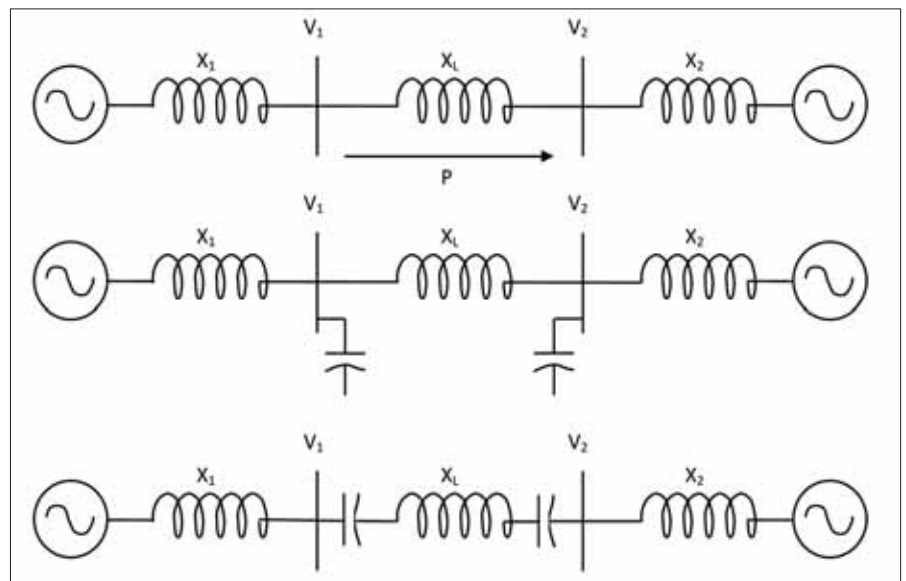


Fig. 3: Improving power flow capacity in transmission systems.

The cost of RPC equipment is normally a fraction of the cost of alternative options of increasing the capacity of the transmission and distribution system (eg. additional lines, transformers, etc.).

Capacitors increase the voltage

Applying capacitors to a system will result in a voltage rise in the system from the point of installation back to the voltage source. This occurs because capacitors reduce the amount of current being carried through the system, reducing $I \cdot R$ and $I \cdot X$ voltage drops. Fixed capacitor banks don't change the amount of voltage variation (without switching), they only increase the average voltage.

The volt drop in transmission system is determined using the formula $I \cdot (R + jX)$. The voltage rise associated with the installation of a capacitor bank is approximated using the formula:

$$\frac{\Delta V}{V} = \frac{X \cdot Q}{V^2} = \frac{Q}{S_{sc}} \quad (1)$$

Where DV is the voltage rise, Q is the capacitor bank size in Mvar, S_{sc} is the 3 phase symmetrical fault level in MVA.

Power flow capacity

The power transferred across the system is a function of the voltage magnitude, the system impedance and the angle, δ , between the two bus voltages.

$$P = \frac{|V_1| \cdot |V_2|}{X_L} \sin \delta \quad (2)$$

To increase power flow capacity, we can increase the voltage magnitude and angle by adding shunt capacitors or reduce the impedance between the two busses by adding series capacitors.

Increasing system capacity

The thermal capacity of generators, transformers, lines and cables also limit the kVA load that can be supplied from the system. Reducing the kvar demand allows additional loads to be added to the system without upgrading the system. Supplying the reactive power needs directly at the load eliminates the need to transfer it through the supply system. Increased system capacity is often the most important benefit justifying the addition of shunt power capacitors on a distribution system. This is particularly significant when loads supplied by the system are increasing rapidly.

There is an economical power factor at which the power system should operate to optimise the cost of adding new system capacity. The most economical power factor based on released kVA (constant kW) can be determined by the following formula:

$$PF = \sqrt{1 - \left(\frac{C}{S}\right)^2} \quad (3)$$

Where PF is the economical power factor
 C is the cost per kvar of capacitor banks
 S is the cost per kVA of alternative supply equipment (lines, transformers, voltage regulators, etc.).

