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Distributed Power Flow Controller (DPFC) : A FACTS Device

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Abstract *— Distributed Power Flow Controller (DPFC) is a new concept in FACTS Technology. It is derived from UPFC by eliminating DC link between the shunt and series converter. It has the same control capability of controlling all the system parameters as that of UPFC and its series converter is distributed over the transmission line which is distributed static series converter which is single phase converter. It is highly reliable, higher controllability and low cost as compared to UPFC. It employs two converters i.e. series and shunt converter and each converter needs a controlling circuit and an additional central controlling circuit which provides reference voltage to series and shunt controlling circuit. This paper gives an overview of controlling scheme of DPFC. The SRF method is used as control strategy for DPFC. The simulation is carried out in MATLAB SIMULINK.*

Keywords— *UPFC, DPFC, SRF method, Voltage sag.*

I. INTRODUCTION

The Flexible AC-Transmission System (FACTS) that is defined by IEEE as “A power-electronic based system and other static equipment that provide control of one or more ac-transmission system parameters to enhance controllability and increase power-transfer capability”, and can be utilized for power-flow control [1].

At present, the Unified Power-Flow Controller (UPFC), is the most powerful FACTS device, which can simultaneously control all the parameters of the system i.e. the line impedance, the transmission angle, and bus voltage. The UPFC is the combination of a Static Synchronous Compensator (STATCOM) which is shunt converter and a Static Synchronous Series Compensator (SSSC) which is series converter, which are coupled via a common DC link, so that bidirectional flow of active power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM can take place. The converter in series with the line provides the main function of the UPFC by injecting a four-quadrant voltage with controllable magnitude and phase. The injected voltage essentially acts as a synchronous ac-voltage source, which is used to vary the transmission angle and line impedance, thereby independently controlling the active and reactive power flow through the line. The series voltage results in active and reactive power injection or absorption between the series converter and the transmission line. This reactive power is generated internally by the series converter (e.g., SSSC), and the active power is supplied by the shunt converter that is back-to-back connected. The shunt converter controls the voltage of the dc capacitor by absorbing or generating active power from the bus; therefore, it acts as a synchronous source in parallel with the system. Similar to the STATCOM, the shunt converter can also provide reactive compensation for the bus [2].

The components of the UPFC handle the voltages and currents with high rating; therefore, the total cost of the system is high. Due to the common dc-link interconnection, a failure that happens at one converter will influence the whole system. To achieve the required reliability for power systems, bypass circuits and redundant backups (backup transformer, etc.) are needed, which on other hand, increase the cost. Accordingly, the UPFC has not been commercially used, even though; it has the most advanced control capabilities [2].

The new concept presented here called ‘Distributed Power Flow Controller (DPFC)’. It is a combined FACTS device, which has taken a UFPC as its starting point. The DPFC has the same control capability as the UPFC; independent adjustment of the line impedance, the transmission angle and the bus voltage. The DPFC eliminates the common DC link that is used to connect the shunt and series converter back-to- back within the UPFC. By employing the Distributed FACTS concept as the series converter of the DPFC, the cost is greatly reduced due to the small rating of the components in the series converters. Also, the reliability of the DPFC is improved because of the redundancy provided by the multiple series converters [2].

II. DISTRIBUTED POWER FLOW CONTROLLER

The failure mode of the combined FACTS devices is that a common DC link between converters reduces the reliability of a device, because a failure in one converter will affect 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 [3].

