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DISTRIBUTED POWER FLOW CONTROLLER

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ABSTRACT : *This paper presents the simulation results of Distributed Power Flow Controller model designed in MATLAB/SIMULINK. A simple two bus system is considered for simulation. Power flow between the two buses is obtained by providing a phase difference between the buses. DPFC consists of one shunt converter and six single phase series converters. The shunt converter is a single phase converter connected between neutral point of -Y transformer and the ground, and is powered by constant DC source.The simulation is carried out to observe steady-state behavior and also step change response of the device. This paper provides the simulation results with and without DPFC and the analysis of the results is given.*

Keywords -*AC–DC power conversion, power electronics, power semiconductor devices, power system control, and power-transmission control.*

I. INTRODUCTION

Modern power systems are designed to operate effectively to supply power on demand to various load centers with high reliability [1]. Power flow in alternating current (AC) systems is unlike other flow problems such as in transportation or telecommunications. However, electricity must follow the laws of physics, so power flow is not routable and cannot be directly controlled. Power flow control is also different from other types of flow problems since electricity must also be produced exactly when it is needed. In a traditional power system, the electrical energy is generated by centralized power plants and flows to customers via the transmission and distribution network. A large majority of power transmission lines are AC lines operating at different voltages [1]. The rate of the transported electrical energy within the lines of the power system is referred to as "Power Flow‟ , to be more specific, it is the active and reactive power that flows in the transmission lines. Power flow is the name given to a network solution that shows currents, voltages, real & reactive power flows at every bus in the system. Power flow is not single calculation such as E=I*R or E = [Z]*I involving linear circuit analysis. The power flow gives us electrical response of the transmission system to a particular set of loads & generator unit outputs. Power flows are an important part of power system design procedures [2]. The future power system will be a meshed network and the power flow within this network, both the direction and quantity, will be controlled. To keep the system stable during faults or weather variations, the response time of the power flow control should be within several cycles to minutes. Without proper controls, the power cannot flow as required, because it follows the path determined by the parameters of generation, consumption and transmission. To fulfill the power flow requirements for the future network, power flow controlling devices are needed.

Approximately two decades ago, flexible AC transmission systems (FACTS) were introduced. The flexible ac-transmission system (FACTS) is defined by IEEE as "a power-electronic based system and other static equipment that provide control of one or more ac-transmission system parameters to enhance controllability and increase power-transfer capability", and can be utilized for power-flow control [3] [4] [5]. A FACTS incorporates power electronics and controllers to enhance power system controllability and increase transfer capability. FACTS devices improve power system operation and stability, and to better utilize the existing transmission infrastructure by controlling power flow. The growing demand and the aging of networks make it desirable to control the power flow in power-transmission systems fast and reliably.

The DPFC is derived from the unified Lower-flow controller (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 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.

II. NEW CONCEPT OF DISTRIBUTED POWER FLOW CONTROLLER

The DPFC employs several D-FACTS devices in series with the transmission line and one conventional controlled voltage-source shunt converter to provide the active power for each D-FACTS device. In order to inject a 360◦ voltage vector to achieve the full control capability as UPFC, there is an exchange of active power between the shunt and series converters needed, and the traditional way for active power exchange is using common DC link as UPFC. The simplified diagram of UPFC employing distributed FACTS devices as series converters with common DC link is shown in Fig.1

The distributed converters are spread along the transmission line. In order to supply active power to all series converters, the common dc link should have the same length as transmission line, which is too expensive and sometimes even

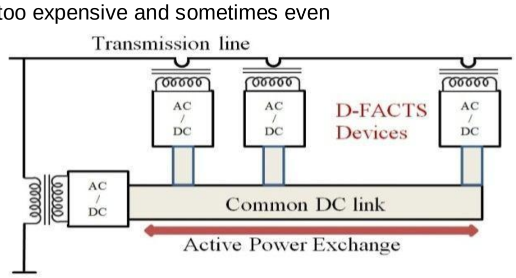

Fig.1. Simplified representation of a conventional UPFC

impossible.Therefore, a method of transferring active power without common dc link is required. The paper presents a new concept of transmitting active power through the same transmission line at a harmonic frequency. According to Fourier analysis, a non-sinusoidal voltage and current can be expressed by the sum of sinusoidal functions in different frequencies with different amplitudes. The definition of active power is 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:

