ARCHIVES OF ELECTRICAL ENGINEERING VOL. 67(3), pp. 545–561 (2018)

DOI 10.24425/123662

Power flow analysis and control of distributed FACTS devices in power system

Vikash Anand, Sanjeev Kumar Mallik

National Institute of Technology Patna
Patna, Bihar (800005), India
e-mail: vikash.ee13@nitp.ac.in, skmallik@nitp.ac.in

(Received: 10.11.2017, revised: 25.05.2018)

Abstract: The deployment of a distributed power-flow controller (DPFC) in a single-machine infinite-bus power system with two parallel transmission lines are considered for the analysis in this paper. This paper presents the network analysis of the DPFC for power flow control. The performance is evaluated on a given test system with a single line-to-ground fault. The improvement in the stability as well as power quality is evident from the results. Thus the DPFC has the ability to enhance the stability and power quality of the system.

Key words: D-FACTS, UPFC, power flow control, stability, THD, FACTS

1. Introduction

Modern power system networks operate under highly stressed conditions. This results in difficulties in achieving the requirements of the reactive power and maintaining the bus voltage within an admissible range, specifically during contingencies. Voltage instability is one of the most important problems associated with the modern power system. Earlier, the emerging power system problems were solved by introducing flexible AC transmission systems (FACTS) devices. According to an IEEE definition of the FACTS [1], it is a power-electronic based system and other static equipment that provide control of one or more ac-transmission system parameters to enhance controllability and increase power transfer capability.

A unified power flow controller (UPFC) is a very powerful FACTS device and has the capability to control all the parameters like the bus voltage, the line impedance and the transmission angle simultaneously. The UPFC has the ability to control the transmitted real and reactive power flows at the sending and receiving end independently, along with maintaining the proper voltage profile of the transmission line [2–6]. Normally in the modern power system, the UPFC is customized for applications with concentrated bulky capacity. The reason for this is that the UPFC deals with high ratings of voltage and current. This increases the total cost of the whole system. It is worth mentioning here that the entire transmission system can be influenced by any slackness occurring in operation at the converters due to the common DC link [6–8]. The massive deployment of the UPFC is restricted due to huge investments costs, a low return on the investment and the reliability issue. Therefore, researchers have revisited the FACTS concept from a fresh perspective and have introduced distributed flexible AC transmission system (D-FACTS) devices [9, 10].

The DPFC is one of the D-FACTS devices, derived from the UPFC, removing the DC link capacitor from the shunt converter and the series converter, and putting the distributed series converters in between the line conductors [11, 12] shown in Fig. 1.

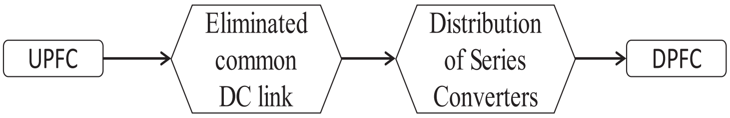

Fig. 1. Evolution of DPFC from the UPFC

The distributed FACTS (D-FACTS) concept is employed in the DPFC, which uses numerous single phase converters of smaller size. This is very different from the UPFC which uses single large-sized three-phase series converters. The redundancy of single-phase converters increases the system's reliability. The single-phase series converters float with respect to ground. Hence, high voltage isolation is not required between the phases. This results in a much lower cost of the DPFC, as compared to the UPFC. Now, the compensating power exchange takes place through the transmission line at the third harmonic frequency. [11, 13–15]. The control capability of the DPFC is similar to that of the UPFC in terms of the adjustment of the line impedance, the transmission angle and the bus voltage [11, 16]. Though the UPFC has many advantages, but its controller design is still a matter of challenge since it is a multi-variable controller. The UPFC has four different control capabilities, and all of them require proper adjustment to avoid any failure in the controller functions because of the existence of the dynamic interactions among the controllers. Hence, for a real time implementation of the UPFC it is necessary to conduct dynamic analysis which requires robust control strategy [17, 18]. Such problems are greatly reduced in the DPFC due to the absence of an inter-linked capacitor between both the converters and also because of the independent control of the shunt and series converter. Also, as compared to the UPFC, the DPFC has the advantages of high control capability, high reliability as well as cost effectiveness. This is why the D-FACTS concept is much in demand in the modern power system.

This paper attempts to study the transients' performance of a system-installed DPFC, equipped with a static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC) compensators without any direct inter-link of a capacitor, in the case of an L-G fault, wherein a shunt controller and series controller are designed around the concept of a current injection model and voltage injection model, respectively, in order to compensate the voltage disturbances in a two bus system. Since the proposed control scheme is transparent and can be effortlessly adjusted on-line, therefore easily accepted by the operating framework. The paper also tries to study the power flow analysis of the designed network circuit between two-bus systems, where the DPFC can be modeled as dependent voltage and a current source identified as an SSSC and STATCOM, respectively.

The paper is divided into five sections. Section 2 discusses the basic model and principles of the DPFC. The network analysis on considering a single unit of the DPFC in the context of power flow control is described in section 3. Section 4 highlights the hierarchy control of the DPFC. Section 5 of this paper brings out the performance analysis of the given system demonstrated in MATLAB/Simulink.

2. Basic principle of the DPFC

One shunt and n series converters are present in the DPFC. The value of n is selected using the formula as:

$$n = \frac{\text{Total kVA rating required}}{\text{kVA rating of single DPFC unit}}\,. \tag{1}$$

The shunt converter is similar to a STATCOM; the series converters (SSSC) employ the D-FACTS concept. Each converter (shunt/series) within the DPFC is independent and has a separate DC link capacitor for providing the required DC voltage. The configuration of DPFC is shown in Fig. 2.

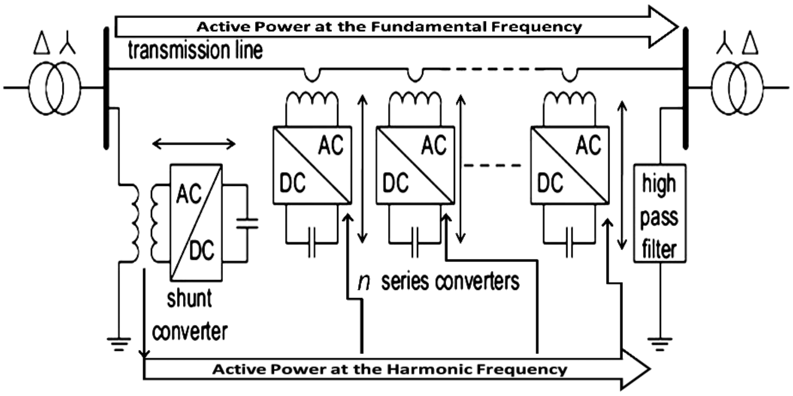

Fig. 2. Basic structure of the DPFC

No direct connection "DC link" is used to exchange the power between the dc port of the shunt converter and the ac port of the series converters. The DPFC uses the transmission line as an inter-connection between these two converters. Its methodology of power exchange stands on the power theory of non-sinusoidal components. As per the Fourier series, a non-sinusoidal component may be expressed in summation of the sinusoidal components at distinct frequencies. The product of voltage and current expresses the active power. Due to the fact that the integrals of a few terms with distinct frequencies are equal to zero, so the equation active power is presented as follows:

$$P = \sum_{i=1}^{\infty} V_i I_i \cos\varphi_i\,, \tag{2}$$

where V_i and I_i represent the voltage and current of the i^{th} harmonic frequency, respectively. φ_i is the angle between voltage and current at the same frequency.

