Performance of Distributed Power Flow Controller

Pranay Rahul Ganji[1], **P. Ram Kishore Kumar Reddy**[2], **P. Lakshmi Supriya**[3]

[1]UG Student, Dept. of EEE, Mahatma Gandhi Institute of Technology, Hyderabad, India
[2]Head and Assistant Professor, Dept. of EEE, Mahatma Gandhi Institute of Technology, Hyderabad, India
[3]Assistant Professor, Dept. of EEE, Mahatma Gandhi Institute of Technology, Hyderabad, India

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Abstract- This paper describes a new component in FACTS Technology, named as the Distribution Power Flow Controller (DPFC), which is originated from the Unified Power Flow Controller (UPFC) with an elimination of the DC link between the shunt and series converters. Hence, the three-phase series converter is segregated into several single-phase series distributed converters through the line. The large number of series converters provide redundancy, thereby increasing the system reliability. The study contains the simulation of a single machine infinite bus power system including two parallel transmission lines, in MATLAB/Simulink environment. The simulated results present that the power quality issues such as voltage sag and swell are mitigated, validating the DPFC ability to improve the power quality.

Key Words- DPFC, FACTS, Sag and Swell Mitigation, UPFC

1. INTRODUCTION

The electrical power system serves to deliver electrical energy to consumers. In a traditional power system, the electrical energy is generated by centralized power plants and flows to the customers via the transmission and distribution network. The rate of the transported electrical energy within the lines of the power system is referred to as 'Power Flow', to be specific, it is the active and reactive power that flows in the transmission lines.

Growing consumption requires transmission networks and generation plants to support this grow. However, the increase of the transmission capacity cannot follow the increased demand due to the high cost, right-of-way issues and environmental problems. A possible solution is to optimize the utilization of the network and to boost the transmitted power to the thermal limit of the network. However, within a meshed network, several parallel paths may exist from the generation plants to the loads. As power tends to flow along the path with the lowest impedance, this results in overloaded lines. Overloaded lines make it difficult to utilize the full transmission capacity of the network. Consequently, to increase the transmission capacity of the whole network, there is a need to shift the power from the overloaded line to other parallel paths.

Also, to enable the trading of electricity between different zones, power systems in different locations are inter-connected. However, inter-area connections result in multiple parallel paths between power plants and consumers, which give rise to loop flow and cause congestions. With such increasing stress on the existing transmission lines require effective power flow control, both in direction and quantity.

Flexible AC Transmission Systems (FACTS) technologies offer competitive solutions to today's power systems in terms of increased power flow transfer capability, enhancing continuous control over the voltage profile, improving the damping of the system, minimizing losses, etc... FACTS technology consists of equipment based on high power electronics with its real-time operating control. Power flow is controlled by adjusting the parameters of a system, such as the voltage magnitude, the line impedance and the transmission angle. Depending on how devices are connected in systems, PFCDs (Power Flow Controlling Device) can be divided into shunt devices, series devices, and combined devices (both in shunt and series with the system).

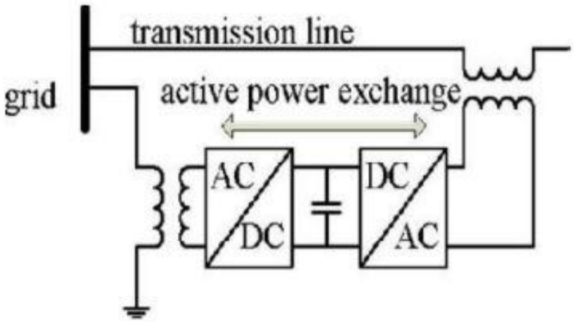


Fig -1: Simplified Representation of UPFC

The Unified Power-Flow Controller (UPFC) is the most powerful FACTS device, which can simultaneously control all the parameters of the system: the line impedance, the transmission angle, and the bus voltage. The UPFC is the combination of Static Synchronous Compensator (STATCOM) and Static Synchronous Series Compensator (SSSC), which are coupled through a common dc link to allow the flow of bidirectional active power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM. The components of the UPFC handle the voltages and currents with a high rating; hence, the total cost of the system is high.

