CONTROL AND PERFORMANCE OF DPFC DURING SHUNT CONVERTER FAILURE

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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 reliability of the DPFC is given by the redundancy of multiple series converters. 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 simulation results are also shown.

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 bidirectional 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. Un fortunately, 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.

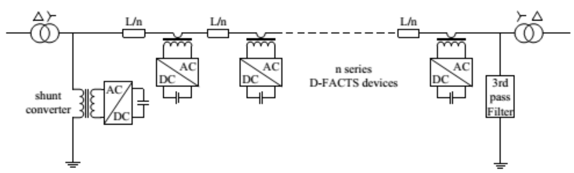


Fig.1. Distributed power flow controller

This paper presents a solution to maintain the DPFC system stable during the shunt converter failure. Adapted DPFC control schemes are applied to every series converter. The principle is to measure the magnitude 3rd harmonic current through the line, and to use this magnitude as a signal to automatically switch between using 3rd harmonic components or fundamental frequency component to keep dc voltage at a constant value. When the 3rd harmonic current is lower than the predefined threshold, the series converters will use the fundamental frequency component to maintain the dc voltage.

This paper begins with introducing the principle of the DPFC and its corresponding control scheme. Once the DPFC principle has been presented, the adapted control scheme for series converters is introduced and analyzed. This control scheme will be verified both by computer simulation and by experiment. The results are presented in the last part of the paper.

PRINCIPLE OF THE DPFC

A .Introduction of the DPFC

Multiple individual converters cooperate together and compose the DPFC, see Fig.1. The series converters consist of multiple units that are connected in series with the transmission lines. They can inject a voltage where the phase angle is controllable over 360◦ and where the magnitude is controllable as well. Consequently they control the power flow through the line. The converter connected between the line and ground is the shunt converter. The function of the shunt converter is to compensate reactive power to the grid, and to supply the active power required by the series converter.

In a normal UPFC, there is active power exchange through the DC link that connects the series converter with the shunt converter. Since there is no common dc link between the shunt and series converters in the DPFC, the active power is exchanged by harmonics through the ac network. The principle is based on the definition of active power, which is the mean value of the product of voltage and current, where the voltage and current comprise fundamental and harmonics. Since the integrals of all the cross-product of terms with different frequencies are zero, the time average active power can be expressed by:

$$P = \sum_{n=1}^{\infty} V_n I_n cos\emptyset_n \qquad (1)$$

Where n is the order of the harmonic frequency and φ_n is the angle between the current and voltage of the nth harmonic. Equation (1) describes that active powers at different frequencies are isolated from each other and that voltage or current in one frequency have no influence on other frequency components. The 3rd harmonic is chosen here to exchange the active power, because it can easily be filtered by Y-Δ transformers.

B. DPFC control principle

The DPFC system consists of two types of converters, and each type of converter requires a different control scheme. The block diagram of the DPFC and its control is shown in Fig.2. The shunt converter is controlled to inject a constant 3rd harmonic current into the transmission line, which is intended to supply active power for the series converters. The shunt converter extracts some active power from the grid at the fundamental frequency to maintain its dc voltage.

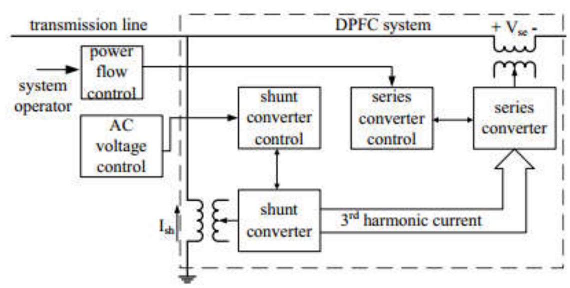


Fig.2. Block diagram of the control of a DPFC

The dc voltage of the shunt converter is controlled by the d component of the current at the fundamental frequency, and the q component is utilized for reactive power compensation. The series converters generate a voltage with controllable phase angle at fundamental frequency, and use the voltage at the 3rd frequency to absorb active power to maintain its dc voltages at a constant value. The power flow control function is realized by an outer control loop, the power flow control block. This block gets its reference signals from the system operator, and the control signals for DPFC series converters are sent remotely via wireless or PLC communication method. The function of each control block shown in Fig.2 can be described as:

• Power flow control: receives the set point for power flow from the system operator, and calculates the fundamental frequency voltage that should be injected by the series converters.