Hence, all the components are independent in the above equation of active power. On the basis of this fact, with-in the DPFC, the shunt converter absorbs the active power in one frequency. But, its output power is generated in different frequency.

Consider, the DPFC is placed in a two-bus system's transmission line. Its simplified circuit configuration is depicted in Fig. 3.

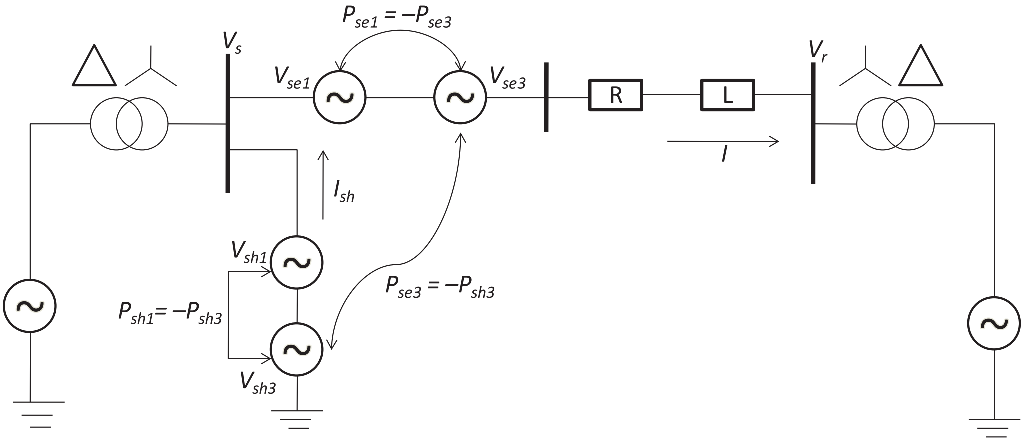

Fig. 3. DPFC system simplified structure

While the active power is generated by the power supply, the power in the fundamental frequency of current is absorbed by the shunt converter. In the meantime, the 3rd harmonic component gets stuck in the Y-Δ transformer, after which the shunt converter's output port pushes the 3rd harmonic current into the Δ-Y transformer's neutral. As a result, the harmonic current circulates in the transmission line and controls the dc voltage of series capacitors.

In order to exchange the active power in the DPFC, the 3rd harmonic is selected. In order to prepare a closed loop for the harmonic current, a high pass filter is required. Since, the 3rd harmonic current gets stuck in the transformer's Δ winding; it eliminates the requirement of the high pass filter at the system's receiving end. Hence, it can be stated that by using the 3rd harmonic concept, in place of high pass filter, a cable is connected between the Δ winding of the transformer and ground, which routes the harmonic current to ground.

3. Network analysis of the DPFC

The steady state analysis of the DPFC is presented in this section. A typical network model of the DPFC's unit having the ability similar to a UPFC (to control the parameters viz. bus voltage, line impedance and power angle, affecting power flow in transmission line), is shown in Fig. 4.

In the absence of a series converter, the shunt converter operates as a STATCOM which has a DC capacitor and a shunt transformer. The reactive power is generated or absorbed from the point of connection (POC). Similarly, in the absence of a shunt converter, the series converter acts as a SSSC with the DC capacitor and the series transformer. The SSSC injects a voltage V_c into the

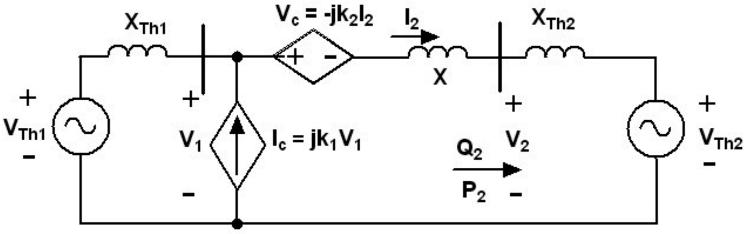

Fig. 4. DPFC's unit model without real power exchange between its two converters

transmission line through a series transformer. Its magnitude is independent of the line current and the phase angle is either 90° or −90°. For these two cases, the shunt and series converters act alone, generating/absorbing reactive power independently. In this way, the DPFC can be represented as a dependent voltage and current source, identified as a SSSC and STATCOM, respectively.

Two voltage sources, V_{th1} and V_{th2} are used to model two independent AC systems having their Thevenin's equivalent reactance X_{th1} and X_{th2}, respectively. The relationship between the current in the shunt converter (I_c) and the effective shunt reactance (X_s) is expressed as:

$$I_c = \frac{V_1}{iX_s}, \tag{3}$$

where V_1 is the voltage.

The coefficient $K_1$of the controllable current source modeling the shunt converter is the equivalent to the shunt converter admittance. Likewise, the coefficient K_2 of the controllable voltage source is the equivalent to the series converter reactance.

The assumed parameters for the analysis of the network circuit are as follows:

$$\begin{array}{rclrclc}
\overline{V}_{th1} & = & 1\angle 30^\circ, & X_{th1} & = & 0.15\ \text{pu}, & -0.5 \le K_1 \le 0.5, \\
\overline{V}_{th2} & = & 1\angle 10^\circ, & X_{th2} & = & 0.15\ \text{pu}, & 0.5 \le K_2 \le 0.5, \\
 & & & X & = & 1\ \text{pu}. &
\end{array}$$

The DPFC's unit model shown in Fig. 4 can be mathematically modeled as:

$$V_1 = \frac{\dfrac{V_{th1}}{i\,X_{th1}} + \dfrac{V_{th2}}{i(X + X_{th2} - K_2)}}{\dfrac{1}{i\,X_{th1}} - i\,K_1 + \dfrac{1}{i(X + X_{th2} - K_2)}}, \tag{4}$$

$$V_2 = \frac{\dfrac{V_1(1 + i\,X_{th1})}{i\,X} + \dfrac{V_{th2}}{i\,X_{th2}}}{\dfrac{1}{i\,X} + \dfrac{1}{i\,X_{th2}}}, \tag{5}$$

$$I_2 = \frac{V_1 - V_2}{i(X - K_2)}, \tag{6}$$

$$S_1 = V_{th1}\frac{V_{th1} - V_1}{i X_{th1}}, \tag{7}$$

$$S_1 = V_{th1}\frac{V_{th1} - V_1}{i X_{th1}}, \tag{8}$$

$$S_2 = V_{th2}\frac{V_{th2} - V_2}{i X_{th2}}, \tag{9}$$

where S_1 and S_2 are the complex power injected at bus B_1 and B_2 respectively; S_{12} is the complex power flow from the bus B_1 to B_2.