In this project UPFC is modified by eliminating the dc link and the series converter is distributed to reduce the cost. The Distributed Power Flow Controller (DPFC) developed by eliminating the common DC link and distributing the series converter as shown in Fig -2.

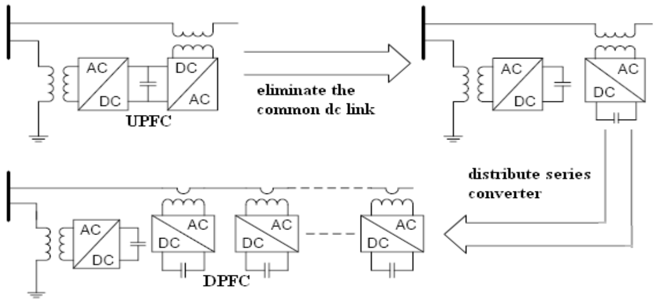


Fig -2: Flowchart from UPFC to DPFC.

2. DPFC ADVANTAGES

The DPFC in comparison with UPFC has the following advantages,

2.1 High Control Capability:

The DPFC has the same control capability as UPFC so as to balance the line parameters such as the line impedance, the transmission angle, and the bus voltage magnitude with lesser cost.

2.2 High Reliability:

The redundancy of series converters increases the reliability during the operation of the converters. Which implies, even if any converter fails, the others continue to work.

2.3 Low Cost:

The rating of single phase series converters is much lower than one three phase converter implying the lesser cost of the equipment.

3. DPFC OPERATING PRINCIPLE

The unique control capability of UPFC is given by back to back connection between the shunt and series converters, which allows the active power to freely exchange. To ensure the DPFC has the same control capability as the UPFC, the active power exchange between converters with an eliminated DC link is provided through the transmission line present between the AC ports of the shunt and the series converters.

According to Fourier analysis, the non-sinusoidal voltage and current can be expressed as the sum of sinusoidal functions in different frequencies with different amplitudes. The active power resulting from this particular non-sinusoidal voltage and current is defined as the mean value of the product of voltage and current. Since the integrals of all cross product of the terms with different frequencies are zero, the active power can be expressed by:

$$P=\sum_{i=0}^{\infty} V_i I_i \cos \emptyset_i \qquad ...(1)$$

where Vi and Ii are the voltage and current at the ith harmonic frequency respectively, and Øi is the corresponding angle between the voltage and current. Eqn. (1) shows that the active powers at different frequencies are independent from each other and the voltage or the current at one frequency has no influence 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.

By applying this method to the DPFC, the shunt converter can absorb active power from the grid at the fundamental frequency and inject the power back at a harmonic frequency. This harmonic active power flows through the transmission line equipped with series converters. According to the required amount of active power at the fundamental frequency, the series converters of the DPFC generates voltage at the harmonic frequency, thereby absorbing active power from the harmonic components. Neglecting losses, the active power generated at fundamental frequency is equal to the power absorbed at harmonic frequency. The active power exchange between the shunt and the series converters in the DPFC system is shown in Fig -3.

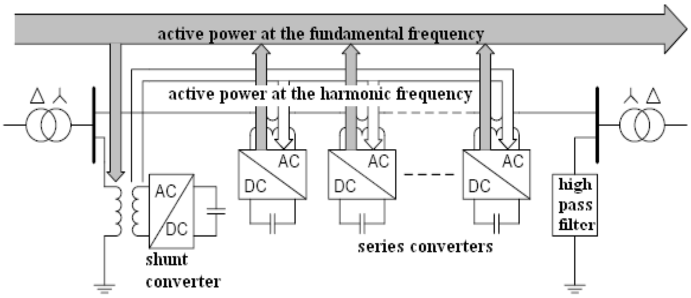


Fig -3: Active power exchange between series and shunt converters

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 harmonic components. The shunt and series converters, the high pass filter and the ground form a closed loop for the harmonic current.

Due to the unique features of 3rd harmonic frequency components in a three-phase system, the 3rd harmonic is selected for active power exchange in the DPFC. In a three phase system, the 3rd harmonic in each phase is identical, which means they are ‘zero-sequence’ components. By using the zero-sequence harmonic, the costly filter can be replaced by a cable that connects the neutral point of the Y-Δ transformer with the ground as shown in Fig -4. Because the Δ-winding appears open-circuit to the 3rd harmonic current, all harmonic current will flow through the Y-winding and concentrate to the grounding cable as shown in Fig -4. Therefore, the large high-pass filter is eliminated.