The elimination of the common DC link also allows the DSSC concept to be applied to series converters. In that case, the reliability of the new device is further improved due to the redundancy provided by the distributed series converters. In addition, series converter distribution reduces cost because no high-voltage isolation and high power rating components are required at the series part. 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) [3], as shown in Figure 2.1

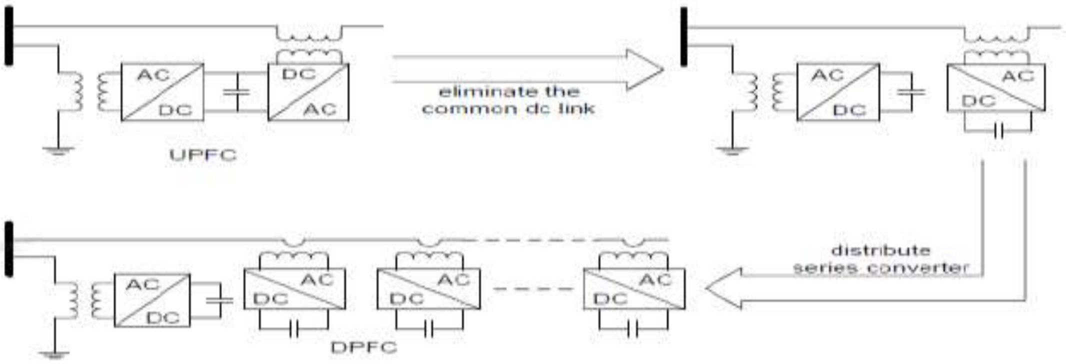

Fig. 2.1: UPFC to DPFC

III. OPERATING PRINCIPLE OF DPFC

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

$$P=\Sigma V_i I_i \cos\theta_i \infty i=1$$

where Vi and Ii are the voltage and current at the *i*th harmonic frequency respectively, and i is the corresponding angle between the voltage and current. The 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, Figure 3.1 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 [2][4].

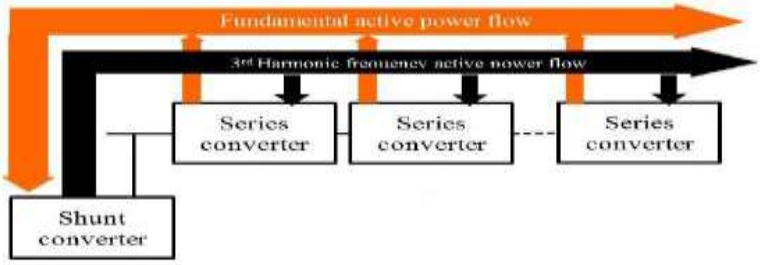

Fig. 3.1: Active power flow in DPFC

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. 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. 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 transformer on the right side 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. Therefore, the large high-pass filter is eliminated.

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. 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. 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 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 [2][4].

IV. CONTROL SCHEME OF DPFC

4.1 Shunt Converter of DPFC

In the DPFC, the shunt converter should be a relatively large three-phase converter that generates the voltage at the fundamental and 3rd harmonic frequency simultaneously. A conventional choice would be a three-leg, three-wire converter. However, the converter is an open circuit for the 3rd harmonic components and is therefore incapable of generating a 3rd harmonic component. Because of this, the shunt converter in a DPFC will require a different type of 3-phase converter. There are several 3-phase converter topologies that can generate 3rd harmonic frequency components, such as multi-leg, multi-wire converters or three single-phase converters. These solutions normally introduce more components, thereby increasing total cost. A new topology for the DPFC shunt converter is proposed. The topology utilizes the existing Y-Δ transformer to inject the 3rd harmonic current into the grid. A single- phase converter is connected between the transformer's neutral point and the ground, and injects a 3rd harmonic current into the neutral point of the transformer. This current evenly spreads into the 3-phase line through the transformer. The converter can be powered by an additional back-to-back converter connected to the low-voltage side of the transformer. The circuit scheme of this topology is shown in Figure 4.1.

For a symmetrical system, the voltage potential at the neutral point and fundamental frequency is zero. Accordingly, the single-phase converter only handles the 3rd harmonic voltages, which are much lower than the voltage at the fundamental frequency. As the single-phase converter is only used to provide active power for the series converter, the voltage and power rating are small. In addition, the single-phase converter uses the already present Y-Δ transformer as a grid connection. The single-phase converter is powered by another converter through a common DC link. In the case of the system with a three-phase converter, the single-phase converter can be directly connected back-to-back to the DC side of the three-phase converter, as shown in Figure 4.1.