$$= \sum (\; I \qquad \phi \;) \qquad (1)$$

Where $\cos\varphi_n$ is power factor in n^{th} harmonic frequency, and $\varphi_n = \theta_{vn} - \theta_{in}$. 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 other frequency component. Consequently, the active power required by series converters can be fed by active power at a different frequency, and the power at harmonic frequency is superimposed on the fundamental component transmitted through the same power line. The chosen harmonic frequency is 3rd harmonic, and the reasons are the following. The most widely used transformer to change voltage level in power system is Y-Delta transformer, which has the capability to block the zero sequence components naturally. Based on the grounding of the neutral point, the transformer will be open circuit to zero sequence component if floated, or short circuit to ground if grounded. In order to block the harmonic which carries the exchange active power, zero sequence harmonic is selected, which means that all the harmonic have the same phase. Since the transmission line impedance is inductive and proportional to frequency, higher transmission frequencies will cause high impedance and lead to a increase of voltage level of converters to transmit the same amount of active power. To reduce the line impedance, the 3rd harmonic is chosen because it is the lowest frequency of zero sequence harmonic. Evolution of DPFC from UPFC is shown in Fig 2.

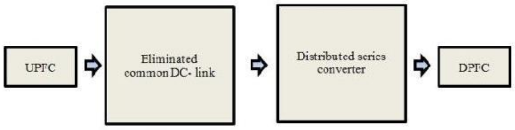

Fig.2. DPFC technology development flow

The simplified diagram of DPFC is illustrated in Fig.3.

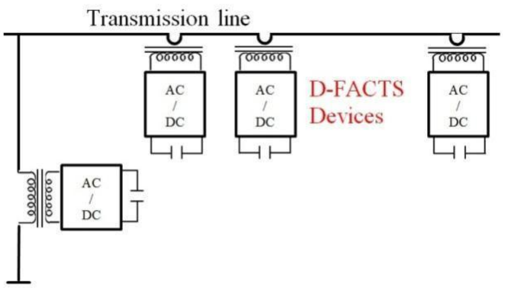

Fig.3. Distributed power flow controller

As shown in Fig.3, the DPFC is connected to a power transmission line with Y-Delta transformers at each end, whose neutral points are floating. Single phase converters are attached to the line. They can inject a relatively small voltage at the fundamental frequency. The required active power which isneeded by series converters is supplied by the shunt converter, and transmitted through the line at 3rd harmonic frequency. The transmission line carries both the current at fundamental and 3rd harmonic frequency. The floating ground Y-Delta transformer is open circuit to 3rd harmonic. To construct a close loop for 3rd harmonic current, a 3rd pass filter is shunt placed at the other end of line. The converters are voltage source converters, using capacitors as energy storage to balance the dc voltage. For lossless converter, the active power generated at fundamental frequency is equal to the power absorbed from 3rd harmonic, P1(t) + P3(t) = 0. For a better understanding of how the active power flows in the DPFC system, a simplified diagram is presented in Fig.4

controllable in both magnitude and phase. It

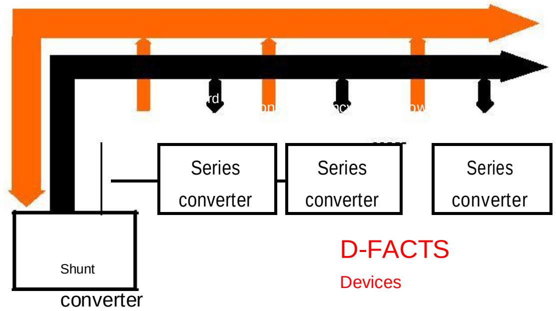

Fig.4 Active power flows in the DPFC system

III. SIMPLIFIED MODEL AND STEADY STATE ANALYSIS

From the conceptual viewpoint, each converter can be replaced by a controllable voltage source in series with impedance. Hence each converter generates voltage at two different frequencies; each converter can be represented by two series connected controllable voltage sources, one at fundamental frequency and the other at 3rd harmonic frequency. The total active power generated by the two frequency voltage source will be zero, if the converter is lossless. The conceptual representation of DPFC is shown in Fig.5, where $V_{se,1}$ equals to the sum of the fundamental voltages for all series converters, and $V_{se,3}$ is the sum of the 3^{rd} harmonic voltages.

The shunt converter generates voltage at 3^{rd} harmonic frequency. As a result, a third harmonic current will flow in the section of the transmission line to feed the active power to series converters.

