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Power Quality Improvement Using FACTS Devices: A Review

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Abstract— During the design of modern power systems for efficient operation and continuous power supply to various load centers one has to consider the growth in the use of power electronics that has caused a greater awareness of power quality. Voltage sags, swells, harmonics etc are the various power quality problems that can cause equipment to fail, or shut down, blown up fuses or tripping of breakers due to large current imbalances. FACTS devices can be used to overcome these effects which can otherwise be very harmful for the residential as well as industrial customer, hampering their work production due to faults and equipment damage. This is a review paper to analyze the current trends in FACTS to improve the power system performance. It contains work which has been carried out by various researchers in the field of FACTS.

Keywords— FACTS , STATCOM , DVR, SSC, DSTATCOM, TCSC, IPFC, UPFC.

I. INTRODUCTION

The power quality has become very important for the performance of many industrial applications like production engineering and information technology, and also has an influence on high technology communication devices control and automation, and on-line service. Thus, power quality has obtained increased attention by both industrial as well as commercial electrical users [1].The power system has to be protected from the surroundings and environment, due to the increased deregulation and overloading of the electricity . As a remedial measure, a power electronics based technology named FACTS has been introduced to control the different parameters of transmission line system [2]. Losses to both the consumers and utilities are a result of poor quality problems. Therefore, the study of power quality problem is becoming a popular research topic. Now a days the consumers are much concerned and aware of various power quality problems and the reasons for this increased concern:

1. The newer-generation load equipments are equipped with microprocessor-based controls and power electronic devices which are very sensitive to power quality variations.
2. With the increased knowledge & awareness regarding various power quality problems and their effects have arisen the customers to challenge the utilities to improve the quality of power delivered.
3. The failure of any component has more important consequences to the whole system due to the advanced trend of the interconnected network with integrated processes. Basically power quality is the quality of the received voltage in most cases. Therefore, to maintain the supply voltage within certain limits is main criteria of utilities.
4. Over the last few years the usage of computers has increased considerably in office and homes due to modern lifestyle and for fast work output so the users have become more sensitive to interruptions while depending on this technology. It should be the prime objective of end user to overcome the inadequacies in power equipment while buying and operating it [3].

Power quality does not only depend on the suppliers but it also depend upon the user that how they consume electricity. Power quality at the generator can be defined as the generator's ability to generate power at 50 Hz with little variation, while power quality at the transmission and distribution level refers to the voltage staying within plus or minus 5 percent. Gerry Heydt in 'Electric Power Quality' defines power quality as - the measure, analysis, and improvement of bus voltage, usually a load bus voltage, to maintain that voltage to be sinusoidal at rated voltage and frequency [4]. With the advancement of technology a large numbers of sophisticated electrical and electronic equipment, such as computers, programmable logic controllers, variable speed drives etc. there is reduction in power quality and this leads to loss in terms of time and money of the industrial and commercial electrical consumers [5].

Implementation of various FACTS devices in the power system can help in reducing the various power quality problems. For the efficient use of power system resources a concept of Flexible AC Transmission Systems (FACTS) was introduced in the late 1980's. The basic concept of FACTS devices is based upon the use of high-voltage power electronics to control real and reactive power flow and voltage in the transmission system [6]-[8].

The paper is organized as follows: Section II provides a brief description of the various power quality problems. Section III presents various FACTS devices and their role in achieving Power Quality, by mentioning the work done in this area. Lastly, conclusions are drawn in Section IV.

II. POWER QUALITY PROBLEMS

A. Various Power Quality Problems are as follows:

a) **Impulse** : Narrow pulse with fast rise and exponential or damped oscillatory decay; 50 V to 6 kV amplitude, 0.5 µs to 2 ms duration can be defined as impulse as shown in Fig. 1(a). Its causes are load switching, fuse clearing, utility switching, arcing contacts etc.

