Comparison of Distributed Power Flow Controller (DPFC) with Unified Power Flow Controller (UPFC) in Power Quality Enhancement

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Abstract: ***A new component within the flexible ac transmission system (FACTS) family, called distributed power-flow controller (DPFC). The DPFC is derived from the unified power-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. MATLAB is used for the simulation result.***

IndexTerms – voltage sag, voltage swell, DPFC, UPFC, power quality.

I. INTRODUCTION

Recent developments in the electric utility industry are encouraging the entry of power quality issue. Extending from the generation units to the utility customers, power quality is a measure of how the elements affect the system as a whole. From customer point of view, the power quality issue is concerned about current, voltage or frequency deviation which results in power failure. To solve the power quality problem in such a situation, the power electronic devices such as flexible alternating-current transmission system (FACTS) and custom power devices(DVR) which are used in transmission and distribution control, respectively, should be developed. The impact of transient parameters in majority of transmission lines problems such as sag (voltage dip), swell (over voltage) and interruption, are also considerable. To mitigate the mentioned power quality problems, the utilization of FACTS devices such as power flow controller (UPFC) and synchronous static compensator (STATCOM) can be helpful.

The Unified Power Flow Controller (UPFC) is comprised of a STATCOM and a SSSC [3], coupled via a common DC link to allow bi-directional flow of active power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM [4]. 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 storagecapacitor.

The distributed power flow controller (DPFC) which has a similar configuration to UPFC structure. The DPFC is composed of a single shunt converter and multiple independent series converters which is used to balance the line parameters, such as line impedance, transmission angle and bus voltage magnitude. To detect the voltage sags and determine the three single-phase reference voltages of DPFC, the SRF method is also proposed as a detection and determination method [1].

The Distributed Power Flow Controller (DPFC) a power flow device within the FACTS family provides low cost and higher reliability when compared to conventional FACTS devices [2].

The Distributed Power Flow Controller (DPFC) is one of the device with in FACTS family, which is derived from the UPFC. As compared with the UPFC, DPFC has the same controlling capability to change all the parameters within the transmission system. In case of DPFC the commonly connected DC link between series and shunt converter is eliminated and application of D-FACTS concept to series converter shown in Fig.2.The active power exchange between the converters is at 3rd harmonic frequency[3]. The D-FACTS concept not only reduces the ratings of the devises but also improves the reliability of the system because of redundancy and reducing the cost of high voltage isolation.

The reliability of the DPFC is improved because of the redundancy of the series converters before failure. If any one of the series converters fails, that will stop voltage injecting into the transmission line and the other series converter units will continue the operation. The performance of DPFC is improved by considering better control scheme during the series converter failure. The control schemes adapted for DPFC corresponding simulation results before and after the DPFC connected are presented also the comparative analysis of after connecting UPFC is presented.

Fig.1 flowchart from UPFC to DPFC

II. DPFC PRICIPLE

Multiple individual converters work together and forms the DPFC. 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 360º and where the magnitude is controllable as well. So they control the 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 DPFC consists of one shunt and several series-connected converters. The shunt converter is similar as a STATCOM, while the series converter employs the D-FACTS concept, which is to use multiple single-phase converters instead of one large rated converter. Each converter within the DPFC is independent and has its own dc capacitor to provide the required dc voltage. The Configuration of the DPFC is shown in Fig. 2.As shown, besides the key components, namely the shunt and series converters, the DPFC also requires a high-pass filter that is shunt connected at the other side of the transmission line, and two Y–Δ transformers at each side of the line. 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 exchange freely. To ensure that the DPFC have the same control capability as the UPFC, a method that allows the exchange of active power between converters with eliminated dc link is the prerequisite.

1. Eliminate DC link

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. 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

$$P = V_i I_i \cos \emptyset_i$$

where V_i and I_i are the voltage and current at the *i*th harmonic frequency, respectively, and φi is the corresponding angle between the voltage and current. Equation 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.

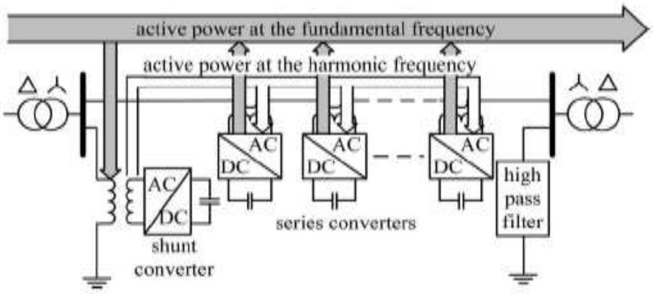


Fig.2. Active power exchange between DPFC converters

The high-pass filter within the DPFC blocks the fundamental 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, can be replaced by a cable that is connected between the neutral point of the Y–Δ transformer on the right side and the ground. Because the Δ winding appears open circuit to the third-harmonic current, all harmonic current will flow through the Y-winding and concentrate to the grounding cable. Therefore, the large-size high-pass filter is eliminated. Another advantage of using third harmonic to exchange active power is that the way of grounding of Y–Δ transformers can be used to route the harmonic current in a meshed network. If the branch requires the harmonic current to flow through, the neutral point of the Y–Δ transformer at the other side in that branch will be grounded and vice versa. Because the transformer of the line without the series converter is floating, it is open circuit for third-harmonic components. Therefore, no third-harmonic current will flow through this line. 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.

