CHAPTER 1

Introduction

1.1 BACKGROUND

This chapter briefly discusses the growth of complex electrical power networks. It introduces the lack of controllability of the active- and reactive-power flows in energized networks. (These flows tend to diffuse in the network, depending primarily on the impedance of power lines.) This chapter also describes the conventional controlled systems, such as automatic governor control and excitation control employed at generating stations. Transformer tap-changer control is another control feature generally available in transmission networks. Arising from the transformer combinations and the use of on-load tap changers, phase-shifting transformers are realized, which are primarily used to mitigate circulating power on network tie-lines.

This introduction and the recognition of limited controllability provide the basis for introducing the concept of the flexible ac transmission system (FACTS). Since newly developed FACTS devices rely on the advances made in semiconductor components and the resulting power-electronic devices, these, too, are introduced.

This chapter also introduces the basic operating principles of new FACTS devices. (These principles are fully discussed in later chapters of this book.) Finally, the chapter presents a brief commentary on emerging deregulation, competition, and open access in power utilities. In that context, the value of FACTS devices for emerging transmission companies is identified.

1.2 ELECTRICAL TRANSMISSION NETWORKS

The rapid growth in electrical energy use, combined with the demand for low-cost energy, has gradually led to the development of generation sites remotely located from the load centers. In particular, the remote generating stations include hydroelectric stations, which exploit sites with higher heads and significant water flows; fossil fuel stations, located close to coal mines; geothermal stations and tidal-power plants, which are sitebound; and, sometimes, nuclear power plants purposely built distant from urban centers. The generation of bulk
power at remote locations necessitates the use of transmission lines to connect
generation sites to load centers. Furthermore, to enhance system reliability, mul-
tiple lines that connect load centers to several sources, interlink neighboring
utilities, and build the needed levels of redundancy have gradually led to the
evolution of complex interconnected electrical transmission networks. These
networks now exist on all continents.

An electrical power transmission network comprises mostly 3-phase
alternating-current (ac) transmission lines operating at different transmission
voltages (generally at 230 kV and higher). With increasing requirement of
power-transmission capacity and/or longer transmission distances, the trans-
mision voltages continue to increase; indeed, increases in transmission volt-
ages are linked closely to decreasing transmission losses. Transmission voltages
have gradually increased to 765 kV in North America, with power transmission
reaching 1500 MVA on a line limited largely by the risk that a power utility
may be willing to accept because of losing a line.

An ac power transmission network comprises 3-phase overhead lines, which,
although cheaper to build and maintain, require expensive right-of-ways. How-
ever, in densely populated areas where right-of-ways incur a premium price,
underground cable transmission is used. Increasing pressures arising from eco-
logical and aesthetic considerations, as well as improved reliability, favor under-
ground transmission for future expansion.

In a complex interconnected ac transmission network, the source-to-a-load
power flow finds multiple transmission paths. For a system comprising multiple
sources and numerous loads, a load-flow study must be performed to determine
the levels of active- and reactive-power flows on all lines. Its impedance and
the voltages at its terminals determine the flow of active and reactive powers
on a line. The result is that whereas interconnected ac transmission networks
provide reliability of power supply, no control exists on line loading except to
modify them by changing line impedances by adding series and/or shunt-circuit
elements (capacitors and reactors).

The long-distance separation of a generating station from a load center
requiring long transmission lines of high capacity and, in some cases in which
a transmission line must cross a body of water, the use of ac/dc and dc/ac
converters at the terminals of an HVDC line, became a viable alternative many
years ago. Consequently, beginning in 1954, HVDC transmission has grown
steadily to the current ±600 kV lines with about 4000 A capacity. Also, direct
current (dc) transmission networks, including multiterminal configurations, are
already embedded in ac transmission networks. The most significant feature of
an HVDC transmission network is its full controllability with respect to power
transmission [1]–[5].

Until recently, active- and reactive-power control in ac transmission networks
was exercised by carefully adjusting transmission line impedances, as well as
regulating terminal voltages by generator excitation control and by transformer
tap changers. At times, series and shunt impedances were employed to effec-
tively change line impedances.
1.3 CONVENTIONAL CONTROL MECHANISMS

In the foregoing discussion, a lack of control on active- and reactive-power flow on a given line, embedded in an interconnected ac transmission network, was stated. Also, to maintain steady-state voltages and, in selected cases, to alter the power-transmission capacity of lines, traditional use of shunt and series impedances was hinted.

