Modelling Of Distributed Power Flow Controller (DPFC) Using Matlab/Simulation

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ABSTRACT - This work will present a new component within the flexible ac-transmission system (FACTS) family, called distributed power-flow controller (DPFC). The proposed DPFC will be derived from the unified power-flow controller (UPFC). The DPFC can be considered as a UPFC with an eliminated common dc link. The active power exchange between the shunt and series converters, which is through the common dc link in the UPFC, is now through the transmission lines at the third-harmonic frequency. The DPFC employs the distributed FACTS (D-FACTS) concept, which 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. Accordingly, the cost of the DPFC system is lower than the UPFC. The DPFC has the same control capability as the UPFC, which comprises the adjustment of the line impedance, the transmission angle, and the bus voltage. The principle and analysis of the DPFC will be presented in this work and the corresponding simulation results will be shown.

Keywords - AC/DC converters, power flow controller, third harmonic frequency, DPFC, power electronics, transmission line parameters control.

1. INTRODUCTION

The growing demand and the aging of networks make it desirable to control the power flow in power transmission systems fast and reliably [1]. 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 control. Currently, the unified power-flow controller (UPFC) shown in Fig. 1, is the most powerful

FACTS device, which can simultaneously control all the parameters of the
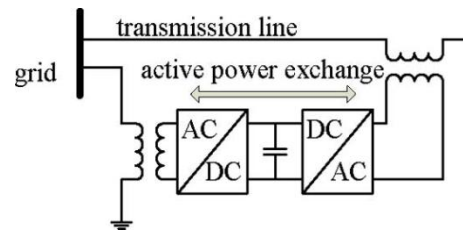
Fig. 1. Simplified representation of a UPFC

The UPFC is the combination of a static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC), which are coupled via a common dc link, to allow bidirectional flow of active power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM[4]. 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 (see e.g., SSSC[5]), 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. 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. This paper introduces a new concept, called distributed power-flow controller (DPFC) that is derived from the UPFC. The same as the UPFC, the DPFC is able to control all system parameters. The DPFC eliminates the common dc link between the shunt and series converters. 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
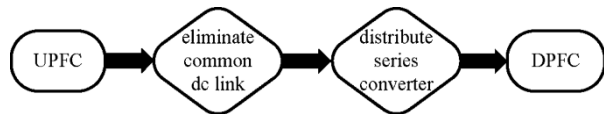

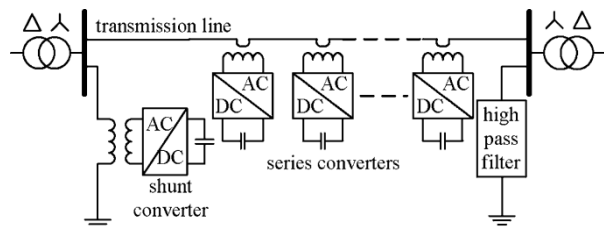**Fig. 2**. Flowchart from UPFC to DPFC

Fig. 3. DPFC configuration.

(D-FACTS) concept [6]. Comparing with the UPFC, the DPFC have two major advantages: 1) low cost because of the low-voltage isolation and the low component rating of the series converter and 2) high reliability because of the redundancy of the series converters. This paper begins with presenting the principle of the DPFC, followed by its steady-state analysis. After a short introduction of the DPFC control, the paper ends with the experimental results of the DPFC.

II. DPFC PRINCIPLE

Two approaches are applied to the UPFC to increase the reliability and to reduce the cost; they are as follows. First, eliminating the common dc link of the UPFC and second distributing the series converter, as shown in Fig. 2. By combining these two approaches, the new FACTS device—DPFC is achieved. The DPFC consists of one shunt and several series-connected converters. The shunt converter is similar as a STATCOM, while the series converter employs the D-FACTS concept, which is to use multiple single-phase converters instead of one large rated 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 Fig. 3. as shown, besides the key components, namely the shunt and series converters,

the DPFC also requires a high-pass filter that is shunt connected at the other side of the transmission line, and two Y−Δ transformers at 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 exchange freely. To ensure that the DPFC have the same control capability as the UPFC, a method that allows the exchange of active power between converters with eliminated dc link is the prerequisite

