Use of capacitors to regulate the voltage in the network

Seminar paper

Power Distribution and Industrial Systems

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1 Power System

The function of power systems consists of the generation, transmission, distribution, regulation, and consumption of electrical energy. Since the accumulation of energy is not a good economical solution, the process of transmission, distribution, and consumption is realized in the same moment. Power systems that lie in a region, state, or continent are interconnected with each other and operate as a single unit, which is maximally harmonized and synchronized. The production and consumption of active and reactive power must be in balance.

Balance of production and consumption restricts the self-regulation of power systems. If the load of the power system would quite increase and if this increase cannot be supplied by the power system, then this would cause the degradation of the quality of electrical energy, the decrease of the system's frequency and voltage. This would cause the consumers to withdraw less energy from the power system with what the demand would decrease and the power system would stabilize in a lower frequency. However, there is only a few percent margin for such self-regulation.

If voltage is propped up with the injection of reactive power, then the demand increases more than supplied by transmitting lines will cause a consequential drop of frequency that may result in system collapse. Alternatively, if there is inadequate reactive power, the system may have voltage collapse. Voltage collapses usually occur on power systems which are heavily loaded or faulted or have shortage of reactive power. Voltage collapse is a system instability involving many power system components. In fact, a voltage collapse may involve an entire power system. Voltage collapse is typically associated with reactive power demand of load not being met due to shortage in reactive power production and transmission. Voltage collapse is a manifestation of voltage instability in the system.

System operators use reactive power resources to maintain the voltage at all the buses around the nominal value. Keeping transmission level voltages at nominal value or within a tight range ensures proper voltages at the distribution levels. Another important factor is that the transmission network security is closely associated with the voltage profile. Since the voltage on a bus is strongly coupled with the supply of reactive power, the voltage control service is also called reactive power support service. It is prudent to control the bus voltages by providing reactive power locally, rather than making it to flow through the grid. There are three major reasons for this. First, the power system equipment is designed to operate within a range of voltages, usually within ± 5% of the nominal voltage. At low voltages, the performance of most of the electrical equipment's is poor. For example,
induction motors can overheat and get damaged. High voltages will not only damage the equipment but also will short their life. 

Second, the power transmission capability available from a transmission line design is limited by technological as well as economical constraints. The reactive power consumes transmission and generation capacity. To maximize the amount of real power that can be transferred across a congested transmission interface, reactive power flows must be minimized. Similarly, reactive power production can limit a generator’s real power capability. Third, moving reactive power on the transmission system incurs real power losses. Thus, additional energy must be supplied to replace these losses.

2 Production and Consumers of Reactive Power

The reactive power flow on the system is reflected negatively on the voltage profile on the power system. Even though these values are tried to be reduced, their presence on the system is unavoidable, this because all the elements on the system need reactive power for their own needs. These needs are especially important for some consumers which their demand change significantly during the time.

Some system operators pay generators their embedded costs for reactive resources. However, determining the embedded costs of generator to provide reactive power support leads to ambiguity. This is so because; the same equipment is used to provide both real and reactive power. Questions like what percentages, for example, of the exciter, generator stator, generator rotor, turbine assembly, and step-up transformer should be assigned to each function are not easy to answer. Table 2.1 shows the comparison of various types of reactive power sources.

<table>
<thead>
<tr>
<th>Reactive Power Source</th>
<th>Speed of response</th>
<th>Ability to support voltage</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronous Generator</td>
<td>Fast</td>
<td>Excellent</td>
<td>High, Yes</td>
</tr>
<tr>
<td>Synchronous Condenser</td>
<td>Fast</td>
<td>Excellent</td>
<td>High, No</td>
</tr>
<tr>
<td>Capacitor</td>
<td>Slow, Stepped</td>
<td>Poor with V2</td>
<td>None, No</td>
</tr>
<tr>
<td>SVC</td>
<td>Fast</td>
<td>Poor with V2</td>
<td>Moderate, No</td>
</tr>
<tr>
<td>STATCOM</td>
<td>Fast</td>
<td>Fair, with V</td>
<td>Moderate, No</td>
</tr>
</tbody>
</table>

Table 2.1 Comparison of various types of reactive power sources
2.1 Production of Reactive Power

The main producers of reactive power in the power system are the synchronous generators, synchronous compensators and static compensators in the form of capacitive batteries. Beside of these, also the lines in certain circumstances appear as producers of the reactive power. It is important to mention that for the synchronous generator, the production of reactive power restricts the production of active power which also decreases the economical effectivity of the power plant.

2.1.1 Synchronous Machines

Synchronous machines that are designed exclusively to provide reactive support are called synchronous condensers. Synchronous Condenser in reality is just a synchronous machine which works as a synchronous motor without a mechanical load or a synchronous generator. Their power factor is not exactly zero, because these machines withdraw from the power grid the needed power to cover their no load losses. When such a machine works as overexcited it produces reactive power and when it works under excited it appears on the grid as a customer of the reactive load. This is why synchronous compensators are appropriate for voltage regulation if we look from the technical aspect, but their application is limited from the cost.

The synchronous generator also can work as a synchronous compensator. During the low loads that usually happen at night time the synchronous generator operates as an under excited machine and appears on the grid as a customer of the reactive power that is generated from the high voltage lines and this way it contributes by decreasing the voltages in the system which sometimes can exceed their allowed values.

The synchronous generators are very fast reactive support devices. The ability of a generator to provide reactive support depends on its real-power production. Figure 2.1 shows the limits on real and reactive production for a typical generator. This is also called as a capability curve of a generator. Like most electric equipment, generators are limited by their current-carrying capability. Near rated voltage, this capability becomes an MVA limit for the armature of the generator rather than a MW limitation, shown as the armature heating limit in the figure. Production of reactive power involves increasing the magnetic field to raise the generator's terminal voltage. Increasing the magnetic field requires increasing the excitation current in the rotating field winding. This too is current limited, resulting in the field-heating limit shown in the figure. Absorption of reactive power is limited by the magnetic-flux pattern in the stator, which results in excessive heating of the stator-end iron, the core-end heating limit. The synchronizing torque is also reduced when absorbing large amounts of reactive power, which can also limit generator capability to reduce the chance of losing synchronism with the system.
During the nominal mode, the regulation consists on the increase of the reactive power of the generator, or his voltage when it comes up to the increase of the active load, while with the decrease of his reactive power, or voltage when his active power is decreased.

