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An Overview of FACTS Controllers for Power Quality Improvement

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ABSTRACT
Large penetration of non-conventional sources of energy (such as wind and solar) into the utility grid usually leads to power quality deterioration of the net system due to the intermittency nature associated with such energy sources. Power quality parameters that may likely be disturbed by such interconnection include voltage profile, frequency waveform, power factor, as well as active and reactive power of the power system. However, grid operators and consumers at all level of usage requires a perfectly balanced three phase a.c power of constant frequency and magnitude with smooth sinusoidal wave shape. In order to compensate for such disturbances, Flexible A.C Transmission System (FACTS) controllers were developed. This paper presents a technological review of different types of FACTS controllers and their application for power quality improvement in a grid network composing of conventional and non-conventional energy sources.
Keywords—FACTS Controller, Power Quality, Reactive Power, Voltage Regulation.

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I. INTRODUCTION

Utility operators are currently facing the challenge of meeting the ever increasing demand of electrical energy to their consumers or end users. While the largest contribution of the energy comes from conventional sources, the remaining has to be tapped from non-conventional sources such as wind and solar. Furthermore, the world wide concern about environmental pollution, global warming, as well as shortage of fossil fuel has also necessitated the need for harnessing environmentally friendly sources of energy that are free from noise and pollution [1]. Wind and solar energy are currently leading in such regard as their penetration level to the utility grid is on the rising edge [2].

Unfortunately, these renewable sources of energy are intermittent in nature as the time for their peak demand may not necessarily coincide with the time for their huge availability [3]. If such energy sources are directly connected to the utility grid, several operational problems may arise that can leads to power quality deterioration. The power quality issues that can arises as a result of such integration include voltage variations (such as voltage sag / voltage dip, voltage swell / voltage rise, voltage transient, harmonic distortion, e.t.c), frequency variations, flicker, power factor variation, as well as active and reactive power variations [4].

Although Power Electronic Converters (PEC) can be used to integrate renewable energy sources with the grid network in compliance with the power quality standards, but, such controllers are associated with high switching frequency and can therefore inject additional harmonic to the system [5]. Flexible A.C Transmission System (FACTS) controllers are now introduced, which make use of Voltage Source Converter (VSC) and a d.c link capacitor for grid integration of renewable energies [6]. FACTS controllers can control transmission line parameters and variables such as line impedance, terminal voltages, and voltage angles in a fast and effective way. They offer an excellent regulation in the transmission of alternating current and provide instantaneous solution to power quality disturbances [7]. FACTS controller is a power electronic based system and other static equipment that provide control of one or more a.c transmission parameters. FACTS controllers can inject or absorb reactive power to a system as per requirement [8]. The main benefit brought about by FACTS controllers is the improvement of system dynamic behavior and thus enhancement of system reliability.

FACTS controllers have the capability of regulating the transmission of alternating current in a power system by raising or lowering the power flow in specific lines while minimizing the power stability problems. The system is based on the possibility of controlling the route of the power flow and the ability of connecting networks that are not fully interconnected. This usually results in trading of energy between different stations. The controllability and flexibility of FACTS controllers make them suitable for mitigating the problems associated with intermittency of wind power. Furthermore, FACTS controllers can provide ancillary services such as voltage control to the grid network that is connected with WPP giving the later a fault ride capability.

Fault ride through (FRT) here means ability of the WPP to remain stable and connected to the grid network during electrical disturbances thereby supporting the transient stability of the system[9].

FACTS controllers provide the following opportunities for increased efficiency of utilities [10]:

- Prevention of cascading outages
- Damping of power system oscillation
- Power control enhancement
- Greater ability to transfer between controlled areas

FACTS controllers provide the following benefits [11]:

- Increased quality of supply for sensitive industries
- Better utilization of existing transmission assets
- Environmental benefits
- Increased transmission system reliability and availability
- Increased dynamic and transient grid stability

FACTS technology therefore opens up new opportunities for controlling power and enhancing the usable capacity of present, as well as new and upgraded, lines. The possibility that current and the power through a transmission line can be controlled enables a large potential of increasing the capacity of existing lines. These opportunities arise through the ability of FACTS controllers to control the interrelated parameters that govern the operation of transmission systems including series impedance, shunt impedance, current, voltage, phase angle and the damping of oscillations.

