

Power Transfer Capability & Reliability Improvement in a Transmission Line using Distributed Power- Flow Controller

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ABSTRACT

The Distributed Power Flow Controller (DPFC) is derived from the Unified power-flow controller (UPFC). The DPFC is a solution to control the power flow in a single transmission line. By eliminating the common DC link and distributing the three phase series converters of the UPFC, a new concept of the Distributed Power Flow Controller (DPFC) is achieved. The active power exchange between the two converters, which is through the common dc link in the UPFC, is now through the transmission lines at the third-harmonic frequency in the DPFC. It inherits the advantages of the UPFC and the DFACTS concept, which allow power flow control for multi-line systems with relatively low cost and high reliability without additional cost. This paper presents two types of DPFCs; one is one three phase shunt converter and four three phase series converters. Another model is one three phase shunt converter and nine single phase series converters. By using three phase series converters, no common dc link between shunt and series converters but cost will increase. By using single phase series converters, no common dc link between shunt and series converters and cost also decreases. Detailed simulations are carried out on two-machine systems to illustrate the control features of these devices and their influence to increase power transfer capability and every series converter consists of D-FACTS concept so Reliability also improves because failure of series converters does not affect.

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1. INTRODUCTION

The flexible ac transmission system (FACTS) technology is the application of power electronics in transmission systems [1]. The main purpose of this technology is to control and regulate the electric variables in the power systems.

This is achieved by using converters as a controllable interface between two power system terminals. Basically, the family of FACTS devices based on voltage source converters (VSCs) consists of a series compensator, a shunt compensator, and a shunt/series compensator. The static Compensator (STATCOM) [2] is a shunt connected device that is able to provide reactive power support at a network location far away from the generators. The static synchronous series compensator (SSSC) [2] is a series device which injects a voltage in series with the transmission line. Ideally, this injected voltage is in quadrature with the line current, such that the SSSC behaves like an inductor or a capacitor for the purpose of increasing or decreasing the overall reactive voltage drop across the line, and thereby, controlling the transmitted power. In this operating mode, the SSSC does not interchange any real power with the system in steady-state. The unified power-flow controller (UPFC) [2] is the most versatile device of the family of FACTS devices, since it is able to control the active and the reactive power, respectively, as well as the voltage at the connection node.

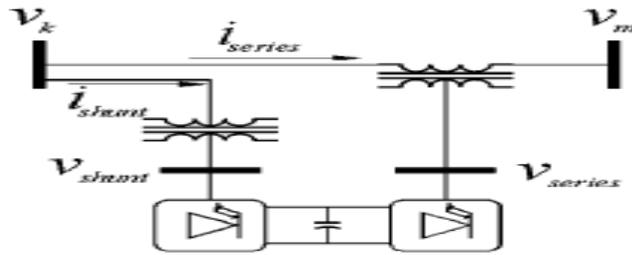


Figure 1. Schematic representation of the UPFC

The Unified Power Flow Controller (UPFC) is comprised of a STATCOM and a SSSC [3], coupled via a common DC link to allow bi-directional flow of active power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM [4]. Each converter can independently generate (or) absorb reactive power at its own AC terminal. The two converters are operated from a DC link provided by a DC storage capacitor. The configuration of a UPFC is shown in Figure 1.

The active power exchange between the shunt and the series converter is through the transmission line at the third-harmonic frequency. The series converter of the DPFC employs the distributed FACTS (D-FACTS) concept [5]. Comparing with the UPFC, the DPFC has two major advantages i.e. low cost because of the low-voltage isolation and the low component rating of the series converter and High reliability because of the redundancy of the series converters and high control capability. DPFC can also be used to improve the power quality and system stability such as power oscillation damping [6], Voltage sag restoration or balancing asymmetry.

2. DPFC TOPOLOGY

The flow chart for DPFC is shown in Figure 2. The DPFC consists of shunt and series connected converters. The shunt converter is similar as a STATCOM, while the series converter employs the Distributed Static series compensator (DSSC) concept, which is to use multiple single-phase converters and three phase series converters. Each converter within the DPFC is independent and has its own DC capacitor to provide the required DC voltage. The configuration of the DPFC is shown in figure. 3.

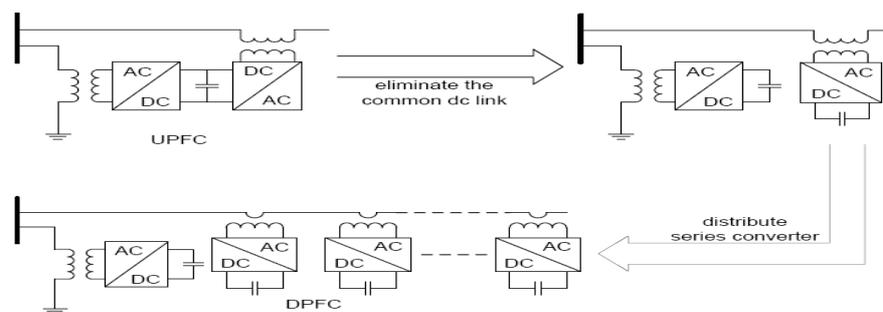


Figure 2. Flowchart from UPFC to DPFC for a single line.