![Figure 2.1 Capability curve of a generator](image)

2.1.2 **Static compensators – Capacitors**

Capacitors and inductors are passive devices that generate or absorb reactive power. They accomplish this without significant real-power losses or operating costs. The output of capacitors and inductors is proportional to the square of the voltage. Capacitor banks are composed of individual capacitors. The individual capacitors are connected in series and parallel to obtain the desired capacitor-bank voltage and capacity rating. The capacitor banks are often configured with several steps to provide a limited amount of variable control.

Capacitors are used as capacitive batteries and produce reactive power. Their U-Q characteristic is pressed in the figure 2.2. From the following equation shows the reactive power produced from a capacitor, we can see that with the decrease of the voltage we will have a lower rate of reactive power produced and vice versa.

\[ Q_c = 3\omega CU^2 \]

This is consider as one of the technical disadvantages, beside of that their application in the distribution networks is quite convenient and quite spread. Actually capacitive batteries represent the main device for voltage and reactive power regulation in the transmission and distribution power system.
Capacitors provide tremendous benefits to distribution system performance. Most noticeably, capacitors reduce losses, free up capacity, and reduce voltage drop:

- **Losses; Capacity** - By canceling the reactive power to motors and other loads with low power factor, capacitors decrease the line current. Reduced current frees up capacity; the same circuit can serve more load. Reduced current also significantly lowers the $I^2R$ line losses.
- **Voltage drop** - Capacitors provide a voltage boost, which cancels part of the drop caused by system reactive loads. Switched capacitors can regulate voltage on a circuit.

If applied properly and controlled, capacitors can significantly improve the performance of distribution circuits. But if not properly applied or controlled, the reactive power from capacitor banks can create losses and high voltages. The greatest danger of overvoltages occurs under light load. Good planning helps ensure that capacitors are sited properly. More sophisticated controllers reduce the risk of improperly controlling capacitors like SVC – *Static VAR Compensation* and STATCOM - Static Synchronous compensator.

### 2.2 Consumers of Reactive Power

The required reactive power can be represented by the daily reactive load diagram as it is represented in figure 2.3. If we compare the daily diagram of active and reactive load we can see that for the active load consumption during 24 hours there are two peaks, one in the morning and one in the evening, in the other hand for the reactive load consumption we can see that there is only one peak which one decreases after the end of the first shift of the industrial consumers. These consumers have the most needs for relative power. For this reason the flow of reactive power through the system elements that are mainly reactive consumers will cause high voltage drops on the system.
2.2.1 Asynchronous Motor

One of the main consumers of reactive power are the asynchronous motors. These motors even in the no load operation they withdraw reactive power from the system round 30% of their nominal power. With the increase of load, the active power consumption is increased and with that the consumption of reactive power which can go up to 50%. The equation that represents the reactive power consumption is described below:

\[ Q_{AM} = Q_0 + p^2 \Delta Q_n = 3U_n I_0 + \left( \frac{P}{P_n} \right)^2 3 \left( \frac{P_n}{\sqrt{3} U_n} \right)^2 X_m \]

When we consider that the area of application of the asynchronous motor in the industry where usually it takes more than 60% of the total consumption we can imagine what are the values of the reactive power required.

2.2.2 Transformer

Transformers are largest consumers of the reactive power in the group of powers systems elements. In percentage to the nominal power the consumption of the transformer is significantly smaller when compared with the asynchronous motor. Unlike the asynchronous machine, the transformer in no load operation it consumes only 1-2% reactive power of its nominal power. A considerable value of reactive power is spent by the current of the loads that flow through the transformers reactance. The following equation shows the consumption of reactive power of a transformers during different loads:

\[ Q_t = Q_0 + s^2 Q_n = 3U_n I_0 + 3 I_n^2 \left( \frac{S}{S_n} \right)^2 \]
For nominal load of the transformer the reactive power consumption goes up to 10% of its nominal power. Even though this value is relatively low we have to consider that the energy has to be transferred from the production line to the consumer, what means that it has to pass 4-5 transformations and in each transformation will have its own consumption or losses. Practically, to deliver 1 MW of active power, we have to spend 0.4 up to 0.5 MVAr of reactive power. So we can conclude that transformers are a considerable reactive consumers in the power system.

### 2.3 Power Lines

Electrical power lines, mounted underground or in air, can appear as consumers of reactive power when they are loaded more than their natural power. But they can appear as a producer of reactive power in the case when they are loaded under their natural power, this phenomena is known as Ferranti effect. In these cases the reactive power that is spent in the longitudinal reactance of the line is generated or compensated from the transversal susceptance of the line. Transmission lines produce reactive power (MVAr) due to their natural capacitance. The amount of MVAr produced is dependent on the transmission lines capacitive reactance $X_C$ and the voltage at which line is energized. In equation form the MVAr produced by a transmission line is:

$$\Delta Q_C = \frac{U^2}{X_C}$$

Transmission lines also use reactive power to support their magnetic fields. Magnetic field strength is dependent on the magnitude of the current flow through the line and the line’s natural inductive reactance $X_L$. It follows then that the amount of MVAr used by a transmission line is a function of current flow and inductive reactance. In equation form the MVAr used by a transmission line is:

$$\Delta Q_L = 3 I^2 X_L$$

The balance of reactive power in a power line is known as Surge Impedance Loading (SIL) of a transmission line. When SIL occurs $\Delta Q_C=\Delta Q_L$ than the surge impedance is equal to:

$$3 I^2 X_L = \frac{U^2}{X_C}$$

$$X_L X_C = \frac{3 U^2}{3 I^2}$$

$$\sqrt{\frac{\omega L}{\omega C}} = \frac{U_f}{I_f} = Z_0$$
The above equation is known as the “surge impedance”. The significance of the surge impedance is that if a purely resistive load that is equal to surge impedance is connected to the end of a transmission line with no resistance, a voltage surge introduced to the sending point of the line would be absorbed completely at the receiving point. The voltage at the receiving point would have the same magnitude as the sending point voltage and would have a phase angle that is lagging with respect to the sending point by an amount equal to the time required to travel across the line from sending to receiving point. The value of SIL to a System Operator is realizing that when a line is loaded above its SIL it acts like a reactor – absorbing MVar from the system and when a line is loaded below its SIL it acts like a capacitor – supplying MVar to the system.