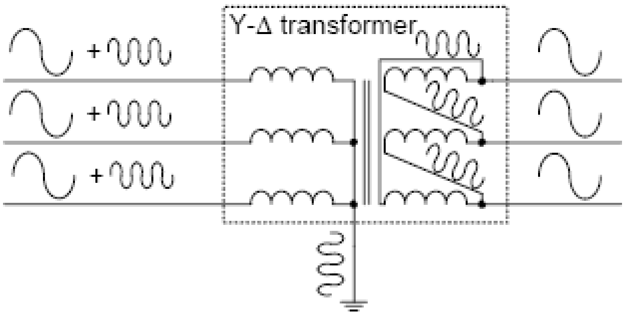


Fig -4: Utilize grounded Y-Δ transformer to filter zero-sequence harmonic

Another advantage of using the 3rd harmonic to exchange active power is that the grounding of the Y-Δ transformers can be used to route the harmonic current in a meshed network. As shown in Fig -5 if the network requires the harmonic current to flow through a specific branch, the neutral point of the Y-Δ transformer in that branch, at the side opposite to the shunt converter, will be grounded.

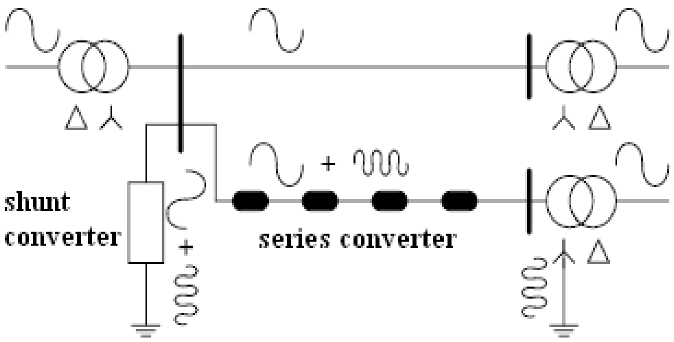


Fig -5: Route the harmonic current by using the grounding of the Y-Δ transformer

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 ith harmonic frequency P_i and the voltages generated by the converters is given by:

$$P_i = \frac{|V_{sh,i}||V_{se,i}|}{X_i}\sin(\theta_{sh,i} - \theta_{se,i}) \qquad \dots(2)$$

where, Xi is the line impedance at ith frequency, |Vsh,i| and |Vse,i| are the voltage magnitudes of the ith harmonic of the shunt and series converters, and (θsh,i − θse,i) is the angle difference between the two voltages. As shown, the impedance of the line limits the active power exchange capacity. To exchange the same amount of active power, the line with high impedance requires higher voltages. Because the transmission line impedance is mostly inductive and proportional to frequency, high transmission frequencies will cause high impedance and result in high voltage within converters. Consequently, the zero-sequence harmonic with the lowest frequency i.e., the 3rd harmonic frequency has been selected.

4. DPFC CONTROL

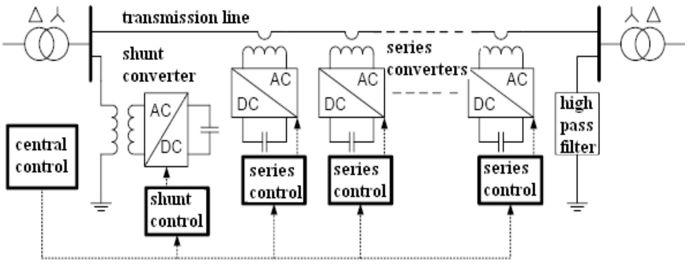


Fig -6: DPFC Control Structure

The shunt and series controls are localized controllers and are responsible for maintaining their own converters’ parameters. The central control takes care of the DPFC functions at the power system level. The function of each controller is given below:

4.1 Central control:

The central control generates the reference signals for both the shunt and series converters of the DPFC. Its control function depends on the specifics of the DPFC application at the power system level. According to the system requirements, 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 concern the fundamental frequency components.

