Improvement of the DPFC performance in Transmission Lines during failure of Series Converter

Syed harron, Nidhi Saraswat, Swati Singh and Kuldeep Singh Kulhar

Syed harron, Assistant Professor, Department of Computer Science and Information Technology, Jain (Deemed to be University), Bangalore, India, Email Id- syed.harron@jainuniversity.ac.in
Ms. Nidhi Saraswat, Assistant Professor, Department of Computer Science Engineering, Sanskriti University, Mathura, Uttar Pradesh, India, Email Id- nidhi.soeit@sanskriti.edu.in
Swati Singh, Assistant Professor, Maharishi School of Engineering & Technology, Maharishi University of Information Technology, Uttar Pradesh, India, Email Id- swatisingh5444@gmail.com
Kuldeep Singh Kulhar, Professor, Civil Engineering, Vivekananda Global University, Jaipur, India, Email Id-k.singh@vgu.ac.in

Abstract: The DPFC is a novel device which is related to FACTS family. It has become visible from the Unified Power Flow Controller. The DPFC is comprised of a shunt converter and a series converter, both interconnected with the grid to regulate power flow. The presence of a common dc link between the shunt and series converters is observed in previous converters such as UPFC. However, in the case of DPFC, the dc link is eliminated. The series controller ensures cost-effective high reliability. In this document, we examine the efficiency of DPFC when a single series converter fails, and we also implement a control scheme to enhance DPFC's performance in such failure scenarios. The control principle relies on the fact that the failure of a single series converter will result in the occurrence of unsymmetrical currents across the entire system. Monitoring the zero and negative sequence currents can help to overcome this failure. A well-suited control scheme has been devised in this study to overcome the challenges arising from the series converter failure and effectively manage the active power, reactive power, grid voltages, and currents. The obtainability of the control scheme and simulation diagrams of DPFC can be achieved through the appropriate design.

Keywords: **VSI; DPFC; UPFC; reactive power.**

Corresponding author: syed.harron@jainuniversity.ac.in

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1. Introduction

Now a day there is a fast growth in the demand of the energy in order to meet the demand, quality and reliability of power supply is necessary. Among all the FACTS devices DPFC offers greater reliability in the power supply at a very low cost [1]. By adjusting all the electrical parameters DPFC can maintain the quality in the power supply, quality nothing but maintaining the voltage and frequency within the limits. DPFC is considered the most potent device in comparison to traditional FACTS devices. The DPFC is comprised of a solitary shunt converter linked between the line and ground, along with multiple series converters connected in series with the transmission line. When UPFC is used with a back-to-back connection linking the shunt and series controllers through a shared dc link, the transfer of real power between the shunt and series controllers occurs through the dc link. The DPFC does not employ the DC link; instead, it depends on the transmission line to transmit real power between converters at the 3rd harmonic frequency. Additionally, it is composed of several single-phase converters working together.

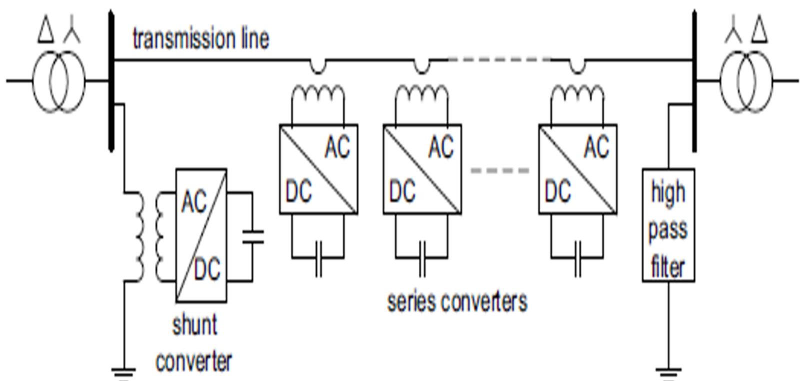

Fig.1. Layout of DPFC unit.

The illustration in Figure 1 depicts the DPFC scheme in a basic two-bus system. During the fault occurrence if any one of the converter fails to operate, the other converters helps in maintaining the continuity in power supply Conversely, the disastrous converter is not capable of supplying the required voltage to the system this causes asymmetry of the series converters and there by the performance of the Distributed Power Flow Controller becomes poor. 1. A suitable control scheme has been developed in this document to address the issues that arise when the series converter fails [3]. The control system design and simulation charts for the Distributed Power Flow Controller are available for access.