3. DPFC OPERATING PRINCIPLE

3.1. Active power exchange with eliminated DC link:

Within the DPFC, the transmission line presents a common connection between the AC ports of the shunt and the series converters. Therefore, it is possible to exchange active power through the AC ports. The method is based on power theory of non-sinusoidal components. According to the Fourier analysis, non-sinusoidal voltage and current can be expressed as the sum of sinusoidal functions in different frequencies with different amplitudes. The active power resulting from this non-sinusoidal voltage and current is defined as the mean value of the product of voltage and current. [5] Since the integrals of all the cross product of terms with different frequencies are zero, the active power can be expressed by:

$$P = \sum_{i=1}^{\infty} V_i I_i \cos \phi_i \tag{1}$$

Equation (1) shows that the active powers at different frequencies are independent from each other and the voltage or current at one frequency has no influence on the active power at other frequencies. The independence of the active power at different frequencies gives the possibility that a converter without a power source can generate active power at one frequency and absorb this power from other frequencies. [5]

The high-pass filter within the DPFC blocks the fundamental frequency components and allows the harmonic components to pass, thereby providing a return path for the harmonic components. The shunt and series converters, the high pass filter and the ground form a closed loop for the harmonic current. [5]

3.2. Using third harmonic components

Due to the unique features of 3rd harmonic frequency components in a three phase system, the 3rd harmonic is selected for active power exchange in the DPFC is shown in Figure 3. In a three-phase system, the 3rd harmonic in each phase is identical, which means they are ‘zero-sequence’ components. Because the zero-sequence harmonic can be naturally blocked by Y- Δ transformers and these are widely incorporated in power systems (as a means of changing voltage), there is no extra filter required to prevent harmonic leakage [5].

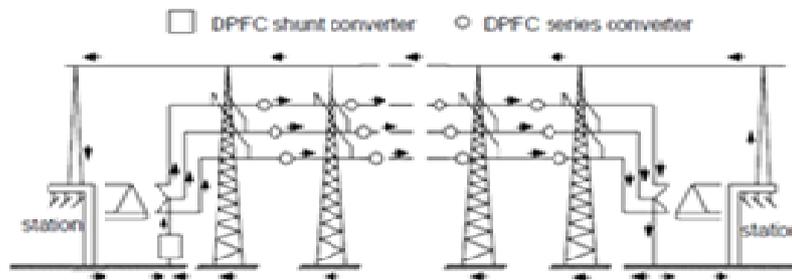


Figure 3. 3rd Harmonic Current flow in DPFC.

By using the zero-sequence harmonic, the costly filter can be replaced by a cable that connects the neutral point of the Y- Δ transformer [7] on the right side in Figure 4. with the ground. Because the Δ -winding appears open-circuit to the 3rd harmonic current, all harmonic current will flow through the Y-winding and concentrate to the grounding cable. [5]

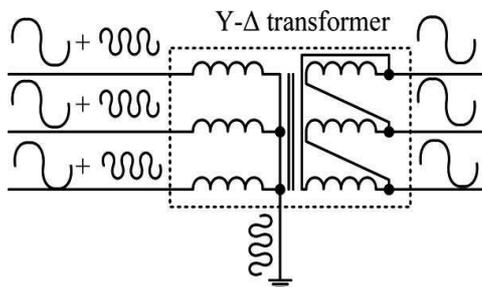


Figure. 4 Utilize grounded Y- Δ transformer to filter

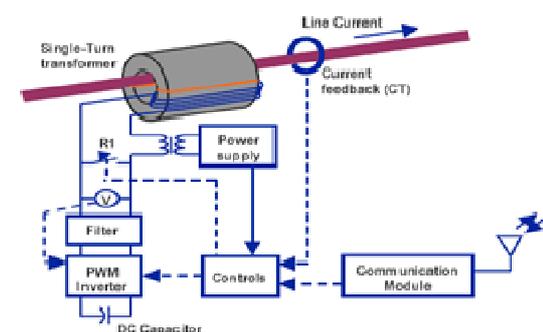


Figure. 5 DSSC Circuit schematic [7]. zero-sequence harmonic

The harmonic at the frequencies like 3rd, 6th, 9th... are all zero-sequence and all can be used to exchange active power in the DPFC. However, the 3rd harmonic is selected, because it is the lowest frequency among all zero-sequence harmonics. [5]

3.3. Distributed Series Converter

This paper introduces the concept of a *Distributed Static Series Compensator* (DSSC) which is shown in Figure 5. That uses multiple low-power single-phase inverters that attach to the transmission conductor and dynamically control the impedance of the transmission line, allowing control of active power flow on the line [4]. The DSSC inverters are self-powered by induction from the line itself, float electrically on the transmission conductors, and are controlled using wireless or power line communication techniques. Implementation of system level control uses a large number of DSSC modules controlled as a group to realize active control of power flow. The steady-state behavior of the DPFC is analyzed and the control capability of the DPFC is expressed in the parameters of both the network and DPFC itself [11]

4. DPFC SIMPLIFICATION AND EQUIVALENT CIRCUIT

To simplify the DPFC, the converters are replaced by controllable voltage sources in series with impedance. [12] Since each converter generates voltages at two different frequencies, they are represented by two series connected controllable voltage sources, one at the fundamental frequency and the other at the 3rd harmonic frequency [8]. For an easier analysis, based on the superposition theorem, the circuit in Figure 6. Can be further simplified by splitting it into two circuits at different frequencies. The two circuits are isolated from each other, and the link between these circuits is the active power balance of each converter, as shown in Figure 7.

