# Distributed Power-Flow Controller for Enhancing Power System Stability

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## Abstract

The growing demand and aging of network make it desirable to control the power flow in power transmission system reliably. The distributed power flow-controller (DPFC) modified from UPFC for increasing system stability and reducing costs. 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 has the same control capability as the UPFC, which comprises the adjustment of the line impedance, the transmission angle, and the bus voltage. The objective of this review paper is to study principle of DPFC and analysis the performance under various abnormal conditions such as the voltage sag and swell, unbalanced 3-phase current. Detailed simulations were carried out to illustrate the control features of these devices and every series converter consists of D-FACTS concept so reliability also improves because failure of series converters does not affect much on system.

**Keywords—** AC-DC power conversion, load flow control, power system control, FACTS, power system stability, distributed FACTS

## 1. Introduction

Modern power system network is getting much more complicated and heavily loaded than ever before. The consequence of such is the risk of stability and reliability of the system and also better utilization of power with minimum loss by installing new FACTS devices such as SSSC, STATCOM, UPFC and DPFC has become crucial [1]. It is known that power through an ac transmission line is the function of line impedance, voltage magnitude and phase angle between the sending end and receiving end voltages. FACTS devices can be utilized to change the power flow by changing the parameters of the network. Thus the power transmission capabilities can be improved. It is desirable to better control the power flow in power transmission systems. FACTS devices, especially UPFC, provide a fast, smooth control of power system parameters. However, for cost and reliability reasons, the application is limited.

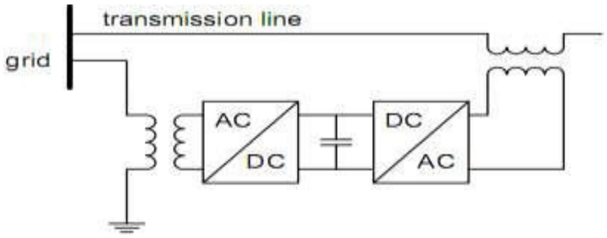

Fig.1 Simplified representation of a UPFC

Unified Power Flow Controller (UPFC) is the most power full FACTS device currently. It can instantaneously control all parameters in a power network, such as line impedance, power angle, and voltage magnitude [2]. The simplified diagram of UPFC is illustrated in Fig.1. However, such solid state power flow controllers are not widely applied because of the following reasons: the high cost due high voltage isolation, high power rating and the relative low reliability. The reliability of UPFC depends on the power electronics. A single component failure will cause the whole system shut down.

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 [3]. 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 [4]), 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.

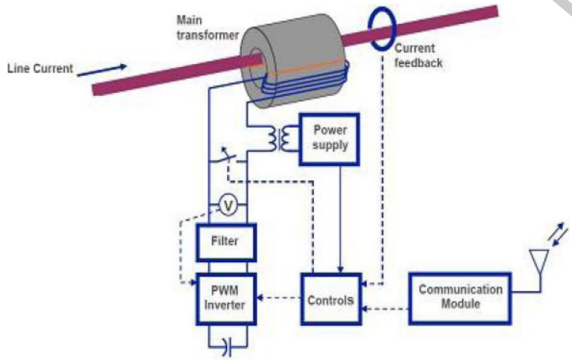

Fig. 2 D-FACTS unit configuration

For a lower cost and higher stability, the distributed FACTS is invented Distributed FACTS device (D-FACTS) is the concept to use multiple low-power converters attached to the transmission line by single turn transformers [5]. The concept brings several advantages compared to conventional FACTS devices, such as lower cost easy for the maintenance and installation, and increasing the system reliability (one device failure will not lead to the entire system shut down). Currently, the presented D-FACTS device is the Distributed Static Series Compensator (DSSC), shown in Fig. 2 which acts like a controlled variable conductor. Since the DSSC has no power source, it can only adjust the line impedance, and is not as powerful as UPFC.