4.2 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 3rd harmonic frequency components, in addition to generating series voltage at the fundamental frequency as required by the central control.

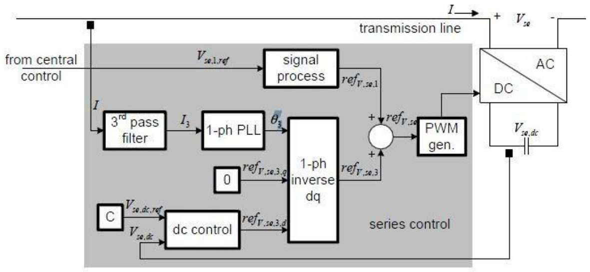


Fig -7: Control Scheme of series converter for fundamental and 3rd harmonic frequency components

4.3 Shunt control:

The objective of the shunt control is to inject a constant 3rd harmonic current into the line to supply active power for the series converters. At the same time, it maintains the capacitor DC voltage of the shunt converter at a constant value by absorbing active power from the grid at the fundamental frequency and injecting the required reactive current at the fundamental frequency into the grid.

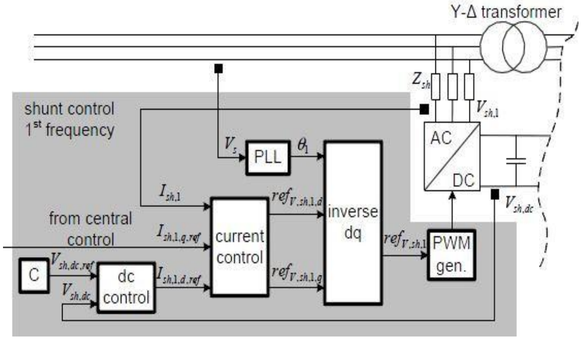


Fig -8: Control Scheme of shunt converter for fundamental frequency component

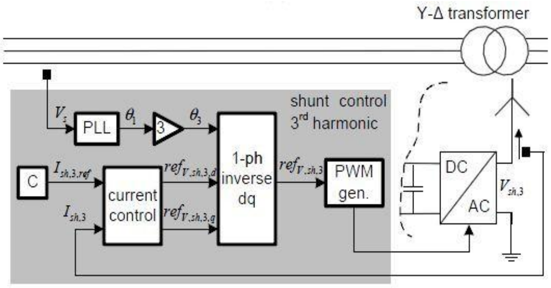


Fig -9: Control Scheme of shunt converter for 3rd harmonic frequency component

The DPFC is modelled in the dq-frame by using Park's transformation. The components of the DPFC in the AC quantity are transformed into the DC quantity. The components in different frequencies are then separately modeled. The shunt control and the series control are also presented. The functions of these controls are to maintain the DC capacitor voltages of the converters and to ensure that the required voltages and currents are injected in to the network.

5. SIMULATION RESULTS

5.1 Without DPFC

The steady state model of the transmission system without DPFC is as shown in Fig -10. The system includes a three phase source which is connected to a non linear RLC load through the parallel transmission lines.

A three phase fault is considered near the load and the time duration of fault is 0.5 seconds. During the fault, the value of voltage sag is about 0.4 per unit and current swell about 0.7 per unit.

