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Analysis of Distributed Power Flow Controller in Power System Network for Improving Power Flow Control

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Abstract

In this paper, a new power flow controlling device called distributed power flow controller (DPFC) is presented that offers the same control capability as the unified power-flow controller (UPFC) but with much lower cost and high reliability. The DPFC eliminates the common DC link within the UPFC, to enable the independent operation of the shunt and the series converter. The D-FACTS concept is employed to the series converter to increase the reliability. Multiple low-rating single-phase converters replace the high-rating three-phase series converter, which significantly reduces the cost and increases the reliability. The active power that is exchanged through the common DC link in the UPFC is now transferred through the transmission line at the 3rd harmonic frequency. The DPFC is modeled in a rotating dq-frame. The modeling and analysis of DPFC in a two area two bus interconnected system is done in MATLAB/Simulink environment and comparison between the DPFC and UPFC considering the power flow and cost are also shown.

Keywords*: flexible AC transmission system, unified power flow controller, distributed FACTS, distributed power flow controller, power-transmission control*

1. Introduction

Nowadays the power system becomes very complex due to the increasing load demand of the electricity and the aging of the networks. There is a great desire to control the power flow in the transmission lines with fast and reliably [1]. Flexible AC transmission system (FACTS) controllers [2] based on power electronic converters offer competitive solutions to todays power systems in terms of increased power flow transfer capability and enhanced controllability, can be used for power flow control. The UPFC currently shown in Figure 1 is the most versatile FACTS device which can simultaneously control all the parameters of the system: the transmission angle, bus voltage and the impedance of the line [3].

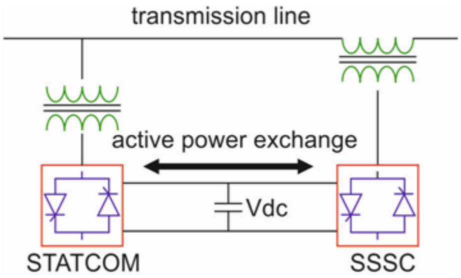

Figure 1. Simplified diagram of UPFC [4]

The UPFC consists of a Static Synchronous Compensator (STATCOM) and a Static Synchronous Series Compensator (SSSC), which are coupled through a common dc link to allow bi-directional flow of active power between the two converters [4]. The series converter injects a voltage in series with the system voltage through a series transformer. The power flow through the line can be regulated by controlling voltage magnitude and angle of series injected

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voltage [5]. The injected voltage and line current determine the active and reactive power injected by the series converter. The main function of the shunt converter (STATCOM) is to supply or absorb the active power demand by the series converter (SSSC). The shunt converter controls the voltage of the DC capacitor by absorbing or supplying active power from the grid [6]. The shunt converter also has a capability of independently supplying or absorbing reactive power to regulate the bus voltage of the grid. Although UPFC have superior power flow control capabilities but it is not widely used due to the following reasons [7]: i) Converter complexity and high voltage and current ratings of components increase the cost of UPFC; ii) The voltage isolation of series and shunt converters requires 3-phase high-voltage transformers which further increase the cost; iii) Due to the common dc link interconnection a failure at one converter willcause the whole system shut down. In that case to achieve the required reliability additional components are needed, which again enhance the cost.

To overcome the above discussed problems a new concept of distributed FACTS (D-FACTS) is proposed by Deepak Divan [8]. The concept of D-FACTS is to use multiple low rated single-phase series converters instead of the large power rated three-phase series converter that attached to the existing power line and can change the impedance of the line so as to control the power flow. This concept not only reduces the total cost but also increase the reliability of the series converters. Currently, the Distributed Static Series Compensator (DSSC) shown in Figure 2 has been presented as a member of D-FACTS devices.