This paper introduces a new concept of distributed power flow controller (DPFC) that combines conventional FACTS and D-FACTS devices. The DPFC gives the possibility of control all system parameters, such as line impedance and power angle. At the same time, it provides higher reliability and lower cost.

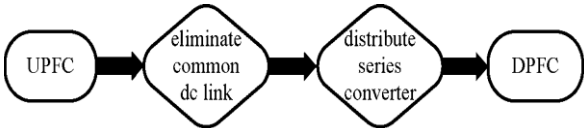

Fig. 3. Flowchart from UPFC to DPFC.

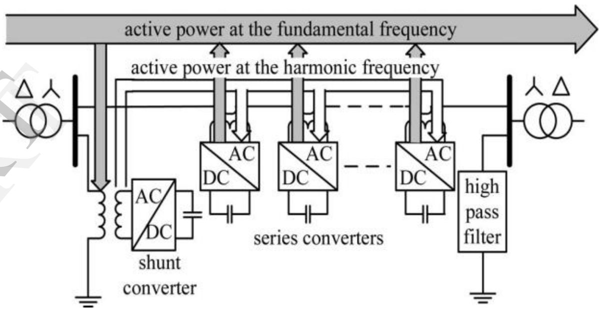

Fig. 4. DPFC configuration.

## 2. DPFC Principle

A couple of approaches are applied to the UPFC to improve 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. 3. By combining these two approaches, the new FACTS device-DPFC is realized.

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. 4.

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 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 identical control capability as the UPFC, a method that allows the exchange of active power between converters with eliminated dc link is the prerequisite [6].

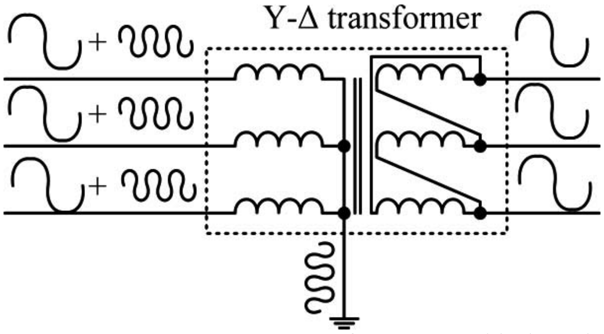

Fig. 5. Utilize grounded Y–Δ transformer to provide the path for the zero sequence third harmonic.

### 2.2 Using third harmonic components

Because of the unique characteristics 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 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 shown in 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.

An additional 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.

### 2.3 Distributed Series Converter

The D-FACTS is a solution for the series-connected FACTS, which can significantly reduce the total cost and increase the reliability of the series FACTS device. The idea of the D-FACTS is to use a large number of controllers with low rating instead of one large rated controller. The small controller is a single-phase converter attached to transmission lines by a single-turn transformer. The converters are hanging on the line so that no costly high-voltage isolation is required. The single-turn transformer uses the transmission line as the secondary winding, inserting controllable impedance into the line directly. Each D-FACTS module is self-powered from the line and controlled remotely by wireless or power-line communication.

The actual design of the D-FACTS results in low cost and high reliability. As D-FACTS units are single-phase devices floating on lines, high-voltage isolations between phases are avoided. The unit can easily be employed at any transmission-voltage level, because it does not require supporting phase-ground isolation. The power and voltage rating of each unit is relatively small. Further, the units are clamped on transmission lines, and therefore, no land is required to establish the equipments for series converters. The redundancy of the D-FACTS provides an uninterrupted operation during a single module failure, thereby giving a much higher reliability than other FACTS devices.

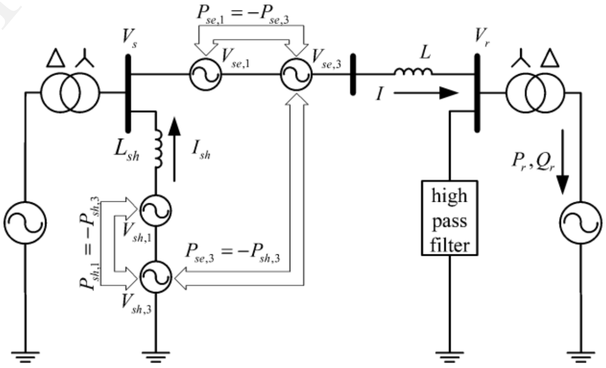

Fig. 6. DPFC simplified representation.

