Distributed Power Flow Controller for Voltage Sag and Swell Mitigation

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Abstract : Distributed power flow controller (DPFC) is device which used to control the power flow and voltage profile at distribution system and replacement of flexible AC transmission line (FACTS) controller. The DPFC springs from the unified power-flow controller (UPFC). DPFC configuration is similar with DPFC controller only common DC link not present in DPFC controller. UPFC controller is the equipment which exchanges the active power in between series and shunt controller using common DC link at third harmonics frequency components. DPFC controller are made up of small series controller in place of large converter controller like UPFC and at each end of line shunt converter are connected. Large number of series connected converter is increase the system reliability**.** Also the initial and running cost of DPFC converter is low as compare with UPFC. But, if we need to change the rating or capacity of line that time DPFC Converter also need to update. The DPFC controller has same controlling capability like UPFC controller which can adjust the resistive property of transmission line and transmission load angle, and bus voltage.
The principle and analysis of the DPFC area unit bestowed during this work and therefore the corresponding experimental results that area unit dispensed in MATLAB simulink. The DPFC controller style in MATLAB Simulink and tested with unbalanced loading condition cable. Performance of DPFC controller is analyzed using MATLAB simulation software.

***Index Terms* – Voltage sag, Voltage swell, Unbalance loading**

I. Introduction

Any electrical power system aims to transfer electricity to consumers at a proper voltage profile. The electrical power system mainly divided into three sections like generation, the transmission of power and distribution for proper utilization of electricity. Normally electricity generation has done in thermal or nuclear power plant and distributed to consumer end using transmission and distribution system. The rate of transmission of power in the transmission line is called Power flow which may include active and reactive power of the transmission line system.
For the last 20 year, the overall behaviour of transmission system changes because of the addition of new technology, a huge electricity market and new development of renewable energy sources. The system becomes now more complex due to the addition of new major components in the power system like electric vehicles, distributed generator and smart grid technology.
For increasing loads of electrical power system is need to increase the generation capacity of power plant for support to this increase loads demand. But due to high cost, environmental problems and right-of-way issues will be causes difficulty for transmission line capacity increment. Hence for this, the transmission power limit of the electrical network will be required to increase and complete utilization of the network is required. In a complex electric network are many parallel transmission lines between generations and load system. Hence, to increase the power handling capacity of the transmission line we need to shift total power into the parallel transmission line system or alternate transmission line option.
During extreme emergency condition, an interconnected transmission line transfers the power above the rating of power and support to huge load condition by increasing the stability of the power system. To reduce the loop power flow in the system, hence need bidirectional power flow in between two different zones of the power system. The electricity market depends upon the supply and demand chain on which basis the price of electricity per unit cost define.
In this paper, we have to propose a distributed power flow controller for voltage sag and swell improvement of the power system. In this approach, the shunt controller of the DPFC controller is a design based on the direct axis and quadrature axis current base controller and the series controller is a design based on hysteresis voltage control. The complete system is designed in MATLAB 2015R and result from analysis done in the simulation environment.

II. MODELLING OF SERIES CONTROLLER

Series controller is used in DPFC controller for control the voltage profile of distribution system in case of voltage sag, voltage swells and harmonics conditions. These conditions was occurs due to the sensitive loads like switching of highly inductive load, highly capacitive load and power electronics converter based load. The series controller is connected between the supply and load terminals using three single phase transformers. The primary winding of isolating or injecting transformer is connected in star configuration and while secondary winding are connected in each phase of transmission line in series configuration. This injecting transformer is required to inject the voltage into the main power system during voltage sag condition while absorb the voltage into the capacitor during voltage swell condition. A small rated R-C (resistive-capacitor) series branch is connected across the secondary winding of injecting transformer for eliminating high switching frequency ripples or harmonics. The voltage source inverter with six IGBT based is used for supply the voltage to primary side of injecting transformer.
The generalized structure of series controller is shown in figure 1. The converter controller is made up of DC voltage source or capacitor to suppressed the switching ripples and series transformer are used to inject or absorb the voltage from transmission line during voltage sag and swell condition.

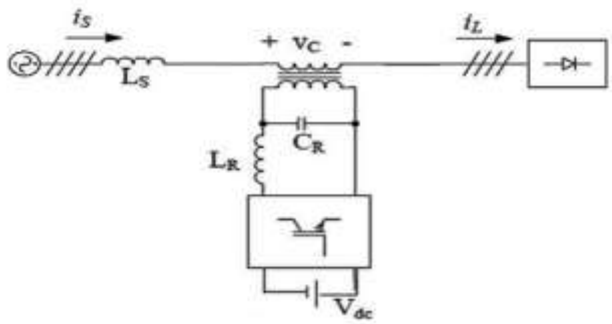

Fig.1 Block diagram of series active power controller

The working of series controller is depends upon the pulse width modulation technique for switching pulse control of converter and depends upon method for calibration of reference voltage for system. Series controller has two main blocks like voltage disturbance identification block and voltage controlling block. Phase lock loop system is used for generation of reference voltage.

