IMPLEMENTATION OF DISTRIBUTED POWER FLOW CONTROLLER (DPFC) FOR POWER QUALITY IMPROVEMENT

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ABSTRACT

The increasing industrialization and Urbanization of life style has led to increasing dependency on the electrical energy. Both electric utilities and end users of electric power are becoming increasingly concerned about the quality of electric power. The term Power quality has become one of the most prolific buzzwords in the power industry since the late 1980s. So proposed technique deals with voltage sag, swell and total harmonic distortion of the power quality issues and distributed power flow controller (DPFC) is used to mitigate the voltage deviation and improve power quality. The distributed power flow controller (DPFC) is an advanced member of the group of flexible AC transmission systems (FACTS). The DPFC is a further development of the UPFC. The DPFC eliminates the common DC link within the UPFC, to enable the independent operation of the shunt and the series converter. Multiple low-rating single-phase converters replace the high-rating three-phase series converter, which greatly reduces the cost and increases the reliability. So proposed technique contains a DPFC sited in a single-machine infinite bus power system including two parallel transmission lines. To simulate the dynamic performance, a three-phase fault is considered near the load and voltage sag, swell and total harmonic distortion (THD) parameters are simulated in MATLAB/Simulink environment.

KEYWORDS: *FACTS, Power Quality, Transmission line, Sag and Swell Mitigation, Distributed Power Flow Controller*

I. INTRODUCTION

The latest buzzword, in energy conscious industries, is the improvement of power quality. The increasingly application of electronic and distributed generation has heightened the interest in power quality in recent years. The term Power Quality is applied o a wide variety of electromagnetic phenomena on the power system. Good quality of electric power can not only result in handsome savings in power bills but also helps in avoiding unwarranted breakdowns [1].

There has been a surge of interest in the development and use of flexible a.c. transmission systems (FACTS) controllers in power transmission systems in recent years there is a great demand of power flow control in power systems of the future and combined FACTS devices are the most suitable devices. For power flow mechanical- and PE-based PFC devices are used. Because of high control capability, the PE-based combined PFCs, specifically UPFC and IPFC are suitable for the future power system [1]. However, the UPFC and IPFC are not widely applied in practice, due to their high cost and the susceptibility to failures.

To reduce the failure rate of the components by selecting components with higher ratings than necessary or employing redundancy at the component or system levels are also options. Unfortunately, these solutions increase the initial investment. Accordingly, new approaches are needed in order to increase reliability and reduce cost of the UPFC and IPFC at the same time. After studying the failure mode of the combined FACTS devices, it is found that a common DC link between converters reduces the reliability of a device, because a failure in one converter will pervade the whole device though the DC link. By eliminating this DC link, the converters within the FACTS devices are operated independently, thereby increasing their reliability. The elimination of the common DC link also allows the DSSC concept to be applied to series converters. In that case, the reliability of the new device is further improved. The UPFC is further developed into a new combined FACTS device: the Distributed Power Flow Controller (DPFC).

The paper is organized as follows: In section I, the overall introduction is prescribed and in section II, the DPFC working principle with eliminated dc link and using third harmonic components active power exchange is discussed. The DPFC modeling is described in section III with separate series and shunt converters modeling. Section IV is dedicated to power quality improvement by DPFC and for that simple case is considered with RLC load and three phase fault is created near the load. Simulation results are presented in section V shows voltage sag, swell and total harmonic distortion (THD) waveforms. Section VI shows future scope for DPFC device.

II. WORKING PRINCIPLE

2.1. Remove DC Link and Active Power Exchange

In DPFC structure, transmission line makes the common connection between series and shunt converters. That is the reason for active power exchange between two converters. According to Fourier technique, non-sinusoidal voltage and current is equal to the summation of sinusoidal component in different frequencies with different amplitudes. The complete method is based on power theory of non-sinusoidal components [2]. The definition of active power getting from non sinusoidal voltage and current is 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,

$$P = \sum_{i=1}^{\infty} V_i \, I_i \, Cos\emptyset_i \quad (1)$$

Where V_i and I_i are the voltage and current at the i_{th} harmonic frequency respectively, and $\emptyset_i$ is the corresponding angle between the voltage and current. Equation (1) presents the active powers at different frequencies are independent from each other and the voltage or current at one frequency has no affect on the active power at other frequencies. The independence of the active power at different frequencies gives the possibility that a converter without a power source can generate active power at one frequency and absorb this power from other frequencies.