When the following equation is equal to 0 we say that the reactive load on the line is balanced otherwise the reactive power that is consumed or produced on a line is represented with the following equation:

$$\Delta Q = \Delta Q_L - \Delta Q_C = 3I^2X_L - \frac{U^2}{X_C}$$

If consider that the voltage $U \approx \text{const.}$, from the abovementioned equation we can conclude that for higher loads the reactive power that is spent in the longitudinal reactance is higher than the reactive power generated from the transversal susceptance, therefore the line appears like a reactive power consumer:

$$\Delta Q_L > \Delta Q_C$$

For loads smaller than the natural power of the lines, this randomly happens during the night time, especially when the lines are not loaded than the lines appear as generators of the reactive power on the power system.

$$\Delta Q_L < \Delta Q_C$$

Practically, Surge Impedance of cables can be quite high (higher than the thermal limits) and they are typically loaded much below their Surge Impedance Loading. This leads to significant generation of reactive power and overvoltage problems if cable length is greater than 80 km.

3 Voltage drop

The regulation of voltage and reactive power flow in the power system it is very important. By level of importance it comes just after the regulation of frequency and active power. Even though this two regulation types are connected with each other in some portion, however they are discussed separately. This because the dependence between voltage and reactive power is exposed as the dependence of frequency with active power.
Despite the frequency that in every point of the power system is the same, the voltage practically in every point of the system is different, that’s because for every power flow or current flow in the system will cause an unavoidable voltage drop.

### 3.1 Calculation of Voltage Drop on a Line

Let us consider the one radial line in which flows the power $S=P+jQ$ in one way as it is schematically presented in the figure 3.1. This line is loaded with a three phase symmetrical load. If the voltage in the beginning of the line is written as $U_1$ and the voltage on the end $U_2$ than the difference of the voltage from the beginning of the line with the one in the end gives us the voltage drop on the line.

![Figure 3.1 Equivalent scheme of a distribution line](image)

In the figure 3.2 the voltage drop is expressed with the vector $AB$. Where the $AC$ represents the longitudinal vector and $CB$ represents the transversal vector.

![Figure 3.2 The phasor diagram representation of voltage drop in a line](image)
From the phasor diagram in figure 3.2 we can see that this relation can be written as:

\[ U_1^2 = (U_2 + \Delta U_{long})^2 + \Delta U_{trans}^2 = (U_2 + R \cos \phi + X \sin \phi)^2 + (X \cos \phi - R \sin \phi)^2 \]

By knowing the relation for power we can write the voltage drop equation by the power flow:

\[ I \cos \phi = \frac{P}{\sqrt{3}U} \]

and

\[ I \sin \phi = \frac{Q}{\sqrt{3}U} \]

After the replacement on the we will have:

\[ U_1^2 = (U_2 + \frac{PR + QX}{U_2})^2 + (\frac{PX - QR}{U_2})^2 \]

When we write in the vectorial form we have:

\[ U_1 = (U_2 + \frac{PR + QX}{U_2}) + j(\frac{PX - QR}{U_2}) \]

![Figure 3.3 Phase diagram of voltage drop of a loaded lined](image)

The transversal component can be neglected because its value is insignificant against the longitudinal component since the resistance is quite small against the reactance, so the equation will take this form:

\[ U_1 = (U_2 + \frac{PR + QX}{U_2}) \]
The transmission lines are almost all reactive, so $X \gg R$. For the voltage drop we can write:

$$\Delta U = U_1 - U_2 = \frac{QX}{U_2}$$

And by this we can conclude that the voltage drop on the line it is dependent from the flow of the reactive power through the line considering that the flow of active power is unavoidable. By this equation we see that it exists a strong relation between the voltage drop and the reactive power.

$$\Delta U \sim Q \quad (8)$$

### 3.1.1 Ferranti effect

The effect in which the voltage at the end of the transmission line is higher than the voltage in the beginning of the line is known as the Ferranti effect. Such type of effect mainly occurs because of light load or open circuit at the receiving end.

![Figure 3.4 Ferranti effect on a power line](image)

Capacitance and inductance are the main parameters of the lines having a length 80 km or above. On such transmission lines, the capacitance is not concentrated at some definite points. It is distributed uniformly along the whole length of the line. At power system frequencies, many useful simplifications can be made for lines of typical lengths. For analysis of power systems, the distributed resistance, series inductance, shunt leakage resistance and shunt capacitance can be replaced with suitable simplified networks.
A short length of a power line (less than 80 km) can be approximated with a resistance in series with an inductance and ignoring the shunt admittances. This value is not the total impedance of the line, but rather the series impedance per unit length of line. For a longer length of line (80–250 km), a shunt capacitance is added to the model. In this case it is common to distribute half of the total capacitance to each side of the line (π model) or in the middle of the line and distribute the resistance and reactance (T model). As a result, the power line can be represented as a two-port network, such as ABCD parameters.

Figure 3.5 Representation scheme for lines shorter than 80 km

Figure 3.6 Representation scheme for lines longer than 80 km

The Ferranti Effect will be more pronounced the longer the line and the higher the voltage applied. The relative voltage rise is proportional to the square of the line length. The Ferranti effect is much more pronounced in underground cables, even in short lengths, because of their high capacitance. It was first observed during the installation of underground cables in Sebastian Ziani de Ferranti's 10 kV distribution system in 1887. Nowadays the Ferranti effect is controlled by installing switchable reactance banks.