In a conventional ac power system, however, most of the controllability exists at generating stations. For example, generators called spinning reserves maintain an instantaneous balance between power demand and power supply. These generators, in fact, are purposely operated at reduced power. Also, to regulate the system frequency and for maintaining the system at the rated voltage, controls are exercised on selected generators.

1.3.1 Automatic Generation Control (AGC)

The megawatt (MW) output of a generator is regulated by controlling the driving torque, $T_m$, provided by a prime-mover turbine. In a conventional electromechanical system, it could be a steam or a hydraulic turbine. The needed change in the turbine-output torque is achieved by controlling the steam/water input into the turbine. Therefore, in situations where the output exceeds or falls below the input, a speed-governing system senses the deviation in the generator speed because of the load-generation mismatch, adjusts the mechanical driving torque to restore the power balance, and returns the operating speed to its rated value. The speed-governor output is invariably taken through several stages of mechanical amplification for controlling the inlet (steam/water) valve/gate of the driving turbine. Figure 1.1 shows the basic speed-governing system of a generator supplying an isolated load. The operation of this basic feedback-control system is enhanced by adding further control inputs to help control the frequency of a large interconnection. In that role, the control system becomes an automatic generation control (AGC) with supplementary signals.

\[
\begin{align*}
T_m &= \text{the mechanical driving torque} \\
T_e &= \text{the mechanical load torque from the generator electrical output} \\
P_m &= \text{the mechanical power input to the generator}
\end{align*}
\]

Figure 1.1 A speed-governor system.
To avoid competing control actions, in a multigenerator unit station each speed-governor system is provided with droop ($R$) characteristics through a proportional feedback loop ($R$, Hz/MW). Figure 1.2 shows an AGC on the principal generating unit with supplementary control. In contrast, the second, third, and remaining generating units in a multiunit station operate with their basic AGCs. In a complex interconnected system, the supplementary control signal may be determined by a load-dispatch center.

1.3.2 Excitation Control

The basic function of an exciter is to provide a dc source for field excitation of a synchronous generator. A control on exciter voltage results in controlling the field current, which, in turn, controls the generated voltage. When a synchronous generator is connected to a large system where the operating frequency and the terminal voltages are largely unaffected by a generator, its excitation control causes its reactive power output to change.

In older power plants, a dc generator, also called an exciter, was mounted on the main generator shaft. A control of the field excitation of the dc generator provided a controlled excitation source for the main generator. In contrast, modern stations employ either a brushless exciter (an inverted 3-phase alternator with a solid-state rectifier connecting the resulting dc source directly through the shaft to the field windings of the main generator) or a static exciter (the use of a station supply with static rectifiers).

An excitation-control system employs a voltage controller to control the excitation voltage. This operation is typically recognized as an automatic voltage regulator (AVR). However, because an excitation control operates quickly, several stabilizing and protective signals are invariably added to the basic voltage regulator. A power-system stabilizer (PSS) is implemented by adding auxiliary damping signals derived from the shaft speed, or the terminal frequency, or the power—an effective and frequently used technique for enhancing small-signal stability of the connected system. Figure 1.3 shows the functionality of an excitation-control system.
1.3.3 Transformer Tap-Changer Control

Next to the generating units, transformers constitute the second family of major power-transmission-system apparatuses. In addition to increasing and decreasing nominal voltages, many transformers are equipped with tap-changers to realize a limited range of voltage control. This tap control can be carried out manually or automatically. Two types of tap changers are usually available: off-load tap changers, which perform adjustments when deenergized, and on-load tap changers, which are equipped with current-commutation capacity and are operated under load. Tap changers may be provided on one of the two transformer windings as well as on autotransformers.

Because tap-changing transformers vary voltages and, therefore, the reactive-power flow, these transformers may be used as reactive-power-control devices. On-load tap-changing transformers are usually employed to correct voltage profiles on an hourly or daily basis to accommodate load variations. Their speed of operation is generally slow, and frequent operations result in electrical and mechanical wear and tear.

1.3.4 Phase-Shifting Transformers

A special form of a 3-phase–regulating transformer is realized by combining a transformer that is connected in series with a line to a voltage transformer equipped with a tap changer. The windings of the voltage transformer are so connected that on its secondary side, phase-quadrature voltages are generated and fed into the secondary windings of the series transformer. Thus the addition of small, phase-quadrature voltage components to the phase voltages of the line creates phase-shifted output voltages without any appreciable change in magnitude. A phase-shifting transformer is therefore able to introduce a phase shift in a line.