2. Distributed series converter

The D-FACTS is a solution for the series-connected FACTS, which can dramatically reduce the total cost and increase the reliability of the series FACTS device. The idea of the D-FACTS is to use a large number of controllers with low rating instead of one large rated controller. The small controller is a single-phase converter attached to transmission lines by a single-turn transformer. The converters are hanging on the line so that no costly high-voltage isolation is required. The single-turn transformer uses the transmission line as the secondary winding, inserting controllable impedance into the line directly. Each D-FACTS module is self-powered from the line and controlled remotely by wireless or power-line communication.

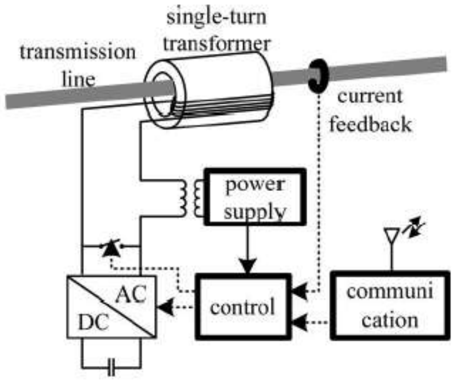


Fig.3. D-FACTS unit configuration

The structure of the D-FACTS results in low cost and high reliability. As D-FACTS units are single-phase devices floating on lines, high-voltage isolations between phases are avoided. The unit can easily be applied at any transmission-voltage level, because it does not require supporting phase-ground isolation. The power and voltage rating of each unit is relatively small. Further, the units are clamped on transmission lines, and therefore, no land is required. The redundancy of the D-FACTS provides an uninterrupted operation during a single module failure, thereby giving a much higher reliability than other FACTS devices.

III. DPFC CONTROL

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.5. The shunt and series control are local controllers and are responsible for maintaining their own converters parameters. The central control takes account of the DPFC functions at the power system level.

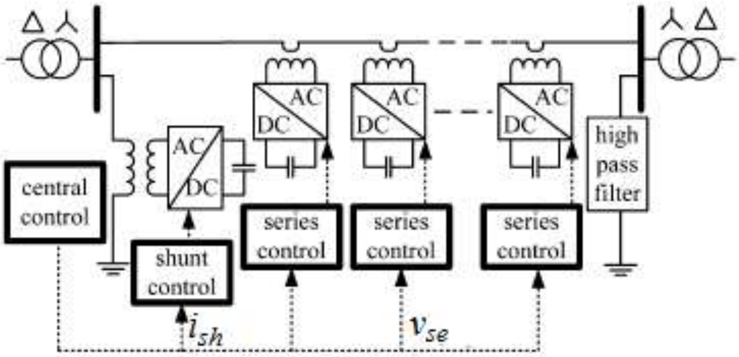


Fig.4.DPFC control block diagram

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.

As the series converter is single phase, there will be voltage ripple at the dc side of each converter. 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 100-, 200-, and 300-Hz 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. 5.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.

IV. DPFC MODELING

The DPFC must be modelled in dq-frame for the design of a DPFC control scheme shown in Fig.6. The model should describe the behaviour of the DPFC at the fundamental and the 3rd harmonic frequency. The modelling of the DPFC consists of the converter and the network modelling. Owing to the use of single-phase series converters, they are modelled as a single-phase system. Fig..4. Gives the flow chart of the DPFC modelling process.

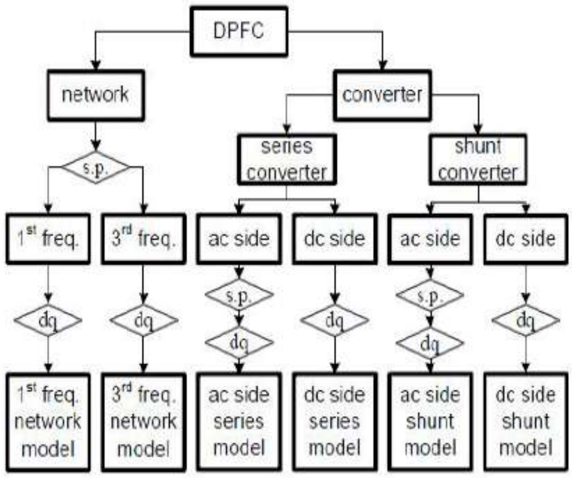


Fig.5. DPFC modeling process flow chart

Two tools are employed for the DPFC modelling: the superposition theorem and Park's transformation. The superposition theorem is first used to separate the components, Park's transformation is designed for analysis of signals at a Single frequency and the DPFC signal consists of two frequency components. Park's transformation is extensively used in electrical machinery analysis, transforms AC components in to DC. The principle of Park's transformation is to project the AC signal in vector representation on to a rotating reference frame, referred to as the 'dq-frame'.