The effect of the DPFC's unit is demonstrated through a MATLAB program. The graphical representation of parameters viz. voltage, current and active and reactive power flow in relation to K_1 and K_2 for respective buses B_1 and B_2 are shown below.

Fig. 5 presents the bus voltage magnitudes with different shunt and series compensation. It is apparent that the shunt device is highly effective in adjusting the bus voltage. As K_1 and K_2 increases from -0.5 to 0.5, magnitudes of bus-voltage V_1 and V_2 also increase accordingly.

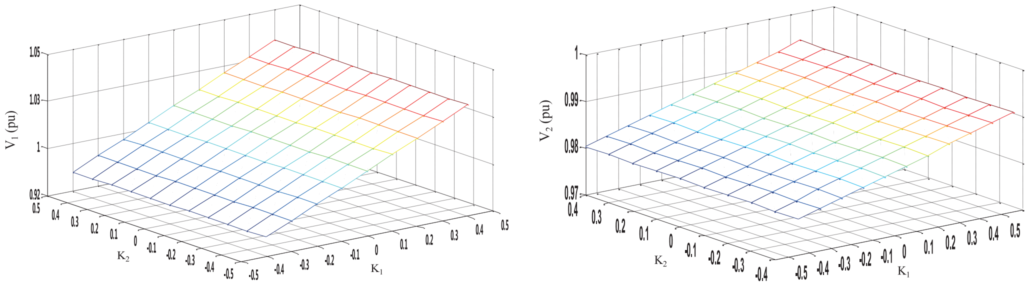

Fig. 5. Bus voltage magnitude with different shunt and series compensation

Fig. 6 shows the line current magnitude with different shunt and series compensation. It can be noticed that the transmission line current can be effectively controlled by the series device.

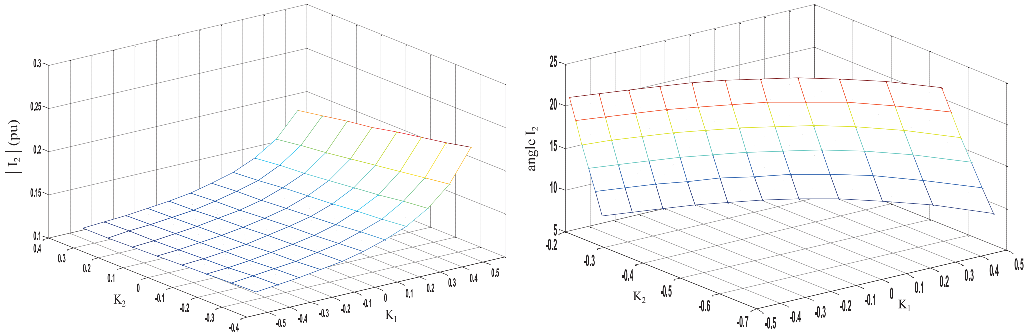

Fig. 6. Line current magnitude and angle with different shunt and series compensation

The effect of the shunt and series device is obvious in adjusting the real and reactive power flow, which is illustrated in Fig. 7.

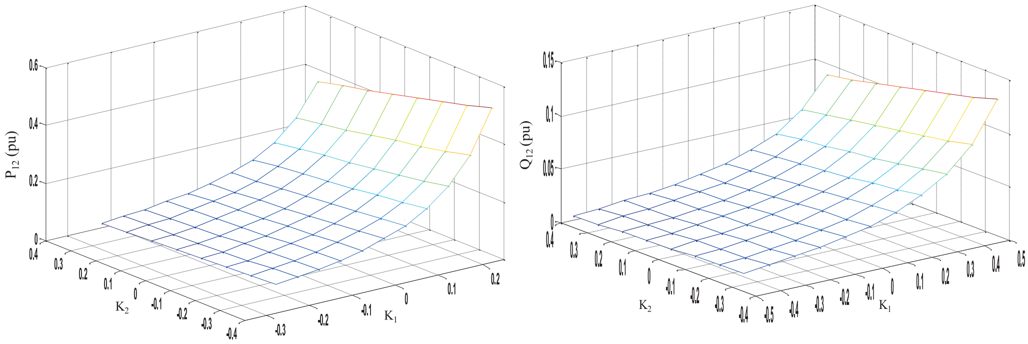

Fig. 7. Transmitted active and reactive power with different shunt and series compensation

The active and reactive power increase with the increase in K_1 and K_2. Fig. 8 illustrates the real and reactive power injected into respective buses B_1 and B_2 from two Thevenin equivalent voltage sources.

