CHAPTER 4

GRID INTEGRATION ISSUES ON POWER QUALITY AND SOLUTION BY FACTS

This chapter deals with the means of power quality that is expected at consumer end and its related topics are initially discussed. Then grid integration issues when renewable sources are considered and Indian wind grid codes that are needed are discussed in detail. Finally the solutions for the issues are narrated high lighting the FACTS technology and its family as the study is on FACTS controllers.

4.1 Overview of Power Quality

Power quality is an important technical concern for utilities and customer-generators. Power quality is analogous to water quality. Just as municipal water suppliers and individual water wells must meet certain standards for bacteria and pollutant levels; utility power is required to be consistently supplied at a certain voltage and frequency.

The term power quality has become one of the most common parameter in the power industry from the past ten years. The term includes a countless number of phenomena observed in electric power systems. Although such disturbances are always occurred in the systems, greater attention has recently been dedicated to minimizing their effects to benefit the end users.

In context to the power quality, the term customer has been employed instead of consumer as electricity is viewed as a product. Large customers are identified as being industrial installations or commercial business complex, where the load consists of motors, lighting, power supplies, etc. For most of the residential customers, power quality is not so critical.

In the past, it can be said that the concepts of power quality and reliability were very similar because the loads were mostly linear and the amount of power electronics components was negligible. The loads were typically lighting, heating, and motors, which in general, are not very sensitive to momentary voltage variations. Moreover, the loads were more or less isolated from each other and process automation was
almost non-existent. In general the loads did not properly work only in the case of an interruption of the supplied voltage.

Power quality is important because electronic devices and appliances have been designed to receive power at or near these voltage and frequency parameters, and deviations may cause appliance malfunction or damage. As with any electrical device, a PV inverter, which converts the DC power from the PV modules into usable AC power for a house, potentially can inject noise that can cause problems. Power quality becomes one critical issue for both utility and consumers.

Generally, good power quality means that the system supplies and maintains load voltage as a pure sinusoidal waveform at specified frequency and voltage to all power consumers in the power system, even though power quality means different things to different people.

A well-established definition of power quality does not exist because it depends on one’s reference frame. For instance, whilst one customer considers a certain voltage waveform as having a “sufficient quality” in order to maintain the production working properly, another customer can realize that the same voltage has a “poor quality”. One aspect of common agreement is to consider the power quality as a customer driven issue, i.e. the customers point of view is determinant for indicating the quality of the power.

Based on this assumption, a power quality problem can be defined as “Any power problem manifested in voltage/current or leading to frequency deviations that result in failure or misoperation of customer equipment” [Dugan, 1996]. This definition means that the decisive measurement of power quality is taken from the performance and productivity of end-user equipment (customer). If the electric power is inadequate for those needs, the quality is said to be “lacking”.

The IEEE Standard 1100 [1992], describes power quality as “the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment”.

It is clear from both definitions that they are vague. The meanings of the terms “misoperation” and “powering” are not totally clear. Therefore, any deviation from
perfectly sinusoidal voltages or currents at fundamental frequency with rated magnitude values is potential candidate to a power quality problem.

Power quality problems are associated to an extensive number of electromagnetic phenomena in power systems with a broad range of time. They are classified as long duration variations and short duration variations.

Deviations from the operating RMS values for more than one minute are usually considered as long duration variations. According to the amplitude variation, they can be related to permanent faults, load variations, and switching operations in the system. As an example, switching a capacitor bank or a large load can cause noticeable changes in the voltage. If there is a counter measure then in this case the voltage regulation, acts very slowly, the voltage change can be characterized as a long-duration variation.

Depending on the magnitude of the voltage change, long duration voltage variations can be classified as:

- Under voltage – decrease in the RMS voltage to less than 90% of the nominal voltage.
- Over voltage – increase in the RMS voltage to more than 110% of the nominal voltage.
- Sustained interruption – supply voltage equal to zero for more than one minute.

These interruptions are usually permanent and require human intervention to repair the system. Short duration voltage variation is mainly caused by either fault conditions or associated fault currents due to connection of large loads that require high starting current. The disturbance can cause a temporary loss of voltage or temporary voltage reduction (sag or dip) or voltage rises (swells) at different nodes of the system.

In any case, the impact on the voltage during the disturbance is of short-duration, until protective devices start operating.
Figure 4.1 shows some of the common faults in general that can occur in power system and cause problems to the power quality [Osborne et al, 1995, Thomas 1994]. In brief these common faults are discussed as below.