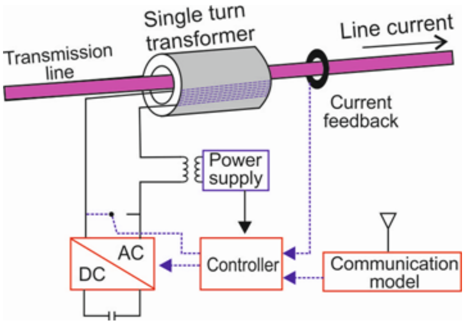


Figure 2. Schematic circuit of a DSSC module [9]

The DSSC is a distributed SSSC, which is made up of large number of a small rated single phase inverter (10~20 kW), a communication link and a single turn transformer (STT) [9]. The DSSC modules are clamped on transmission lines so that no extra high-voltage isolation and additional land is required. The single-turn transformer uses the transmission line as its secondary winding and injects a controllable voltage directly into the line. Most of the voltage injected by a DSSC unit is in quadrature with the line current, to emulate inductive or capacitive impedance. The DSSC is remotely controlled via wireless communication or a PLC (power line communication) [10]. As compare to UPFC the DSSC is not a powerful FACTS device because the control capability of the DSSC is limited, it can only inject reactive power. In this paper, DPFC is introduced as a new FACTS device, which minimizes the limitations of the conventional UPFC. The DPFC is developed by eliminating the common dc link between the shunt and series converters and has the same capability to simultaneously control all the parameters of the system at much lower cost and higher reliability.

This paper is organized as follows: In section II, the DPFC principle is discussed. In section III, the steady-state behavior of DPFC is analyzed. In section IV, the DPFC control scheme is developed. Finally, the modeling of DPFC, simulation results under steady state and step change conditions and cost analysis with UPFC are presented in section V.

2. Research Method

2.1.1. DPFC Principle

The DPFC consists of shunt and series converters. The shunt converter is similar as a STATCOM, while the series converter employs the D-FACTS concept. The simplified diagram of DPFC with a two bus system is shown in Figure 3.

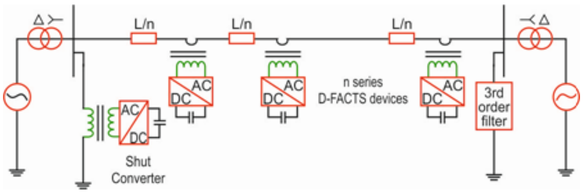


Figure 3. Generalized DPFC configuration [11]

In the above configuration there is no common dc link between the shunt and series converters, the active power can only be exchanged is through the transmission line at third harmonic frequency. The method of active power exchange in the DPFC is based on the principle of power theory of non-sinusoidal components [11]. The power theory is explained by Fourier analysis method. It states that, “non-sinusoidal voltage and current can be expressed as the sum of sinusoidal functions in different frequencies with different amplitudes”. The active power defined as the mean value of the product of voltage and current can be defined by:

$$P = \sum_{n=1}^{\infty} V_n \, I_n \, cos \, \emptyset_n \, [11] \tag{1}$$

Where n is the order of the harmonic frequency and Øn is the angle between the voltage and current of the nth harmonic. Eqn. (1) describes that the active powers at different frequencies are isolated from each other and the voltage or current in one frequency has no influence on the active power at other frequencies. The 3rd harmonic is selected here to exchange active power, because it can be easily blocked by Y-Δ transformers. The high-pass filter blocks the fundamental frequency components and makes a closed loop for third harmonic current.

2.1.2. Steady-State Analysis of DPFC

The steady-state behavior of the DPFC is analyzed with an assumption that each converter is replaced by controllable voltage sources in series with impedance, and generates the voltages at two different frequencies [12]. The DPFC is placed in a two-bus system with the sending end and the receiving end voltages Vs and Vr, respectively as shown in Figure 4.