$$P_r + jQ_r = V_r . I^* \quad (2)$$

According to above procedure in the DPFC, the shunt (STATCOM) converter can take active power from the line at fundamental frequency and return it back at a harmonic frequency. This active power flows through transmission line. So whatever amount of active power required at fundamental frequency is supplied by DPFC series converter which produces voltage at harmonic frequency. In this way active power is absorbed from harmonic components. Neglecting losses, the active power generated at the fundamental frequency is equal to the power absorbed at the harmonic frequency.

2.2. Using Third Harmonic Components

The 3^{rd} harmonic is selected for active power exchange in the DPFC because of its unique features. . In a three-phase system, the 3rd harmonic in each phase is similar, which means they are 'zero-sequence' components. Because the zero-sequence harmonic can be naturally blocked by Y-Δtransformers therefore there is no extra filter required to prevent harmonic leakage.

The harmonic at the frequencies like 3rd, 6th, 9th... are all zero-sequence and all can be used to exchange active power in the DPFC. However, the 3rd harmonic is selected, because it is the lowest frequency among all zero-sequence harmonics. The relationship between the exchanged active power at the i_{th} harmonic frequency Pi and the voltages generated by the converters is expressed by the well known the power flow equation and given as:

$$P_i = \frac{|V_{sh,i}||V_{se,i}|}{X_i} \, Sin(\emptyset_{sh,i} - \emptyset_{se,i}) \quad (3)$$

Where Xi is the line impedance at i_{th} frequency, |Vsh,i| and |Vse,i| are the voltage magnitudes of the i_{th} harmonic of the shunt and series converters, and $(\emptyset_{sh,i} - \emptyset_{se,i})$ is the angle difference between the two voltage [3]. The impedance of transmission line has capacity to limits active power exchange through it. As we know transmission line is almost inductive in nature and directly proportional to frequency. And therefore high frequencies will cause high impedance and result in high voltage within converter.

Consequently, the zero-sequence harmonic with the lowest frequency - the 3rd harmonic - has been selected.

III. DPFC MODELING

DPFC modeling consists of converter modeling and network modeling. Series converter employs the DSSC (distributed static series converter) concept. In DSSC concept single phase converters are used hence they modeled as single phase system. Two tools are employed for the DPFC modeling: the superposition theorem and Park's transformation. The superposition theorem is applicable to linear networks consisting of independent sources, linear dependent sources, linear passive elements and linear transformers, hence it can be applicable. However, for the converter, certain approximations are needed for the application of the superposition theorem [4].
Park's transformation is defined for signals at a single frequency. But DPFC signals consist of two frequency components, first at fundamental and second at 3rd harmonic frequency. Therefore superposition theorem is first used to separate the components. Then, the component at different frequencies are subjected to Park's transformation and analyzed separately. In the case of balanced three-phase circuits, application of the dqo transform reduces the three AC quantities to two DC quantities. Simplified calculations can then be carried out on these DC quantities before performing the inverse transform to recover the actual three-phase AC results. In the following section detail description about separate modeling is given,

3.1. Connection of Separated model

The block diagram of separated model is shown in fig.1. As shown, the DPFC model consists of the fundamental frequency network model, the 3rd harmonic frequency network model, the series converter model and the shunt converter model.

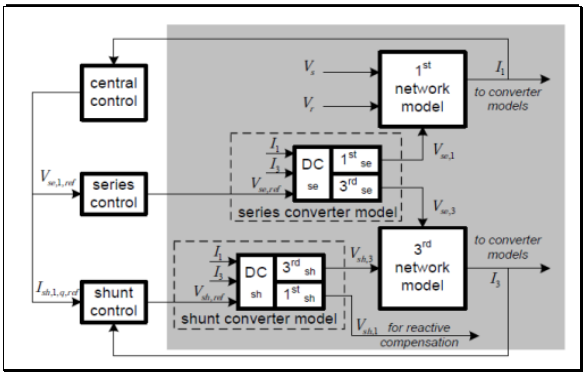

Figure 1. Connection for separated model

The inputs for fundamental network model are sending end and receiving end voltage. This model is used for calculation of current I_1 and it returns back to the shunt, series converter model. From series and shunt converter model it is use for DC voltage calculation and central control helps for the application at power system level. Similarly 3_{rd} harmonic network model takes the input as shunt and series voltage at and third harmonic frequency. The Output from 3rd network model, current I_3 is return back to shunt converter model. DC shunt converter model has input current at fundamental and 3rd harmonic frequency [4].