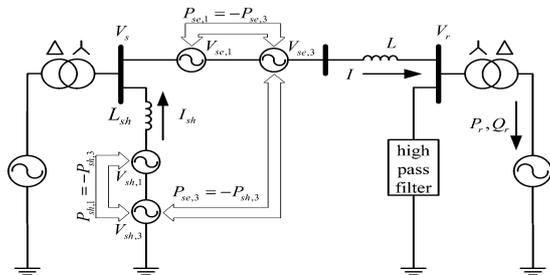


Figure 6. DPFC simplified representation. [5]

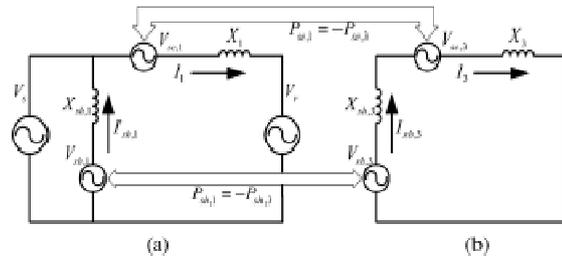


Figure 7. DPFC equivalent circuit: (a) the fundamental Frequency ; (b) the 3rd harmonic Frequency [5]

5. POWER FLOW CONTROL CAPABILITY

The power flow control capability of the DPFC can be illustrated by the active power P_r and reactive power Q_r at the receiving end, the active and reactive power flow can be expressed as follows: [9]

$$\begin{aligned}
 P_r + jQ_r &= V_r I_1^* \\
 &= V_r \left(\frac{V_s - V_r - V_{se,1}}{jX_1} \right)
 \end{aligned}
 \tag{2}$$

The power flow (P_r, Q_r) consists of two parts: the power flow without DPFC compensation (P_{r0}, Q_{r0}) and the part that is varied by the DPFC ($P_{r,c}, Q_{r,c}$). The power flow without DPFC compensation (P_{r0}, Q_{r0}) is given by:[5]

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

Accordingly, by substituting (3) into (2), the DPFC control range on the power flow can be expressed as:

$$P_{r,c} + jQ_{r,c} = V_r \left(\frac{V_{se}}{jX_1} \right)^*
 \tag{4}$$

The control range of the DPFC is a circle in the complex PQ-plane, whose center is the uncompensated power flow (P_{r0}, Q_{r0}) and whose radius is equal to $|V_r||V_{se,1}|/X_1$. By assuming that the voltage magnitude at the sending and receiving ends are both V , [10] the control capability of the DPFC is given by the following formula

$$(P_r - P_{r0})^2 + (Q_r - Q_{r0})^2 = \left(\frac{|V||V_{se,1}|}{X_1} \right)^2 \quad (5)$$

In the complex PQ-plane, the locus of the power flow without the DPFC compensation $f(P_{r0}, Q_{r0})$ is a circle with radius $|V|^2 / X_1$ around its center (defined by coordinates $P = 0$ and $Q = |V|^2 / X_1$). Each point of this circle gives P_{r0} and Q_{r0} values of the uncompensated system [13] at the corresponding transmission angle θ . The boundary of the attainable control range for P_r and Q_r is obtained from a complete rotation of the voltage $V_{se,1}$ with its maximum magnitude. [13]

6. MATHEMATICAL ANALYSIS OF DISTRIBUTED POWER FLOW CONTROLLER

Sending end voltage = 220 V [Ph-Ph, rms]

Phase difference = 0°

Transmission angle $\theta = \tan^{-1}(Q \div P) = \tan^{-1}(100 \div 10^4) = 0.5729^\circ$

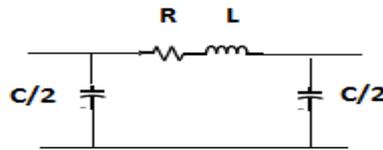


Figure 8. Three phase Pi section line

7. SIMULATION RESULTS

To simulate the effect of the DPFC on Distributed system is processed using MATLAB. One shunt converter and nine single phase series converters are built and tested. The specifications of the DPFC in MATLAB are listed below.