2. Principle of DPFC

2.1. Introduction of the DPFC

Schematic diagram of a DPFC with Multiple series converters is shown in Fig.1. A single shunt converter is utilized in this setup, connecting between the line and ground. Its purpose is to provide the real power to the series converters. The DPFC is comprised of a series of converters that are interconnected with the transmission line. Series converters are used to inject the voltage in series with the transmission line and also series converters are capable of controlling the powers of real and reactive flow through the transmission cable.

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If a UPFC is used with a back-to-back connection between shunt and series controllers through a shared dc link, the transfer of real power between the series and shunt controllers occurs via the dc link. But in DPFC the real power exchange between the two converters takes place in the absence of dc link. A common connection within the DPFC is established between all the ac terminals of the series converters through a transmission line. As a result, there is a possibility of real power exchange in the course of ac terminals. Mainly this technique is purely based on non-sinusoidal components. The Fourier analysis states that real power can be represented as a combination of sinusoidal functions involving non-sinusoidal currents and voltages of varying amplitudes and frequencies. The active power is given by;

$$\boldsymbol{P} = \sum_{i=1}^{\infty} \boldsymbol{V_i I_i} \cos \boldsymbol{\phi_i} \qquad (1)$$

From the above equation (1) I and V are the corresponding non sinusoidal currents and voltages at the i^{th} harmonic frequency. Equation (1).illustrates the real power at changed frequencies is separated from each other, and the voltage and current related to particular frequency has no authority on the real power at remaining frequencies. With this independent behaviour the real power can be supplied from one frequency and power can be utilized by other frequencies.

2.2. DPFC control principle

The DPFC is comprised of three distinct control methods for regulating three converters: shunt control, series control, and central control units, as illustrated in Figure 2.

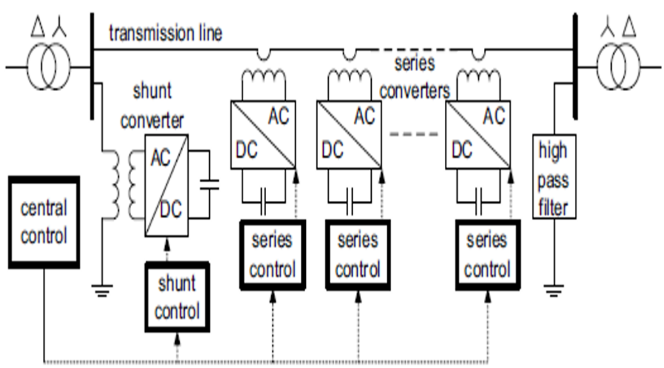

Fig. 2. Control scheme of a DPFC.

The control methodologies of series and shunt are versatile controllers that are employed to regulate their respective parameters within a limited range. The functions that are performed by DPFC are controlled through a central control. The roles of every controller are outlined.

Central control: Mainly this control concentrates on the various functions that are performed by DPFC such as controlling the power flow, eliminating low frequency power oscillations etc. According the system requirements, the series converters receives reference voltage signals and the shunt converter receives reference current signals which are provided by the central control at the fundamental frequency. It also controls all the electrical parameters which are related to the shunt and series controllers.

Shunt control: The main goal of the shunt control is to introduce a steady 3rd harmonic current component alongside the transmission line at the fundamental frequency, as mandated by the central control.

Series control: voltage is injected in series with the transmission line by providing proper series control. Each and every series converter is employed with its individual series Control. The primary objective of series control is to regulate the direct current voltage of the capacitor within its converter.

3. Behavior of DPFC during Failure of a Series Converter

There are primarily two types of failures that can occur in series Converter of DPFC: open circuit and short circuit. The short circuit failure is not considered as a severe one in the series converters. The transmission line will remain uninterrupted, and the flow of power through the line will not be affected. Serious problem arises for the period of the open circuit failure, when an open circuit occurs in the series converter the transmission line will also exhibits open circuit and hence the power flow through the line gets interrupted. In order to overcome this type of failure, every series converters is provided with a bypass circuit. A parallel connection is established between the crowbar and the output terminals of the series converter. Crowbar acts like a switch under normal operating conditions it acts like open switch , during open circuit condition it is connected to the converter and offers bypass for the transmission line. Consequently the series converter which is failed is seen as a short circuit in the transmission line due to this failure, an unbalanced voltage is injected between the phases. Due to this unbalanced voltage the current flowing through the transmission line also becomes unbalanced and finally the quality of the power gets reduced. Assuming that the DPFC is positioned within a transmission network with two ports, as depicted in Figure 1. let V_s and V_r be the sending and receiving end voltages. 1In the case where the voltage supplied by each series converter is denoted as Vse and the quantity of series converters per phase is n, then. The failure of the series converters in phase a is indicated by:

$$V_{se} = \begin{bmatrix} \frac{n-k}{n} V_{se}, a \\ V_{se}, b \\ V_{se}, c \end{bmatrix} \tag{2}$$

Sequence analysis reveals that unbalanced series voltage is determined by:

$$V_{se} = \begin{bmatrix} {V_{se}}^{+} \\ {V_{se}}^{-} \\ {V_{se}}^{0} \end{bmatrix} \tag{3}$$

The relation between V_{se}^{-} ,V_{se}^{0} for number of failure converter is given as:

$$v_{se}^{-} + v_{se}^{0} = \frac{k}{n} v_{se} \tag{4}$$

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Hence, the distorted line current at the fundamental frequency resulting from the malfunction of the series converter is:

$$\begin{bmatrix} i_l^+ \\ i_l^- \\ i_l^+ \end{bmatrix} = \begin{bmatrix} 1/Z_l^+ & 0 & 0 \\ 0 & 1/Z_l^- & 0 \\ 0 & 0 & 1/Z_l^0 \end{bmatrix} \begin{bmatrix} V_s - V_{sr} + V_{se}^+ \\ V_{se}^- \\ V_{se}^0 \end{bmatrix} \tag{5}$$

The magnitude of line currents mainly depend upon the zero and negative sequences because these currents consists of both these components during the series converter failure .The failure in series converter not only manipulate the frequency of third harmonic but also it causes change in the current that flows through the line .There is no need of supplying real power to the damaged converter, as a result the fundamental real power which flows in between the phases will be altered, due to this there will be a modification in third harmonic current. To come across the third harmonic current in every phase, the corresponding arrangement of the DPFC at the third harmonic is needed, as shown Fig.3.consider a fixed third harmonic current component I_3 which is supplied from the shunt converter. Series converters can either supply or absorb the real power under third harmonic frequency, so under this condition they operate in the same way as the variable resistors.

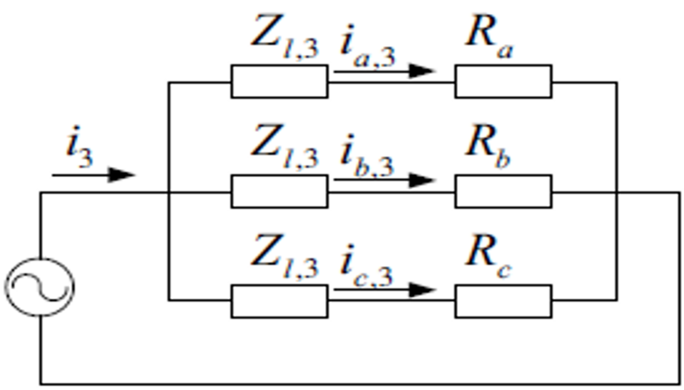

Fig.3. The 3rd harmonic arrangement of a DPFC.

Hence the series converters at third harmonic are schematically shown as the resistances $[R_aR_bR_c]$.The power which is absorbed by the resistors $[P_{se}]$ is shown in the below equation:

$$P_{se} = \mathrm{Re}(V_{se}\, i_l) \tag{6}$$

4. Control Scheme to Improve the Performance

The main theory of the auxiliary control is based on, balancing the voltages between the phases by injecting the more voltages into the line through the remaining converters. Mainly there are two needs of the auxiliary control they are:

- To give the accurate reference voltage, the Series converter must have the capacity to differentiate the phases with the defective converter.

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- The communication channel of the central control must not depend upon the series converters because to supply more amount of voltages from the remaining phases of the converter.

Based on the number of energized converters the reference signals are supplied to every phase through the series converter. But mainly there are two disadvantages associated with this technique. The first reason is this technique mainly based on the communication channel that exists between the series converter and central control .If a few fake reports are given it will cause inaccurate compensation. The second reason is, the series converter which is failed is not completely short circuited there is a presence of small amount of inductance that is generated through the single-turn transformer. This inductance cannot be eliminated through this technique.