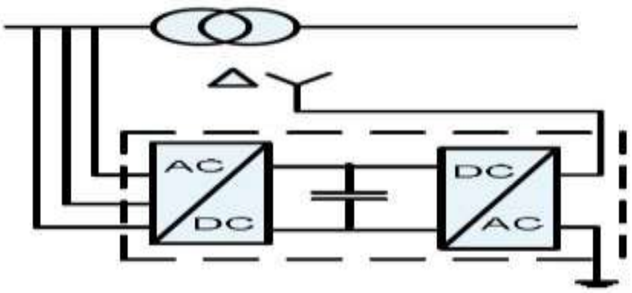

Fig. 4.1: Shunt converter of DPFC

4.1.1 Three Phase Converter of Shunt

The control of the shunt converter at the fundamental frequency aims to inject a controllable reactive current into the grid and to keep the DC voltage of the capacitor at a constant level. As shown in Figure 4.2, this control consists of two major blocks: the current control and the DC control. The current control is the inner control loop, which controls the current Ish,1. The reference of the q component of the current is from the central control and the reference signal of the d component is generated by the DC control. For Park's transformation, the rotation reference frame is created by the PLL using the bus voltage as input [10].

For DC control block- Neglecting losses

$$1/2 C_{sh} dV^2/dt = P_1 - P_3$$

For current control block

$$I_{sh,dc,1} = 3/2\,(V_{sh,1,d,ref}\, I_{sh,1,d} + V_{sh,1,q,ref}\, I_{sh,1,q})$$

Park's transformation is used here for conversion of stationary frame components to rotating frame i.e. abc to dq