A. Net work modeling:

This section presents mathematical representation of network with DPFC at fundamental and 3rd harmonic frequencies. By using superposition theorem the network is separated by two frequency circuits, which are fundamental and 3rd harmonic frequency circuits.

1) Fundamental frequency circuit: During the process of the network modeling must consider the following assumptions;

- The DPFC converters can be considered controllable voltage sources.
- Transmission system is balanced one.
- Grounding can be treated as ideal conductor with zero impedance and mutual impedance between phases can be neglected.

With these assumptions, the network with the DPFC series converters at the fundamental frequency can be simplified as shown in Fig.6.

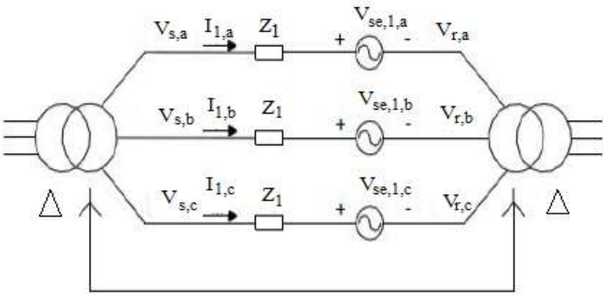


Fig.6. Fundamental frequency network equivalent circuit

According to the equivalent circuit, the relationship between the line current and series voltage is given by:

$$\begin{bmatrix} V_{s,a} \\ V_{s,b} \\ V_{s,c} \end{bmatrix} - \begin{bmatrix} V_{r,a} \\ V_{r,b} \\ V_{r,c} \end{bmatrix} - \begin{bmatrix} V_{se,1,a} \\ V_{se,1,b} \\ V_{se,1,c} \end{bmatrix} = \begin{bmatrix} Z_1 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_1 \end{bmatrix} . \begin{bmatrix} i_{1,a} \\ i_{1,b} \\ i_{1,c} \end{bmatrix}$$

The voltage at the sending and the receiving ends can be considered as the inputs and line current is the output. A block diagram of the fundamental network model is shown in Fig.7.

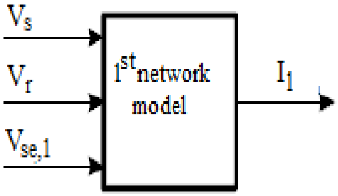


Fig. 7. Input and output of the fundamental frequency network model

2) 3rd harmonic frequency circuit: shunt converter injects the current at 3rd harmonic frequency. The 3^{rd} harmonic currents provides closed path through the neutral point of Y-Δ transformer. The equivalent circuit for the 3rd harmonic frequency network can be simplified as shown in Fig.8.

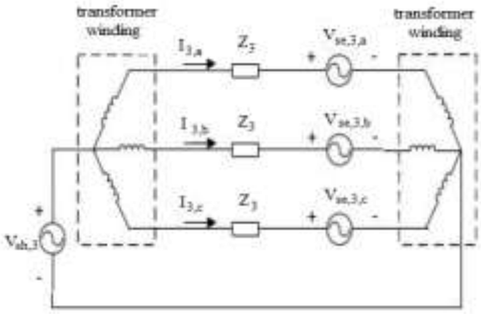


Fig.8. 3^{rd} harmonic frequency network equivalent circuit

The zero sequence reactance of the two transformer windings and the line impedance can be combined. This total impedance at the 3rd harmonic frequency is represented by Z3. Therefore, the relationship between the voltages and the currents at the 3rd harmonic frequency is:

$$\begin{bmatrix} V_{sh,3} - V_{se,3,a} \\ V_{sh,3} - V_{se,3,b} \\ V_{sh,3} - V_{se,3,c} \end{bmatrix} = \begin{bmatrix} Z_1 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_1 \end{bmatrix} . \begin{bmatrix} i_{3,a} \\ i_{3,b} \\ i_{3,c} \end{bmatrix}$$

The inputs of the model are the voltages Vsh,3 and Vse,3, which come from the converter models, while the output of the model is the 3rd harmonic current of each phase I3, as shown in Fig.9.

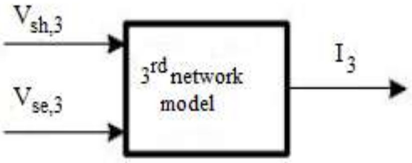


Fig.9. Input and output of the 3rd harmonic frequency network model

B. Series converter modeling *:*

The series converter is PWM control single phase converter, which is identical. The AC side and the DC side voltages of the series converter are Vse and Vse,DC respectively and refV,sef is the modulation amplitude of the reference AC signal in pu, which is generated by the series control. The AC voltages consist of fundamental and the 3rd harmonic frequency components. Their relationship can be illustrated as follows:

$$V_{se} = V_{se,1} + V_{se,3}$$

1). AC side modeling*:* The AC side voltage of the converter can be approximated with the product of the AC reference signal and the DC voltage as Vse:

$$V_{se} = ref_{vse,1}.V_{se,dc}$$

By applying the super- position theorem to the equation, equation can be separated into:

$$\begin{bmatrix} V_{se,1} \\ V_{se,3} \end{bmatrix} = \begin{bmatrix} ref_{vse,1} \\ ref_{vse,3} \end{bmatrix} . V_{se,dc}$$

The input signals of the AC side model of the series converter is refV,se and Vse,dc and the output is the AC voltage Vse, which comes from the DC side model

.

