Voltage Sag and Swell Mitigation Using DPFC and Improve Power Quality

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Abstract- Modern power utilities have to respond a no.of challenges such as growth of electricity demand specially non-linear loads in power grids consequently some high quality electrical power should be considered. The DPFC is a new FACT device. In this work DPFC considered as a UPFC with an eliminated common dc link and it is used to mitigate the voltage sag and swell and improve power quality. 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. 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, transmission angle and bus voltage. Which is simulated in Matlab/Simulink environment and the corresponding results will be shown.

Keywords – FACTS, Power Quality, Sag and Swell Mitigation, Distributed Power Flow Controller.

I. INTRODUCTION

In recent years, power quality disturbances become most issue which makes many researchers interested to find the best solutions to solve it. Power quality in the power system is the important issue for industrial, commercial and residential applications today. The voltage problem is mainly considered from under-voltage (voltage sag) condition over current caused by short circuit or fault somewhere in the system. Preventing voltage sag and swell condition, many research works have been implemented. Voltage sag is widely recognized as one of the most important power quality disturbances. The IEC 61000-4-30 defines the voltage sag (dip) as a temporary reduction of the voltage at a point of the electrical system below a threshold. According to IEEE Standard

1159-1995, defines voltage sags as an rms variation with a magnitude between 10% and 90% of nominal voltage or current and duration between 0.5cycles and one minute. Single line to ground faults (SLGFs), which are the most frequent types of fault system responsible for around 70% of all faults.

It can be caused by short circuits, varying loads, motor starting up. A swell is defined as an increase to between 1.1 and 1.8 Pu in RMS voltage or current at the power frequency for durations from 0.5 Cycles to 1 min. In 1988, Hingorani defined the FACTS concept and described the wide prospects of the application. Nowadays, FACTS technology has shown strong potential in all aspects. Many examples of FACTS devices and controllers are in operation. The concept of Flexible AC Transmission System (FACTS) was introduced as a family of power electronic equipments which have emerged for controlling and optimizing flow of electrical power in the transmission line.

The growing demand and the aging of networks make it desirable to control the power flow in power transmission systems fast and reliably. The flexible ac-transmission system (FACTS) that 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. Currently, the unified power-flow controller (UPFC) shown in Fig. 1, is the most powerful system: the line impedance, the transmission angle, and bus voltage.

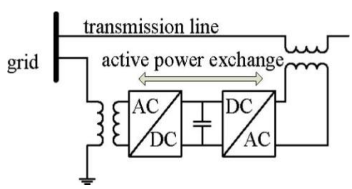

Fig. 1. Simplified representation of a UPFC.

The UPFC is the combination of a static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC), which are 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. The converter in series with the line provides the main function of the UPFC by injecting a four-quadrant voltage with controllable magnitude and phase. The injected voltage essentially acts as a synchronous ac-voltage source, which is used to vary the transmission angle and line impedance, thereby independently controlling the active and reactive power flow through the line. The series voltage results in active and reactive power injection or absorption between the series converter and the transmission line. This reactive power is generated internally by the series converter (see e.g., SSSC), and the active power is supplied by the shunt converter that is back-to-back connected. 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. Similar to the STATCOM, the shunt converter can also provide reactive compensation for the bus. The components of the UPFC handle the voltages and currents with high rating; therefore, the total cost of the system is high. 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 circuits and redundant backups (backup transformer, etc.) are needed, which on other hand, increase the cost. Accordingly, the UPFC has not been commercially used, even though, it has the most advanced control capabilities. This paper introduces a new concept, called distributed power-flow controller (DPFC) that is derived from the UPFC. The same as the UPFC, the DPFC is able to control all system parameters. 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 concept.

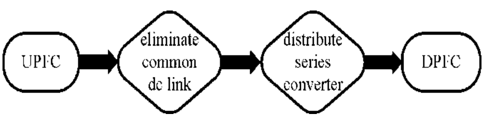

Fig. 2. Flowchart from UPFC to DPFC.

