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Performance Analysis of DPFC Under Different Load Conditions

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ABSTRACT

The Distributed Power Flow Controller (DPFC) is a new device within the FACTS family. It is emerged from the UPFC and has relatively low cost and a high reliability. The DPFC consists of two types of converters that are in shunt and series connected to grids. The common dc link between the shunt and the series converters is eliminated. The active power exchange between the shunt and series converters that is through the common dc link in the UPFC, is now though the transmission line at the 3rd harmonic frequency. The redundancy of the series converters provides the high reliability of the system. In this paper, the DPFC behavior during the failure of a single series converter unit is considered. A control scheme to improve the DPFC performance during the failure is proposed. The principle of the control is based on the facts that, the failure of single series converter will lead to unsymmetrical current at the fundamental frequency. By controlling the negative and zero sequence current to zero, the failure of the series converter is compensated. In this paper, the principle of the DPFC are firstly introduced, and followed by the behavior of the DPFC during the failure of a single series converter. The design of the control scheme and corresponding simulation are presented.

KEYWORDS : Distributed Power Flow Controller (DPFC), DQ-controller, Power quality, Distribution system, sag, FACTS

I. INTRODUCTION

In nowadays power system, there is a great desire for the fast and reliable control of the power flow because of the growing demand of energy, the aging of networks and distributed generation. The Distributed Power Flow Controller (DPFC) recently presented in [1], is a powerful device within the family of FACTS devices, which provides a higher reliability than conventional FACTS devices at lower cost. It is derived from the UPFC and has the same capability to simultaneously adjust all the parameters of the power system: line impedance, transmission angle, and bus voltage magnitude [2]. Within the DPFC, the common dc link between the shunt and series converters is eliminated, which provides flexibility for independent placement of series and shunt converter. Instead of one large three-phase converter, the DPFC employs multiple single-phase converters (D-FACTS concept [3]) as the series compensator. In this way, the series converters can float with respect to the ground thus reducing the cost of high voltage isolation. The DPFC uses the transmission line to exchange active power between converters at the 3rd harmonic frequency [1]. This concept not only reduces the rating of the components but also provides a high reliability because of the redundancy. The scheme of the DPFC in a simple two-bus system is illustrated in Fig. 1.

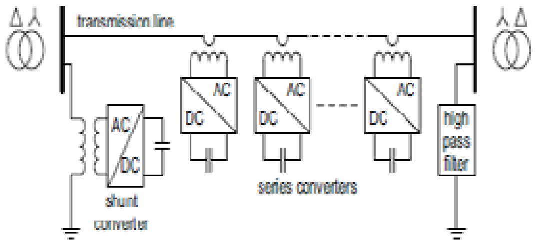


Fig. 1. Distributed power flow controller

The high reliability of the DPFC is provided by the redundancy of the converters. If one converter fails, the others will continue operation. However, the failed converter will stop providing the desired voltage, thereby causing asymmetry of the series converters and reducing the performance of the DPFC. In this paper, the behavior of the DPFC during a single series converter failure is discussed. A control scheme that improves the DPFC performance during series converter failure is proposed, and the design of the control scheme and corresponding simulation are also presented.

DPFC PRINCIPLE

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 3600 and where the magnitude is controllable as well, thereby controlling the active and reactive 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. 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 have the same control capability as the UPFC, a method that can let active power exchange between converters with eliminated dc link is the precondition.

Within the DPFC, there is a common connection between the ac terminals of the converters in different lines, which is the transmission line. Therefore, it is possible to exchange the active power through the ac terminals. The method is based on the power theory of non-sinusoidal components. According to the Fourier analysis, a non-sinusoidal voltage and current can be expressed by the sum of sinusoidal functions in different frequencies with different amplitudes. The active power resulted by 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:

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

where Vn and In are the voltage and current at the nth harmonic frequency respectively, and φn is the corresponding angle between the voltage and current. Equation (1) describes that active power at different frequencies is isolated from each other, and voltage or current in one frequency has no influence on the active power at other frequencies. The independency of the active power at different frequencies gives the possibility that a converter without power source can generate active power at one frequency and absorb this power from other frequencies. The 3rd harmonic is selected to exchange the active power in the DPFC, because it is a zero-sequence harmonic and can be naturedly blocked by Y-Δ transformers, which are widely used in power system to change voltage level.

DPFC control principle

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. 2.

