MITIGATION OF VOLTAGE STABILITY AND POWER FLOW CONTROL USING DISTRIBUTED POWER FLOW CONTROLLER

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Abstract: *This paper presents an approach to assess the benefits of FACTS devices, which are effective in controlling the bus voltage, active and reactive power flow through transmission lines. The new FACTS device DPFC (Distributed Power Flow Controller), derived from UPFC, has high controlling capability and high reliability at a lower cost. Within DPFC, by eliminating the dc common link between shunt and series converter, the active and reactive power exchange is accomplished by the third harmonic frequency for controlling capability. The D-FACTS concepts are employed by a small multiple independent single-phase series converter for system reliability at low cost and also improves the power quality. As UPFC, the DPFC too has a controlling capability of power system parameters as line impedance, the transmission angle and the bus voltage. This DPFC system was simulated in the MATLAB/SIMULINK environment and the simulation results are also shown.*

Key words: *D−FACTS, DPFC, UPFC, STATCOM, PLL.*

1. Introduction.

In the recent decade, transmission lines in power systems are being interconnected with national and international connections. This network is desirable if the power flow in power transmission systems are fast and reliable [1]. In the trading of electrical energy, high power flows occur in tie lines between control areas [2]. In fact, the grid connections also increase greatly because of load demand in an electric distribution system [1, 3]. With regard to this, the power companies are also concerned with power quality issues [4].

There has been an increase in electricity demands and as electric power affects the performance of electrical device [5], there is also a need for development of new technologies based on power electronics. In modern power electronics especially FACTS (Flexible Alternating Current Transmission System) devices are introduced in existing transmission systems to achieve the control function, the power transfer capacity, the stability improvement [6, 7] and thereby improve the power quality. This FACTS device is defined by IEEE as “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” [6].

This paper introduces a new FACTS device called DPFC (Distributed Power Flow Controller). The DPFC structure is developed from the UPFC (Unified Power Flow Controller) as shown in Fig. 1. The DPFC device is made up of one shunt converter and several small independent series converters as shown in Fig. 2. The UPFC is the most powerful FACTS device and is a combination of a STATCOM (Static Synchronous Compensator) and a SSSC (Static Synchronous Series Compensator) coupled to a common dc link which allows the flow of active power between the series output terminal of SSSC and the shunt output terminal of STATCOM [8]. This UPFC can control all parameters of a system such as line impedance, transmission angle and bus voltage.

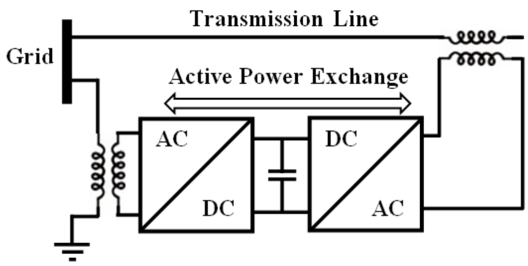

Fig. 1. A Simple representation of a UPFC.

The SSSC effectively controls the active power flow in a transmission line through a large power converter to alter the power line impedance [9] and the STATCOM controls the reactive power flow in transmission line through a shunt converter which controls the bus voltage [10]. The injected voltage acts as a synchronous ac voltage source which is used to vary the transmission angle. The DPFC that is developed from UPFC has the same capacity to control all system parameters. In DPFC structure, one shunt converter supplies the active power and absorbs the reactive power from dc capacitor which is similar to STATCOM in UPFC and the independent series converters voltage results in active and reactive power injection or absorption between the transmission line and the series converter which is same as SSSC in UPFC.

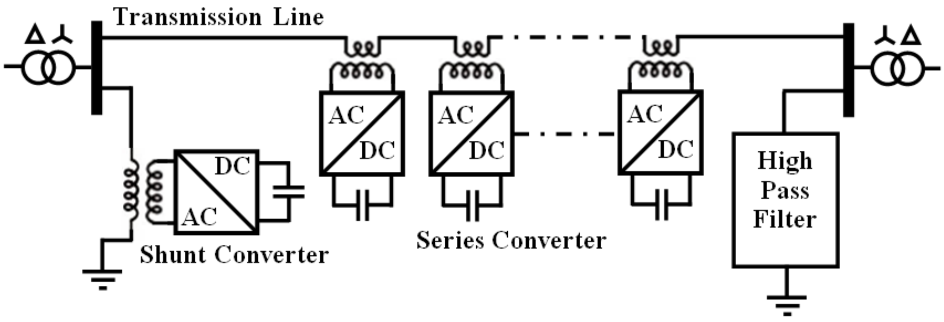

Fig. 2 A DPFC with Shunt and Series Converter.