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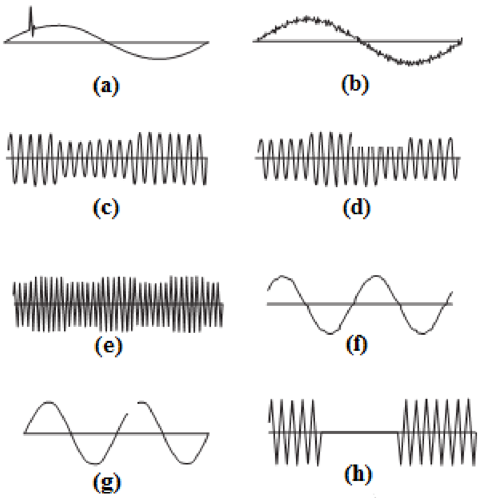

Fig. 1. Power Quality Problems

b) **EMI:** It can be depicted from Fig. 1(b) and is defined as the repetitive low energy disturbances in the 10 kHz to 1 GHz band, with 100 μV to 100 V amplitude. It can be caused by normal equipment operation (switching power supplies, motor speed controllers etc) carrier power line communication and wireless broadcasting.

c) **SAG:** It is defined as the decrease in voltage between 0.1pu to 0.9pu and it can be seen in Fig. 1(c). It is due to the starting of heavy load, utility switching and ground fault.

d) **Swell:** An increase in voltage between 1.1pu to 1.8pu can be termed as swell as shown in Fig. 1(d). The main causes of swell are load reduction, utility switching.

e) **Flicker:** Small repetitive fluctuation in voltage level is called flicker. Flicker has been shown in Fig. 1(e). Pulsating load is its main cause.

f) **Notches:** It is known as repetitive dips in the line voltage, with short durations and it can be seen in Fig. 1(f). The main reasons for its occurrence are current commutation in controlled or uncontrolled three-phase rectifier circuit.

g) **Waveform distortion:** The deviation from ideal sine wave due to the presence of harmonics or inter harmonic is called as waveform distortion. Fig. 1(g) represents waveform distortion. It can be caused by rectifiers, phase-angle controllers, other nonlinear and/or intermittent loads.

h) **Outage:** Zero-voltage condition of a single phase or several phases in a multi-phase system, for more than a half-period is known as outage and can be seen from Fig. 1(h). Load equipment failure, ground fault, utility equipment failure, accidents, lightning and other acts of nature are major causes of outage.

B. The Influence of Power Quality Problems

Power quality problem is definitely harmful for both the power system and customers having various influences as :

1) There is reduction in the efficiency and life span of the generating equipment, transmission line and electrical equipment due to additional loss of power system device.
2) There is overheating in some part of transformer being produced by mechanical vibration, noise and overvoltage.
3) There is an increase in false tripping and maloperation of relay protection and automation which can lead to inaccurate measurement of electric testing instrument.
4) There is production of noise due to any disturbance on telecommunication system and even interfere the communication quality, or sometimes it could cause message dropping.
5) There can be overheating, ageing of insulation, life-span shortening and even damages in capacitor and transmission line due to harmonic production and these harmonics also causes parallel resonance and series resonance in part of power system.

FACTS are power electronics based and other static controller to enhance controllability and increase power transfer and provide control of one or more ac transmission system parameters as defined in IEEE definitions and standards [6],[7].

III. ROLE OF FACTS DEVICES

Flexible Alternating Current Transmission Systems (FACTS) devices have been proposed for effective power flow control and regulating bus voltage in electrical power systems, thus resulting in an increased transfer capability, low system losses and improved stability.

A. Types of FACTS devices or FACTS controllers:

(a) Shunt FACTS Controller: The shunt controllers are connected in parallel with the transmission line. They inject the voltage and current in parallel with the transmission system.

(i) Static Synchronous Compensator:

According to IEEE definitions and standards, a static synchronous generator operated as a shunt connected static var compensator whose capacitive or inductive o/p current can be controlled independent of ac system voltage.