2) DC side modeling*:* The DC voltage of the series converter Vdc,se is related with the DC current Idc,se and the relationship is given by:

$$C_{se} \frac{dV_{dc,se}}{dt} = I_{dc,se}$$

The DC side current of the series converter is approximated to:

$$I_{dc,se} = ref_v . I$$

$$I_{dc,se} = (ref_{vse,1} + ref_{vse,3}).(I_1 + I_3)$$

Accordingly, the input signals for the DC side model Are, $ref_{vse,1}$, $ref_{vse,3}$, I_1 and I_3, and the output is the DC voltage Vse,dc. By combining the models of the AC side and the DC side, the series converter model is shown in Fig.10.

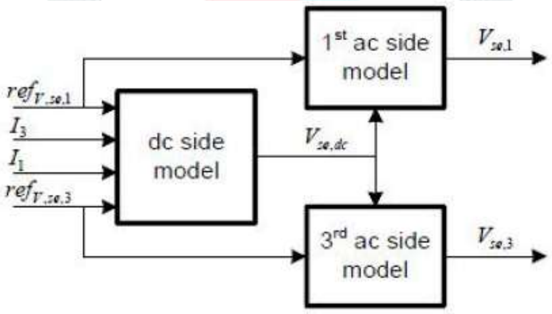


Fig.10. Block diagram of the series converter model

C. Shunt converter modeling:

The shunt converter consists of a three-phase converter that is back-to-back connected to a single phase converter. Similar as a STATCOM, the three phase converter is connected to the low-voltage side of the Y-Δ transformer to absorb active power from the grid. The single-phase converter is connectedbbetween the ground and the neutral point of the Y- Δ transformer to inject 3rd harmonic current. The simplified model of the shunt converter is shown in Fig.11.

1) AC side modeling*:* AC voltage can be approximately written as follows:

$$V_{sh,1} = ref_{v,sh,1}.V_{sh,dc}$$

$$V_{sh,3} = ref_{v,sh,3}.V_{sh,dc}$$

2) DC side modeling*:* The capacitor DC voltage of the shunt converter is given with the following equation:

$$C_{sh} \frac{dV_{sh,dc}}{dt} = I_{sh,dc,1} - I_{sh,dc,3}$$

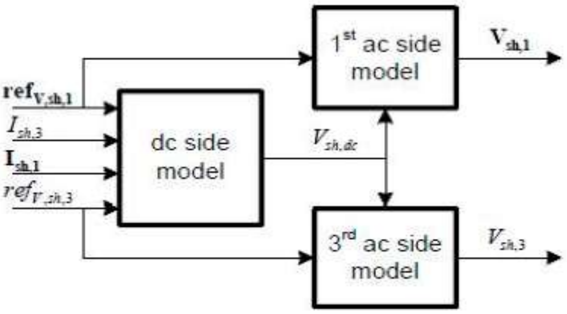


Fig.11. Block diagram of the shunt converter model

V. SIMULINK MODELING AND RESULTS

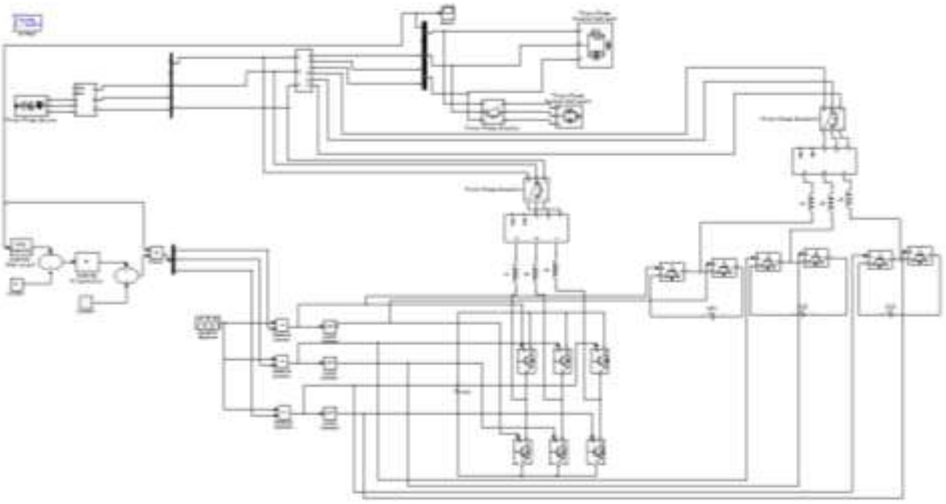


Fig. 12. Simulation model of the DPFC for mitigation of voltage sag

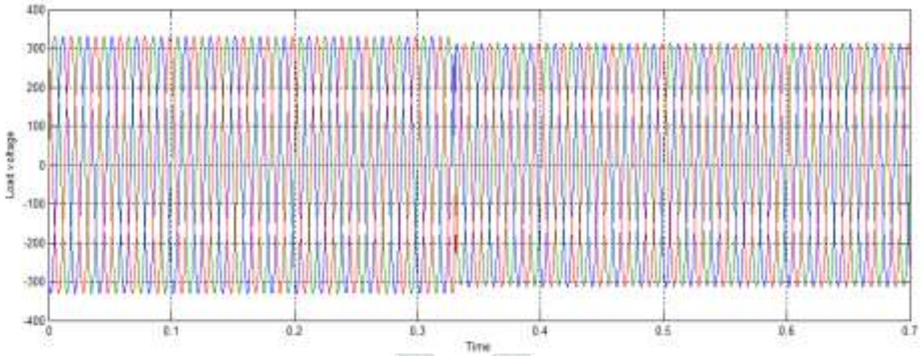


Fig.13. Three-phase voltage sag waveform without DPFC

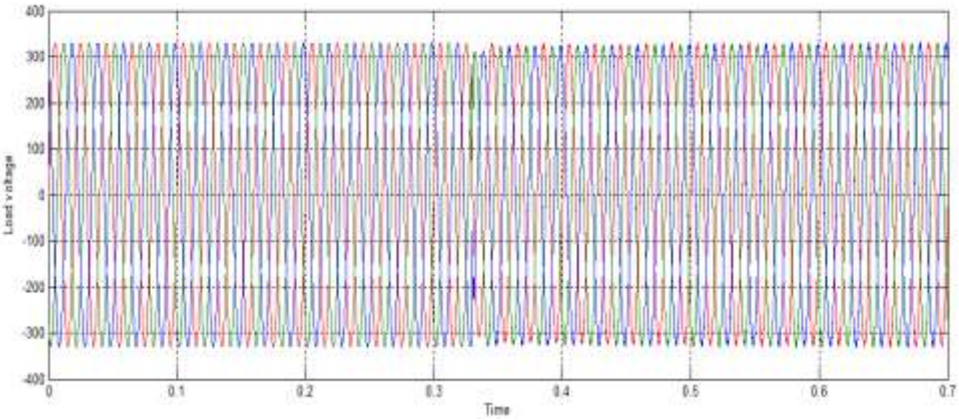


Fig.14. Three-phase voltage sag waveform with DPFC

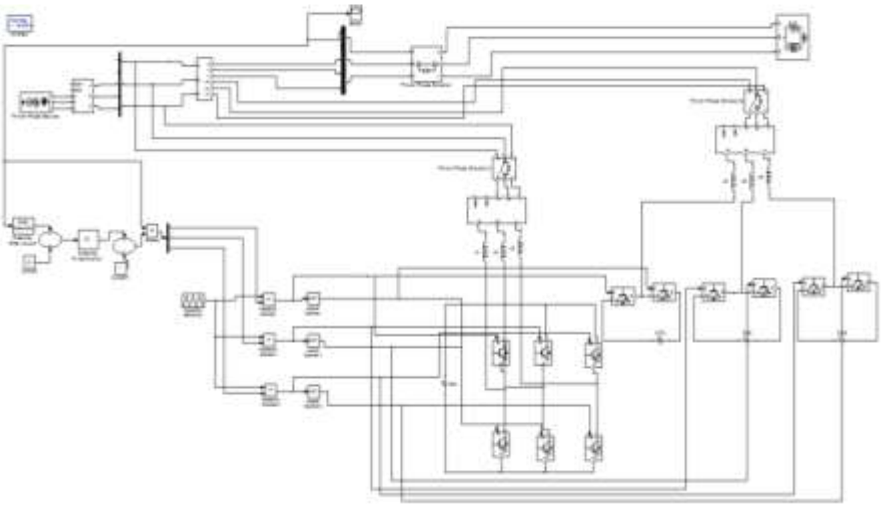