## 3. Analysis of the DPFC

In the conceptual point of view, each converter can be replaced by a controllable voltage source in series with impedance. Hence each converter generates voltage at two different frequencies; each converter can be represented by two series connected controllable voltage sources, one at fundamental frequency and the other at 3rd harmonic frequency. The total active power generated by the two frequency voltage source will be zero, if the converter is lossless. The conceptual representation of DPFC is shown in Fig. 6, where $V_{se,1}$

equals to the sum of the fundamental voltages for all series converters, and Vse3 is the sum of the 3rd harmonic voltages. The shunt converter generates voltage at 3rd harmonic frequency. As a result, a third harmonic current will flow in the section of the transmission line to feed the active power to series converters. The capacitor dc voltage of shunt converter is compensated by the absorbing active power at fundamental frequency.

The series converters inject a fundamental voltage which is controllable in both magnitude and phase. It absorbs the active power from 3rd harmonic frequency to balance their dc voltages. Based on the superposition theorem, the circuit can be split into two circuits at different frequencies. The two circuits are isolated from each other, and the link between two circuits is the active power balance of each converter, see in Fig. 6.

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. Since 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]:

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

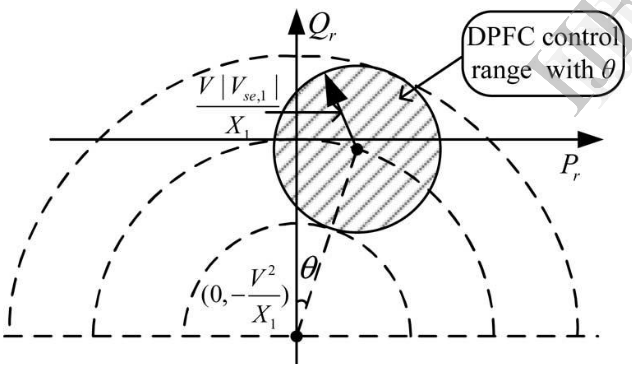

Fig. 7. DPFC active and reactive power control range with the transmission angle θ.

where $P_{r0}$ ,$Q_{r0}$ , and θ are the active, reactive power flow, and the transmission angle of the uncompensated system, where $P_{r0}$ ,$Q_{r0}$ , and θ are the active, reactive power flow, and the transmission angle of the uncompensated system, Xse,1 = ω$L_{se}$ 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($P_{r0}$,$Q_{r0}$ ) is a circle with the radius of |V|2/|X1| around the canter defined by coordinates P = 0 and Q = |V|2/|X1|. Each point of this circle gives the $P_{r0}$ and $Q_{r0}$ 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 voltage $V_{se,1}$ with its maximum magnitude. Fig. 7 shows the control range of the DPFC with the transmission angle θ.

## 4. 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. 8. 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.

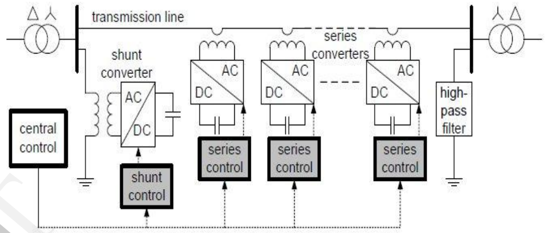

Fig. 8. DPFC control block diagram.

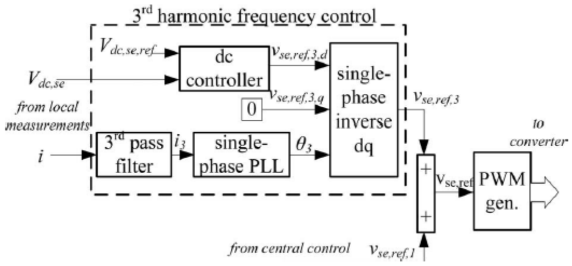

Fig. 9. Block diagram of the series converter control.