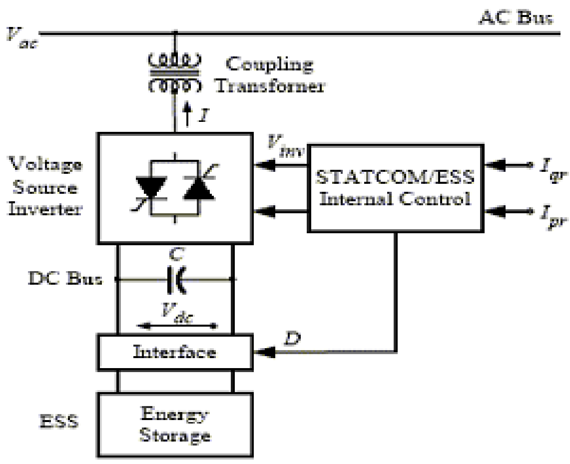

Fig. 2. Static Synchronous Compensator

A *STATic synchronous COMpensator* (STATCOM) as shown in Fig. 2, emulates an inductive or a capacitive reactance at the point of connection with the transmission line by injecting sinusoidal current, of variable magnitude, at the point of connection in quadrature with the line voltage. The line voltage regulation can be achieved by regulating the reactive current flow through STATCOM which has been verified by the modelling technique of STATCOM using an *Electromagnetic Transients Program*(EMTP) simulation package [9].

Distribution static compensator (DSTATCOM) is used in distribution system for the compensation of reactive power and unbalance caused by various loads and it works on the principle of VSC (voltage source converter). To compensate the reactive power a current injected into the system by D-STATCOM to correct the voltage sag, swell and interruption . DSTATCOM is shown below in Fig. 3.

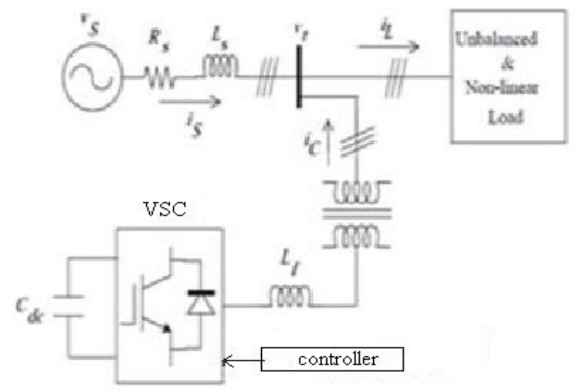

Fig. 3. Distribution STATic COMpensator

An efficiently controlled DSTATCOM can be used to compensate the reactive power and unbalance. The DSTATCOM's performance is dependent on the control algorithm used for extraction of reference current components [10].

A test system with/without DSTATCOM and a Battery Energy Storage System (BESS) has been done using Simulink and SimPower System in MATLAB environment for a wide variety of system disturbances under different tested conditions [11].

A paper has been published describing implementation of a neural-network (NN)-controlled DSTATCOM using a dSPACE processor for power quality improvement in a three-phase four-wire distribution system and its performance has been analysed in MATLAB [12].

For improving the power quality of power systems dynamic modeling and the control design of a distribution static compensator coupled with ultra-capacitor energy storage (UCES) has also been proposed and the control technique employed is based on the instantaneous power theory on the synchronous-rotating *dq* reference frame. Three modes of operation have been considered, i.e. voltage control for voltage fluctuations ride-through, current/voltage harmonics mitigation and dynamic active power control [13].

A mathematical model of DSTATCOM in voltage sag compensation mode along with SVPWM switched DSTATCOM simulation in power factor control mode has been presented for power factor and voltage sag compensation [14].

DSTATCOM can also be applied to industrial systems for mitigation of voltage dip problem which generally occurs during the starting of an induction motor [15].

The distribution system performance under all types of fault can be improved by using a 12-pulse DSTATCOM configuration with IGBT which can be modeled and simulated using the PSCAD/EMTDC [16].