The formula compares the cost of capacitor banks to the cost of transformers, regulators, etc., as alternative means of providing increased system capacity.

A power factor of 0.96 is often viewed as the target power factor for customers to maintain before additional charges are levied by utilities. If this is the most economical system power factor, then the cost of capacitors is about 30% of the cost of increasing the system capacity through alternate means. The target power factor can also be determined from the amount of additional system capacity desired. From Fig. 5, select the current system power factor curve and follow it through to the required additional capacity. Read the required corrected power factor from the horizontal axis.

Feeder capacity is limited by the permissible voltage drop (5% or 10% depending on the voltage level). Application of capacitors reduces the voltage drop. The additional feeder capacity resulting from adding kvar of capacitors and achieving a similar voltage drop can be calculated by the following formula:

$$\Delta kVA = \frac{X(kvar)}{X \sin \theta + R \cos \theta} \quad (4)$$

Where R and X are the feeder resistance and inductive reactance and $\cos \theta$ is

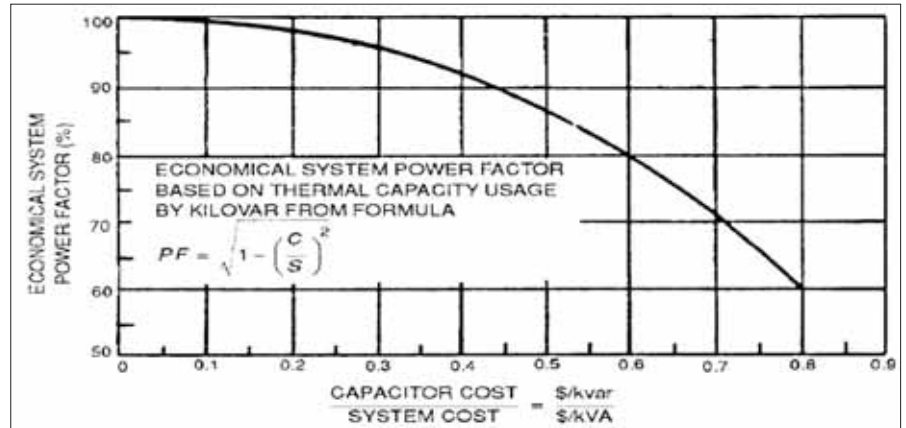


Fig. 4: Economic power factor for system capacity increases.

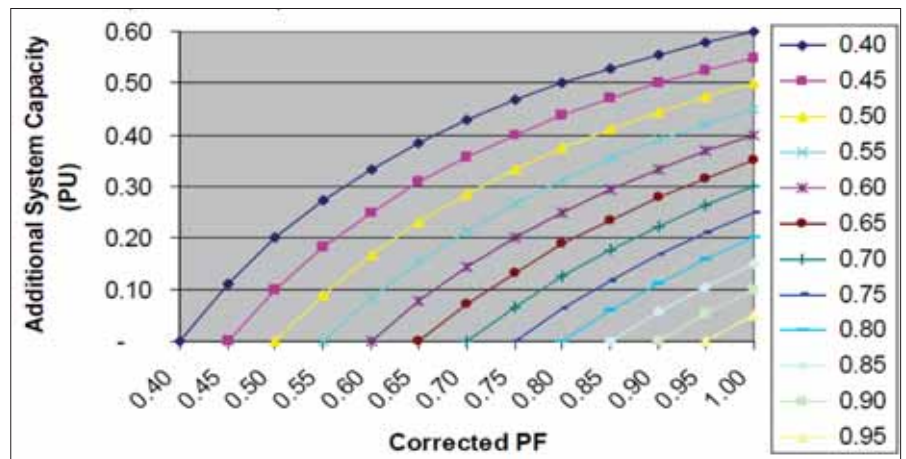


Fig. 5: Additional system capacity required.

