REACTIVE POWER & VOLTAGE CONTROL

1. Introduction

In general, performance of distribution systems and quality of the service provided are measured in terms of freedom from interruptions and maintenance of satisfactory voltage levels at the customer's premises that are within limits appropriate for this type of service. Due to economic considerations, an electric utility company cannot provide each customer with a constant voltage matching exactly the nameplate voltage on the customer's utilization apparatus.

Therefore, a common practice among the utilities is to stay with preferred voltage levels and ranges of variation for satisfactory operation of apparatus. In general, based on experience, too-high steady-state voltage causes reduced light bulb life, reduced life of electronic devices, and premature failure of some types of apparatus. On the other hand, too-low steady-state voltage causes lowered illumination levels, shrinking of TV pictures, slow heating of heating devices, difficulties in motor starting, and overheating and/or burning out of motors. However, most equipment and appliances operate satisfactorily over some range of voltage so that a reasonable tolerance is allowable.

2. Voltage drop in electrical networks

The approximate relationship between the magnitude of the voltage difference of two nodes in a network and the flow of power was shown to be

$$\Delta V \approx \frac{RP + XQ}{V}$$

Also it was shown that the transmission angle δ is proportional to

$$\delta \propto \frac{XP - RQ}{V}$$

Hence it may be seen that for networks where $X >> R$, that is, most high voltage power circuits, ΔV, the voltage difference, is determined mainly by Q while the angle δ is controlled by P.

Consider the simple system linking two generating stations A and B, as shown in Fig. 5.1. Initially the system is considered to be only reactive and R is ignored. The machine at A is in phase advance of that at B and V_1 is greater than V_2; hence there is a flow of real power from A to B. It is seen that P is determined by δ and Q mainly, by $V_1 - V_2$. In this case $V_1 > V_2$ and reactive power is transferred from A to B. By varying the generator excitations such that $V_2 > V_1$, the direction of the reactive power is reversed.

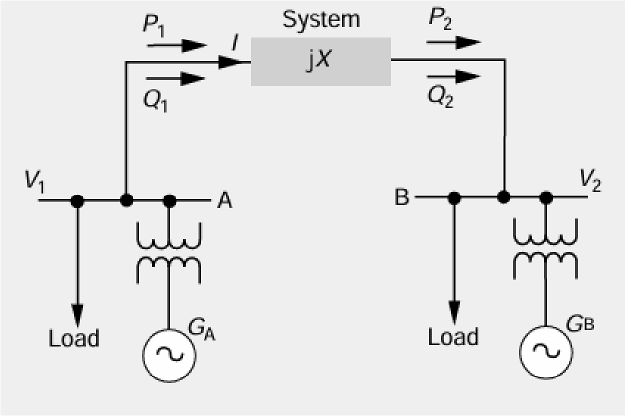


Fig. 5.1: System of two generators interconnected

Hence, real power can be sent from A to B or B to A by suitably adjusting the amount of steam (or water) admitted to the turbine, and reactive power can be sent in either direction by adjusting the voltage magnitudes. These two operations are approximately independent of each other if $X >> R$, and the flow of reactive power can be studied almost independently of the real power flow.

If it can be arranged that Q_2 in the system in Fig. 5.1 is zero, then there will be no voltage drop between A and B, a very satisfactory state of affairs. Now assume that the interconnecting system has some resistance and that V_1 is constant. Consider the effect of keeping V_2, and hence the voltage drop ΔV, constant. From equation (1)

$$Q_2 = \frac{V_2 \Delta V - R P_2}{X} = K - \frac{R}{X} P_2$$

where K is a constant and R is the resistance of the system.

If this value of Q_2 does not exist naturally in the circuit then it will have to be obtained by artificial means, such as the connection at B of capacitors or inductors.

If the value of the power changes from P_2 to $P_2{}'$ and if V_2 remains constant, then the reactive power at B must change to $Q_2{}'$ such that

$$Q_2{}' - Q_2 = \frac{R}{X}(P_2{}' - P_2)$$

that is, an increase in real power causes an increase in the reactive power needed to maintain V_2. The change, however, is proportional to (R/X), which is normally small. The voltage can be controlled by the injection into the network of reactive power of the correct sign.

3. Methods of Voltage Control

To keep distribution-circuit voltages within permissible limits, means must be provided to control the voltage, that is, to increase the circuit voltage when it is too low and to reduce it when it is too high. There are numerous ways to control voltage and to improve the distribution system's overall voltage regulation.

