

Shunt capacitor banks increase capacity of distribution networks

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There is tremendous growth currently being experienced in South Africa and it manifests itself to the power supply industry as a rapid growth in demand on the distribution networks. Distribution networks form the bulk of the electricity supply industry infrastructure, but don't get the attention enjoyed by the transmission networks or generation infrastructure.

The increased demand poses a challenge to both Eskom and the relevant municipalities to supply these additional loads as efficiently and cheaply as possible. The application of shunt capacitor banks is a cost effective manner to increase capacity, but as the voltages change within the distribution range, the optimum placement, sizing and fusing technology of the capacitor banks also changes.

Shunt capacitor banks reduce current

Electrical loads have a combination of both active and reactive power. Active power is supplied by the generating stations while reactive power can either be supplied from the generating stations or by making use of shunt capacitor banks strategically located on the power system (or other, generally more expensive, reactive power compensation schemes). Reactive power compensation with capacitors is by far the most cost effective way to meet reactive power requirements of consumer loads. Fig.1 illustrates the use of capacitors near loads.

The addition of shunt capacitors releases thermal capacity in the distribution networks by reducing current flowing through the networks, which is required to supply the loads. Fig. 2 shows the effect of capacitors on thermal loading. The addition of capacitor Q_c improves the power factor thus reducing thermal loading by Δ_s from S to S_1 . The system can serve an additional load of Δ_s .

Apart from the consumer loads, long distribution lines have their own requirements of reactive power. If all the reactive power requirements were to be supplied from the generating stations the total current would need to be produced by the generators and transmitted via the transmission and distribution networks to the loads. Therefore the transmission lines and associated equipment (conductors, transformers, switchgear etc.) would need to be larger to carry all the current. Simply put, shunt capacitor banks reduce the total current that needs to be transmitted through the distribution equipment. Fig. 3 illustrates the system capacity released by application of capacitors.

To determine the capacity released, select the curve with the current power factor of

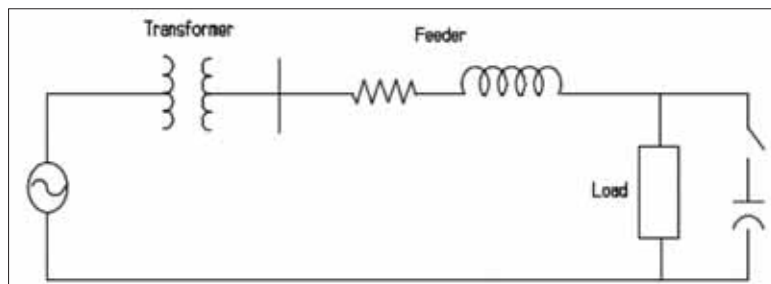


Fig. 1: Supplying reactive power requirements from capacitors located near loads.

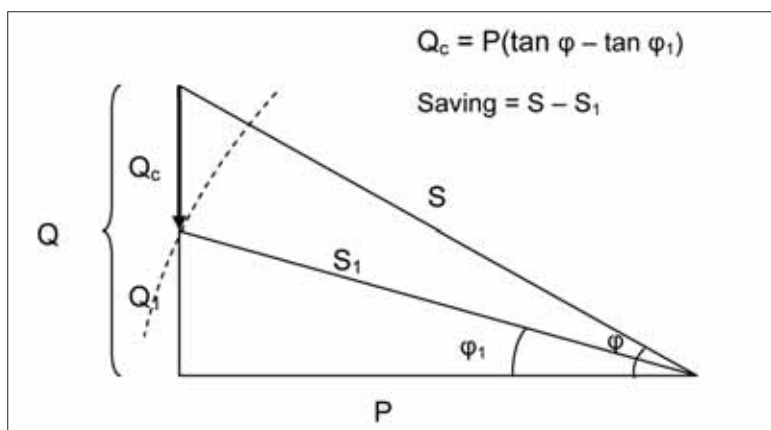


Fig. 2: Vector representation of capacitor effect on thermal loading.

