Chapter 2
Equipment for Voltage and Reactive Power Control

Chapter 1 explained how voltage support requires reactive power control. In this chapter, we describe in detail the main equipment in power systems that are able to deliver or absorb the reactive power through particular aspects of control as they relate to voltage and reactive power.

Reactive power switchable compensating equipment is discussed first, then voltage and reactive power continuous control devices are described, with a distinction made between rotating electrical machines and static power electronic converters (i.e., static VAR compensator (SVC), static compensator (STATCOM) and unified power flow controller (UPFC)). A detailed description of the features of voltage-reactive power control schemes and dynamic performances is provided. Lastly, we present the on-load tap changing transformer (OLTC), a voltage discrete control device, explaining in detail its operation and applications.

2.1 Introduction

We recall from previous considerations that the practical way to perform voltage regulation in a power system requires, in large part, control of generated and consumed reactive power and its flow at different voltage levels (i.e., in transmission or distribution grids).

The main equipment in a power system is the synchronous generator, which is able to deliver or absorb a significant amount of reactive power. The automatic voltage regulator (AVR) controls the generator's excitation in order to maintain stator edge voltage at set-point value. Because this local priority control is mainly concerned with generator voltage at its MV/LV bus level, it does not use the generator's available reactive power resources to the fullest to cover the needs of real voltage control at the HV load buses.

Compensating equipment, which is generally installed in the substation, also contributes to system voltage support. This equipment can be categorised as:

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- Reactive power sources or loads; includes: shunt capacitors, shunt reactors, synchronous compensators and static compensators;
- Equipment providing compensation of line inductive reactance; includes: fixed or switched series capacitors;
- Equipment providing variable ratio on transformer windings; includes: tap-changing transformers.

Shunt reactors and capacitors as well as series capacitors are passive compensation devices: they can be permanently connected or they can be switchable. In the first case, these devices are designed as part of the basic grid, the one to be controlled; in the second, they are part of control resources that support basic grid voltages by recovering voltage variations. From here, the discussion mainly concerns “switchable” and therefore controllable reactive power resources. Stepping control of these devices is usually of a manual, local or remote type.

Synchronous and static compensators are continuous, closed-loop units. The reactive power they absorb or generate is automatically adjusted, so the voltage level of the buses to which they are connected remains constant. This equipment, similar to generators, maintains the controlled bus voltage at a set-point value. In terms of voltage control they do not differ from real generators.

The above mentioned devices can be used alone or in any combination. Some are only suitable for constant or slow-varying compensation, whereas others allow for fast variation of reactive power or shunt susceptance.

2.2 Reactive Power Compensation Devices

Shunt capacitors are used to increase a lagging power factor contribution, whereas shunt reactors are employed when leading power factor corrections are required, as in the case of lightly loaded cables. In both cases the device supplies/absorbs reactive power to recover voltage values around the nominal value.

When voltage is lowered, there is a decrease in VARs produced by shunt capacitors or absorbed by reactors; thus, when the need is greatest, capacitor effectiveness generally decreases, unless it is controlled before a significant decrease in voltage occurs. On the other hand, when loads are light, voltages are high, and the reactive power produced by capacitors or absorbed by reactors is larger than the nominal values, so their contribution increases if they are not properly controlled.

2.2.1 Shunt Capacitors

Capacitors are connected either directly to a bus bar or to the tertiary winding of a main transformer and are disposed along the route to minimise losses and voltage drops. They compensate locally the reactive power used by consumers and are distributed throughout the system. The main advantages of shunt capacitors are low cost and flexibility of installation and operation.