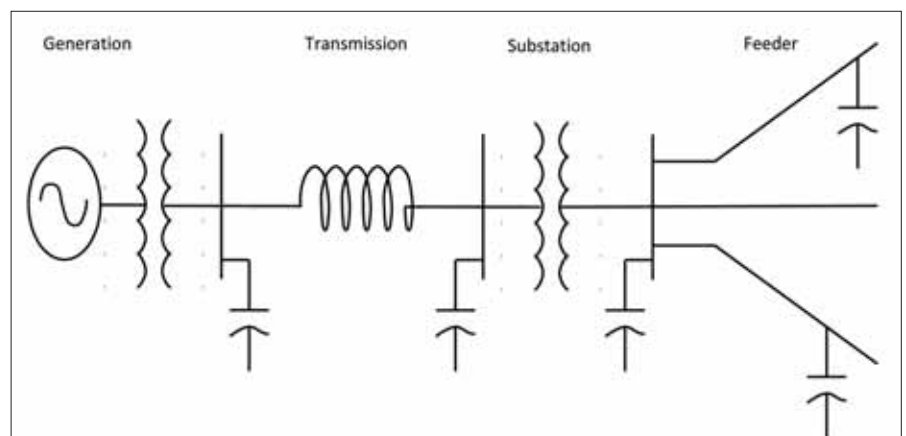


Fig. 6: Typical locations for capacitor banks.

the power factor of the load. Distribution feeders in the USA make extensive use of overhead line compensation to maximise the capacity.

Reducing losses

There is also an economical power factor based on loss reduction. Capacitors

reduce I^2R losses by eliminating kvar flow, so fewer kilowatt-hours need be generated. The maximum economical power factor based on peak kW loss reduction can be approximated using the

$$\cos \theta = \frac{1}{\sqrt{1 + \left(\frac{C}{2RP}\right)^2}} \quad (5)$$

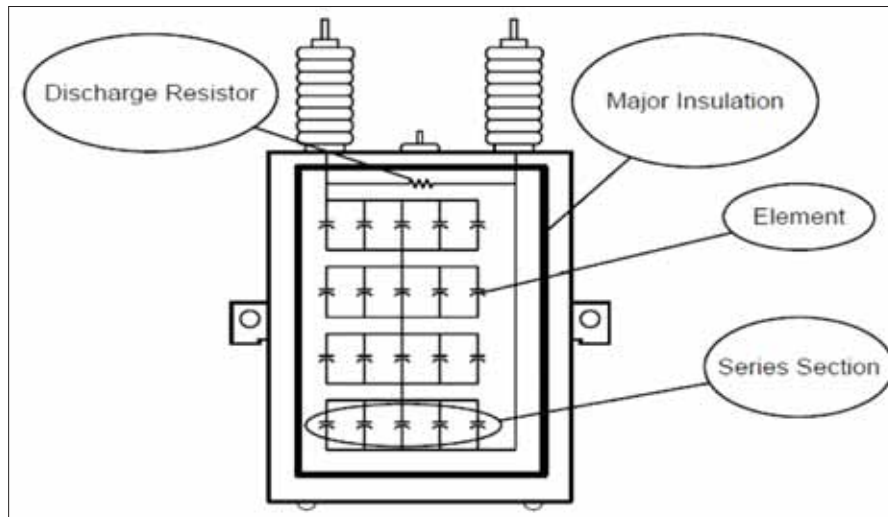


Fig. 7: Fuseless capacitor construction.