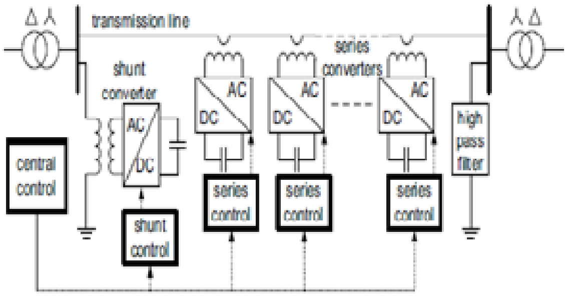


Fig. 2. Block diagram of the control of a DPFC

The shunt and series control are localized controllers and are responsible for maintaining their own converters' parameters. The central control is focus on the DPFC functions in power system level. The functions of each controller are listed: • Central control: The central control generates the reference signals for both the shunt and series converters of the DPFC. It is focus on the DPFC applications in the power system level, such as power flow control, low frequency power oscillation damping and balancing unsymmetrical components, etc. According 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.

- 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 mean time, it maintains the capacitor dc voltage of the shunt converter by absorbing active power from the grid at the fundamental frequency, and injects required reactive current at the fundamental frequency to the grid.
- Series control: Each series converter has its own series control. The controller is used to maintain the capacitor dc voltage of its own converter by using the 3rd harmonic frequency components, and to generate series voltage at the fundamental frequency that is required by the central control.

II. DPFC BEHAVIOR DURING SERIES CONVERTER FAILURE

Two types of failures can happen in the DPFC series converters: short circuit and open circuit. The short circuit for the series converters is not a problem, because it will not interrupt the transmission line. However, when the series converters have an open circuit, the transmission line will be also open circuit thereby influencing the whole network. To prevent the open circuit of the series converters, a bypass circuit is provided for each series converter. A crowbar is in parallel to the output terminals of the series converter. Once the series converter has an open circuit, the crowbar will be connected and provide the bypass for the transmission line. Accordingly, the failed series converter appears short circuit to the transmission line, therefore the voltage injected by series converters becomes unbalance between phases. This unbalanced series voltage leads to unsymmetrical current in the line thereby decreasing power quality of the network.

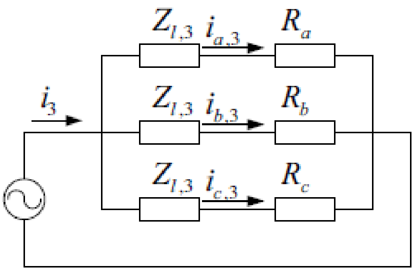


Fig. 3. The equivalent network of the DPFC at the 3rd harmonic

The faulty series converter do not require any active power, therefore the required active power between phases is different which results a change of the 3rd hamornic current. To find the 3rd harmonic current in each phase, the equivalent network of the DPFC at the 3rd harmonic is needed, as shown in Fig. 3.

I3 is the constant 3rd harmonic current generated by the shunt converter. At the 3rd harmonic frequency, the series converters are control to only generate or absorb active power, and they act like variable resistors. Therefore the series converters can be represented by the resistances [Ra,Rb,Rc] at the 3rd frequency.

III. CONTROL SCHEME TO IMPROVE THE PERFORMANCE

The principle of the supplementary control is to let the remained converters in the line with the fault converters inject more voltages to maintain the voltage balance between phases at the fundamental frequency. As the series converters are centralize controlled, this supplementary control is within the central controller. There are two requirements of the supplementary control:

- The controller should be able to distinguish the phase with the faulty converter and give correct compensation voltage reference.
- The communication between central control and series converters in different phases should be independent to enable the series converters in one phase to generate different voltage from the other phases.

One approach to compensate the converter failure is to let series converters report their status of the operation (active/ inactive) back to the central controller. The controller generates corresponding reference signals for each phase according to the number of the active converters. However, there are two major drawbacks of the method. First, this method highly relies on the communication between the converters and the central controller. Any false report will lead to an incorrect compensation. Second, the failed series converter is not pure short circuit and there will be a small unpredictable inductance inserted because of the single-turn transformer, and this inductance cannot be compensated by this method. The proposed control scheme is based on the fact that, the failure of a single series converter will lead to unsymmetrical current at the fundamental frequency. By controlling the negative and zero sequence current to zero, the failure of the series converter is automatically compensated. For this purpose, two current control loops is added to the existing DPFC controller to control zero and negative sequence current, respectively. These two supplementary controllers are located in the central controller. All these controllers operate all the time. The control scheme of the central control with these supplementary controllers is shown in Fig. 4.