In this paper, the state of the art in the development of different types of FACTS controllers is presented. The paper thus reviewed the main objectives, the types, and the benefits of FACTS controllers. Furthermore, various FACTS controllers are described, their control attributes in power quality improvement and their role in power system stability is also analyzed.

II. CLASSIFICATION OF FACTS CONTROLLERS

The IEEE defined FACTS as “a power electronic based system and other static equipment that provide control of one or more a.c transmission system and increase the capacity of power transfer.” [12]. FACTS controllers can be classified based on two avenues, namely; based on technological features and based on the type of connection to the network.

A. FACTS Classification Based on Technological Features

Depending on technological features, FACTS controllers can be divided into two categories:

- First generation FACTS Controllers
- Second generation FACTS Controllers

The first generation FACTS controllers work like passive elements using impedance or tap changer transformers controlled by thyristors. They use thyristors with ignition controlled by SCR gate.

The second generation FACTS controllers use semiconductors with ignition and extinction controlled by gate such as GTO´s, and IGBT. They work like angle and module controlled voltage sources and without inertia, based in converters, employing electronic tension sources (three-phase inverters, auto-switched voltage sources, synchronous voltage sources, voltage source control) fast proportioned and controllable and static synchronous voltage and current sources.

The major difference between the first and second generation FACTS controllers is in terms of reactive power generation capacity and ability to interchange active power.

Table 1: Two Generation of FACTS Controllers [13]

FACTS Controller	Control Attributes
First Generation FACTS Controllers	
Static Var Compensator (SVC, TCR, TCS, TRS)	Voltage control and stability, compensation of VAR´s, muffling of oscillations
Thyristor Controlled Series Compensations (TCSC,TSSC)	Current control, muffling of oscillations, transitory, dynamics and of voltage stability, limitation of fault current

Thyristor Controlled Reactor Series (TCSR,TSSC)	Current control, muffling of oscillations, transitory, dynamics and of voltage stability, limitation of fault current
Thyristor Controlled Phase Shifting Transformer (TCPST,TCPR)	Control of active power, muffling of oscillations, transitory, dynamics and of voltage stability
Thyristor Controlled Voltage Regulator (TCVR)	Control of reactive power, voltage control, muffling of oscillations, transitory, dynamics and voltage stability
Thyristor Controlled Voltage Limiter (TCVL)	Limits of transitory and dynamic voltage
Second Generation FACTS Controllers	
Synchronous Static Compensator (STATCOM without storage)	Voltage control, compensation of VAR´s, muffling of oscillations, stability of voltage
Synchronous Static Compensator (STATCOM with storage)	Voltage control and stability, compensation of VAR´s, muffling of oscillations, transitory, dynamics and of tension stability
Static Synchronous Series Compensator (STATCOM without storage)	Current control, muffling of oscillations, transitory, dynamics and of voltage stability, limitation of fault current
Static Synchronous Series Compensator (STATCOM with storage)	Current control, muffling of oscillations, transitory, dynamics and of voltage stability
Unified Power Flow Controller(UPFC)	Control of active and reactive power, voltage control, compensation of VAR´s, muffling of oscillations, transitory, dynamics and of voltage stability, limitation of fault current
Interlink Power Flow Controller (IPFC) or Back to Back (BtB)	Control of reactive power, voltage control, muffling of oscillations, transitory, dynamics and of voltage stability

A1. ***First Generation FACTS Controllers***

1. Static Var Compensator (SVC)

Static Var Compensator or SVC is a shunt connected FACTS controller that can adjusts its output to exchange capacitive or inductive currents thereby generating or absorbing reactive power so as to control power system parameters such as bus voltage. It provides bus bar voltage stabilization and damping of power system oscillations. SVCs are usually applied by utilities in transmission applications for many purposes among which is rapid voltage control at weak points in electrical power system network [14]. SVC is of two types, viz;

- Thyristor Controlled Reactor, TCR
- Thyristor Switched Capacitor, TSC

The classification string symbol for SVC is 1P-NC-LF-ZES-NDC (i.e, S1 = 1P, S2 = NC, S3 = LF, S4 = ZES and S5 = NDC) which literally means it is a one port circuit with a parallel connection to the power system; it uses natural commutation; its switching frequency is low; it contains insignificant energy storage element; and it has no d.c port [15].