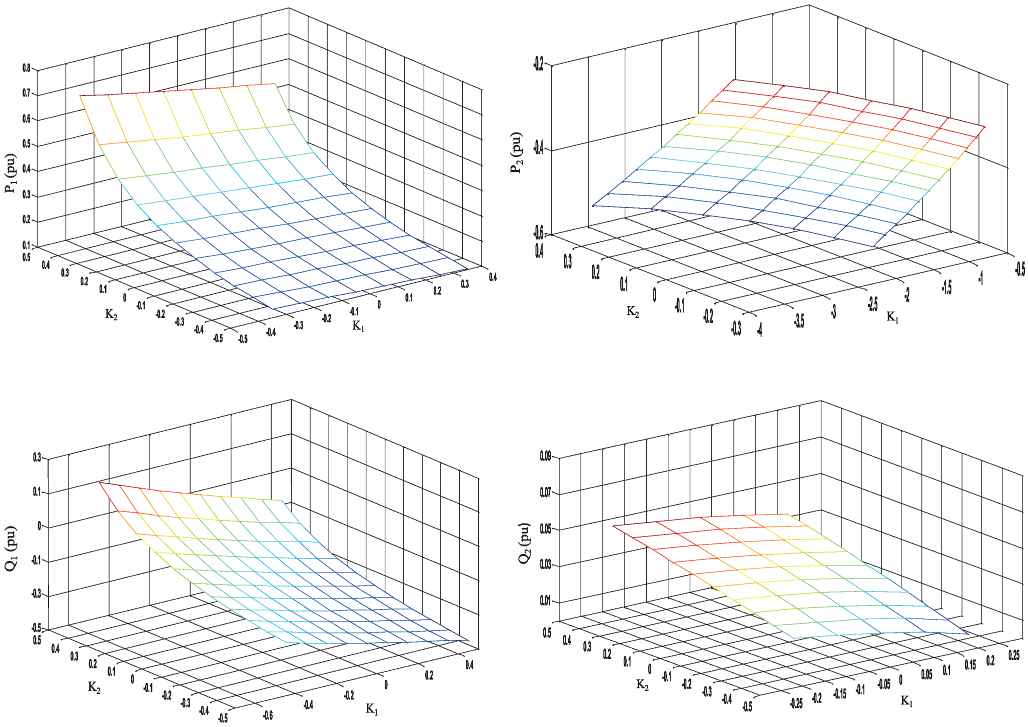

Fig. 8. Generated power from voltage sources with different shunt and series compensation

4. DPFC control

The DPFC consists of three control modules, namely, central control, shunt control and series control for the control of different converters, as shown in Fig. 9.

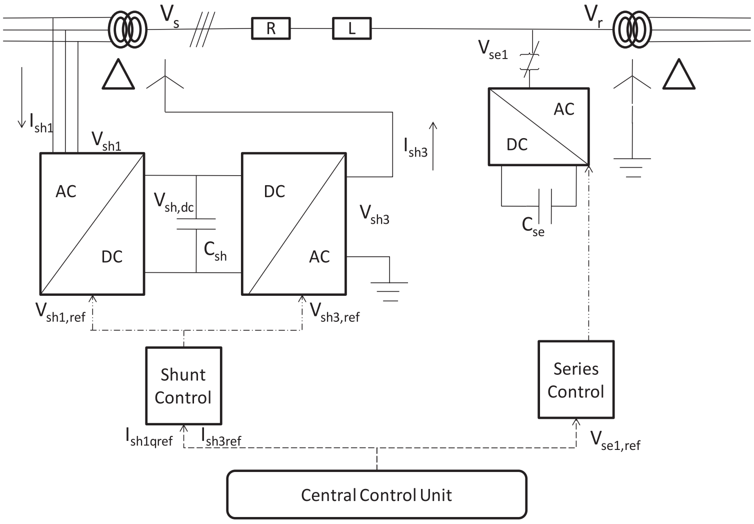

Fig. 9. The circuit configuration of the DPFC

The shunt and series control units act as local controllers with specific converter parameters. At the level of the power system, the DFFC function is facilitated by the central control unit.

4.1. Central control

The central controller creates reference signals for shunt and multiple series converters. These reference signals are generated using a single phase to dq transformation ($abc - \alpha\beta - dq$) as given in Fig. 10. Its control function is dependent upon the voltage and reactive/active power requirement of the power system. The three phase “abc” signal creates a virtual $\alpha\beta$ phase system. The stationary $\alpha\beta$ frame is converted into the rotating dq frame using (10).

$$\begin{matrix} Xd \\ Xq \end{matrix} = \begin{matrix} \sin\theta & \cos\theta \\ \cos\theta & -\sin\theta \end{matrix} \begin{matrix} X\alpha \\ X\beta \end{matrix} \tag{10}$$

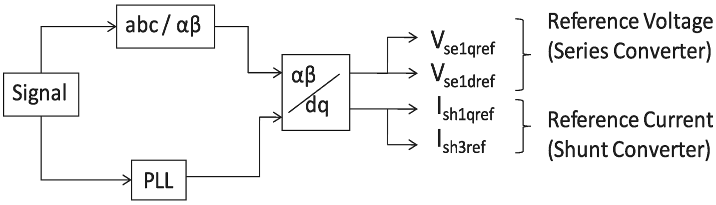

Fig. 10. Block of central control

4.2. Series control

Every single phase converter possesses a series control through the line. The control inputs being the line current, series capacitor voltage, and the series voltage reference in the *dq* frame.

The reference signal for generating the pulse of the series converter through a PWM generator is obtained using the reference signal from the central control unit as well as the fundamental and 3rd harmonic component of the line current, as shown in Fig. 11.

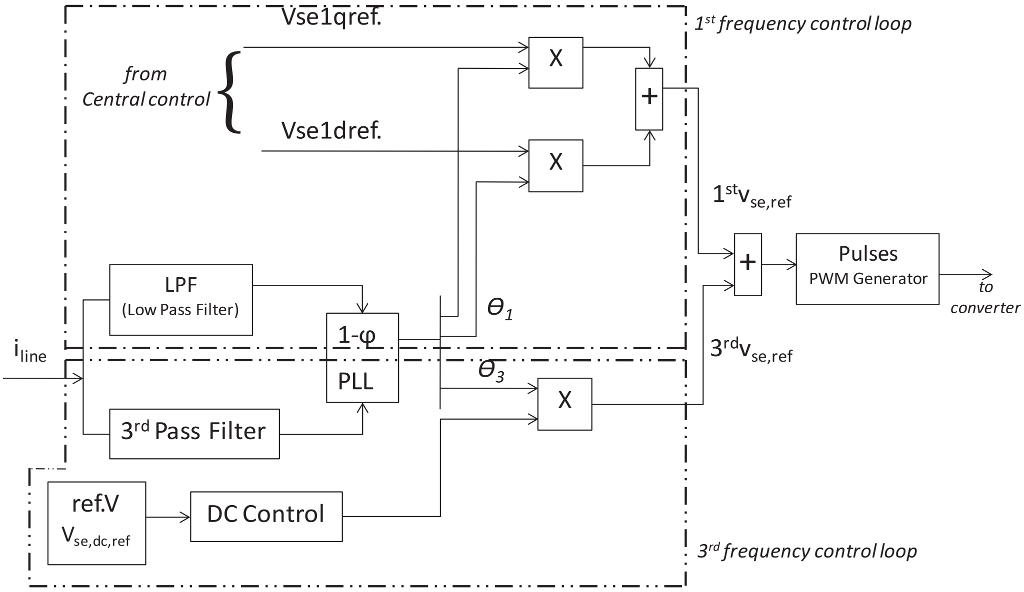

Fig. 11. Block of series converter control

4.3. Shunt control

The shunt converter is equipped with a three-phase converter and a single phase converter connected via the dc shunt capacitor. The capacitor's DC voltage is controlled by the three-phase converter, which receives active power from the grid at power frequency. The shunt converter constantly injects the 3rd harmonic current into the lines via the transformer's neutral cable. Each converter has its own control module for different frequency operation.

