2

Quality of Delivery

The term quality of delivery refers to the ability of the various components – generation, transmission, and distribution – to deliver the electric power to all points of consumption in the amount and quality demanded by the customer. Because a power station which works without any failures is not a source of any trouble in supplying quality, the generated system voltages are almost perfectly sinusoidal, therefore for the purposes of this thesis the term *quality of delivery* will be treated as a matter of two issues, related to limitations of the transmission systems as well as to PQ problems of the distribution systems.

2.1 Limitations of the Transmission Systems

The limitations of the transmission system can take many forms and may include one or more of the following characteristics [2].

Voltage magnitude. On an *AC* power system, voltage is controlled by changing production and absorption of reactive power. There are a few reasons why it is necessary to handle reactive power and to control voltage. First, both customer and EPS equipment are designed to operate within a range of voltages. At low voltages, many types of equipment perform poorly; induction motors can overheat and be damaged, and some electronic equipment will not operate at all. High voltages can damage equipment and shorten its working life. Second, to maximize the amount of real power that can be transferred across a transmission system, reactive power flows must be minimized. Third, reactive power on the transmission system causes real-power losses. Both capacity and energy must be supplied to replace these losses. Voltage control is complicated by two additional factors. First, the transmission system itself is a nonlinear consumer of reactive power, depending on system loading. At very low levels of system load, transmission lines act as capacitors and increase voltages (the system consumes reactive power that must be generated). At high load levels, transmission lines absorb reactive power and thereby lower voltages (the system consumes a large amount of reactive power that must be replaced). The system's reactive power requirements also depend on the generation and transmission configuration. Consequently, system reactive requirements vary in time as load levels and load and generation patterns change.

The EPS operator has several devices available that can be used to control voltages. For example generators which inject reactive power into the power system, tending to raise system voltage, or which absorb reactive power, tending to lower system voltage. Additionally transformer tap changers can be used for voltage control. These arrangements can force voltage up (or down) on one side of a transformer, but it is at the expense of reducing (or raising) the voltage on the other side. The reactive power required to raise (or lower) voltage on a bus is forced to flow through the transformer from the bus on the other side. Fixed or variable taps often provide ±10% voltage selection.

Thermal limits. If the transmission line has not been loaded to its thermal limit (the thermal rating of normally designed transmission lines depends mainly on the voltage level at which they operate and the reactance) the power transfer capability can be increased by the use of, *e.g.*, switchable capacitors and controlled reactors. Such devices can supply or absorb reactive power, respectively raising or lowering the voltage of the transmission line. Also series compensation is used to increase the capability of power transfer by reducing the reactance of the transmission line.

Transient and dynamic stability. Transient stability refers to the ability of the power system to survive after a major disturbance, while dynamic stability refers to sustained or growing power swing oscillations between generators or a group of generators initiated by a disturbance (fault, major load changes *etc.*).

The mitigation of these oscillations is commonly performed with Power System Stabilizers (PSSs), sometimes additionally in conjunction with Automatic Voltage Regulators (AVRs).

2.1.1 FACTS to Enhance Limitations of the Transmission Systems

Most transmission system equipment (*e.g.*, capacitors, inductors, and tap changing transformers) is relatively static and can respond only slowly and in discrete steps, in contrast to FACTS devices which provide very fast response. Generally, FACTS devices can be divided into three major categories: series, shunt or combined devices.

The series devices impact the driving voltage and hence the current and power flow directly. Therefore, if the purpose of the application is to control the current/power flow and to damp oscillations, the series controllers are several times more powerful than the shunt devices. The SSSC or TSSC are the exemplary series devices of the FACTS family.

The shunt devices draw from or inject current into the line, thus they are applied to control voltage at and around the point of connection through injection of reactive current. The STATCOM or SVC are the exemplary shunt devices of the FACTS family.

This does not mean that the series controllers cannot be used for voltage control. Because the voltage fluctuations are largely a consequence of the voltage drop in series impedances of lines, inserting a series compensator might be the

Table 2.1. FACTS to enhance limitations of the transmission systems

Subject	Problem	Corrective action	Advisable FACTS
Voltage limits	Low voltage at heavy load	Supply reactive power	SVC, STATCOM
		Reduce line reactance	TCSC
	High voltage at low load	Absorb reactive power	SVC, STATCOM
	High voltage following an outage	Absorb reactive power, prevent overload	SVC, STATCOM
	Low voltage following an outage	Supply reactive power, prevent overload	SVC, STATCOM
Thermal limits	Transmission circuit overload	Increase transmission capacity	TCSC, SSSC, UPFC, IPFC
Stability	Limited transmission power	Decrease line reactance	TCSC, SSSC, UPFC, IPFC
Load flow	Power distribution on parallel lines	Adjust line reactances	TCSC, SSSC, UPFC, IPFC
		Adjust phase angle	UPFC, SSSC, IPFC

most cost-effective way of improving the voltage profile. Nevertheless, shunt devices are much more effective in maintaining a required voltage profile at a substation bus.