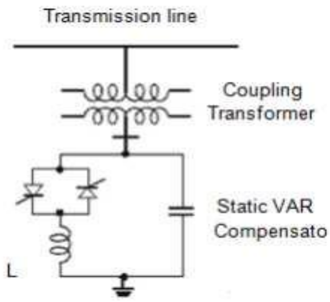

Fig 1: Static Var Compensator (SVC)

2. Fixed Capacitor Thyristor Controlled Reactor (TCR)

This is a shunt connected thyristor controlled inductor whose effective reactance can be varied continuously by partial conduction control of the thyristor value. FC-TCR consists of a capacitor in parallel with a thyristor controlled reactor. It is a reactive power compensation device capable of providing continuous lagging and leading VARs to the system. In the figure shown below, Is is the system current, Ir is the reactor current and Ic is the capacitor current. The function of the capacitor, C is to supply leading VAR to the system whereas the supply of lagging VAR can be achieved by rating the TCR larger than the capacitor.

TCR has for long been used as one of the economical alternatives of FACTS controllers. Firing delay angle control is used to control the current in the reactor from maximum to zero [16].

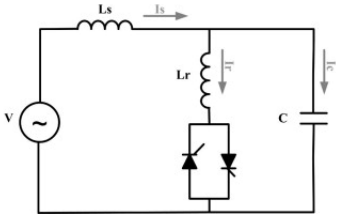

Fig 2: Fixed Capacitor Thyristor Controlled Reactor (FC-TCR)

3. Thyristor Controlled Series Capacitor (TCSC)

This is a capacitance reactance compensator that comprises of a series capacitor bank shunted by a thyristor controlled reactor that provides a smoothly variable series capacitive reactance. TCSC consists of a series reactor shunted by a thyristor controlled reactor to provide a smooth variable series inductive reactance. It is thus an inductive reactance compensator that combines a thyristor controlled reactor and a capacitor to control capacitive reactance. The reactor control is achieved by controlling the firing angle of the thyristor.

TCSC is capable of injecting a series voltage that is proportional to and in quadriture with the line current. When inserted on a transmission line, TCSC can modify the equivalent reactance of the line, thereby varying the flow of active power in the system. TCSC does not require an interfacing equipment like transformer [17].

The classification string symbol for TCSC is 1S-NC-LF-ZES-NDC (i.e, S1 = 1S, S2 = NC, S3 = LF, S4 = ZES and S5 = NDC) which literally means it is a one port circuit in series with a transmission line; it uses natural commutation; its switching frequency is low; it contains insignificant energy storage element; and it has no d.c port [15].

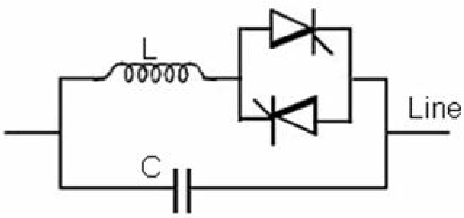

Fig 3: Thyristor Controlled Series Capacitor (TCSC)

A2. Second Generation FACTS controllers

1. Static Synchronous Compensator (STATCOM)

This is a static synchronous generator operated as a shunt connected static VAR compensator whose capacitive or inductive output current can be controlled independent of the a.c system voltage. It is a member of GTO based FACTS family. It is a shunt connected reactive power compensation device that can regulate bus voltage at the point of common coupling (PCC). STATCOM can control the electric power system parameters by generating or absorbing reactive power. It consists of two-level voltage source converter with d.c energy storage; a coupling transformer connected in shunt with the a.c system and control devices. The VSC converts the d.c voltage across the d.c energy storage device into a set of three phase a.c output voltage. The three phase voltages are in phase with the a.c voltage and are coupled with the a.c system through the reactance of the coupling transformer. Active and reactive power control can be achieved by varying the magnitude and phase angle of the STATCOM. It can generate or absorb independently controllable real and reactive power at its output terminals when fed from an energy source or energy storage device. It is based on the principle that a voltage VSC generates a controllable AC voltage behind a transformer leakage reactance so that the voltage difference across the reactance produces active and reactive power exchange between the STATCOM and the transmission network [18].