**Voltage Sag:** A voltage sag as defined by IEEE Standard 1159-1995, IEEE Recommended Practice for Monitoring Electric Power Quality, is a decrease in RMS voltage (0.1-0.9) at the power frequency for durations from 0.5 cycles to 1 minute. According to this definition, voltage drops lasting less than half cycle cannot effectively be characterized by a change in the RMS value. In such cases these events are considered transients. The term *sag* has been used to describe a short-duration (0.5 cycles – 1 min.) decrease in the voltage, while the term *dip* is recommended by IEC to describe this phenomenon. Voltage sags are usually associated with system fault currents and can also be caused by energization of heavy loads or starting of large motors. Typical fault clearing time vary from 3 to 30 cycles, depending on fault current magnitude and the type of over current protection.

**Voltage Flicker:** Flicker is another power quality problem that affects our daily lives, which is defined as the “impression of fluctuating brightness or colour, occurring when the frequency of observed variation lies between a few hertz and the fusion frequency of images”. The frequency range of voltage flicker is between 1 Hz and 10 Hz. It occurs when heavy loads are periodically turned on and off in a weak distribution system. Starting large motors require an inrush of current,
which causes a decrease in voltage. This voltage depression may cause a visible flicker on lighting circuits connected to the same power system.

**Harmonic Distortion**: Harmonic distortion is found in both voltage and current waveforms. Most current distortion is generated by electronic loads, also referred as non-linear loads. These non-linear loads might be single phase loads such as point-of-sale terminals or three phase loads as in variable speed drives. At one time, almost all electrical loads were linear and they had little effect on electrical system operation. That all changed, however, with the coming of the solid-state electronic revolution. Today, we have an environment rich in nonlinear loads, such as UPS equipment, computers, variable-speed drives, and electronic fluorescent lighting ballasts. Operation of these devices represents a double-edged sword. Although they provide greater efficiency, they can also cause serious consequences to power distribution systems in the form of harmonic distortion.

**Momentary interruption**: Electric power utilities may define momentary interruptions differently, some considering a momentary interruption to be an outage of less than 1 minute in duration while others may consider a momentary interruption to be an outage of less than 5 minutes in duration. Interruptions are mainly caused by faults and equipment failures. In the first case, its duration is determined by the operating time of the protection system. Utilities usually adopt the instantaneous reclosing technique, i.e. a utility breaker, opened when a fault is detected and is rapidly reclosed after the fault is cleared. If the fault is not permanent, the interruption interval is limited and certainly less than one minute.

**Voltage Swells**: Swell is defined as an increase between 1.1 and 1.8 pu in RMS voltage with duration from 0.5 cycles to one minute. The term momentary overvoltage is also used as a synonym for swell. Switching off a large inductive load or energizing a large capacitor bank is a typical system manoeuvres that cause swells. Although not as common as voltage sags, swells are also usually associated with system faults. The severity of a voltage swell during a fault condition is a function of the fault location, system impedance, and grounding.

**Transients**: Basically, transients are momentary changes in voltage or current that occurs over a short period of time. This interval is usually described as approximately
1/16 of a voltage cycle or about one millisecond. Voltage transients normally last only about 50 microseconds and current transients last typically 20 microseconds according to the ANSI C62.41-1991.

**Electrical Noise:** In electronics, noise is a random fluctuation in an electrical signal, a characteristic of all electronic circuits. Noise generated by electronic devices varies greatly, as it can be produced by several different effects.

The source of power quality problems may originate in the following parts of electric power system shown in Figure 4.2 [Osborne et al., 1995]. Regardless of the location of the problem, the possible source can usually be attributed to lightning strike, system fault, switching of large loads, breaker operation, utility switching, nonlinear loads, ferro resonance, semiconductor switching devices, improper grounding.

Important points on power quality discussed would be of very interesting when DGs are integrated. There are lot of issues and associated problems because the integration affects the power quality. The next sub chapter deals with DG issues when integrated with the grid.

**Figure 4.2 Sources of Power Quality Problems**
4.2 Grid Integration and Associated Issues

Distribution networks traditionally have been designed to take power from high voltage grids and distribute this power to end consumers. The introduction of generating capacity connected to the distribution system need not cause great changes to this system, provided that the capacity does not actually send power into the network. Once power is sent into the network, the flow of electricity will be changed and even reversed from the normal design. This can lead to a number of technical problems that can affect the stability of the network and quality of electricity supplied. These problems include:

**Voltage control:** Electricity sent into the distribution network tends to cause an increase in voltage. This can be beneficial in some instances where operators have problems with low voltages. But in a system operating under normal conditions, these electricity flows can cause difficulties. Difficulties can be alleviated by requiring connection at higher voltage or by upgrading transformers for improved local voltage control. There are related concerns with voltage fluctuations and their potential impact on neighbouring consumers.