An appropriate control scheme is designed to prevail over the problems occurred during the failure of the series converter. If a single series converter is failed it will cause the flow of unsymmetrical currents throughout the system. This failure can be overcome by monitoring the zero and negative sequence currents. For this reason, two auxiliary controllers are placed in the central control to monitor both the negative and zero sequence currents .Auxiliary controllers includes two current control loops which are added to the existing distributed power flow controller. The diagram illustrating the control scheme of the central controller, along with the Auxiliary controllers, can be seen in Figure 4. Firstly the 3phase line currents are determined through the sequence analyzer. There are three symmetrical current components. Power flow can be controlled by positive sequence current component. Remaining two currents are used in eliminating the failures that occur in series converter.

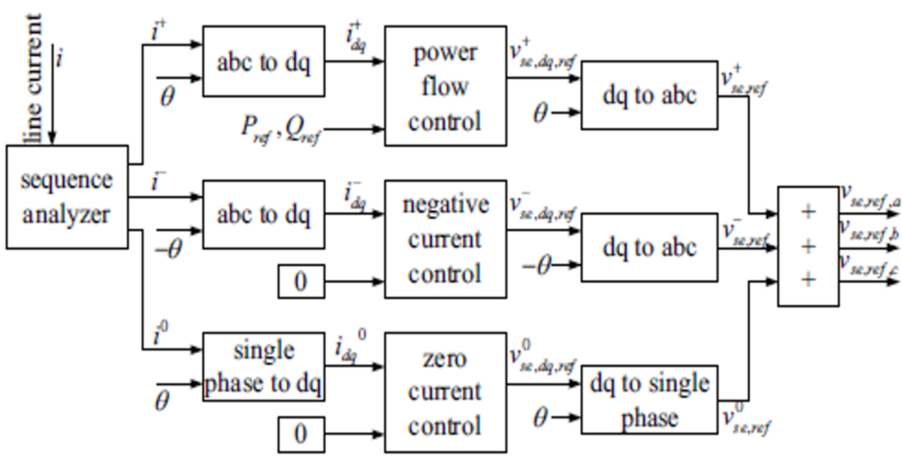

Fig.4: Control of converter to compensate unbalance effect.

Two current controllers are utilized to ensure that both zero and negative sequence currents are driven to zero in the event of converter failure. The reference signals for the converters are constructed by adding the voltages produced by the controllers to the positive sequence voltage component.

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5. Design of DPFC Controller

A conventional method for current control synchronous PI control method is in use for controlling negative and zero components [4]. The design is to alter the fixed alternating voltages and currents into a rotating reference frame, here the currents which are monitored by the controllers are maintained constant throughout the steady-state period. The outputs generated from the controls are again fed back to the fixed reference frame. Park Transformation technique is utilized for evaluating the symmetrical components [5] [6] [7]. Conventional method is used for determining the negative sequence currents and single-phase Transformation is used for computing the zero sequence components. Both the transformation methods make use of the bus voltages. The construction of negative and zero sequence circuits is analogous with the Distributed power flow controller circuit. The easier way to represent the negative and zero sequence circuits with the Distributed power flow controller is by substituting the ideal voltage sources in place of Distributed power flow controller series converter as shown in Fig.5.

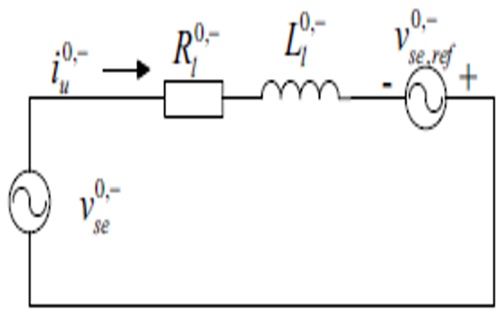

Fig.5. Sampled negative and zero sequence network.

