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Distributed Power-Flow Controller (DPFC) Simulation

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Abstract:
This paper describes the steady-state response and control of power in transmission line equipped with FACTS devices. Detailed simulations are carried out on two-machine systems to illustrate the control features of these devices and their influence to increase power transfer capability and improve system reliability. The DPFC is derived from the unified power-flow controller (UPFC) and DPFC has the same control capability as the 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 interaction between the DPFC, the network and the machines are analyzed.
Keywords: FACTS, DPFC, modelling, power transmission, AC-DC power conversion, semiconductor devices, power system control.

I. Introduction

The flexible ac transmission system (FACTS) technology is the application of power electronics in transmission systems. The main purpose of this technology is to control and regulate the electric variables in the power systems. This is achieved by using converters as a controllable interface between two power system terminals. The resulting converter representations can be useful for a variety of configurations. Basically, the family of FACTS devices based on voltage source converters (VSCs) consists of a series compensator, a shunt compensator, and a shunt/series compensator. The static Compensator (STATCOM) is a shunt connected device that is able to provide reactive power support at a network location far away from the generators. Through this reactive power injection, the STATCOM can regulate the voltage at the connection node. The static synchronous series compensator (SSSC) is a series device which injects a voltage in series with the transmission line.

Ideally, this injected voltage is in quadrature with the line current, such that the SSSC behaves like an inductor or a capacitor for the purpose of increasing or decreasing the overall reactive voltage drop across the line, and thereby, controlling the transmitted power. In this operating mode, the SSSC does not interchange any real power with the system in steady-state.

The unified power-flow controller (UPFC) is the most versatile device of the family of FACTS devices, since it is able to control the active and the reactive power, respectively, as well as the voltage at the connection node.

The Unified Power Flow Controller (UPFC) is comprised of a STATCOM and a SSSC, coupled via a common DC link to allow bi-directional flow of active power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM. Each converter can independently generate (or) absorb reactive power at its own AC terminal. The two converters are operated from a DC link provided by a DC storage capacitor.

The UPFC is not widely applied in practice, due to their high cost and the susceptibility to failures. Generally, the reliability can be improved by reducing the number of components; however, this is not possible due to the complex topology of the UPFC. To reduce the failure rate of the components, selecting components with higher ratings than necessary or employing redundancy at the component or system levels. Unfortunately, these solutions increase the initial investment necessary, negating any cost related advantages. Accordingly, new approaches are needed in order to increase reliability and reduce cost of the UPFC.

The same as the UPFC, the DPFC is able to control all system parameters like line impedance, transmission angle and bus voltage. 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 and high control capability. DPFC can also be used to improve the power quality and system stability such as power oscillation damping, Voltage sag restoration or balancing asymmetry.

II. DPFC Topology:

By introducing the two approaches outlined in the previous section (elimination of the common DC link and distribution of the series converter) into the UPFC, the DPFC is achieved. Similar as the UPFC, the DPFC consists of shunt and series connected converters. The shunt converter is similar as a STATCOM, while the series converter employs the DSSC concept, which is to use multiple single-phase converters instead of one three-phase converter. Each converter within the DPFC is independent and has its own DC capacitor to provide the required DC voltage. The configuration of the DPFC is shown in Figure 1.

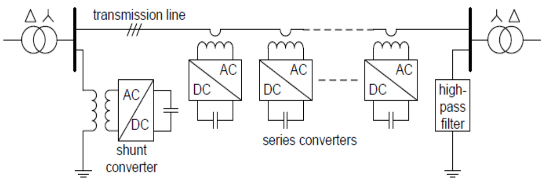


Figure 1: DPFC configuration

As shown, besides the key components - shunt and series converters, a DPFC also requires a high pass filter that is shunt connected to the other side of the transmission line and a $Y-\Delta$ transformer on each side of the line. The reason for these extra components will be explained later. The unique control capability of the UPFC is given by the back-to-back connection between the shunt and series converters, which allows the active power to freely exchange. To ensure the DPFC has the same control capability as the UPFC, a method that allows active power exchange between converters with an eliminated DC link is required.

III. DPFC Operating Principle

Active Power Exchange With Eliminated Dc Link

Within the DPFC, the transmission line presents a common connection between the AC ports of the shunt and the series converters. Therefore, it is possible to exchange active power through the AC ports. The method is based on power theory of non-sinusoidal components. According to the Fourier analysis,non-sinusoidal voltage and current can be expressed as the sum of sinusoidal functions in different frequencies with different amplitudes. The active power resulting from this non-sinusoidal voltage and current is defined as the mean value of the product of voltage and current. Since the integrals of all the cross product of terms with different frequencies are zero, the active power can be expressed by:

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

Where VI and Ii are the voltage and current at the i^{th} harmonic frequency respectively, and ϕ_i is the corresponding angle between the voltage and current. Equation (1) 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.