An infinite bus is a source of constant frequency and voltage either in magnitude or angle. Single Machine Infinite Bus System (SMIB) equipped with a UPFC is connected to the remote system through a transformer and a parallel transmission line having "π" section models as shown in Fig.3. A UPFC is placed in the transmission line at point m (between middle of two line sections m-n) to improve the dynamic behavior of the system. The UPFC consists of shunt and series converters controlled by sinusoidal pulse width modulation (SPWM) controller.

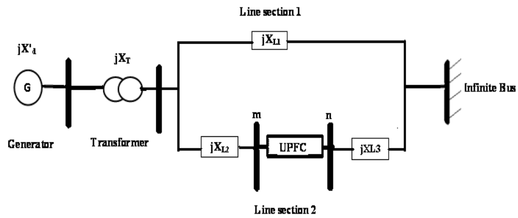

Fig.3. Single line diagram of UPFC with parallel transmission lines

The Distributed Power Flow Controller (DPFC) recently presented in is a powerful device within the FACTS family, 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. The DPFC eliminates the common dc link between the shunt and series converters, and uses the transmission line to exchange active power between converters at the 3rd harmonic frequency. Instead of one large three-phase converter, the DPFC employs multiple single phase converters (D-FACTS) as the series compensator. This concept reduces the rating of the components and provides a high reliability because of the redundancy. Since the DPFC can instantaneously control the active and reactive power flow and the voltage magnitude.

In this objective, a distributed power flow controller, introduced a new FACTS device, is used to mitigate voltage and current waveform deviation and improve power quality in a matter of seconds. The DPFC structure is derived from the UPFC structure that is included one shunt converter and several small independent series converters, as shown in Fig. 4. The DPFC has same capability as UPFC to balance the line parameters, i.e., line impedance, transmission angle, and bus voltage magnitude .

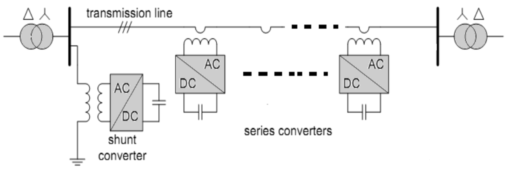

Fig.4. The structure of DPFC

II. DPFC PRINCIPLE

The basic issues in DPFC principle are DC-link elimination and using 3rd-harmonic current to active power exchange. In the following subsections, the DPFC basic concepts are explained.

A. Eliminate DC-Link and Power Exchange

Within the DPFC, there is a common connection between the ac terminals of the shunt and the series converters, which is the transmission line. Therefore, it is possible to exchange the active power through the ac terminals of the converters. The method is based on the power theory of non sinusoidal components.

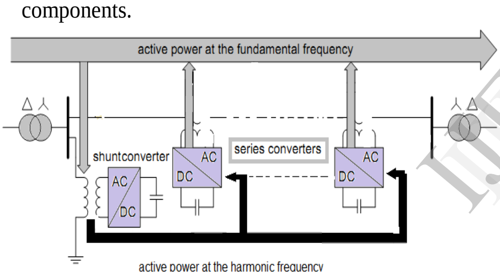

Fig. 5. Active power exchange between DPFC converters.

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 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

$$p = \sum_{i=1}^{\infty} V_i I_i \cos \varphi_i \quad (1)$$

where *Vi* and *Ii* are the voltage and current at the *i*th harmonic frequency, respectively, and *φi* is the corresponding angle between the voltage and current. Equation (1) describes that the active power at different frequencies is isolated from each other and the 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.

By applying this method to the DPFC, the shunt converter can absorb active power from the grid at the fundamental frequency and inject the current back into the grid at a harmonic frequency. This harmonic current will flow through the transmission line. 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. Assuming a lossless converter, the active power generated at fundamental frequency is equal to the power absorbed from the harmonic frequency. For a better understanding, Fig. 5 indicates how the active power exchanges between the shunt and the series converters in the DPFC system.