3.1. Injection of Reactive Power

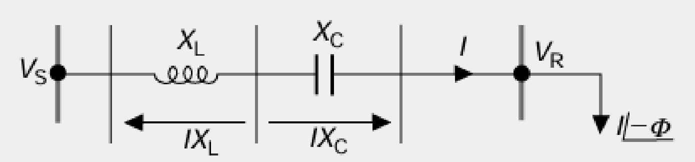
In general, four methods of injecting reactive power are available, involving the use of:
1. static shunt capacitors and reactors; 2. static series capacitors; 3. synchronous compensators; 4. static VAr compensators and STATCOMs.

1) Shunt Capacitors and Reactors

The shunt capacitors are used across an inductive load so as to supply part of the reactive vars required by the load so that the reactive vars transmitted over the line are reduced, thereby the voltage across the load is maintained within certain desirable limits. Similarly, the shunt reactors are used across capacitive loads or lightly loaded lines to absorb some of the leading vars again to control the voltage across the load to within certain desirable limits. Capacitors are connected either directly to a bus bar or through a tertiary winding of the main transformer and are disposed along the route to minimize the voltage drop and the losses. The disadvantage of the use of shunt capacitor or reactor is that with the fall of voltage at a particular node the correction vars are also reduced i.e., when it is most needed, its effectiveness falls. Similarly, on light loads when the corrective vars required are relatively less, the capacitor output is large.

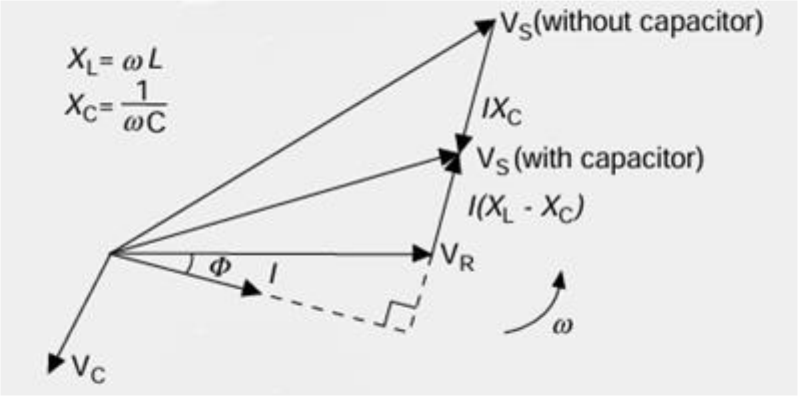
2) Series Capacitors

If a static capacitor is connected in series with the line, it reduces the inductive reactance between the load and the supply point and the voltage drop is approximately



Line with series capacitor,

$$\Delta V = RIcos\varphi_r + (X_L - X_C)Isin\varphi_r$$



Phasor diagram for fixed VR

Fig. 5.2: Phasor diagram when series capacitor is connected on a line

It is clear from the vector diagram (Fig. 5.2) that the voltage drop produced by an inductive load can be reduced particularly when the line has a high X/R ratio. In practice X_C may be so chosen that the factor $(X_L - X_C)Isin\varphi_r$ becomes negative and numerically equal to $RIcos\varphi_r$ so that the voltage drop becomes zero. The ratio X_C/X_L expressed as a percentage is usually referred to as the percentage compensation. If I is the full load current and X_C is the capacitive reactance of the series capacitor, then the drop across the capacitor is $X_C I$ and the VAr rating is $X_C I^2$. The voltage boost produced by the series capacitor

$$\Delta V = X_C Isin\varphi_r$$

One drawback of series capacitors is the high overvoltage produced across the capacitor terminals under short circuit conditions. The drop across the capacitor is $X_C I_f$, where I_f is the fault current which is of the order of 20 times the full load current under certain circuit condition. A spark gap with a high speed contactor is used to protect the capacitor under these conditions.

Comparison between Series and Shunt Capacitors

(i) The voltage boost due to a shunt capacitor is evenly distributed over the transmission line whereas the change in voltage between the two ends of the series capacitor where it is connected, is sudden. The voltage drop along the line is unaffected.

(ii) Let Qc ′ be the reactive power of the shunt capacitor, Er the receiving end voltage and X the reactance of the line; the current through the capacitor will be Qc ′/Er and the drop due to this current in the line will be (Qc ′/Er)X.