Fig. 15. Simulation model of the DPFC for mitigation of voltage swell

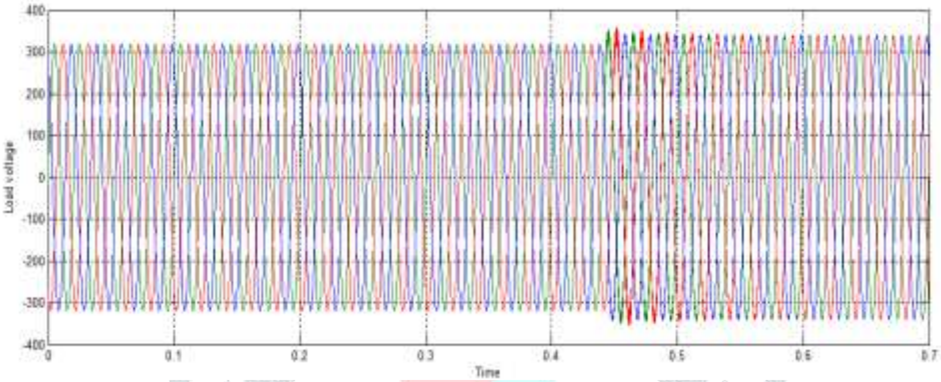


Fig.16.Three-phase voltage swell waveform without DPFC

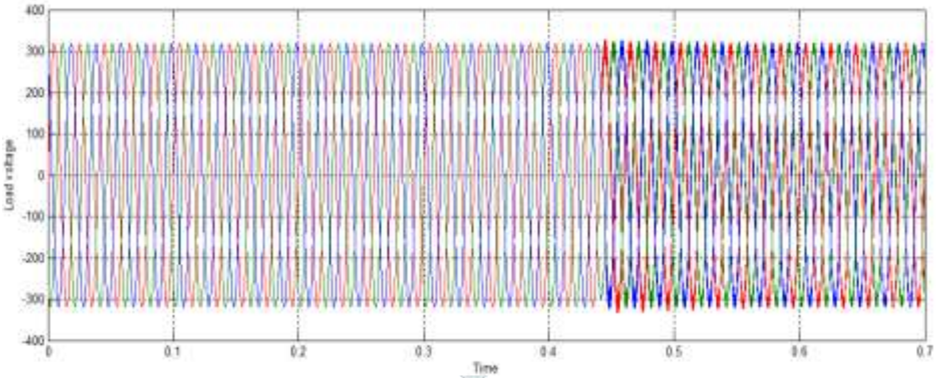


Fig.17. Three-phase voltage swell waveform with DPFC

VI. COMPARATIVE ANALYSIS OF DPFC WITH UPFC

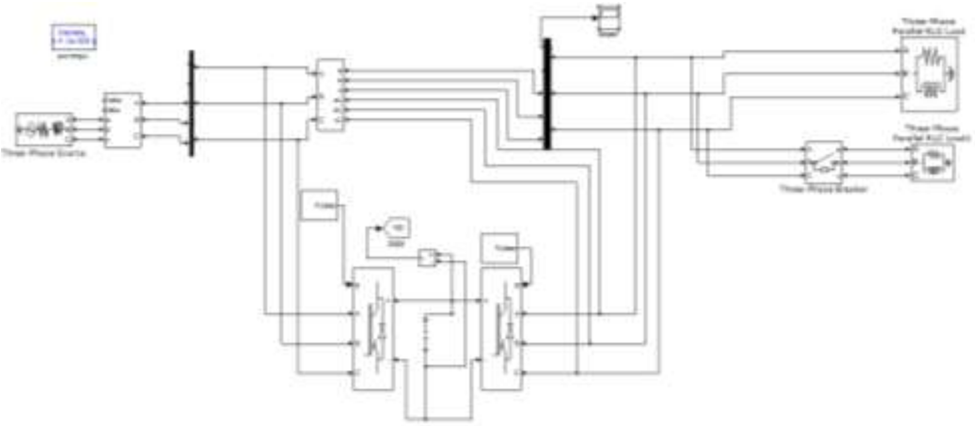


Fig.18. Simulation model for mitigation of voltage sag with UPFC

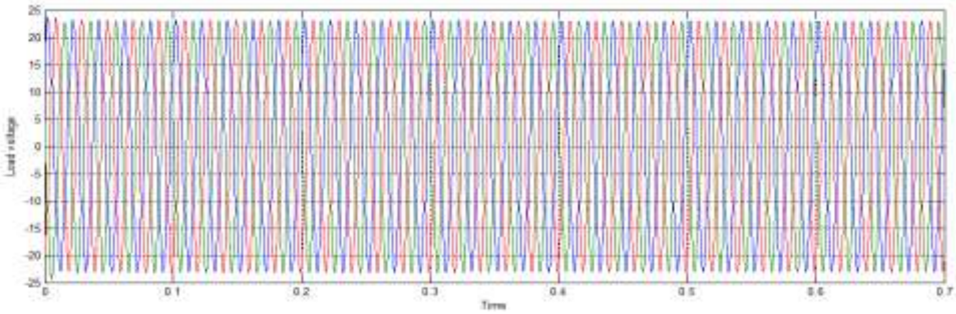


Fig.19. Three-phase voltage sag waveform with UPFC

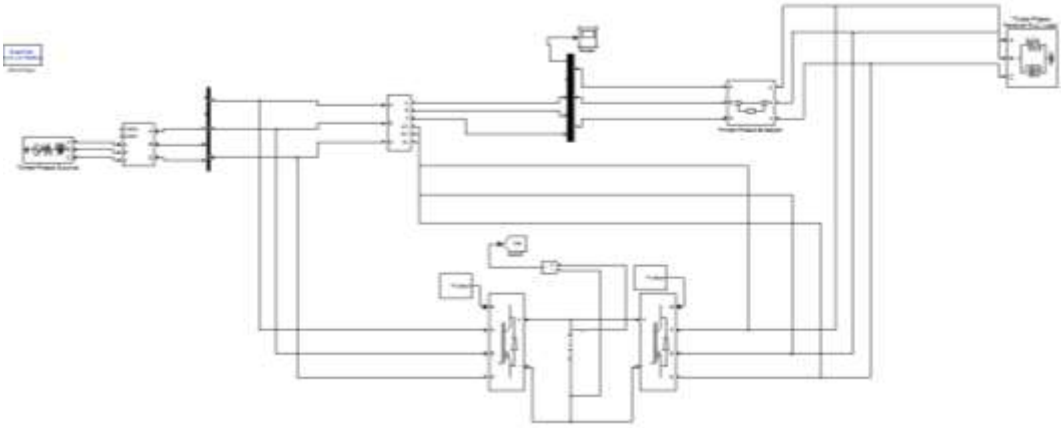