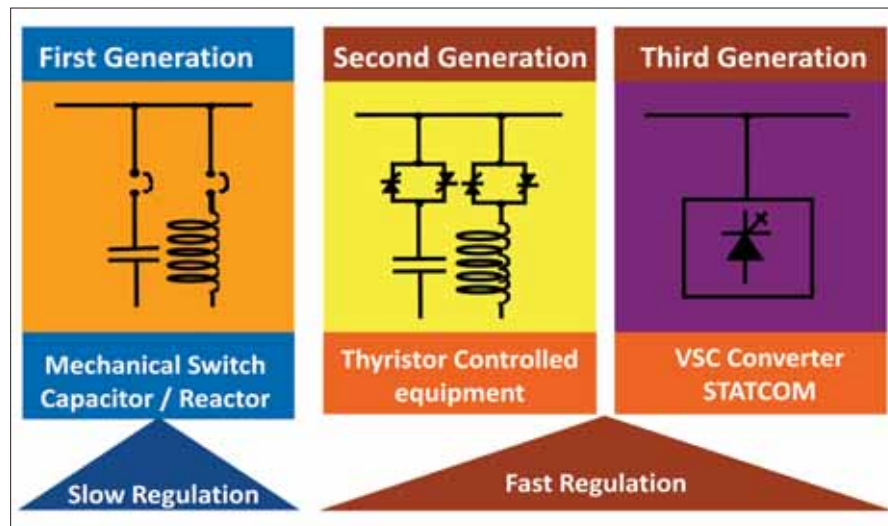


Fig. 8: History of development of reactive power compensation.

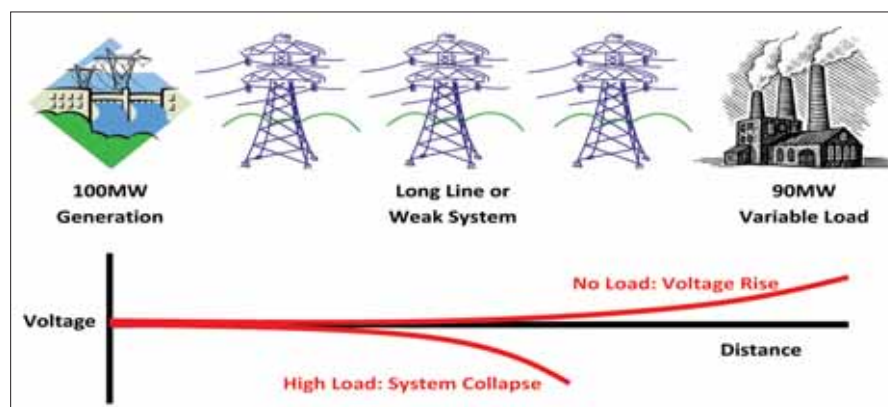


Fig. 9: Voltage problems with variable loads.

and in standard sizes where possible to optimise spares holding. Voltage rise associated with each step should be limited, depending on the switching frequency: Normally, fluctuations not exceeding 2% are acceptable for one switching in/out per hour, 3% for one switching in/out per 24 hours and 5% for seasonal switching. High voltage shunt capacitor banks are best suited to high voltage transmission systems with regular load and voltage profiles, where standard sizes are possible.

Fuseless capacitor banks offer the highest reliability from 66 kV and up, because of their safe failure mode without arcing and gasses. There should be sufficient series sections so that the balance of elements can operate safely after one or two element failures. Extensive OEM destructive testing has resulted in design guidelines, such as limiting the energy per series section to limit the explosive capacity during a failure, and to limit the normal current rating. The destructive testing has therefore meant that a definite tank rupture curve can be obtained. Fuseless capacitor banks also have lower losses because there are no I^2R fuse losses and they are easier to maintain with shorter outages. As a result, Eskom have standardised on fuseless capacitor banks from 66 kV and higher to maximise the availability on their network.

Medium voltage substation capacitor banks are good for releasing supply capacity in the distribution system. Internally fused capacitors are preferred for smaller banks and externally fused capacitors are preferred for larger banks to ensure maximum reliability and stability of the banks even after a few element failures. MV substation capacitor banks are suitable for industrial customers where low power factor loads requires additional transformer capacity. They are often configured as harmonic filters to eliminate harmonic resonance; and therefore the sizing and design requires high engineering input. So it is normally more effective to adjust the tariff to encourage customers with low power factor to install their own PFC.