$$V_{sh,1} = V_{ref,sh,1} * V_{sh,dc}$$

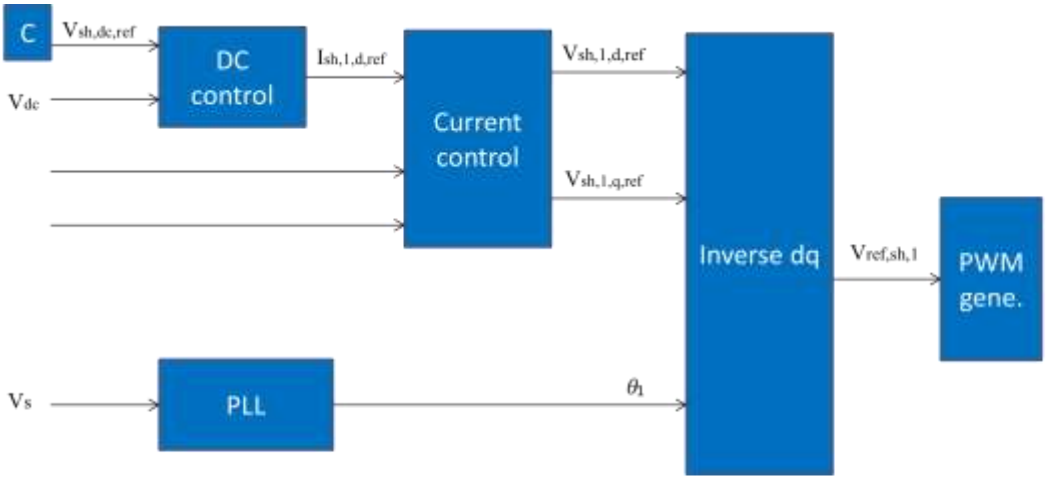

Fig. 4.2: Shunt controller for 3-ph converter

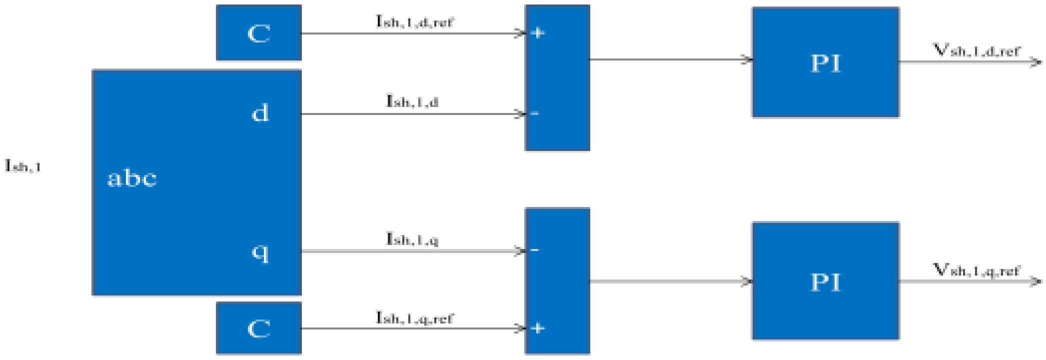

Fig. 4.3: Shunt current controller

4.1.2 Single Phase Converter of Shunt

The converter that is connected between the neutral point of the Y-Δ transformer and the ground is a single-phase converter. It is responsible for injecting a constant 3rd harmonic current into the grid, therefore requiring a current controller. The 3rd harmonic current is locked with the bus voltage at the fundamental frequency. A PLL is used to capture the bus voltage frequency, and the output signal of the PLL $\theta 1$ is multiplied by 3 to create a virtual rotation reference frame for the 3rd harmonic component [9].

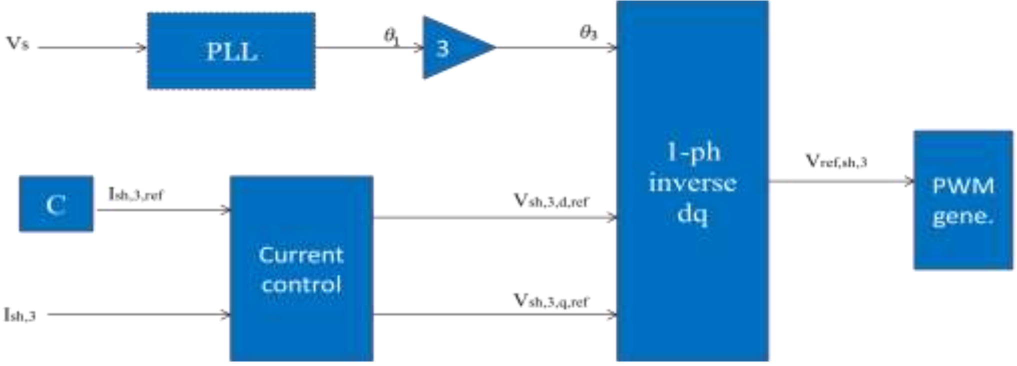

Fig. 4.4: Shunt controller of 1-ph converter

AC voltage can be written as:

$$V_{sh,3} = V_{ref,sh,3} * V_{sh,dc}$$

Single-phase Park's transformation for converting 3rd harmonic current to 3rd DC current is:

$$I_{sh,dc,3}=(V_{ref,sh,3,d} \sin 3\theta + V_{ref,sh,3,q} \cos 3\theta)*(I_{sh,3,d} \sin 3\theta + I_{sh,3,q} \cos 3\theta)$$

