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POWER-FLOW CONTROL IN TRANSMISSION SYSTEM BY USING DISTRIBUTED POWER-FLOW CONTROLLER (DPFC)

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Abstract - Nowadays, the increase in the usage of non-linear loads especially the power electronic equipments leads to deterioration of the quality of voltage waveforms at the point of common coupling (PCC) of various consumers to improve the waveform various power flow controlling devices are available. Power flow is controlled by adjusting the parameters of a system, such as voltage magnitude, line impedance and transmission angle. One of the DPFC is UPFC. DPFC is obtained from UPFC. This is to use multiple small-size single-phase converters instead of the one large-size three-phase series converter in the UPFC. The large number of series converters provides redundancy, thereby increasing the system reliability. As the D-FACTS converters are single-phase and floating with respect to the ground, there is no high-voltage isolation required between the phases.

Index Terms - AC-DC power conversion, load flow control, power system control, power-transmission control.

I. INTRODUCTION

An increasing demand for high quality, reliable electrical power and increasing number of distorting loads may leads to an increased awareness of power quality both by customers and utilities. The most common power quality problems today are voltage sags, harmonic distortion and low power factor. The development of power electronics devices such as Flexible AC Transmission System (FACTS) [1] and customs power devices have introduced and emerging branch of technology providing the power system with versatile new control capabilities. There are different ways to enhance power quality problems in transmission and distribution systems. Unified Power Flow Controller (UPFC) [2] is considered to be the most versatile FACTS controller with all encompassing capabilities of voltage regulation, series compensation and phase shifting. It can independently and rapidly control both real and reactive power flows in the transmission line. UPFC has shunt and series controllers [3]. The basic function of the shunt converter is to supply or absorb the active power demanded by the series converter. The shunt converter controls the voltage of the DC capacitor by absorbing or generating active power from the bus, therefore it acts as asynchronous source in parallel with the system.

After studying the failure mode of the combined FACTS devices, it is found that a common DC link between converters reduces the reliability of a device, because a failure in one converter will pervade the whole device though the DC link. By eliminating this DC link, the converters within the FACTS devices are operated independently, thereby increasing their reliability.

By applying the two approaches eliminating the common DC link and distributing the series converter, the UPFC is further developed into a new combined FACTS device: the Distributed Power Flow Controller (DPFC), Similar as the UPFC, the DPFC consists of shunt and series connected converters. The shunt converter is similar as a STATCOM [4], while the series converter employs the DSSC concept, which is to use multiple single-phase converters instead of one three-phase converter. Each converter within the DPFC[5] is independent and has its own DC capacitor to provide the required DC voltage.

II. DISTRIBUTED POWER-FLOW CONTROLLER (DPFC)

By introducing the two approaches outlined in the previous section (elimination of the common DC link and distribution of the series converter) into the UPFC, the DPFC is achieved. Similar as the UPFC, the DPFC consists of shunt and series connected converters. The shunt converter is similar as a STATCOM, while the series converter employs the SSSC [6] concept, which is to use multiple single-phase converters instead of one three-phase converter. 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.no.1

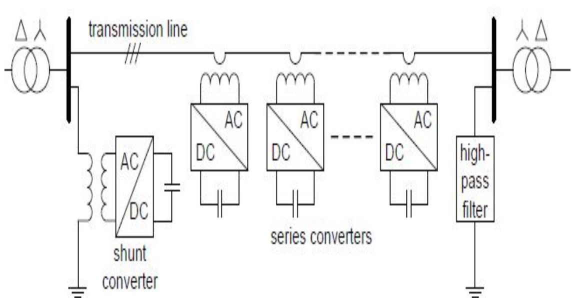


Fig.no1. DPFC configuration.

As shown in Fig. no. 1, besides the key components - shunt and series converters, a DPFC also requires a high pass filter that is shunt connected to the other side of the transmission line and a Y-Δ transformer on each side of the line. The reason for these extra components will be explained later. The unique control capability of the UPFC is given by the back-to-back connection between the shunt and series converters, which allows the active power to freely exchange. To ensure the DPFC has the same control capability as the UPFC, a method that allows active power exchange between converters with an eliminated DC link is required.