A. Eliminate DC Link

Within the DPFC, there is a common connection between the ac terminals of the shunt and the series converters, which is the transmission line. Therefore, it is possible to exchange the active
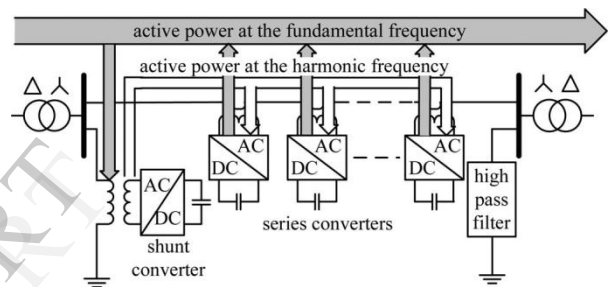


Fig. 4. Active power exchange between DPFC converter

power through the ac terminals of the converters. The method is based on the power theory of non-sinusoidal According to the Fourier analysis, a non-sinusoidal voltage and current can be expressed by 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

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

where V_i and I_i are the voltage and current at the ith harmonic frequency, respectively, and θ is the corresponding angle between the voltage and current. Equation (1) describes that the active power at different frequencies is isolated from each other and the voltage or current in one frequency has no influence on the active power at other frequencies. The independency of the active power at different frequencies gives the possibility that a converter without 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 current back into the grid at a harmonic frequency. This harmonic current will flow through the transmission line.

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. Assuming a lossless converter, the active power generated at fundamental frequency is equal to the power absorbed from the harmonic frequency. For a better understanding, Fig. 4 indicates how the active power exchanges between the shunt and the series converters in the DPFC system. The high-pass filter within the DPFC blocks the fundament 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 the closed loop for the harmonic current. Due to the unique characters of third-harmonic frequency components, the third harmonic is selected to exchange the active power in the DPFC. In a three-phase system, the third harmonic in each phase is identical, which is referred to as "zero-sequence".The zero-sequence harmonic can be naturally
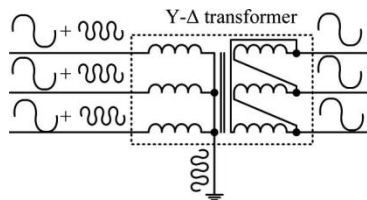
Fig.5. Utilize grounded Y−Δ transformer to provide the path for the zero sequence third harmonic.
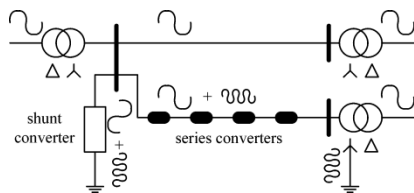
Fig. 6. Route the harmonic current by using the grounding status of the Y−Δ transformer.

blocked by Y−Δ transformers, which are widely used in power system to change voltage level. Therefore, there is no extra filter required to prevent the harmonic leakage to the rest of the network. In addition, by using the third harmonic, the costly high-pass filter, as shownin Fig. 4, can be replaced by a cable that is connected between the neutral point of the Y−Δ transformer on the right side in Fig. 3 and the ground. Because the Δ winding appears open

circuit to the third-harmonic current, all harmonic current will flow through the Y-winding and concentrate to the grounding cable, as shown in Fig. 5. Therefore, the large-size high-pass filter is eliminated. Another advantage of using third harmonic to exchange active power is that the way of grounding of Y−Δ transformers can be used to route the harmonic current in a meshed network. If the branch requires the harmonic current to flow through, the neutral point of the Y−Δ transformer at the other side in that branch will be grounded and vice versa. Fig. 6 demonstrates a simple example of routing the harmonic current by using a grounding Y−Δ transformer. Because the transformer of the line without the series converter is floating, it is open circuit for third-harmonic components. Therefore, no third-harmonic current will flow through this line. Theoretically, the third-, sixth-, and ninth-harmonic frequencies are all zero- sequence, and all can be used to exchange active power in the DPFC. As it is well known, the capacity of a transmission line to deliver power depends on its impedance. Since the transmission-line impedance is inductive and proportional to the frequency, high transmission frequencies will cause high impedance. Consequently, the zero-sequence harmonic with the lowest frequency—third harmonic is selected.

B. DPFC Advantages

The DPFC can be considered as a UPFC that employs the DFACTS concept and the concept of exchanging power through harmonic. Therefore, the DPFC inherits all the advantages of the UPFC and the D-FACTS, which are as follows.