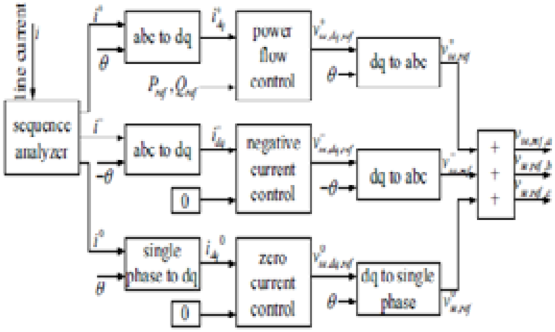


Fig. 4. Control scheme for unbalance compensation

The sequence analyzer processes the three-phase line current first. The positive sequence current is used for power flow control purposes and the other sequence currents are for series converter failure compensation. When there is no failed series converter, the negative and zero sequence current is zero. In the case of series converter failure, the two current controllers force the negative and zero sequence current to become zero. The voltages created by the two controllers are added together with the positive voltage to construct the reference signals for the series converters in different phases.

IV. CONTROLLER DESIGN

A popular method for current control - synchronous PI control is employed for the zero and negative sequence controller because of the simplicity for implementation [4]. The idea is to transform ac currents and voltages into a rotating reference frame, where the controlled currents are constant in 'steadystate'. Ordinary PI controllers can be used on the transformed values, and the outputs of the controls can be transformed back to the fixed reference frame. For the negative components, the conventional Park Transformation is used. As the zero sequence currents are in-phase, the single-phase Park Transformation [5],

[6], [7] is employed. Both transformations utilize the bus voltage at the fundamental frequency as the rotation reference frame.

V. Results

Fig. 5 shows the matlab implementation of DPFC. Dynamic response of DPFC voltage and current and the transition sequence from capacitive mode of operation to inductive mode of operation with no transient over voltage appeared, and this transition for operation mode takes a few milliseconds. This smooth transition is due to the novel controller, which is based on the decoupled control strategy and the variation of the capacitor dc voltage.