III. DPFC OPERATING PRINCIPLE

A. 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. Since the integrals of all the cross product of terms with different frequencies are zero, the active power can be expressed by:

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

where *V*i and *I*i are the voltage and current at the *i*th harmonic frequency respectively, and is the corresponding angle between the voltage and current. Above Equation 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. By applying this method to the DPFC, the shunt converter can absorb active power from the grid at the fundamental frequency and inject the power back at a harmonic frequency. This harmonic active power flows through a transmission line equipped with series converters. According to the amount of required active power at the fundamental frequency, the DPFC series converters generate a voltage at the harmonic frequency, thereby absorbing the active power from harmonic components. Neglecting losses, the active power generated at the fundamental frequency is equal to the power absorbed at the harmonic frequency. For a better understanding, Fig.no.1 indicates how the active power is exchanged between the shunt and the series converters in the DPFC system. 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.

B. Using third harmonic components

Due to the unique features of 3rd harmonic frequency components in a three-phase sys-tem, the 3rd harmonic is selected for active power exchange in the DPFC. In a three-phase system, the 3rd harmonic in each phase is identical, which means they are 'zero-sequence components

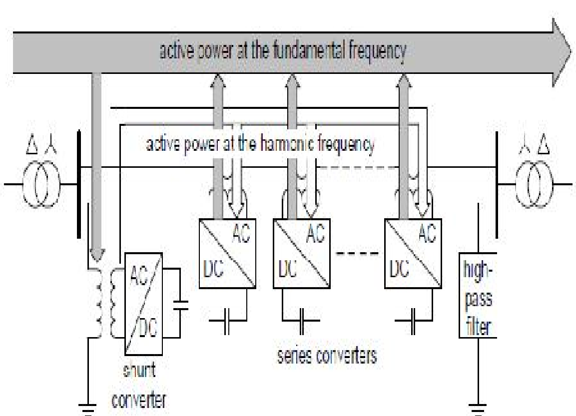


Fig.no.2. Active power exchange between DPFC converters

Because the zero-sequence harmonic can be naturally blocked by Y-Δ trans-formers and these are widely incorporated in power systems (as a means of changing voltage), there is no extra filter required to prevent harmonic leakage. As introduced above, a high-pass filter is required to make a closed loop for the harmonic current and the cutoff frequency of this filter is approximately the fundamental frequency. Because the voltage isolation is high and the harmonic frequency is close to the cutoff frequency, the filter will be costly. By using the zero-sequence harmonic, the costly filter can be replaced by a cable that connects the neutral point of the Y-Δ trans-former on the right side in Fig. no. 2 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 as shown in Figure 3 Therefore, the large high-pass filter is eliminated.

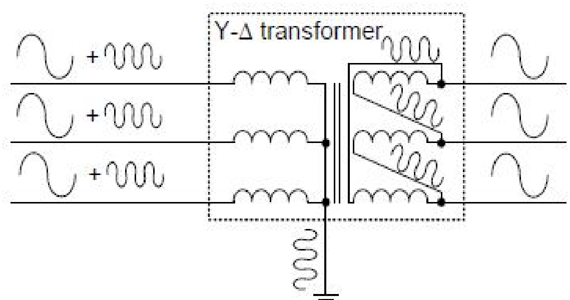


Fig.no.3. Utilize grounded Y-Δ transformer to provide the path for the zero sequence third harmonic.

Another advantage of using the 3rd harmonic to exchange active power is that the grounding of the Y-Δ transformers can be used to route the harmonic current in a meshed network. If the network requires the harmonic current to flow through a specific branch, the neutral point of the Y-Δ transformer in that branch, at the side opposite to the shunt converter, will be grounded and vice versa. Fig. no. 4 shows a simple example of routing the harmonic current by using the grounding of the Y-Δ transformer.

Because the floating neutral point is located on the transformer of the line without the series converter, it is an open-circuit for 3rd harmonic components and therefore no 3rd harmonic current will flow through this line.