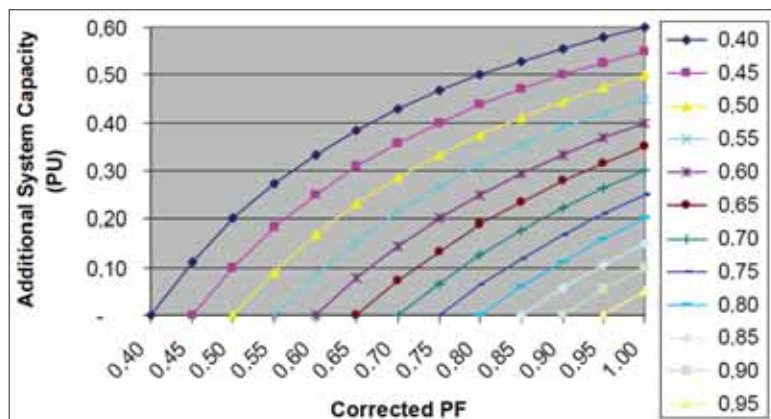


Fig. 3: Additional system capacity released through application of capacitors.

the load/feeder (legend) and then follow the curve the point to which the capacitor bank will improve the power factor (X axis) which gives the system capacity released (Y axis). The following are some of the benefits that can be realised through the use of shunt capacitor bank installations for reactive power compensation:

- Generation capacity is released
- System capacity is released
- System losses are reduced
- Voltage levels are raised (Improved quality of supply)
- Improved voltage regulation

Positioning capacitor banks to optimise distribution networks

The application of shunt capacitor banks reduces the losses (I^2R loss) associated with the transmission and distribution of the current to the consumers' loads. These losses in turn result in voltage drop. Customers situated at the end of weak systems often have problems starting and operating their electrical equipment due to low voltages, which may result in sluggish motor operation (motor torque has direct proportionality with the square of the supply voltage, $(T \propto V^2)$), dimmed lighting etc.. Placing capacitor banks near the electrical loads helps voltage support by reducing losses. Intelligent switching of the banks improves voltage regulation.

The main options available to improve voltage regulation on distribution networks are transformer tap changers, substation capacitor banks, fixed feeder capacitor banks and voltage regulators. The key difference between capacitor banks and voltage regulators is that capacitor banks reduce the losses across the length of the feeder and voltage regulators only improve the voltage at a particular point.

Software based load flow simulations are required in order to optimize the positioning of voltage support equipment, however there are a number of "rules of thumb" that can be used as the first case in the various optimisation iterations to determine the maximum losses reduction and optimum voltage regulation.

- 2/3 rule: For a feeder with evenly distributed loads, place a fixed capacitor bank with size 2/3 of the reactive power demand of the total load (low load case) at a position 2/3 along the distance of the feeder.
- 1/2 rule: For a feeder with uniformly decreasing distributed loads, the maximum loss reduction is achieved with a capacitor bank located 1/2 along the distance of the feeder.

Thereafter use switched capacitor banks to compensate for load variations. Switched capacitor banks are normally sized to limit the voltage rise at switching to between 2.5 and 5% (depending on each utility's preference). After fixed and switched capacitor banks are applied, voltage regulators can be applied to ensure that the voltage levels at all points along the feeder are within the power quality requirements of the utility.

Distribution networks form the bulk of electrical infrastructure

Electricity distribution networks are the backbone by which electricity supply is distributed to the customers. As such, ensuring the economical operation of the distribution network within power quality standard is imperative. Reactive power compensation at distribution

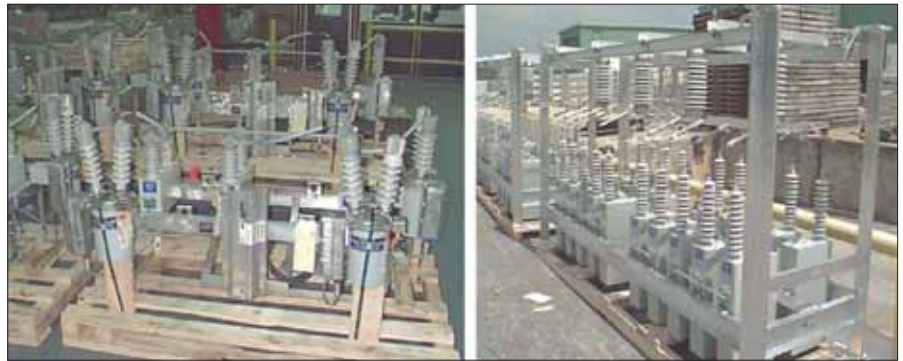


Fig. 4: Typical capacitor bank assemblies.

level is therefore imperative to maximize the power transmission capacity of the distribution networks.