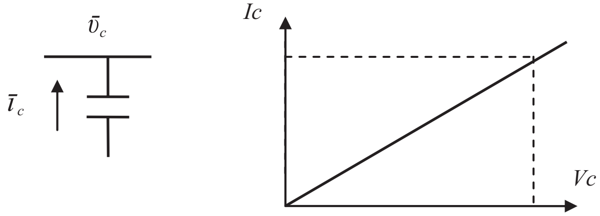


Fig. 2.1 Current-voltage characteristic of a capacitor

The shunt capacitor's principal disadvantage is that its reactive power output reduction at low voltages is proportional to the voltage squared. Moreover, switching reduces capacitor lifetime. The primary application of this compensation device is generally in distribution grids to supply the reactive power as close as possible to the point where it is consumed, i.e., at load buses.

The output characteristic (I–V) is linear, defined by rated values of voltage and current, as shown in Fig. 2.1. From Chap. 1, § 1.2:

$$\bar{V}_C = -jX_C(jI_C) = X_C I_C = V_C.$$

Therefore,

$$I_C = \frac{V_C}{X_C} = \omega C V_C \quad \text{and} \quad Q_C = \omega C V_C^2.$$

Compensation schemes include both fixed and switchable capacitor banks. In the case of transmission systems, shunt capacitors are used to compensate for inductive ($\omega L I^2$) losses and to ensure satisfactory voltage levels during heavy load conditions. Capacitor banks are switched either manually or automatically by voltage relays. Their location in the field is determined after completion of detailed power flows, contingency analysis and studies of dynamic transients.

On/off switching of capacitor banks provides a conventional means of controlling system voltages to recover large voltage deviation, typically due to the load difference from night to day or after a large contingency. It cannot contribute to real-time voltage continuous control because the number of switching manoeuvres possible is limited.

Shunt capacitors are sensitive to over-voltages and over-currents, which are limited by appropriate protections.

2.2.2 Mechanically Switched Capacitors (MSC)

The basic scheme of a mechanically switched capacitor (MSC) typically consists of a single capacitor unit or a bank of capacitor units connected to the power system either directly by a circuit breaker or via a transformer. Pre-strike- and re-strike-free circuit breakers are needed to avoid system over-voltages due to capacitor switching transients, possibly damped by series small reactors, which also reduce harmonics.

Response time is equal to the switching time dictated by the circuit breaker arrangement, which is on the order of 100 ms following initiation of an operating instruction. Frequent switching is not possible unless discharge devices are provided. Normal switching frequency is 2–4 times/day with the capacitors connected under heavy system load and disconnected under light system load conditions.

Harmonics from a power system may provide additional load (current and voltage stress) to the capacitor. Losses are very low, typically 0.02–0.05 % of the nominal MVA rating. Shunt capacitors in use range in size from a few KVARs at low voltage (LV) in a single unit to hundreds of MVARs in a bank of units at EHV applications.

Because of the linear voltage versus current characteristic, the output of a shunt capacitor during system disturbances is most unfavourable as its reactive output is proportional to the square of the voltage, thus giving a much reduced reactive power output at a reduced voltage.

2.2.3 Shunt Reactors

Generally, shunt reactors are used to compensate line capacitance effects by limiting voltage rise when a circuit is open or when a load is light. They are often used for EHV overhead lines longer than 150–200 km, where capacitive line-charging current flowing through high-value inductive reactance causes a voltage rise, with the highest values present at the sending end of the line.

The output characteristic (*V–I*) is linear in the operating range and deviates from linearity for iron-core or shrouded iron reactors due to saturation, as shown in Fig. 2.2.