• Series converter control: generates switching signals according to the received data, and stabilizes dc capacitor voltage by controlling 3rd harmonic components.

• AC voltage control: gives the set points to shunt converter for reactive power compensation at the fundamental frequency.

• Shunt converter control: generates 3rd harmonic current, the reactive current at the fundamental frequency and stabilize the dc voltage.

ADAPTED CONTROL DURING THE SHUNT CONVERTER FAILURE

As mentioned above, the dc voltages of the series converters are maintained by the 3rd harmonic current injected by the shunt converter. This dc voltage cannot be maintained during the shunt converter failure, since there is no 3rd harmonic injected. Therefore, the adapted control scheme is applied on the series converters, and aims to provide a stable dc voltage at all situations. This section presents the principle and analysis of the adapted control scheme, and corresponding revises within the power flow control loop.

A. Principle of the Adapted Control Scheme

The currents at the fundamental and 3rd harmonic frequencies flow through the series converters, and theoretically both can be utilized for dc voltage stabilization. The principle of the adapted control for series converters is to use different frequency current to maintain dc voltage at different conditions. Two operation modes are defined for the series converter control:

• Full-control mode: In this mode, the DPFC operates in normal condition. The series converters inject both controllable active and reactive components into the grid at the fundamental frequency, and the dc voltage is stabilized by absorbing active power at 3rd harmonic frequency.

• Limited-control mode: The DPFC operates in this mode when there is a shunt converter failure. The series converters can only provide reactive compensation to the line, which means only control the line impedance like a SSSC. No component at the 3rd harmonic frequency is injected by the series converters, and the dc voltage of the series converter is stabilized by the active component at the fundamental frequency. In this mode, the DPFC can still control the active power flow through the line by adjusting the line impedance. The signal for switching the series converters between these two modes is the magnitude of the 3rd harmonic through the line, which can be easily captured by series converters without extra cost and well represents the status of the shunt converter. A threshold is predefined for each series converter. When the magnitude 3rd harmonic current is lower than the threshold, which means a shunt converter failure, the series converters are switched from the full-control mode to limited-control mode. The adapted control scheme is realized by the DSP controller in each series converter, and the calculation capability of the DSP in the series converter limited. Theoretically, two dc voltage control loops are required to enable the series converter to switch between the two modes, where each loop is responsible for one of the frequency components. This solution increases the computational effort for the DSP, because two loops need to be processed although only one loop is active. A control scheme with only one dc control loop is proposed, and structure is illustrated in Fig.3.

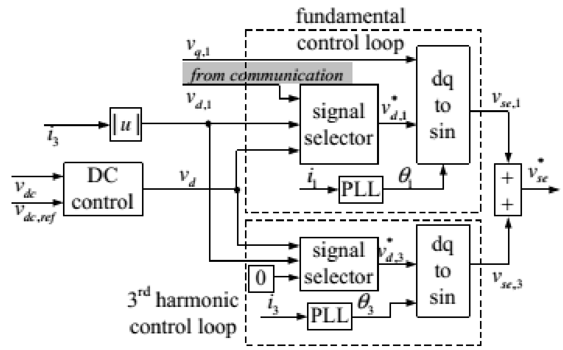


Fig.3. The adapted series converter control

In the full-control mode, the upper selector forwards the control signal from communications and the lower selector chooses the output from the dc control. While in the limited control mode, the upper selector forwards the dc control output signal regardless the active compensation signal from communications. As shown, the control loops for the fundamental and 3rd harmonic frequency share the same dc voltage controller and the output of the dc control are connected to different frequency control loops by signal selectors. The 'Park-Transformation' is employed to transform ac values at different frequency into dc values. Two rotation reference frames for both frequencies are generated by the PLLs, and the line currents are selected as the input of the PLLs.

The structures of the dc control for both frequencies are identical, and the output of the dc control is in dc quantity. Therefore, the output can be the d component reference of the control loops for both frequencies. The proposed control scheme only possesses one dc control loop and consequently does not increase any computation complexity.

B. Analysis

This section presents the design of the dc control, and analyzes the influence of the dc control integration. The parameters for the dc control are calculated in the full-control mode, since this mode is normal operation. The series converter is single-phase full bridge converter, and its simplified diagram is shown in Fig.4.