Fig.20. Simulation model of voltage swell mitigation with UPFC

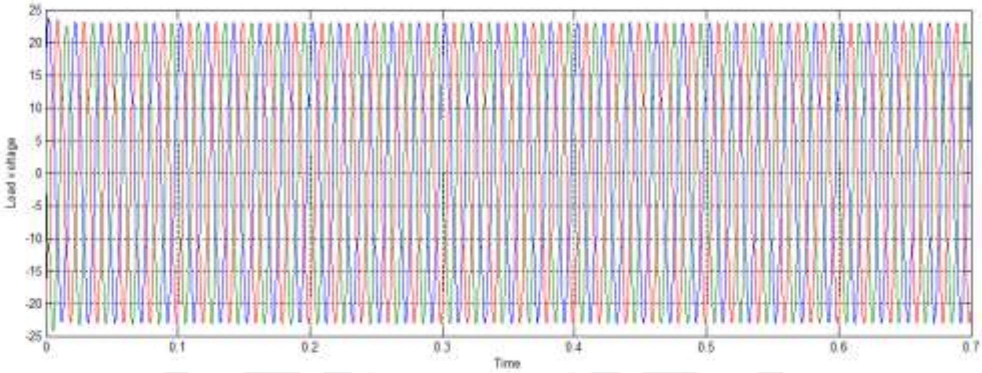
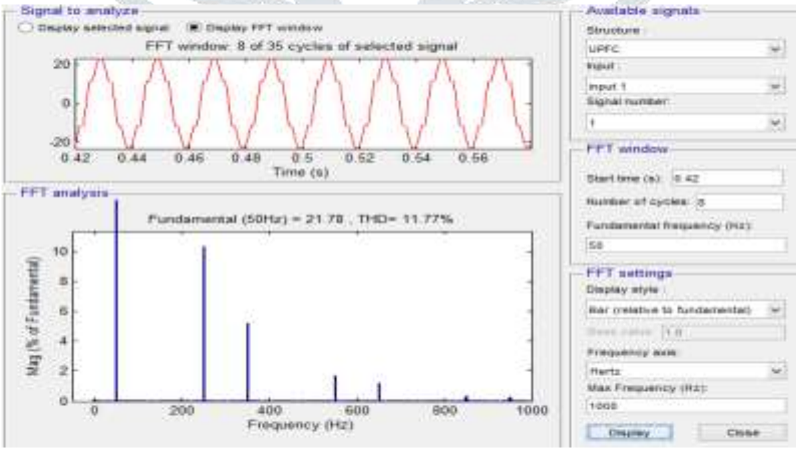


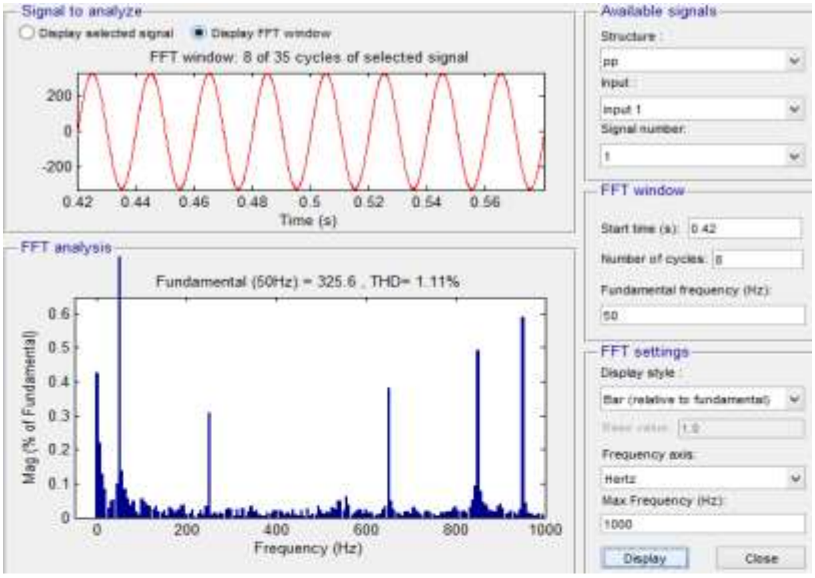
Fig.21. Three-phase voltage swell waveform with UPFC



Fundamental (50Hz) = 21.78 , THD= 11.77%

Structure : UPFC
Input : input 1
Signal number: 1
Start time (s): 0.42
Number of cycles: 8
Fundamental frequency (Hz): 50
Display style : Bar (relative to fundamental)
Base value : 1.0
Frequency axis: Hertz
Max Frequency (Hz): 1000