3.2. Network Modelling

This section presents mathematical model at both fundamental and 3rd harmonic frequency.

3.2.1. Fundamental frequency Network Modelling

In the network modeling, the DPFC converters can be considered controllable voltage sources. In a practical transmission system, perfect balance between phases is often assumed because the effect of the asymmetry is usually small, especially if the lines are transposed along their lengths. According to equivalent circuit, voltage at fundamental frequency injected by the series converters is Vse,1, the line impedance is Z1, and the voltages at the sending and receiving ends are Vr and Vs, respectively. The relationship between voltage and current is given by,

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

3.2.2. Third Harmonic Frequency Network Modelling

The basic function of shunt converter is to maintain the capacitor voltage by absorbing active power from grid and inject a constant 3rd harmonic current into line to supply active power for series converters [5].

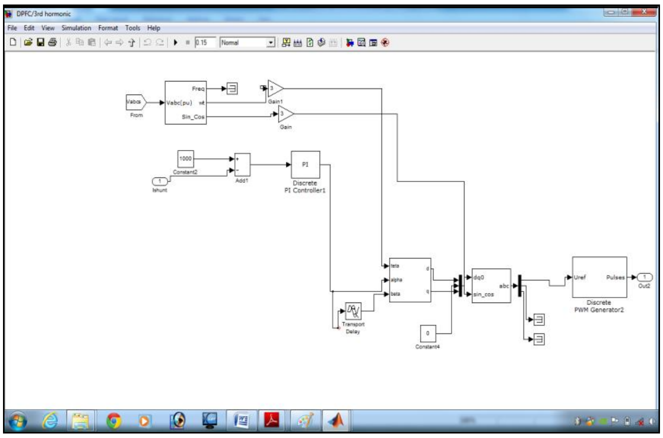

Figure 2. Matlab format 3rd harmonic freq. Modelling

winding. The converter with voltage source, transformer winding and impedance shown in fig.2.The current flowing through transmission line is I_3 with controllable voltage source connected in series with same line. This total impedance at the 3rd harmonic frequency is represented by Z3. The transmission line impedance and transformer impedance shows total impedance of line. Therefore, relationship between the voltages and the currents at the 3rd harmonic frequency is given,

$$\begin{bmatrix} V_{sh,3} - V_{se,3,a} \\ V_{sh,3} - V_{se,3,b} \\ V_{sh,3} - V_{se,3,c} \end{bmatrix} = \begin{bmatrix} Z_3 & 0 & 0 \\ 0 & Z_3 & 0 \\ 0 & 0 & Z_3 \end{bmatrix} \begin{bmatrix} I_{3,a} \\ I_{3,b} \\ I_{3,c} \end{bmatrix}$$

Separate series and shunt converter modelling are given below,

3.3. Series Converter Modelling

The series converter is PWM control single phase converter. It's simplified block diagram shown in Fig.3. The basic function of series converter is to maintain the capacitor DC voltage of its own converter by using the 3rd harmonic frequency components and generate the series voltage at the fundamental frequency that is prescribed by the central control.