The classification string symbol for STATCOM is 1P-FC-HF-CES-DC (i.e, S1 = 1P, S2 = FC, S3 = HF, S4 = CES and S5 = DC) which literally means it is a one port circuit that is shunted across a bus bar; it uses force commutation; its switching frequency is high; its energy storage element is a d.c capacitor; and it has a d.c port [15].

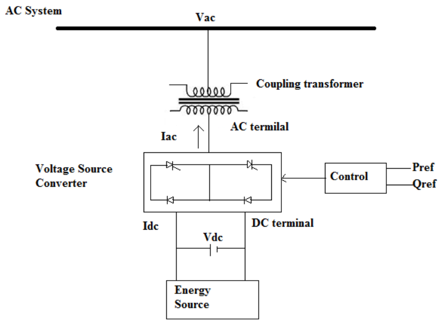

Fig 4: Static Synchronous Compensator (STATCOM)

2. *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 quadriture with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power. The SSSC may include transiently rated energy storage or energy absorbing devices to enhance the dynamic behavior of the power system by additional temporary active power compensation, to increase or decrease momentarily, the overall active (resistive) voltage drop across the line. SSSC is capable of controlling the flow of real and reactive power through the system. It is mostly used for series compensation of power.

A typical SSSC is shown in figure 5 below; in which the VSC converts the supply voltage from a d.c source into a.c. The coupling transformer is used to inject a quadriture voltage in the line. The injected voltage, Vc lags the line current, I by 90o, and hence, series compensation is done. Thus, SSSC is capable of providing real and reactive power flow control through the system.

The injected voltage is almost in quadrature with the line current. A small part of the injected voltage that is in phase with the line current provides some losses in the inverter. Most of the injected voltage, which is in quadrature with the line current, provides the effect of inserting an inductive or capacitive reactance in series with the transmission line. The variable reactance influences the electric power flow in the transmission line [19].

The classification string symbol for SSSC is 1S-FC-HF-CES-DC (i.e, S1 = 1S, S2 = FC, S3 = HF, S4 = CES and S5 = DC) which literally means it is a one port circuit in series with a transmission line; it uses force commutation; its switching frequency is high; its energy storage is capacitor; and it has a d.c port [15].

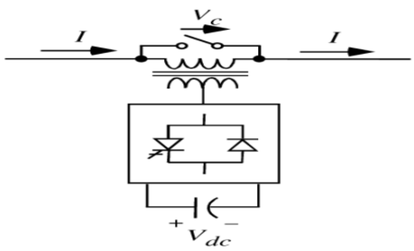

Fig 5: Static Synchronous Series Compensator (SSSC)

3. *Unified Power Flow Controller (UPFC)*

As the name implies, this FACTS device is capable of controlling all power parameters, namely; voltage, phase angle, impedance, power factor, real and reactive power. It can therefore be used for the enhancement of real and reactive power flow, steady state stability as well as dynamic stability among others.

A UPFC is shown in figure 6. It is made up of two VSCs that are coupled through a common d.c link that provides bidirectional flow of real power the two outputs, - shunt STATCOM and series SSSC. One of the VSCs is a STATCOM based converter that is connected in parallel with the transmission line in order to maintain a balance between power generation into and absorption from the system. The other VSC is SSSC based converter that is connected in series with the line for the enhancement of power flow and transient stability by injecting voltage of variable magnitude and phase angle [20]. Real power flows between the shunt and series a.c terminals of the UPFC through the common d.c link. The switching operation of the two converters is used by the UPFC to generate or absorbs its reactive power. The reactive power does not flow through the d.c link, instead, each converter generates or absorbs its reactive power independently [21]

The classification string symbol for UPFC is 2-FC-HF-CES-DC (i.e, S1 = 2, S2 = FC, S3 = HF, S4 = CES and S5 = DC) which literally means it is a two port circuit in series with a transmission line and in parallel with the bus bar; it uses force commutation; its switching frequency is high; its energy storage element is capacitor; and it has a d.c port [15].