The pulse for the shunt converters are generated using two references corresponding to the fundamental and 3rd harmonic frequency component as shown in Fig. 12. The fundamental harmonic frequency component reference is generated from the source voltage, dc shunt voltage of the capacitor and the current reference signal from the central control unit. Similarly, the 3rd harmonic frequency component reference is obtained from the source voltage, 3rd harmonic current reference signal from the central control unit and the transformer neutral shunt current.

The DPFC system has been modeled in a vector-control *dq* transformation. The basic control of the DPFC is developed upon this model. The level of the capacitor DC voltage of each converter is stabilized by the basic control which also ensures that the converters inject the voltages into

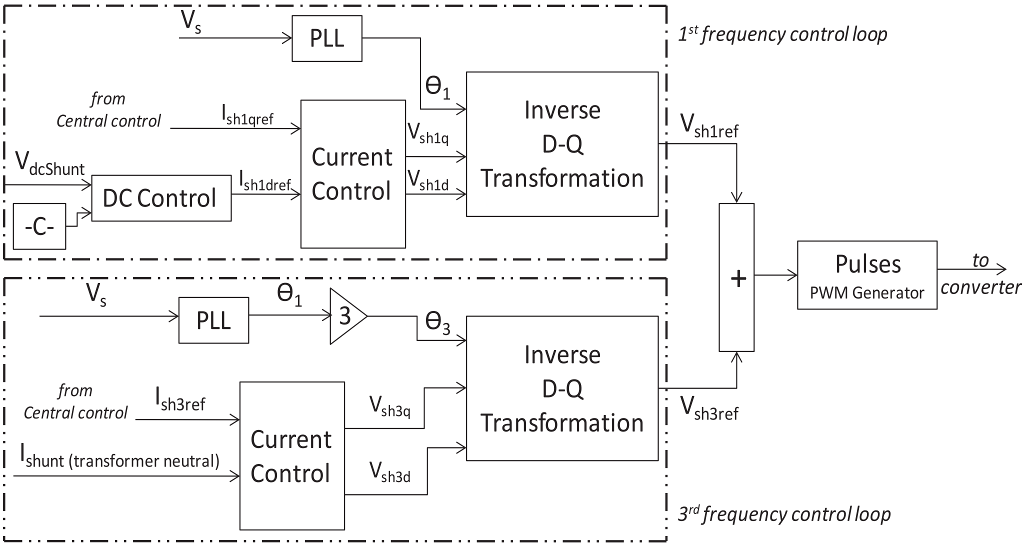

Fig. 12. Block of shunt converter control

the network as per the command received from the central control. A constant current is injected by the shunt converter at the 3^{rd} harmonic frequency, whereas its DC voltage is stabilized by the fundamental frequency component. At the fundamental frequency, the central control unit provides for the reference of the output voltage for the series converter whereas the 3^{rd} harmonic component maintains the DC voltage.

5. Performance analysis demonstrated in MATLAB

The overall model of the system under investigation is shown in Fig. 13. This system consists of a three phase source connected to a non-linear RLC load via parallel transmission lines (line 1 and line 2) having the same length. The DPFC is set in the transmission line, wherein the shunt converter is connected to the second transmission line 2 in parallel through a $Y{-}\Delta$ three-phase transformer and one single-phase series converter is distributed through each line. The system parameters selected in this model is listed in Table 1.

The transient performance of the circuit is investigated using a single line-to-ground fault applied on line 1. A line-to-ground fault is applied on phase A of line 1 at $t = 0.02$ s and the fault current reaches a value of 10 kA. The two circuit breakers, which are initially closed and then open at $t = 0.1$ s. After breaker opening, the fault current drops to a small value. The line and the series capacitance start to discharge through the fault and shunt reactance. The fault is cleared at $t = 0.12$ s, one cycle after the line opening. The sequence of the event is depicted through the graphical presentation of voltage and current at the buses B_1 and B_2 in Fig. 14. The waveform of the fault current at the phase A is represented in Fig. 15.