Figure 1.4 shows such an arrangement together with a phasor diagram. The phasor diagram shows the phase shift realized without an appreciable change in magnitude by the injection of phase-quadrature voltage components in a 3-phase
system. When a phase-shifting transformer employs an on-load tap changer, controllable phase-shifting is achieved. The interesting aspect of such phase shifters is that despite their low MVA capacity, by controlling the phase shift they exercise a significant real-power control. Therefore, they are used to mitigate circulating power flows in interconnected utilities. A promising application of these devices is in creating active-power regulation on selected lines and securing active-power damping through the incorporation of auxiliary signals in their feedback controllers. From this description, it is easy to visualize that an incremental in-phase component can also be added in lines to alter only their voltage magnitudes, not their phase.

The modification of voltage magnitudes and/or their phase by adding a control voltage is an important concept. It forms the basis of some of the new FACTS devices discussed in this book. The injected voltage need not be realized through electromagnetic transformer–winding arrangements; instead, by using high-speed semiconductor switches such as gate turn-off (GTO) thyristors, voltage source inverters (VSIs)—synchronized with the system frequency—are produced. The application of a VSI to compensate the line-voltage drop yields a new, fast, controllable reactive-power compensator: the static synchronous series compensator (SSSC). The application of a VSI to inject a phase-quadrature voltage in lines yields a new, fast, controllable phase shifter for active-power control. Once a synchronized VSI is produced, it is indeed easy to regulate both the magnitude and the phase angle of the injected voltages to yield a new, unified power-flow controller (UPFC).

1.4 FLEXIBLE AC TRANSMISSION SYSTEM (FACTS)

The FACTS is a concept based on power-electronic controllers, which enhance the value of transmission networks by increasing the use of their capacity.
As these controllers operate very fast, they enlarge the safe operating limits of a transmission system without risking stability. Needless to say, the era of the FACTS was triggered by the development of new solid-state electrical switching devices. Gradually, the use of the FACTS has given rise to new controllable systems. It is these systems that form the subject matter of this book.

Today, it is expected that within the operating constraints of the current-carrying thermal limits of conductors, the voltage limits of electrical insulating devices, and the structural limits of the supporting infrastructure, an operator should be able to control power flows on lines to secure the highest safety margin as well as transmit electrical power at a minimum of operating cost. Doing so constitutes the increased value of transmission assets.

The search for enhanced controllability of power on ac transmission networks was initiated by newly acquired current and power controllability in HVDC transmission. Replacement of mercury-arc valves by thyristors yielded robust ac/dc converters, minimized conversion losses, and yielded fast control on transmitted power—so much so that line-to-ground fault clearing became possible without the use of circuit breakers. Instead, by rapidly attaining current zero through the use of current controllers and, in addition, by rapidly recovering the electromagnetic energy stored in the energized line, the faulted dc line could be isolated by low interruption–rating isolators.

The very fast power controllability in HVDC systems made them candidates for special applications in back-to-back configurations to control the power exchange between the networks they linked. The rapid control of power led to the added use of HVDC links for enhancing transient stability of connected systems through active-power damping. The enhancement in stability was accomplished by adding auxiliary signals in the current controllers of the converters [16], [17].

### 1.4.1 Advances in Power-Electronics Switching Devices

As mentioned previously, the full potential of ac/dc converter technology was better realized once mercury-arc valves were replaced by solid-state switching devices called thyristors. Thyristors offered controlled turn-on of currents but not their interruption. The rapid growth in thyristor voltage and current ratings accelerated their application, and the inclusion of internal light triggering simplified the converter controls and their configurations even more. Most applications, however, were based on the natural commutation of currents. In special cases where forced commutation was required, elaborate circuitry using discharging capacitors to create temporary current zeroes were employed.