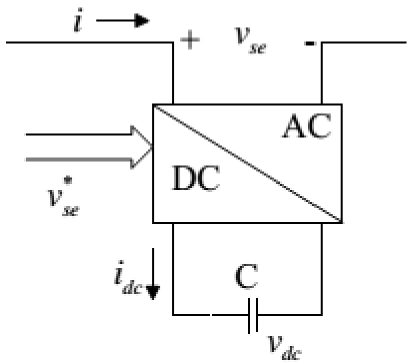


Fig.4. The simplified diagram of a series converter

The voltage v_{se}* is the control voltage for the series converter generated by the control, and the voltage injected by the series converter is given by: $v_{se} = v_{se}*v_{dc}$. As the switching frequency of the converter is much larger than the grid frequency, the current at the dc side can be approximated to [4]:

$$i_{dc} = v^*_{se}.i \tag{2}$$

As both the control voltage and ac current consist of the components at the fundamental and 3rd harmonic frequency, the relationship between the dc voltage and current can be written as:

$$C\frac{dv_{dc}}{dt}=i_{dc}(t) = (v^*_{se,1} + v^*_{se,3})(i_1 + i_3) \tag{3}$$

Where the subscript represents the order of the component frequency. The dc current contains multiple frequency components. Since the dc voltage is the integration of dc current, only the current terms with non-zero mean contribute the dc voltage. The terms with zero mean appear as a ripple in the dc voltage, and the amplitude of the oscillation depends on the capacitance. Therefore, the zero mean terms within the dc current will be neglected, and through 'Park transformation' equation 3 can be simplified to:

$$C\frac{dv_{dc}}{dt} = \frac{1}{2}(v^*_{1,d}i_{1,d} + v^*_{1}i_{1,q}) + \frac{1}{2}(v^*_{3,d}i_{3,d} + v^*_{3,q}i_{3,q}) \tag{4}$$

Since the reference frame of the series converter controller is line current for both frequencies components as shown in Fig.3, the q components of the current is zero, so 3 can be rewritten as:

$$C\frac{dv_{dc}}{dt} = \frac{1}{2}(v^*_{1,d}i_{1,d} + v^*_{3,d}i_{3,d}) \tag{5}$$

In the full-control mode, the 3rd harmonic component is used to stabilize the dc voltage, and the fundamental frequency component is treated as a disturbance h(s). By using the Laplace transformation, the transfer function from $v_{3,d}$* to v_{dc} is found to be:

$$G(s) = \frac{v_{dc}(s)}{v^*_{3,d}(s)} = \frac{I_{3,d}}{2sC} \tag{6}$$

The Internal Model Control (IMC) [5], [6] is used for designing the dc controller because of its simplicity. An inner The Internal Model Control (IMC) [5], [6] is used for designing the dc controller because of its simplicity. An inner feedback loop is introduced for active damping [7], as the transfer function has a pole in the origin. Therefore, the dc control scheme with control function F(s) and active damping conductance R is illustrated in Fig.5.

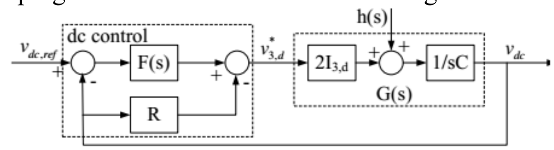


Fig.5. DC control scheme of the series converter

By using the IMC method, the control function F(s) is calculated as: C R

$$F(s) = \frac{2C\alpha_d}{I_{3,d}} + \frac{R\alpha_d}{S} \tag{7}$$

Where α_d is a design parameter, and means the desired bandwidth of the closed-loop system here. The relationship between the bandwidth and the rise time t_{rise} (from 10% to 90% of the final value) is $\alpha_d = \ln 9/t_{rise}$[7]. A suitable choice is to make the inner feedback loop as fast as the closed-loop system, accordingly the parameters of the dc control is:

$$k_p = \frac{2C\alpha_d}{I_{3,d}},\ k_i = \frac{2C\alpha_d^2}{I_{3,d}},\ R=\frac{2C\alpha_d}{I_{3,d}} \tag{8}$$

When the shunt converter has a failure, series converters are switched to limited-control mode and use the d component of the voltage at the fundamental frequency $V^*_{d,1}$ for dc voltage stabilization. Therefore, the transfer function from $V^*_{d,1}$ to v_{dc} can be found from (5):

$$G(s) = \frac{v_{dc}(s)}{v^*_{1,d}(s)} = \frac{I_{1,d}}{2sC} \tag{9}$$

By comparing the two transfer functions (6) and (9), it is found that their structures are identical only with different ratios. Therefore, it can conclude that the dc controller designed for the full-control mode works in the limited-control mode, but with different transient response time.