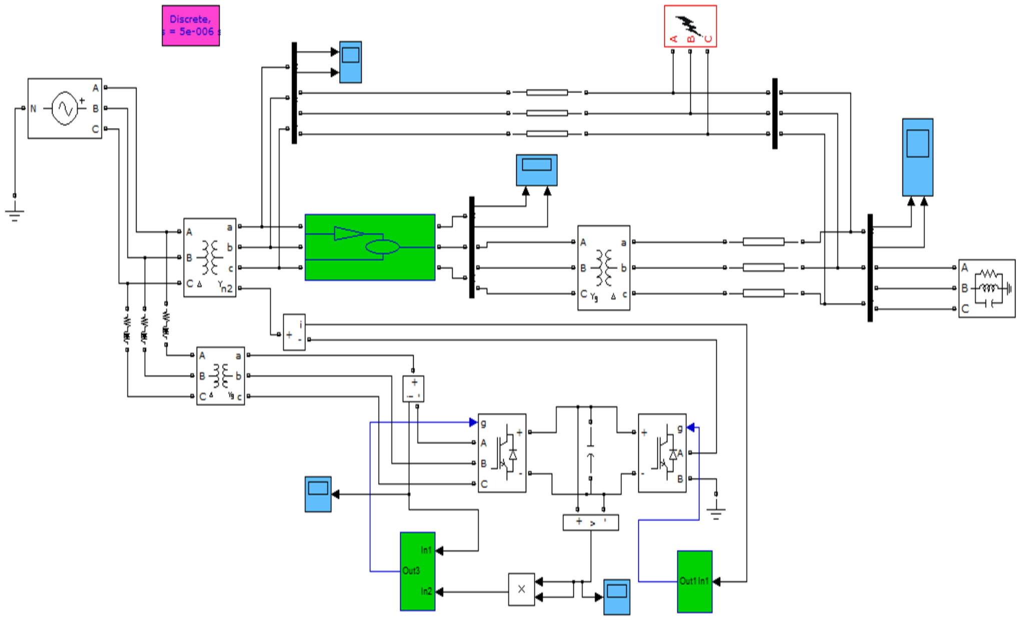

Fig. 13. DPFC model in MATLAB/Simulink

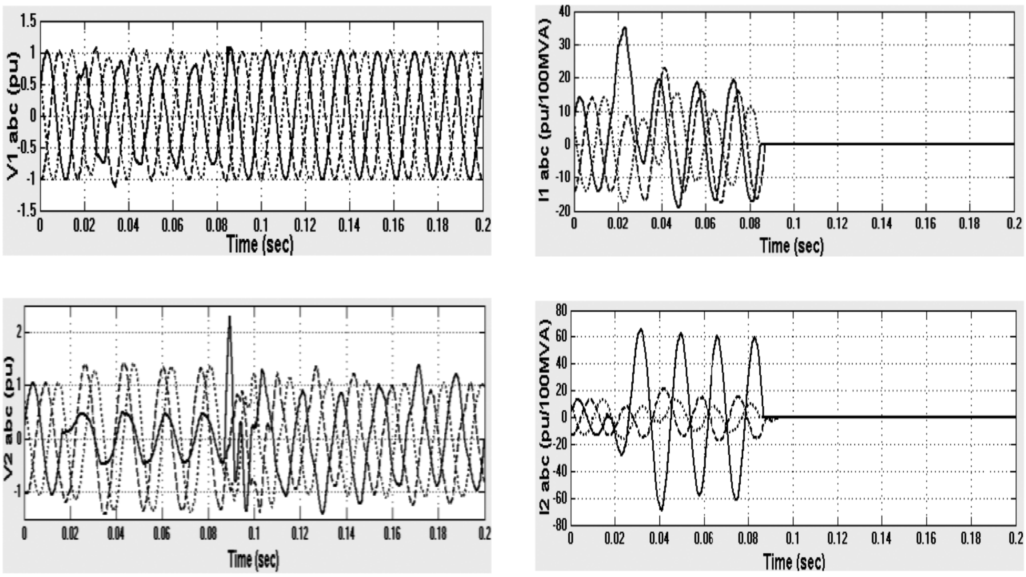

Fig. 14. Three-phase voltage and current waveform at bus B_1, B_2

At the fault occurrence instant, the series converter of phase A injects voltage into the faulty line to maintain the required bus voltage and stops after clearing the fault, which has been depicted

Table 1. MATLAB/Simulink system parameters

Three phase source	
Voltage	230 kV
Power / Frequency	100 MW / 50 HZ
X / R ratio	3
Short circuit capacity	11000 MW
Transmission line	
Resistance	0.012 pu/km
Inductance / Capacitance Reactance	0.12 / 0.12 pu/km
Length of transmission line	100 km
Shunt converter 3–ϕ	
Nominal power	60 MVAR
DC link capacitor	600 µF
Coupling transformer	
Nominal power	100 MVA
Voltage rating	230/15 kV
Series converter	
Voltage rating	6 kV
Nominal power	6 MVAR
Line to ground fault	
Type	A–G
Ground resistance	0.01 Ω

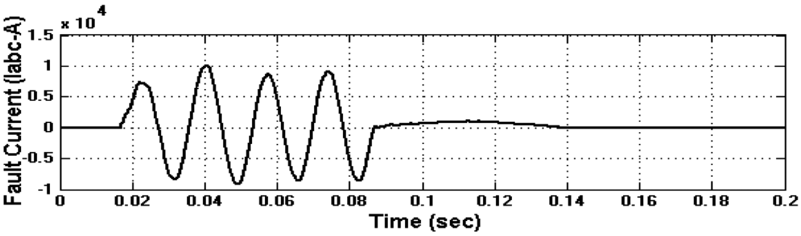

Fig. 15. Waveform of fault current at phase A

in Fig. 16. The nature of the SSSC's capacitor voltage, which becomes constant after the fault clearing time at 0.12 s, has been shown in Fig. 17.

Due to the fault occurring in the line, DC voltage of the STATCOM is also disturbed. After clearing the fault, the capacitor of the STATCOM is used to maintain the constant DC voltage at 2 pu. The nature of the V_{dc} shunt has been depicted in Fig. 18.

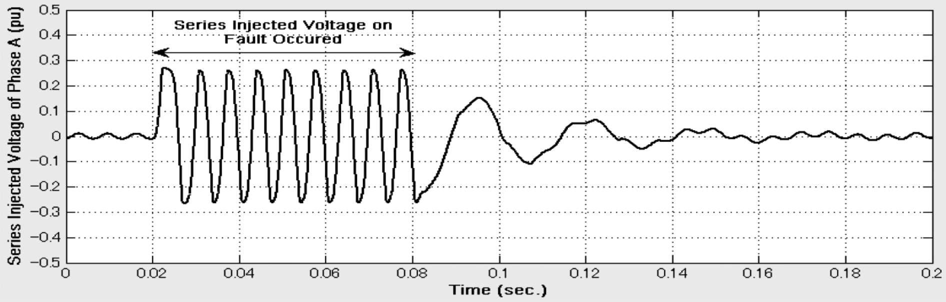

Fig. 16. Waveform of injected series voltage at phase A

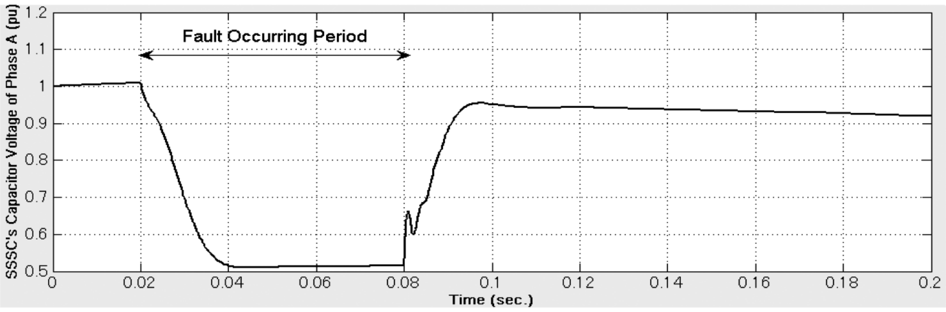

Fig. 17. Waveform of one unit SSSC's capacitor voltage at phase A

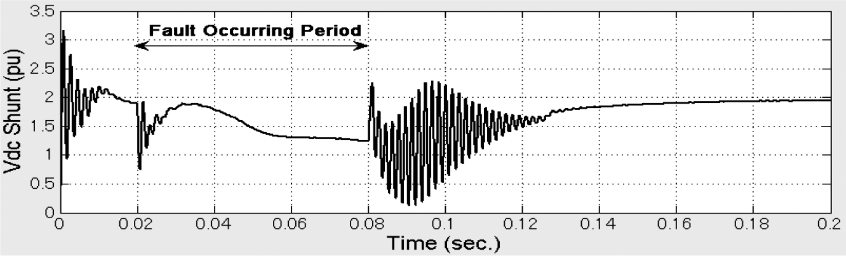

Fig. 18. Waveform of STATCOM's DC voltage

In the sequence of events depicted through the above graphical presentation, Fig. 19 shows the active power and reactive power waveforms, which correlate well with the system's disturbance at 0.02 s and after clearing the fault, both these powers achieve the steady state at 0.12 s.