From Chap. 1, § 1.2 and during linear performance,

$$\bar{V}_L = jX_L(-jI_L) = X_L I_L = V_L.$$

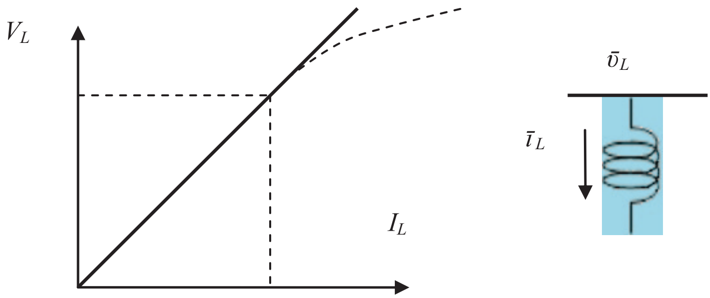


Fig. 2.2 Voltage-current characteristic of a shunt reactor

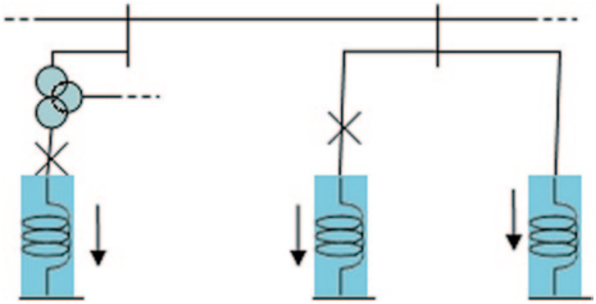


Fig. 2.3 Connection configurations of shunt reactors: switchable and permanent reactors

Therefore,

$$I_L = \frac{V_L}{X_L} = \frac{V_L}{\omega L}; \quad Q_L = \frac{V_L^{\ 2}}{\omega L}.$$

Shunt reactors can be connected directly to an electric line or through a transformer installed in the terminal station (Fig. 2.3). In the case of robust systems, shunt reactors are permanently connected to the long electrical lines to limit temporary (lasting less than 1 s) or switching over-voltages up to 1.5 p.u. Additional shunt reactors can be also used on electrical lines to limit over-voltages due to lightening.

Response time is equal to the switching time given by the circuit breaker arrangement, which is on the order of 100 ms following initiation of an operating instruction. Frequent switching is not possible. Normal switching frequency is 2–4 times/day, with reactors connected under a light system load and disconnected under heavy system load conditions.

Harmonics are produced by reactor current distortion in a saturation range at higher than nominal voltages. Losses are low, typically about 0.2–0.4 % of nominal MVA rating. Shunt reactors, in use, range from a few MVARs to hundreds of MVARs at HV-EHV applications.

2.2.4 Mechanically Switched Reactors (MSR)

During heavy load conditions, shunt reactors must be disconnected; for this reason they are equipped with switching devices. Mechanically switched reactors (MSR) are used only on short lines supplied by weak systems. Shunt reactors cannot contribute to real-time voltage continuous control due to limits on the number of switching manoeuvres.

The basic scheme of the MSR typically consists of a shunt reactor connected by a circuit breaker or a disconnect switch to a transmission line bus bar or a transformer tertiary winding.

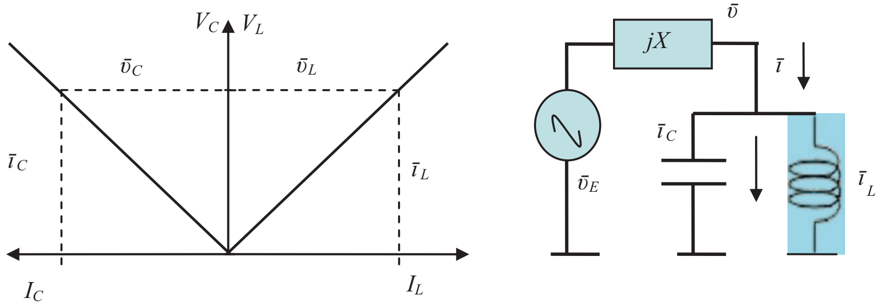


Fig. 2.4 *V–I* characteristics of shunt reactor and shunt capacitor in parallel

2.2.5 Multiple Compensation Device Operating Point

Representing the linear characteristics of capacitor and reactor on the same *V–I* plane, where it is assumed the current enters at the positive sign, Fig. 2.4 shows the case of the contemporary operation of a shunt capacitor in parallel with a shunt reactor.