**Reactive power:** Depending on the type of generation, DG can either supply reactive power or absorb reactive power. This behaviour of DGs affects the performance of the power system due to variations in reactive power leading to voltage swells or dip at PCC.

**Protection:** DG flows might reduce the effectiveness of protection equipment and create operational difficulties under certain conditions. For example, while customers may want the ability to operate in "island" mode during a distribution circuit outage, restoring power to them involves important technical and safety considerations. Protection systems are required to ensure that DG systems are not supplying the network during outage conditions and can be resynchronized to the grid when power is restored.

Although DG is becoming an important paradigm for electricity generation, it will ever not able to replace the centralized power production. In fact centralized generation remains necessary to maintain a stable operation of the power system in
terms of voltage and frequency. It is also noticed that a stable operation of the bulk power grid is very much necessary for the DG units connected to the network via asynchronous machines. The load balance is a fundamental issue to transfer to the DG controls for which, important role will be played by electronic devices.

Synchronizing power with the grid is also a problem with having distributed systems able to feed into the grid network (Dugan and McDermott, 2001). Especially when dealing with sources that create DC electric power, additional equipment such as inverters to convert DC power to AC power (Barker and De Mello, 2000; Slootweg and Kling, 2002).

To minimize reactive power exchange between wind power plant and distribution network, dynamic compensation of reactive power could be employed which would help in preventing the voltage collapse at the terminals of wind farms and lead to improving the stability of the wind farm.

In this research work issues with wind integration is taken as the main study and the voltage impact of installing DG on IEEE 16 bus test feeder is carried out as test system and also on a real system where the wind farm integrates the grid. The DG installation and their effects are studied based on simulation studies and suitable measures are taken by FACTS Controllers which will be discussed later in Chapter 6.

4.3 Grid Codes

Electrical power can be generated as much as required from an aggregation of multiple wind turbines as a wind farm or wind park. To interconnect the wind energy to the utility grid, there must be an appropriate grid interconnection and control system to ensure high power quality and stability. As the level of penetration of the wind energy is increasing, there are regulations for the interconnection regarding the power quality and reliability. The power electronic grid interconnection supports the variable speed wind power, real and reactive power control, and reduces the influences of fluctuations in the wind such as voltage flickers. It generates other problems due to the switching devices of the power converters. One problem of the grid interconnection is harmonic distortions of the grid currents and voltages. The
harmonic distortions degrade the power quality. This leads to more severe problems in the power system such as transformer saturations, failure of protective devices, etc.

The first part of this research is about the grid interconnection of a wind farm that improves the voltage profile and supports the increasing demand and next is about the FACTS controller usage to maintain the grid codes at the point of common coupling.

### 4.4 FACTS Controllers

FACTS philosophy was first introduced by Hingorani and Gyugyi, (1999) from the Electric power research institute in USA in 1988, although the power electronic controlled devices had been used in the transmission network for many years before that. The objective of FACTS devices is to bring a system under control and to transmit power as ordered by the control centres, it also allows increasing the usable transmission capacity to its thermal limits. The phase angle, voltage magnitude at chosen buses and line impedances of transmission system can be controlled by FACTS devices.

Transmission systems are being pushed closer to their stability and thermal limits while the quality of power delivered is greater than ever. Changes are continuously being introduced to a once predictable and monopoly business due to the ongoing expansion and growth of the electric industry including deregulation. Traditional solutions to upgrade the transmission system, which have been primarily in the form of new transmission lines, substations, and associated equipment, are becoming difficult. FACTS technologies provide advanced solutions as cost-effective alternatives to new transmission line construction [(Ye and Kazerani, 2000); (Edris, 2000); (Liu et al., 2002); (Douglas et al., 1998), Mutale and Strbac, 2000].

Power electronics based equipments, called FACTS, provide technical solutions to address the new operating challenges being presented today, by improving utilization of the existing power system through the application of advanced control technologies.
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, offering utilities and industry the ability to:

- Dynamically control power flows on specific transmission and distribution routes.
- Allow secure loading of transmission and distribution lines to their full thermal capacity.
- Improve power quality.