3.1.2 Tap Transformers for voltage regulation

Transformers are used to transfer power between different voltage levels or to regulate real or reactive flow through a particular transmission corridor. Most transformers come equipped with taps on the windings to adjust either the voltage transformation or the reactive flow through the transformer. Such transformers are called either load-tap-changing (LTC) transformers or tap-changing-under-load (TCUL) transformers. A tap changer is a mechanism in transformers which allows for variable turn ratios to be selected in discrete steps. Transformers with this mechanism obtain this variable turn ratio by connecting to a number of access points known as taps along the primary high voltage and low current winding. These systems usually possess 1 tap per 1% of the rated and allow a regulation in a range from ±5% up to ±20% variation from the nominal transformer rating which, in turn, allows for stepped voltage regulation of the output.

This method is applied for the regulation of the transformers on the power system. This voltage regulation method is quite effective for the regulation of voltage on the bus bars that don’t suffer much load changes. This method is based on changing the number of windings of the transformers to minimize the current handling requirements of the
contacts. By this we can increase the voltage on the secondary side and by this we will partly compensate the voltage drops on the system. This method is applied in the middle and high voltage levels (35 kV and up) by installing the transformers in the peak point of the system.

### 3.2 Power Factor correction

Most loads in modern electrical distribution systems are inductive. Examples include motors, transformers, gaseous tube lighting ballasts, and induction furnaces as represented in table 3.1.

<table>
<thead>
<tr>
<th>Devices</th>
<th>cos Φ</th>
<th>tan Φ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard asynchronous motor loaded at</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0%</td>
<td>0.17</td>
<td>5.8</td>
</tr>
<tr>
<td>25%</td>
<td>0.55</td>
<td>1.52</td>
</tr>
<tr>
<td>50%</td>
<td>0.73</td>
<td>0.94</td>
</tr>
<tr>
<td>75%</td>
<td>0.80</td>
<td>0.75</td>
</tr>
<tr>
<td>100%</td>
<td>0.81</td>
<td>0.62</td>
</tr>
<tr>
<td>Incandescent lamp</td>
<td>=1</td>
<td>=0</td>
</tr>
<tr>
<td>Noncompensated fluorescent lamps</td>
<td>=0.5</td>
<td>=1.73</td>
</tr>
<tr>
<td>Compensated fluorescent lamps (0.93)</td>
<td>0.93</td>
<td>0.39</td>
</tr>
<tr>
<td>Discharge lamps</td>
<td>0.4–0.6</td>
<td>2.29–1.33</td>
</tr>
<tr>
<td>Resistance furnaces</td>
<td>=1</td>
<td>=0</td>
</tr>
<tr>
<td>Induction furnaces with built-in compensation</td>
<td>=0.85</td>
<td>=0.62</td>
</tr>
<tr>
<td>Dielectric heating furnaces</td>
<td>=0.85</td>
<td>=0.62</td>
</tr>
<tr>
<td>Resistance welding machines</td>
<td>0.8–0.9</td>
<td>0.75–0.48</td>
</tr>
<tr>
<td>Arc welding single-phase static stations</td>
<td>=0.5</td>
<td>1.73</td>
</tr>
<tr>
<td>Arc welding rotary sets</td>
<td>0.7–0.9</td>
<td>1.02–0.48</td>
</tr>
<tr>
<td>Arc welding transformers–rectifiers</td>
<td>0.7–0.8</td>
<td>1.02–0.75</td>
</tr>
<tr>
<td>Arc furnaces</td>
<td>0.8</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Table 3.1 Power factor for common devices

Inductive or reactive loads, such as with capacitors or inductors, storage energy in the loads that results in a phase difference between the current and voltage waveforms. During each cycle of the AC voltage, extra energy, in addition to any energy consumed in the load, is temporarily stored in the load in electric or magnetic fields, and then returned to the power grid a fraction of the period later. So we can say that loads require two kinds of currents or energies:

- **Active or working power (kW)** to perform the actual work of creating heat, light, motion, machine output, and so on.
- **Reactive power (kVAr)** to sustain the magnetic field. Reactive power does not perform useful “work,” but circulates between the generator and the load. It places a heavier drain on the power source, as well as on the power source’s distribution system.
The power factor of a power system is defined as the ratio of the real power flowing to the load to the apparent power in the circuit, and is a dimensionless number in the closed interval of −1 to 1. A high power factor signals efficient utilization of electrical power, while a low power factor indicates poor utilization of electrical power. To determine power factor (PF), divide working power (kW) by apparent power (kVA). In a linear or sinusoidal system, the result is also referred to as the cosine $\phi$.

However distribution companies typically charge industrial customers a penalty for power factor lower than something like 0.85 or 0.9. For other customers, there is typically no charge. Losses on the customer side of the meter are usually small enough to make it not worthwhile to use sophisticated correction schemes.

### 3.2.1 Concept of Leading and Lagging Power Factors

Many consider that the terms “lagging” and “leading” power factor are somewhat confusing, and they are meaningless, if the directions of the flows of real and reactive powers are not known. In general, for a given load, the power factor is lagging (positive) if the load withdraws reactive power; on the other hand, it is leading (negative) if the load supplies reactive power. Hence, an induction motor has a lagging power factor since it withdraws reactive power from the source to meet its magnetizing requirements. But a capacitor (or an overexcited synchronous motor) supplies reactive power and thus has a leading power factor, as shown in Figure 3.4:

![Diagrams of power factor](image)

*Figure 3.7 Examples of some of the sources of leading and lagging reactive power at the load*
On the other hand, an underexcited synchronous motor withdraws both the real and reactive power from the source, as indicated. The use of varmeters instead of power factor meters avoids the confusion about the terms “lagging” and “leading.” Such a varmeter has a zero center point with scales on either side, one of them labeled “in” and the other one “out.”

4 Capacitors in Power Systems

For the reduction of cost and improved reliability, most of the world’s electric power systems continue to be interconnected. Interconnections take advantage of diversity of loads, availability of sources and fuel price for supplying power to loads at minimal cost. Compensation in power systems is, therefore, essential to alleviate some of these problems. Series/shunt compensation has been in use for the past many years to achieve this objective.