The figure demonstrates two facts:

- The reactor absorbs current while the capacitor delivers current. According to the link between voltage and current discussed in § 2.2.1 and § 2.2.3:

$$I = I_C + I_L, \qquad V = V_C = V_L,$$

$$I_L = \frac{V_L}{X_L} = \frac{V_L}{\omega L}, \qquad Q_L = \frac{V_L^2}{\omega L},$$

$$I_C = -\omega C V = V\frac{1}{X_C}, \qquad Q_C = -\omega C V_C^2.$$

- When the reactance values of the two passive components $\bar{v}_C$ and $\bar{v}_L$ are equal in absolute value, their algebraic sum is zero; then the operating point is fixed by the external voltage, with no impact of the shunts on the grid voltage ($I = 0.0$); that is, the voltage axis also represents the resultant characteristic of the two shunts. In this case the full recirculation of reactive power between the two compensating devices is active, in the amount

$$Q_L = \frac{V^2}{\omega L} = -Q_C = \omega C V^2,$$

with $V = V_E$ (see Fig. 2.4).

This obvious result confirms that simultaneous use of the two types of permanently connected compensating equipment does not make sense. On the other hand,

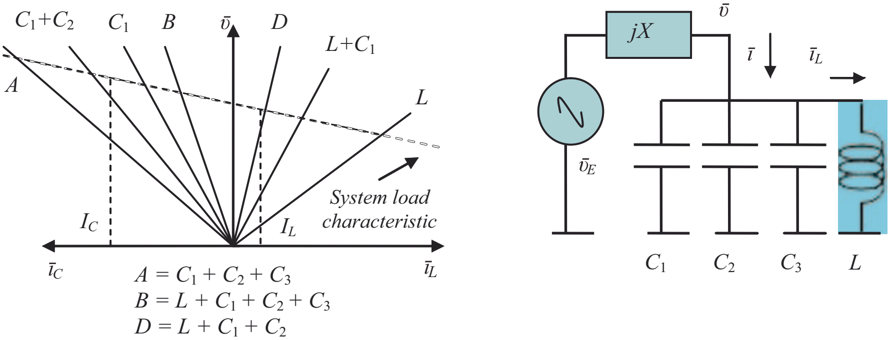


Fig. 2.5 *V–I* characteristics of MSC and MSR in parallel, fixing different operating points with system load characteristic, under a hypothesis of constant V_E and X

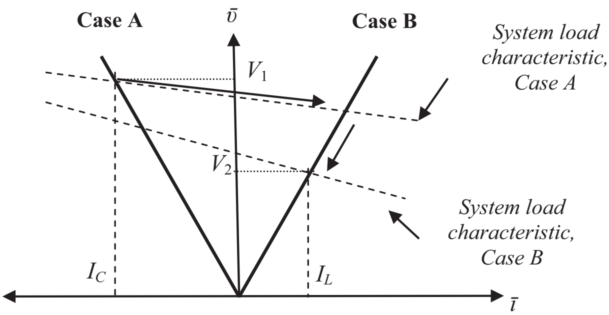
their switchable use by means of MSC and MSR in parallel is a possible solution for buses with a wide range of voltage variation.

It can be seen in Fig. 2.5 that the operating point is defined by the intersection of the system load characteristic with the combined characteristic of the shunt compensating equipment. The I value can be of capacitive or inductive type, depending on the combined operating conditions of the MSR and the MSC.

To better recognise the impact of compensating equipment on bus voltage it is necessary we eliminate the wrong hypothesis: namely, that the equivalent system seen by the local bus does not take into account the shunt commutations. In fact, any switching of reactor or capacitor impacts the equivalent values of V_E and X, thus changing the shape of the system load characteristic, as Fig. 2.6 shows.