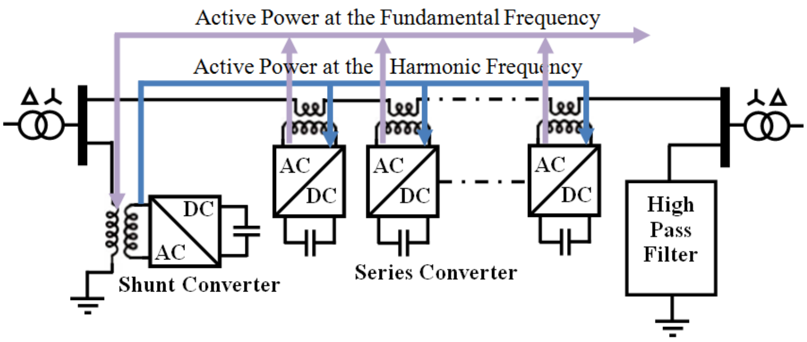

Fig. 3 A DPFC without common dc link for Power Exchange.

This DPFC device is also used to alleviate the disturbance and improve the power system quality and reliability [11-13].

When the UPFC is compared with DPFC the major significances are: first, elimination of common dc link between series and shunt converters; second, it transfers the active power exchange between the converters at third harmonic frequency and it employs multiple single phase converter as a series compensator instead of one large three phase converter.

2. Principle of DPFC.

The basic concepts of DPFC principle is achieved by first eliminating the common dc link of the UPFC and the distributed series converter as shown in Fig.3.

2.1 Eliminated DC Link.

In a normal UPFC, the active power exchange will pass through the common dc link that is connected between the series and shunt converter. Since there is no common dc link between series and shunt converter in the DPFC, the active power is exchanged by third order harmonics and through the ac network. The method of power exchange is based on the power theory of non-sinusoidal components, which means the product of voltage and current components provides the active power.

The average active power can be expressed by

$$P = \sum_{i=1}^{\infty} V_i I_i Cos\Phi_i \qquad (1)$$

Where, i is the order of harmonic frequency, V_i and I_i are the voltage and current at i-th harmonic frequency respectively and Φ_i is the angle between the voltage and current at same frequency. In equation (1) generates the active power at different frequencies and are isolated from each other. The voltage or current in one frequency has no influence on other active power frequency. Based on this fact, in DPFC the shunt converter absorbs the active power in one frequency and generates output power in another frequency. The output terminal of shunt converter injects the third harmonic current into the grid. Consequently the harmonics current will flow through the transmission line. This harmonics current controls the dc voltage of series capacitors thereby absorbing the active power from harmonic components.

The third harmonic is chosen because it can easily be filtered and blocked by star-delta transformer. The high pass filter in DPFC blocks the fundament frequency components and allows the harmonic components to pass through ground. Therefore shunt and series converters, the high pass filter and the ground form the closed loop for the harmonic current as shown in Fig.4.

2.2 Distributed Series Converter.

The DPFC employ a multiple individual single phase series converter connected in series to the transmission line. It can inject a 360° controllable voltage at the fundamental frequency. This series-connected FACTS devices employ as D-FACTS (Distributed-FACTS). The single turn transformer is attached to the transmission line along with the single phase converter with a small controller. This single turn transformer uses the transmission line as a secondary winding. Each D-FACTS devices are self-powered from the line and controlled by wireless communication as shown in Fig.5.

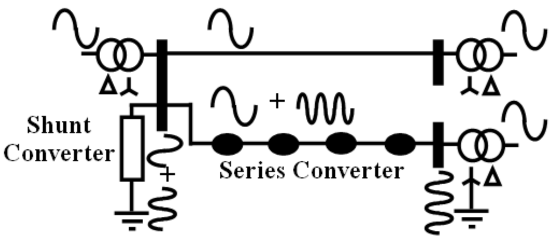

Fig. 4 A DPFC with closed loop for the Harmonic Current.