1) High control capability. The DPFC can simultaneously control all the parameters of the power system: the line impedance, the transmission angle, and the bus voltage. The elimination of the common dc link enables separated installation of the DPFC converters. The shunt and series converters can be placed at the most effectively location. Due to the high control capability, the DPFC can also be used to improve the power quality and system stability, such as low-frequency power oscillation damping [8], voltage sag restoration, or balancing asymmetry.

2) High reliability. The redundancy of the series converter gives an improved reliability. In addition, the shunt and series converters are independent, and the failure at one place will not influence the other converters. When a failure occurs in the series converter, the converter will be short-circuited by bypass protection, thereby having little influence to the network. In the case of the shunt converter failure, the shunt converter will trip and the series

converter will stop providing active compensation and will act as the D-FACTS controller [9].

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. However, as the DPFC injects extra current at the third harmonic frequency into the transmission line, additional losses in the transmission line and transformer should be aware of.

III. 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

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

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. The third-harmonic frequency control is the major control loop with the DPFC series converter control. The principle of the vector control is used here for the dc-voltage control [10]. The third-harmonic current through the line is selected as the rotation reference frame for the single-phase park transformation, because it is easy to be captured by the phase-locked loop (PLL) [11] in the series converter. As the line current contains two frequency components, a third high-pass filter is needed to reduce the fundamental current. The d-component of the third harmonic voltage is the parameter that is used to control the dc voltage, and its reference signal is generated by the dc-voltage control loop. To

minimize the reactive power that is caused by the third harmonic, the series converter is controlled as a resistance at the third-harmonic frequency. The q-component of the third-harmonic voltage is kept zero during the operation. As the series converter is single phase, there will be voltage ripple at the dc side of each converter. The frequency of the ripple depends on the frequency of the current that flows through the converter. As the current contains the fundamental and third harmonic frequency component, the dc-capacitor voltage will contain 100-, 200-, and 300-Hz frequency component [12], [13]. There are two possible ways to reduce this ripple. One is to increase the turn ratio of the single-phase transformer of the series converter to reduce the magnitude of the current that flows into the converter. The other way is to use the dc capacitor with a larger capacitance.
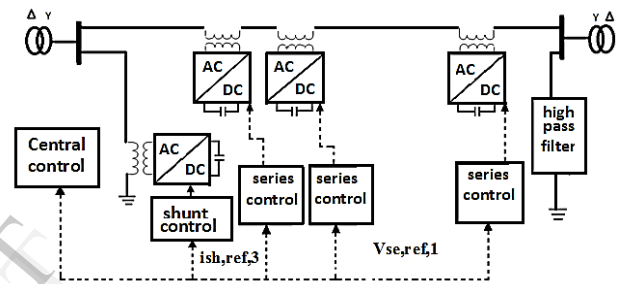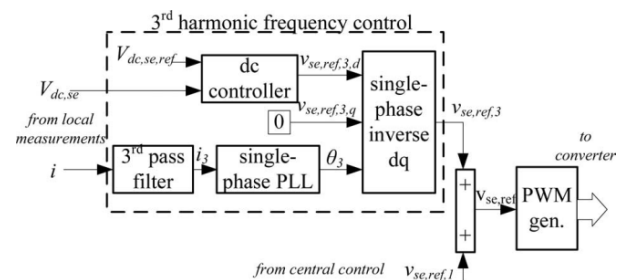

Fig.7. DPFC control block diagram

Fig. 8. Block diagram of the series converter control.
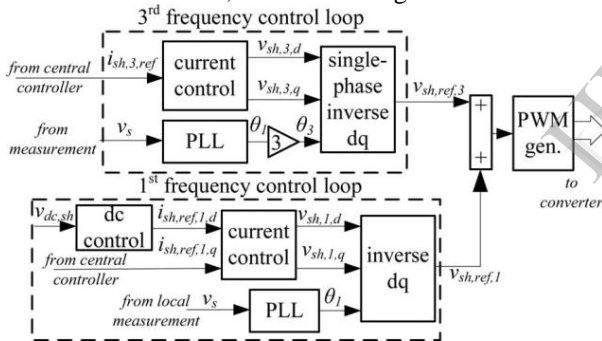
C. Shunt Control

The block diagram of the shunt converter control is shown in Fig.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 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.