The total harmonic distortion (THD) of voltage and current without the DPFC employed in the system at the buses B_1 and B_2, are expressed in Fig. 20 and Fig. 21, respectively. Similar results are obtained with the deployment of the DPFC in the system at buses B_1 and B_2, they are shown in Fig. 22 and Fig. 23, respectively.

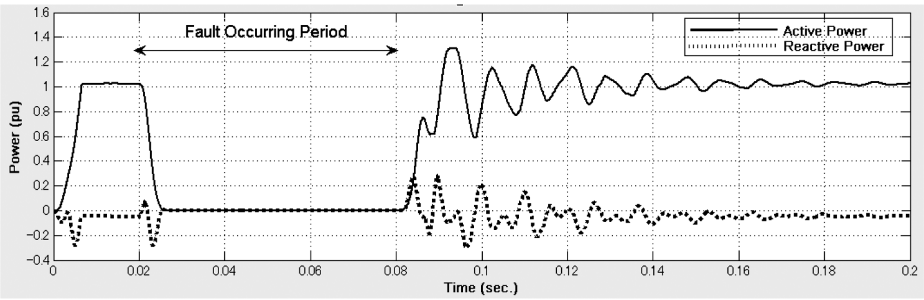

Fig. 19. Waveform of Active Power and Reactive Power

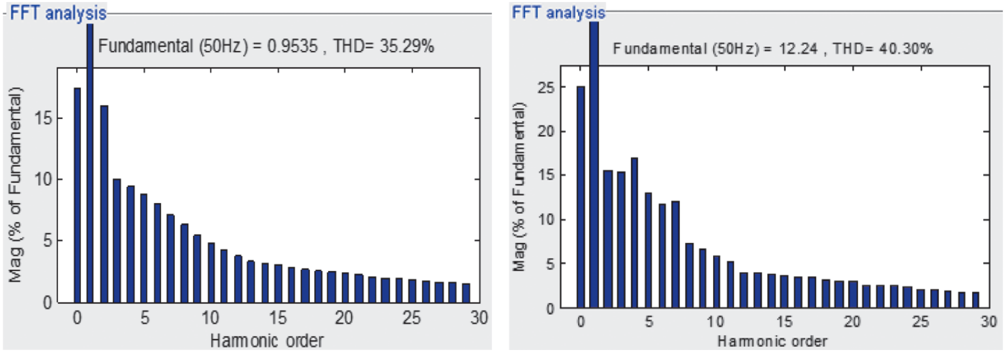

Fig. 20. Total harmonic distortion of voltage and current at bus B_1 without DPFC compensation

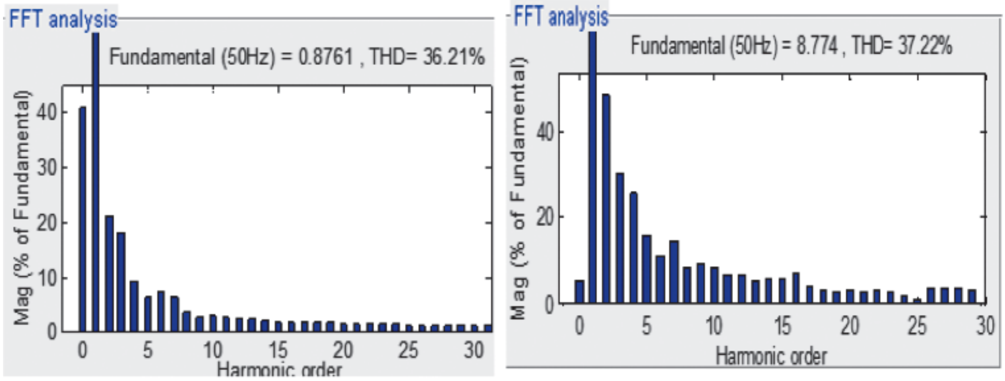

Fig. 21. Total harmonic distortion of voltage and current at bus B_2 without DPFC compensation

The graphical results of the system under study with/without compensation of the DPFC represented in terms of the THD of voltage and current, indicate the enhancement of power quality with the deployment of the DPFC in system. The same results of the THD of voltage and current with or without the DPFC employed are also tabulated in Table 2.

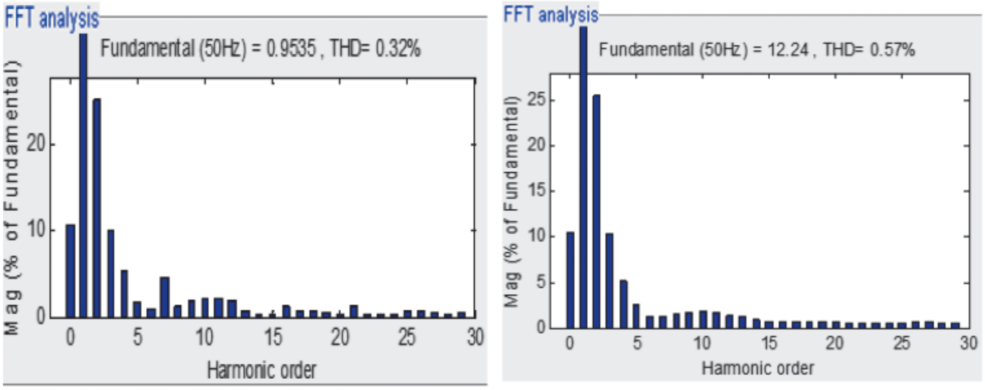

Fig. 22. Total harmonic distortion of voltage and current at bus B_1 with DPFC compensation

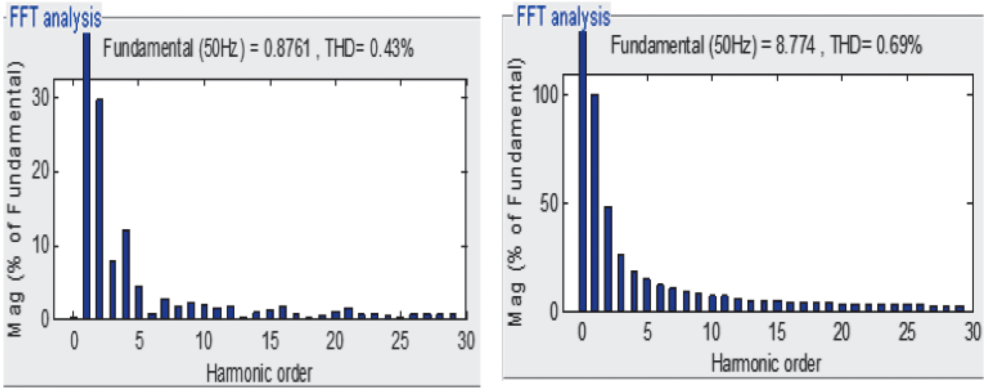

Fig. 23. Total harmonic distortion of voltage and current at bus B_2 with DPFC compensation