Two different shunt resultant characteristics can be seen in Fig. 2.6: Case A, where the capacitive effect is dominant, and Case B, where the inductive effect prevails. Starting from A and switching off a capacitor shunt, a new resultant shunt characteristic B is determined, with current I changing from delivery I_C to absorption I_L. This produces not only a change in V but also in the equivalent V_E and X values being the grid voltages less sustained by a change in the reactive power from injection into the grid to absorption from the grid.

Fig. 2.6 *V–I* shunt characteristics of capacitive and inductive dominant effects and trajectories following commutation from operating point *A* to *B*, taking into account consequent change in equivalent system load characteristic



The result would be in a presumably lower V_E value and/or a different slope of the system load characteristic, thereby determining a different operating point at lower voltage V (from V_1 to V_2 in the figure).

2.3 Voltage and Reactive Power Continuous Control Devices

VAR generators are distinguished as either rotating electrical machines or static power electronics converters. The unique feature of VAR generators is their ability to deliver or absorb reactive power with continuity and in a repetitive way, without significant equipment fatigue on building materials or without internal losses. This happens until the generator's working point is maintained inside an operation within a field of continuity, bounded by capability curves that fix the maximum reactive power generation or absorption to be compatible with allowed thermal stresses, available cooling and/or design rating.

Among rotating electrical machines, the synchronous generator is not simply a megawatt generator but also a VAR generator: it allows the functional separation between the active and reactive power controls and the delivery or absorption of VARs up to limits without appreciable impact on the active power produced. Accordingly, as it is not able to deliver MW of power, a synchronous compensator is a pure VAR generator.

Considering power electronic converters, the main VAR generators are the so-called:

- Static VAR compensator (SVC);
- Static compensator (STATCOM);
- Unified power flow controller (UPFC).

Obviously, any VAR generator can, in principle, support voltages at its terminal edges or in the local grid buses.

2.3.1 Synchronous Generators

Synchronous generators are primary voltage control devices and they are primary sources of a spinning reactive power reserve. Through excitation controllability they allow continuous fast control of their stator voltages and of reactive power delivered to or absorbed by the grid. A closed-loop control scheme with an automatic voltage regulator (AVR), such as the basic one pictured in Fig. 2.7, is generally used for this purpose.

Excitation control systems (ECS) of synchronous generators can be classified as either "rotating" or "static". The first category comprises rotating machines such as DC power amplifiers that feed the synchronous generator field. Rotating types include:

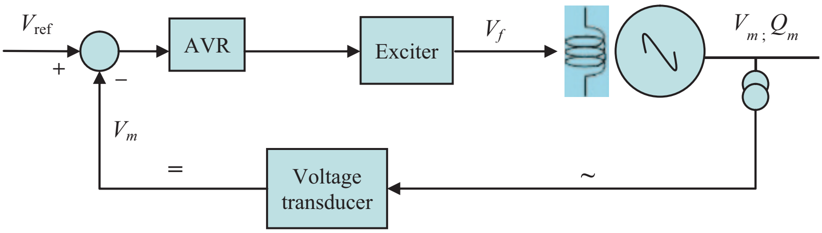


Fig. 2.7 Basic voltage control scheme of a synchronous generator

- ECS with exciting dynamo and electromechanical voltage regulator;
- ECS with exciting dynamo and electronic\microprocessor-based voltage regulator;
- ECS with alternator and rotating diodes, with electromechanical voltage regulator.

The second category considers as a DC power amplifier that feeds the synchronous generator field, a power electronic converter, typically thyristor-based. Static types include:

- ECS with static exciter and electronic/microprocessor-based voltage regulator.

ECS with Exciting Dynamo

We refer to the exciting dynamo represented in Fig. 2.8, where symbols have the obvious meaning. At high values of flux linkage ϕ, magnetic saturation $S_{at}[V_f]$ modifies the linear dependence between control current I_c and output voltage V_f, thus determining the represented static nonlinear characteristic to be taken into account in the exciter control scheme.