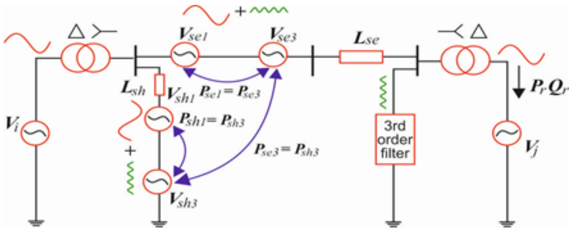


Figure 4. Simplified representation of DPFC in two bus system [12]

The transmission line is represented by an inductance L with the line current I. The voltage injected by series converters areVse1 and Vse3 at the fundamental and 3rd harmonic frequencies, respectively. The shunt converter is connected to the sending end bus through the inductor Lsh and generates the voltage Vsh1 and Vsh3, and the current injected by the shunt converter is Ish. The active and reactive power flows at the receiving end are Pr and Qr. The active and reactive power flow can be expressed as follows:

$$P_r + jQ_r = V_r \cdot I_1{}^* = V_r \cdot \left(\frac{V_s - V_r - V_{se1}}{jX_1}\right)^* \tag{2}$$

Where X1 = ω1L is the line impedance at the fundamental frequency. The power flow without DPFC compensation (Pr0, Qr0) is given by:

$$P_{r0} + jQ_{r0} = V_r \cdot \left(\frac{V_s - V_r}{jX_1}\right)^* \tag{3}$$

The power flow control range of the DPFC can be expressed as:

$$P_{rc} + jQ_{rc} = \frac{V_r V_{se1}^*}{jX_1} \tag{4}$$

Where P_rc and Q_rc are the active, reactive power control range of DPFC, respectively. As the voltage at the receiving end and the line impedance are fixed, the power flow control range of the DPFC is proportional to the maximum voltage of the series converter where the phase angle of voltage V*se1 can be rotated over 360◦, thereby controlling the active and reactive power flow through the transmission line. From Eqn. (2) and Eqn. (3), the control capability of the DPFC is given by:

$$(P_r - P_{r0})^2 + (Q_r - Q_{r0})^2 = \left(\frac{V|V_{se1}|}{X_1}\right)^2 \tag{5}$$

The control range of the DPFC is a circle in the complex PQ-plane, the locus of the power flow without the DPFC compensation f(Pr0,Qr0) is a circle with radius |V|2/|X1| around its center (defined by coordinates P = 0 and Q = |V|2/|X1|). Each point of this circle gives Pr0 and Qr0 values of the uncompensated system at the corresponding transmission angle θ. The boundary of the attainable control range for Pr and Qr is obtained from a complete rotation of the voltage Vse1 with its maximum magnitude as shown in Figure 5.

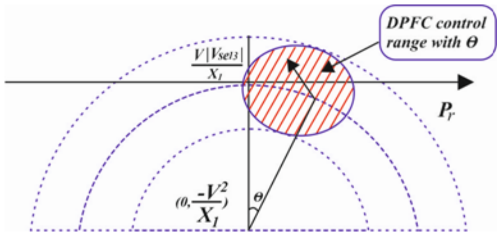


Figure 5. DPFC active and reactive power control range with the transmission angle θ [13]

The voltage injected by the series converter Vse1 at fundamental frequency is given by:

$$V_{se1} = \left[\frac{(S_r - S_{r0})jX_1}{V_r}\right]^* \tag{6}$$

Where S_r and S_r0 are the apparent power in compensated network and apparent power in uncompensated network, respectively. To inject a 360◦ rotatable voltage, an active and reactive power at the fundamental frequency has to be supplied to the series converter, although the reactive power is locally provided to the series converter and the requirement of active power is supplied by the shunt converter at the 3rd harmonic frequency through the transmission line, which is given as:

$$P_{se1} = \frac{X_1}{|V_r|^2}|S_r||S_{r0}|\,sin(\varphi_{r0} - \varphi_r) \tag{7}$$

Where φr0 is the power angle at the receiving end of the uncompensated system, which is equal to tan−1(Pr0/Qr0) while φr is the power angle at the receiving end of the system with DPFC compensation.

2.1.3. DPFC Control Scheme

The DPFC has three types of controllers: central controller, shunt control and series control, as shown in Figure 6.