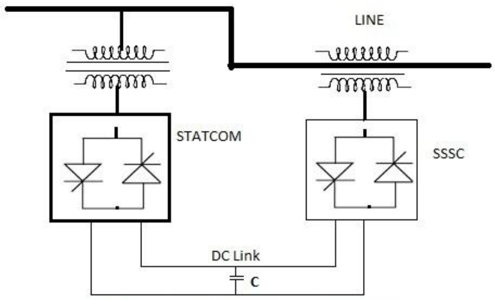

Fig 6: Unified Power Flow Controller (UPFC)

*4. **Interphase Power Controller (IPC)***

This is a series FACTS controller capable of providing active and reactive power control in a power system. It is made up of two branches, - capacitive and inductive, that are separately subjected to phase shifted voltages. The branch impedances are adjusted in order to set the active and reactive power independently. Thus, IPC can regulate the direction as well as the amount of active power transmitted through a transmission line.

The classification string symbol for IPC is 2s-NC-LF-ZES-NDC (i.e, S1 = 2, S2 = NC, S3 = LF, S4 = ZES and S5 = NDC) which literally means it is a two port circuit in series with a transmission line and in parallel with a bus bar; it uses natural commutation; its switching frequency is low; it contains insignificant energy storage element; and it has no d.c port [15].

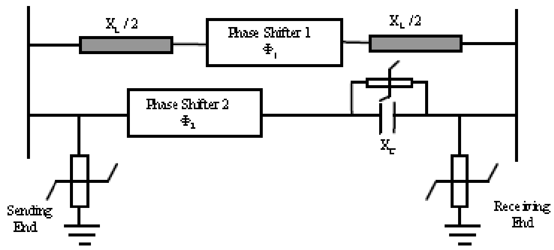

Fig. 7: Interphase Power Controller (IPC)

5. Dynamic Voltage Restorer (DVR)

DVR is a series connected FACTS device used for voltage regulation especially across sensitive loads. A typical DVR is shown in figure 8. It consists of a VSC with an energy storage connected to the d.c link. The VSC is connected in series with the power network by means of a series-connected injection transformer and coupling filters. DVR is used as a protection device to sensitive equipments and critical loads against electrical disturbances such as voltage dip.

DVR works in two mode of operations, namely; standby mode and boost mode. During steady state condition of the power system, the DVR will be in standby mode with the DVR voltage being exactly zero. Under such condition, the booster transformer's low voltage winding is shorted through the VSC so that, the individual converter legs are triggered thereby establishing a short circuit path for the transformer connection, hence, no semiconductor switching. However, upon detection of a fault (such as voltage fluctuations), the DVR will switch to boost mode. In this mode, the DVR voltage is greater than zero; hence, it will inject a compensation voltage through the booster transformer [22].

DVR only introduces a partial amount of voltage. Thus, in the event of voltage sag for example, the DVR responds quickly thereby injecting a sufficient voltage of appropriate magnitude and phase angle. DVR has a very short response time of about 25 milliseconds that is limited by the power electronics devices [23].

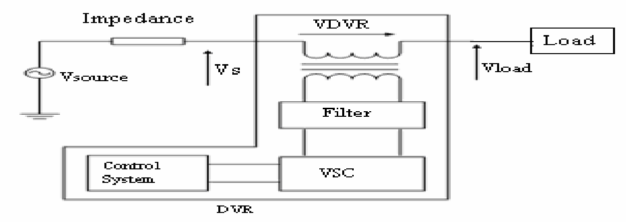

Fig 8: Dynamic Voltage Restorer (DVR)

B. FACTS Classification Based on Connection Type

Depending on the type of connection to the electric power network, FACTS controllers are classified as in [24] - [27] as:

- Serial controllers
- Derivation controllers
- Serial to serial controllers
- Serial-derivation controllers

1. Serial FACTS Controllers

These FACTS controllers works by injecting a serial tension (i.e, a variable impedance multiplied by the current that flows through it) in quadriture with the line current. Basically, a series controller may consist of a variable electronics based source at the fundamental frequency or variable impedance such as a capacitor or reactor. Provided the voltage is in phase quadriture with the line current, a serial controller only supplies or consumes reactive power, hence; any other phase angle only represents active power management. Members of this type of controller include SSSC, IPFC, TCSC, TSSC, and TCSR.