The exciting dynamo in the ECS is coaxial to the synchronous generator and achieves generator stator edge voltage regulation by controlling the dynamo excitation, usually through a thyristor bridge fed by an auxiliary, coaxial, permanent magnet alternator.

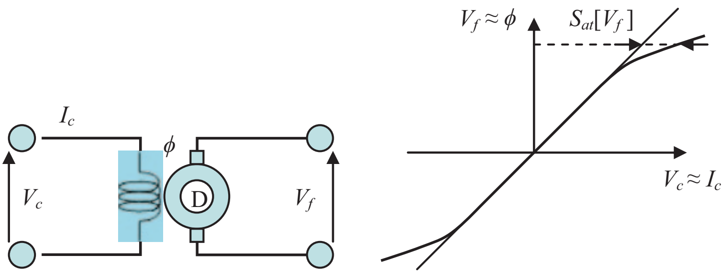


Fig. 2.8 Basic scheme of a dynamo and its magnetic characteristic

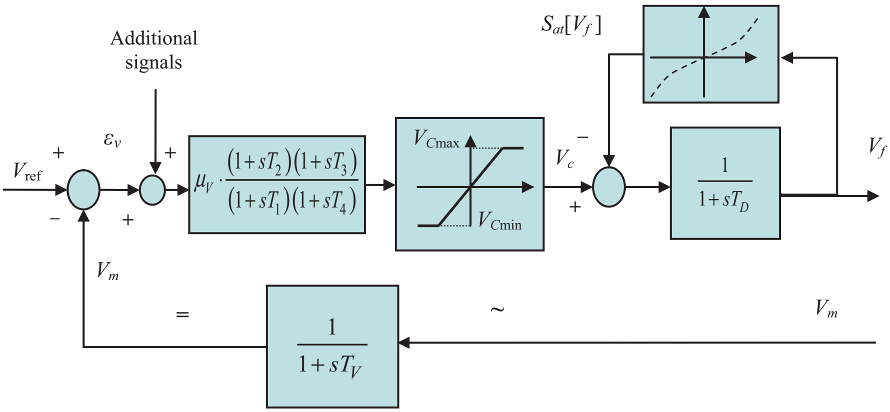


Fig. 2.9 Block diagram of ECS with exciting dynamo and AVR of electronic type

The block diagram of an ECS with dynamo is represented in Fig. 2.9, where the dynamo is characterised by a first order linear model (time constant T_D), which has a feedback that takes into account the magnetic saturation effect $S_{at}[V_f]$ on the control voltage, V_f. The control amplifier, which is of the second order when it is of an electronic type, has a linear operating field between its saturations represented by V_{Cmax} and V_{Cmin} values. A first order measurement filter (with small time constant T_V) of the generator voltage recloses the main feedback on the entering summing junction that compares the voltage set-point V_{ref} with the generator voltage measurement V_m. The voltage regulator is designed and tuned to achieve an adequate stability of the synchronous generator's voltage control loop up until the time it operates inside its saturation field.

In the case of an electromechanical voltage regulator of the first order, loop stability requires an additional negative transient feedback $sKT/(1+sT)$ from V_f to the second summing junction, where the voltage error ε_v is combined with other signals.

ECS with Alternator and Rotating Diodes

An alternator coaxial to the main synchronous generator feeds a diode bridge that provides the field excitation. Synchronous generator voltage regulation is achieved by controlling the field voltage of the exciting alternator. This solution, employing as it does rotating diodes, offers many advantages because slip rings and brushes are absent.

The block diagram of the ECS with alternator and rotating diodes seen in Fig. 2.10 is the same as that of Fig. 2.9, the case of an electronic regulator. Time T_D is the dominant time constant of the linear model representing the alternator feeding excitation windings through the bridge. $S_{at}[V_f]$ is the magnetic saturation effect on the control voltage, V_f, due to the alternator field winding.

With an electromechanical voltage regulator of the first order, outer voltage control loop stability would require an additional negative transient feedback

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