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Simulation and Analysis of Distributed Power Flow Controller in High Voltage Transmission System

Han Su Yin*, Shwe Zan Aung**

*(Department of Electrical Power Engineering, Yangon Technological University/ Yangon, Myanmar)

** (Project & System Design, Omega Integration Pte. Ltd)

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Abstract:

In power transmission systems, the power flow must be controlled quickly and reliably. As the load changes, the voltage variation in transmission lines can damage the consumer's equipment distributed side. For reducing these problems, the power flow controller is used in transmission lines. Thus, this paper presents a power flow controlling device called Distributed Power Flow Controller (DPFC). This device offers the same control capability as the unified power-flow controller (UPFC) but with much lower cost and higher reliability. The DPFC eliminates the common DC link within the UPFC. It employs two converters i.e. series and shunt converter, and each converter needs a controlling circuit and an additional central controlling circuit which provides reference voltage to series and shunt controlling circuit. The active power that is exchanged through the common DC link in the UPFC is now transferred through the transmission line at the 3rd harmonic frequency. The interaction between the DPFC, the network and the machines are analyzed in this paper. The DPFC is modeled by using dq-frame. To simulate the dynamic performance, three phase symmetrical fault is considered near the load and, the modeling and analysis of power flow with DPFC in two areas with two buses interconnected system with star-delta transformers at each end is done by using MATLAB/ Simulink.

Keywords **—FACTS, AC-DC Power Conversion, DPFC, Power System Control, Power flow controller.**

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I. INTRODUCTION

An electrical power system deals with electrical generation, transmission, distribution and consumption. In traditional power system, the electrical energy is generated by centralized power plants and flows to consumers via the transmission and distribution network. The rate of the transported electrical energy within the lines of the power system is referred to as 'Power Flow". To be specific, it is the active and reactive power that flows in the transmission lines. During the last twenty years, the operation of power systems has changed due to growing consumption, the development of new technology, the behaviour of the electrical market and the development of renewable energies. [1]

The Flexible AC-Transmission System (FACTS) technology is the application of power electronics in transmission system and can be utilized for power-flow control. Currently, the unified power-flow controller (UPFC) shown in Fig. 1 is the most powerful FACTS device, which can simultaneously control all parameters of the system: the line impedance, the transmission angle and bus voltage. [2] The unified power-flow controller (UPFC) is the most versatile device of the family of FACTS devices. [3] 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 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. [4]

The two converters operated from a DC link and provided by a DC storage capacitor. The UPFC is not widely applied in practice due to their high cost. Since the components of the UPFC handle the voltages and current with high rating, therefore the total cost of the system is high.

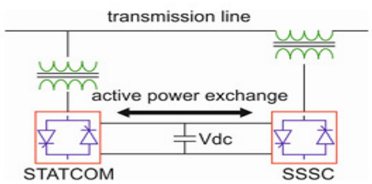

Fig. 1Simplified Diagram of UPFC

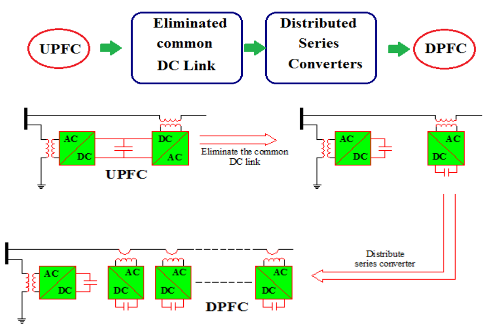

Fig. 2 Flow Chart of UPFC to DPFC

Due to the common DC link interconnection, a failure that happens at one converter will influence the whole system. To achieve the required reliability for power systems, bypass circuit or redundant backups are needed, which leads to increase in the cost. The same applies to the UPFC. The Distributed Power Flow Controller (DPFC) recently presented is a power flow device within the FACTS family, which provides much lower cost and higher reliability than the conventional FACTS devices. It is derived from the UPFC and has the same capability of simultaneously adjusting all the parameters of power system like line impedances, transmission angle and bus voltage magnitude.

II. PREPERATION PRINCIPLE OF DPFC T

There are two approaches for the active power flow. They are:

- Active power exchange with eliminated DC Link
- Using third harmonic components

A. Active Power Exchange with DC Link Elimination

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 $Ø_i$ is the corresponding angle between the voltage and current. 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. [5][6]

B. Using third harmonic components

In a three-phase system, the third harmonic in each phase is identical i.e. zero sequence components. Because the zero-sequence harmonic can be naturally blocked by Y-Δ transformers and these are widely used in power systems, there is no extra filter required to stop harmonic leakage. [7] As introduced above, a high-pass filter is required to make a closed loop for the harmonic frequency of this filter, which 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. But, by using the zero-sequence harmonic, this costly filter can be replaced by a cable that connects the neutral point of the Y-Δ transformer as shown in Fig. 3 with the ground.