The AC side of series converter is represented by V_{se} and it is connected to the main transmission line. Similarly DC side is given by $V_{se, DC}$ and it is connected to the series control through reference signal. The modulation amplitude of the reference AC signal is $refV_{sef}$ in pu, which is generated by the series control. Due to the identity of the series converters, Fig. 3 shows a converter that is availed in all three phases [6]. To distinguish the converter in different phases, a subscript of phase could be added to the voltages and currents if necessary.AC voltage and current consists of two components at different frequencies, fundamental and 3rd harmonic frequency that are denoted by subscripts 1 and 3 respectively.

$$V_{se} = V_{se,1} + V_{se,3} \quad (4)$$

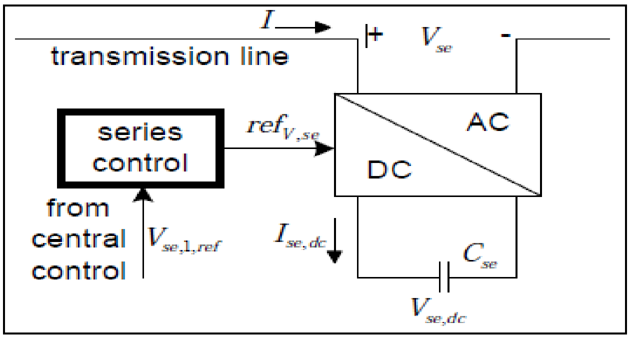

Figure 3. Block diagram of Series Converter Model

3.3.1. AC Side and DC Side Modelling

The series converter is a PWM converter. The AC side voltage is given by product of AC reference signal and DC voltage. In mathematical form expressed as,

$V_{se}=refV_{se*}V_{se,DC}$ (5)

The reference signal is pu value with the range from -1 to 1. The transmission network is a linear system and the superposition theorem can therefore be applied. However, for the converter, certain approximations are needed for the application of the superposition theorem. The superposition theorem is first used to separate the components [6]. Then, the component at different frequencies are subjected to Park's transformation and analyzed separately given as,

$$\begin{bmatrix} V_{se,1} \\ V_{se,3} \end{bmatrix} = \begin{bmatrix} refV_{se,1} \\ refV_{se,3} \end{bmatrix} \times V\text{se, dc}$$

The DC voltage of the series converter is $V_{dc,\,se}$ and DC current is $I_{dc,\,se}$. The relationship between DC voltage and current is given by,

$$C_{se}\frac{dV_{dc,se}}{dt} = I_{dc,se} \qquad (6)$$

The DC side voltage and current consists of both fundamental and harmonic component. At the same time DC current is given by,

$I_{dc,se} =$ $refV_{se} \cdot I = (refV_{se,1} + refV_{se,3})(I1 + I3)$ (7)

3.3.2 Series converter model

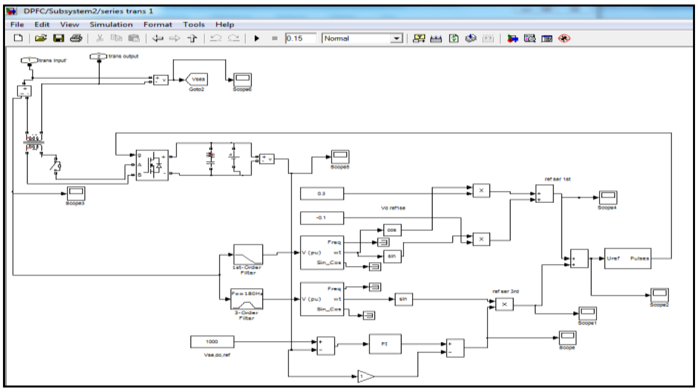

Figure 4. Matlab Format of Series Converter Model

3.4. Shunt Converter Modelling

Basically shunt converter is operated like STATCOM. The basic function of shunt converter is to inject a constant 3rd harmonic current into line to supply active power for series converters. The idea is to supply the reactive power locally that is required by the load [6]. By varying the impedance of the shunt device, the injected reactive current I_{sh} can be adjusted, thereby indirectly controlling the line current I.