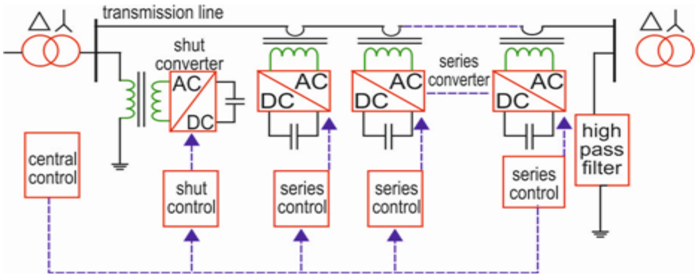


Figure 6. Block diagram of the control of a DPFC [14]

The function of each controller is defined as given below:

2.1.3.1. Central Control

The reference signals generated by the central control block are sent to both the shunt and series converters remotely via PLC communication method. According to the system requirements, the central control block generates reference signal of voltage Vse1ref for the series control block and reference signal of q component of the shunt current Ish1qref for the shunt control block at the fundamental frequency.

2.1.3.2. Series Control

The series converters generate a voltage with controllable phase angle as well as magnitude at fundamental frequency, and use 3rd harmonic frequency components to absorb active power to maintain its DC capacitor voltages at a constant value [14]. The block diagram of the DPFC series converter control is shown in Figure 7. The series converter control has different types of blocks: central control, single-phase PLL, dc controller, 3rd pass filter, single-phase inverse dq and PWM generator. To control the series converter, Vector Control principle [15] is used here. The principle is to transform voltages and currents in to a rotating reference frame, referred to as the ‘dq-frame’ and convert ac quantities to dc, using so called ‘Park’s transformation’ [16]. Due to the use of single-phase series converters, a single-phase Park’s transformation is applied here.

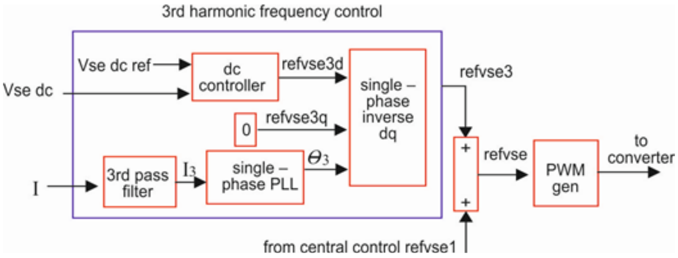


Figure 7. Block diagram of Series Converter Control [17]

The 3rd harmonic current through the transmission line is selected as the rotation reference frame for Park’s transformation because it can be easily measured by the series converter locally without extra cost. As the line current contains two frequency components, a 3rd high pass filter is required to extract the third harmonic current. The single-phase Phase-Lock-Loop (PLL) [18] track the magnitude and phase angle information from the line current and feed it to the single phase inverse Park’s transformation. The DC series voltage and reference signal of the DC series voltage are taken as the input of the DC control loop which generates the required control signal with the help of PI controller. In addition, by using the Internal Model Control (IMC) method [19] the PI controller parameter is calculated. The q component of the reference signal of the series converter at 3rd harmonic frequency is kept at zero during the operation. The above DC quantities together with phase angle are transformed back in to AC by the inverse Park’s transformation. The reference signals at both frequency components together gives reference signal to series converters which is generated by series control block.

2.1.3.3. Shunt Control

The shunt converter is connected between the ground and the neutral point of the Y-Δ transformer to inject 3rd harmonic current into the line to supply active power for the series converters. At the same time, it maintains the capacitor DC voltage of the shunt converter at a constant value by absorbing active power from the grid at the fundamental frequency and injecting the required reactive current at the fundamental frequency into the grid [20]. The block diagram of shunt control is shown in Figure 8.