Table 2. THD of voltage and current with or without compensation of DPFC at buses B_1 and B_2

Parameters	**THD**	
	Without DPFC	**With DPFC**
Voltage at bus B_1	35.29%	0.32%
Voltage at bus B_2	36.21%	0.43%
Current near bus B_1	40.30%	0.57%
Current near bus B_2	37.22%	0.69%

6. Conclusions

The proposed model of the DPFC is explained mathematically assuming no real power is exchanged between its two converters. It is also implemented in MATLAB/Simulink for network analysis and further can be extended for different applications in the power system. On the occurrence of the L-G fault, the deployment of the DPFC in the system is one of the effective methods of improving power quality in the transmission system. The controller methodology proposed here is based on a current and voltage injection model and quickly tracks the current and voltage reference settings with a very limited overshoot. It also quickly regulates the ac-bus and DC link voltage along with a settling time of approximately 2 to 3 cycles. The voltage and current harmonic is analyzed with/without the employment of the DPFC in the system. On implementation of the DPFC in the system, it is observed that the even harmonics are removed and the odd harmonics fall within a satisfactory range. As a result, the THD of voltage and current are minimized below 5% which is as per the IEEE-519 standards [19]. Also, the dynamic stability of the system is improved on the deployment of the DPFC in the system.

The function of the DPFC is the same as that of the unified power flow controller (UPFC) and has similar controlling ability in balancing the line parameters viz. line impedance, transmission angle and bus voltage magnitude. The DPFC offers effective control and higher reliability at low cost. It can be concluded that the DPFC shows an adequate capability in quality improvement and control of power flow.

References

[1] Edris A.A., *Proposed Terms and Definitions for Flexible AC Transmission System (FACTS)*, IEEE Transactions on Power Delivery, vol. 12, no. 4, pp. 1848–1853 (1997).

[2] Gyugyi L., Schander C.D., Williams S.L., Rietman T.R., Torgerson D.R., Edris A., *The Unified Power Flow Controller: A New Approach to Power Transmission Control*, IEEE Transactions on Power Delivery, vol. 10, no. 2, pp. 1085–1097 (1995).

[3] Enslin J.R., *Unified Approach to Power Quality Mitigation*, Proceedings of IEEE International Symposium Industrial Electronics, South Africa, pp. 8–20 (1998), DOI: 0.1109/ISIE.1998.707741.

[4] Song Y.H., Johns A., *Flexible AC Transmission Systems (FACTS)*, IEE Power Series, vol. 30 (1999).

[5] Papic I., Zunko P., Pouh D., Weinhold M., *Basic Control of Unified Power Flow Controller*, IEEE Transactions on Power System, vol. 12, no. 4, pp. 1734–1739 (1997).

[6] Kannan S., Jayaram S., Salama M.M.A., *Real and Reactive Power Coordination for a Unified Power Flow Controller*, IEEE Transactions on Power Systems, vol. 19, no. 3, pp. 1454–1461 (2004).

[7] Hingorani N.G., Gyugyi L., *Understanding FACTS, Concepts and Technology of Flexible AC Transmission System*, Institute of Electrical and Electronics Engineers (2000).

[8] Divan D., Johal H., *Distributed FACTS – A New Concept for Realizing Grid Power Flow Control*, Proceedings IEEE 36th Power Electronics Specialist Conference, Brazil, pp. 8–14 (2005).

[9] Sen K.K., *SSSC – Static Synchronous Series Compensator: Theory, Modelling and Application*, IEEE Transactions on Power Delivery, vol. 13, no. 1, pp. 241–246 (1998).

[10] Divan D.M., Brumsickle W.E., Schneider R.S., Kranz B., Gascoigne R.W., Bradshaw D.T., Ingram M.R., Grant I.S., *A Distributed Static Series Compensator System for Realizing Active Power Flow Control on Existing Power Lines*, IEEE Transactions on Power Delivery, vol. 22, no. 1, pp. 642–649 (2007).

[11] Yuan Z., Sjoerd W.H.D.H., Braham F., Dalibar C., *A FACTS Device: Distributed Power Flow Controller (DPFC)*, IEEE Transactions on Power Electronics, vol. 25, no. 10, pp. 1085–1097 (2010).

[12] Zhang R., Cardinal M., Szczesny P., Dame M., *A Grid Simulator with Control of Single-phase Power Convertors in D-Q Rotating Frame*, Power Electronics Specialists Conference (PESC), IEEE, Australia, pp. 1431–1436 (2002).

[13] Patne N.R., Krishna L.T., *Factor Affecting Characteristics of Voltage Sag due to Fault in the Power System*, Serbian Journal of Electrical Engineering, vol. 5, no. 1, pp. 171–182 (2008).

[14] Ramya K., Christober C.A.R., *Analysis and Regulation of System Parameter Using DPFC*, IEEE International Conference on Advance in Engineering, Science and Management (ICAESM), Tamil Nadu, India, pp. 505–509 (2012).

[15] Bangarraju J., Rajagopal V., Jaya L.A., *Power Quality Enhancement Using Power Balance Theory Based DSTATCOM*, Advances in Electrical and Electronics Engineering, vol. 14, pp. 1–10 (2016).

[16] Uzuunovic E., Canizaras C.A., Reeve J., *Fundamental Frequency Model of Unified Power Flow Controller*, North American Power Symposium (NAPS), Cleveland, Ohio, pp. 294–299 (1998).

[17] Albatsh M., Mekhilef S., Ahmad S., Mokhlis H., *Fuzzy-Logic-Based UPFC and Laboratory Prototype Validation for Dynamic Power Flow Control in Transmission Lines*, IEEE Transactions on Industrial Electronics, vol. 64, no. 12, pp. 9538–9548 (2017).

[18] Albatsh F.M., Ahmad S., Mekhilef S., Alhamrouni I., Hamid M.F.A., *Power Flow Control using Fuzzy Based UPFC under different operating conditions*, Journal of Electrical Systems, vol. 13, no. 2, pp. 398–414 (2017).

[19] http://www.schneider-electric.com.tw/documents/Event/2016_electrical_engineering_seminar/IEEE_STD_519_1992vs2014.pdf, accessed July 2017.