Fig.22. FFT analysis of mitigation of voltage sag with UPFC



○ Display selected signal ● Display FFT window

FFT window: 8 of 35 cycles of selected signal

Fundamental (50Hz) = 325.6 , THD= 1.11%

Structure : pp

Input : input 1

Signal number: 1

Start time (s): 0.42

Number of cycles: 8

Fundamental frequency (Hz): 50

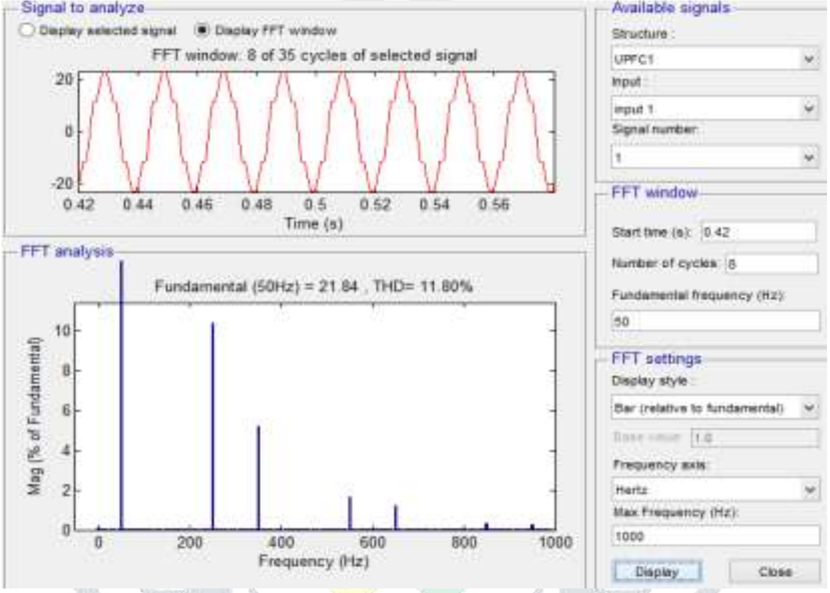
Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 1000

Fig.23. FFT analysis of mitigation of voltage sag with DPFC



○ Display selected signal ● Display FFT window

FFT window: 8 of 35 cycles of selected signal

Fundamental (50Hz) = 21.84 , THD= 11.80%

Structure : UPFC1

Input : input 1

Signal number: 1

Start time (s): 0.42

Number of cycles: 8

Fundamental frequency (Hz): 50

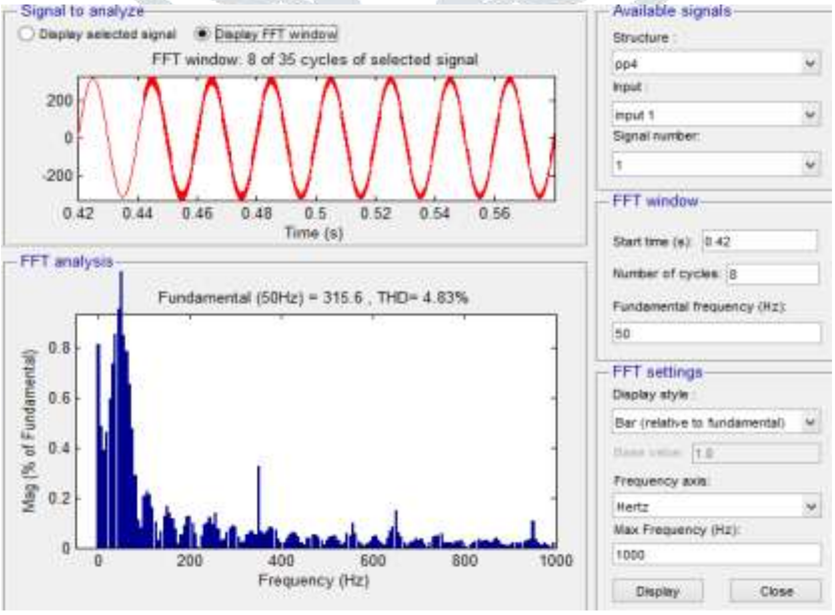
Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 1000

Fig.24. FFT analysis of mitigation of voltage swell with UPFC



○ Display selected signal ● Display FFT window

FFT window: 8 of 35 cycles of selected signal

Fundamental (50Hz) = 315.6 , THD= 4.83%

Structure : pp4

Input : input 1

Signal number: 1

Start time (s): 0.42

Number of cycles: 8

Fundamental frequency (Hz): 50

Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 1000

Fig.25. FFT analysis of mitigation of voltage swell with DPFC

Device used	%THD of voltage sag	%THD of voltage sag
UPFC	11.77%	11.80%
DPFC	1.11%	4.83%

Table 1. Comparative analysis of THD using UPFC and DPFC

CONCLUSION

This paper present the concept of D-FACTS i.e. Distributed FACTS concept applied to UPFC for the reliable operation and forms the new FACTS device DPFC. Also the comparison between the UPFC and DPFC for power quality improvement on the basis of THD is given in this paper. DPFC 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. To improve power quality in the power transmission system, the harmonics due to nonlinear loads, voltage sag and swell are mitigated. To simulate this the load will increased because of this voltage sag will appear. Also the load will disconnect because of this voltage swell will appear. DPFC gives an acceptable performance in power quality improvement.

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