2.1 Control technique for series controller

The hysteresis pulse width modulation method is used for control the series controller. The series controller is controlled such that it injects voltages (V_{ca} ,V_{cb} ,V_{cc}) which cancel out the distortions and/or unbalance present in the supply voltages (V_{sa} ,V_{sb} ,V_{sc}) thus making the voltages at the PCC (V_{la} ,V_{lb} ,V_{lc}) perfectly balanced and sinusoidal with the desired amplitude**.** Hence , series controller is add or absorb the voltage Vla, Vlb, Vlc into the system using injecting transformer at point of common coupling (PCC). The controller subsystem for series controller is shown in figure 2.

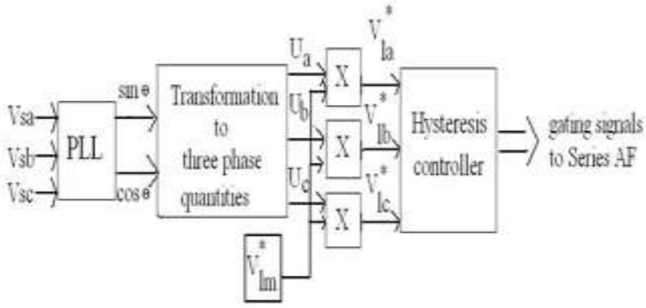

Fig.2 Control scheme for series active power controller for DPFC

2.2 Hysteresis controller design

The phase lock loop system is unitized for convert measured system input voltage (which is distorted or unbalance) converted into synchronized three phase voltage supply. The phase lock loop is generate the reference three phase voltage which is equal to the fundamental components of voltage at supply frequency with standard phase difference in each phase of voltage i.e. 1 per unit. Three phase distorted/unbalanced voltages are measured using PTs at each sending end of line. That measured voltage is then send to PLL system for conversion of SinΘ and CosΘ frequency components.

The measured system voltage is multiply with gain for convert input sinusoidal three phase parameters into per unit values. The sin and cosine components generated by PLL system is used for calibration of three phase unit vector voltages (Ua, Ub, Uc) in per unit using equation (1) as

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} Sin\theta \\ Cos\theta \end{bmatrix} \quad \text{...... (1)}$$

After calibration of reference three phase per unit voltage from PLL system is then multiply with peak RMS voltage of system (Vlm*) using equation (2)

$$\begin{bmatrix} V_{la}^* \\ V_{lb}^* \\ V_{lc}^* \end{bmatrix} = V_{lm}^* \times \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \quad \text{.......................... (2)}$$

From voltage measurement at bus bar after generator, it is observe that, the peak RMS voltage is 338 volts (= $\frac{415*\sqrt{2}}{\sqrt{3}}$). Calibrated voltage from equation (2) is then fed to the hysteresis controller as reference voltage for firing pulses generation for converter (inverter/rectifier) operation**.** Then output of hysteresis controller is six pulses for six switches of converter subsystem of series controller. The firing pulses generated by hysteresis controller is based on comparison of voltage at PCC with reference voltage for system and control the firing pulses of inverter subsystem for control the input primary side voltage of three phase injection transformer.. Hence, injecting transformer insert or absorb the voltage into the transmission line using ripple capacitor and remove the unbalance voltage condition from system. Simulation model of control system for series controller is shown in figure 3.

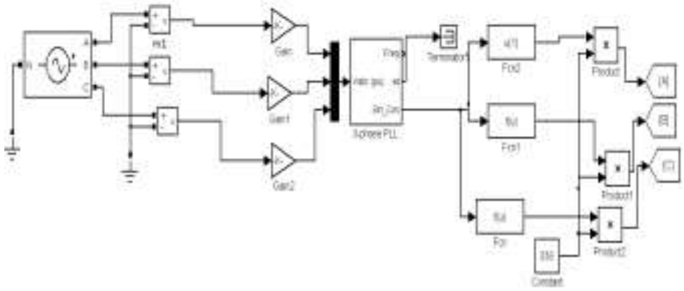

Fig.3 Reference voltage generator for SAF for transient stability improvement

Based on comparison of standard reference voltage vector with load side voltage in hysteresis controller is pass trough relay switch to allow the upper and lower limit of firing pulses. Hence, pulses send to the each switch of six pulse converter controller for series controller shown in figure 4.

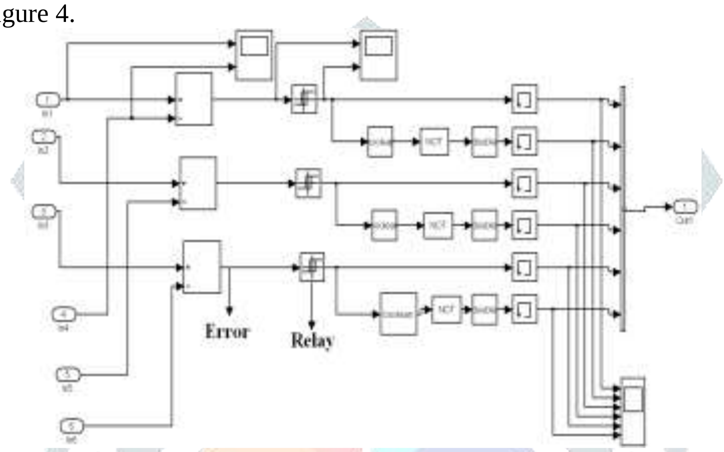

Fig.4 Hysteresis voltage controller

The vector difference between the reference voltage and the actual voltage is error voltage, which is given as the input to the relay block. The relay system act as upper and lower threshold logic for hysteresis controller subsystem shown in figure 5 and the respective pulses produced for the upper switch, leg1 of SAPF is shown in Figure 6.