Power factor = $\cos \theta = 0.99$

Impedance calculations:

Three phase Pi section line

R = positive + zero sequence resistance (ohms) = 0.39913

L = positive + zero sequence inductance (H) = 5.0596×10^{-3}

C = positive + zero sequence capacitance (F) = 20.491×10^{-9}

Line impedance = 2.30659 ohms

Finding line current:

$I_l = \text{KVA} \div V = (10.10 \times 10^3) \div 2449.489 = 4.123 \text{ A}$

To find the receiving end voltage:

$I_{c2} = j \cdot \omega \cdot (C \div 2) \cdot V_r = j \cdot 3.862 \cdot 10^{-6} \cdot V_r$

$I_l = I_r + I_{c2} = 4.123 \angle 0.5729^\circ + j \cdot 3.862 \cdot 10^{-6} \cdot V_r$

$V_s = V_r + (4.12390 \cdot 5729 + j \cdot 3.862 \cdot 10^{-6} \cdot V_r) \cdot 2.30659$

$V_r = (529.371 - j \cdot 0.0945) \div (1 + j \cdot 8.908 \cdot 10^{-6}) = 529.309 - j \cdot 0.09 \text{ V}$

To find active and reactive powers without compensation:

$P_{r0} + j Q_{r0} = V_r ((V_s - V_r) \div j X_1)$
 $= 529.37 \angle -0.01^\circ \cdot ((538.88 \angle 0^\circ - 529.37 \angle 0.01^\circ) \div j \cdot 2.306)$ =
 $20.21 - j \cdot 2185.3 \text{ VA}$

To find active and reactive powers with compensation:

$P_r + j Q_r = V_r ((V_s - V_r - V_{se,1}) \div j X_1)$
 $= 529.37 \angle -0.01^\circ \cdot ((538.88 \angle 0^\circ - 529.37 \angle -0.01^\circ - 1273.2 \angle 0^\circ) \div j \cdot 2.306) = 101.26 + j \cdot 290089.44$

To find the vectors S_r and S_{r0} :

$S_{r0} = P_{r0} + j Q_{r0} = 2185.4 \text{ VA}$, $S_r = P_r + j Q_r = 290089.46 \text{ VA}$,
 $S_{\text{range}} = 287904 \text{ VA}$

To find active and reactive powers of series converters:

$P_{se,1} + j Q_{se,1} = V_{se,1} \cdot I_l = 24291.73 + j \cdot 4.239 \text{ VA}$

Voltage of series converters:

$V_{se,1} = (28904 \cdot 2.30569) \div 529.37 = 1253.976 \text{ V}$

Control range of DPFC:

$V_s = 538.88$, $V_{se} = 1273.2$, $V_r = 529.37$, $X = 1.907$, $\theta = 0.5729^\circ$
 Calculation of Radius:
 $V_s \cdot V_r \div X_1 = 538.88 \cdot 529.37 \div 1.907 = 149589.35$

Figure 10 and 11 illustrates the line active & reactive power and Injected voltage & current. The series converters are able to absorb and inject reactive power in the line at the fundamental frequency and increase the active power flow in the system.

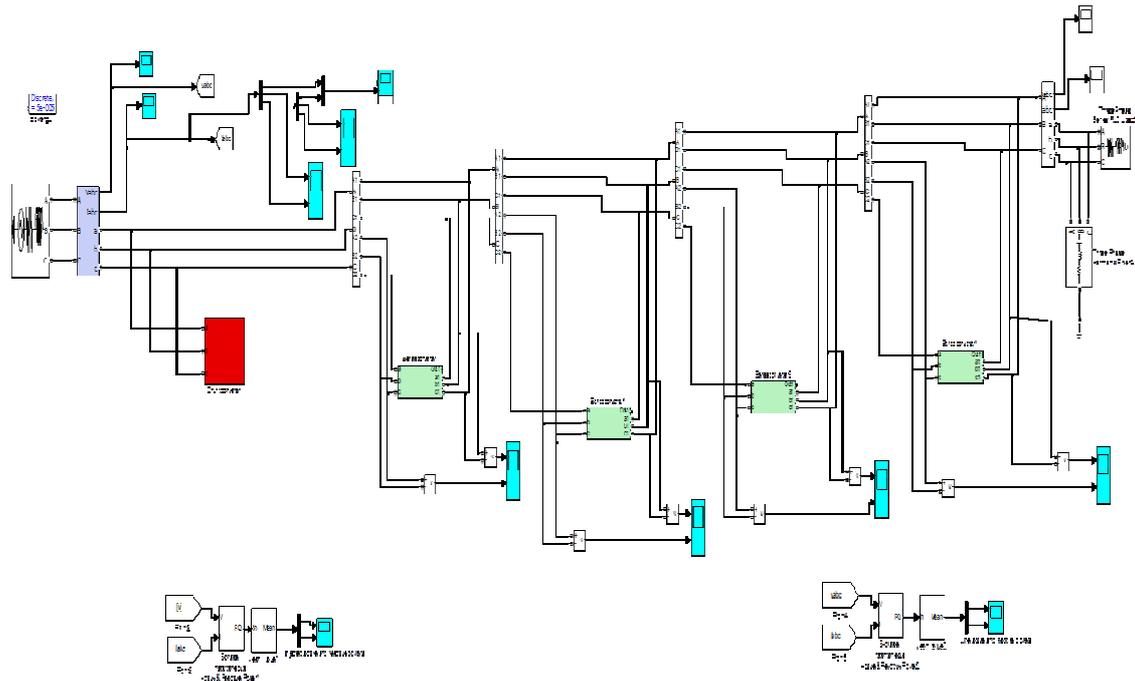


Figure 9. Simulation Model for transmission system with DPFC (one three phase shunt converter and four three phase series converters)