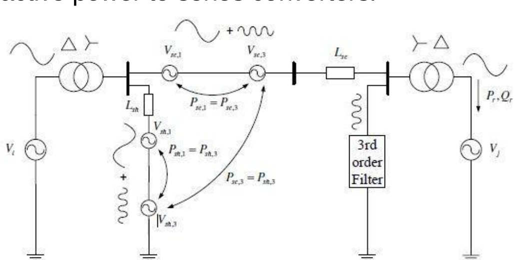

Fig.5. Conceptual representation of DPFC in two buses system

The capacitor dc voltage of shunt converter is compensated by the absorbing active power at fundamental frequency. The series converters inject a fundamental voltage which is absorbs the active power from 3^{rd} harmonic frequency to balance their dc voltages. Based on

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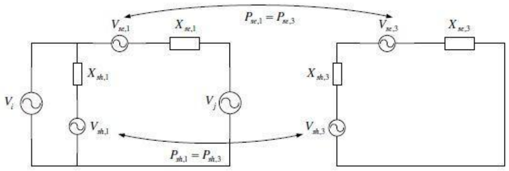
the superposition theorem, the circuit can be split into two circuits at different frequencies. The two circuits are isolated from each other, and the link between two circuits is the active power balance of each converter, see in Fig.6.



(a) Fundamental circuit (b) Harmonic circuit
Fig.6. Electrical circuits in fundamental and 3rd harmonic frequency

As shown in Fig.6, the circuit of a DPFC at fundamental frequency is the same as a UPFC, therefore the DPFC have the same characteristic as UPFC. The control ranges of DPFC depend on the voltage at fundamental frequency injected by series converter, and have the relationship:

$$(P - P) + (Q - Q) = | | \qquad (2)$$

where P_{r0} and Q_{r0} are the active and reactive power flow without UPFC at a certain phase angle $\theta = \theta i - \theta j$, $X_{se,1} = \omega L_{se}$ is the line impedance in fundamental frequency, $|V| = |Vi| = |Vj|$ is the voltage magnitu~~de at~~ both ends (assuming unified voltage control). The function f (P_{r0}, Q_{r0}) is a circle with a radius of | | | , | around the center defined by coordinates P = 0 and Q = −| | | , | in a (P_r, Q_r) reference frame. Each point of this circle gives the P_{r0} and Q_{r0} values of the uncompensated system at the corresponding phase angle θ. The boundary of the attainable control region for Pr and Qr is obtained from a complete rotation of phasor $V_{se,1}$ with its maximum magnitude [6].

The active power exchanged between shunt and series converters are though the same transmission line at 3rd harmonic frequency instead of common dc link, which increase the line current RMS value accordingly. The amount of active power is equal to the power required by series converter at fundamental frequency which is given by:

$$P_{se} = Re\{S_{se}\} = \frac{\sin(\phi_{r0} - \phi_r)}{\quad} \qquad (3)$$

| |

Fig.7.The relationship between P_{se} and

Where φ_{r0} is the power angle at the receiving end of the uncompensated system, and φ_r is power angle at receiving end with the DPFC (the reference power angle). The line impedance $X_{se,1}$ and voltage magnitude V_r are constant, so the active power is proportional to $|S_r||S_{r0}|$ sin $(\varphi_{r0} - \varphi_r)$, which is twice the area of the triangle (o, r_0, r). Consequently, the active power P_{se} can be written as:

$$P_{se} = C_p A_{(o,ro,r)} \qquad (4)$$

Where $C_p = \overline{\quad}$, and $A(o,r_0,r)$ is the area of triangle (o, r_0, r). The angle difference $\varphi_{r0} - \varphi_r$ can be positive or negative; the sign gives the direction of the active power through the UPFC series part, positive sign means the UPFC series part absorbing active power from 3rd harmonic component and vice versa. Fig.7 illustrates the relationship between P_{se} and the apparent power at receiving end at certain power angle.

For certain control range of the DPFC S_{range} when the changed apparent power $S_r - S_{r0}$ is vertical to the power without compensation S_{r0}, the area of triangle (o, r_0, r) is maximum, and the active power transmitted in line is maximum consequently, see in Fig.8.

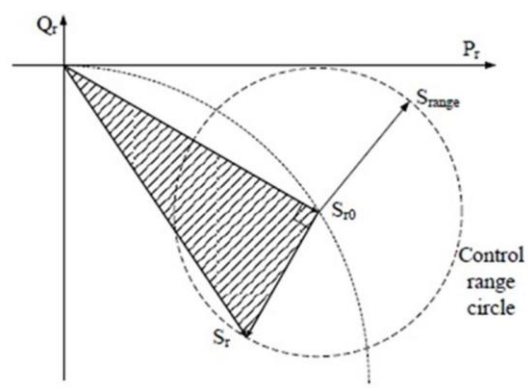


Fig.8.The maximum P_{se} of the control range S_{range}

the receiving end power

Therefore the relationship between the control range and maximum active power transmission can be represented by:

$$P_{se} = C_p A_{(o,ro,r)} = | \quad |S \quad |S \qquad (5)$$

Where | |' |S | is the ratio of and it means how much maximum active power required to achieve the control range S_{range}. In a typical power system network, if the voltage and power are both 1pu, the impedance will be around 0.1pu; therefore the ratio is round 10%.