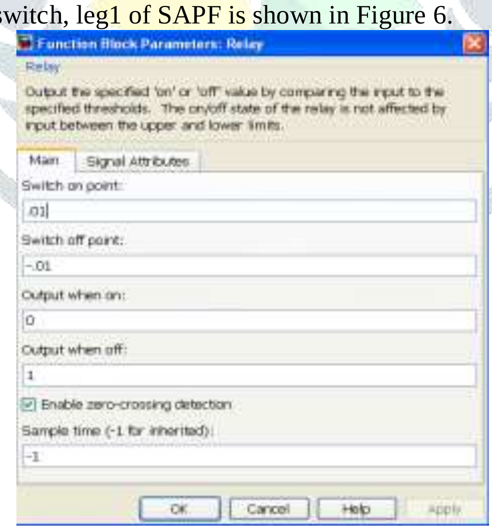

Fig.5 Relay function parameters

III. MODELLING OF SHUNT CONTROLLER

3.1 Shunt Controller Subsystem

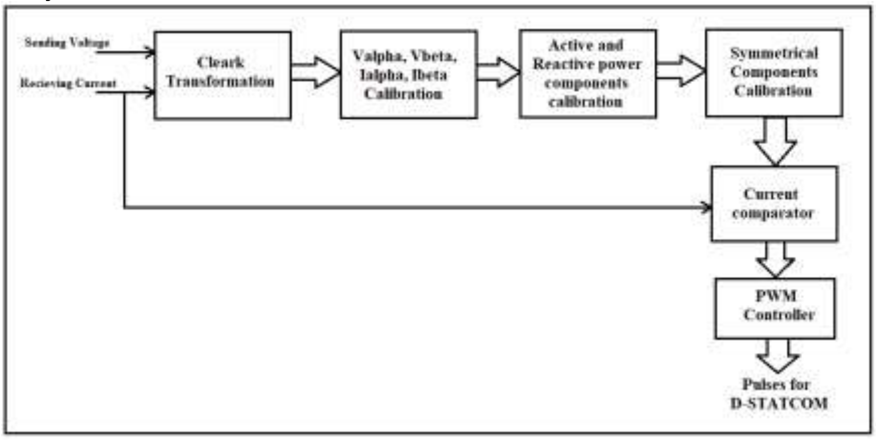

Fig.6 Shunt controller design for DPFC

Figure 6 shows the matlab simulink model of shunt controller system for DPFC system. In this universal bridge which is act as inverter which convert the DC link supply into AC output which fed to the transmission line. That controller control the current of transmission line based on firing pulses of inverter. As the voltage of transmission line drops due to high loading then that time controller absorbed the current from transmission line by decreasing pulses rate of inverter. Similarly, for high voltage increases due to highly capacitive load then that time controller insert the current into the transmission line by increasing the pulse rate of inverter.

Figure 8 shows the shunt controller pulse generator subsystem model in which different block consist of like Clarke transformation for conversion of three phase voltage and three phase current into Valpha, Vbeta, Ialpha and Ibeta conversion. The Three phase voltage convert into Alpha and Beta component are calibrate using following formula:

$$V_{alpha} = \sqrt{\frac{2}{3}} * (V_a - 0.5V_b - 0.5V_c) \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

$$V_{beta} = \sqrt{2} * (V_a + 0.5V_b - 0.5V_c) \quad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

The Three phase current convert into Alpha, Beta and Null component are calibrating using following formula:

$$I_{alpha} = \sqrt{\frac{2}{3}} * (I_a - 0.5I_b - 0.5I_c) \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

$$I_{beta} = \sqrt{2} * (I_a - 0.5I_b + 0.5I_c) \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

$$I_{null} = \sqrt{\frac{1}{3}} * (I_a + I_b + I_c) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