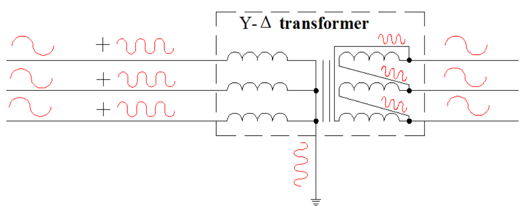

Fig. 3 Utilize Grounded Y-Δ Transformer to Filter Zero-Sequence Harmonic

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 Fig. 3. Therefore, the large high-pass filter is eliminated. [8]

Another advantage of using the 3rd harmonic to exchange active power is that the grounding of the Y-Δ transformers can be used to direct the harmonic current in a meshed network. If the network requires the harmonic current to flow through a particular branch, the neutral point of the Y-Δ transformer in that branch, at the side opposite to the shunt converter, will be grounded and vice versa.

Fig. 4 shows a simple example of routing the harmonic current by using the grounding of the Y-Δ 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. [9]

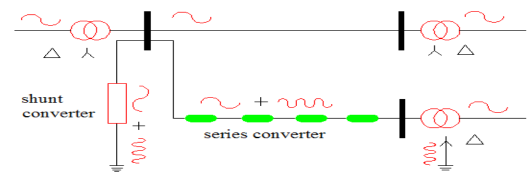

Fig. 4 Route the Harmonic Current by using the Grounding of the Y-Δ Transformer

The harmonic at the frequencies like 3^{rd}, 6^{th}, 9^{th}... 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.

III. CONTROL SCHEME OF DPFC

To control multiple converters, a DPFC consists of three types of controllers: central control, shunt control and series control, as shown in Fig. 5. 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.

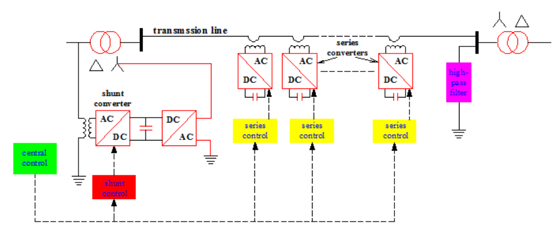

Fig. 5 DPFC Control Block Diagram

A. 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 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.

B. 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 third-harmonic frequency components and to generate series voltage at the fundamental frequency that is prescribed by the central control. The third-harmonic frequency control is the major control loop with the DPFC series converter control. The principle of the vector control is used here for the dc-voltage control. 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) in the series converter. [10] As the line current contains two frequency components, a third high-pass filter is needed to reduce the fundamental current.

The d-component of the third harmonic voltage is the parameter that is used to control the dc voltage, and its reference signal is generated by the dc-voltage control loop. To minimize the reactive power that is caused by the third harmonic, the series converter is controlled as a resistance at the third-harmonic frequency. The q- component of the third-harmonic voltage is kept zero during the operation. As the series converter is single phase, there will be voltage ripple at the dc side of each converter.

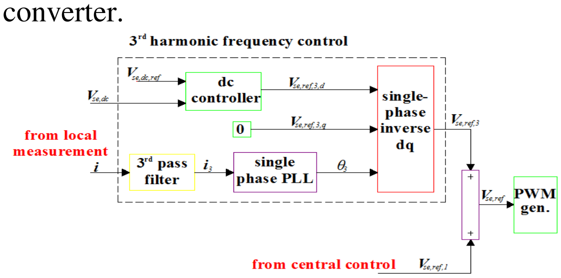

Fig. 6 Block Diagram of Series Converter Control

The frequency of the ripple depends on the frequency of the current that flows through the converter. As the current contains the fundamental and third harmonic frequency component, the dc-capacitor voltage will contain 100Hz, 200Hz, and 300Hz frequency component. There are two possible ways to reduce this ripple. One is to increase the turn ratio of the single-phase transformer of the series converter to reduce the magnitude of the current that flows into the converter. The other way is to use the dc capacitor with a larger capacitance.

C. Shunt Control

The block diagram of the shunt converter control is shown in Fig. 7. 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. [11] 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. 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.