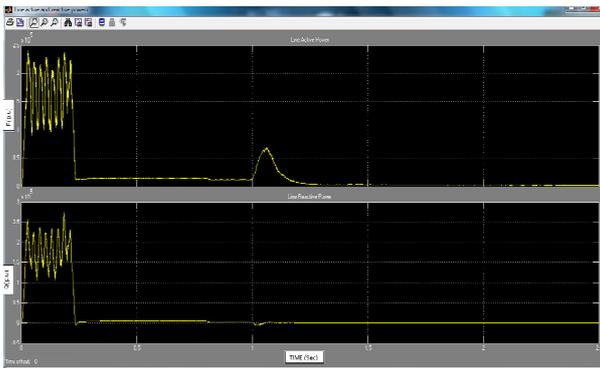


Figure 10. Line active & reactive power

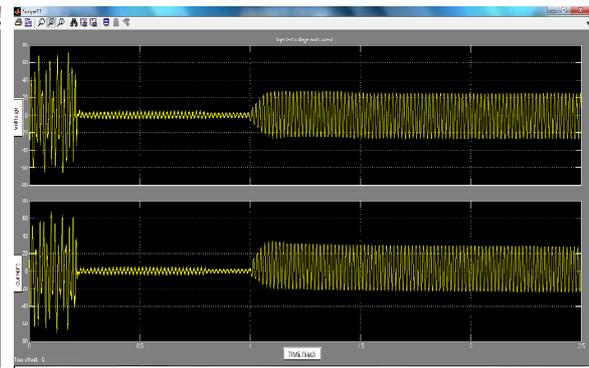


Figure 11. Injected voltage & current

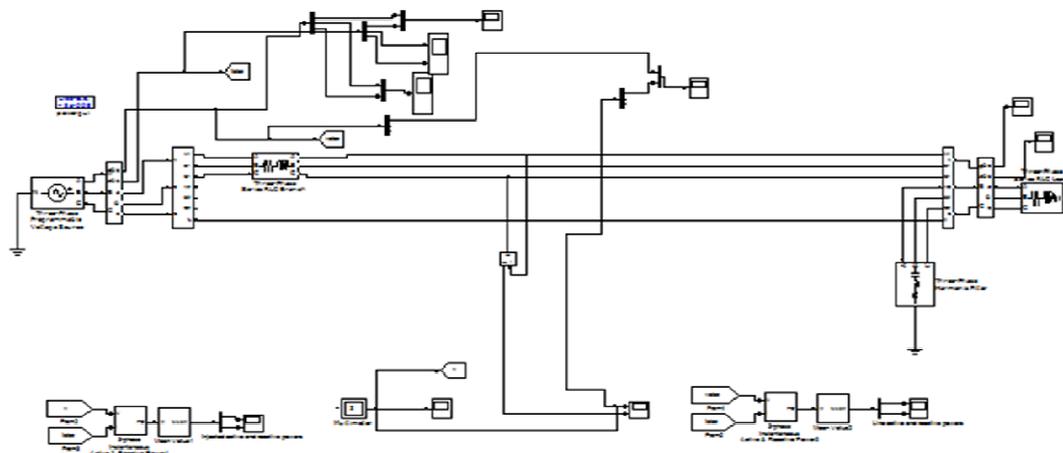


Figure 12. Simulation model for Transmission system without DPFC (Line-Ground)