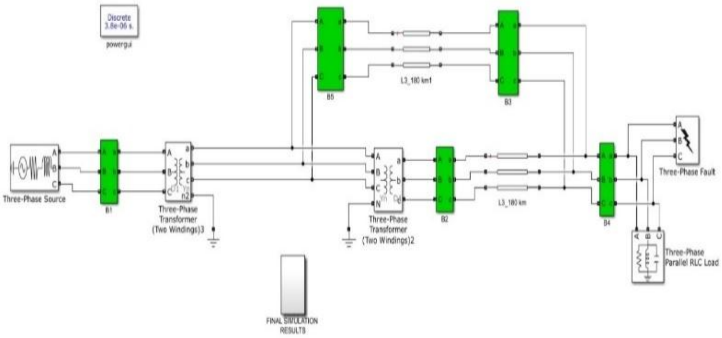


Fig -10: Simulation Model of the Transmission System with a Three Phase Fault

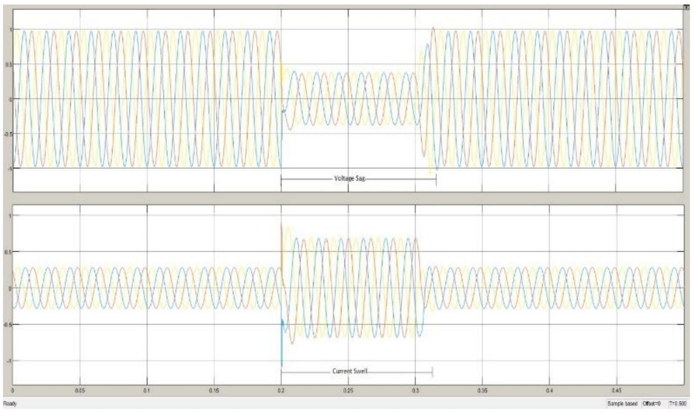
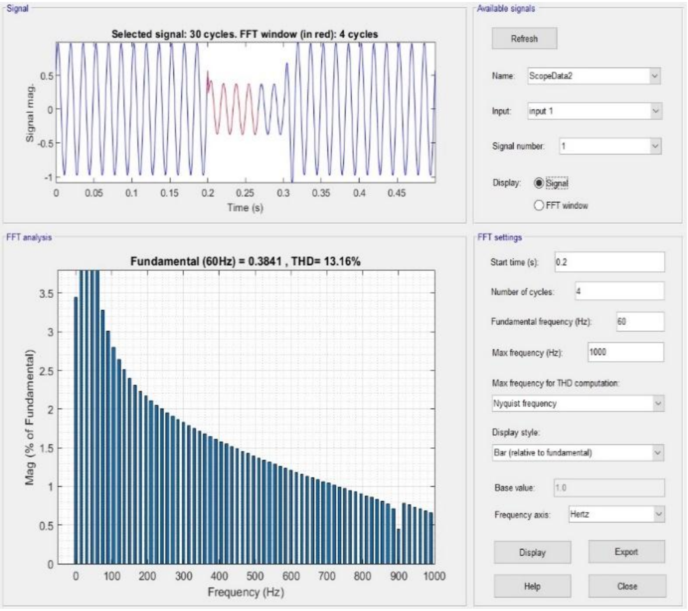


Fig -11: Load Voltage and Current Waveforms with Sag and Swell



Name: ScopeData2
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0.2
Number of cycles: 4
Fundamental frequency (Hz): 60
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Fig -12 Total Harmonic Distortion of Load Voltage without DPFC

5.2 With DPFC

The DPFC is placed in the transmission line, where the shunt converter is connected to the transmission line 2 parallel with the Y-Δ transformer and the series converter distributed along this line as shown in Fig -13.

After implementation of the DPFC, the load voltage sag and the current swell are mitigated and are restored by a greater extent significantly as shown in Fig -14. It is also observed that the total harmonic distortion (THD) of load voltage is minimised from 13.16 to 1.29 percentage, i.e., the standard THD is less than 5 percent according to IEEE standards.