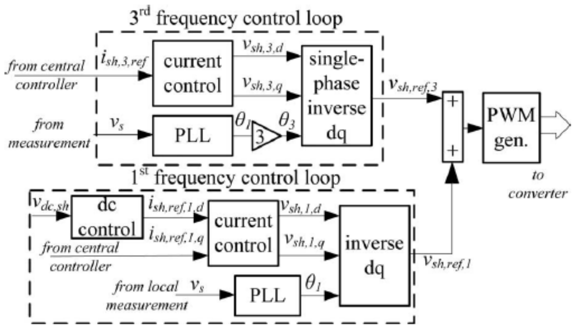

Fig. 10. Block diagram of the shunt converter control.

### 4.1 Central Control

The central control generates the reference signals for both the shunt and series converters of the DPFC. It is aimed 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.

### 4.2. Series Control

Every single 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 given by the central control loop with the DPFC series converter control.

The principle of the vector control is used here for the dc-voltage control [7]. 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) [8] in the series converter.

### 4.3. Shunt Control

The block diagram of the shunt converter control is shown in Fig. 10. 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 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. 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.

## 5. DPFC Advantages and Applications

The DPFC can be viewed as a UPFC which uses the D-FACTS 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.

**5.1 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 [9], voltage sag restoration [10], or balancing asymmetry.

**5.2 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 [11].

**5.3 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.

When the DPFC is applied in power systems, the reliability issue is important. The fault tolerance of the DPFC is investigated, including the protection method for different types of failures and the use of supplementary controls, to improve system performance during converter failures. Two control modes are predefined for each series converter, namely full-control mode and limited-control mode. In normal situations, the series converters operate in the full-control mode, which uses the 3rd harmonic component to maintain the DC voltage.

When the shunt converter has a failure, the 3rd harmonic current cannot be injected and the series converter will operate in the limited-control mode. In the limited-control mode, the series converter uses the active power at the fundamental frequency to stabilize the DC voltage. It is also capable of controlling the reactive power injection at the fundamental frequency.

Due to the over-voltage protection, during a failure, the series converter appears as a short circuit to transmission lines. Accordingly, the network becomes asymmetric during the failure of a series converter because of the asymmetrical voltage injection. To compensate for this asymmetry, a supplementary control is applied to the central controller. The controller monitors the voltages at the sending and receiving ends and the line current, to calculate the total voltage injected by all series converters. By comparing this calculated voltage and the reference voltage generated by the central control, the operation status of the series converters is known. According to the operation status, the controller can automatically adjust the reference for each series converter [12].

The two supplementary controls are verified both in Matlab Simulink and in the experimental setup. This proves that the supplementary controls can improve DPFC performance during converter failures and therefore, the DPFC have relatively high reliability [13].

DPFC can compensate both negative and zero sequence components, consequently the DPFC is more powerful than other FACTS device for compensation of unbalanced currents. Additional controllers are supplemented to existing DPFC controller, and their principle is to monitor the negative and zero sequences of the current through the transmission line, and to force them to be zero by applying an opposing voltage [14].

## 6. Conclusion

In this paper, the essential features of DPFC controller with various applications were discussed. The potential to enhancement of power system stability as well as reliability of power system was explained. In power system transmission, it is required to maintain the voltage magnitude, phase angle and line impedance. Consequently, to control power flow over designated transmission line and enhancement of power system stability FACTS devices are used in modern power system network. In this review paper the role of DPFC device in power system and current status of electric power system network are addressed. Therefore, the following results are found, power flow control is achieved by using FACTS (DPFC) devices and transient stability is improved and faster steady state is achieved. Hence congestion is less by improving transient stability and reliability. By using different control strategies, performance of DPFC can be further modified as per the requirement.

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