The main driving forces for implementing power electronic technology into the electrical networks are [Brauner, 2000]:

- The liberalization and resulting competition in the energy market.
- Economical utilization of lightly loaded network lines.
- The call for a sustainable society with renewable and distributed resources.
- Utilizing installed network and generating assets better.
- Flexibility required in electrical customers and tariff structures.
- Price reduction of power electronic converters and devices.
- Revolutionary applications of power electronics in all the fields.
- Switching operation of Power Electronics Devices

### 4.4.1 Basic Types of FACTS Controllers

In general, FACTS controllers can be divided into three categories [Hingorani and Gyugyi, 2000]:

- Series Controllers,
- Shunt Controllers,
- Combined series-shunt Controllers.

**Series Controllers:** The series controllers could be variable impedance, such as capacitor, reactor or power electronics based variable voltage source at main frequency, sub-synchronous and harmonic frequencies (or combination) to serve the desired need. In principle, all series controllers inject a voltage in series with the
line. Even variable impedance multiplied by the current flowing through it, represents an injected series voltage in the line. As long as the phase voltage is in quadrature with the line current, the series controller only supplies or consumes variable reactive power any other phase relationship will involve handling of real power as well.

**Shunt Controllers:** The shunt Controller may be a variable impedance (reactor or capacitor), variable source, or a combination of these. In principle, all shunt controllers inject a shunt current into the system at the point of connection. Even variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of shunt current into the line. As long as the injected phase current is in quadrature with the line voltage, the shunt controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

**Combined series-shunt Controllers:** This could be a combination of separate shunt and series controllers, which are controlled in a co-ordinated manner, or a Unified Power Flow Controller with series and shunt elements. In principle, combined shunt and series Controllers inject current to the system with the shunt part of the controller and voltage in series in the line with the series part of the controller. However, when the shunt and series controllers are unified, there can be a real power exchange between the series and shunt controllers via the DC power link.

The FACTS Terms & Definitions Task Force of the FACTS Working Group of the DC and FACTS Subcommittee of IEEE made the definition of each above FACTS controllers and presented as follows:

**Static Synchronous Compensator (SSC or STATCOM):** Static synchronous generator operated as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage.

**Static Var Compensator (SVC):** It is a shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electric power system (typically bus voltage).
Unified Power Flow Controller (UPFC): A combination of a static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC) which are coupled via a common dc link, to allow bi-directional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM, and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source. The UPFC, by means of angularly unconstrained series voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance, and angle or, alternatively, the real and reactive power flow in the line. The UPFC may also provide independently controllable shunt reactive compensation.

Interphase Power Controller (IPC): A series-connected controller of active and reactive power consisting, in each phase, of inductive and capacitive branches subjected to separately phase-shifted voltages. The active and reactive power can be set independently by adjusting the phase shifts and/or the branch impedances, using mechanical or electronic switches. In the particular case where the inductive and capacitive impedances form a conjugate pair, each terminal of the IPC is a passive current source dependent on voltage at the other terminal.

Static Synchronous Series Compensator (SSSC): A static, synchronous generator operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the and thereby controlling the transmitted electric power.

Thyristor Controlled Series Capacitor (TCSC): A capacitive reactance compensator which consists of a series capacitor bank shunted by thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance.

Thyristor Controlled Phase Shifting Transformer (TCPST): It is a phase-shifting transformer, adjusted by thyristor switches to provide a rapidly variable phase angle.
Superconducting Magnetic Energy Storage (SMES): A superconducting electromagnetic energy storage device containing electronic converters that rapidly injects and/or absorbs real and/or reactive power or dynamically controls power flow in an AC system.

4.4.2 FACTS Applications in Power Systems

The application of FACTS controllers in power system can be used in various cases and following benefits are achieved.

- Control of power flow
- Increase the loading capability of lines
- Improve transient stability limit during contingencies
- Reduce the short-circuit power level
- Compensate reactive power
- Improve dynamic voltage stability
- Control loop power flow
- Damp power oscillation
- Mitigate voltage unbalance due to single-phase loads

Application of different FACTS controllers which suits to achieve the above mentioned benefits and contributions of each FACTS controller are shown in comparison Table 4.1

<table>
<thead>
<tr>
<th>FACTS Controller</th>
<th>Voltage Control</th>
<th>VAR Compensation</th>
<th>Oscillation Damping</th>
<th>Stability Control</th>
<th>Power Flow Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>STATCOM</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>BESS/SMES</td>
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<td>SVC</td>
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<td>TCSR</td>
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<td>SSSC</td>
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<td>TCSC</td>
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<td>IPFC</td>
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<td>TCPST</td>
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### 4.4.3 Static Synchronous Compensator-STATCOM

The STATCOM is a shunt device of the FACTS family using power electronics to control power flow and improve transient stability on power grids. The STATCOM regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the STATCOM generates reactive power (STATCOM capacitive). When system voltage is high, it absorbs reactive power (STATCOM inductive). With the commercial breakthrough of high power gate turn-off devices, the road is paved for an additional step forward in flexibility of AC transmission and distribution systems with STATCOM. The name is an indication that STATCOM has a characteristic similar to the synchronous condenser, but as an electronic device it has no inertia and is superior to the synchronous condenser in several ways, such as better dynamics, a lower investment cost, lower operating and maintenance costs.

