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A Facts Device: Distributed Power-Flow Controller (DPFC)

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***Abstract*— *This paper presents a new component within the flexible Ac-transmission system (FACTS) family, called distributed Power-flow controller (DPFC). The DPFC is 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 are presented in this paper and the corresponding experimental results that are carried out on a scaled prototype are also shown*.

Keywords*— *Bidirectiona, converter, demonstrates, high control capability series control.

I. INTRODUCTION

The growing demand and the aging of network smoke it desirable to control the power flow in power-transmission systems fast and reliably. 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. Currently, the unified power-flow controller (UPFC) is the most powerful FACTS device, which can simultaneously control all the parameters of the system: the line impedance, the transmission angle, and bus voltage.

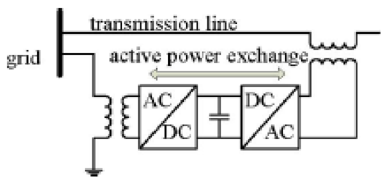

Fig. 1. Simplified representation of a UPFC.

The UPFC is the combination of a static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC), which is 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. 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), 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 D-FACTS) concept. 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

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II. DPFC OPERATING PRINCIPLE

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:

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

Where VI and Ii are the voltage and current at the ith harmonic frequency respectively, and ϕ_i is the corresponding angle between the voltage and current. 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, there by 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 2 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.

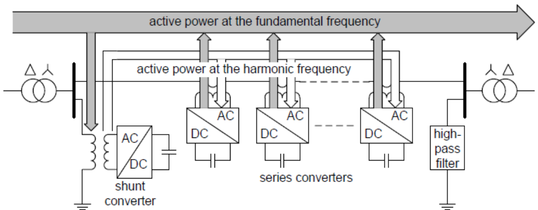

Fig. 2. Active power exchange between DPFC converters.

III. 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 $Y-\nabla$ 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 $Y-\nabla$ transformer on the right side in figure 2 with the ground. Because the ∇-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.

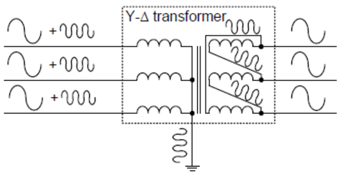

Fig. 3. Utilize grounded $Y-\nabla$ transformer to filter zero-sequence harmonic.

Another advantage of using the 3rd harmonic to exchange active power is that the grounding of the $Y-\nabla$ 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 $Y-\nabla$ transformer in that branch, at the side opposite to the shunt converter, will be grounded and vice versa. Figure 4 shows a simple example of routing the harmonic current by using the grounding of the $Y-\nabla$ 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.

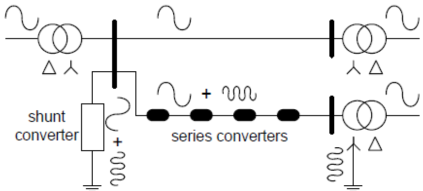

Fig. 4. Route the harmonic current by using the grounding of the $Y-\nabla$ transformer.

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 ith harmonic frequency Pi and the voltages generated by the converters is expressed by the well known the power flow equation and given as:

$$P_i = \frac{|V_{sh,i}||V_{se,i}|}{X_i}\sin(\theta_{sh,i} - \theta_{se,i})$$

Where Xi is the line impedance at ith frequency, $|V_{sh,i}|$ and $|V_{se,i}|$ are the voltage magnitudes of the i^{th} harmonic of the shunt and series converters, and $(\theta_{sh,i} - \theta_{se,i})$ 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

IV. DPFC Control

To control multiple converters, a DPFC consists of three types of controllers: central control, shunt control and series control, as shown in figure 5.

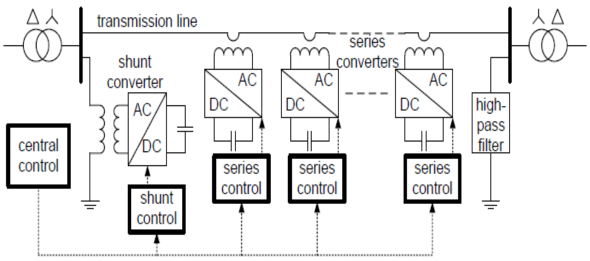

Fig. 5. DPFC control block diagram.

The shunt and series control are localized controllers and are responsible for maintaining their own converters' parameters. The central control takes care of the DPFC functions at the power system level. The function of each controller is listed:

Central control: The central control generates the reference signals for both the shunt and series converters of the DPFC. Its control function depends on the specifics of the DPFC application at the power system level, such as power flow control, low frequency power oscillation damping and balancing of asymmetrical components. According to the system requirements, 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 concern the fundamental frequency components.