In South Africa, electrical energy is generally distributed at 11 kV, 22 kV, 33 kV, 44kV, 66 kV, 88 kV and 132 kV. Within this range, and with different sizes of capacitor banks, the recommended fusing technology changes. The use of appropriate fusing technologies for shunt capacitor bank applications plays a vital role in the economics, maintainability and reliability of reactive power compensation. Proper selection is critical especially in the distribution voltage range. The main purpose of the fuse is to protect the capacitor from case rupture during a fault.

The optimum choice of fusing technology does depend on the options available depending on the voltage, size and placement of the capacitor bank. Fig. 4 shows typical capacitor bank assemblies.

Internally fused capacitors

Internally fused capacitor units are made up of individual capacitor elements connected in appropriate series and parallel combinations to achieve the required voltage and reactive power output rating, and these elements each have individual fuses connected in series with them (Fig. 5). These fuses are meant to disconnect the capacitor element from service to avoid capacitor case rupture due to the discharge of parallel energy. When one of the elements in an internally fused capacitor fails this results in a current flowing through its fuse (parallel discharge from the other parallel elements) and the fuse operates and disconnects the element from the rest of the circuit. The parallel connected elements remain in circuit thus reducing the overvoltage applied to the remaining series sections. However if many series elements have failed, then the remaining parallel elements will be insufficient to discharge sufficient energy to blow the new failed capacitor element. For this reason internally fused capacitor units typically require at least nine elements per series group.

Capacitor banks are generally equipped with unbalance protection schemes that sense the unbalance voltages or currents in the bank as a result of fuse operations.

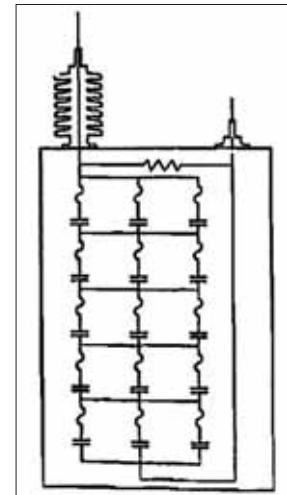


Fig. 5: Typical internally fused capacitor unit.

However in large high voltage capacitor banks with many capacitor units in series the unbalance currents will be so low that extremely sensitive unbalance current transformers are required or the protection can be unreliable. It is also very difficult to find the faulty capacitor because of the slight changes in capacitances during element failure. This is more critical in larger capacitor banks and internally fused technology is more suited for small medium voltage substation capacitor banks up to about 3 Mvar.

Externally fused capacitors

An externally fused capacitor unit consists of individual capacitor elements arranged in suitable series and parallel combinations to achieve the required voltage and reactive power output rating of the unit, and protected by a single fuse external to the unit. If an element fails, this results in the whole series element welding together which effectively means that the capacitor unit will have one less series section. The series section's voltage will be uniformly redistributed across the remaining healthy series sections. The current through the capacitor unit will also increase proportionally and after a sufficient number of series sections have shorted the external fuse will operate due to the increased current thus disconnecting the capacitor from service.

The capacitor banks are protected by use

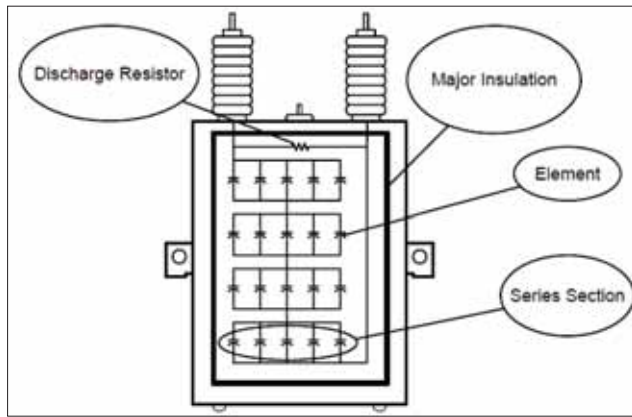


Fig. 6: Typical fuseless capacitor unit.