A STATCOM can be seen as a voltage source behind a reactance. It provides reactive power generation as well as absorption purely by means of electronic processing of voltage and current waveforms in a Voltage Source Converter (VSC). This means that capacitor banks and shunt reactors are not needed for generation and absorption of reactive power, giving a compact design, a small footprint, as well as low noise and low magnetic impact. The VSC has the same rated current capability when operating with capacitive or inductive reactive current. Therefore a VSC having a certain MVA rating gives STATCOM twice the dynamic range in MVAR. This also contributes to a compact design. A DC capacitor bank is utilised to support (stabilise) the controlled DC voltage needed for the operation of the VSC. The VSC technology has been exploited in industrial and traction applications for more than a decade. It is capable of yielding full output of capacitive generation almost independently of the system voltage (constant current output at lower voltages). This is particularly useful in situations where the STATCOM is needed to support the system voltage during and after faults where voltage collapse would otherwise be a limiting factor.

The reactive power of STATCOM is produced by means of power electronic equipment of Voltage Source Converter type. The VSC may be of 2-level or 3-level type depending of the required output power and voltage. Each VSC module uses three phase-legs; each comprising two or four strings of series connected GTOs.
4.4.4 Operating Principle of STATCOM

The principle of operation of the STATCOM is explained from the Figure 4.3 showing the active and reactive power transfer between a source $V_1$ and a source $V_2$.

\[ P = \frac{(V_1 V_2) \sin \delta}{X} \]
\[ Q = \frac{V_1 (V_1 - V_2 \cos \delta)}{X} \]

Where, $V_1$ is Line to Line voltage of source 1
$V_2$ is Line to line voltage of source 2
$X$ is Reactance
$\delta$ is Phase angle of $V_1$ with respect to $V_2$

In steady state operation, the voltage $V_2$ generated by the VSC is in phase with $V_1$ then $\delta=0$, $P=0$ and only reactive power is flowing. If $V_2$ is lower than $V_1$, $Q$ is flowing from $V_1$ to $V_2$ (STATCOM is absorbing reactive power). On the reverse, if $V_2$ is
higher than $V_1$, $Q$ is flowing from $V_2$ to $V_1$ (STATCOM is generating reactive power).

The amount of reactive power when $\delta$ is zero given by,

$$Q = \left( V_1 (V_1 - V_2) \right) / X.$$

A capacitor connected on the DC side of the VSC acts as a DC voltage source. In steady state the voltage $V_2$ has to be phase shifted slightly behind $V_1$ in order to compensate for transformer and VSC losses and to keep the capacitor charged. Figure 4.4 represents the principal operation of STATCOM.

![Figure 4.4 Principal operation of STATCOM](image)

The STATCOM can be operated in two different modes:

- In voltage regulation mode (the voltage is regulated within limits)
- In var control mode (STATCOM reactive power output is kept constant)

When the STATCOM is operated in voltage regulation mode, it implements the V-I characteristic as shown in Figure 4.5. As long as the reactive current stays within the positive maximum and negative maximum current values ($+I_{\text{max}}$, $-I_{\text{max}}$) imposed by the converter rating, the voltage is regulated at the reference voltage $V_{\text{ref}}$. However, a
voltage droop is normally used (usually between 1% and 4% at maximum reactive power output), and V-I characteristic has the slope indicated in the Figure 4.5

In the voltage regulation mode, the V-I characteristic is described by the following equation:

\[ V = V_{\text{ref}} + X_S I \]

Where,

\( V \) is Positive sequence voltage

\( I \) is Reactive Current (\( I > 0 \) indicates an inductive current)

\( X_S \) is Slope or droop reactance

Knowing the role of FACTS and its importance and STATCOM role in absorbing or generating reactive power, it can be concluded that for maintenance of grid code when wind DG integrates, STATCOM is found to be better option.

![Figure 4.5 V-I Characteristics of STATCOM](image)