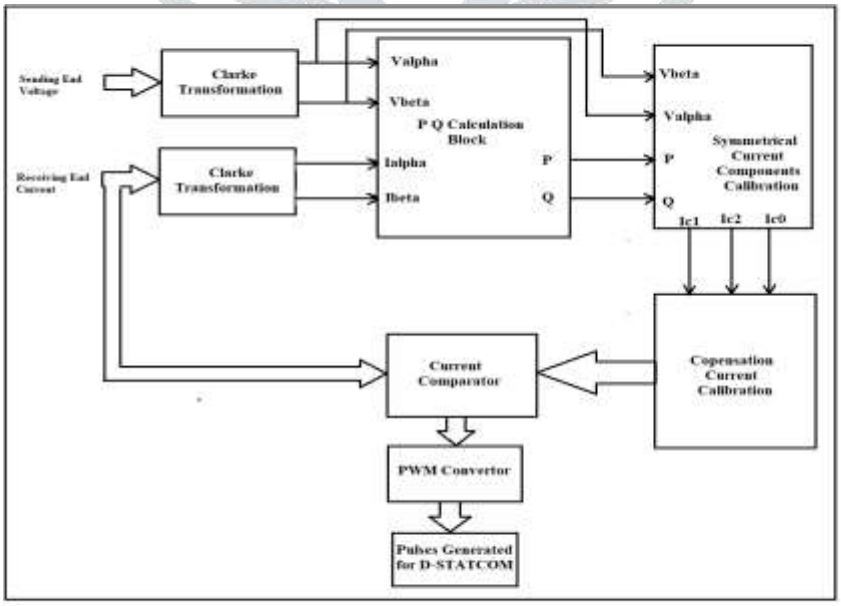

Fig.7 PQ components calibration subsystem model

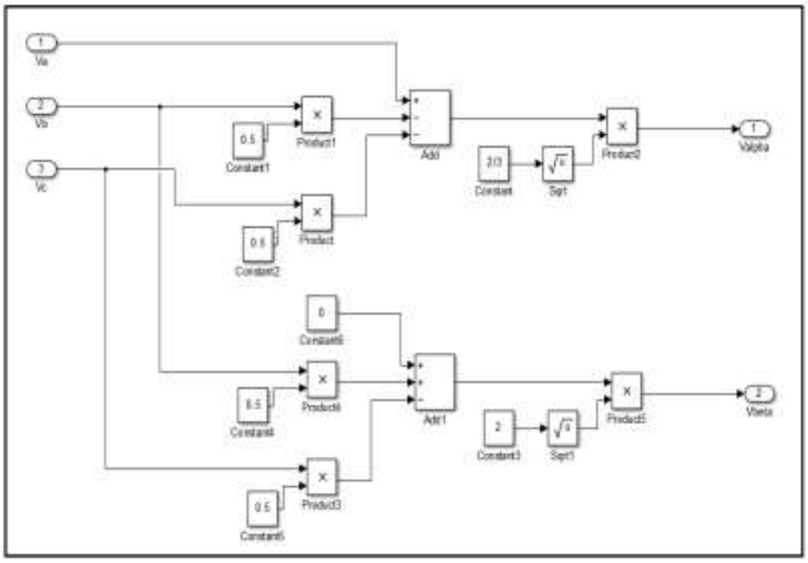

Fig.8 Clarke transformation for Valpha and V beta Calibration

That calibrated Valpha, Vbeta, Ialpha and Ibeta component then transfer to P and Q components calibration subsystem. The complete PQ component calibration subsystem model is shown in figure 10.

The P and Q components are calibrated in subsystem model using following formula:

$$P = \left(V_{alpha} * I_{alpha}\right) + \left(V_{beta} * I_{beta}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

$$Q = \left(V_{beta} * I_{alpha}\right) - \left(V_{alpha} * I_{beta}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

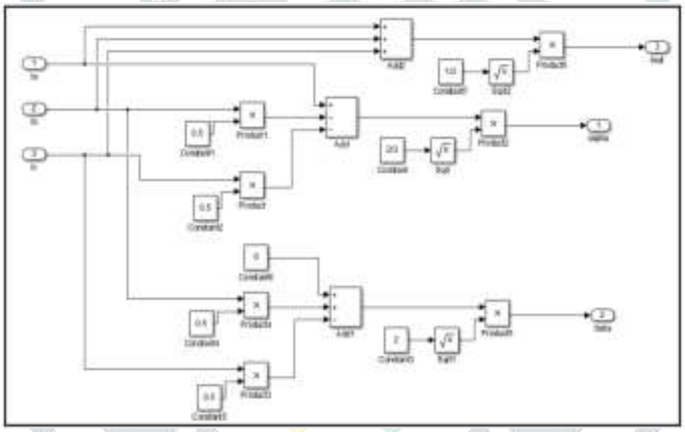

Fig.9 Clarke transformation for Ialpha and I beta Calibration

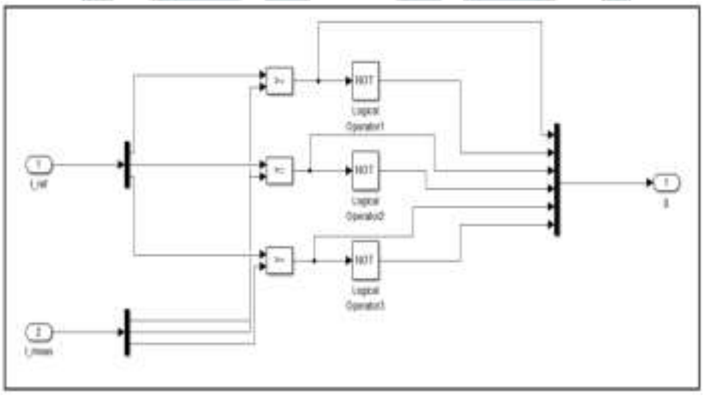

Fig.10 Hysteresis based Ireference and Imean current comparison subsystem mode

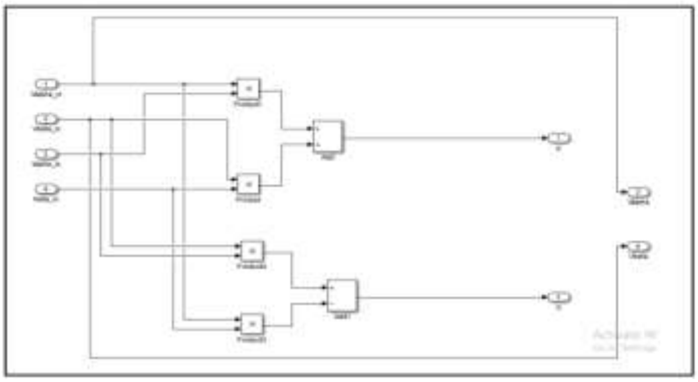

Fig.11 P and Q components calibration subsystem model

Then P and Q components as well as Valpha and V beta components are send to positive and negative sequence components calibration subsystem model are as follow:

$$I_{c1} = \left(\frac{-1}{V_{alpha}^2 + V_{beta}^2}\right) * \left(\left(P_{osc} * V_{alpha}\right) * \left(Q * V_{beta}\right)\right) \quad \text{.... (9)}$$

$$I_{c2} = \left(\frac{-1}{V_{alpha}^2 + V_{beta}^2}\right) * \left(\left(P_{osc} * V_{beta}\right) * \left(Q * V_{alpha}\right)\right) \quad \text{...... (10)}$$

Where,
Ic1 = Positive sequence component
Ic2 = Negative sequence component
Then again positive sequence, negative and null components of currents are then convert into phase current Ia, Ib and Ic for comparison with reference current shown in figure 11. The phase currents are given as:

$$I_a = \sqrt{\frac{2}{3}} * \left(\left(I_{c1}\right) + \left(0.7072 * I_{null}\right)\right) \quad \text{..................... (11)}$$

$$I_b = \sqrt{\frac{2}{3}} * \left(\left(-0.5 * I_{c1}\right) + \left(\sqrt{\frac{2}{3}} * I_{c2}\right) + \left(0.7072 * I_{null}\right)\right) \quad \text{... (12)}$$

$$I_c = \sqrt{\frac{2}{3}} * \left(\left(-0.5 * I_{c1}\right) - \left(\sqrt{\frac{2}{3}} * I_{c2}\right) + \left(0.7072 * I_{null}\right)\right) \quad \text{.... (13)}$$

IV. MATLAB SIMULATION MODEL

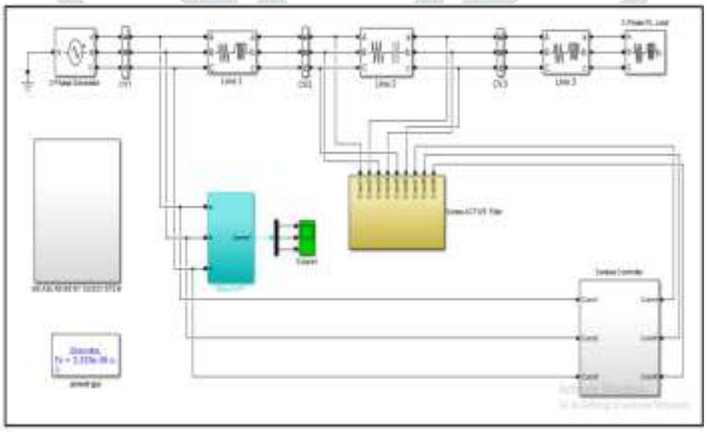

Fig.12 Proposed MATLAB simulation model

Table.1 Parameter specification of MATLAB model

Sr No	Name of simulink block	Parameters
1	3 phase generator	Three phase to phase voltage = 415 V; Phase angle of phase A = 0 Degree; Frequency of supply = 50 Hz
2	Line 1	Inductance L = 0.5mH; Resistance R = 0.1 Ω
3	Line 2	Capacitance c = 6 µF; Resistance R = 6 Ω
4	Line 3	Inductance L = 1 mH; Resistance R = 50 Ω
5	Three phase load	Nominal phase to phase voltage = 400V; Nominal frequency = 50Hz; Active power = 10 KW; Inductive reactive power = 100 VAr

The Series controller is used to compensate the source side disturbances such as voltage sags, swells and also harmonic distortions. In this configuration, the filter is connected in series with the line being compensated.

V. SIMULATION RESULTS AND DISCUSSION

5.1 With DPFC System

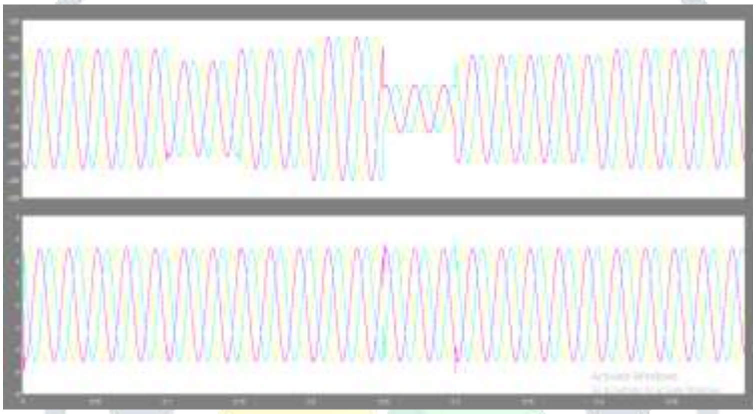

Fig.13 Sending end three phase voltage and current of transmission line with voltage sag and swell condition

Figure 13 shows the input side of three phase voltage and three phase current of transmission line which contains voltage sag and swell conditions. Total simulation time is 0.5 second in which voltage swell is occurs at 0.1 sec then again voltage becomes normal at 0.15 seconds. Then again voltage well occurs at 0.2 second and then again voltage swell at 0.25 second and so on. Hence voltage fluctuations are present at sending end voltage of transmission line.