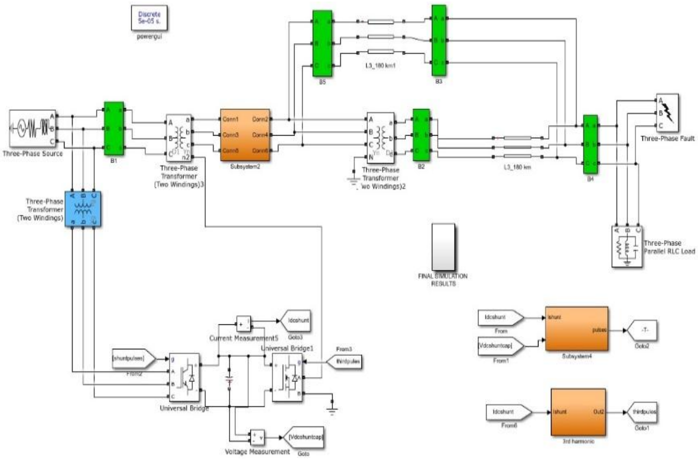


Fig -13: Simulation Model with DPFC Implementation

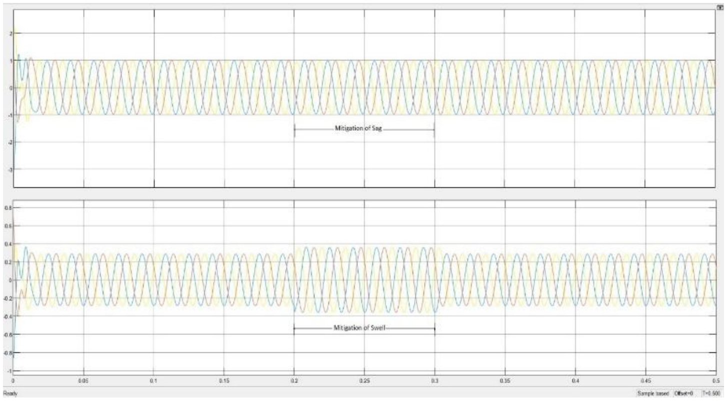
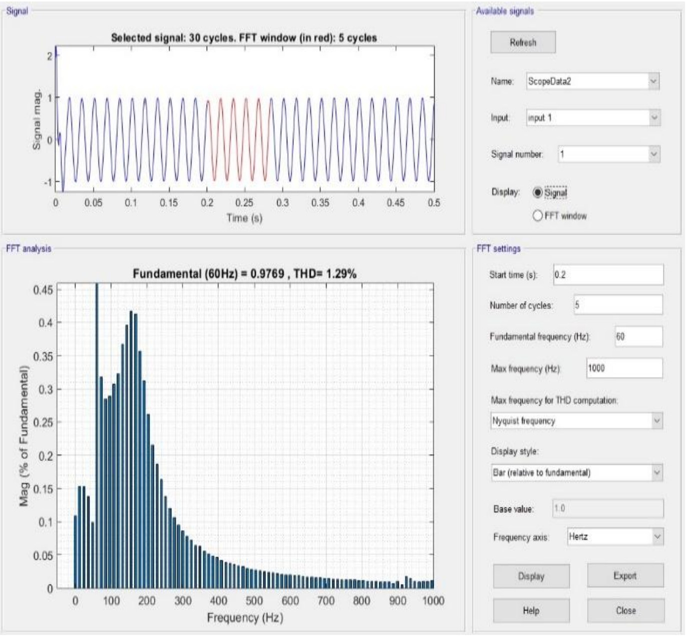


Fig -14: Mitigation of Sag and Swell with DPFC implementation



Name: ScopeData2
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0.2
Number of cycles: 5
Fundamental frequency (Hz): 60
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Fig -15:. Total Harmonic Distortion of Load Voltage with DPFC

6. CONCLUSION

This paper presents a concept of sag and swell mitigation using DPFC which is emerged from UPFC. It inherits the same control capability of UPFC to balance the line parameters such as the line impedance, transmission angle and bus voltage magnitude. Due to the elimination of the common DC link and distribution of single phase series converters in the line, the DPFC offers high control capability, high reliability and low cost. The simulation model of the DPFC has proved that it can mitigate the power quality problems such as sag and swell to significant levels improving the overall performance of the system.

Table -1: Improvement in values of Voltage Sag and Current Swell

Without DPFC		With DPFC	
Voltage Sag	Current Swell	Voltage Sag	Current Swell
0.4p.u	0.7p.u	Nominal	Nominal

Table -2: Comparision analysis for Total Harmonic Distortion (THD)

Without DPFC	With DPFC
Total Harmonic Distortion (THD)	Total Harmonic Distortion (THD)
13.16%	1.29%

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BIOGRAPHIES

Pranay Rahul Ganji is currently pursuing under graduation in Electrical and Electronics Engineering at MGIT, Hyderabad. His area of interest is Power Systems.

Dr.P. Ram Kishore Kumar Reddy is presently Professor and Head of the Electrical and Electronics Engineering Department, MGIT, Hyderabad. His research areas include Power Systems and control systems.

Mrs. P. Lakshmi Supriya is presently working as Assistant Professor, MGIT, Hyderabad. Her area of Interest is power systems.