A DSTATCOM can also be applied in three-phase, four-wire distribution system feeding commercial and domestic consumers for load balancing, neutral current elimination, power factor correction and voltage regulation [17].

To maintain voltage stability and improve power quality of distribution grid, a control strategy combining control of state feedback and feed forward has been employed using a nonlinear dynamic mathematical model of DSTATCOM and thus improving the transient response performance and anti-disturbing ability of the system [18].

A three-level voltage inverter based dynamic model of DSTATCOM has been established by way of lead-in switch function and using PWM current control technology for realizing dynamic var compensation effectively [19].

A three-leg voltage source inverter (VSI) configuration with a dc bus capacitor as a DSTATCOM has been demonstrated through MATLAB/SIMULINK for power quality improvement in a three-phase, three-wire distribution system . Different control strategies have been employed and compared like hysteresis control, PWM current controllers , PI controller and sliding mode controller [20].

In order to balance the supply current, and improving the power factor to a desired value the theory of instantaneous symmetrical components has been used here to extract the three-phase reference currents and then these reference currents are then tracked using voltage source inverter (VSI), operated in a hysteresis band control technique [21]. The nonlinear state-space model of the multilevel DSTATCOM has been presented from the dq0 reference frame that can adapt to load changes and have effective steady-state compensation and a better dynamic response [22].

(ii) Static VAR Compensator:

According to IEEE definitions and standards, 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 electrical power system.

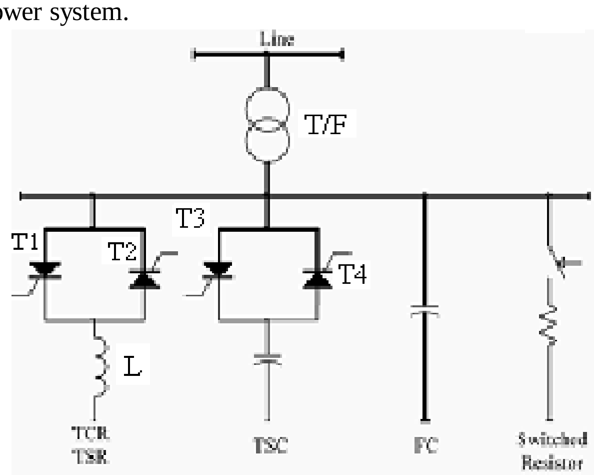

Fig. 4. Static VAR Compensator

Static VAR compensator (SVC) can be seen in Fig. 4. A comparative power flow study using SVC and STATCOM models on IEEE 14-Bus Test Network has been carried out and it has been shown that in both cases, the state variables of SVC and STATCOM have been combined with the bus voltage magnitudes and the angles of the network for Newton Power flow solution for achieving power quality and stability [23].

(b) Series FACTS Controller: These controllers are connected in series with the transmission line and they inject the voltage and current in series with the transmission system.

(i) Static Synchronous Series Compensator:

According to IEEE definitions and standards, a static synchronous generator or dynamic voltage restorer operated without an external electrical energy source or a series compensator where o/p voltage is in quadrature and controllable independently of the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and there by controlling the transmitted electric power. SSSC is also known as dynamic voltage restorer. The DVR was first installed in 1996 and is shown in Fig. 5.