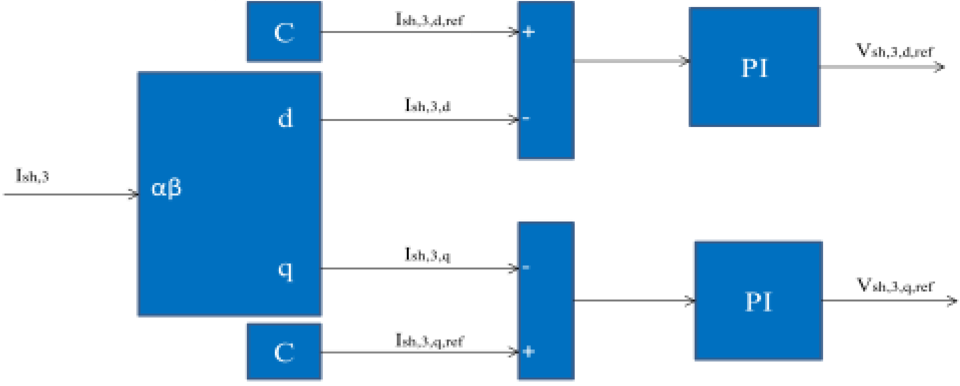

Fig. 4.5: Current controller block

4.2 Series Converter

Distributed static series compensator is nothing but SSSC with reduced power rating. Instead of high power conventional SSSC, numbers of low power DSSC modules are clamped around the conductor. Each DSSC module consists of small rated (~10 kVA) single phase inverter and a single turn transformer (STT) that is mechanically clamped on to existing transmission line. DSSC controls effective impedance of the transmission lines by injecting voltage in series with the line so as to control the active power flow [7].

Each DPFC series converter is locally controlled by its own controller, and the scheme for each series control is identical. To control the series converter, separate control loops are employed for the two frequency components. The 3rd harmonic control loop is used for DC voltage control.

The principle of the proposed method is to transform the control signal from AC quantities into DC quantities by using Park's transformation at the sending end and convert the received DC control signals back to AC locally, at each series converter. For the inverse transformation at the receiving end, the line current is used as the rotation reference frame, instead of the line-to-line voltage that is commonly used. The line current can easily be measured by the series converter locally without extra cost. A Single-phase Phase Lock Loop (PLL) is employed in each DPFC floating series converter to achieve the phase and frequency information of the grid. In this case, only the d and q information in DC quantities is transmitted to the converters. Together with the phase and frequency information from the line current, the signals in DC quantities can be transformed back into AC by the inverse Park's transformation. Because DC quantities are transmitted, the series converter can continue operation at the last received setting if the communication is lost [8].

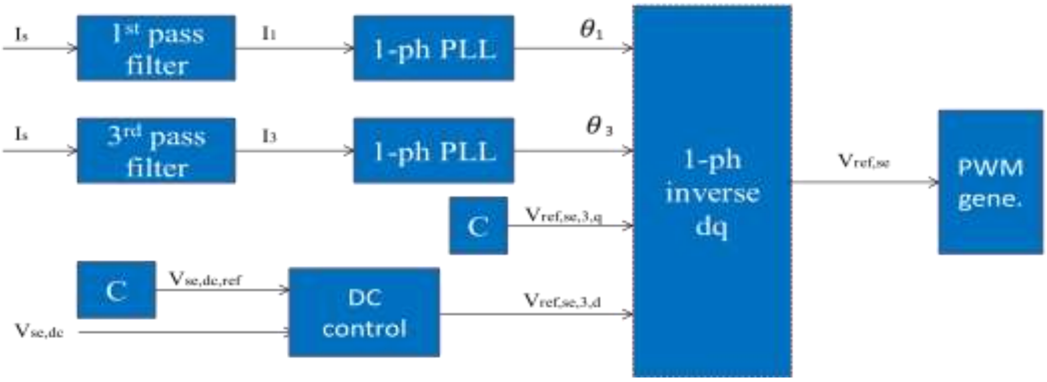

Fig. 4.6: Series controller

The 3rd harmonic frequency control is the major control loop with the DPFC series converter control. Its task is to maintain the DC capacitor voltage.

The principle of vector control is used here for DC voltage control. Normally, the voltage is used as the rotation reference frame for Park’s transformation, but here the 3rdharmonic current through the line is selected because it is easily measured by the series converter. As the line current contains two frequency components, a 3rd band pass filter is needed to extract the 3rd harmonic current. The single-phase Phase-Lock-Loop (PLL), creates a rotation reference frame from the 3rd harmonic current. The d component of the 3rd harmonic voltage is the parameter used to control the DC voltage. The control signal is generated by the DC voltage control loop. Because the q component of the 3rd harmonic voltage will only cause reactive power injection to the AC network, the q component is kept at zero during the operation [8].