3.4.1. AC side and DC side Modeling

Similar to the series converter modelling, the AC voltage can be written as follows:

$$V_{sh,1} = refV_{sh,1} \times V_{sh,dc}$$

$$V_{sh,3} = refV_{sh,3} \times V_{sh,dc}$$

where the modulation amplitudes $refV_{sh,1}$ and $refV_{sh,3}$ are pu values with the range from -1 to 1. The capacitor DC voltage of the shunt converter is given with the following equation:

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

3.4.2. Shunt converter model

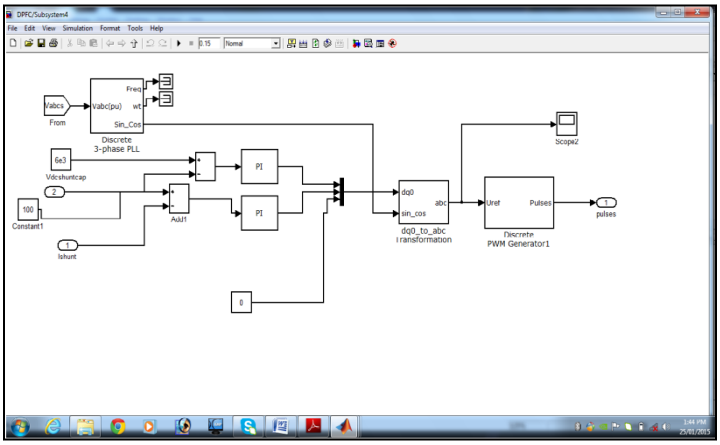

Figure 5. Matlab Format of Series Converter Modeling

IV. DPFC MODELLING

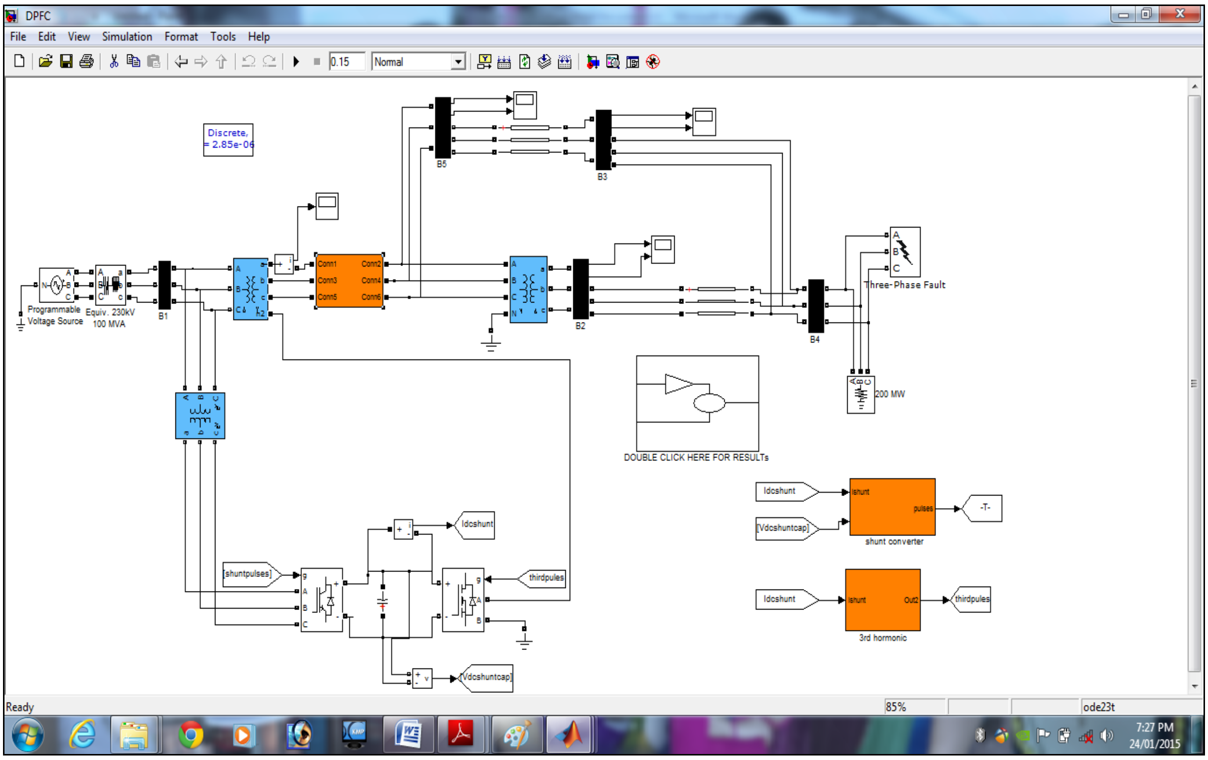

Figure 5. Complete Matlab Model of DPFC

For power quality improvement a particular system is considered. The whole model presented in mat lab form shown in fig.6. The system contain two parallel transmission line consists of three phase shunt converter and distributed single phase series converters. The shunt converter is connected to second transmission line through Y-Δ three phase transformer [7]. And series converter is distributed along with the line according to the length of transmission line. For determination of DPFC topology a fault is created of 5sec and then voltage sag, swell and harmonic distortion are observed. Simulation parameters are shown in table with specification.