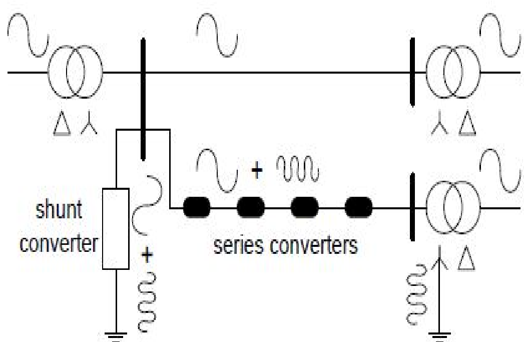


Fig.no.4. Route the harmonic current by using the grounding status of the Y–Δ transformer.

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. The relationship between the exchanged active power at the *i*th harmonic frequency Pi and the voltages generated by the converters is expressed by the well known the power flow equation and given as

$$P = \frac{|Vsh||Ese|}{X}\cos(\phi sh - \phi se) \qquad (2)$$

Where X is the line impedance at ith frequency, |Vsh| and |Vse| are the voltage magni-tudes of the ith harmonic of the shunt and series converters, and Øsh − Øse is the angle difference between the two voltages. As shown, the impedance of the line limits the active power exchange capacity. To exchange the same amount of active power, the line with high impedance requires higher voltages. Because the transmission line impedance is mostly inductive and proportional to frequency, high transmission frequencies will cause high impedance and result in high voltage within converters. Consequently, the zero-sequence harmonic with the lowest frequency the 3rd harmonic has been selected.

C. DPFC Advantages

The DPFC inherits all the advantages of the UPFC and the D-FACTS, which are as follows.

1) High control capability:

Control the transmission angle and bus voltage elimination of common dc link enables separated installation of the DPFC converters

2) High Reliability:

Failure at one place will not influence the other converters [7].

3) Low cost:

There is no phase-to-phase voltage isolation required by the series converter. Also the power rating of each converter is small and can be easily produced in series production lines.

IV. ANALYSIS OF THE DPFC

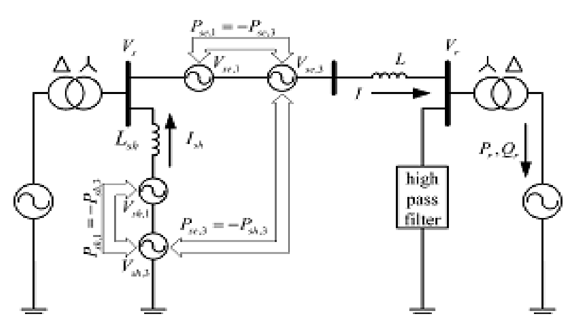


Fig.no.5. DPFC Simplified representation.

In this section, the steady-state behavior of the DPFC is analyzed, and the control capability of the DPFC is expressed in the parameters of the network and the DPFC. To simplify the DPFC, the converters are replaced by controllable voltage sources in series with impedance. Since each converter generates the voltage at two different frequencies, it is represented by two series-connected controllable voltage sources, one at the fundamental frequency and the other at the third-harmonic frequency. Assuming that the converters and the transmission line are lossless, the total active power generated by the two frequency voltage sources will be zero. The multiple series converters are simplified as one large converter with the voltage, which is equal to the sum of the voltages for all series converter, as shown in Fig. 5, in Fig 5 the DPFC is placed in a two-bus system with the sending-end and the receiving-end voltages Vs and Vr, respectively. The transmission line is represented by an inductance with the line current I. The voltage injected by all the DPFC series converters is Vse,1 and Vse,3 at the fundamental and the third-harmonic frequency, respectively. The shunt converter is connected to the sending bus through the inductor Lsh and generates the voltageVsh,1 andVsh,3; the current injected by the shunt converter is Ish. The active and reactive power flow at the receiving end is P_r and Q_r, respectively. This representation consists of both the fundamental and third-harmonic frequency components. Based on the superposition theorem, the circuit in Fig.5 can be further simplified by being split 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 Fig.no.6.

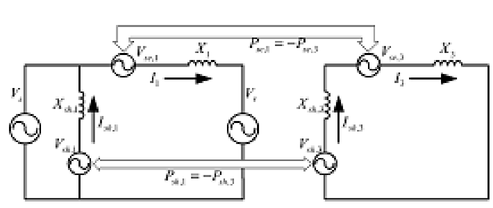


Fig.no.6. DPFC equivalent circuit (a) Fundamental frequency (b) Third-harmonic frequency.