Load compensation is the management of reactive power to improve power quality i.e. voltage profile and power factor. The reactive power flow is controlled by installing shunt compensating devices (capacitors/reactors) at the load end bringing about proper balanced between generated and consumed reactive power.

On power systems, capacitors do not store their energy very long—just one-half cycle. Each half cycle, a capacitor charges up and then discharges its stored energy back into the system. The net real power transfer is zero. Just when a motor with low power factor needs power from the system, the capacitor is there to provide it. Then, in the next half cycle, the motor releases its excess energy, and the capacitor is there to absorb it. Capacitors and reactive loads exchange this reactive power back and forth. This benefits the system because that reactive power (and extra current) does not have to be transmitted from the generators all the way through many transformers and many kilometers of lines; the capacitors can provide the reactive power locally. This frees up the lines to carry real power, power that actually does work.

Capacitor units are made of series and parallel combinations of capacitor packs or elements put together as shown in Figure 4.1.
Capacitors are made within a given tolerance. The IEEE standard allows reactive power to range between 100% and 110% when applied at rated sinusoidal voltage and frequency (at 25°C case and internal temperature) (IEEE Std. 18-2002). In practice, most units are from +0.5% to +4.0%, and a given batch is normally very uniform. Capacitor losses are typically on the order of 0.07 to 0.15 W/kVar at nominal frequency.

Losses include resistive losses in the foil, dielectric losses, and losses in the internal discharge resistor. Capacitors must have an internal resistor that discharges a capacitor to 50 V or less within 5 min when the capacitor is charged to the peak of its rated voltage. This resistor is the major component of losses within a capacitor.

Capacitors have very low losses, so they run very cool. But capacitors are very sensitive to temperature and are rated for lower temperatures than other power system equipment such as cables or transformers. Also, capacitors are designed to operate at high dielectric stresses, so they have less margin for degraded insulation. Standards specify an upper limit for application of 40°C or 46°C depending on arrangement. These limits assume unrestricted ventilation and direct sunlight. At the lower end, IEEE standard 18 specifies that capacitors shall be able to operate continuously in a −40°C ambient.

### 4.1 Line Compensation

As the power demand increases, the voltage drop and losses are increased since the voltage drop is proportional to the demand current and losses are proportional to the square of demand current. Ideal voltage profile for a transmission line is flat, while this may not be achievable, the characteristics of the line can be modified by line compensators so that:

- Ferranti effect is minimized.
- Under excited operation of synchronous generators is not required.
iii. The power transfer capability of the line is enhanced. Modifying the characteristics of a line is known as line compensation.

Various compensating devices can be used as:

- Capacitors
- Capacitors and inductors
- Active voltage source (synchronous machines)

When a number of capacitors are connected in parallel to get the desired capacitance it is known as a bank of capacitors, similarly a bank of inductors. A bank of capacitors and/or inductors can be adjusted in steps by switching (mechanically).

Capacitors and inductors as such are passive line compensators, while synchronous generator is an active compensator. When solid-state devices are used for switching off capacitors and inductors, this is regarded as active compensation. Regarding the connection type of static compensators we can have shunt and series compensation.

4.2 Serial Capacitors

Series capacitors, are capacitors connected in series with line, it is not commonly used due to the specialized type of apparatus with a limited range of application. Also, because of the special problems associated with each application. As shown in the figure 4.2, a series capacitor compensates the inductive reactance. In other words, a series capacitor is a negative reactance in series with the positive (inductive) reactance with the effect of compensating for part or all of it. Therefore, the primary effect of the series capacitor is to minimize, or even suppress the voltage drop caused by the inductive reactance in the circuit. At times, a series capacitor can even be considered as a voltage regulator that provides for a voltage boost which is proportional to the magnitude and power factor of the through current. Therefore, a series capacitor provides a voltage rise which increases automatically and instantly as the load grows. Also, a series capacitor produces more net voltage rise than a shunt capacitors at a lower power factor. However, a series capacitor betters the systems power factor much less than a shunt capacitor and has little effect on the source current.
Consider the feeder circuit and its voltage phasor diagram as shown in figure 4.2 and Xc. The voltage drop through the feeder can be expressed approximately as:

\[ \Delta V = IR \cos \phi + IX_L \sin \phi \]

Where \( R \) is the resistance of the line, \( X_L \) the inductive reactance of the line, \( \cos \phi \) is the receiving end power factor and \( \sin \phi \) is the sin of the power factor angle.

As we can see from the phasor diagram the magnitude of the second term in the above equation is much larger than the first. The difference gets to be much larger when the power factor is smaller and the ratio of \( R/X_L \) is small.

However when a series capacitor is applied, as shown in the figure 4.2b and 4.2c the resultant voltage drop can be calculated as:

\[ \Delta V = IR \cos \phi + I(X_L - X_C) \sin \phi \]

Where \( X_C \) is the capacitive reactance of the series capacitor.

The purpose of series compensation is to cancel part of the series inductive reactance of the line using series capacitors. This helps in:

i. increase of maximum power transfer

ii. reduction in power angle for a given amount of power transfer

From practical point of view, it is not desirable to exceed series compensation beyond 80% of the reactance of the line. If the line it is 100% compensated than it would behave as purely resistive element and would cause series resonance even at fundamental frequency.
frequency. The location of series capacitors is decided by economical factors and severity of fault currents.

The benefits of the series capacitor compensator are associated with a problem. The capacitive reactance \( X_C \) forms a series resonant circuit with the total series reactance:

\[
X = X_l + X_{gen} + X_{trans}
\]

The natural frequency of oscillation of this circuit is given by:

\[
f_C = \frac{1}{2 \pi \sqrt{L C}} = f \frac{X_c}{X}
\]

Where \( f \) – system frequency

\[
\frac{X_c}{X} - degree \ of \ compensation, \ which \ is \ recommended \ from \ 25\% \ up \ to \ 75\%
\]

For this degree of compensation \( f_c < f \) which is subharmonic compensation.

