VOLTAGE REGULATION OF 3-PHASE TRANSMISSION SYSTEMS BY USING DISTRIBUTED POWER FLOW CONTROLLER (DPFC)

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Abstract: Distributed Power Flow Controller (DPFC) is a new device within the family of FACTS. It is derived from UPFC by eliminating common DC link between the shunt and series converter. The active power exchange between the shunt and series converters which is through the common DC link in UPFC is now through the transmission lines at the third harmonic frequency in DPFC. The DPFC has the same control capability as the UPFC, but with much lower cost and higher reliability. It employs two converters namely series and shunt converters and each converter needs a controlling circuit and an additional central circuit which provides reference voltage to series and shunt controlling circuit. This paper addresses one of the applications of the DPFC namely compensation of unbalanced voltage in the 3-phase transmission systems. It consists of voltage, real and reactive power variations with and without DPFC using MATLAB/SIMULINK is simulated.

IndexTerms – FACTS, UPFC, DPFC.

I. INTRODUCTION

Power Quality is becoming an important issue for both electric utilities and the receiving end users [1]. Unbalanced voltages and currents in a network are one of the concerns under the power quality issue. The unbalance is mainly produced by the great number of single-phase loads which are unevenly distributed over the phases [2]. The unbalance voltages can cause extra losses in components of the network, such as generators, motors and transformers, while unbalanced currents cause extra losses in components like transmission lines and transformers [3]. Active filters and power factor corrector can be applied to compensate the unbalance at the load side, however their contributions to transmission systems is not large because they are focused on single load [4], [5]. FACTS devices can be employed to compensate the unbalanced currents and voltages in transmission systems. Unfortunately, it is found that the capability of most of FACTS devices to compensating unbalance is limited. The most powerful device – the UPFC [7] consists of common DC link for active power exchange. This paper will show that the DPFC can compensate unbalance voltage in the 3-phase transmission systems.

The Distributed Power Flow Controller (DPFC) recently presented in [9], is a powerful device within the family of FACTS devices, which provides much lower cost and higher reliability than conventional FACTS devices. It is derived from the UPFC and has the same capability of simultaneously adjusting all the parameters of the power system: line impedance, transmission angle, and bus voltage magnitude. 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. The DPFC uses the transmission line to exchange active power between converters at the 3rd harmonic frequency [9]. Instead of one large three-phase converter, the DPFC employs multiple single-phase converters (D-FACTS concept [10]) as the series compensator. This concept not only reduces the rating of the components but also provides a high reliability because of the redundancy. Comparing with the UPFC, the DPFC have the following 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.
3) High controllability.

The scheme of the DPFC in a simple two-bus system is illustrated in Fig.1.
II. DPFC OPERATING PRINCIPLE

A. 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:

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

where \( V_i \) and \( I_i \) are the voltage and current at the \( i \)th harmonic frequency respectively, and \( \phi_i \) 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, thereby 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.

B. 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-\( \Delta \) transformers 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-\( \Delta \) transformer on the right side with the ground. Because the \( \Delta \)-winding appears open-circuit to the 3rd harmonic current, all harmonic current will flow through the Y-winding and concentrate to the grounding cable. Therefore, the large high pass filter is eliminated.

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. 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. 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 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.

III. DPFC CONTROL SCHEME

The basic control block diagram of DPFC is shown in Fig.2.

Fig.2. DPFC basic control

A. Series Converter of DPFC

Distributed static series compensator is nothing but SSSC with reduced power rating. Instead of high power conventional SSSC, numbers of low power DSSC modules are clamped around the conductor. Each DSSC module consists of small rated (~10 kVA) single phase inverter and a single turn transformer (STT) that is mechanically clamped on to existing transmission line. DSSC controls effective impedance of the transmission lines by injecting voltage in series with the line so as to control the active power flow. Each DPFC series converter is locally controlled by its own controller, and the scheme for each series control is identical. To control the series converter, separate control loops are employed for the two frequency components. The 3rd harmonic control loop is used for DC voltage control. The principle of the proposed method is to transform the control signal from AC quantities into DC quantities by using Park’s transformation at the sending end and convert the received DC control signals back to AC locally, at each series converter. For the inverse transformation at the receiving end, the line current is used as the rotation reference frame, instead of the line-to-line voltage that is commonly used. The line current can easily be measured by the series converter locally without extra cost. A Single-phase Phase Lock Loop (PLL) is employed in each DPFC floating series converter to achieve the phase and frequency information of the grid. In this case, only the d and q information in DC quantities is transmitted to the converters. Together with the phase and frequency information from the line current, the signals in DC quantities can be transformed back into AC by the inverse Park’s transformation. Because DC quantities are transmitted, the series converter can continue operation at the last received setting if the communication is lost.