The power-flow control capability of the DPFC can be illustrated by the active power *P*r and reactive power *Q*r received at the receiving end. Because the DPFC circuit at the fundamental frequency behaves the same as the UPFC, the active and reactive power flow can be expressed as follows:

$$(P_r - P_{r0})^2 + (Q_r - Q_{r0})^2 = \left(\frac{|V||V_{se,1}|}{X_1}\right)^2 \quad (3)$$

Where P_{r0}, Q_{r0} , and θ are the active, reactive power flow, and the transmission angle of the uncompensated system,Xse,1 =ωLse is the line impedance at fundamental frequency, and |V| is the voltage magnitude at both ends. In the PQ-plane, the locus of the power flow without the DPFC compensation f(Pr0,Qr0) is a circle with the radius of|V|2/|X1| around the center defined by coordinates P=0andQ=|V|2/|X1|. Each point of this circle gives thePr0 andQr0 values of the uncompensated system 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 voltageVse,1 with its maximum magnitude.

V. DPFC CONTROL

To control the multiple converters, DPFC consists of three types of controllers; they are central controller, shunt control, and series control, as shown in Fig. 7. The shunt and series control are local controllers and are responsible for maintaining their own converters' parameters. The central control takes account of the DPFC functions at the power-system level. The function of each controller is listed next.

A. Central Control

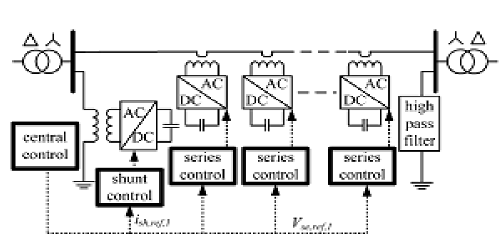


Fig.no.7. DPFC control block diagram.

The central control generates the reference signals for both the shunt and series converters of the DPFC. It is focused on the DPFC tasks at the power-system level, such as power-flow control, low-frequency power oscillation damping, and balancing of asymmetrical components. According to the system requirement, the central control gives corresponding voltage-reference signals for the series converters and reactive current signal for the shunt converter. All the reference signals generated by the central control are at the fundamental frequency.

B. Series Control

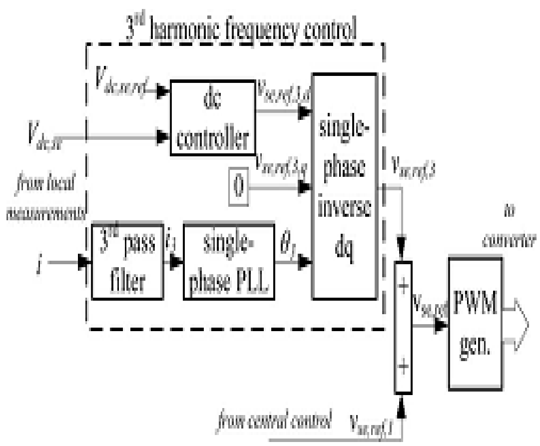


Fig.no.8. Block diagram of the series converter control.

Each series converter has its own series control. The controller is used to maintain the capacitor dc voltage of its own converter by using the third-harmonic frequency components and to generate series voltage at the fundamental frequency that is prescribed by the central control.