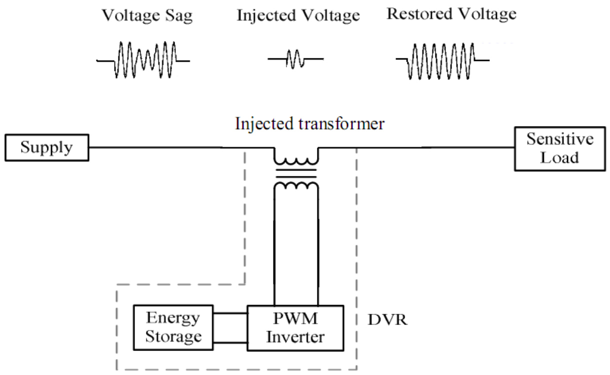

Fig. 5. Static Synchronous Series Compensator

DVR is useful for compensating voltage quality problems that are due to voltage sag. Due to its excellent dynamic capabilities, it is well suited to protect critical or sensitive load from short duration voltage dips or swells. When a fault occurs in a distribution network, a sudden voltage dip will appear on adjacent load feeders. With a DVR installed on a critical load feeder, the line voltage is restored to its nominal value within the response time of a few milliseconds thus avoiding any power disruption to the load [24], [25]. DVR protects loads against voltage sags by series injection of the missing portion of the utility voltage. To obtain missing voltage the distorted source voltage is compared with its pre-fault value to generate the control signal for PWM. The size and rating of DVR depend on its capability in supplying or absorbing real power in the steady-state [26]. Dynamic Voltage Restorer (DVR) is normally installed in a distribution system between the supply and the critical load feeder. Its primary function is to rapidly boost up the load-side voltage in the event of a disturbance in order to avoid any power disruption to that load. There are various circuit topologies and control schemes that can be used to implement a DVR [27]. To compensate the voltage deviation caused in a feeder the Interline DVR (IDVR) operated by Multiple Pulse Width Modulation (PWM) has been proposed which consists several DVRs connected to different distribution feeders in the power system sharing a common energy storage. One DVR in the IDVR system works in voltage-sag/swell compensation mode while the other DVR in the IDVR system operate in power-flow control mode [28]. GA-based optimization can be used for the location, the type and the rating of the various FACTS devices like static var compensator, static compensator, and dynamic voltage restorer and the performance of the proposed algorithm has been tested and illustrated on 295-bus generic distribution system [29].

A schematic diagram of IDVR has been shown in Fig. 6.

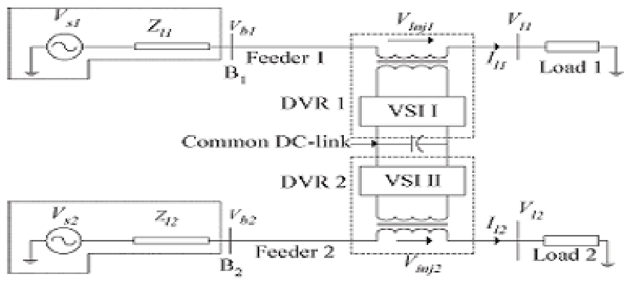

Fig. 6. Schematic diagram of an IDVR

A concept of interline dynamic voltage restoration (IDVR) has been proposed in which several DVRs in different feeders are connected to a common DC-link energy storage and thus reducing the cost of installation. For both the voltage control and the power flow control modes a closed-loop controller that consists of an inner current loop and an outer voltage loop has been incorporated into the IDVR system [30].

(iii) Thyristor Controlled Series Capacitor:

According to IEEE definitions and standards, a capacitive reactance compensator which consists of series capacitor bank shunted by thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance. Fig. 7 shows a Thyristor Controlled Series Capacitor.

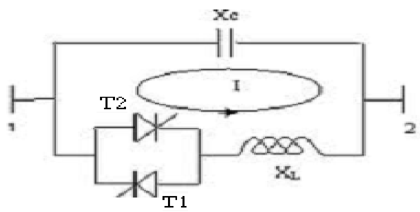

Fig. 7. Thyristor Controlled Series Capacitor

Thyristor Controlled Series Capacitor (TCSC) has been modeled in a simple two bus system with distributed parameter line. A Fuzzy logic controller and a PID controller have been used to control firing angles of TCSC but it has been verified that the fuzzy logic controller can generate better dynamic response [31]. A single-machine infinite-bus power system installed with a TCSC has been proposed whose control parameters have been optimized using genetic algorithm. The modelling and simulation have validated the effectiveness of the proposed approach to achieve system stability [32].The TCSC controller can provide a very fast action to increase the synchronization power by quick change in the equivalent capacitive reactance to the full compensation during a fault. The TCSC controller can be designed to control the power flow, to increase the transfer limits or to improve the transient stability and damping the oscillations FACTS devices such as thyristor controlled series capacitors are difficult to model due to their nonlinear switching behaviour. It has been shown that passive damping has a significant effect on modal damping [33],[34].