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 3rd harmonic frequency components, in addition to generating series voltage at the fundamental frequency as required by the central control.

Shunt control: The objective of the shunt control is to inject a constant 3rd harmonic current into the line to supply active power for the series converters. At the same time, it maintains the capacitor DC voltage of the shunt converter at a constant value by absorbing active power from the grid at the fundamental frequency and injecting the required reactive current at the fundamental frequency into the grid.

The detailed schematics and designs of the DPFC control will be introduced in following chapters.

V. Variation of the Shunt Converter

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 [July 99]. 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-_ 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 6. 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 $Y-\nabla$ 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 STATCOM, the single-phase converter can be directly connected back-to-back to the DC side of the STATCOM, as shown in figure 6.

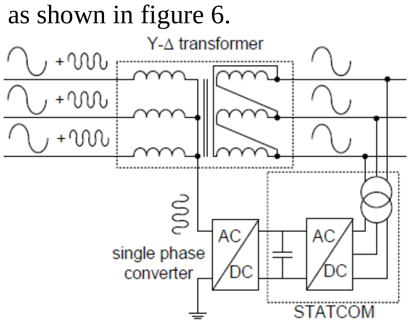

Fig. 6. DPFC shunt converter configuration.

VI. 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, 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.

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

VII. ANALYSIS OF THE DPFC

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 figure 7.

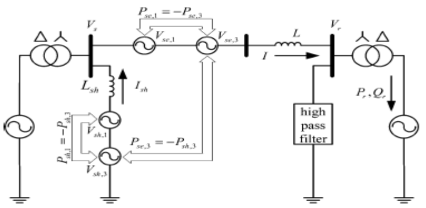

Fig. 7. DPFC simplified representation.

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 *L* with the line current *I*. The voltage injected by all the DPFC series converters is *V*se,1 and *V*se,3 at the fundamental and the third-harmonic frequency, respectively. The shunt converter is connected to the sending bus through the inductor *L*sh and generates the voltage *V*sh,1 and *V*sh,3 ; the current injected by the shunt converter is *I*sh. The active and reactive power flow at the receiving end is *Pr* and *Qr*, respectively. This representation consists of both the fundamental and third-harmonic frequency components. Based on the superposition theorem, the circuit in figure 7 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 figure 8.

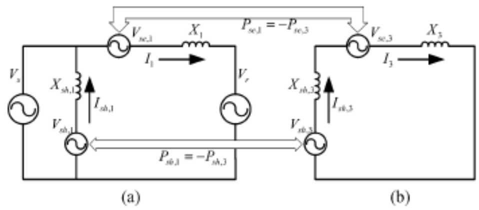

Fig. 8. DPFC equivalent circuit. (a) Fundamental frequency. (b) Third harmonic frequency.

The power-flow control capability of the DPFC can be illustrated by the active power *Pr* and reactive power *Qr* 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 (1)

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

Where *Pr*0, Qr0, and θ are the active, reactive power flow, and the transmission angle of the uncompensated system, *X*se,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* (*Pr*0, *Qr0*) is a circle with the radius of |*V* |2/|*X*1 | around the center defined by coordinates *P* = 0 and *Q* = |*V* |2/|*X*1 |. Each point of this circle gives the *Pr*0 and *Qr*0 values of the uncompensated system at the corresponding transmission angle θ. The boundary of the attainable control range for *Pr* and *Qr* is obtained from a complete rotation of the voltage *V*se,1 with its maximum magnitude. Figure 9 shows the control range of the DPFC with the transmission angle θ.

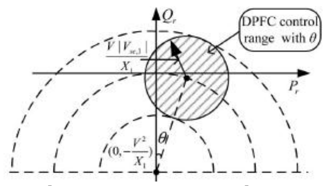

Fig. 9. DPFC active and reactive power control range with the transmission angle θ.

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To ensure the series converters to inject a 360◦ rotatable voltage, an active and reactive power at the fundamental frequency is required. The reactive power is provided by the series converter locally and the active power is supplied by the shunt converter. This active power requirement is given by

$$P_{se,1} = \mathrm{Re}(V_{se,1}I_1^*) = \frac{X_1}{|V_r|^2}|s_r||S_{r0}|\sin(\varphi_{r0} - \varphi_r)$$

Where $\phi\ r\ 0$ is the power angle at the receiving end of the uncompensated system, which equals tan−1 (*Pr*0/*Qr*0) and ϕr is the power angle at receiving end with the DPFC compensation. The line impedance *X*1 and the voltage magnitude |*Vr* | are constant; therefore, the required active power is proportional to $|s_r||S_{r0}|\sin(\varphi_{r0}\varphi_r)$, which is two times the area of the triangle that is formed by the two vectors $|S_{r0}|$ and *Sr* . Figure 10 illustrates the relationship between *P*se,1 and the power flow at the receiving end at a certain power angle *θ*.