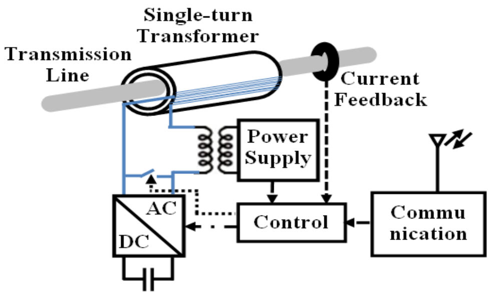

Fig. 5 A D-FACTS Independent Series Converter.

3. Per Phase Modeling of DPFC.

Fig. 6 shows the DPFC controller diagram. The controller is developed to control the power flow controller circuits by receiving the signals, such as currents and voltages, from the circuits, and sending the switching signals to the circuits. The switching model and the average model of DPFC are obtained by dq0 frame. Based on the derived small signal models, the closed-loop decoupled control can be designed.

The single-phase output-current differential equation for the average model is:

$$\frac{di_a}{dt}=\frac{V_{dc}d_a}{L}-\frac{V_{eq}}{L}-\frac{Ri_a}{L} \quad (2)$$

The dc-link voltage differential equation is:

$$\frac{dV_{dc}}{dt}=-\frac{V_{dc}}{R_L C}-\frac{d_a i_a}{C} \quad (3)$$

To implement the per phase dq transformation, an accurate extraction of a single ac information can be used to find the dc information in a single phase ac signal. For a single phase signal:

$$X(t)=X_m Sin(\omega t-\phi) \quad (4)$$

can be broken down in two orthogonal sinusoidal signals.

$$X(t)=X_d Sin(\omega t)+X_q Cos(\omega t) \quad (5)$$

Where,

$$X_d=X_m Cos(\phi) \text{ and } X_q=-X_m Sin(\phi) \quad (6)$$

The single-phase output-current differential equation matrix in dq0 frame for the average model is:

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix}=\frac{V_{dc}}{L}\begin{bmatrix} d_d \\ d_q \end{bmatrix}-\frac{1}{L}\begin{bmatrix} V_{deq} \\ V_{qeq} \end{bmatrix}-\frac{R}{L}\begin{bmatrix} i_d \\ i_q \end{bmatrix}+\begin{bmatrix} \omega i_d \\ -\omega i_q \end{bmatrix} \quad (7)$$

The single phase dc-link voltage differential equation matrix for the converter is:

$$\frac{dV_{dc}}{dt}=-\frac{V_{dc}}{R_L C}-\frac{1}{C}\begin{bmatrix} d_d & d_q \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (8)$$

Where: i_a is the Line current, V_{dc} is the DC capacitor voltage, V_{eq} is the equivalent DPFC injecting voltage, L is the transmission line inductive impedance, R is the transmission line resistive impedance, C is the DC capacitance, R_L is the equivalent converter loss impedance.

So the small signal transfer functions can be derived as:

$$G_{id}=\frac{i_d}{d_d+i_q\omega L/V_{dc}}=\frac{\frac{V_{dc}}{L}}{s+\frac{R}{L}} \quad (9)$$

$$G_{iq}=\frac{i_q}{d_d-i_d\omega L/V_{dc}}=\frac{\frac{V_{dc}}{L}}{s+\frac{R}{L}} \quad (10)$$

$$G_{Vid}=\frac{V_{dc}}{d_d}=-\frac{\frac{i_d}{C}}{s+\frac{1}{R_L C}} \quad (11)$$

For a real controller based control system, the delay and low pass filter for sensor signals influence for the controller design should be considered to get more accurate model.

$$\text{Delay: } G_D=\frac{1-sT_D/2}{1+sT_D/2} \quad (12)$$

$$\text{Low Pass Filter: } G_f=\frac{1}{1+sR_f C_f} \quad (13)$$

Where, T_d is the total delay including calculation, A/D conversion and switching delay. Low pass filter in the controller is designed to eliminate the high frequency noises from the sensor paths. Based on the above description, the control loop can be described as below:

If the direct voltage compensation is applied, the voltage loop gain is

$$T_{vd}=H_{vd}G_{vid}G_D G_f \quad (14)$$

The q-axis duty cycle can be given by the station control or the current loop control. If the current is introduced as the control parameter, the current loop gain is

$$T_{id} = H_{iq} G_{iq} G_D G_f \quad (15)$$

Based on the small signal transfer function loop gain, the converter model and feedback control design is used to achieve required stability and transient performance.