IV. Using Third Harmonic Components

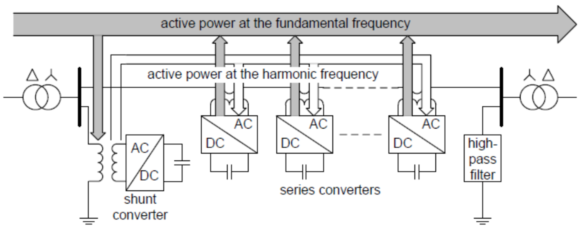


Figure 2: Active power exchange between DPFC converters

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 $Y-\Delta$ 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 cut off frequency of this filter is approximately the fundamental frequency.

Because the voltage isolation is high and the harmonic frequency is close to the cut off 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 $Y-\Delta$ transformer on the right side in Figure 2 with the ground. Because the Δ-winding appears open-circuit to the 3rd harmonic current, all harmonic current will flow through the Y-winding and concentrate to the grounding cable as shown in Figure 3. Therefore, the large high-pass filter is eliminated.

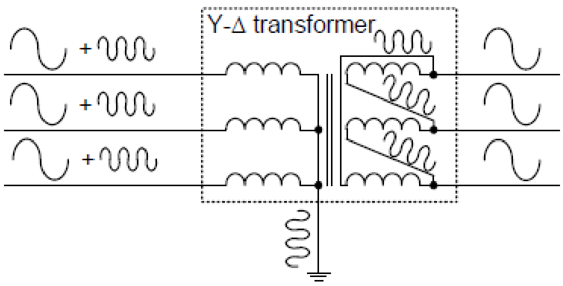


Figure 3: Utilize grounded $Y-\Delta$ transformer to filter zero-sequence harmonic

Another advantage of using the 3rd harmonic to exchange active power is that the grounding of the $Y-\Delta$ 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 $Y-\Delta$ 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 $Y-\Delta$ 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.

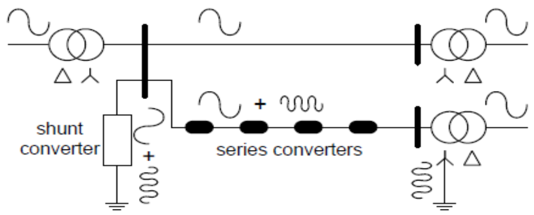


Figure 4: Route the harmonic current by using the grounding of the $Y-\Delta$ transformer

The harmonic at the frequencies like 3rd, 6th, 9th... are all zero-sequence and all can be used to exchange active power in the DPFC. However, the 3rd harmonic is selected, because it is the lowest frequency among all zero-sequence harmonics. The relationship between the exchanged active power at the i^{th} harmonic frequency Pi and the voltages generated by the converters is expressed by the well known the power flow equation and given as:

$$P_i = \frac{|V_{sh,i}||V_{se,i}|}{X_i}\sin(\theta_{sh,i} - \theta_{se,i}) \qquad (2)$$

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

V. 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.

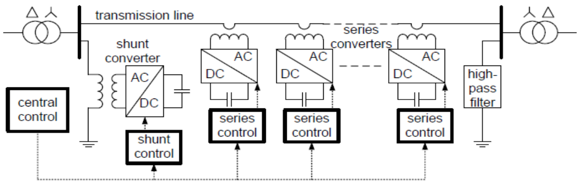


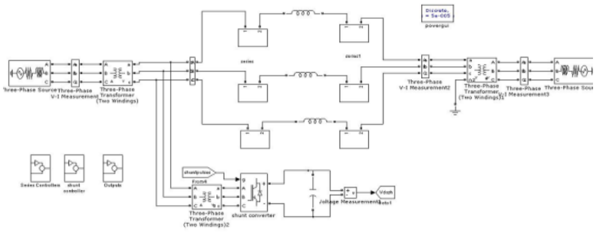
Figure 5: DPFC control block diagram

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.

VI. Laboratory Results

Simulation Model of the series converter control



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 shown in Fig. 7. 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 dc-voltage source. The specifications of the DPFC experimental setup are listed in the Table I.

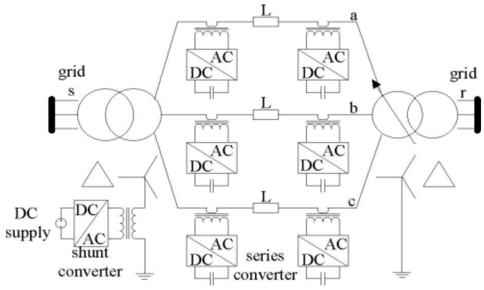


Fig. 7. DPFC experimental setup circuit

Table I: Specification Of The Dpfc Experimental Setup

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	°
L	line inductance	6	mH
$V_{sh,max}$	shunt converter maximum ac voltage	50	V
$I_{sh,max}$	shunt converter maximum ac current	9	A
$V_{sh,dc}$	shunt converter dc source supply	20	V
$I_{sh,ref,3}$	reference 3^{rd} harmonic current injected by the shunt converter	3	A
f_{sw}	switching frequency for the 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

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

To verify the DPFC principle, 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. Figs. 8-10 show one operation point of the DPFC setup. For clarity, only the waveforms in one phase are shown. The voltage injected by the series converter, the current through the line, and the voltage and current at the Δ side of the transformer are illustrated.