V. SIMULATION AND RESULTS

In this section simulation analysis of DPFC is described. In this two converters are used i.e. shunt and series converter. The developed model of DPFC in MATLAB/SIMULINK environment is shown in Fig. 5.1. The shunt converter maintains the dc link voltage to reference value. While series converter compensates voltage related problems for maintaining required load voltage. Voltage sag is given for 0.1pu from 0.5 to 0.7.

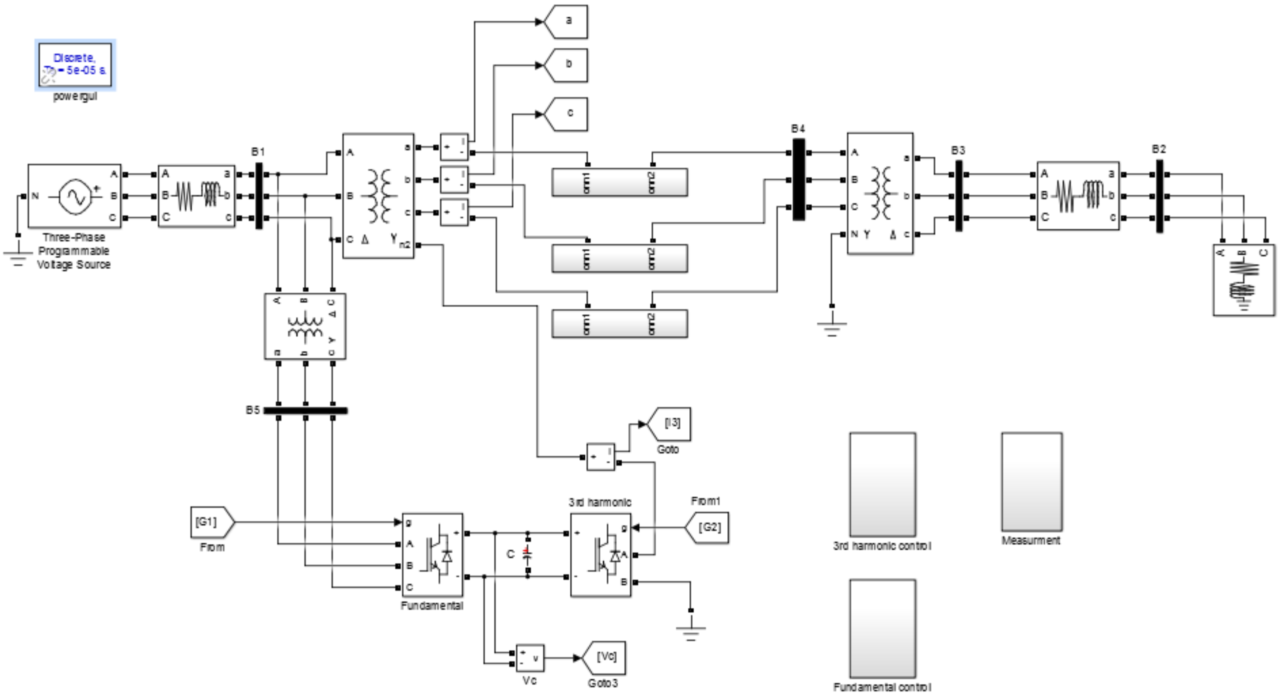

Fig. 5.1: Simulink model of DPFC

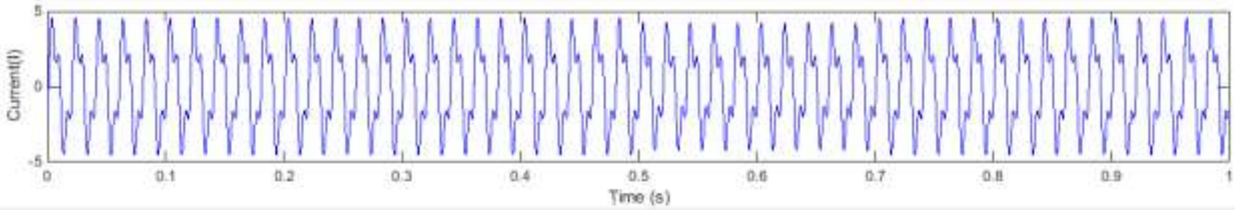

Fig. 5.2: Line current