From the above consideration it follows that a combination of the series and shunt controllers can provide the best of both, *i.e.*, an effective power/current flow and line voltage control. The UPFC or IPFC are the exemplary combined devices of the FACTS family [18, 46, 47 ,120].

The application of these above mentioned devices depends on the problem which has to be solved. Thus Table 2.1 presents an overview of problems occurring in the transmission system and which FACTS to use to solve these problems.

2.2 Power Quality

The term Power Quality has arisen in trying to clarify responsibilities of utilities and customers in respect to each other, but unfortunately is still an area of disagreement between power engineers. Many PQ related standards are at present in existence and are under constant revision. The definition of power quality given in the Institute of Electrical and Electronic Engineers (IEEE) dictionary [121] is as follows: *"Power quality is the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment"*.

The IEEE Working Group on Power Quality Definitions of SCC22 states: *"A point of view of an equipment designer or manufacturer might be that power quality is a perfect sinusoidal wave, with no variations in the voltage, and no noise present on the grounding system. A point of view of an electrical utility engineer might be that power quality is simply voltage availability or outage minutes. Finally, a point of view of an end-user is that power quality or "quality power" is simply the power that works for whatever equipment the end-user is applying. While each hypothetical point of view has a clear difference, it is clear that none is properly focused."*

The International Electrotechnical Commission (IEC) does not use the term Power Quality in standards, but electromagnetic compatibility and the following definition of power quality is given [122]: *"The characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters - Note: These parameters might, in some cases, relate to the compatibility between electricity supplied on a network and the loads connected to that network".*

A Union of the Electricity Industry (EURELECTRIC) report [123] on Power Quality in European networks states: *"The quality of the electricity supply is a function of its suitability as an energy source for the electrical equipment designed to be connected to the supply network. The two primary components of supply quality are:*

- *continuity (freedom from interruption): the degree to which the user can rely on its availability at all times;*
- *voltage level: the degree to which the voltage is maintained at all times within a specified range"*

[...]

"The term 'power quality' is frequently used to describe these special characteristics of the supply voltage, particularly in developed countries where discontinuity and ordinary voltage variation have largely been eliminated as matters of frequent concern. The principal phenomena concerned in power quality are:

- *harmonics and other departures from the intended frequency of the alternating supply voltage;*
- *voltage fluctuations, especially those causing flicker;*
- *voltage dips and short interruptions;*
- *unbalanced voltages on three-phase systems;*
- *transient overvoltages, having some of the characteristics of high-frequency phenomena*

Power quality can be defined as the degree of any deviation from the nominal values of the abovementioned characteristics. It can be also defined as the degree to which both the utilization and delivery of electric power affects the performance of electrical equipment."

Table 2.2. The PQ issues [67]

Category	Typical characteristics Spectrum	Duration	Magnitude
1.0 Transients			
1.1 Impulsive		*50 ns - 1ms*	*< 6 kV*
1.2 Oscillatory		*5μs - 0.3 ms*	*0 - 4 p.u.*
2.0 Short duration variations			
2.1 Interruptions		*10 ms - 3 min.*	*< 1 %*
2.2 Sag		*10 ms - 1 min.*	*1 - 90 %*
2.3 Swell		*10 ms - 1 min.*	*110 - 180 %*
2.4 Rapid voltage changes		not defined	*> ±5 %*
3.0 Long duration variations		stationary	*< 106 % > 90 %*
3.1 Under voltages		*> 1 min.*	*80 - 90 %*
3.2 Over voltages		*> 1 min.*	*106 - 120 %*
4.0 Voltage unbalance		stationary	*0.5 - 2 %*
5.0 Curve distortion			
5.1 *DC* offset	*n=0*	stationary	*0 - 0.1 %*
5.2 Harmonics	*n=2 - 40*	stationary	*0 - 20 %*
5.3 Interharmonics	*0 - 6 kHz*	stationary	*0 - 2 %*
5.4 Notches		stationary	
5.5 Noise	Broadband	stationary	*0 - 1 %*
5.6 Signal transmission	*< 148 kHz*	stationary	*0.09*
6.0 Voltage fluctuations	*< 25 Hz*	intermittent	*0.2 - 7%*
7.0 Net frequency variations	*50 Hz*	*< 10 s*	*1 %*

A report of the Council of European Energy Regulators (CEER) Working Group on Quality of Electricity Supply [124] states: *"The main parameters of voltage quality are frequency, voltage magnitude and its variation, voltage dips, temporary or transient overvoltages and harmonic distortion. European Standard EN 50160 lists the main voltage characteristics in low and medium voltage networks, under normal operating conditions".*

From all these definitions, it can be stressed that the Power Quality is usually considered to include two aspects of power supply, namely Voltage Quality and Supply Reliability. The Voltage Quality part includes different disturbances, such as rapid changes, harmonics, interharmonics, flicker, unbalance and transients; whereas the reliability part involves phenomena with a longer duration, such as interruptions, voltage dips and sags, over and under voltages and frequency deviations. According to [3] and [67] the PQ issues may be classified as in Table 2.2.