Overhead line compensation (OHLC) banks are excellent for rural distribution. Located closer to the load, capacitors located on the distribution lines are a more effective means for supplying the reactive power requirements while minimizing system losses. Fixed banks are sized for minimum load conditions. Switched banks are normally used for voltage regulation due to fluctuating voltage profiles. OHLC banks are normally simple installations, with minimum protection and control functionality, and that means the cost in \$/kvar is very low.

Universal rules for the application of OHLC banks limit the engineering input requirements. The capacitor banks should be located where they produce the

where:

C is the cost of capacitors in \$/kvar

P is the cost of peak losses in \$/kW

and R is the system resistance, per unit.

Shunt capacitor banks

Shunt capacitor banks are typically installed in transmission and distribution

system at either end of the transmission lines (high voltage shunt banks), in MV substations and on MV distribution feeders.

Step size is the key driver of high voltage shunt capacitor banks. They should be reasonably large to balance the cost of the capacitors to the necessary switchgear

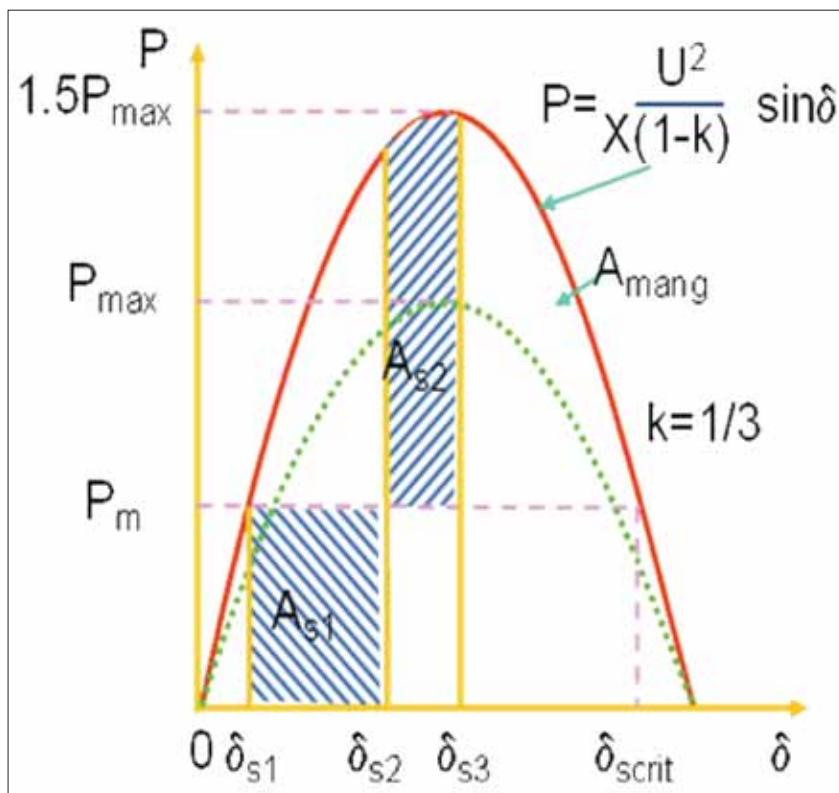


Fig. 13: SC increase voltage and angular stability.

waveform. By changing the firing angle, we are able to change the current waveform in the reactor and therefore the output of the reactor. Because of the change of the waveform, the TCR also generates significant harmonic currents.

Static synchronous compensators (Statcom)

Statcoms generate a sine wave from a voltage source, normally a DC capacitor. Hence they are referred to as Voltage Source Converters (VSC).