C. Power Flow Controller Changes

The outer control loop - power flow control for the DPFC is designed for controlling both active and reactive power flow through the line, therefore there are two control loops correspondingly. However, during the shunt converter failure, the DPFC is operated in limited-control mode and can only adjust the line impedance. As the active power flow control through the line is priority in a normal power system, the remained control freedom of varying line impedance is utilized for controlling the active power flow through the line. The simplest way of changing power flow controller is to disable the reactive power flow control loop during the shunt converter failure, as shown in Fig.6. The output of the reactive power flow control loop is disabled by the signal selector according to the 3rd harmonic current magnitude. As shown, in this method, the control still generates the active voltage control signal $v_{d,1}$ for series converters, although this control signal is disregarded by the series converters.

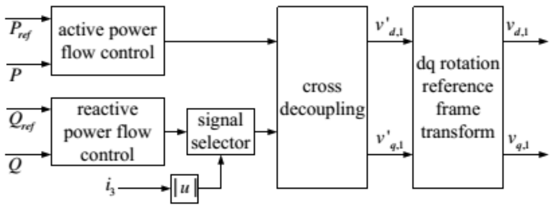


Fig.6.The adapted power flow control loop

Accordingly, the transient performance of this change of the power flow controller is not very good. However, as the power flow control is the control loop outside the DPFC system, the transient optimization will not be discussed here.

SIMULATION

The simulation of the DPFC during the shunt converter failure has been done in Matlab, simulink. The system shown in Fig. 7 is used as a test example. The magnitudes of the voltages at buses are both 1pu with 1.5 degree angle difference. The transmission line is represented by a 0.06pu inductor, and the resistance is neglected. Accordingly, the power flow of the system without compensation is around P=-1pu, and Q=0.06pu. In the simulation, the power flow is limited by the DPFC to P=-0.6pu and Q=-0.02pu. And the DPFC uses constant 0.4pu 3rd harmonic current to exchange active powers between the shunt and series converters.

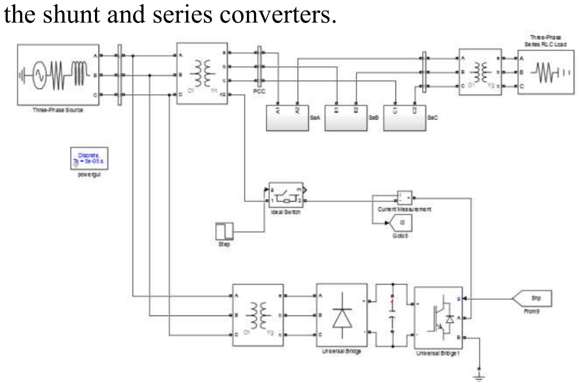


Fig.7. simulation circuit of DPFC with R-Load

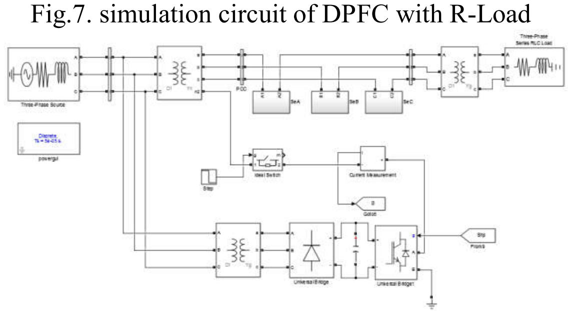
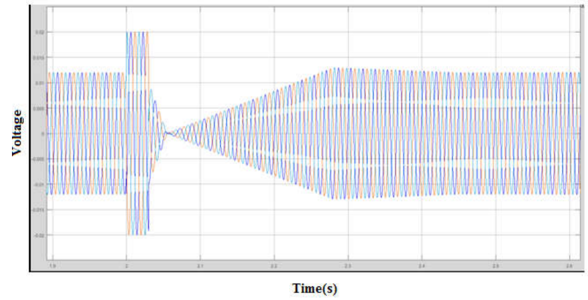


Fig.8. simulation circuit of DPFC with R-Load

To simulation the shunt converter failure, the shunt converter is switched off at the time t=2s. Fig.9 shows the 3-phase fundamental voltages generated by the series converters.