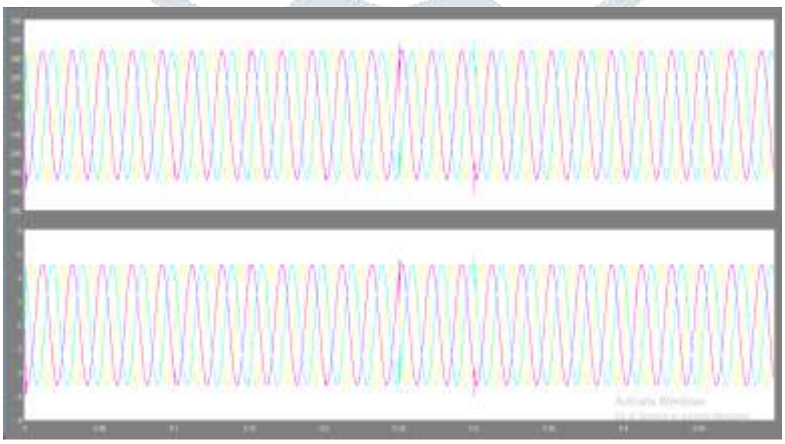

Fig.14 Receiving end three phase voltage and current of transmission line without voltage swell and sag

Figure 14 represents the three phase voltage and three phase current profile for load side of distribution system in which here it is observed that there are constant rated voltage and current profile available at load side of distribution system using DPFC controller.

Figure 15 shows the sending end voltage and current of transmission line which contains voltage momentary interruption and harmonics condition. Total simulation time is 0.5 second in which voltage interruption is occurs at 0.1 sec then again voltage becomes normal at 0.15 seconds. Then again voltage harmonics occurs at 0.2 second and then again voltage becomes normal at 0.4 second and so on. Hence voltage fluctuations are present at sending end voltage of transmission line.

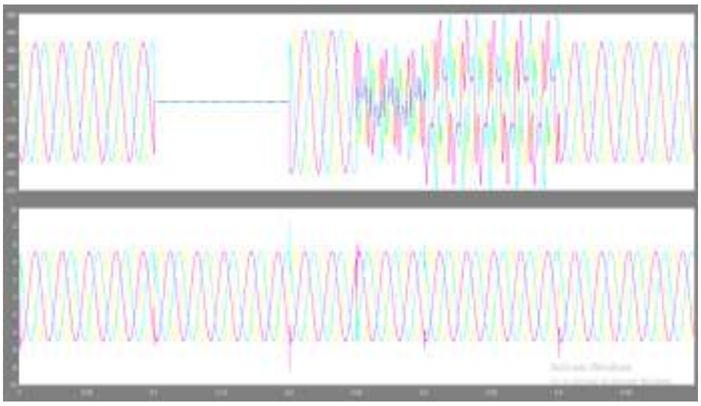

Fig.15 Sending end three phase voltage and current of transmission line with harmonics and interruption condition

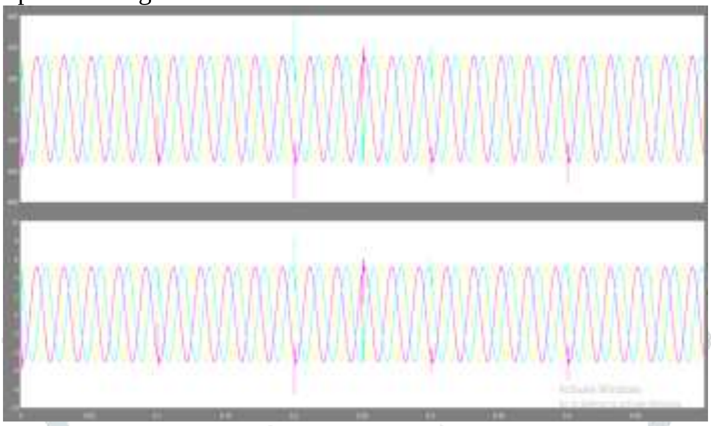

Fig.16 Receiving end three phase voltage and current of transmission line without harmonics and interruption

Figure 16 represents the three phase voltage and three phase current profile for load side of distribution system during harmonics and momentary interruption at receiving end of line in which here it is observed that there are constant rated voltage and current profile available at load side of distribution system using DPFC controller.

Figure 17 shows the sending end or load side three phase voltage and current of transmission line which contains voltage sag/swell and short duration LG fault condition at phase A to ground at receiving end of line. Total simulation time is 0.5 second in which voltage sag is occurs at 0.1 sec then again voltage becomes normal at 0.15 seconds. Then again voltage swell with LG fault occurs at 0.2 second and then again voltage becomes normal at 0.4 second and so on.

Figure 18 represents the three phase voltage and three phase current profile for load side of distribution system during voltage sag/swell with short duration fault at receiving end of line in which here it is observed that there are constant rated voltage and current profile available at load side of distribution system using DPFC controller.