Thyristors are now available in large sizes, eliminating the need for parallelizing them for high-current applications. Their voltage ratings have also increased so that relatively few are required to be connected in series to yield switches or converters for power-transmission applications. Actually, the present trend is to produce high-power electronic building blocks (HPEBBs) to configure high-power switches and converters, thus eliminating the custom-design needs
at the device level. Availability of HPEBBs should accelerate development of new FACTS devices. The HPEBB thyristors are available in compact packaging and in sufficiently large sizes (e.g., 125-mm thyristors: 5.5 kV, 4 kA or 4.5 kV, 5.8 kA) for most applications. For switching applications, such as that for tap changers or static phase shifters, anti-parallel–connected thyristor modules, complete with snubber circuits, are available. These switches provide sufficiently high transient-current capacity to endure fault currents.

The GTO semiconductor devices facilitate current turn-on as well as turn-off by using control signals. This technology has grown very rapidly; consequently, high-power GTOs are now available (100 mm, 6 kV or 150 mm, 9 kV). Full on–off control offered by GTOs has made pulse width–modulated (PWM) inverters easy to realize [18].

Advances in semiconductor technology are yielding new efficient, simple-to-operate devices. The insulated gate bipolar transistor (IGBT) and the metal-oxide semiconductor (MOS)–controlled thyristor (MCT) control electric power using low levels of energy from their high-impedance MOS gates, as compared to high-current pulses needed for thyristors or GTOs. Unfortunately, the available voltage ratings of these devices are still limited.

The MOS turn-off (MTO) thyristor combines the advantages of both thyristors and MOS devices by using a current-controlled turn-on (thyristor) and a voltage-controlled turn-off having a high-impedance MOS structure [19]. Hybrid MTOs are being proposed that show substantially low device losses relative to GTOs. Because MTOs use nearly half the parts of GTOs, their application promises significant reliability improvement.

The availability of new and significantly improved switching devices in convenient packages (HPEBB) will aid the development of new, more versatile FACTS devices. The symbolic representation and equivalent circuits of a thyristor, GTO, and MCT are shown in Fig. 1.5.

1.4.2 Principles and Applications of Semiconductor Switches

In high-power applications, semiconductor devices are used primarily as switches. To accommodate switching in an ac system, two unidirectional conducting devices are connected in an antiparallel configuration, as shown in Fig. 1.6. Such a switch may be employed per phase to connect or disconnect a shunt-circuit element, such as a capacitor or reactor, or to short-circuit a series-connected–circuit element, such as a capacitor. A reverse-biased thyristor automatically turns off at current zero, for which reason an antiparallel thyristor connection is used to control the current through a reactor by delaying its turn-on instant, as shown in Fig. 1.6(b). It is easy to see that the current through a connected reactor may be controlled from full value to zero by adjusting the delay angle, \( \alpha \), of the gate’s firing signal from 90° to 180°.

Thus a thyristor switch offers current control in a reactor, rendering it a controlled reactor. However, because a capacitor current leads the applied voltage by approximately 90°, the capacitor switching always causes transient in-rush
Figure 1.5  Semiconductor switching devices for power-electronics applications: (a) a thyristor (silicon-controlled rectifier); (b) a gate turn-off (GTO) thyristor; and (c) a P-MCT equivalent circuit.
currents that must be minimized by switching charged capacitors at instants when the voltage across the switch is near zero. Therefore, a thyristor switch is used only to turn on or turn off a capacitor, thereby implementing a switched capacitor.

Parallel combination of switched capacitors and controlled reactors provides a smooth current-control range from capacitive to inductive values by switching the capacitor and controlling the current in the reactor. Shunt combinations of thyristor-controlled reactors (TCRs) and thyristor-switched capacitors (TSCs) yield static var compensators (SVCs), which are described in detail in Chapters 3–6.

Thyristor switches may be used for shorting capacitors; hence they find application in step changes of series compensation of transmission lines. A blocked thyristor switch connected across a series capacitor introduces the capacitor in line, whereas a fully conducting thyristor switch removes it. In reality, this step control can be smoothed by connecting an appropriately dimensioned reactor in series with the thyristor switch—as shown in Fig. 1.7—to yield vernier con-

![Figure 1.7 A thyristor-controlled series capacitor (TCSC).](image)
A GTO-based static synchronous compensator (STATCOM).

In the foregoing applications, thyristor switches were used to control the current through circuit elements, such as capacitors and reactors. The switches are also used to perform switching actions in on-load tap changers, which may be employed as thyristor-controlled phase-shifting transformers (TCPSTs).