Even though series compensation has often been found to be cost-effective compared to shunt compensation, but sustained oscillations below the fundamental system frequency can cause the phenomenon, referred to a sub-synchronous resonance (SSR), which first was observed in 1937, but got world-wide attention only in the 1970s, after two turbine-generator shaft failures occurred at the Majave Generating station in Southern Nevada. Theoretical studies pointed out that interaction between a series capacitor-compensated line, oscillating at subharmonic frequency, and torsional mechanical oscillation of turbine-generator set can result in negative damping with consequent mutual reinforcement of the two oscillations. Sub synchronous resonance is often not a major problem, and low cost counter measures and protective measures can be applied. Some of the corrective measures are:

i. Detecting the low levels of subharmonic currents on the line by use of sensitive relays, which at a certain level of currents triggers the action to bypass the series capacitors.

ii. Modulation of generator field current to provide increased positive damping at subharmonic frequency.

Series inductors are needed for line compensation under light load conditions to counter the excessive voltage rise (Ferranti effect).

As the line load and, in particular the reactive power flow over the line varies, there is need to vary the compensation for an acceptable voltage profile. The mechanical switching arrangement for adjusting the capacitance of the capacitor bank in series with the line is shown in figure 4.3. Capacitance is variably opening the switches of individual capacitances with the capacitance \( C1 \), being started by a bypass switch. This is a step-
wise arrangement. The whole bank can also be bypassed by the starting switch under any emergent conditions on the line. As the switches in series with capacitor are current carrying suitable circuit breaking arrangement are necessary. However, breaker switched capacitors in series are generally avoided these days the capacitors either are fixed or thyristor switched.

![Diagram of mechanical switching arrangement](image)

*Figure 4.3 Mechanical switching arrangement to adjust the capacitance of the capacitive banks*

With fast advanced thyristor devices and associated switching control technology, the series capacitance bank can be controlled much more effectively; both stepwise and smooth control.

### 4.2.1 Overcompensation

Usually, the series capacitor size reactance is selected in such a way that the resultant capacitive reactance is smaller than the reactance of the line. However, in lower voltage levels where the resistance of the line is larger than the inductive reactance the reverse might be preferred. The resultant condition is known as overcompensation. Figure 4.4 shows a voltage phasor diagram for overcompensation at normal load. At times, when the selected level of overcompensation is strictly based on normal load, the resultant overcompensation of the receiving-end voltage may not be pleasing at all because lagging current of a large motor at start can produce a large voltage rise, as shown in figure 4.4, which is especially harmful to lights (shortening their lives) and causes light flicker.
Figure 4.4 Overcompensation of the end voltage: (a) at normal load and (b) at the start of a large motor

Figure 4.5 Voltage phasor diagram with leading power factor: (a) without series capacitors and (b) with series capacitors

As it can be seen from the figure, the voltage in the end of the line is reduced as a result of having series capacitors.

When \( \cos \phi = 1 \), \( \sin \phi = 0 \) and therefore all loses are:

\[
\Delta U = IR
\]

Thus, in voltage regulation, series capacitors practically have no value. That’s because of the aforementioned reasons and others (e.g., Ferro resonance in transformers, sub synchronous resonance during motor starting, shunting of motors during normal operation and difficulty in the protection of capacitors from system fault current), series capacitors do not have large application in distribution systems. However, they are employed in sub transmission systems to modify the load division between parallel lines. For example:

- Often a new sub transmission systems to modify the load division between parallel lines.
- Often a new sub transmission line with larger thermal capability is parallel with an already existing line. It may be very difficult, if not impossible, to load the subtransmission line without overloading the old line.
4.3 Shunt Capacitors

The main use of shunt capacitors is in improving the power factor, which is the ratio of the active power to the apparent power. It illustrates the relationship of the active power that is used to produce real work, and the reactive power required to enable inductive components such as transformers and motors to operate. As those components, with pronounced inductive characteristics, are common in industrial facilities and power networks, reactive power is inductive and current is lagging.

On the other hand, capacitive loads supply reactive power and the relevant current is leading. Most loads require the two types of power to operate. The reactive current flowing to a load will not affect the active power drawn by the load, but the supply circuit must carry the vector sum of the active and reactive current. This later will contribute to the power dissipated in the supply and distribution network (losses), to the voltage drop, and to the network capacity requirements. A poor power factor will therefore result in lower energy efficiency and reduced power quality, in some cases affecting the product quality and the process productivity.

Many utilities employ shunt capacitor banks to help improve feeder voltage profile via power factor correction. The capacitors, decrease demand current, decrease system losses and reduce the voltage drop. Consequently, the voltage profile is improved. The capacitors are connected to the feeder at specific locations at which the voltage variation along the feeder does not violate tolerance of ± 5% of nominal voltage (figure 4.6).

![Diagram of feeder voltage profile with capacitors](image-url)
Shunt capacitors are, capacitors connected in parallel with lines, are used extensively in distribution systems. Shunt capacitors supply the type of reactive power or current to counteract the out of phase component of current required by an inductive load. In a sense, shunt capacitors modify the characteristic of an inductive load by drawing a leading current that counteracts some or all of the lagging component of the inductive load current at the point of installation. Therefore, a shunt capacitor has the same effect as an overexcited synchronous condenser, generator, or motor.

As shown in Figure 4.7, by the application of shunt capacitor to a line, the magnitude of the source current can be reduced, the power factor can be improved, and consequently the voltage drop between the beginning line and the load is also reduced. However, shunt capacitors do not affect current or power factor beyond their point of application. Figure 4.7a and c shows the single-line diagram of a line and its voltage phasor diagram before the addition of the shunt capacitor, and Figure 4.7b and d shows them after the addition.