Where $V_{se}^{0,-}$ be the unequal voltages that are associated with the zero and negative sequences these voltages are generated by the Distributed power flow controller. I is the unequal current that flows through the line. The correlation among current and voltages is given by dq transformation as.

$$v_{se,d,ref}^{0,-} = R_l^{0,-} i_{u,d}^{0,-} + L_l^{0,-} \frac{di_{u,d}^{0,-}}{dt} - \omega L_l^{0,-} i_{u,d}^{0,-} - v_{se,d}^{0,-} \quad (7)$$

$$v_{se,d,ref}^{0,-} = R_l^{0,-} i_{u,d}^{0,-} + L_l^{0,-} \frac{di_{u,d}^{0,-}}{dt} + \omega L_l^{0,-} i_{u,d}^{0,-} - v_{se,d}^{0,-}$$

Unequal voltages and currents are treated as disturbances, the transfer function for the d- axis and q-axis components is given from the $V^{0,-}{}_{se,ref}$ to current $i_l^{0,-}$, relationship is given by;

$$G(S) = \frac{1}{R_l^{0,-} + sL_l^{0,-}} \quad (8)$$

The parameters related to current control are evaluated using internal control model (ICM) technique [8] [9]. To eliminate the disturbances such as unequal voltages and currents in every control loop, extra inner feedback loops are added to the system. The controller function $F(s)$ is determined using internal control model (ICM) technique as follows;

$$F_d^{0,-}(s) = \propto_d^{0,-} L_l^{0,-} + \propto_d^{0,-} \left(R_l^{0,-} + R_d^{0,-}\right)/_s \quad (9)$$

$$F_q^{0,-}(s) = \propto_d^{0,-} L_l^{0,-} + \propto_d^{0,-} \left(R_l^{0,-} + R_d^{0,-}\right)/_s$$

From the above equation (8) α_q and α_d be the bandwidths which are related to q and d components. An appropriate design for the active damping must have the similar time constant as that of the control loop, consequently the active conductance for every control loop is determined as follows:

$$R_d^{0,-} = \propto_d^{0,-} L_l^{0,-} - R_l^{0,-} \quad (10)$$

$$R_q^{0,-} = \propto_q^{0,-} L_l^{0,-} - R_l^{0,-}$$

6. Simulation Results

By using the MATLAB/Simulink the simulation results are obtained. A fixed voltage source is connected to the each transformer at the two sides of the infinite bus and this DPFC system is tested in a two-bus system. A voltage of 0.012 p.u is generated by each series converter at fundamental frequency. At t=1s, a series converter is manually short circuited, and the system's response with and without the complementary controller is provided. The 3-phase current at the fundamental frequency at voltages and currents delta side of the transformer as shown in Fig.(7),(8),(9). When the converter is failure the 3-phase system without the controller becomes unsymmetrical as shown Fig.10.

The phase difference caused by the series converter failure is effectively compensated by the complementary controller. In the event that a fault occurs in phase a of a single series converter, the control signal for phase a must be doubled compared to when there is no fault. The control signals for the remaining phases must remain unchanged. This adjustment is made possible by implementing a DPFC controller to enhance both active and reactive power, as illustrated in Figure 11.

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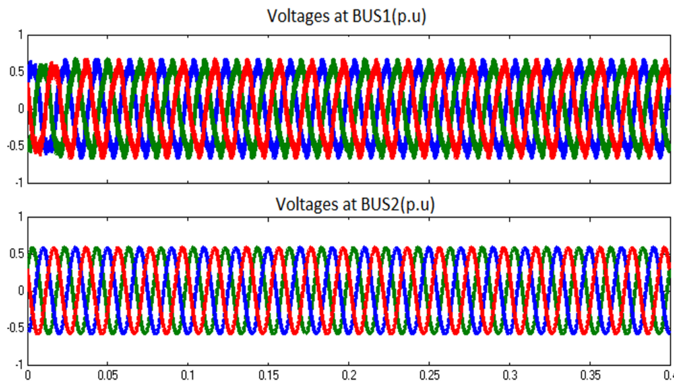

Fig.7. 3-phase voltages with DPFC at bus1 and bus2.