Table 1. Simulation System Parameters

Parameters	Value
Three phase source	
Rated Voltage	230 KV
Rated Power/Frequency	100 MW/60HZ
X/R	3
Short Circuit Capacity	11000 MW
Transmission Line	
Resistance	0.012 pu/km
Inductance/Capacitance Reactance	0.12/0.12 pu/km
Length of transmission line	100 km
Shunt Converter 3-phase	
Nominal Power	60 MVAR
DC link Capacitor	600µF
Coupling Transformer(shunt)	
Nominal power	100 MVA
Rated Voltage	230/15 KV
Series Converter	
Nominal Power	6 MVAR
Rated Voltage	6 KV
Three-Phase fault	
Type	ABC-G
Ground resistance	0.01 ohm

V. SIMULATION RESULT

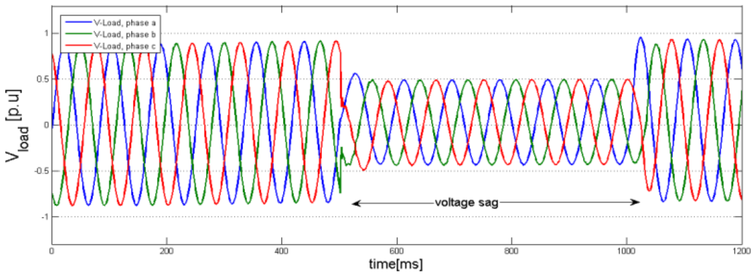

Figure 6. Three-phase load voltage sag waveform

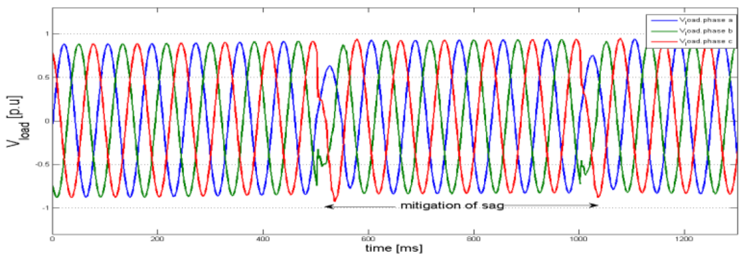

Figure 7. Mitigation of three phase load voltage sag with DPFC

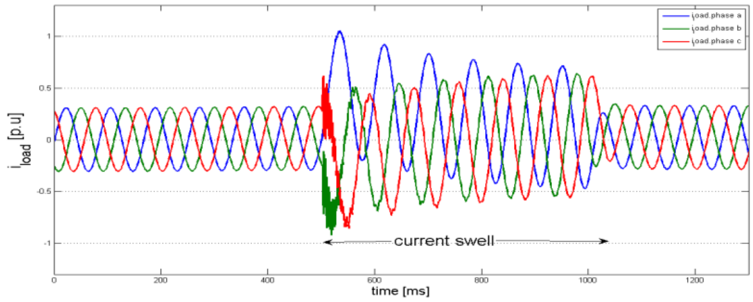

Figure 8. Three-phase load current swell waveform without DPFC

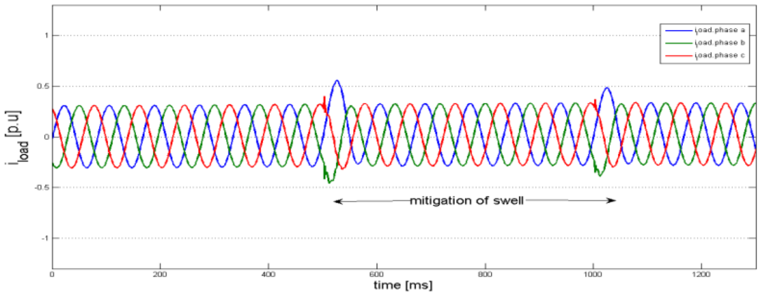

Figure 9. Mitigation of 3-phase load current swell with DPFC

Without DPFC implementation system shows sag and swell about 0.5 percent. But after placing DPFC in the circuit according to the system configuration, value of sag and swell reduced. The Total Harmonic Distortion measures the total harmonic distortion (THD) of a periodic distorted signal. The signal can be a measured voltage or current. Due to DPFC even harmonics are eliminated. And odd harmonic reduced to acceptable limits[8].

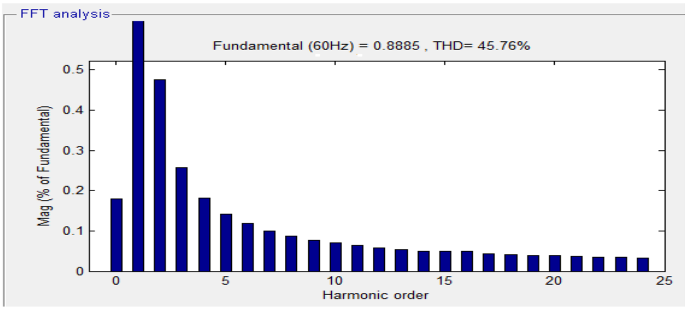

Figure 10. THD of load voltage without DPFC

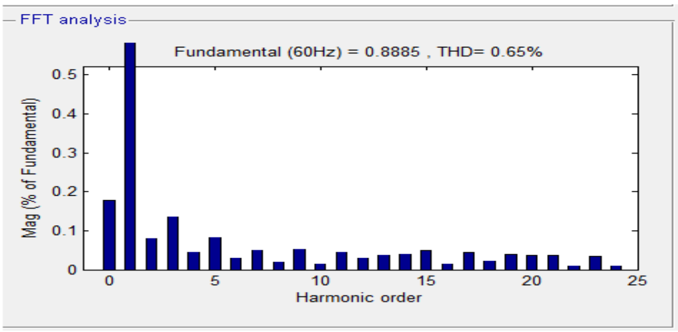

Figure 11. THD of load voltage DPFC

VI. FUTURE SCOPE

The paper shows that the DPFC has a lower cost and should be more reliable than the UPFC. However, the DPFC also require modification for future research are:

• Communications: Because the series converters operate outdoors, the communication (wireless or PLC) between the central control and series converters is susceptible to disturbances, such as lighting or a geomagnetic storm[7]. Accordingly, the communication should be reliable enough to continue operating in spite of these disturbances.