The high-pass filter within the DPFC blocks the fundament frequency components and allows the harmonic components to pass, thereby providing a return path for the harmonic components. The shunt and series converters, the high-pass filter, and the ground form the closed loop for the harmonic current.

Due to the unique characters of third harmonic frequency components, the third harmonic is selected to exchange the active power in the DPFC. In a three phase system, the third harmonic in each phase is identical, which is referred to as “zero sequence.” The zero-sequence harmonic can be naturally blocked by Y–Δ transformers, which are widely used in power system to change voltage level. Therefore, there is no extra filter required to prevent the harmonic leakage to the rest of the network. In addition, by using the third harmonic, the costly high pass filter, as shown in Fig. 5, can be replaced by a cable that is connected between the neutral point of the Y–Δ transformer on the right side in Fig. 4 and the ground. Because the Δ winding appears open circuit to the third-harmonic current, all harmonic current will flow through the Y-winding.

Theoretically, the third-, sixth-, and ninth-harmonic frequencies are all zero-sequence, and all can be used to exchange active power in the DPFC.

As it is well known, the capacity of a transmission line to deliver power depends on its impedance. Since the transmission-line impedance is inductive and proportional to the frequency, high-transmission frequencies will cause high impedance. Consequently, the zero-sequence harmonic with the lowest frequency third harmonic is selected.

B.DPFC Advantages:

The DPFC can be considered as a UPFC that employs the DFACTS concept and the concept of exchanging power through harmonic. Therefore, the DPFC inherits all the advantages of the UPFC and the D-FACTS, which are as follows.

1) *High control capability.*

The DPFC can simultaneously control all the parameters of the power system: the line impedance, the transmission angle, and the bus voltage. The elimination of the common dc link enables separated installation of the DPFC converters. The shunt and series converters can be placed at the most effectively location. Due to the high control capability, the DPFC can also be used to improve the power quality and system stability, such as low-frequency power oscillation damping ,voltage sag restoration, or balancing asymmetry.

2) *High reliability.*

The redundancy of the series converter gives an improved reliability. In addition, the shunt and series converters are independent, and the failure at one place will not influence the other converters. When a failure occurs in the series converter, the converter will be short-circuited by bypass protection, thereby having little influence to the network. In the case of the shunt converter failure, the shunt converter will trip and the series converter will stop providing active compensation and will act as the D-FACTS controller

3) *Low cost.*

The single-phase series converters rating are lower than one three-phase converter. Furthermore, the series converters do not need any high voltage isolation in transmission line connecting; single-turn transformers can be used to hang the series converters.

III. CONTROLLER IN DPFC

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. 6.

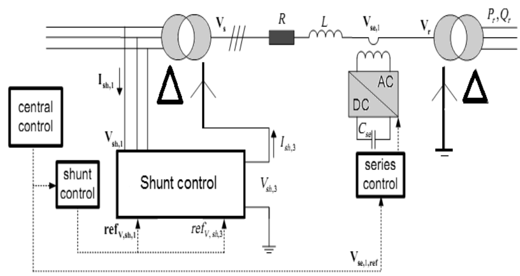

Fig. 6. DPFC control structure

A. Central Control

The central control generates the reference signals for both the shunt and series converters of the DPFC. It is focused on the DPFC tasks at the power-system level, such as power-flow control, low-frequency power oscillation damping, and balancing of asymmetrical components. According to 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.

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. 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.

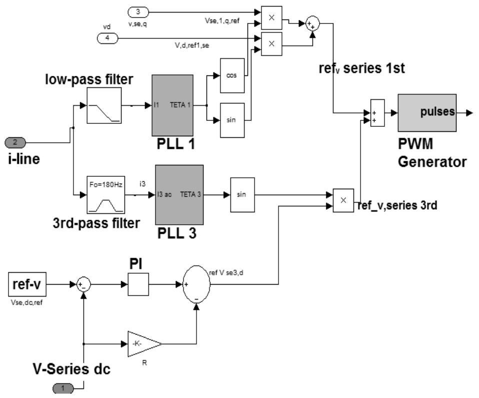

Fig. 7. Block diagram of series control structure in Matlab/Simulink

C. Shunt Control

The block diagram of the shunt converter control is shown in Fig. 8. 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. 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.