C. Shunt Control

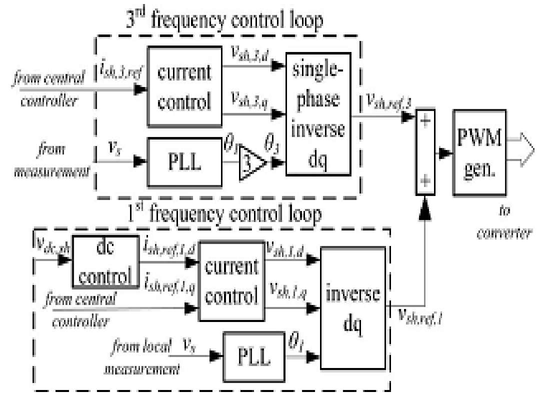
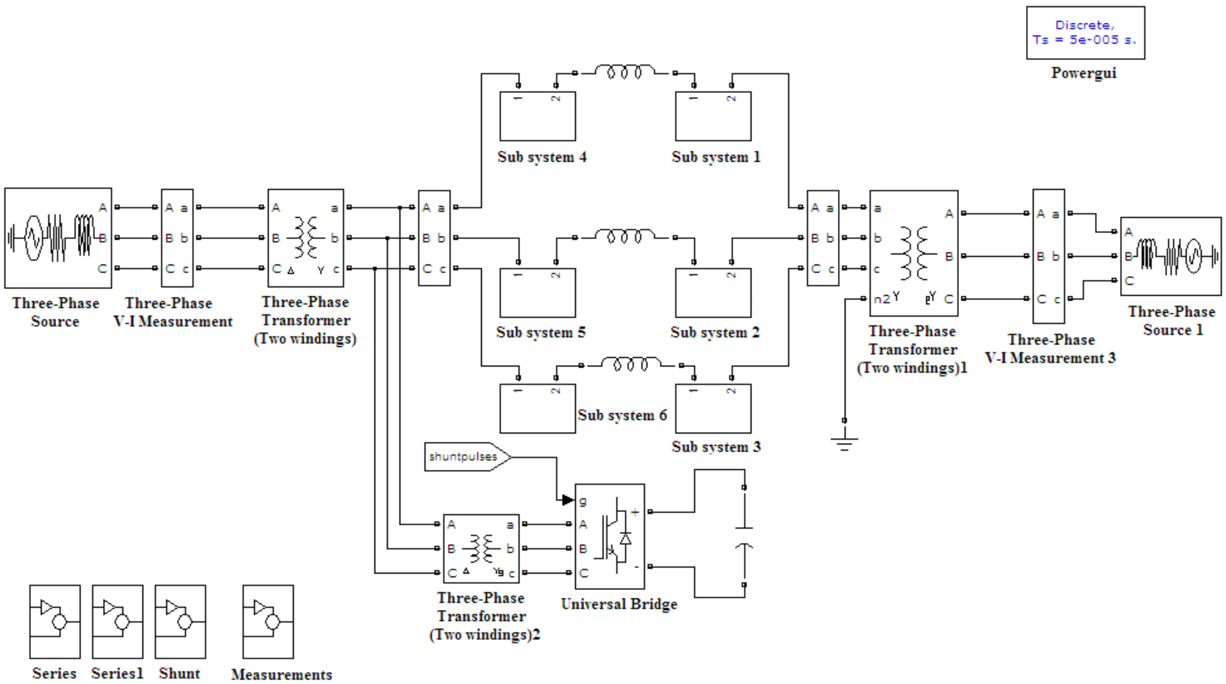


Fig.no.9. Block diagram of the shunt converter control.

The block diagram of the shunt converter control is shown in Fig.no.9. The objective of the shunt control is to inject a constant third harmonic current into the line to provide active power for the series converters. The third-harmonic current is locked with the bus voltage at the fundamental frequency. A PLL [8] is used to capture the bus-voltage frequency, and the output phase signal of the PLL is multiplied by three to create a virtual rotation reference frame for the third-harmonic component. The shunt converter's fundamental frequency control aims to inject a controllable reactive current to grid and to keep the capacitor dc voltage at a constant level. The control for the fundamental frequency components consists of two cascaded controllers. The current control is the inner control loop, which is to modulate the shunt current at the fundamental frequency. The q-component of the reference signal of the shunt converter is obtained from the central controller, and d-component is generated by the dc control.

VI. SIMULATION MODEL



VII. RESULTS

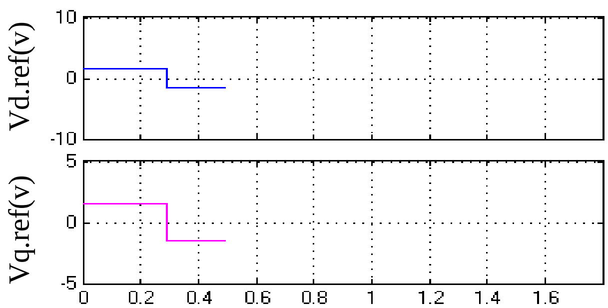


Fig.no.10.Reference voltage for the series converters.