Generally, the use of fully rated circuit elements is expensive, so to perform similar functions, another important class of FACTS controllers is realized by dc/ac converters. The application of GTO devices makes forced commutation possible, and therefore PWM converters offer a more elegant solution. The output voltages of PWM converters contain low-harmonic content. The voltage-source converters (VSCs) form the basic element of this new class of FACTS controllers, and numerous applications of this technology exist.

An alternative to a thyristor-controlled SVC is a GTO-based VSC that uses charged capacitors as the input dc source and produces a 3-phase ac voltage output in synchronism and in phase with the ac system. The converter is connected in shunt to a bus by means of the impedance of a coupling transformer. A control on the output voltage of this converter—lower or higher than the connecting bus voltage—controls the reactive power drawn from or supplied to the connected bus. This FACTS controller is known as a static compensator (STATCOM) [20] and is shown symbolically in Fig. 1.8. (This subject is discussed in Chapter 10.)

The use of voltage-source converters to inject a voltage by way of series-connected transformers leads to another interesting group of FACTS controllers: the SSSCs, which inject voltages to compensate for the line-reactance voltage drops [6]–[8]. It is easy to visualize that if the reactive drop of a line is partly compensated by an SSSC, it amounts to reducing the line reactance ($X_L$), or in other words, it is akin to controlled series compensation. The injected voltage in the line is independent of the line current. Figure 1.9 shows a 1-line diagram of an SSSC, which controls the active-power flow on a line.
The functions of an SSSC and a STATCOM, in fact, may be combined to produce a unified power-flow controller (UPFC) [6]–[8], [21]. A 1-line diagram of a UPFC is shown in Fig. 1.10. In the UPFC shown, a dc energy source is shared between the STATCOM and SSSC. Normally, no net energy is drawn from this source, but to compensate for the controller losses, the STATCOM can operate so that it draws the compensating active power from the connected ac bus. Thus a UPFC offers a fast, controllable FACTS device for the flow of combined active–reactive power in a line.

Finally, there are FACTS controllers classified as power-conditioning equipment. These controllers are employed as battery-energy–storage systems (BESSs) or superconducting magnetic-energy–storage (SMES) systems [6]–[8], [10]–[13]. These controllers also use GTO-based converters, which operate in dual roles as rectifiers for energy storage and inverters for energy return.

1.5 EMERGING TRANSMISSION NETWORKS

A historic change is overtaking electrical power utility businesses. Customers are demanding their right to choose electrical energy suppliers from competing
vendors—a movement that has arisen from the benefits of lower costs of such services as long-distance telephone calls, natural-gas purchases, and air travel. The industries embracing these activities have been recently deregulated, and in these sectors, competition has been introduced. The basic belief is that competition leads to enhanced efficiency and thus lower costs and improved services.

For nearly 100 years, electrical power utilities worldwide have been vertically integrated, combining generation, transmission, distribution, and servicing loads. Also, most such utilities have operated as monopolies within their geographic regions. Their method of operation has been “power at cost,” and their principal financers have been governments. Therefore, to many people the pressure of electrical power utilities to operate efficiently has been missing.

Operating the electrical energy sector competitively requires the unbundling of generation, transmission, and distribution. Competition is expected to exist among generators as well as retailers. The transmission and distribution (i.e., the controlling wires) must, out of necessity, be regulated. The new order requires new agencies taking the responsibility to link customers (loads) with generators (market operators) and, at the same time, to clearly understand the limitations and capabilities of power-transmission and -distribution networks [22], [23].

On becoming responsible for its own business, a power-transmission company must make the best use of its transmission capacity and ensure that transmission losses are reduced to their lowest values. Also, any loss of transmission capacity means loss of income for the company; therefore, all actions must be taken to ensure that unwanted circulating power is not clogging the available transmission capacity. In addition, energy congestion in critical transmission corridors must be avoided to eliminate the risk of missed business opportunities. Finally, to offer the greatest flexibility to market operators, a transmission company must create the maximum safe operating limits to allow power injection and tapping from its buses without risking stable operation. The success of a transmission company depends on offering the maximum available transmission capacity (ATC) on its lines.

From the foregoing discussion, it is evident that in the emerging electrical energy business, transmission companies have a greater need to make their networks more flexible. Fortunately, advances in power-electronics technology now offer new fast, controllable FACTS controllers to secure the needed flexibility [15], [22], [23].

The subject matter contained in this book is intended to assist engineers seeking FACTS knowledge and help utilities meet the energy challenge.

REFERENCES