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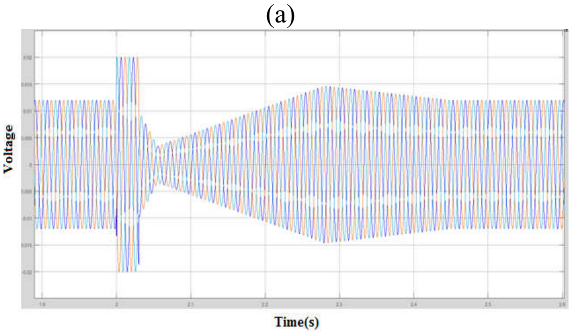

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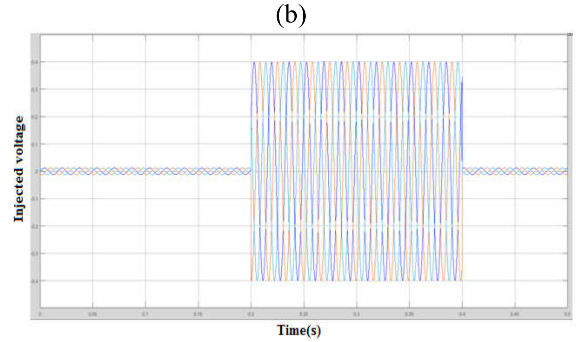

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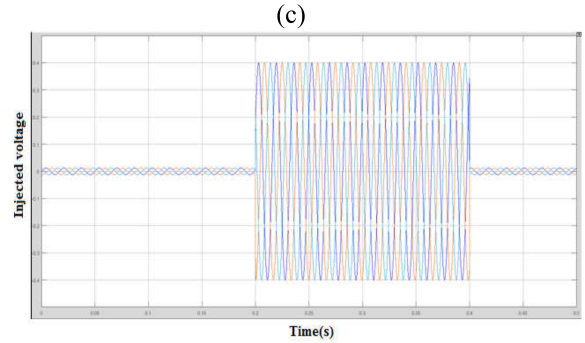
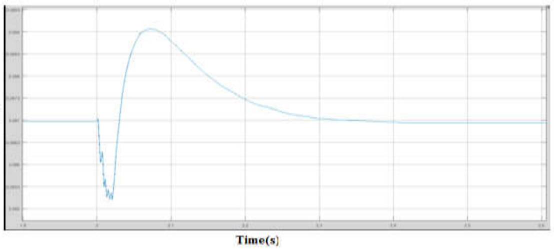


(d)

Fig.9. AC voltage generated by the series converter after the shunt converter failure at t=2s (a) R- load (b) RL- load (c) R- load with Sag (d) RL- load with Sag

In the normal operation, the voltages generated by the series converters contain both the fundamental and 3rd harmonic frequency components, and the dc voltages are maintained by the 3rd harmonic. After the failure, there is no 3rd harmonic current in the line, and the series converters use the fundamental components to control their dc voltage. Therefore, only the components at the fundamental frequency are injected into the line during the shunt converter failure. The transient of the voltage in Fig. 9 is caused by switching off the reactive power flow control loop. This overshooting can be eliminated by optimization of the power flow control loop; however it is out of the scope of this paper. The dc voltages of the series converters are illustrated in Fig.10



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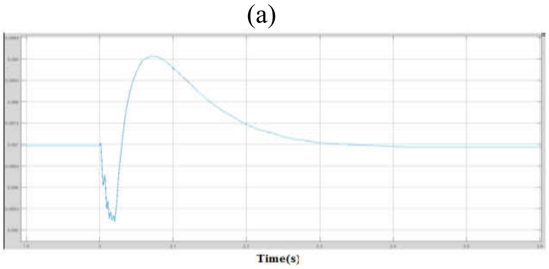

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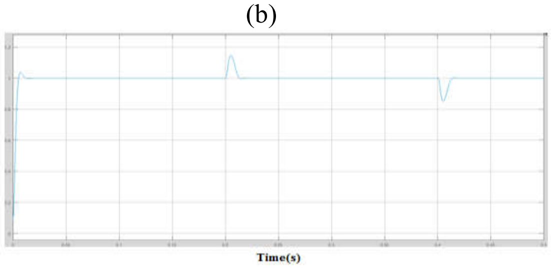