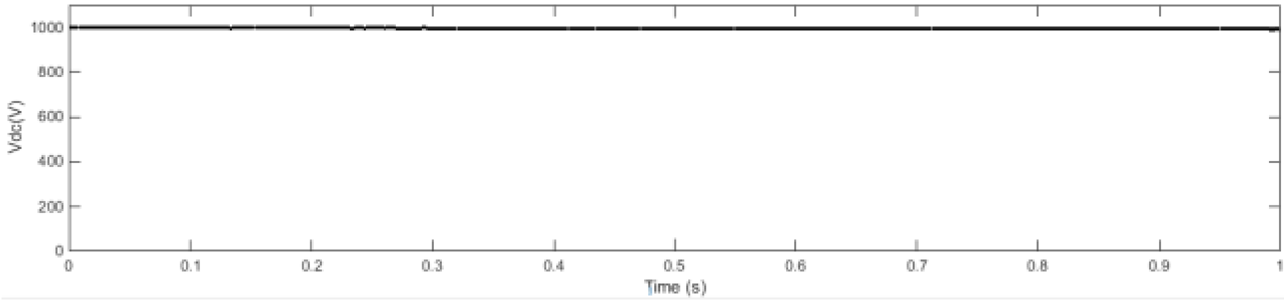

Fig. 5.3: Capacitor voltage

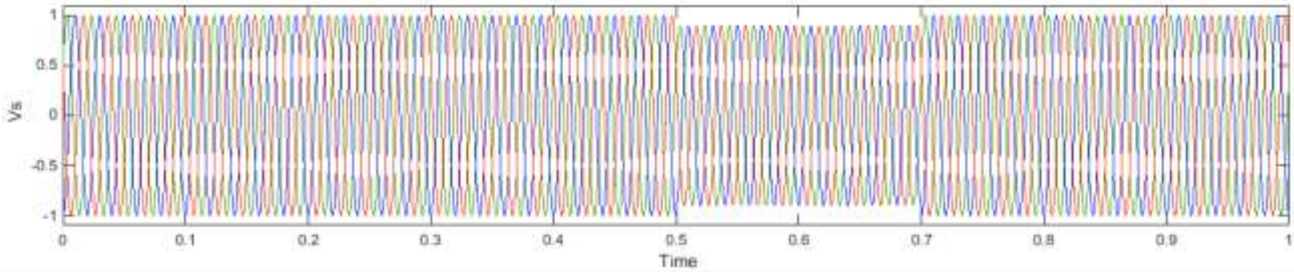

Fig. 5.4: Source voltage without DPFC

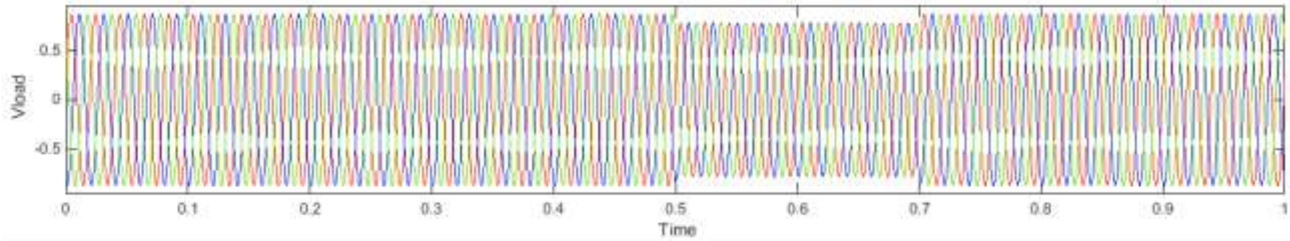

Fig. 5.5: Load voltage without DPFC

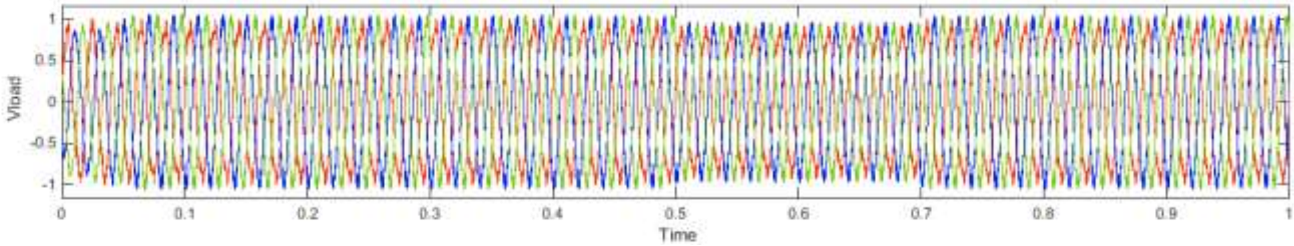

Fig. 5.6: Load voltage with DPFC

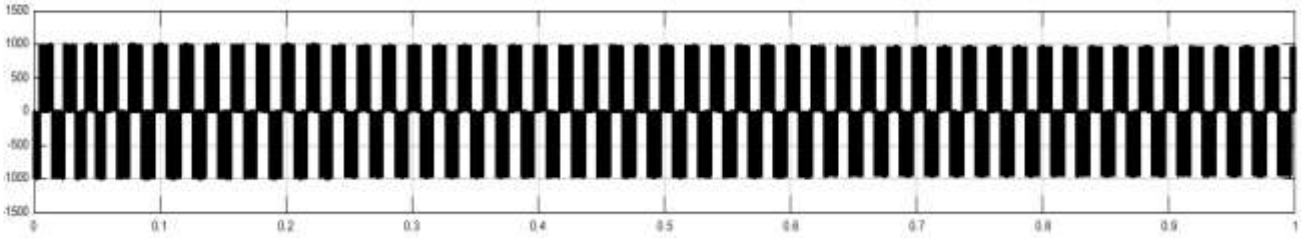

Fig. 5.6: Series converter voltage primary side of transformer

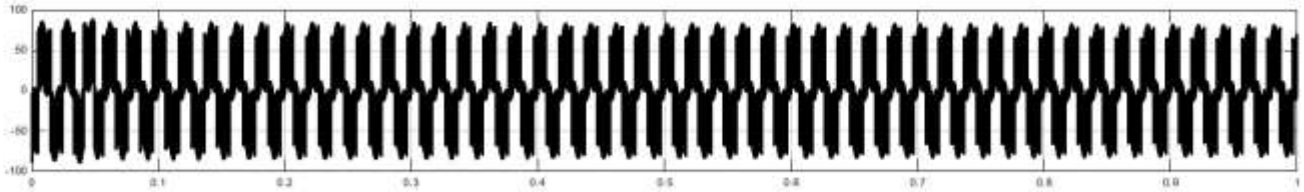

Fig. 5.7: Series converter voltage secondary side of transformer

VI. CONCLUSION

The control scheme of DPFC is studied and presented. The control scheme consists of individual control of each converter. The shunt converter is having a 3-phase and a single phase converter, the controlling scheme for each part of shunt converter is also presented. The series converter is single phase converter in each phase throughout the transmission line. The central control is only meant for supplying reference voltages to series and shunt converter. The DPFC model was developed and simulated in MATLAB/SIMULINK environment. It is observed that voltage sag is mitigated during 0.5s to 0.7s as voltage injected by the series converter.

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