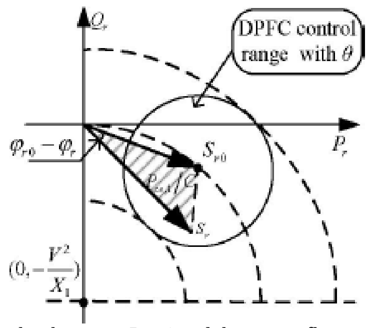

Fig. 10. Relationship between *P*se,1 and the power flow at the receiving end.

Consequently, the required active power by the series converter can be written as follows:

$$P_{se,1} = CA_{(O,r0,r)}$$

Where the coefficient $C = 2X_1/|V_r|^2$ and $A_{(O,r0,r)}$ is the area of the triangle (0, *Sr*0, *Sr)*. The angle difference $\phi r0 - \phi r$ can be positive or negative, and the sign gives the direction of the active power through the DPFC series converters. The positive sign means that the DPFC series converters generate active power at the fundamental frequency and *vise versa*. The active power requirement varies with the controlled power flow, and the active power requirement has its maximum when the vector *Sr* − *Sr*0 is perpendicular to the vector *Sr*0.

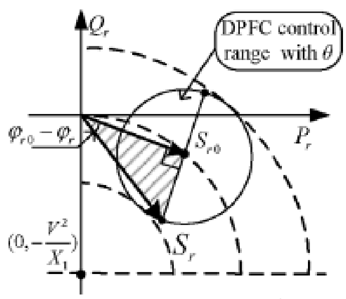

Fig. 11. Maximum active power requirement of the series converters.

The relationship between the power flow control range and the maximum active power requirement can be represented by

$$P_{se,1,\max} = \frac{|X_1||S_{r0}|}{|V_r|^2}|S_{r,c}|$$

Where |*Sr,c* | is the control range of the DPFC.
Each converter in the DPFC generates two frequency voltages At the same time. Accordingly, the voltage rating of the each Converter should be the sum of the maximum voltage of the two frequencies component

$$V_{se,\max} = |V_{se,1,\max}| + |V_{se,3,\max}|$$

During the operation, the active power requirement of the series converter varies with the voltage injected at the fundamental frequency. When the requirement is low, the series voltage at the third-harmonic frequency will be smaller than $|V_{se,3,\max}|$. This potential voltage that is between *V*se,3 and $|V_{se,3,\max}|$ can be used to control the power flow at the fundamental frequency, thereby increasing the power-flow control region of the DPFC. When $S_{r,c}$ is perpendicular to the uncompensated power S_{r0}, the series converters require maximum active power, and the radius of the DPFC control region is given by

$$S_{r,c} = \frac{|V_r||V_{se,1,\max}|}{X_1}$$

If *Sr, c* is in the same line as *Sr*0, the series converters only provide the reactive compensation and the boundary of the DPFC control region will extend to

$$S_{r,c} = \frac{|V_r|(|V_{se,1,\max}| + |V_{se,3,\max}|)}{X_1}$$

It shows that the control region of the DPFC can be extended to a shape that is similar as an ellipse,.

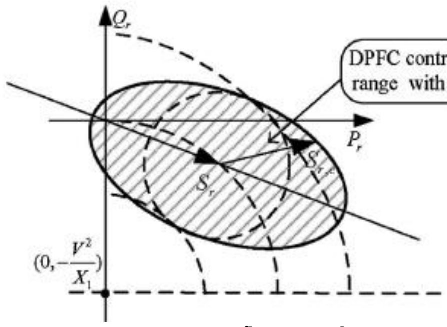

Fig. 12. DPFC power-flow control range.

To obtain the same control capability as the UPFC, the rating of the DPFC converter at the fundamental frequency should be the same as the one for the UPFC. Because the voltages and currents at the third-harmonic frequency have to be added, the rating of the DPFC converter is slightly larger than the UPFC. The increased rating is related with the active power exchanged at the third-harmonic frequency. For a transmission line, the line impedance |*X*1 | is normally around 0.05 p.u. (per unit). Assuming the bus voltages |*V* | and uncompensated power flow |*Sr* 0| is 1 p.u., and then, from (7), we can see that to control 1-p.u. power flow, the exchanged active power is around 0.05 p.u.