As compared to the traditional control devices, the TCSC offers smooth and flexible control of the line impedance with much faster response. The Newton-Raphson ac power flow method has been used to perform the modeling of TCSC for power flow studies. The performance of the proposed algorithm has been tested on IEEE-30 bus systems [35].

(c) Combined series-series controllers: These controllers have two series controllers which are connected in series with the transmission line coupled via common dc power link to transmit the current, voltage and power.

(i) Interline Power Flow Controller: According to IEEE definitions and standards, it consists of two or more SSSC which are coupled via common dc power link to facilitate bidirectional flow of real power between the ac terminals of SSSC. Interline Power Flow Controller (IPFC) can be seen in Fig. 8.

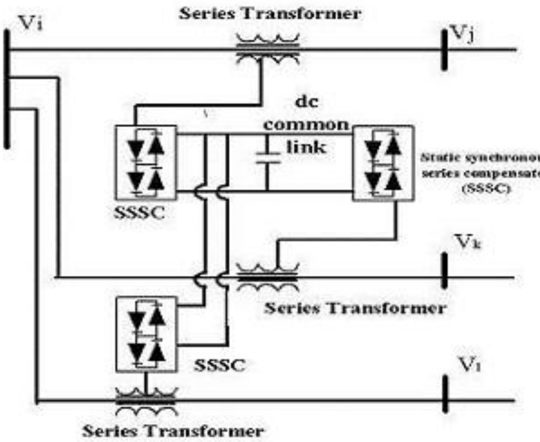

Fig. 8. Interline Power Flow Controller

IPFC is a new concept for an overall real and reactive compensation and effective power flow management of multi-line transmission systems by transferring the power from overloaded to under loaded lines. It consists of a number of inverters with a common dc link to facilitate real power transfer among the lines of transmission system. The prime inverters can be controlled to provide totally different operating functions, e.g., independent P and Q control, phase shifting (transmission angle regulation), transmission impedance control, etc [36],[37].

In order to analyse the flexibility of power flow control, the steady state operation of the IPFC has been investigated through its mathematical model using improved control strategies. A mathematical model based on the *d-q* orthogonal coordinates was developed to address the issues like the relationship between the transmission angle and the IPFC controlled region [38],[39].

The power injection model has been incorporated in Newton-Raphson (NR) power flow solution method on IEEE 14-bus system on the basis of a MATLAB program to demonstrate the performance of the IPFC model and its effects in power flow studies [40]. To verify the capability of IPFC in controlling the power flow in power system a case study has been conducted on 6-bus & 3-machine and 30-bus & 6- machine systems, and the results have been examined in the absence and presence of IPFC in the network [41].

A controller has been made using ATP- Electromagnetic Transients Program as study and investigation tool in which the IPFC employs two dc/ac inverter with a common DC-link to provide series compensation in the transmission system [42]. For improving the transient stability performance of power systems an integrated approach of radial basis function neural network (RBFNN) and Takagi-Sugeno (TS) fuzzy scheme with a genetic optimization of their parameters has been implemented on TCSC connected in a single-machine infinite bus power system and then applied to IPFC connected in a multi machine power system [43].

An extended Heffron-Phillips model of a single machine infinite bus (SMIB) system installed with IPFC has been established and used to analyze the damping torque contribution of the IPFC in damping the low frequency oscillations and maintaining the control of the power system. Under various loading conditions the potential of various IPFC control signals has been investigated for the power system oscillation stability. To enhance the transient stability of the system a power oscillation damping controller has been designed for the IPFC using phase compensation technique. The eigen value analysis of the linearized Phillips-Heffron model have been used to identify the oscillation modes with low damping ratio. To control the power flow demand in the IPFC connected transmission lines additional power flow controllers have also been incorporated into the system [44]-[46].