![Voltage phasor diagrams](image)

**Figure 4.7 Voltage phasor diagrams for a feeder circuit of a lagging power factor: (a) and (c) without compensation and (b) and (d) with shunt capacitor compensation.**

Voltage drop in lines, or in short transmission lines, with lagging power factor can be approximated as:

\[ \Delta V = I_R R + I_X X \]

Where:

- \( R \) is the total resistance of the feeder circuit, \( \Omega \)
\(X_L\) is the total inductive reactance of the feeder circuit, \(\Omega\)

\(I_R\) is the real power (or in-phase) component of the current, \(A\)

\(I_X\) is the reactive component of the current lagging the voltage by 90° \(A\)

When a capacitor is installed at the receiving end of the line, as shown in figure 4.7b, the resultant voltage drop can be calculated approximately as:

\[
\Delta V = I_R R + I_X X_L - I_C X_L
\]

Where \(I_C\) is the reactive component of current leading the voltage by 90°.

Shunt compensation is more or less like load compensation. It needs to be pointed out here that shunt capacitors/inductors cannot be distributed uniformly along the line. These are normally connected at the end of the line and/or at midpoint of the line.

Shunt capacitors raise the load PF which greatly increases the power transmitted over the line as it is not required to carry the reactive power. There is a limit to which transmitted power can be increased by shunt compensation as it would require very large size capacitor bank, which would be impractical.

When switched capacitors are employed for compensation, these should be disconnected immediately under light load conditions to avoid large excessive voltage rise.

4.3.1 Capacitor installation types

In general, capacitors installed on feeders are pole-top banks with necessary group fusing. The fusing applications restrict the size of the bank that can be used. Therefore, the maximum sizes used are about 1800 kVAR at 15 kV and 3600 kVAR at higher voltage levels. Usually, utilities do not install more than four capacitor banks (of equal sizes) on each feeder.

Figure 4.8 illustrates the effects of a fixed capacitor on the voltage profiles of a feeder with uniformly distributed load at heavy load and light load. If only fixed-type capacitors are installed, as can be observed in Figure 4.8c, the utility will experience an excessive leading power factor and voltage rise at that feeder. Therefore, some of the capacitors are installed as switched capacitor banks so they can be switched off during light-load conditions. Thus, the fixed capacitors are sized for light load and connected permanently. The switched capacitors can be switched as a block or in several consecutive steps as the reactive load becomes greater from light-load level to peak load and sized accordingly.
Figure 4.8 The effects of the fixed capacitor on the voltage profile of (a) feeder with uniformity load, (b) at heavy load and (c) at light load.

This curve is called the reactive load–duration curve and is the cumulative sum of the reactive loads (e.g., fluorescent lights, household appliances, and motors) of consumers and the reactive power requirements of the system (e.g., transformers and regulators). Once the daily reactive load–duration curve is obtained, then by visual inspection of the curve, the size of the fixed
Capacitors can be determined to meet the minimum reactive load. For example, from figure 4.9 one can determine that the size of the fixed capacitors required is 600 kVAr.

The remaining kVAR demands of the loads are met by the generator or preferably by the switched capacitors. However, since meeting the kVAR demands of the system from the generator is too expensive and may create problems in the system stability, capacitors are used. Capacitor sizes are selected to match the remaining load characteristics from hour to hour.

Many utilities apply the following rule of thumb to determine the size of the switched capacitors:

Add switched capacitors until:

\[
\frac{\text{kVAR from switched + fixed capacitors}}{\text{kVAR of peak reactive feeder load}} \geq 0.70
\]

From the voltage regulation point of view, the kilovars needed to raise the voltage at the end of the line to the maximum allowable voltage level at minimum load (25% of peak load) are the size of the fixed capacitors that should be used. On the other hand, if more than one capacitor bank is installed, the size of each capacitor bank at each location should have the same proportion. However, the resultant voltage rise must not exceed the light-load voltage drop. The approximate value of the percent voltage rise can be calculated from:

\[
\Delta U_\% = \frac{Q_{c,3f} \times x L_1}{10 V_L^2}
\]

Where:

\( \Delta U_\% \) is the percent voltage rise

\( Q_{c,3f} \) is the three-phase reactive power due to fixed capacitors applied, kVAR

\( x_L \) is the line reactance, \( \Omega/\text{min} \)
\( l \) is the length of feeder from sending end of feeder to fixed capacitor location, min

\( V_l \) is the line-to-line voltage, kV

Some utilities use the following rule of thumb: The total amount of fixed and switched capacitors for a feeder is the amount necessary to raise the receiving-end feeder voltage to maximum at 50% of the peak feeder load. Once the kilovars of capacitors necessary for the system are determined, there remains only the question of proper location. The rule of thumb for locating the fixed capacitors on feeders with uniformly distributed loads is to locate them approximately at two-thirds of the distance from the substation to the end of the feeder.

For the uniformly decreasing loads, fixed capacitors are located approximately halfway out on the feeder. On the other hand, the location of the switched capacitors is basically determined by the voltage regulation requirements, and it usually turns out to be the last one-third of the feeder away from the source.

### 4.4 Power factor correction

A typical utility system would have a reactive load at 0.80 power factor during the summer months. Therefore, in typical distribution loads, the current lags the voltage, as shown in figure 4.10a. The cosine of the angle between current and sending voltage is known as the power factor of the circuit. If the in-phase and out-of-phase components of the current \( I \) are multiplied by the receiving-end voltage on the line \( V_2 \), the resultant relationship can be shown on a triangle known as the power triangle, as in figure 4.10b. This figure shows the triangular relationship that exists between kilowatts, kilovoltamperes, and kilovars.

![Figure 4.10 (a) Phasor diagram and (b) Power triangle for a typical distribution load](image)

Note that, by adding the capacitors, the reactive power component \( Q \) of the apparent power \( S \) of the load can be reduced or totally suppressed. Figures 4.11a and 4.12 illustrate how the reactive power component \( Q \) increases with each 10% change of power factor. Figure 4.11a also illustrates how a portion of lagging reactive power \( Q_{old} \) is cancelled by the leading reactive power of capacitor \( Q_c \).

Note that, as illustrated in figure 4.11, even a 0.80 power factor of the reactive power (kVA) size is quite large, causing a 25% increase in the total apparent power (kVA) of
the line. At this power factor, 75 kVAR of capacitors is needed to cancel out the 75 kVAR of the lagging component.