IV. SIMULATION RESULTS

To verify the principle and control of the DPFC, one shunt converter and three single phase series converters the design was simulated to predict the steady state performance.a prototype based on proposed topology is simulated using MATLAB/SIMULATION. Therefore, two situations are demonstrated: the DPFC behaviour in steady state and the step response. In steady state, the series converter is controlled to insert a voltage vector with both d- and q-component, which is $V_{se,d,ref} = 0.3$V and $V_{se,q,ref} = -0.1$ V. The DPFC controls the power flow through transmission lines by varying the voltage injected by the series converter at the fundamental frequency. Fig (11)-(14) illustrates the simulation results of step response. A step change of the fundamental reference voltage of the series converter is made, which consists of both active and reactive variations, as shown in Fig. 10.


Fig.9.Block diagram of the shunt converter control

As shown, the dc voltage of the series converter is stabilized before and after the step change. To verify if the series converter can inject or absorb active and reactive power from the grid at the fundamental frequency, the power is calculated from the measured voltage and current in Figs. 11 and 12.

The measured data in one phase are processed in the computer by using MATLAB. To analyze the voltage and current at the fundamental frequency, the measured data that contains harmonic distortion are filtered by a low-pass digital filter with the 50-Hz cutoff frequency. Because of this filter, the calculated voltage and current at the fundamental frequency have a 1.5 cycle delay to the actual values, thereby causing a delay of the measured active and reactive power. Fig. 13 illustrated the active and reactive power injected by the series converter. A comparison is made between the measured power and the
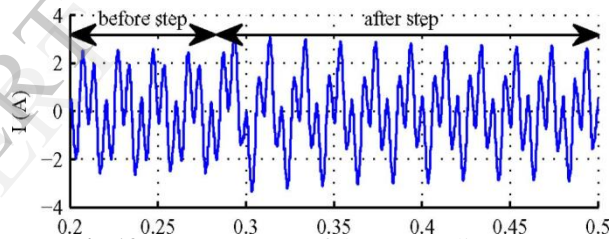
calculated power. We can see that the series converters are able to absorb and inject both active and reactive power to the grid at the fundamental frequency.
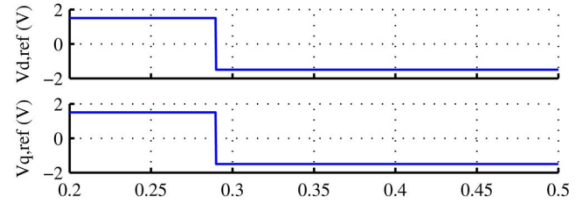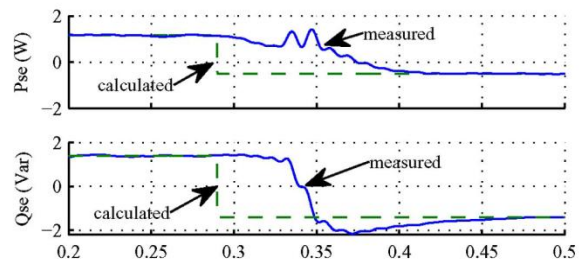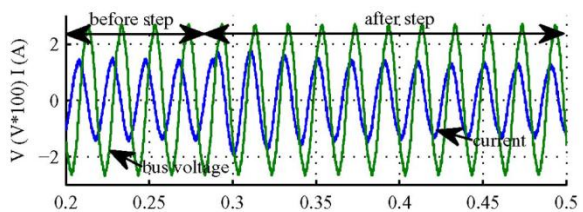

Fig. 10. Reference voltage for the series converters
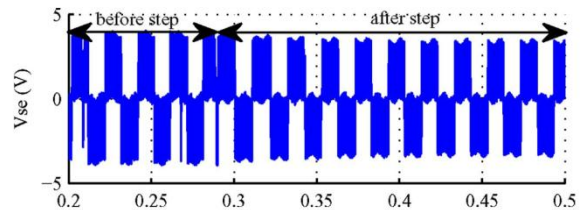
Fig. 11. Step response of the DPFC: series converter voltage

Fig.12. Step response of the DPFC: line current.

Fig.13.Step response of the DPFC: active and reactive power injected by the series converter at the fundamental frequency

Fig.14. Step response of the DPFC: bus voltage and current at the Δ side of the transformer.