Another Mathematical model of the IPFC has been presented to investigate the flexibility of power flow control, and the steady state operation of the Interline Power Flow Controller (IPFC) has been investigated in the presence of operating constraints of the IPFC [47].

In order to ensure a globally optimum control strategy in the Lyapunov sense, the newly developed IPFC energy functions has been implemented such that the magnitudes of the IPFC's series-injected voltages remain set to their maximum values and only the angles of these voltages change [48].

To investigate the inter-system oscillations, a linear model of VSC-based FACTS devices has been developed that takes into account the dynamics of dc links and then incorporated into a production-grade software for small signal analysis of large power systems [49].

For state estimation a model with IPFC has been introduced on the basis of conventional power system state estimation model, in which power injection model has been used and the effect of IPFC on the power flow has been transferred to the lines which are connected to it [50].

(d) Combined Series and Shunt Connected Controller: In these controllers, one controller is connected in series and another is connected in parallel and they both are coupled via a coordinated control and a common dc power link in transmission line to transmit the current, voltage and power.

(i) Unified Power Flow Controller: According to IEEE definitions and standards, Unified Power Flow Controller (UPFC) consists of STATCOM and SSSC which are coupled via common dc power link to allow bidirectional flow of real power between the series o/p terminals of the SSSC and shunt o/p terminals of the STATCOM. The basic structure of UPFC has been shown in Fig. 9.

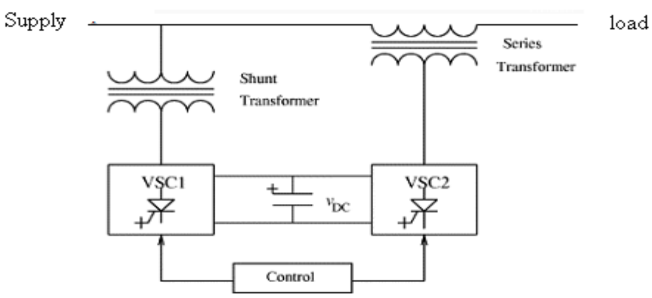

Fig. 9. Unified Power Flow Controller

The most promising FACTS device, UPFC, is capable of providing an adaptive voltage magnitude control as well as active and reactive power control and their regulation. A new mathematical model of UPFC incorporated in Newton-Raphson load flow algorithm has been developed. Voltage Stability Index has been used for optimal location of UPFC and Particle Swarm Optimization (PSO) technique has been used to set the parameters of UPFC being tested on IEEE 5-Bus and IEEE 14-Bus systems using MATLAB [51].

A numerical method tested with Matlab consisting of a set of equations for a system including the UPFC and an equivalent two bus power network has been successfully validated with analog model and EMTP [52].

The mathematical models for new UPFC series control modes have been presented which include direct voltage injection, bus voltage regulation, line impedance compensation and phase angle regulation [53].

In comparison with the classical decoupled control strategy, for better stability and transient performance a modified control structure with a predictive control loop and pre control signal has been designed for a dc-voltage control and control of harmonic current [54].

The selection of damping control signal for the design of UPFC damping controller and the effect of UPFC DC voltage regulator on power system oscillation stability and the have been studied and demonstrated on the Phillips–Heffron model [55].

The modeling of converter-based controllers in which two or more VSCs are coupled to a dc link like UPFC, IPFC and GUPFC has been presented for load-flow calculations [56].The modeling and simulation of IEEE 30 bus system employing UPFC has been described with and without implementation of UPFC [57].

SVC, and UPFC have been explained and modelled. Integration of FACTS devices and wheeling transactions into SCADA systems have been investigated. PF and OPF algorithms have been used for incorporating different policies and accounting methods [58].

A comparison among the load flow results using three models of UPFC : decoupled UPFC model, injection UPFC model and comprehensive NR UPFC model have been incorporated in a MATLAB power flow program at different operation modes [59].