4. DPFC Control.

The DPFC device consists of series converters and shunt converter. Each converter required a different control strategy. In this paper the proposed DPFC consists of series controller, shunt controller and central controller as shown in Fig. 6.

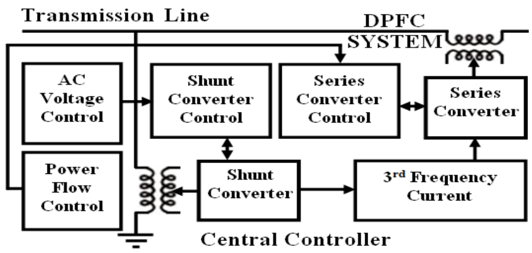

Fig. 6 Block diagram of Controller of DPFC.

4.1 Series Controller.

The series converter is a single phase converter. Each converter has its own series controller as shown in Fig. 7. The series converter generates a 360° rotatable voltage at fundamental frequency and the controller is used to maintain the capacitor dc voltage in its own converter. In single phase transformation, the third harmonic current is chosen as the rotation reference frame because it is easy to capture by PLL (Phase Locked Loop) in the series converter.

The high pass filter is required to reduce the fundamental current. The line current has two components as d and q components. The d component of the third harmonics voltage is used to control the dc voltage by generating reference signal through the dc voltage control loop. The reactive power is reduced by the series converter as resistance at third harmonics frequency. The q component of the third harmonics voltage is kept at zero during the operation.

4.2 Shunt Controller.

The block diagram of the shunt converter is shown in Fig.8. To provide the active power to the series converter a constant third harmonic current is injected by a shunt converter controller. The shunt converter extracts some active power from the grid at the fundamental frequency to maintain its dc voltage.

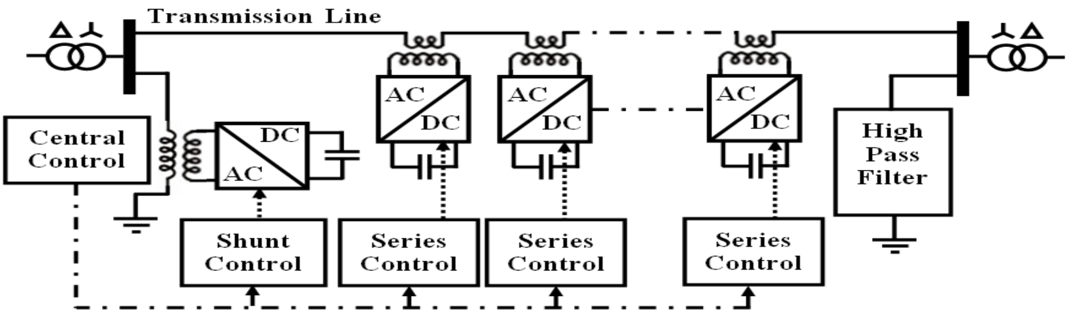

Fig. 7 Block diagram of the Series Converter Control.

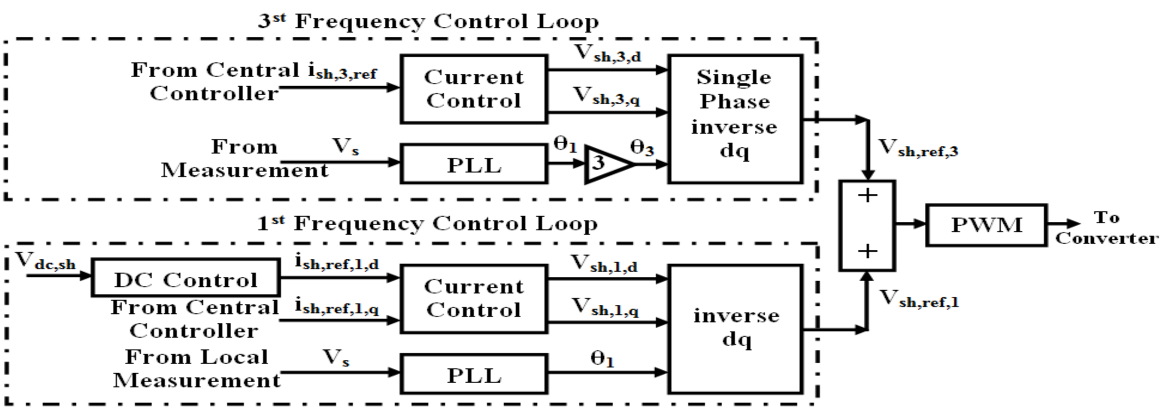

Fig. 8 Block diagram of the Shunt Converter Control.