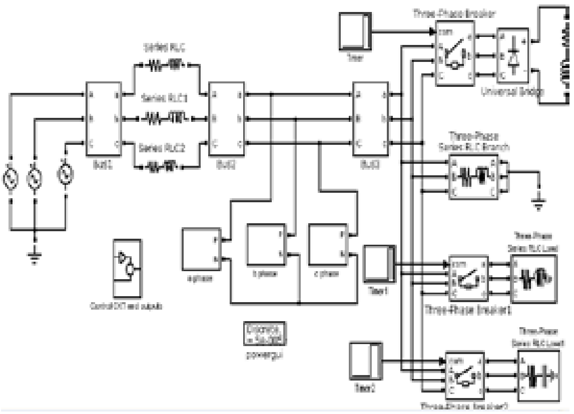


Fig. 5: matlab implementation of DPFC system

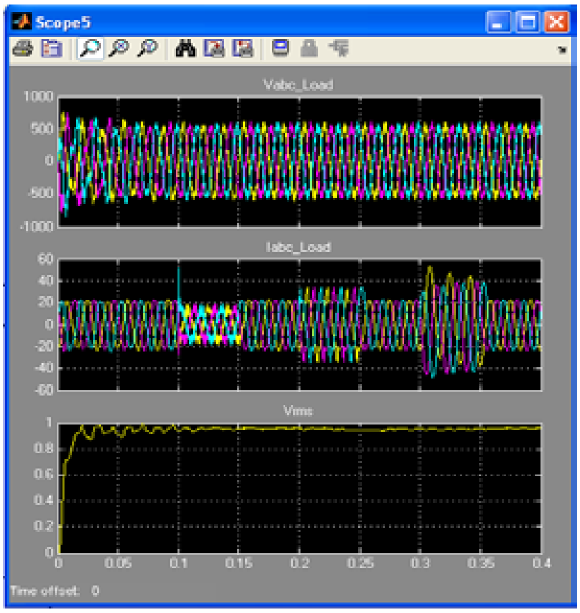
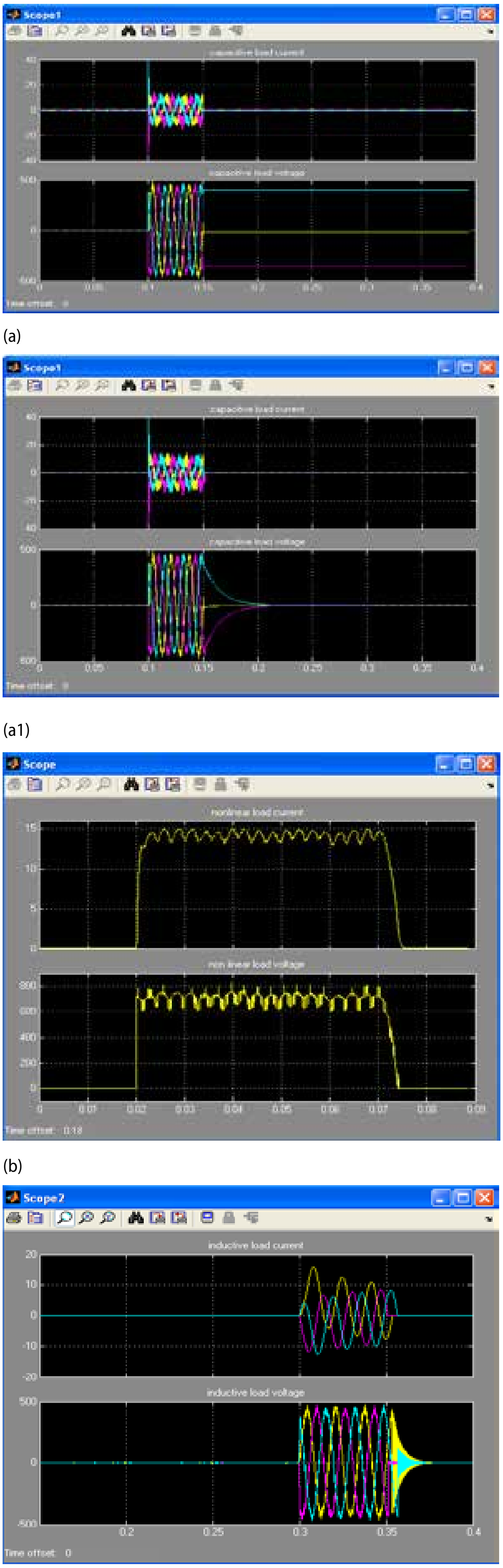


Fig 6: load voltage, load current and Vrms.

In Fig 5, throughout analysis common impedance Z (R + jX) is connected to line, here this impedance secondary ports connected to ground, so this impedance acts as a load. Due to this impedance normal load current is flow through load this is shown in fig 6 this is known as normal load current. from time 0.1 sec to 0.15 sec. connected 5000 var capacitive load to the transmission line and remove this from line at 0.15 sec. this performance is shown in fig 6: in this fig.6. From Time 0.1sec to 0.15 load current is reduced because of capacitive load connected to line only capacitive load current is shown in fig 7a. From time 0.15 to 0.2 sec normal load connected so current is same as previous load current. From time 0.2 sec to 0.25 sec, connected nonlinear load, so non-linear current is flow through load after 0.25 sec remove nonlinear load, so normal current is flow through this load. This nonlinear load current is also shown in fig 7b. from 0.3 sec to 0.35 sec inductive load is connected to line, so load current is increase after 0.35 sec remove this inductive load so again load current is reach normal load current, this is shown in fig 7. Only inductive load current is shown in fig 7c.fig 7(a1) is represent the resistive load is connected parallel to capacitive load, so voltage will reach zero after remove the capacitive load.



(a)

(a1)

(b)

(c)

Fig. 7: The load voltage is same as supply voltage at all time.

VI. CONCLUSIONS

The paper presents a novel controller for application of DPFC. These full descriptive digital models are validated for voltage stabilization reactive compensation and dynamically power flow control using three novel decoupled current control strategies. The control strategies implement decoupled current control and auxiliary tracking control based on a pulse width modulation switching technique to ensure fast controllability, minimum oscillatory behavior, and minimum inherent phase locked loop time delay as well as system instability reduced impact due to a weak interconnected ac system. The load voltage is same as supply voltage at all time, so load voltage is constant. This novel configuration tested under different conditions and presented results based on matlab.

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