The above issues are important in describing the actual phenomena which may cause the PQ problem. Another way to categorize the different disturbances is to look at possible causes for each kind of disturbance and to look at the consequences they might give. They are summarized in Table 2.3. [5]

It may also be advisable to take the reactive power into consideration as a PQ parameter, since the magnitude of the losses in the network and the sizes of transformers may be increased, due to the reactive power in the network. However since the voltage is chosen here as the PQ parameter the effect of the reactive power must be considered under the term voltage fluctuation, and the effect of reactive power must then be compensated with regard to this term.

2.2.1 Equipment Used to Enhance PQ

Just as FACTS controllers improve transmission systems, the equipment used to enhance the quality of power that is delivered to customers is called CUPS.

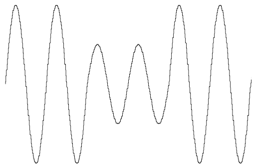
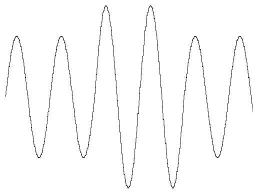
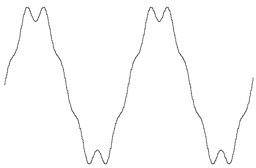
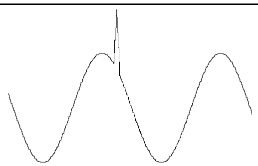
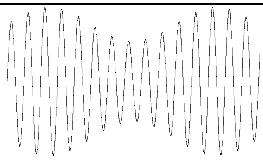
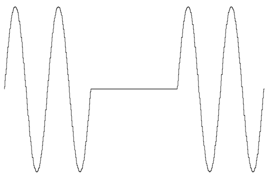
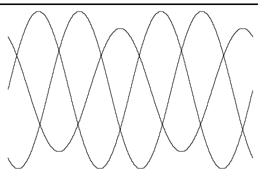
There are many different types of devices, which may be used to enhance the PQ, and these may be generally divided into two groups: stepwise devices and compensating type devices. Stepwise devices may regulate the voltage by use of an electronically controlled voltage tap changer, or by the use of stepwise-coupled capacitors. Such apparatus may also be used for compensation of reactive power. However, the analysis of these devices will not be performed in this thesis.

Compensating type devices usually include VSCs controlled by various control strategies, which, depending on the topology, may be divided into three major types: current, voltage and combined compensation.

The typical current compensation device may be considered the PAPF, which can operate in two modes: i) current - acts as active filter, power factor corrector, load balancer *etc.*; ii) voltage - regulates a bus voltage against any distortion, sag/swell, unbalance and even short duration interruptions.

Voltage based compensation is classified as voltage harmonics filtration, voltage regulation and balancing, and removing voltage sags and dips and in general is carried out by using, *e.g.*, SAPF.

Table 2.3. Voltage disturbances [5]

Disturbance		**Origin**	**Consequences**
Voltage sag, undervoltage 2.2		Short circuits in the network grid. Start up of large motors.	Disconnection of sensitive loads. Fail functions.
Voltage swells. Overvoltages 2.3		Earth fault on another phase. Shut down of large loads. Lightning strike on network structure. Incorrect setting in substations.	Disconnection of equipment may harm equipment with inadequate design margins.
Harmonic distortion 5.2-5.3		Nonlinear loads. Resonance phenomena. Transformer saturation.	Extended heating. Fail function of electronic equipment.
Transients 1.1-1.2		Lightning strike. Switching event.	Insulation failure. Reduced lifetime of transformers, motors *etc.*
Voltage fluctuations, flicker 6.0		Arc furnaces. Wind turbines. Start up of large motors.	Ageing of insulation. Fail functions. Flicker.
Short duration interruptions 2.1		Direct short circuit. Disconnection. False tripping. Load shedding.	Disconnection.
Unbalanced 4.0		One phase loads. Weak connections in the network.	Voltage quality for overloaded phase. Overload and noise from 3-phase equipment.

Current and voltage compensation may also be combined. This combination is referred to as the UPQC. The conditioning functions of the UPQC are shared by the SAPF and PAPF. The SPAF performs harmonic isolation between supply and load, voltage regulation and voltage flicker/imbalance compensation, however the PAPF performs harmonic current filtering and negative sequence balancing as well as regulation of the *DC* link voltage.

VAPF [103-110, 125] and SVAPF [111, 119] offer a different way of PQ improvement. Generally in VAPF the PQ improvement is possible because the parallel connected VSC acts as a sinusoidal voltage source, with fundamental frequency (*50Hz*). A quite similar way of improving power quality is possible using the SVAPF device which additionally possesses an extra current source.

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