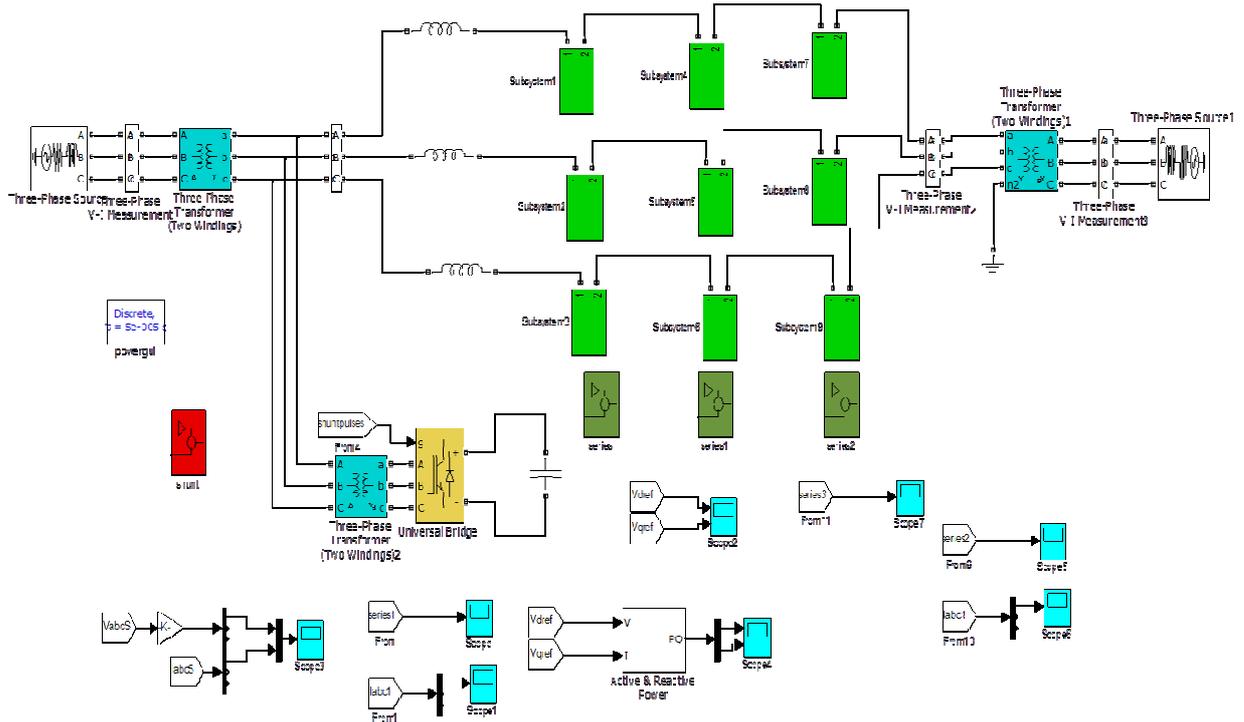


Figure 13. Simulation Model for transmission system with DPFC (Line-Ground)

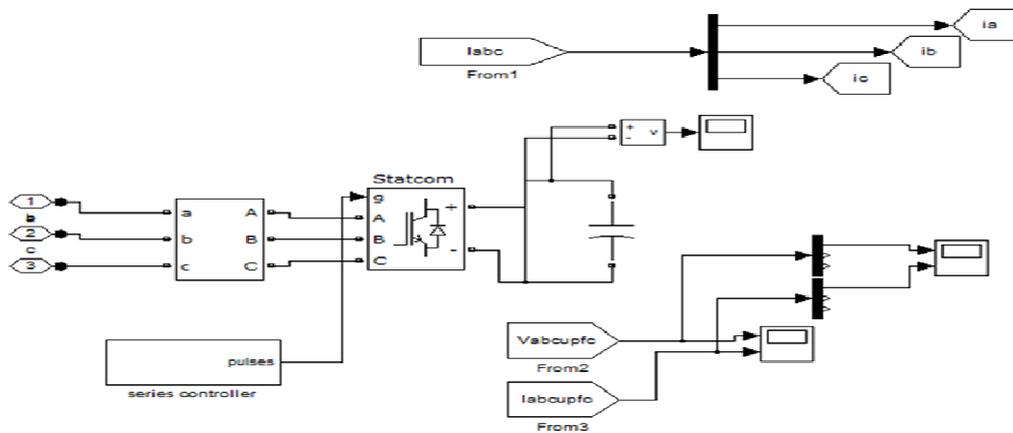


Figure 14. Simulation model for Shunt Converter

Table 1. Parameters of STATCOM	
STATCOM	Value
Number of bridge arms	3
Snubber resistance R_s (ohms)	1×10^5
Snubber capacitance C_s (f)	1×10^{-6}
Power electronic device	IGBT/Diodes
R_{on} (ohms)	1×10^{-3}
Forward voltages [Device V_f (v) Diode V_{fd} (v)]	[0 0]
[T f(s) T f(t)]	[1×10 , 2×10]

Table 2. Parameters of Three phase RL Load	
Three phase RL Load Configuration	value
	Y (grounded)
Nominal phase to phase voltage V_n (V_{rms})	1000 V
Nominal Frequency (HZ)	60 HZ
Active Power P (W)	10×10^3 W
Inductive reactive power Q_1 (positive Var)	100 Var
Capacitive reactive power Q_c (negative Var)	0

Figure 14. represents the simulation model for shunt converter. STATCOM used is in configuration with IGBT/Diode. Control is done by using a controller as shown in the figure.

Table 3. Parameters of Three phase Harmonic filter

Three-phase Harmonic filter	Value
Type of filter	Single-tuned
Filter connection	Y (neutral)
Nominal L-L voltage and frequency [Vn (Vrms) fn (HZ)]	[315x103 60]
Nominal reactive power (Var)	49x106 Var
Tuning frequency (HZ)	[5x60] HZ
Quality factor (Q)	16

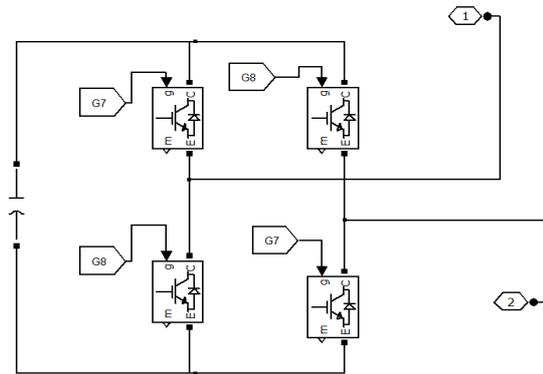


Figure 15. Simulation model for Series Converter

Figure 15 represents the simulation model of a single phase series converter. Four IGBT devices are in each single phase converter. Figure 16 contains two frequency components ie., fundamental and Third harmonic frequency components. The constant 3rd harmonic current injected by the shunt converter is evenly dispersed to the 3 phases and is superimposed on the fundamental voltage and current.