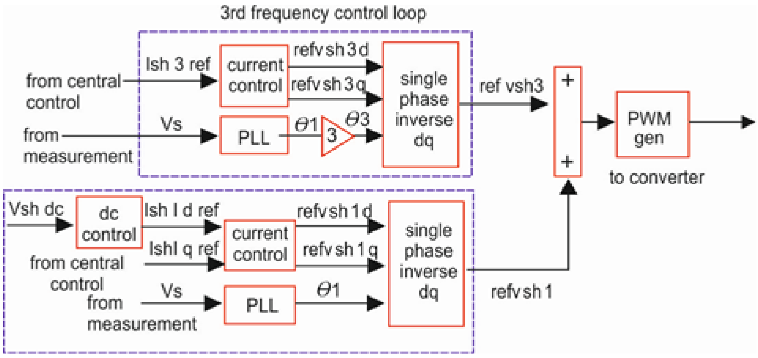


Figure 8. Block diagram of shunt converter control [17]

Shunt control block comprised of two control loops. Fundamental frequency control loop and 3rd harmonic frequency control loop. Fundamental frequency control loopmainly consists of two blocks: the DC control and current control. The bus voltage is selected as rotation reference frame for fundamental loop. The reference of the q component of the current and the reference signal of the d component is generated by the central control and the DC control blocks. The current control block generates required control signals to the single-phase inverse dq frame with the help of PI controller. In the 3rd harmonic frequency control loop the third harmonic current generated by shunt converter is synchronized with the bus voltage at the fundamental frequency. A PLL is used to track the bus voltage frequency, and the output signal is multiplied by constant factor 3 to create decoupled double synchronous rotation reference frame for the 3rd harmonic component [21]. The similar current control scheme is used for 3rd harmonic frequency components. Both frequency control loops together give reference signal to shunt converters to maintain constant DC voltage of the shunt converter and constant 3rd harmonic current injected in to the grid.

3. Results and Analysis

In this section modeling of DPFC and simulation results are presented.

3.1. A. Modeling of DPFC

The circuit model of the DPFC as shown in Figure 9 is a simple two area system which consists of major components: two three phase sources, 3-phase transmission lines, Δ-Y power transformers, one shunt converter and set of six series converters.

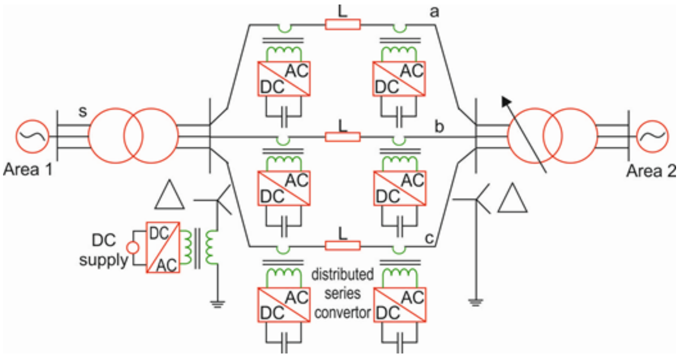
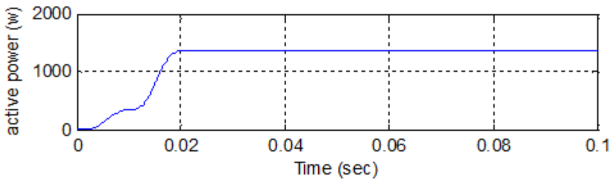


Figure 9. Simulation circuit of the DPFC with two-area system [22]