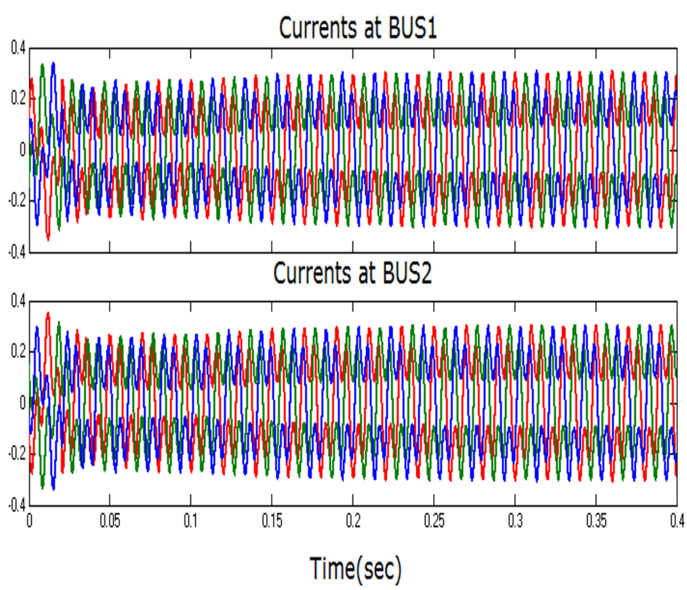

Fig.8. 3-phase currents with DPFC at bus1 and bus2.

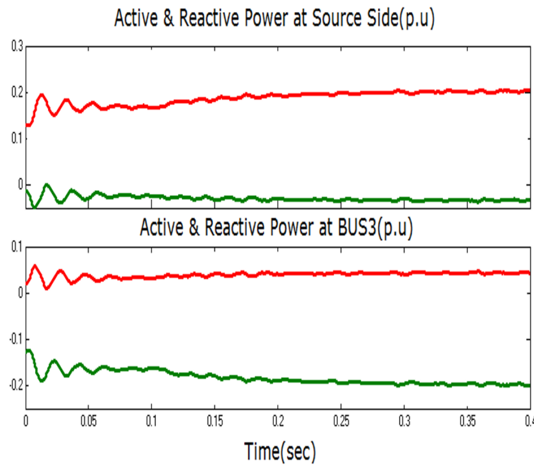

Fig.9. Active & Reactive power under failure of converters.

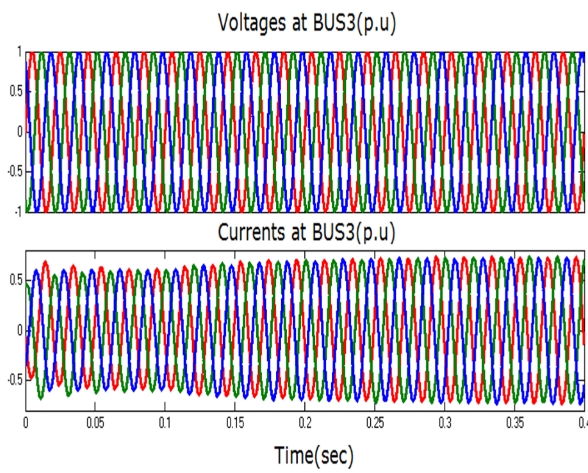

Fig.10. 3-phase voltage and current with DPFC at bus3.

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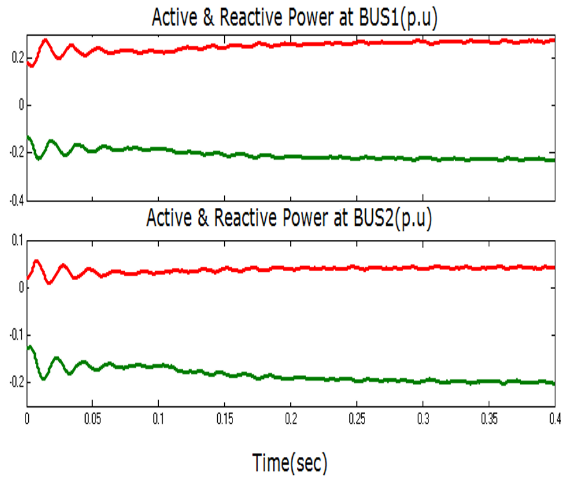

Fig.11. Active & Reactive power with DPFC converter.

7. Conclusion

This paper examines the performance of a distributed power flow controller during the failure of a single series device unit for a specific period. The converter which is damaged is represented as a short circuit in the transmission line, due to this unequal voltages are introduced among the phases and also this failure not only manipulate the frequency of third harmonic but also it causes change in the current that flows through the line. An appropriate control scheme is designed to prevail over the problems occurred during the failure of the series device. This failure can be overcome by monitoring the zero and negative sequence currents. For this reason, two auxiliary controllers are used to force the zero and negative sequence currents to zero. The analysis of active power, reactive power, grid voltages, and currents has been conducted, and a suitable control scheme has been simulated using MATLAB/Simulink.

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