The aim of shunt converter controller is to inject a controllable reactive current to the grid and to keep the capacitor voltage at a constant level. The two components d and q are at the fundamental frequency. The d component is generated by the dc voltage control and the q component is utilized for reactive power compensation.

4.3 Central Controller.

This DPFC task is achieved by the central controller such as power flow control, low frequency, power oscillation, damping and balancing of asymmetrical components. The purpose of central controller is to generate the reference signal to the power system requirements. It controls the voltage reference signals for the series converters and reactive current signal of the shunt converter. These reference signals are generated at the fundamental frequency by central controller.

5. Simulation Results.

The DPFC simulation results consist of series converters and shunt converter and were simulated and verified by using MATLAB environment. The shunt converter is connected between the neutral connection of transformer and the ground.

The multiple series converter is controlled by the central controller. The reference voltage signal is given to the series converter by the central controller by measuring the voltage and current signals.

The DPFC system is evaluated in two cases, by steady state response and step responses. For the simplicity, single phase waveforms are illustrated. Fig.9 shows the current through line during operation of DPFC in steady state. The third harmonic current is injected by shunt converter which uniformly disperses to the three phases and is superimposes the fundamental current as shown in Fig.9.

The voltage injected by the series converter and the injected voltage contains two fundamental frequency components are shown in the Fig. 10. The dc capacitor voltage characterizes the amplitude of the pulse width modulated waveform, which is sustained by the third harmonic component of steady state.

The third harmonic filtering by the star-delta transformer during the operation of DPFC in steady state is shown in Fig.11. There is no leakage on voltage and current in delta side transformer.

At the fundamental frequency the power flow is control by the DPFC through the transmission line by varying the injected voltage of series converter. The step response of DPFC system is shown in Fig.12 to Fig.15. The fundamental reference voltage of series converters is shown in Fig.12.

The series converters inject or absorb active and reactive power from the grid at the fundamental frequency when the dc voltage in series converter stabilized before and after the step change. The phase shift of the series voltage at the fundamental frequency is shown in Fig.13.

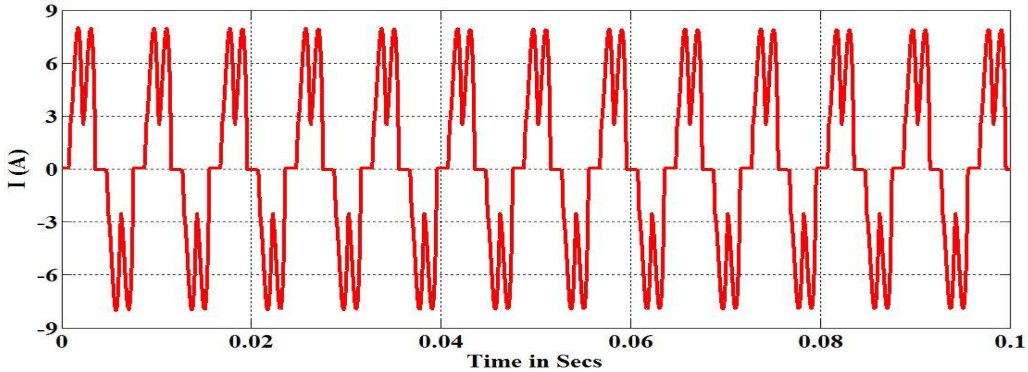

Fig.9 DPFC Operation in Steady State: Line Current.