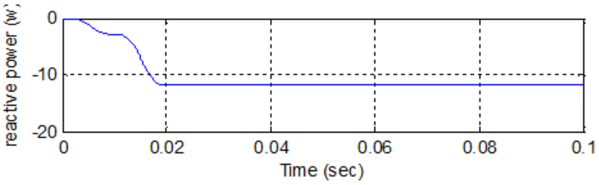
The system contains two buses with fixed voltage, where the buses are connected through inductors. The DPFC is placed between the two-buses with the sending end and the receiving end bus voltages Vs and Vr, respectively. The power flow between the two buses is obtained by providing a phase angle difference between the bus voltage angles. The shunt converter of the DPFC is a single phase universal bridge voltage source converter that is connected between the neutral point of Δ-Y transformer and the ground, and is powered by constant DC voltage source. The series converters of the DPFC use a same type of single phase converter that is connected to the transmission line by a single phase linear transformer. There is no power supply at dc side to support the series converter DC voltage. Both the shunt and series converters use GTO-diode as the switching device with PWM control scheme [23]. The simulation parameters of the DPFC device are listed in the Appendix (see Table 1). The DPFC model is simulated in Matlab Simulink, using SimPowerSystems toolbox. The DPFC simulation results are discussed in two parts: i) the active and reactive power flow through the transmission line at 1o transmission angle with DPFC system and without DPFC system, ii) the DPFC behavior in steady state and step response.

Case- I: Simulation Model without DPFC and with DPFC

In this case, the simulation model without DPFC and with DPFC is simulated for 0.1 sec to observe the values of active and reactive power flow through the transmission line. The theoretical values of power flow for without DPFC and with DPFC system are obtained by Eqn. (3) and Eqn. (2) and are given as: P+jQ=1344.37-j11.73 VA and P+jQ=67.76-j11.73 VA .The simulated values of active and reactive power flows in the line for 1o of transmission angle are shown in Figure 10 and Figure 11. The output wave forms can be seen in the MATLAB scope block.

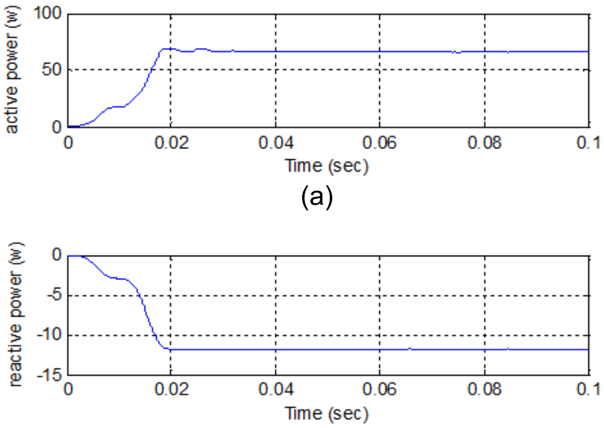


(a)



(b)

Figure 10. (a) Active Power through the line (b) Reactive Power through the line with 1o transmission angle without DPFC



(a)

(b)

Figure 11. (a) Active power through the line (b) Reactive power through the line with 1o transmission angle with DPFC
CaseII: DPFC behavior in steady state and step response.

The Simulation model with DPFC is simulated under steady-state and step change conditions and their results are shown in Figures (12) to (19).

CaseII (A) Steady-state results

Under steady-state conditions the series converter is controlled to inject a fundamental voltage of 2V. The line current, voltage injected by the series converter and the voltage and current at the Δ-side of the transformer are shown in Figures (12) to (14). For convenience only the waveforms in one phase are shown. The constant 3rd harmonic current injected by the shunt converter evenly disperses to the three phases and is superimposed on the fundamental current as shown in Figure (12). It is observed from Figure (13) that the voltage injected by series converter is a pulse width modulated (PWM) waveform containing two frequency components. The amplitude of the waveform represents the dc-capacitor voltage at the line side of the transformer which is well maintained by exchanging active power with the line at 3rd harmonic frequency.