Even with this extra voltage and current at the third-harmonic frequency, the cost of the DPFC is still much lower than the UPFC, for the following reasons: 1) the UPFC converter handles the line-to-line voltage isolation that is much larger than voltage injected by the series converter; 2) no land requirement for the series converter; and 3) the active and passive components for the DPFC converter are low-voltage components (less than 1kV and 60 A), which is much cheaper than the high-voltage components in the UPFC.

VIII. Laboratory Results

An experimental setup has been built to verify the principle and control of the DPFC. One shunt converter and six single phase series converters are built and tested in a scaled network, as two isolated buses with phase difference are connected by the line. Within the experimental setup, the shunt converter is a single-phase inverter that is connected between the neutral point of the Y–Δ transformer and the ground. The inverter is powered by a constant-voltage source. The specifications of the DPFC experimental setup are listed in the within the setup, multiple series converters are controlled by a central controller. The central controller gives the reference voltage signals for all series converters. The voltages and Currents within the setup are measured by an oscilloscope and processed in computer by using the MATLAB. The photograph of the DPFC experimental setup is illustrated in Fig. 18.To verify the DPFC principle, two situations are demonstrated: the DPFC behavior 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. one operation point of the DPFC setup. For clarity, only the waveforms in one phase are shown. The voltage injected by DPFC operation in steady state line. DPFC operation in steady state: series converter voltage. DPFC operation in steady state: bus voltage and current at the Δ side of the transformer. series converter, the current through the line, and the voltage and current at the Δ side of the transformer are illustrated. The constant third-harmonic current injected by the shunt converter evenly disperses to the three phases and is superimposed on the fundamental current, as shown in The voltage injected by the series converter also contains two frequency components in. The amplitude of the pulse width modulated (PWM) waveform represents the dc-capacitor voltage, which is well maintained by the third-harmonic component in steady state. As shown, the dc voltage has a small oscillation; however, it does not influence the DPFC control. Demonstrates the third-harmonic filtering by the Y–Δ transformers. There is no third-harmonic current or voltage leaking to the Δ side of the transformer. The DPFC controls the power flow through transmission lines by varying the voltage injected by the series converter at the fundamental frequency. Illustrate the step response of the experimental setup. A step change of the fundamental reference voltage of the series converter is made, which consists of both active and reactive variations, as. 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. The measured data in one phase are processed in the computer by

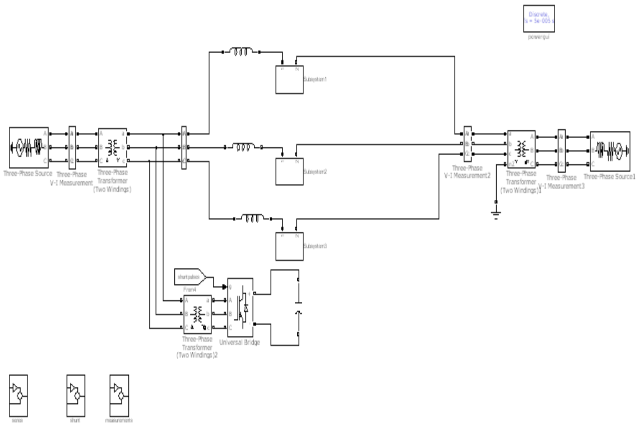

Fig. 13 .Model of the series converter control.

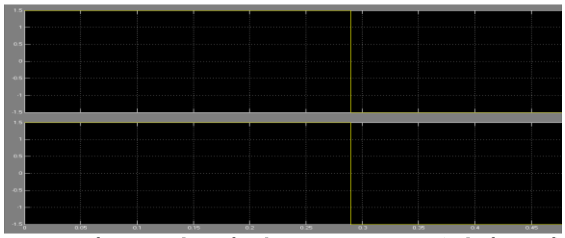

Fig. 14. Reference voltage for the series converters (Vdref, Vqref).

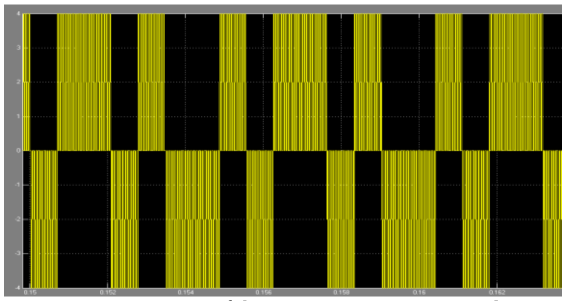

Fig. 15.Step response of the DPFC: series converter voltage.