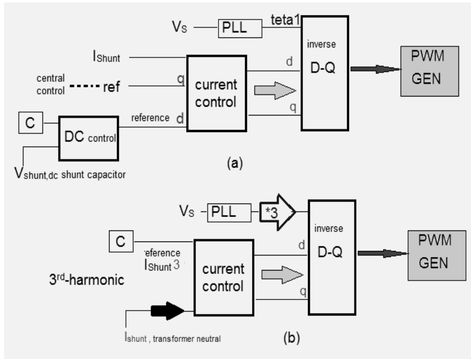

Fig. 8. The shunt control configuration: (a) for fundamental frequency (b) for third-harmonic frequency

IV. POWER QUALITY ENHANCEMENT

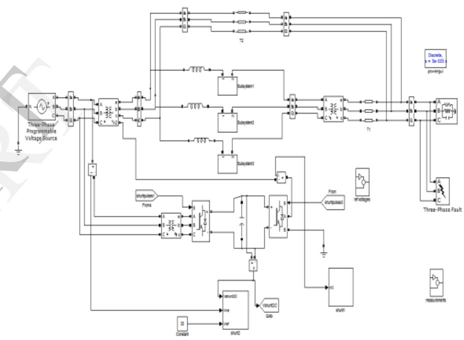

FIG.9. Simulation model of the DPFC

This modeling has been developed using Matlab/Simulink environment as shown in Fig. 9. The system is simulated with a three-phase source connected to a non-linear load. The simulation parameters are listed in Table 1. The supply is connected to load through the parallel transmission lines including the transmission line 1 and 2. The parallel transmission lines have same length. The DPFC is incorporated in transmission line 2. For analyzing dynamic performance, the inductive and capacitive loads are connected. The fault should be connected near the load to receive transient analysis. The shunt three-phase converter is connected to the transmission line 2 in parallel through a Y-Δ three-phase transformer, and series converters are distributed through this line.

V.SIMULATION RESULTS

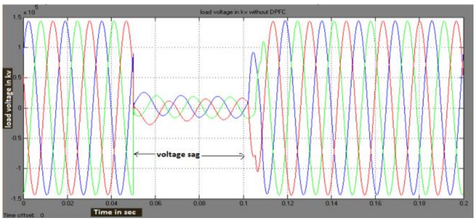

Fig. 10. Three-phase load voltage sag waveform

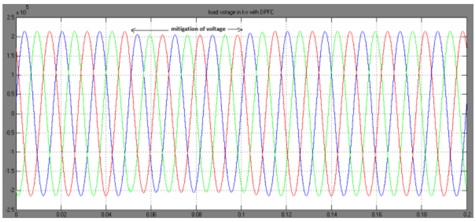

Fig. 11. Mitigation of three-phase load voltage sag with DPFC

The case study, considering sag/swell condition is implemented in single machine infinite bus system and analyzed results are as follows. To analyze voltage dip, a three-phase fault near the system load, as shown in Fig. 9. is created. The time duration for this fault is 0.5 seconds (500-1000 ms). The three phase fault causes observable voltage sag during this time, as shown in Fig. 10. The voltage sag value is about 0.5 per unit. The DPFC can compensate the load voltage sag effectively. The voltage sag mitigation with DPFC is shown in Fig. 11.