The dynamic behavior of IPFC & UPFC has been compared and rationalized by developing the small-signal models and validating them using detailed electromagnetic transients simulation [60].To improve the dynamic performance of the power system, a nonlinear dynamic model of the network consisting UPFC has been established using linearisation and network reduction for transient studies and the decoupled control algorithms for active and reactive power have been developed [61].

To minimize the capacity of the shunt compensator and to maintain power flow control sensitivity the perpendicular voltage control model of UPFC has been proposed. The protection and control of UPFC model for transmission capability improvement have been verified using a real time analog simulator [62].

An approach to solve first-swing stability problem using UPFC, by using the local variable of system along with a comprehensive analysis has been presented for better stability performance [63].

A power flow study of a five bus system with and without UPFC has been carried out and has been implemented with MATLAB to conclude that UPFC is able to control voltage, impedance, and phase angle [64].

MATLAB program has been used to model UPFC and to verify the performance of UPFC with different controllers like PID controller and ANFIS controller [65].

For the analysis of the steady state operation of Unified Power Flow Controller connected in a power system, an improved steady state mathematical model has been presented employing conventional techniques such as Newton-Raphson method and has been simulated on IEEE 30-bus systems using commercial software [66].

The modeling of the unified power flow controller (UPFC) on the IEEE 30-bus system and the IEEE 118-bus system has been presented to illustrate the feasibility and the performance of the system. The control modes including power flow, voltage, angle and impedance control functions have been incorporated into a Newton-Raphson power flow algorithm [67].

ii) Generalised Unified Power Flow Controller (GUPFC):.

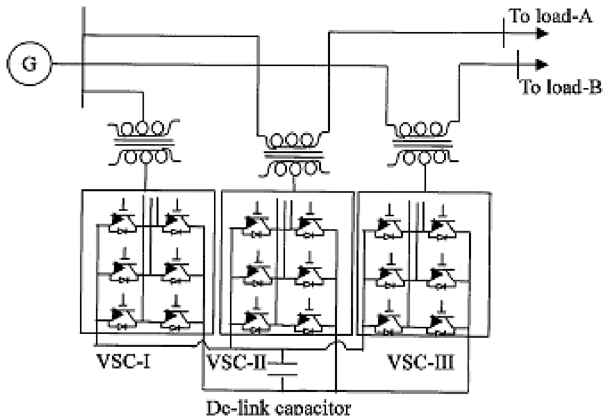

Fig. 10. Generalised Power Flow Controller

As shown in Fig. 10, a Generalized Unified Power Flow Controller consists of three or more converters out of which one is shunt connected while the remaining converters are series connected, resulting in the control of both real and reactive power flow in the line and to provide flexibility and additional degrees of freedom. The shunt connected converter not only provides the necessary power required, but also the reactive current injected at the converter bus. A novel concept of a similar mathematical model for the GUPFC on the IEEE 30 bus power system demonstrating the feasibility as well as the effectiveness of the GUPFC in the OPF method has been presented [68].

Compared with the conventional application of the UPFC, the GUPFC have shown great advantages. For the desired power flow distribution in Sichuan power gird, and also the voltage control of a substation a control law for the four-converter GUPFC has been proposed [69].

Mathematical models of the IPFC and GUPFC and their implementation in Newton power flow based on the IEEE 30-bus and 300-bus systems have been presented to demonstrate the performance of these FACTS devices [70].

IV. CONCLUSION

After going through this review based on the given title, we conclude that the different FACTS devices give better performance and good control of the parameters of power system by mitigating power quality problems. Among the various techniques/ FACT devices, the Combined Controllers like IPFC, UPFC, GUPFC gives better results than rest of the FACT devices because it gives more degrees of freedom, minimum errors and faster operation after optimization of various parameters of facts devices to improve and protect the parameters of power system and thus help to maintain power quality and better power flow.

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