Similarly let Qc be the rating of the series capacitor I, the line current and sin ϕr the sine of the power factor angle of the load. The drop across the series capacitor will be (Qc/I) sin ϕr since the magnitude of the voltage across the capacitor is Qc/I.

For a typical load with p.f. 0.8 lag, sin ϕr = 0.6 and assume IX/Er = 0.1.

For equality of voltage boost with the two applications

$$\frac{Q_c' X}{E_r} = \frac{Q_c \sin \phi_r}{I}$$

$$\frac{Q_c'}{Q_c} = \frac{\sin \phi_r}{IX / E_r} = \frac{0.6}{0.1} = 6$$

It is evident that for the same voltage boost the reactive power capacity of a shunt capacitor is greater than that of a series capacitor.

(iii)The shunt capacitor improves the p.f. of the load whereas the series capacitor has little effect on the p.f.

(iv)For long transmission lines where the total reactance is high, series capacitors are effective for improvement of system stability.

3) Synchronous Compensators

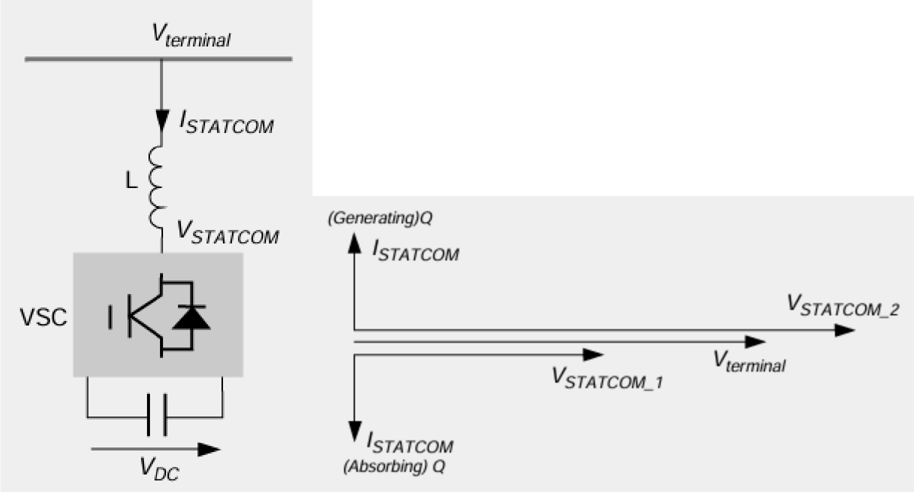
A synchronous compensator is a synchronous motor running without a mechanical load and, depending on the value of excitation, it can absorb or generate reactive power. As the losses are considerable compared with static capacitors, the power factor is not zero. When used with a voltage regulator the compensator can automatically run overexcited at times of high load and underexcited at light load. A great advantage of the synchronous compensator is its flexibility for use for all load conditions because it supplies vars when over-excited, i.e. during peak load conditions and it consumes vars when under-excited during light load conditions. There is smooth variation of reactive vars by synchronous capacitors as compared with step by step variation by the static capacitors. Synchronous machines can be overloaded for short periods whereas static capacitors cannot. For large outputs the synchronous compensators are much better than the static capacitors from economic viewpoint because otherwise a combination of shunt capacitors and reactors is required which becomes costlier and also the control is not smooth as is achieved with synchronous compensators. The main disadvantage of the synchronous compensator is the possibility of its falling out of step which will thus produce a large sudden change in voltage. Also these machines add to the short circuit capacity of the system during fault condition. Being a rotating machine, its stored energy is useful for increasing the inertia of the power system and for riding through transient disturbances, including voltage sags.

4) FACTS: Static VAr Compensators (SVCs) and STATCOMs

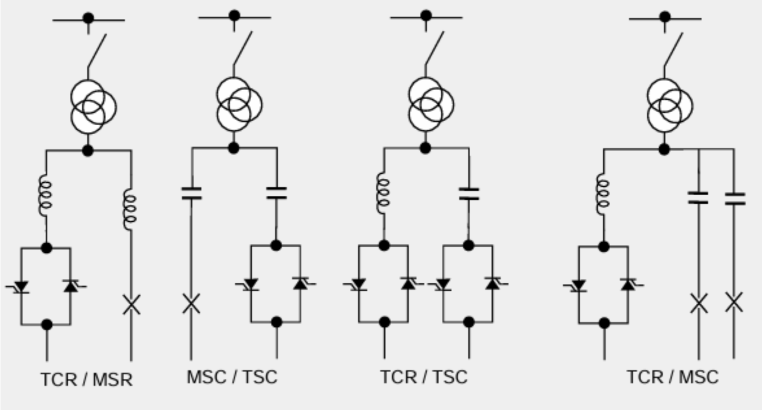
Synchronous compensators are rotating machines and so are expensive and have mechanical losses. Hence they are being superseded increasingly by power electronic compensators: SVCs and STATCOMs.