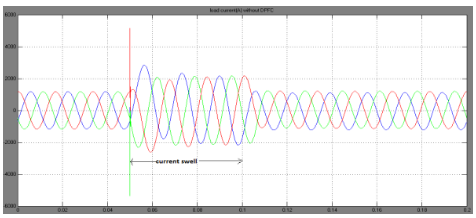

Fig. 12. Three-phase load current swell waveform without DPFC

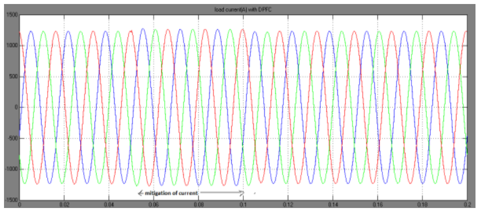

Fig.13.Mitigation of three-phase load current with DPFC

After creating three-phase fault, Fig. 12. depicts the load current swell around 1.1 per unit. The fault time duration is 0.5 seconds. In this case, after implementation of the DPFC, the load current magnitude is comparatively come down. The current swell mitigation for this case can be observed from Fig. 13.

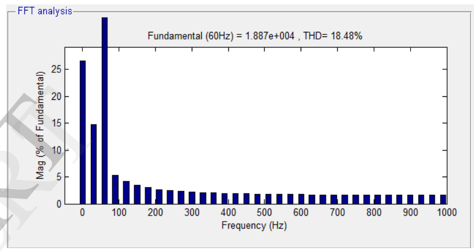

Fig. 14. Total harmonic distortion of load voltage without DPFC

The load voltage harmonic analysis without presence of DPFC is illustrated in Fig. 12. It can be seen, after DPFC implementation in system, the even harmonics is eliminated , the odd harmonics are reduced within acceptable limits, and total harmonic distortion (THD) of load voltage is minimized from 45.67 to 0.65 percentage (Fig. 13), i.e., the standard THD is less than 5 percent in IEEE standards.

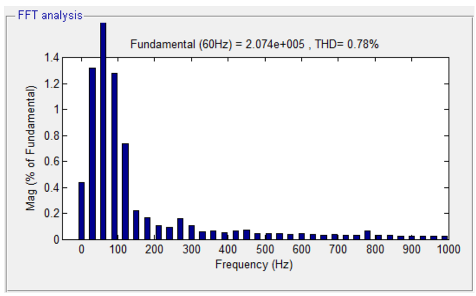

Fig. 14. Total harmonic distortion of load voltage with DPFC

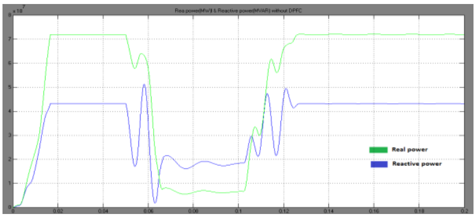

Fig16.Real&reactive power graph without DPFC

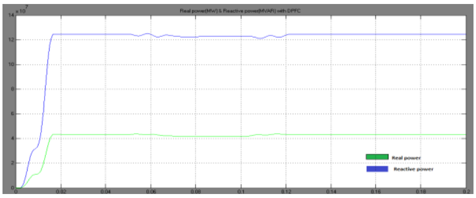

Fig.17.Real&Reactive power graph with DPFC

VI. CONCLUSION

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 small 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 of is low. The DPFC is modeled and three control loops, i.e., central controller, series control, and shunt control are design. The system under study is a single machine infinite-bus system, with and without DPFC. To simulate the dynamic performance, a three-phase fault is considered near the load. It is shown that the DPFC gives an acceptable performance in power quality mitigation and power flow control

TABLE -1 Simulated system parameters

Parameters	**Values**
Three phase source	
Rated voltage	230kV
Rated power/Frequency	100MW/60HZ
X/R	3
Short circuit capacity	11000MW
Transmission line	
Resistance	0.012pu/km
Inductance/capacitance reactance	0.12/0.12pu/km
Length of transmission line	100km
Shunt converter 3-phase	
Nominal power	60MVAR
DC link capacitor	600UF
Coupling transformer(shunt)	
Nominal power	100MVA
Rated voltage	230/15kV
Series converters	
Rated voltage	6kV
Nominal power	6MVAR
Three-phase fault	
Ground resistance	0.01ohm

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