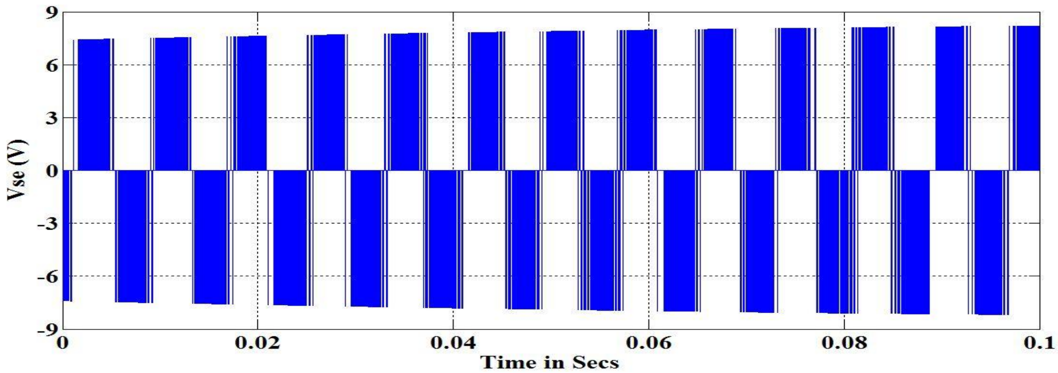

Fig.10 DPFC Operation in Steady State: Series Converter Voltage.

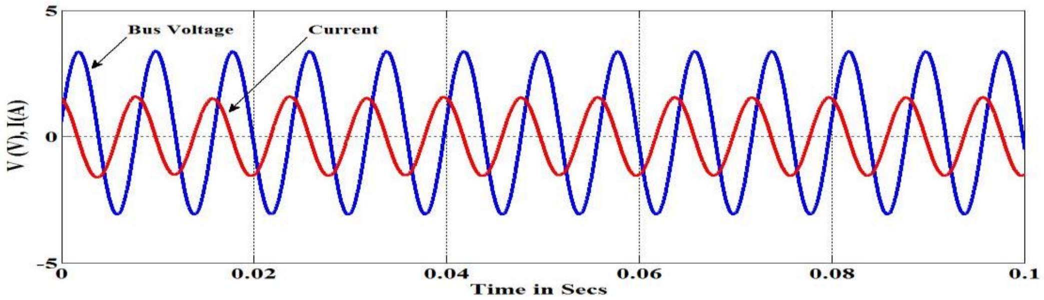

Fig.11 DPFC Operation in Steady State: Bus Voltage and Current.

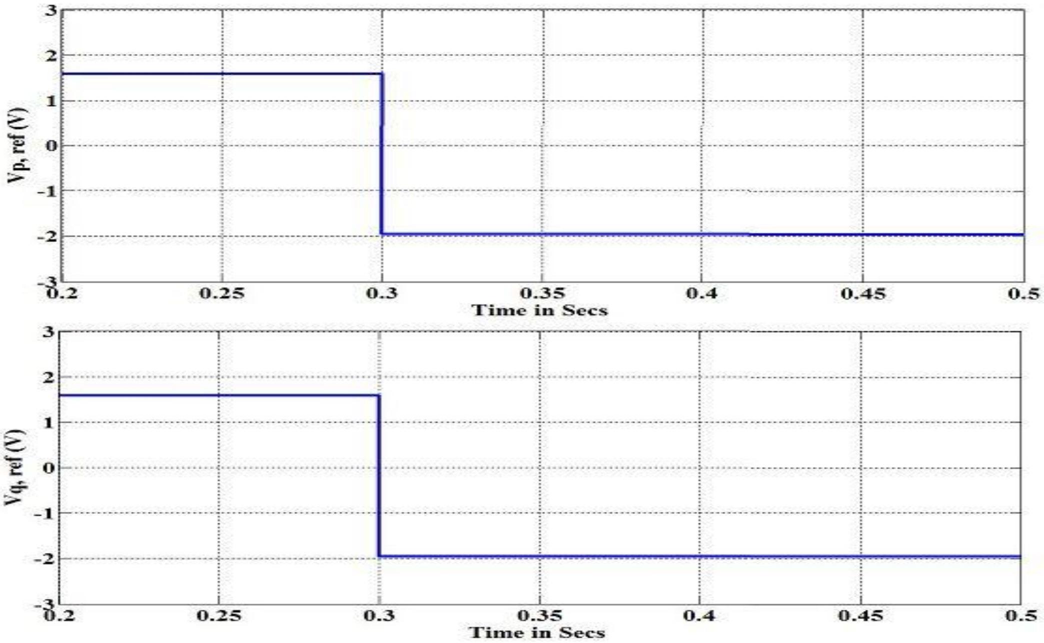

Fig.12 Reference Voltage of Series Converters.