As previously mentioned, the generation of reactive power at a power plant and its supply to a load located at a far distance is not economically feasible, but it can easily be provided by capacitors (or overexcited synchronous motors) located at the load centers. Figure 4.12 illustrates the power factor correction for a given system.

![Figure 4.11 Illustration of (a) the use of a power triangle for the power factor correction by employing capacitive reactive power and (b) the required increase in the apparent and reactive powers as a function of the load power factor, holding the real power of the load constant.](image)

As illustrated in the figure, capacitors draw leading reactive power from the source; that is, they supply lagging reactive power to the load. When a shunt capacitor of $Q_c$ kVA is installed at the load, the power factor can be improved from:
\[
\cos \phi_1 = \frac{P}{\sqrt{P^2 + Q_1^2}}
\]

Up to:
\[
\cos \phi_1 = \frac{P}{\sqrt{P^2 + Q_2^2}} = \frac{P}{\sqrt{P^2 + (Q_1 - Q_c)^2}}
\]

Where

\[\begin{align*}
\text{Figure 4.12 Illustration of power factor correction by employing a shunt capacitor}
\end{align*}\]

5 Questions

1. Who are the main producers and consumers of reactive power?
   Chapter 2
2. What are the main factors of voltage drop?
   Chapter 3.1
3. What are the advantages and disadvantages of series capacitor banks?
   Chapter 4.2
4. What are the advantages and disadvantages of shunt capacitor banks?
   Chapter 4.3
5. Homework task

For the industrial consumer that is connected directly to the power line of 110 kV, it is needed to determine the power of the capacitive bank connected in parallel with near the consumer in order to correct the power factor from 0.8 to 0.95. Determine also the increase of voltage after the correction.

The impedance of the line is \( z = 0.2 + j4 \) [\( \Omega/km \)], the admittance is \( y = 0 + j 2.7 \times 10^{-6} \) [\( \Omega/km \)], length of the line is \( l = 50 \) [km], the voltage at the beginning \( U_1 = 111.6 \) [kV], at the end of the line \( U_2 = 104 \) [kV] with a connected load \( S = 40 \) [MVA] and \( \cos \theta = 0.8 \) (ind).
Solution:

The apparent power is

\[ S_1 = S_1 (\cos \theta_1 + j \sin \theta_1) = 40 (0.8 + j0.6) = (30 + j24) \text{ [MVA]} \]

According to the power triangle in the figure 5.1 we can write:

\[ Q_1 = P_1 \tan \theta_1 \]

We can see that in order to achieve a better power factor we have to decrease the angle \( \theta \) from \( \theta_1 \) to \( \theta_2 \), by knowing the angle \( \theta_2 \) we can easily determine the reactive power flow in the line after compensation as:

\[ Q_2 = P_1 \tan \theta_2 \cos \theta_2 = \frac{P_1}{\sqrt{P_1^2 + (Q_2 - Q_C)^2}} = \frac{P_1}{S_2} = 0.95 \]

Therefore the power of the compensator to correct the power factor is:

\[ Q_c = Q_1 - Q_2 = P_1 (\tan \theta_1 - \tan \theta_2) = 32 (0.75 - 0.328) = 13.48 \text{ [MVAr]} \]

\[ Q_c = -j13.48 \text{ [MVAr]} \]

We can conclude that the after the compensation the power that is withdrawn from the load is:

\[ S_2 = P_1 + jQ_2 = (32 + j24) + (-j13.48) \]

\[ = (32 + j10.52) \text{ [MVA]} \]

To determine the voltage at the end of the line after compensation we suppose that the voltage in the beginning is constant. The power line we represent with the \( \pi \) model as below:
Where the parameters of the line are:

\[ Z_L = (0.2 + j0.4) \times 50 = (10 + j20) \, [\Omega] \]

\[ Y_L = (0 + j \times 27 \times 10^{-6}) \times 50 = j135 \times 10^{-6} \, [S] \]

Now we calculate the voltage at the end point after compensation according to the equivalent scheme of the power line, and since the active power does not change we can write:

\[ U_1 = U_{2after} + \frac{P_1 R_L + Q'_2 X_L}{U_{2after}} + j \frac{P_1 X_L - Q'_2 R_L}{U_{2after}} \]

Because of the Ferranti effect the reactive power at the end of the line will change as some part of the reactive power will be compensated by the lines with a value of \( Q_{c2} \):

\[ Q'_2 = Q_1 - Q_{c2} = 10.52 - U_{2after} 67.5 \times 10^{-6} \]

\[ U_1^2 = \left[ U_{2after} + \frac{P_1 R_L + (10.52 - U_{2after} 67.5 \times 10^{-6}) X_L}{U_{2after}} \right]^2 + \left[ \frac{P_1 X_L - (10.52 - U_{2after} 67.5 \times 10^{-6}) R_L}{U_{2after}} \right]^2 \]

By having only the \( U_{2after} \) as unknown we will obtain:

\[ U_{2after}^4 - 11441 \, U_{2after}^2 + 56961.4 = 0 \]

After the calculation the real solution is:

\[ U_{2after} = 106.73 \]

In the case of the compensation of the power factor up to 0.95 the voltage will increase for:

\[ \Delta U_2 = U_{2after} - U_{2before} = 106.73 - 104 = 2.73 \, kV \]
7 Conclusion

Reactive power control compensation devices are designed to ensure stable levels of electric power voltage by maintaining predetermined voltage levels at network control points. In some cases, especially for long-distance power transmission, these devices are also expected to maintain predetermined levels of static and dynamic stability of electric power systems and load stability.

The reactive power transfer through the lines can be reduced with different compensation methods. By the compensation the reactive power we will increase the total power capability transfer and reduce the total current which means reducing also the voltage drops.

In practice these static compensating devices are mostly shunt capacitor banks and shunting reactors that perform graduated control of reactive power, reactor groups commutated by modern switches, which can be discussed as an extension of this seminar paper.

8 References