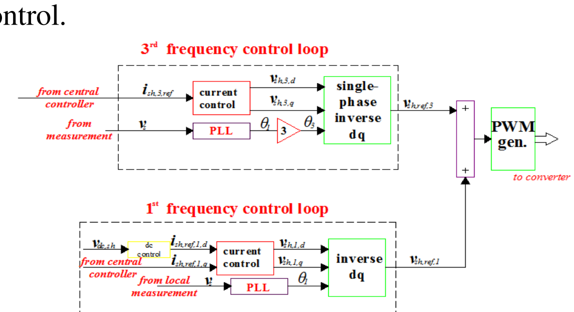

Fig. 7 Block Diagram of Shunt Converter Control

IV. SIMULATION MODEL OF DISTRIBUTED POWER FLOW CONTROLLER

For case study, 230kV, 13.36km transmission line from Paunglaung to Pyinmana, is chosen. Then, this transmission line is analyzed using MATLAB simulation model. The system contains a three-phase source connected to a nonlinear RLC load through parallel transmission lines. The DPFC is placed in transmission line, to which the shunt converter is connected in parallel through a Y-Δ three-phase transformer, and series converters are distributed through this line. To simulate the dynamic performance, a three phase fault is considered near the load. The time duration of the fault is 0.3 seconds. Firstly, the existing system without DPFC by using MATLAB model is analyzed as shown in Fig. 8.

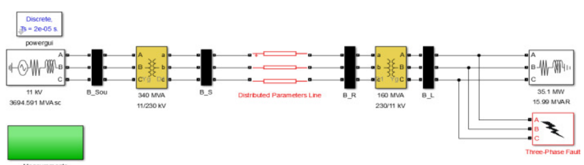

Fig. 8 Simulation Model of Fault Conditions without DPFC

A. Series Converter Control SIMULINK Model

Within the setup shown in Fig. 9, multiple series converters are controlled by a central controller. The central controller gives the reference voltage signals for all series converters. The voltages and current within the setup are measured by its simulink outputs.

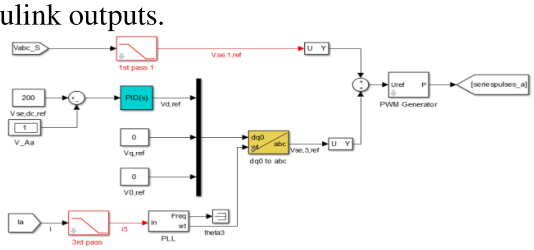

Fig. 9 Simulated Model for Series Converter

B. 4.2 Shunt Converter Control SIMULINK Model

The basic function of the shunt converter is to supply or absorb the active power demanded by the series converter. 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. 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. Fig. 10 shows one operation point of the DPFC setup, which includes voltage and current injected by the series converter, and the voltage and current at the Δ side of the transformer.

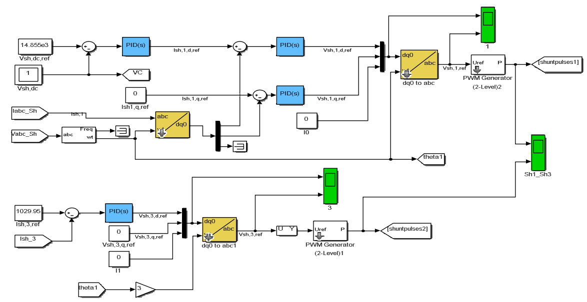

Fig. 10 Simulated Model for Shunt Converter

C. Simulation and Results

The simulation model of existing system with DPFC by using MATLAB model is analyzed as shown in Fig. 11.

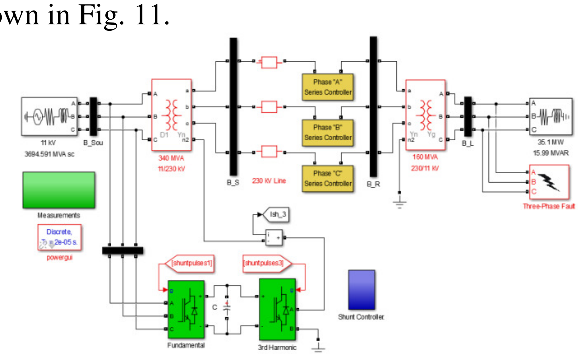

Fig. 11 Simulation Model of Existing System with DPFC under Fault Condition

The existing system is simulated by using MATLAB without and with DPFC under fault condition. The following Fig. 12 is the simulation results of voltage and current for supply side without DPFC under fault condition. The sending end voltage is reduced to 195kV instead of 230kV.