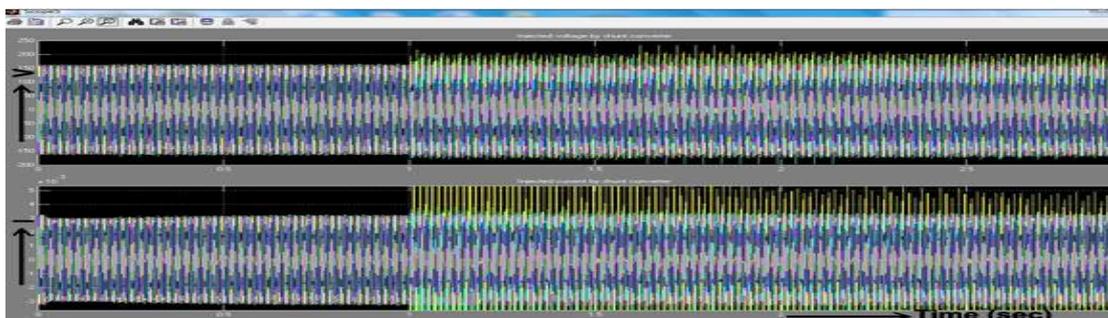


Figure 16. Injected voltage and current injected by shunt converter

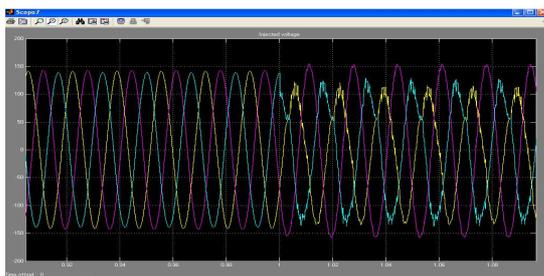


Figure 17. Injected Voltage by Series Converter

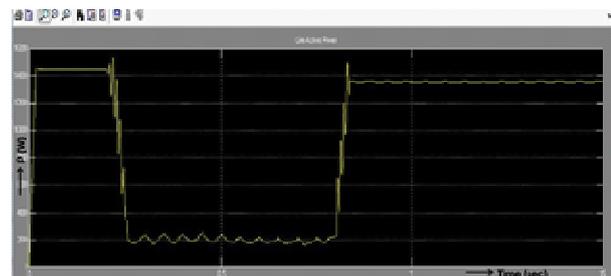


Figure 18. Line active power for without DPFC

Figure 17 contains two frequency components i.e., fundamental and Third harmonic frequency components as shown in Figure 4. The constant 3rd harmonic voltage injected by the series converter is evenly dispersed to the 3 phases and is superimposed on the fundamental voltage. Figure 18 and 19 illustrates the line active power of transmission system without and with DPFC. The series converters are able to absorb and inject active power in the line at the fundamental frequency.

Figure 20 and 21 illustrates the line reactive power for without and with DPFC. The series converters are able to absorb and inject reactive power in the line at the fundamental frequency and increase the active power flow in the system.

