CHAPTER 3

FACTS CONTROLLERS

3.1 General

With the ongoing expansion and growth of the electric utility industry, including deregulation in many countries, numerous changes are continuously being introduced to a once predictable business. Although electricity is a highly engineered product, it is increasingly being considered and handled as a commodity. Thus, transmission systems are being pushed closer to their stability and thermal limits while the focus on the quality of power delivered is greater than ever.

In the evolving utility environment, financial and market forces will continue to demand a more optimal and profitable operation of the power system with respect to generation, transmission, and distribution. Now, more than ever, advanced technologies are paramount for the reliable and secure operation of power systems. To achieve both operational reliability and financial profitability, it has become clear that more efficient utilization and control of the existing transmission system infrastructure is required. Improved utilization of the existing power system is provided through the application of advanced control technologies. Power electronics based equipment, or Flexible AC Transmission Systems (FACTS), provide proven technical solutions to address these new operating challenges being presented today. FACTS technologies allow for improved transmission system operation with minimal infrastructure investment, environmental impact, and implementation time compared to the construction of new transmission lines. Traditional solutions to upgrade the electrical transmission system infrastructure have been primarily in the form of new transmission lines,
substations, and associated equipment. However, as experiences have proven over the past decade or more, the process to permit, site, and construct new transmission lines has become extremely difficult, expensive, time-consuming, and controversial.

FACTS technologies provide advanced solutions as cost-effective alternatives to new transmission line construction. The potential benefits of FACTS equipment are now widely recognized by the power systems engineering and T&D communities. With respect to FACTS equipment, voltage sourced converter (VSC) technology, which utilizes self-commutated thyristors/transistors, has been successfully applied in a number of installations world-wide.

3.2 Power Transfer Limit

One or more of the following network characteristics limits power flow over a transmission system.

- Stability limit
- Thermal limit
- Voltage limit
- Loop flow

Technically limitations on power transfer can always be removed by adding new transmission and/or generator capacity. FACTS are designed to remove such limitations and meet the operator's goals without having to understand major system additions.

3.3 Power System Constraints

As noted in the introduction, transmission systems are being pushed closer to their stability and thermal limits while the focus on the quality of power delivered is greater than ever. The limitations of the transmission system can take many forms and may involve power transfer between areas (referred to here as transmission bottlenecks) or within a single area or region (referred to here as a regional constraint) and may include one or more of the following characteristics:
• Steady-State Power Transfer Limit
• Voltage Stability Limit
• Dynamic Voltage Limit
• Transient Stability Limit
• Power System Oscillation Damping Limit
• Inadvertent Loop Flow Limit
• Thermal Limit
• Short-Circuit Current Limit
• Others

Each transmission bottleneck or regional constraint may have one or more of these system-level problems. The key to solve these problems in the most cost-effective and coordinated manner is through systems engineering analysis.

3.4 Controllability of the Power Systems

To illustrate that the power system only has certain variables that can be impacted by control, consider the basic and well-known power-angle curve, shown in Figure 3.1. Although this is a steady-state curve and the implementation of FACTS is primarily for dynamic issues, this illustration demonstrates the point that there are primarily three main variables that can be directly controlled in the power system to impact its performance. These are

• Voltage (V)
• Angle between Bus Voltages (δ)
• Impedance (Z)

One could also make the point that direct control of power is a fourth variable of controllability in power systems.

Figure 3.1 illustrates the controllability of power systems with the establishment of which variables can be controlled in power system and the solutions to control the variables are conventional equipment and FACTS controllers.
3.5 Benefits of Control of the Power Systems

Once power system constraints are identified and through system studies viable solutions options are identified, the benefits of the added power system control must be determined. The following offers a list of such benefits:

- Increased Loading and More Effective Use of transmission Corridors
- Added Power flow Control
- Improved Power System Stability
- Increased System Security
- Increased System Reliability
- Elimination or Deferral of the Need for New Transmissions Lines

The advantages in this list are important to achieve in the overall planning and operation of power systems. However, for justifying the costs of implementing added power system control and for comparing conventional solutions to FACTS controllers, more specific metrics of the benefits to the power system are often required. Such benefits can usually be tied back to an area or
region for a specific season and year at a defined dispatch (usually given by an ISO or equivalent) while meeting the following criteria, the examples are,

- **Voltage Stability Criteria**
  - e.g., P-V voltage or power criteria with minimum margins e.g., Q-V reactive power criteria with minimum margins

- **Dynamic Voltage Criteria**
  - e.g., Avoiding voltage collapse
  - e.g., Minimum transient voltage dip/sag criteria (Magnitude and duration)

- **Transient Stability Criteria**

- **Power System Oscillation Damping** e.g., Minimum damping ratio

Each of the above listed items can usually be measured in terms of a physical quantity such as power transfer through a critical transmission interface, power plant output area or region load level. This allows for a direct quantification of the benefits of adding power system control and provides a means to compare such benefits by the various solution options considered, whether they be conventional or FACTS based.