Symbol	Description	Value	Unit
V_s	Nominal voltage of grid s	220	V
V_r	Nominal voltage of grid r	220	V
θ	Transmission angle between grid s and r	1	Degree
L	Line inductance	6	mH
$V_{ph,max}$	Shunt converter maximum ac voltage	50	V
$I_{ph,max}$	Shunt converter maximum ac current	9	A
$V_{ph,dc}$	Shunt converter dc source supply	20	V
$I_{ph,ref,3}$	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

TABLE 1
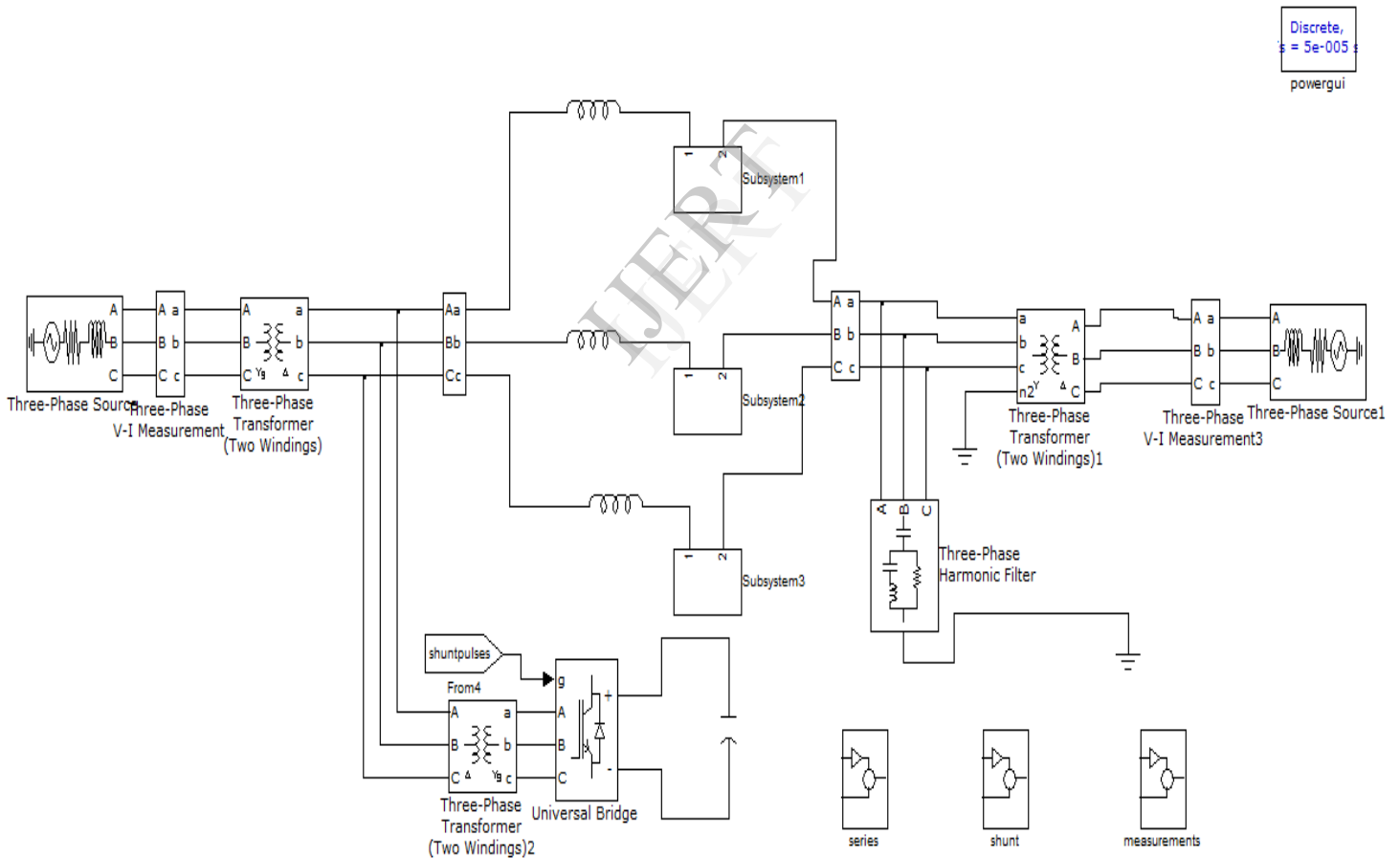
Fig: MATLAB/SIMULATION MODEL OF PROPOSED DPFC

V. CONCLUSION

This paper has presented a new concept called DPFC. 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 converters instead of one large-size converter. The reliability of the DPFC is greatly increased because of the redundancy of the 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 of is low. The results of simulation shows that the shunt and series converters 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.

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