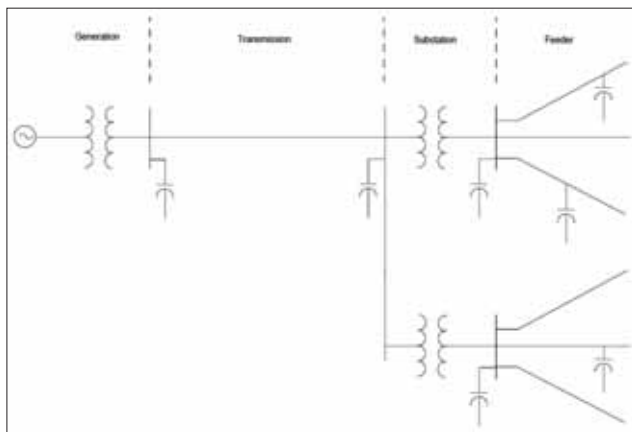


Fig. 7: Typical capacitor bank placement.

of unbalance protection schemes which sense the unbalance in voltage or current due to fuse operations. In an externally fused capacitor unit, if an element fails then a neutral potential develops and in a double star configuration a neutral current will flow whether or not the fuse blows. This unbalance scheme works well with this technology for large medium voltage banks as the change in the bank's unbalance due to element failure is fairly large and easy to detect. With enough series section in the bank, if an element fails the voltage rise across the healthy elements must be less than 10% to ensure that the bank can continue operating safely. For smaller banks, should a capacitor element's fuse blow, there is a significant rise in voltage of the remaining units which causes the whole capacitor bank to trip. It is for this reason that the externally fused technology is less suitable for smaller banks.

The risk of case rupture is greatly reduced since failed capacitors are rapidly removed from service through fuse operation. Minimal downtime during maintenance is achieved as the failed capacitor units are easily identified by the open external fuses. This makes externally fused capacitor banks easier to maintain and operate.

Eskom's experience with high voltage externally fused capacitors is frequent spurious fuse blowing, while there was no problem with the capacitors the fuses were supposedly protecting. This nuisance fuse

blowing has resulted in externally fused capacitors not being used at high voltages any more from a reliability point of view.

Fuseless capacitors

At higher voltages fuseless technology is the most preferred and is fast becoming the standard fusing technology. It is definitely the preferred fusing technology with Eskom. 33 kV seems to be the voltage level at which the advantages of fuseless technology is borderline, mainly because of the sensitivity that can be achieved with the protection. Fig. 6 shows a typical fuseless capacitor bank.

The phases of protection of a fuseless capacitor bank are:

- The safe failure mode of all film capacitors
- The limits to the overvoltages across healthy series sections after element failure
- Protective relaying

In a fuseless capacitor bank, should the dielectric fail, the energy in the resultant arc will puncture many layers of the thin film and foil within that particular element. The arc causes the film layers to reduce thereby allowing many layers of the aluminium foil electrodes to touch and weld together forming a stable electrical joint. The welded joint is capable of carrying indefinitely the full capacitor unit rated current and transient currents associated with normal current, without causing any thermal degradation or

gassing. Thus an entire series section is shorted in the event of a failed element.

This safe failure mode of fuseless capacitor units allows them to remain in service with shorted series sections thereby ensuring availability of the capacitor bank which would otherwise not be the case with externally fused or internally fused capacitor banks.

Fuseless capacitors typically have about four to eight series sections per capacitor unit (depending on the voltage rating). If a series section fails, then the voltage is distributed across the healthy elements. If one element in a single section fails, the voltage across the remaining series sections will be at least $8/7 = 114\%$ and the bank will need to be tripped soon as capacitors can only survive this voltage for a limited time. If there are two capacitor units in series, then voltage rise across the healthy elements is about 7%, which the capacitor should be able to withstand for extended periods. If further series elements fail, then the bank would need to trip out to protect the healthy capacitors. For safe and stable operation, the voltage across the healthy series sections should be less than 110% when two series elements have failed.

Neutral unbalance current protection is however subject to ambiguity. If an element fails in both sides of the double star, then they will cancel each other out and the protection will not operate when the second element fails. Depending on the capacitor design and application 33 kV banks must have three or more capacitors in series, and this is the voltage level at which fuseless technology is borderline from a stable and safe operation point of view.

HVT has, together with its predecessors, installed more than 95% of the Eskom high voltage capacitor banks and has standardised on the fuseless technology at higher voltages due to their better reliability, increased availability and improved maintainability.

Conclusion

Capacitor banks are a critical component of improving the voltage regulation and increasing distribution network capacity. Fig.7 shows typical capacitor bank placement.

For medium voltage (11 kV, 22 kV and sometimes 33 kV) substation and feeder capacitor banks, externally fused substation and pole top capacitor banks are best suited. For higher voltages (from 33 kV and up) fuseless capacitor banks installed in substations are preferred. At 33 kV, smaller banks would tend to be externally fused and larger banks would tend to be fuseless.

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