SVCs use shunt connected reactors and capacitors controlled by thyristors. The reactive power is provided by the shunt elements (capacitors and inductors) but these are controlled by thyristors. The output of the Thyristor Controlled Reactor (TCR) is controlled by delaying the switching on of the thyristor within the 50Hz cycle. The thyristor switches off when the current drops to zero. The firing angle of the thyristor can be varied within each cycle and hence the VAr absorption by the TCR controlled. TCRs may be used with Mechanically or Thyristor Switched Capacitors to create an SVC to export and import VArs. When a capacitor is connected to a strong voltage source, very large currents can flow. Hence Thyristor Switched Capacitors are only operated in integral cycles and the operation of the thyristors is timed so that they switch when there is no instantaneous voltage across the capacitor.

A STATCOM (Static Compensator) is also a power electronic device to provide reactive power but it operates on a different principle (Fig. 5.4). A STATCOM consists of a Voltage Source Converter (VSC) connected to the power system through a coupling reactance (L). The VSC uses very large transistors that can be turned on and off to synthesize a voltage sine wave of any magnitude and phase. VSTATCOM is a 50Hz sine wave kept in phase with Vterminal. If the magnitude of VSTATCOM is greater than that of Vterminal then reactive power is generated by the STATCOM while if the magnitude of VSTATCOM is less than that of Vterminal then reactive power is absorbed by the STATCOM. A very small phase angle is introduced between VSTATCOM and Vterminal so that a small amount of real power flows into the STATCOM to charge the DC capacitor and provide for the losses of the converter. However, the principle of operation is that the reactive power is provided by the interaction of the two voltage magnitudes across the reactor. The DC capacitor is only used to operate the power electronics and control the ripple current. STATCOMs can be controlled very fast and have a smaller physical equipment footprint than SVCs.



Operation of a STATCOM



Possible combinations of controlled reactors and capacitors forming an SVC.
TCR: Thyristor Controlled Reactor, MSR: Mechanically Switched Reactor,
MSC: Mechanically Switched Capacitor, TSC: Thyristor Switched Capacitor

2.2. Tap-Changing Transformers

1) On-load /Off-load tap changing transformers

The main job of a transformer is to transform electric energy from one voltage level to another. Almost all power transformers on transmission lines are provided with taps for ratio control i.e., control of secondary voltage. There are two types of tap changing transformers:
(i) Off-load tap changing transformers.
(ii) On-load (under-load) tap changing transformers.

By changing the transformation ratio, the voltage in the secondary circuit is varied. Hence voltage and reactive power control is obtained. In distribution circuits, tap-changing transformers are the primary method of voltage control. In a distribution transformer, the tap-changer compensates for the voltage drop across the reactance of the transformer but also for the variations in the voltage applied to the primary winding caused by changes of load within the high voltage network. In transmission circuits reactive power is dispatched by altering the taps of transformers and this, in turn, controls the network voltages.

The tap changing transformers do not control the voltage by regulating the flow of reactive vars but by changing the transformation ratio, the voltage in the secondary circuit is varied and voltage control is obtained. This method is the most popular as it can be used for controlling voltages at all levels.

Fig. 5.5 refers to the off-load tap changing transformer which requires the disconnection of the transformer when the tap setting is to be changed. The modern practice is to use on-load tap changing transformer which is shown in Fig. 5.6. In the position shown the voltage is a maximum and since the currents divide equally and flow in opposition through the coil between Q_1 and Q_2, the resultant flux is zero and hence minimum impedance. To reduce the voltage, the following operations are required in sequence: (i) open Q_1; (ii) move selector switch S_1 to the next contact; (iii) close Q_1; (iv) open Q_2; (v) move selector switch S_2 to the next contact; and (vi) close Q_2.