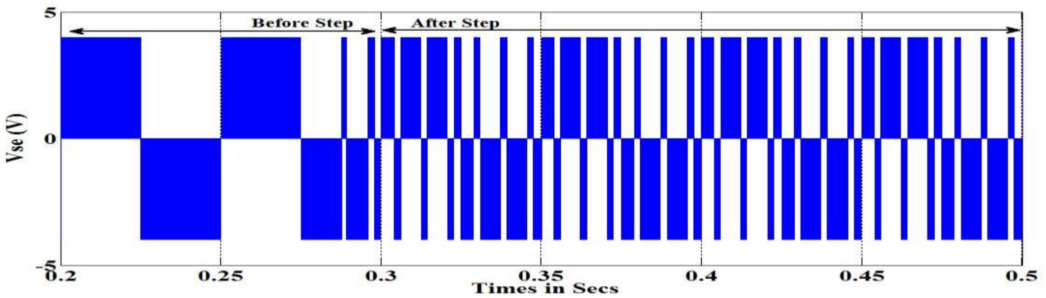

Fig.13 Step Response of DPFC: Series Converter Voltage.

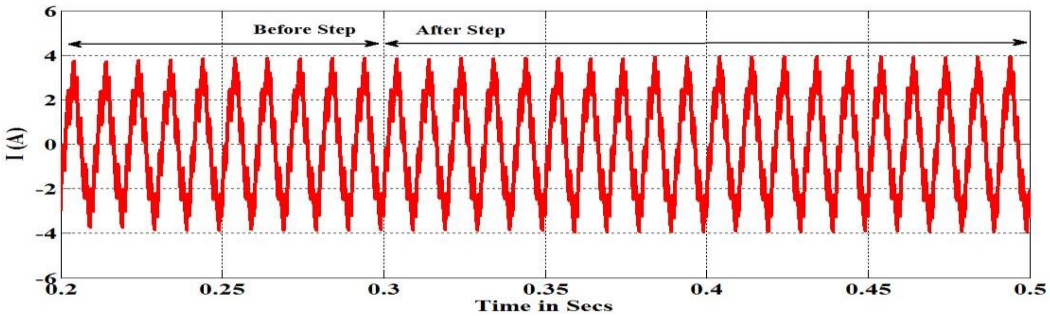

Fig.14 Step Response of DPFC: Line Current.