The 3rd harmonic frequency control is the major control loop with the DPFC series converter control. Its task is to maintain the DC capacitor voltage. The principle of vector control is used here for DC voltage control. Normally, the voltage is used as the rotation reference frame for Park’s transformation, but here the 3rd harmonic current through the line is selected because it is easily measured by the series converter. As the line current contains two frequency components, a 3rd band pass...
filter is needed to extract the 3rd harmonic current. The single-phase Phase-Lock-Loop (PLL), creates a rotation reference frame from the 3rd harmonic current. The d component of the 3rd harmonic voltage is the parameter used to control the DC voltage. The control signal is generated by the DC voltage control loop. Because the q component of the 3rd harmonic voltage will only cause reactive power injection to the AC network, the q component is kept at zero during the operation. Control scheme of series converter is shown in Fig.4.

![Control scheme of series converter](Fig.4)

**B. Shunt converter of DPFC**

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. 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-Δ 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 circuit scheme of this topology is shown in Fig.5. 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-Δ 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 three-phase converter, the single-phase converter can be directly connected back-to-back to the DC side of the three-phase converter, as shown in Fig.5.

![Simplified diagram of shunt converter](Fig.5)

**i. Three phase shunt converter**

The control of the shunt converter at the fundamental frequency aims to inject a controllable reactive current into the grid and to keep the DC voltage of the capacitor at a constant level. As shown in Figure 6, this control consists of two major blocks: the current control and the DC control. The current control is the inner control loop, which controls the current $I_{sh1}$. The reference of the q component of the current is from the central control and the reference signal of the d component is generated by the DC control. For Park’s transformation, the rotation reference frame is created by the PLL using the bus voltage as input.
The capacitor DC voltage of the shunt converter is given with the following equation:

$$C_{sh} \frac{dV_{sh,dc}}{dt} = I_{sh,dc,1} - I_{sh,dc,3}$$  \hspace{1cm} (2)

By applying Park’s transformation to the fundamental frequency components, the DC current at the three-phase side can be found:

$$I_{sh,dc,1} = \frac{3}{2} (V_{sh,1,d,ref}I_{sh,1,d} + V_{sh,1,q,ref}I_{sh,1,q})$$  \hspace{1cm} (3)

Park’s transformation is used here for conversion of stationary frame components to rotating frame i.e. abc to dq

$$V_{sh1} = V_{ref,sh,1} + V_{sh,dc}$$  \hspace{1cm} (4)

**ii. Single phase shunt converter**

The converter that is connected between the neutral point of the Y-Δ transformer and the ground is a single phase converter. It is responsible for injecting a constant 3rd harmonic current into the grid, therefore requiring a current controller. The 3rd 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 signal of the PLL $$\theta_1$$ is multiplied by 3 to create a virtual rotation reference frame for the 3rd harmonic component.

$$V_{sh3} = V_{ref,sh,3} + V_{sh,dc}$$  \hspace{1cm} (5)

Single-phase Park’s transformation for converting 3rd harmonic current to 3rd DC current is:

$$I_{sh,dc,3} = (V_{ref,sh,3,d} \sin 3\theta + V_{ref,sh,3,q} \cos 3\theta) \ast (I_{sh,3,d} \sin 3\theta + I_{sh,3,q} \cos 3\theta)$$  \hspace{1cm} (6)

IV. SIMULATION RESULTS

The simulation of application of the DPFC to compensate unbalance has been done in Matlab, simulink. The circuit diagram without DPFC is shown in Fig.7. The results of Fig.7, i.e. voltage, real and reactive powers at bus 2 is shown in Fig.8, Fig.9, and Fig.10, respectively.
The circuit diagram with DPFC is shown in Fig.11. The results of Fig.11, i.e. voltage, real and reactive powers at bus 2 is shown in Fig.12, Fig.13 and Fig.14, respectively.

Fig.11. Circuit diagram of with DPFC
Fig. 12. Voltage at bus \(-2\)

Fig. 13. Real power at bus \(-2\)

Fig. 14. Reactive power at bus \(-2\)

The comparison of results of voltage and power with and without DPFC are tabulated below.

Table 1

<table>
<thead>
<tr>
<th>DPFC</th>
<th>Voltage (volts)</th>
<th>Real power (MW)</th>
<th>Reactive power (MVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without DPFC</td>
<td>6500v</td>
<td>0.4520</td>
<td>0.0684</td>
</tr>
<tr>
<td>With DPFC</td>
<td>8500v</td>
<td>0.5326</td>
<td>0.2251</td>
</tr>
</tbody>
</table>
V. CONCLUSIONS

This paper investigates the capability of the DPFC to balance a network. It is found that DPFC can compensate the unbalance voltages in the three phase transmission line, consequently DPFC is more powerful than any other FACTS device to compensate unbalance voltages. Compensating the unbalance voltages with and without DPFC are separately simulated and their results are compared. It is observed that using DPFC unbalanced voltages are compensated more than without using DPFC. Therefore, power quality of the system can be improved. In future we can also use renewable energy resources along with the DPFC for more betterment.

VI. REFERENCES