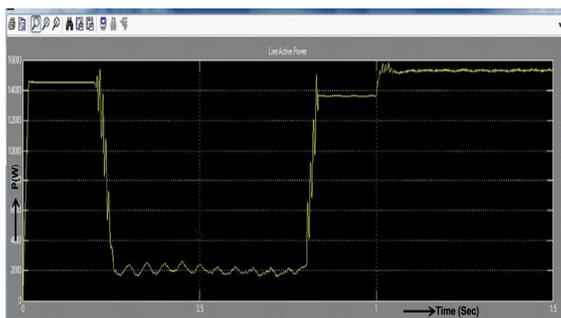


Figure 19. Line active power for with DPFC

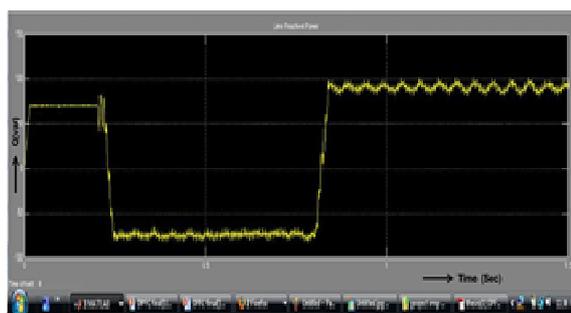


Figure 20. Line reactive power for without DPFC

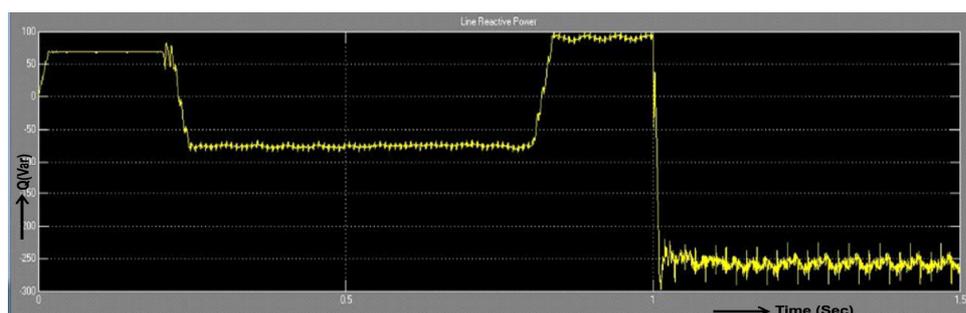


Figure 21. Line reactive power for with DPFC

8. CONCLUSION

Analytical expressions were derived for the active and reactive powers of series converter. The DPFC emerges from the UPFC and inherits the control capability of the UPFC, which is the simultaneous adjustment of the line impedance, the transmission angle, and the bus-voltage magnitude. The common dc link between the shunt and series converters, which is used for exchanging active power in the UPFC, is eliminated. This power is now transmitted through the transmission line at the third-harmonic frequency. The series converter of the DPFC employs the D-FACTS concept, which uses multiple small single-phase and three phase converters. The series converter which is a voltage source inverter injects an almost sinusoidal voltage in series with the transmission line. This injected voltage is almost in quadrature with the line current, thereby emulating an inductive reactance or a capacitive reactance in series with the transmission line. The reliability of DPFC is higher than UPFC because of redundancy in large number of series converters. The total cost of the DPFC is also much lower than the UPFC, because no high-voltage isolation is required at the series-converter part and the rating of the components is low when single phase series converters are used. The simulation results, obtained by MATLAB show the efficiency of DPFC, in controlling line both active and reactive power flow. It is proved that the shunt and series converters (single-phase & three phase) in the DPFC can exchange active power at the third-harmonic frequency, and the series converters are able to inject controllable active and reactive power at the fundamental frequency. By comparing single-phase & three phase series converters in the DPFC, a single phase converter is of low rating and reduces the cost.

REFERENCES

- [1] Y.-H. Song and A. Johns, *Flexible ac Transmission Systems (FACTS)* (IEE Power and Energy Series), vol. 30. London, U.K.: Institution of Electrical Engineers, 1999.
- [2] N. G. Hingorani and L. Gyugyi, *Understanding FACTS : Concepts and Technology of Flexible AC Transmission Systems*. New York: IEEE Press, 2000.
- [3] K. K. Sen, "Sssc-static synchronous series compensator: Theory, modeling, and application," *IEEE Trans. Power Del.*, vol. 13, no. 1, pp. 241–246, Jan. 1998.
- [4] A.-A. Edris, "Proposed terms and definitions for flexible ac transmission system (facts)," *IEEE Trans. Power Del.*, vol. 12, no. 4, pp. 1848–1853, Oct. 1997.
- [5] Zhihui Yuan, Sjoerd W.H.de Haan, Jan Braham Ferreira, Dalibor Cvoric "A FACTS Device: Distributed Power Flow Controller (DPFC)" *IEEE Transactions Power Electronics*, vol. 25, no.10, pp.2564-2572, October 2010.

- [6] M. D. Deepak, E. B. William, S. S. Robert, K. Bill, W. G. Randal, T. B. Dale, R. I. Michael, and S. G. Ian, "A distributed static series compensator system for realizing active power flow control on existing power lines," *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 642–649, Jan. 2007.
- [7] Y. Zhihui, S.W. H. de Haan, and B. Ferreira, "Utilizing distributed power flow controller (dpfc) for power oscillation damping," in *Proc. IEEE Power Energy Soc. Gen. Meet. (PES)*, 2009, pp. 1–5.
- [8] D. Divan and H. Johal, "Distributed facts—A new concept for realizing grid power flow control," in *Proc. IEEE 36th Power Electron. Spec. Conf. (PESC)*, 2005, pp. 8–14.
- [9] Y. Zhihui, S. W. H. de Haan, and B. Ferreira, "Dpfc control during shunt converter failure," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, 2009, pp. 2727–2732.
- [10] Y. Sozer and D. A. Torrey, "Modeling and control of utility interactive inverters," *IEEE Trans. Power Electron.*, vol. 24, no. 11, pp. 2475–2483, Nov. 2009.
- [11] L. Huber, B. T. Irving, and M. M. Jovanovic, "Review and stability analysis of pll-based interleaving control of dcm/ccm boundary boost pfc converters," *IEEE Trans. Power Electron.*, vol. 24, no. 8, pp. 1992–1999, Aug. 2009.
- [12] M. Mohaddess, A. M. Gole, and S. Elez, "Steady state frequency response of statcom," *IEEE Trans. Power Del.*, vol. 16, no. 1, pp. 18–23, Jan. 2001.
- [13] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics : Converters, Applications, and Design*, 3rd ed. Hoboken, NJ: Wiley, 2003.

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