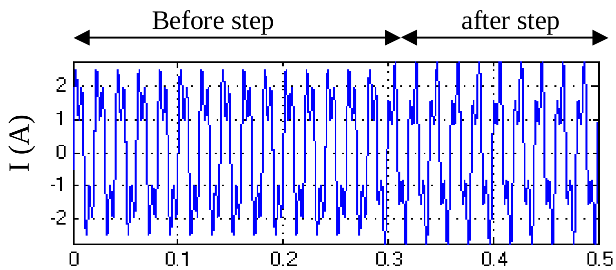


Fig.no.11. Step response of the DPFC: line current.

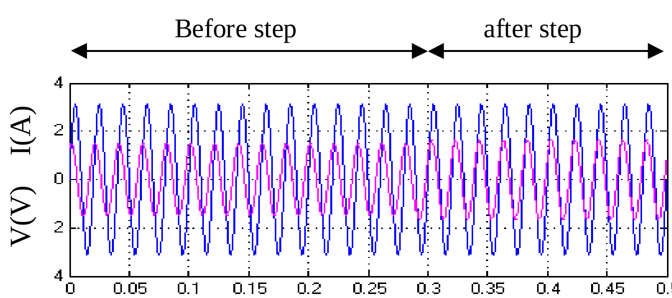


Fig.no.12. Step response of the DPFC: Bus voltage and current at the Δ side of the transformer.

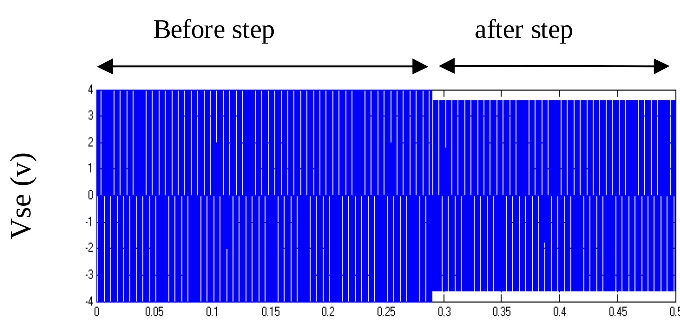


Fig.no.13. Step response of the DPFC: Series Converter voltage.

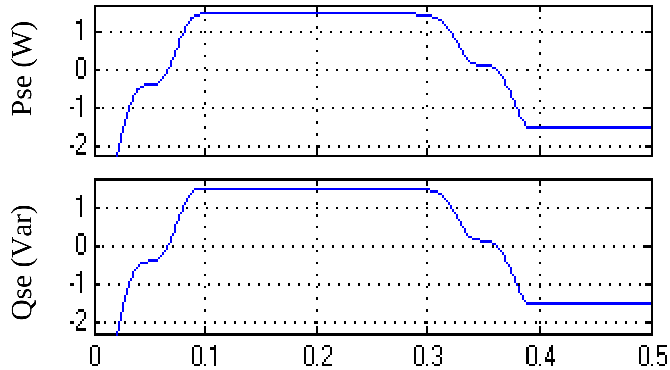


Fig.no.14. Active and reactive power injected by the series converter at the fundamental frequency.

VIII. CONCLUSION

To improve power quality in the power transmission system, there are some effective methods, using a new FACTS device called distributed power flow controller (DPFC) is presented. The DPFC structure is similar to unified power flow controller (UPFC) and has a same control capability to balance the line parameters, i.e., line impedance, transmission angle, and bus voltage magnitude. However, the DPFC offers some advantages, in comparison with UPFC, such as high control capability, high reliability, and low cost. The DPFC is modeled and three control loops, i.e., central controller, series control, and shunt control are design. The system under study is a single machine infinite-bus system, with and without DPFC. It is shown that the DPFC gives an acceptable performance in power quality mitigation and power flow.

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