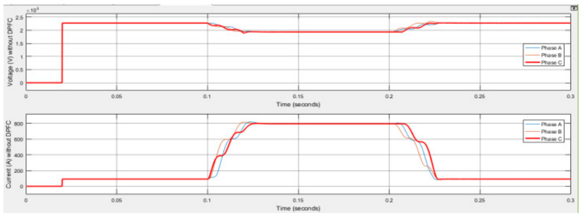

Fig. 12 Sending End Voltage and Current of Existing System without DPFC under Fault Condition

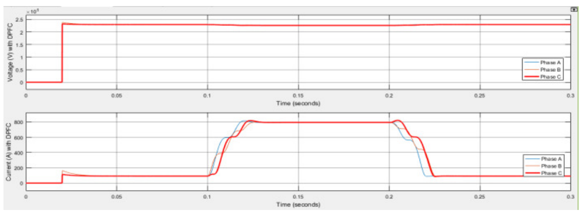

Fig. 13Sending End Voltage and Current of Existing System with DPFC under Fault Condition

By using DPFC, under fault condition, the supply voltage is improved from 226kV to 230kV as shown in Fig. 13.

When the receiving end voltage and current is simulated under fault condition without DPFC, this voltage is reduced 190 kV as shown in the following Fig. 14.

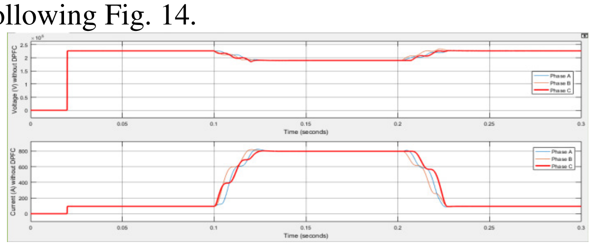

Fig. 14Receiving End Voltage and Current of Existing System without DPFC under Fault Condition

When DPFC is used in the existing system under the fault condition, the receiving end voltage is improved from 226kV to 230kV as shown in Fig. 15.

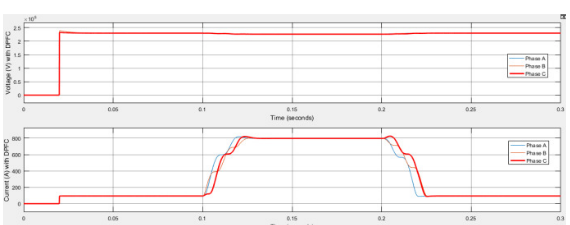

Fig. 15Receiving End Voltage and Current of Existing System with DPFC under Fault Condition

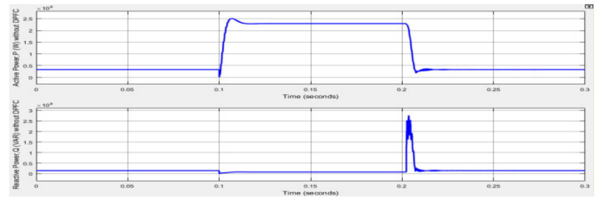

Fig. 16Active and Reactive Power of Existing System without DPFC for Supply side under Fault Condition

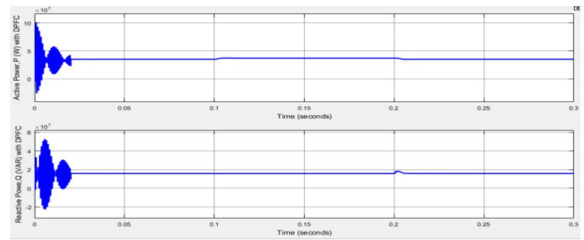

Fig. 17 Active and Reactive Power of Existing System with DPFC for Supply side Under Fault Condition

Active and reactive power of supply side is simulated without DPFC and with DPFC under fault condition as shown in Fig. 16 and Fig. 17 respectively. Without DPFC, active power is 235MW but, by using DPFC, active power is maintained as the scheduled power 37 MW. When DPFC is not used in the existing system under fault condition, the reactive power is 182 MVAR but, by using DPFC this reactive power is reduced to 17.5 MVAR.

TABLE I
SIMULATION PARAMETERS OF SYSTEM

Symbol	Description	Value	Unit
V_s	Sending end bus voltage	230	kV
V_r	Receiving end bus voltage	230	kV
θ	Transmission angle between sending and receiving end bus voltages	0.186	°
L	Line inductance	12.9	mH
$V_{sh,max}$	Shunt converter maximum ac voltage	530	V
$I_{sh,max}$	Shunt converter maximum ac current	25	A
$V_{sh,dc,ref}$	Reference shunt converter dc source supply	14.855	kV
$I_{sh,ref,3}$	Reference 3rd harmonic current injected by the shunt converter	1.03	kA
f_{sw}	Switching frequency for shunt and series converter	5	kHz
$V_{se,max}$	Maximum ac voltage at line side of the series converter	247.5	V
$I_{se,max}$	Maximum ac current at line side of the series converter	563	A

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