2. Derivation (Shunt) FACTS Controllers

Derivation controllers work by injecting current into the system at the point of interconnection in quadriture with the line. Usually, they consist of a variable electronic based, a variable impedance, or both. The current that flows through the variable impedance represents the current being injected to the line. In other words, the variable current can as well be caused by variable shunt impedance connected to the line voltage. The controllers that belong to this category include STATCOM, TCR, TSC, and TCBR.

3. Serial-Serial FACTS Controllers

A Serial-Serial FACTS Controller is a combination of well coordinated serial controllers in a multiline transmission system. It is just a unified controller, in which the serial controllers provide reactive compensation for each line, thereby transferring active power between the lines via a power link. Active and reactive power balance is achieved either by the line feeder controller or through the transmission capacity of the active power that presents a unified serial controller. The unified nature therefore enables it to achieve active power transfer between each other by proper connection of the d.c terminals of the converters of the controllers. A typical example of serial-serial controller is IPFC.

4. Serial-Derivation (Combined Series-Shunt) FACTS Controllers

As the name implies, this controller is a coordinated combination of separate series and derivation controllers. They work by injecting 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. Thus the shunt and series part of the controllers are unified, in which case, real power exchange between the series and shunt controllers can be achieved via a proper link. Members of this class of controllers include UPFC, TCPST, and TCPAR.

III. ADVANTAGES, APPLICATIONS AND BENEFITS OF UTILIZING FACTS CONTROLLERS

A. Advantages of Using FACTS Controllers in Power System

- Mitigation of potential sub-synchronous resonance
- Real and reactive power flow control
- Increased quality of supply for sensitive industries
- Increased transmission system reliability and availability
- Increased dynamic and transient grid stability
- Better utilization of existing transmission system assets

B. Applications of FACTS Controllers

- Interconnection of renewable energies such as wind and solar into the grid
- Interconnection of distributed generation and storage
- Power quality improvement
- Power flow control
- Voltage control
- Power conditioning
- Stability improvement
- Flicker mitigation
- Increase of transmission capacity

C. Benefits of utilizing FACTS Controllers

- Increase (control) power transfer capability of a line
- Mitigate sub-synchronous resonance (SSR)
- Improve system transient stability limit
- Increasing the loadability of the system
- Power quality improvement
- Limit short circuit currents
- Enhance system damping
- Alleviate voltage stability
- Load compensation

IV. ROLE OF FACTS CONTROLLERS IN POWER SYSTEM OPERATION

Table 2: The Role of FACTS controllers in Power System Operation [28]

Subject	Problem	Corrective Action	FACTS Controller
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 at outage	Supply reactive power, prevent overload	SVC, STATCOM
Thermal limits	Transmission circuit overload	Increase transmission capacity	TCSC, SSSC, UPFC
Load flow	Power distribution on parallel lines	Adjust line reactance	TSCS, SSSC
		Adjust phase angle	UPFC, SSSC, PAR
	Load flow reversal	Adjust phase angle	UPFC, SSSC, PAR
Short circuit power	High short circuit current	Limitation of short circuit current	TCSC, UPFC
Stability	Limited transmission power	Decrease line impedance	TCSC, UPFC

V. CONCLUSION

The paper has presented a technological review on the flexible a.c transmission system (FACTS) devices used for power quality improvement especially during the integration of non-conventional sources of energy such as wind and solar into the grid network. The paper outlined some advantages, benefits as well as other applications of FACTS controllers. The paper concludes with outlining the basic roles of FACTS controllers in power system operation.

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