### 3.6 Conventional devices For Enhancing Power System Control

- Series Capacitor - Controls impedance
- Switched Shunt Capacitor and Reactor - Controls voltage
- Transformer LTC - Controls voltage
- Phase Shifting Transformer - Controls angle
- Synchronous Condenser - Controls voltage
- Special Stability Controls - Typically focuses on voltages control but can often include direct control of power
- Others (When Thermal Limits are Involved) - Can be included reconductoring, raising conductors, dynamic line monitoring, adding new lines, etc.
3.7 FACTS Technology

The FACTS technology helps us to alleviate these difficulties by enabling utilities to get the maximum service from their transmission facilities and enhance grid reliability. FACTS technology is a collection of controllers which can control series impedance, shunt impedance, current, voltage and phase angle.

FACTS is nothing but the Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability. FACTS technology is a collection of controllers, which can be applied individually or in coordination with others to control one or more of the interrelated system parameters mentioned above.

FACTS Controller is power electronic-based system and other static equipment that provide control of one or more AC transmission system parameters.

When the power system is controlled through mechanical switches, there is no high-speed control. Also due to the increasing complexity of the power system, the grid operator is not able to meet the dynamic swings in the power system with the help of mechanical switches. As the mechanical switches tend to wear out quickly when compared to static electronic devices, the maintenance becomes tough and the life of the entire power system gets reduced.

As most of the transmission systems are AC transmission systems, FACTS technology is necessary to specify some but not all of these difficulties by enhancing the control over the transmission of power and to enhance the grid reliability with the same existing line itself, unlike HVDC where new transmission system has to be installed. FACTS pave way to control the current through the line at a reasonable cost. Hence, the capacity of the line can be increased with larger conductors. The FACTS controller enables the line to carry power closer to its thermal rating.
3.8 Relative Importance of Controllable Parameters

- Control of the line impedance $X$ can provide a powerful means of current control.
- When the angle is not large, which is often the case, control of $X$ or the angle substantially provides the control of active power.
- Control of angle, which in turn controls the driving voltage, provides a powerful means of controlling the current flow and hence active power flow when the angle is not large.
- Injecting a voltage in series with the line and with any phase angle with respect to the driving voltage can control the magnitude and the phase of the line current.
- When the angle is not large, controlling the magnitude of one or the other line voltages can be a very cost-effective means for the control of reactive power flow through the interconnection.
- Combination of the line impedance control with a series controller and voltage regulation with a shunt controller can also provide a cost effective means to control both the active and reactive power flow between the two systems.

3.9 TYPES OF FACTS CONTROLLERS

FACTS controllers can be divided into four categories.

3.9.1 Series Controller

Series Controller could be variable impedance or variable source. All series controllers inject voltage in series with the line. Variable impedance multiplied by the current flow through it, represents an injected series voltage in the line. As long as the voltage is in phase quadrature with the line current, the series controller only supplies or consumes variable reactive power.
3.9.2 Shunt Controller

Shunt Controller could be variable impedance, variable source or a combination of these. Shunt controllers inject current into the system at the point of connection. Variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of current into the line. As long as the injected current is in phase quadrature with the line voltage, the shunt controller only supplies or consumes variable reactive power.

3.9.3 Combined Series - Series Controller

This could be a combination of separate series controllers, which are controlled in a coordinated manner, in multilane transmission system or it could be a unified controller in which series controllers provide independent series reactive compensation for each line and also transfer real power among the lines via the power link. The term unified means that the DC terminals of all controller converters are connected together for real power transfer.

3.9.4 Combined Series-Shunt Controller

This could be a combination of separate shunt and series controllers, which are controlled in a coordinated manner, a Unified Power Flow Controller with series and shunt elements. Combined shunt and series controllers inject current into the system with the shunt part of the controller and voltage in series in the line with the series part of the controller.

3.10 CONTROLLERS FOR ENHANCING POWER SYSTEM CONTROL

- Static synchronous Compensator (STATCOM) -Controls voltage
- Static VAR Compensator (SVC) -Controls voltage
- Unified Power Flow Controller (UPFC)
- Convertible Series Compensator (CSC)
- Inter-line Power Flow Controller (IPFC)
- Static Synchronous Series Controller (SSSC)
Each of the above mentioned (and similar) controllers impact voltage, impedance, and/or angle (and power)

- Thyristor Controlled Series Compensator (TCSC) - Controls impedance
- Thyristor Controlled Phase Shifting Transformer (TCPST) - Controls angle
- Super Conducting Magnetic Energy Storage (SMES) - Controls voltage and power

3.11 ADVANTAGES OF FACTS TECHNOLOGY

- Rapid response
- Dynamic control of power flow in selected transmission lines within the network to enable optimal power flow conditions
- Damping of the power swings from local and inter-area oscillations
- Suppression of subsynchronous oscillations
- Decreases DC offset voltages
- Reduction of short circuit current
- Frequent variation in output
- Smoothly adjustable output

3.11.1 FUTURE DIRECTION OF FACTS TECHNOLOGY

The technology behind phase – controlled thyristor – based FACTS controllers has been present for several decades and is therefore considered mature. More utilities are likely to adopt this technology in the future, even as the newer, more promising switch- mode GTO – based FACTS technology is fast emerging. Foreseen in the near future is the application of a hybrid technology involving both thyristors and GTOs; for instance, STATCOM – compensated HVDC converters that perform better than SVC-compensated HVDC links.