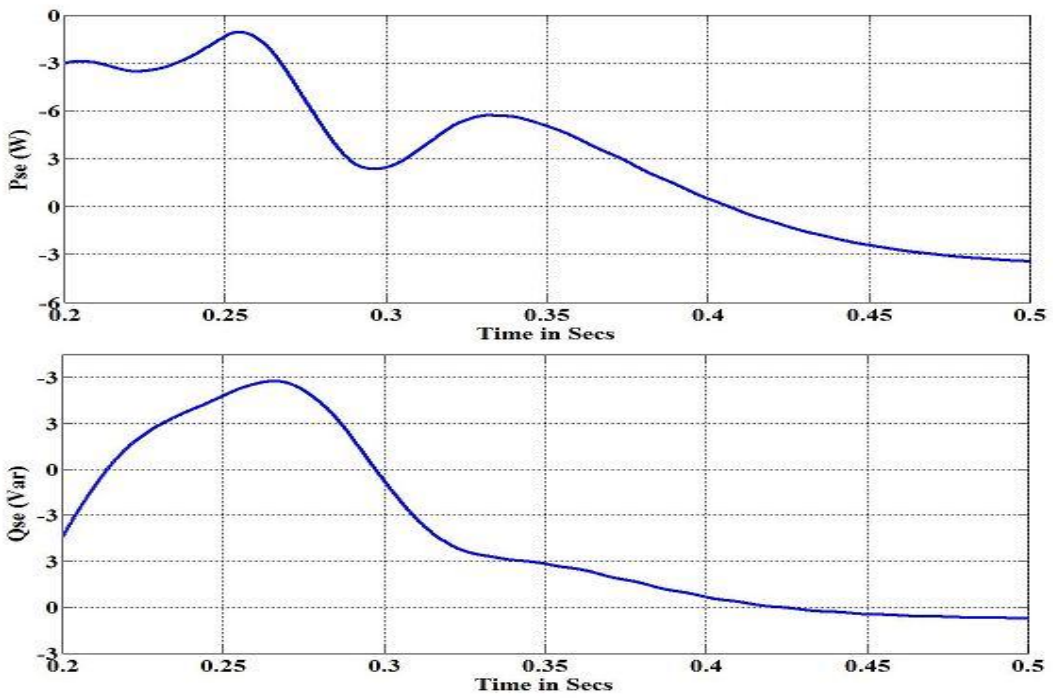

Fig.15 Active and Reactive Power Injection.

Table 1
Simulation Specifications

138	Line to line voltage of generator (kV)
0	Voltage phase of generator
5+j18.85	Line impedance of 30-mile line(ohm)
870	Line current (A)
1020	Switching frequency (Hz)
2500	DC voltage of total converter (V)
16.2	DC capacitance(mF)
1	Internal converter loss (kW)
100	Digital Delay (us)
4	Low pass filter R (ohm)
1	Low pass filter C (nF)

Fig.14 shows the line current when operation of DPFC in step response. It also shows the phase shift of the line current at the fundamental frequency.

The active and reactive power injection by series converter is shown in Fig. 15. The voltage and current at fundamental frequency contains harmonic distortion are filtered by a low pass filter with cut-off frequency.

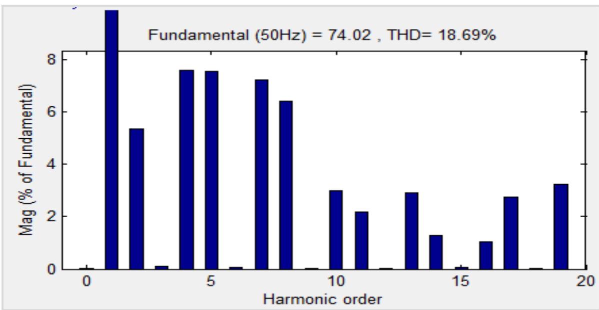

Fig.16 FFT analysis of Current Waveform without DPFC.

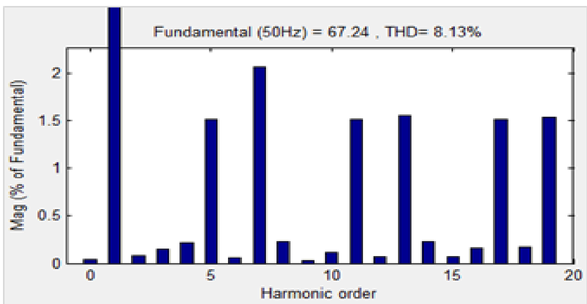

Fig.17 FFT analysis of Current Waveform with DPFC.

The harmonic analysis was carried out with the DPFC system. The DPFC system also eliminates the harmonics in current waveform. The harmonics were within acceptable limits and the total harmonic distortion (THD) of current was measured by FFT analysis in the MATLAB/SIMULINK environment and it is shown in the Fig. 16 and Fig. 17 with and without DPFC system respectively. It also almost meets the IEEE and IEC standard of harmonics.

6. Conclusion.

This paper presents a new FACTS device DPFC. The DPFC structure is similar to UPFC controller with a lower cost and high reliability. It also has control capability to balance the line parameters like line impedance, transmission angle and bus voltage. The DPFC was designed by three control loop namely series controller, shunt controller and central controller. This is based on the dq transformation. The shunt and series converter of the DPFC is exchange the active power through the transmission line at the third harmonic frequency. The series converter employs D-FACTS concepts instead of one large size converter. These series converters are able to inject controllable active and reactive power at the fundamental frequency. The DPFC device is simulated in steady state and step voltage response. This shows that active power can be successfully exchanged between series and shunt converter. The series converters have the capability of both active and reactive power compensation on the line. To conclude the DPFC has overcome the UPFC by eliminating the common dc link between shunt and series converter. It has high capability to control all the power system parameter. Due to high controlling capability the DPFC can also improve the power quality and system stability. The D-FACTS controller of series converter gives high reliability and low cost due to small independent single phase series converter. The effectiveness of the proposed DPFC was verified using MATLAB/Simulink.

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