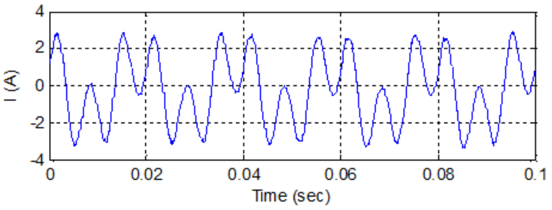


Figure 12. DPFC operation in steady-state: line current

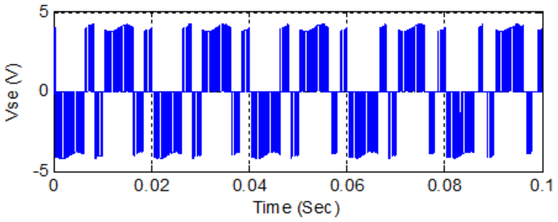


Figure 13. DPFC operation in steady-state: series converter voltage

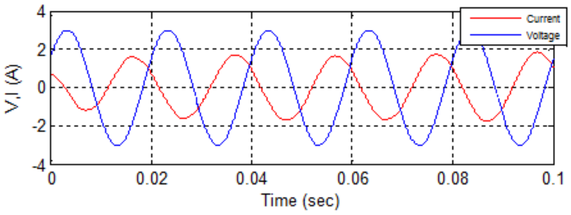


Figure 14. DPFC operation in steady-state: bus voltage and current at the Δ side of the transformer

The voltage and current waveforms which are shown in Figure (14) Contains no third-harmonic component. This shows the third-harmonic filtering property of the Y-Δ transformer. The step response results are shown in Figures (15) to (19). A step change of the fundamental reference voltage of the series converter is made as shown in Figure 15 (15). As shown in Figure 16, the dc voltage of the series converter is stabilized before and after the step change and a phase shift of the series converter voltage is observed at 0.285 simulation time. The line current through the line is shown in Figure 17. It is observed that the change in the voltage injected by the series converter changes the current flowing through the line. The active and reactive powers injected or absorbed by the series converter are shown in Figure 18.