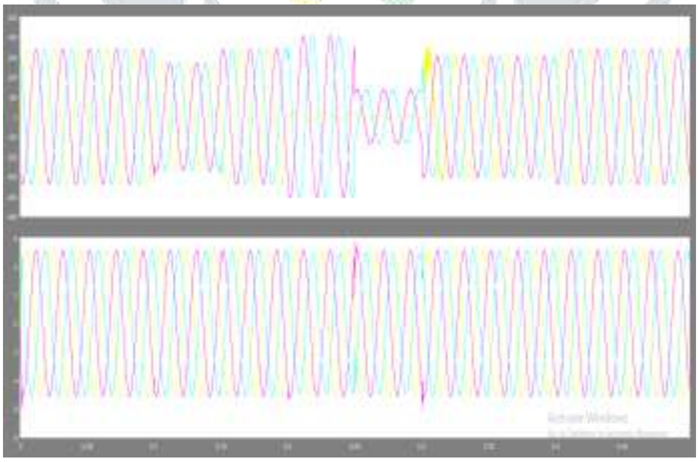

Fig.17 Sending end transmission line voltage and current waveform during voltage sag and swell and LG fault (AG) with DPFC controller

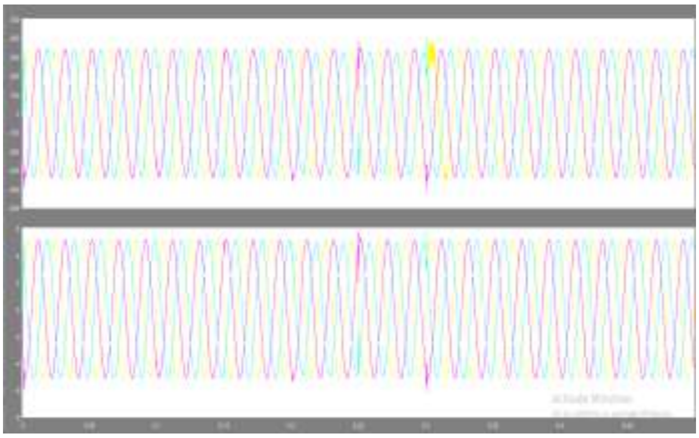

Fig.18 Receiving end transmission line voltage and current waveform during voltage sag and swell and LG fault (AG) with DPFC controller

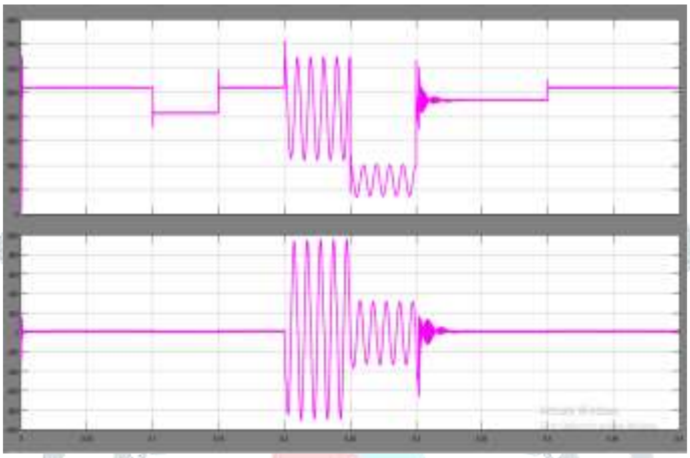

Fig.19 Sending end line active and reactive power during voltage sag, swell and fault conditions with DPFC controller in system

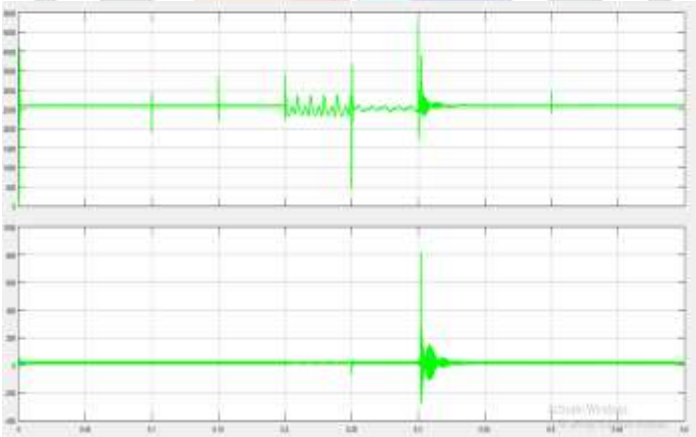

Fig.20 Receiving end line active and reactive power during voltage sag, swell and fault conditions with DPFC controller in system

5.2 Without DPFC system

Figure 21 shows the sending end or load side three phase voltage and current of transmission line which contains voltage sag/swell and short duration LG fault condition at phase A to ground at receiving end of line. Total simulation time is 0.5 second in which voltage sag is occurs at 0.1 sec then again voltage becomes normal at 0.15 seconds. Then again voltage swell with LG fault occurs at 0.2 second and then again voltage becomes normal at 0.4 second and so on.

Figure 18 represents the three phase voltage and three phase current profile for load side of distribution system during voltage sag/swell with short duration fault at receiving end of line. In which here it is observed that there are fluctuations and harmonics present at voltage and current profile available at load side of distribution system using without DPFC controller.