IV. RESULTS

The simulated values of active and reactive power flows with and without control through the transmission line for $1^0$and 90^0 transmission angles are shown in following Figures.

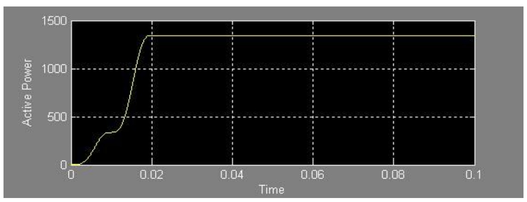


Fig.8 (a) Active Power through the line without control with 1^o transmission angle

Fig.8 (b) Reactive Power through the line without control with 1^o transmission angle

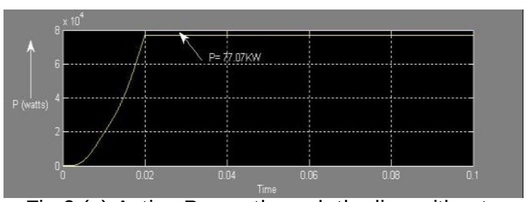


Fig.9 (a) Active Power through the line without control with 90^o transmission angle

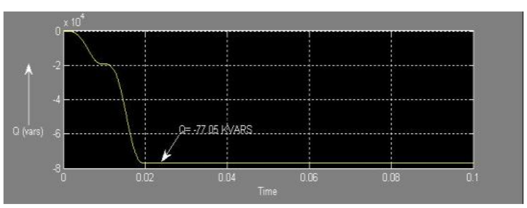


Fig.11 (a) Active Power through the line with control with 90^o transmission angle

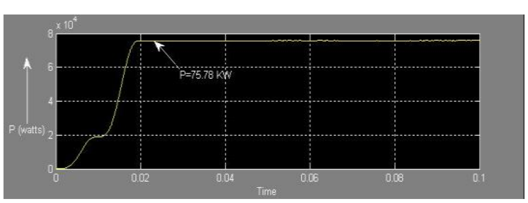


Fig.11 (b) Reactive Power through the line with control with 90^o transmission angle

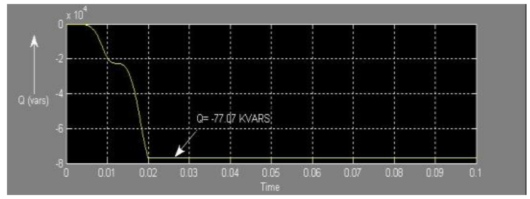


Fig.9 (b) Reactive Power through the line without control with 90^o transmission angle

Fig.8and Fig.9 shown above indicates power flow through the transmission line without controlling for different transmission angle. Fig.10and Fig.11 shown below indicates power flow through the transmission line with controlling for different transmission angle.

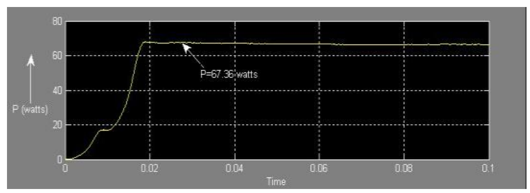


Fig.10 (a) Active Power through the line with control with 1^o transmission angle

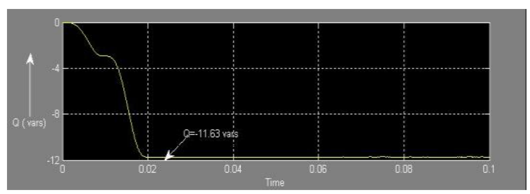


Fig.10 (b) Reactive Power through the line with control with 1^o transmission angle

CONCLUSION

This paper presents the new concept of DPFC system and the method of transmitting active power through the same line at different frequency. The distributed converters bring the following benefits: reduce cost for both equipment and maintenance; increase the reliability of the whole system, even when the shunt converter breaks, series converters can also work as variable conductor; break the location constrain, the converters are physical separated without losing control capability. Since the exchange active power is through the same line which transmits the fundamental power, the transmission capability of the line will be reduced. The level of reduction depends on the control range of DPFC, and it is around 10% or less of the range related to the transmission line parameters.

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