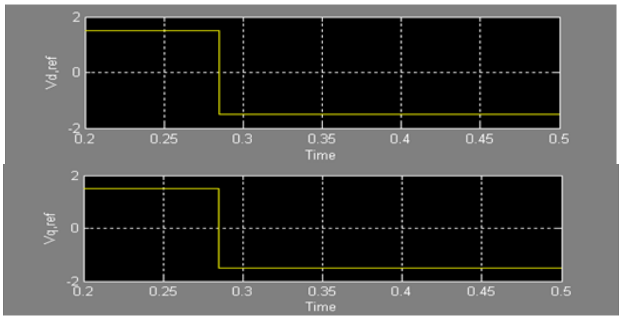


Figure 15. Reference voltage for the series converters

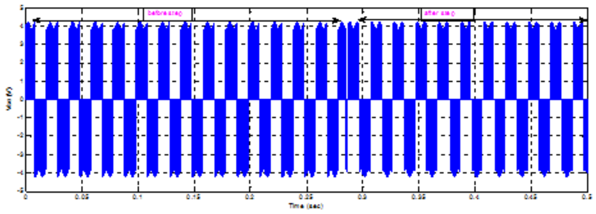


Figure 16. Step response of DPFC: series converter voltage

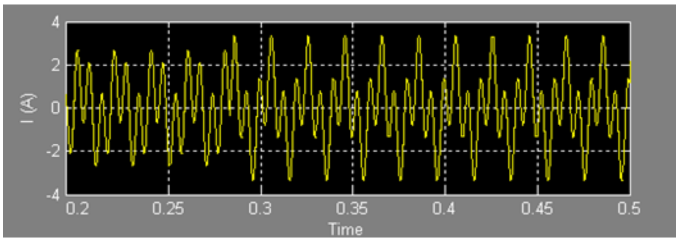


Figure 17. Step response of the DPFC: line current

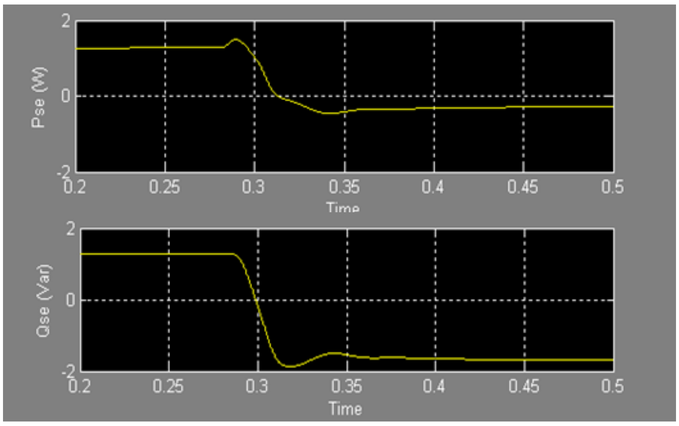


Figure 18. Step response of the DPFC: active and reactive power injected by the series converter at the fundamental frequency

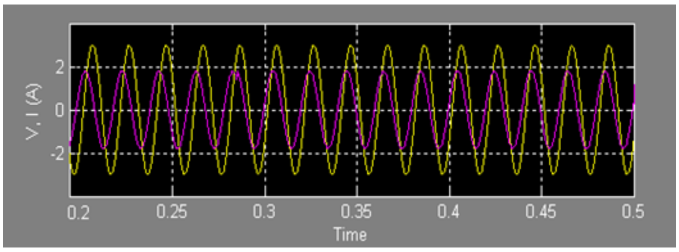


Figure 19. Step response of the DPFC: bus voltage and current at the Δ side of the transformer

It is observed from Figure (19) that the Δ-side of the network contains no 3rd harmonic component and a phase shift of the current is observed in waveforms

4. Conclusion

This paper presents a new power flow controller within the FACTS family, called DPFC. The main objective of this paper is to minimize the limitations of the conventional UPFC thus to reduce the cost and increase the reliability of the system, and to verify the principle and control of the DPFC in the real transmission network. The DPFC which is emerged from the UPFC by eliminating the common dc link between the shunt and series converter, can simultaneously control all the parameters of the system as the UPFC. As far as cost and reliability concerns the DPFC have two major advantages over UPFC verify, that the DPFC solution is economical than UPFC: 1) the series converter of the DPFC use the D-FACTS concept, which employs multiple low rated single-phase series converters instead of the single large power rated three-phase series converter that increases the reliability of the DPFC during series converter failures; 2) the high voltage and current rating of the components and the high voltage isolation requirement at series converter part are eliminated that minimizes the total cost of the DPFC. The DPFC principle is verified through a two area system. The two area system consists of a simple two bus network, one shunt converter and six series converters.

The shunt and series control blocks are developed in MATLAB/SIMULINK environment with d-q theory approach. The two bus DPFC system is simulated under the steady state and the step response. The above waveforms clearly shows that the shunt and series converters in the DPFC can exchange active power at the 3rd harmonic frequency and the series converters can generate controllable voltage at fundamental frequency, and use 3rd harmonic frequency components to absorb active power to maintain its DC capacitor voltages at a constant value. The waveform shown in Figure (10) and Figure (11) with DPFC and without DPFC verify that DPFC compensates the active and reactive power demand in transmission lines, and the level of compensation depends on the control range of DPFC.

APPENDIX

Table 1. Simulation parameters of the DPFC device

Symbol	Description	Value
V_s	Sending end bus voltage	220 V
V_r	Receiving end bus voltage	220 V
θ	Transmission angle between sending and receiving end bus voltages	1°
L	Line inductance	6 mH
$V_{sh,max}$	Shunt converter maximum ac voltage	50 V
$I_{sh,max}$	Shunt converter maximum ac current	9 A
$V_{sh,dc}$	Shunt converter dc source supply	20 V
$I_{sh,ref,3}$	Reference 3rd harmonic current injected by the shunt converter	3 A
f_{sw}	Switching frequency for shunt and series converter	6 kHz
$V_{se,max}$	Maximum ac voltage at line side of the series converter	7 V
$I_{se,max}$	Maximum ac current at line side of the series converter	15 A

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