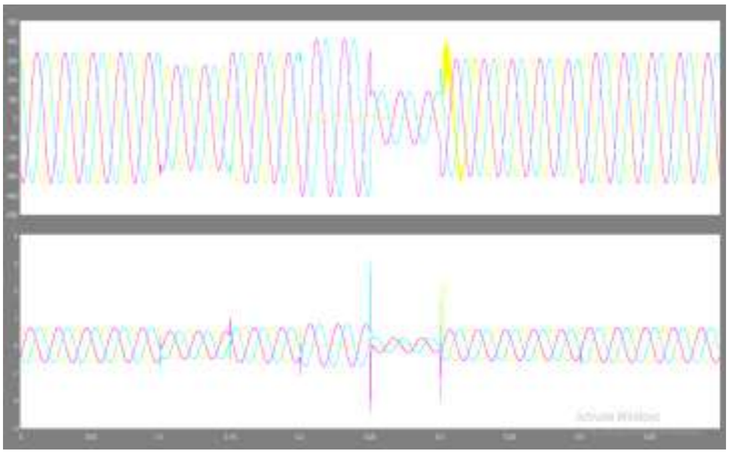

Fig.21 Sending end transmission line voltage and current waveform during voltage sag and swell and LG fault (AG) without DPFC controller

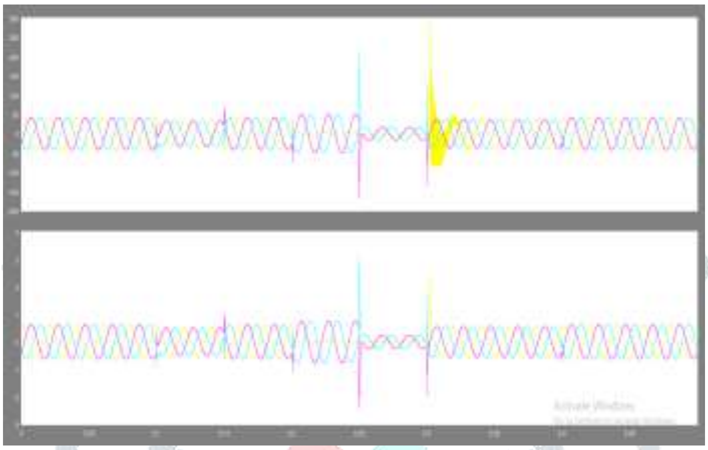

Fig.22 Receiving end transmission line voltage and current waveform during voltage sag and swell and LG fault (AG) without DPFC controller

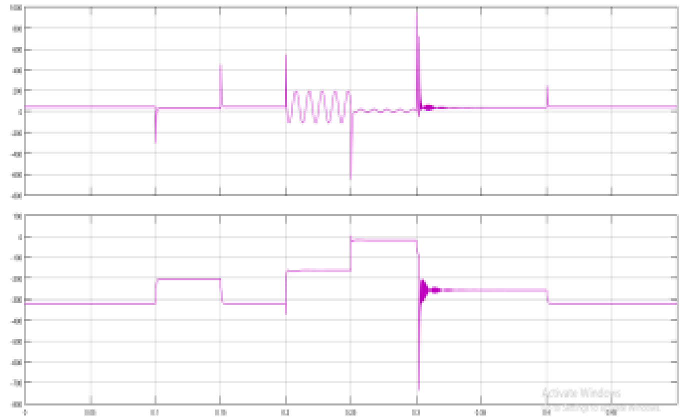

Fig.23 Sending end line active and reactive power during voltage sag, swell and fault conditions without DPFC controller in system

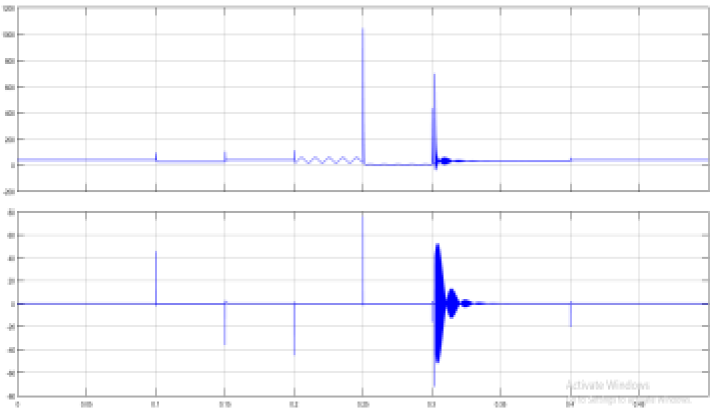

Fig.24 Receiving end line active and reactive power during voltage sag, swell and fault conditions without DPFC controller in system

5. CONCLUSION

The basic control stabilizes the level of the capacitor DC voltage of each converter and ensures that the converters inject the voltages into the network according to the command from the central control.

The shunt converter injects a constant current at the 3rd harmonic frequency, while its DC voltage is stabilized by the fundamental frequency component. When the DPFC is applied in power systems, the reliability issue is important.

The fault tolerance of the DPFC is investigated, including the protection method for different types of failures and the use of supplementary controls, to improve system performance during converter failures.

The complete system was design in MATLAB 2015 simulink software. And complete system is tested and analyzed for voltage sag, voltage swell and short duration of fault. Also effectiveness of system will be analyzed by considering the system analysis without DPFC controller.

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