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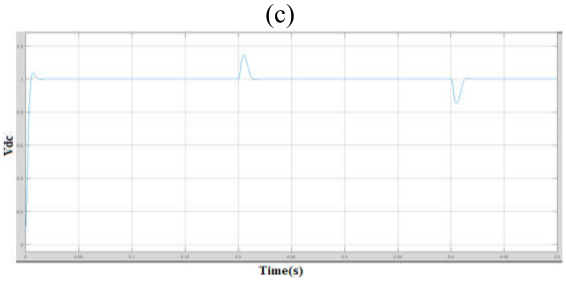
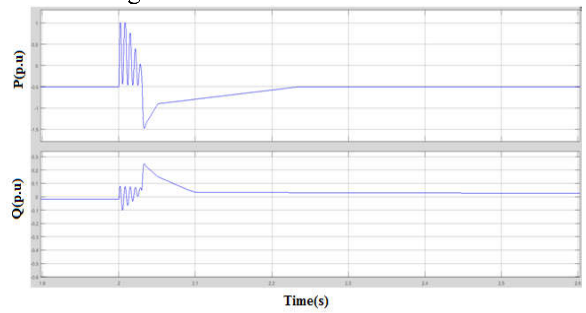


(d)

Fig.10. DC voltages of the series converters after the shunt converter failure at t=2s (a) R- load (b) RL- load c) R- load with Sag (d) RL- load with Sag

The dc voltages of the series converters in all phases are well controlled during the failure. The variations of the dc voltage are less than 1% during the operation. As the DPFC loses one control freedom during the shunt converter failure, only the active power flow is controlled in this case. The active and reactive power flow through the line is shown in Fig.11



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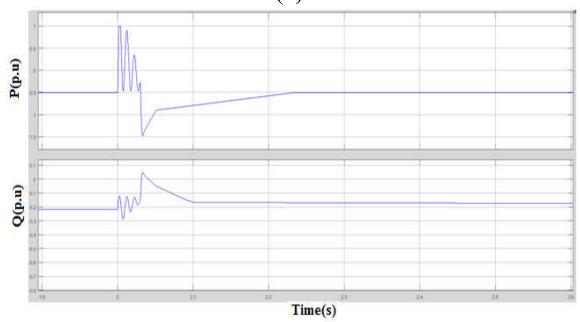

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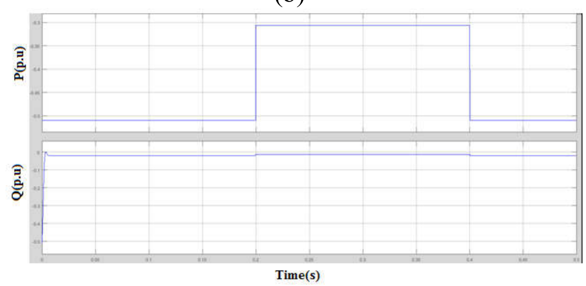

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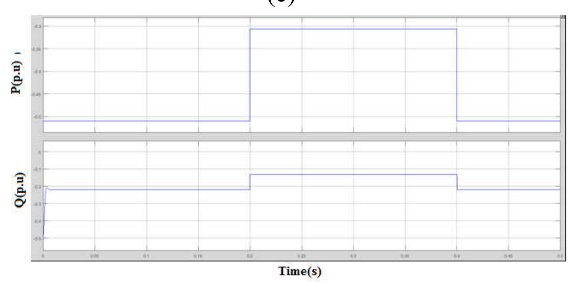

(d)

Fig.11. Active and reactive power flow through the line after the shunt converter failure at t=2s (a) R- load (b) RL- load (c) R- load with Sag (d) RL- load with Sag

The active power is controlled by the DPFC at -0.6pu during the whole operation, while the reactive power flow cannot be controlled after the shunt converter failure. The experimental setup is powered by the grid at 220V, and only one set of series converters is applied in this test. The shunt converter is manually turn off at the t=0.8s, and for clarity only the waveforms in one phase are shown. To clear out the transient caused by the power flow controller, the control signals for series converters are fixed.

CONCLUSIONS

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 s mall 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 is low. The DPFC concept has been verified in MATLAB-SIMULINK. 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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