• Weight reduction of the series converter: Since the series converters are hung on transmission lines, they result in extra pressure for towers. A lightweight series converter unit is desirable.
• 3rd harmonic current management: The 3rd harmonic components within the DPFC lead to extra losses in transmission lines and transformers. In this thesis, the 3rd harmonic current within the DPFC is set at a constant value. The magnitude of the 3rd harmonic current can be managed in a way that it is adjusted according to the requirement for active power. Consequently, the loss of the DPFC can be reduced [8]. Besides the above concerns, additional DPFC applications for utility grid are also interesting for future research:
• Centralized control for multiple DPFC: As the DPFC series converter can be easily applied to multiple lines, the centralized control of multiple DPFCs is an interesting potential application.

VII. CONCLUSIONS

This paper deals with problems related with harmonics in power system networks and introduce a very new FACT device called “Distributed Power Flow Controller”. Now days Power quality has become one of the most prolific buzzwords in the power industry. DPFC is similar as UPFC but with eliminated dc link and offer some advantages like high control capability, high reliability, and low cost. For analyzing DPFC two parallel lines was considered and fault is created near the load. Before implementation of DPFC significant voltage sag is observable during the fault. The voltage sag value is about 0.5 per unit. After adding a DPFC, load voltage sag can be mitigated effectively. The load current swell about 1.1 per- unit, is observed during the fault. After implementation of the DPFC, the load current swell is removed effectively. 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. It is shown that the DPFC gives an acceptable performance in power quality mitigation and power flow control.

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