Thus six operations are required for one change in tap position. The voltage change between taps is often 1.25 per cent of the nominal voltage where nominal voltages are the voltages at the ends of the transmission line and the actual voltages are tsV_1 and trV_2 where ts and tr are the fractions of the nominal transformation ratios, i.e., the tap ratio/nominal ratio.

The tap changing operation is normally motor operated. A closed loop control of the secondary voltage level is possible.

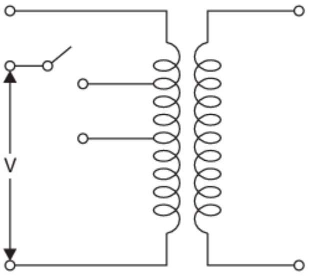


Fig. 5.5: Off-load tap changing transformer

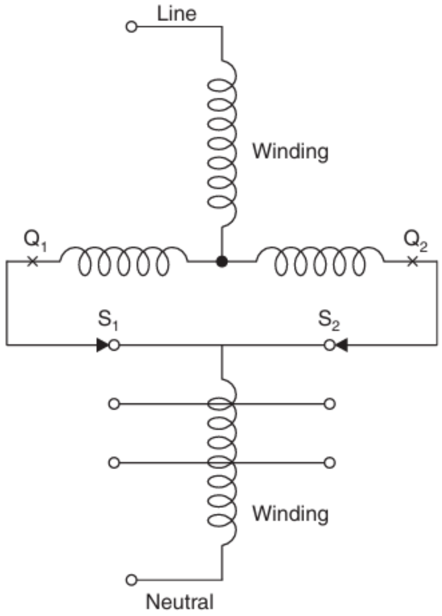


Fig. 5.6: On-load tap changing transformer

2) Booster Transformers

The two-winding load tap changing transformer performs two functions, transforming the voltage and bucking or boosting the voltage whereas the booster transformer performs the latter function only. It can be installed at a sub-station as an additional equipment if voltage regulation is further found to be necessary or it can be installed as a separate piece of equipment at any intermediate point in the line. The latter application may be desirable on economical or technical grounds to increase the voltage at an intermediate point in a line rather than at the ends as with tap changing transformer.

For small outputs and voltages up to 2000V, the simplest booster consists of an auto transformer with necessary tappings, whereas for higher voltages and larger sizes it is necessary to utilize on-load tap changing gear and also to perform the switching in an isolated circuit, the voltage of which is only a fraction of the line voltage. One method is to energize the primaries of the boosting transformers by means of a regulating transformer, the secondary of which is provided with tappings along with tap changing gear as shown in Fig. 5.7. The voltage changes are made by means of a motor operated controller and arrangements are made to reverse the connections to the primaries of the regulating transformers so that both buck and boost can be obtained. The sensing device for voltage variation should be sensitive to current rather than voltage as the current varies 100% from no load to full load whereas the voltage varies only by 10% or so.

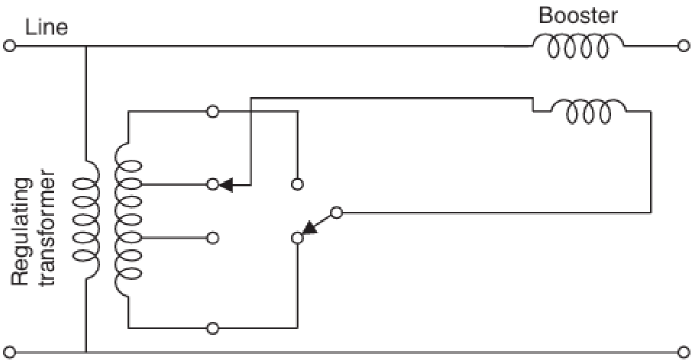


Fig. 5.7: Booster transformer along with regulating transformer

The following are the advantages of booster transformer:

(i) The transformer can be used at any intermediate point in the system.

(ii) When it is used along with a fixed ratio transformer it can be taken out for inspection or overhaul without affecting much the system.

(iii) The rating of the booster is the product of the current and the injected voltage and is hence only about 10% of that of a main transformer.

The disadvantages of the booster, when it is used in conjunction with the main transformer, are:

(i) The two are more expensive than a transformer with on-load tap changing gear.

(ii) They are less efficient due to the losses in the booster.

(iii) They take more floor space.

The booster transformers are normally used in distribution feeders where the cost of tap changing transformer is very high.