The second generation of FACTS controllers, such as the STATCOM, the SSSC, and the UPFC, use switch-mode GTO-based VSC configurations. Novel GTO-centered topologies are being researched and are expected to evolve
into another mature family of FACTS controllers. Recent advances in silicon power switching devices that significantly increase their power ratings will contribute even further to the growth of FACTS technology.

3.11.2 UNIFIED POWER QUALITY CONDITIONER (UPQC)

The modern power distribution system is becoming highly vulnerable to the different power quality problems. The extensive use of non-linear loads is further contributing to increased current and voltage harmonics issues. Furthermore, the penetration level of small / large-scale renewable energy systems based on wind energy, solar energy, fuel cell, etc., installed at distribution as well as transmission levels is increasing significantly.

Unified power quality control was widely studied by many researchers as an eventual method to improve power quality of electrical distribution system. The function of unified power quality conditioner is to compensate supply voltage flicker/imbalance, reactive power, negative sequence current and harmonics.

In other words, the UPQC has the capability of improving power quality at the point of installation on power distribution systems or industrial power systems. Therefore, the UPQC is expected to be one of the most powerful solutions to large capacity loads sensitive to supply voltage flicker / imbalance. The UPQC consisting of the combination of a series active power filter (APF) and shunt APF can also compensate the voltage interruption if it has some energy storage or battery in the DC link. The shunt APF is usually connected across the loads to compensate for all current-related problems such as the reactive power compensation, power factor improvement, current harmonic, compensation, and load unbalance compensation, whereas the series APF is connected in a series with the line through series transformers. It acts as controlled voltage source and can compensate all voltage sources and can compensate all voltage related problems, such as voltage harmonics, voltage sag, voltage swell, flicker, etc.
The proposed control technique has been evaluated and tested under non-ideal mains voltage and unbalanced load conditions using Matlab/simulink software. The proposed method is also validated through experimental study. The following diagram shows the generalized UPQC system.

![Diagram of grid connected PV system](image)

**Fig. 3.2. General structure of grid connected PV system**

UPQC has shunt and series voltage source inverters which are 3-phase 3-wire shunt inverter connected to point of common coupling (PCC) by shunt transformer. The series inverter stands between source and coupling as current source and it operates as voltage source.

The equations for real and reactive power through the line are as follows:

\[ P = \frac{V_s V_r}{X} \sin(\delta_1 - \delta_2) \]  
\[ Q = \frac{V_r}{X} (V_s - V_r) \]

Where, P represents Real power and Q represents Reactive power. These equations are given by neglecting the resistance of the line.
UPQC is able to compensate current harmonics, to compensate reactive power, voltage distortions and control load flow but cannot compensate voltage interruption because of non availability of sources.

Common interconnected PV systems structure is shown in Fig 3.3 is composed of PV array, DC/DC and DC/AC converters.

![Fig. 3.3. Configuration of UPQC with PV array](image)

The design of the boost converter is done by using the following equations.

\[ V_o = \frac{V_i}{(1 - \delta)} \]  

(3.3)

Inductance and capacitance are calculated by using the following equations

\[ L = \frac{V_i \delta}{f \Delta I} \]  

(3.4)

\[ C = \frac{\delta}{2 f R} \]  

(3.5)
In this case, UPQC finds the ability of injecting power using PV to sensitive load during source voltage interruption. Two operational modes of UPQC are as follows:

**Interconnected mode**

Where, PV transfers power to load and source.

**Islanding mode**

Where, the source voltage is interrupted and PV provides a part of load power separately.

### 3.11.3 Controller designing

Controlling strategy is designed and applied for two interconnected and islanding modes. In interconnected mode, source and PV provide the load power together while in islanding mode, PV transfers the power to the load alone. By removing voltage interruption, system returns to interconnected mode.

The controlling structure of the proposed system is composed of following parts:

#### 3.11.3.1 Shunt inverter control

In this study, shunt inverter undertakes two main duties. First is, Compensating both current harmonics generated by nonlinear load and reactive power, second is injecting active power generated by PV system.

The power loss caused by inverter operation should be considered in this calculation. Also, shunt inverter control undertakes the duty of (stabilizing) DC link voltage during series inverter operation to compensate voltage distortion.
3.11.3.2 Series inverter control

The series converter of the UPQC provides simultaneous controls of real and reactive power flow in the transmission line. To do so, the series converter injected voltage is decomposed into two components. One component of the series injected voltage is in quadrature-injected component controls the transmission line real power flow. This strategy is similar to that of a phase shifter. The in-phase component controls the transmission line reactive power flow. This strategy is similar to that of a tap changer.

3.12 Conclusion

The fundamentals of FACTS controllers and technology and concept of UPQC are presented in this chapter.