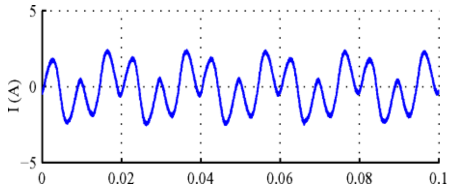


Fig. 8. DPFC operation in steady state: line current.

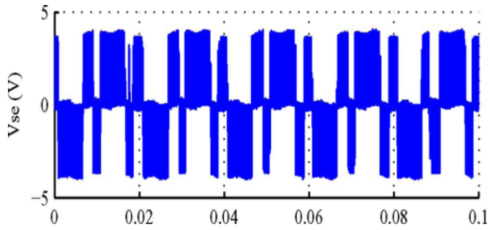


Fig. 9. DPFC operation in steady state: series converter voltage.

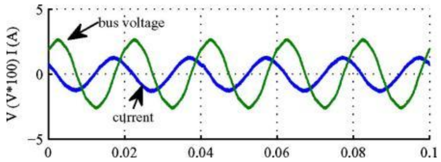


Fig. 10. DPFC operation in steady state: bus voltage and current at the Δ side of the transformer.

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 Fig. 8. The voltage injected by the series converter also contains two frequency components in Fig. 9. 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. Fig. 10 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. Figs. 11-15 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 shown in Fig. 11.

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. 12 and 13. 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 cut off 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. 14 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.

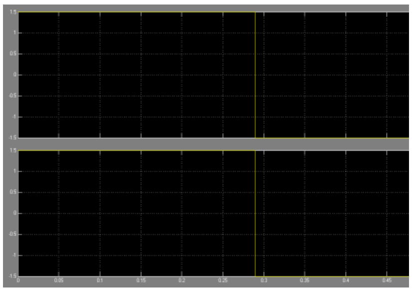


Fig. 11. Reference voltage for the series converters.

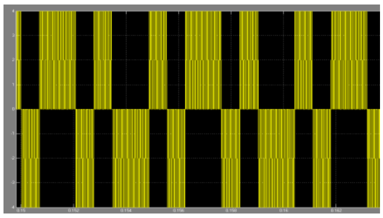


Fig. 12. Step response of the DPFC: series converter voltage.

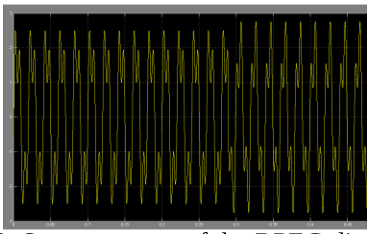


Fig. 13. Step response of the DPFC: line current.

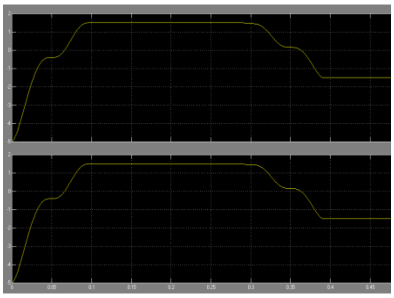


Fig. 14. Step response of the DPFC: active and reactivse power injected by the series converter at the fundamental frequency.

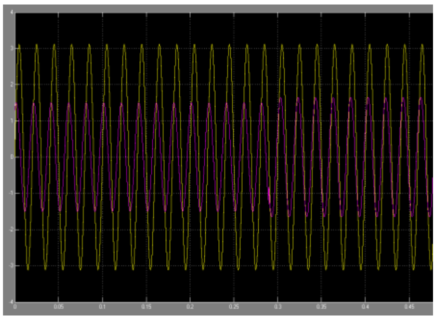


Fig. 15. Step response of the DPFC: bus voltage and current at the Δ side of the transformer.

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.

References

[1] Y.-H. Song and A. Johns, Flexible ac Transmission Systems (FACTS) (IEE Power and Energy Series), vol. 30. London, U.K.: Institution of Electrical Engineers, 1999.

[2] N. G. Hingorani and L. Gyugyi, Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems. New York: IEEE Press, 2000.

[3] L.Gyugyi, C.D. Schauder, S. L.Williams, T. R. Rietman,D. R. Torgerson, And A. Edris, ―The unified power flow controller: A new approach to power transmission control,‖ IEEE Trans.Power Del., vol. 10, no. 2, pp. 1085– 1097, Apr. 1995.

[4] A.-A. Edris, ―Proposed terms and definitions for flexible ac transmission system (facts),‖ IEEE Trans. Power Del., vol. 12, no. 4, pp. 1848–1853, Oct. 1997.