Statcom's use IGBT semiconductors which can also switch off. A series of cascaded and individually controlled bi-directional inverter bridges are turned on or off, as required, to generate an output voltage waveform. The number of modules determines the smoothness of the voltage waveform. The Statcom is shunt connected to the supply through a reactor and is therefore a controlled current source. Statcom acts like a capacitor or reactor depending on the control. The output waveform can be also adjusted continuously, to dynamically inject or filter harmonic currents for active filtering. The Statcoms response time is typically around 3 ms to 5 ms, making it faster and more flexible to the system needs.

Series compensation (SC)

Series capacitors compensate for the inductive line impedance to increase transmission system power transfer capacity and voltage and angular stability during transients.

The spark gap and MOV are the key technologies to protect the capacitors from over voltages. The whole capacitor bank is at the line potential, so it needs to be insulated from ground, and is difficult to measure the key parameters in the system. The first level of protection is the MOV, which is fast, but has limited protective capability. The second level is the spark gap, which needs to be triggered. The last level is "tripping" of the SC, which is done by closing the bypass circuit breaker. Therefore control and protection dominate the design requirements for series compensation systems.

Conclusion

Reactive power compensation is critical to strengthen weak transmission and distribution networks and the most economical means to increase their power transfer capability within the power quality constraints. The key objectives of RPC is to improve the voltage, increase power flow capacity, release thermal capacity and reduce losses.

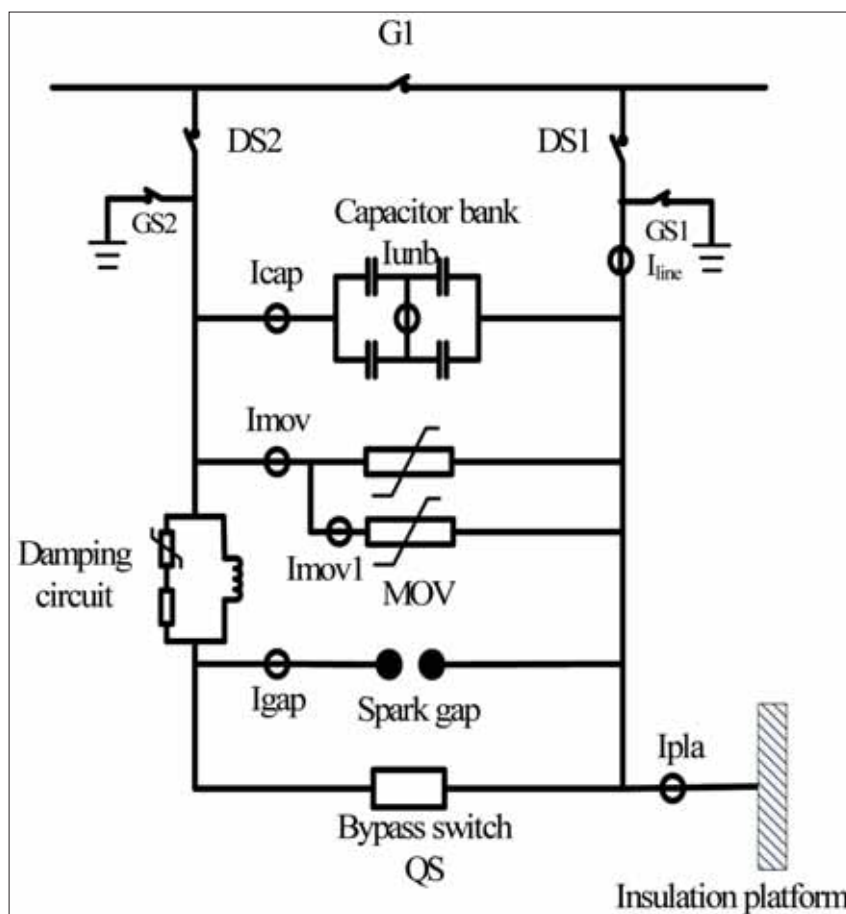


Fig. 14: SC single line diagram.

Thyristors are switched on at the firing angle and remain on until the current waveform

crosses the zero point. By their nature, reactors resist rapid changes to the current