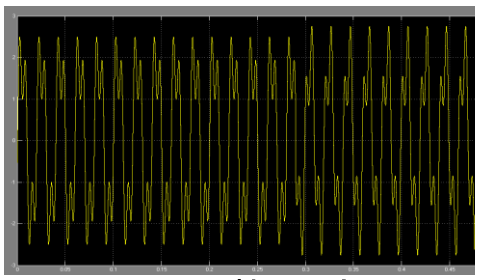

Fig. 16.Step response of the DPFC: line current.

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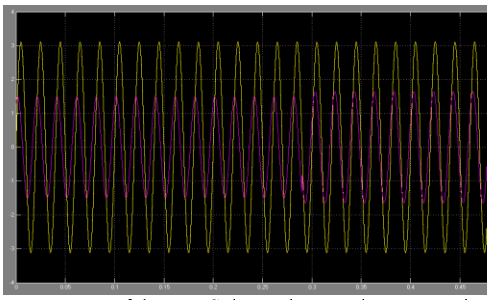


Fig. 17.Step response of the DPFC: bus voltage and current at the Δ side of the transformer.

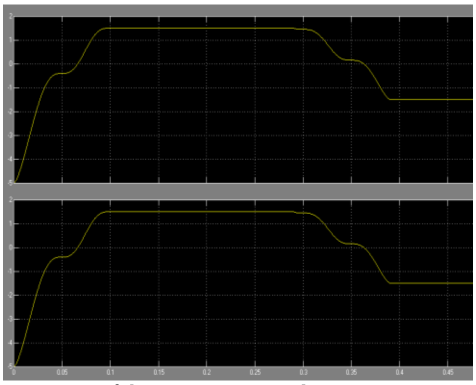


Fig. 18. Step response of the DPFC: active and reactive power injected by the series converter at the fundamental frequency.

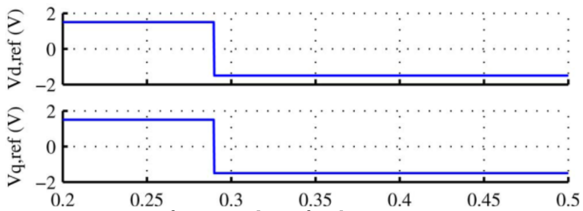


Fig. 19. Reference voltage for the series converters.

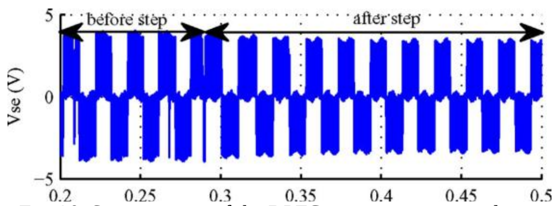


Fig. 20. Step response of the DPFC: series converter voltage.

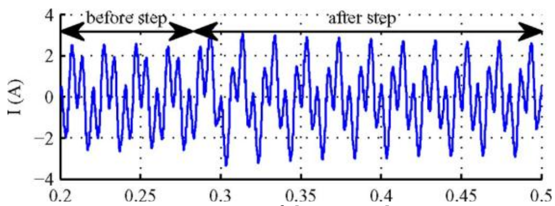
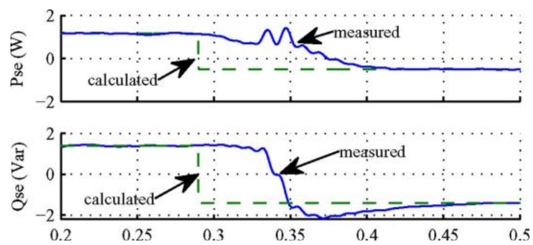


Fig. 21. Step response of the DPFC: line current.



Step response of the DPFC: active and reactive power injected by the series converter at the fundamental frequency 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-Hzcutoff 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 illustrated the active and reactive. 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.

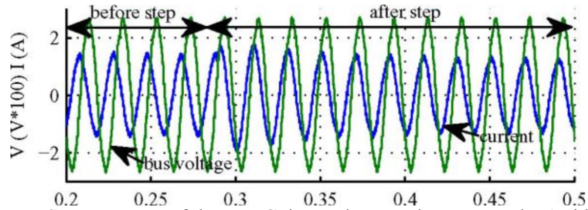


Fig. 22. Step response of the DPFC: bus voltage and current at the Δ side of the transformer.

IX. 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 DPFC concept has been verified by an experimental setup. It is proved 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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