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Distributed Power Flow Controller (DPFC) to improve the Power Quality of Thirty Three Bus Radial System

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Abstract: The objective of this work is to analyze the voltage profile in thirty three bus radial system by employing DPFC. This work deals with the modeling and the simulation of the thirty three Bus Radial Systems with and without Distributed Power Flow Controller (DPFC). The DPFC proposed in the present work is expected to improve the power quality of a Thirty Three bus system. The DPFC is the combination of a single shunt converter and several series converters. The shunt converter acts as STATCOM and series converters act as multiple DVRs. The shunt converter injects a part of the reactive power required by the load. The series converters are made to inject voltage at various points along the line to compensate for the line impedance drop. DPFC is the recent device in the family of FACTS which can improve the voltage quality of the buses. Total line impedance is calculated using the data available in the handbook and the simulation studies are performed. Thirty Three Bus Systems with and without DPFC are simulated and their simulation results are compared. The results of comparative study are presented to show the improvement in real and reactive powers.

Keywords: *Unified power flow controller (UPFC), Distributed power flow controller (DPFC), Flexible AC Transmission System (FACTS), Dynamic Voltage Regulator (DVR),Static Compensator (STATCOM)*

I. INTRODUCTION

Power Quality is becoming an important issue for both electric utilities and end users [1]. Unbalanced voltages and currents in a network are one of the concerns under the power quality issue. The unbalance is mainly generated by the great number of single-phase loads which are unevenly distributed over the phases [2]. The unbalanced voltages can produce extra losses in components of the network, such as generators, motors and transformers, while unbalanced currents cause extra losses in components like transmission lines and transformers [3]. Active filters and power factor corrector can be applied to compensate the unbalance at the load side. However their contributions to transmission systems are not large because they are focused on single load [4]. The most powerful device – the UPFC [6] cannot compensate zero-sequence unbalance current, because of the converter topology [7]. DPFC can also be used to improve the power quality and system stability such as power oscillation damping [8] The DPFC employs a shunt based Static Compensator (STATCOM) and multiple series converters to improve the power quality. DPFC has advantages like improved voltage profile and reduced power loss. It increases the power transfer capability and can be utilized for power flow control. The UPFC is not widely applied in practice due to their high cost and the redundancy to failure. Due to the common DC link interconnection a failure that happens at one converter will influence the whole system. The Distributed Power Flow Controller (DPFC) recently presented in is a power flow device within the FACTS family, which provides much lower cost and higher reliability than the conventional FACTS devices. It is derived from the UPFC and has the same capability of simultaneously adjusting all the parameters of power system like line impedances, transmission angle and bus voltage magnitude. The DPFC eliminates the common DC link between the shunt and series converters and uses the transmission line to exchange active power between converters at the 3rd harmonic frequencies. DPFC can compensate both active and reactive powers. The zero and negative sequence unbalanced currents can also be compensated by DPFC. The Distributed Power Flow Controller (DPFC) recently presented in [9], is a powerful device within the family of FACTS devices, which provides much lower cost and higher reliability than conventional FACTS devices. It is obtained from the UPFC and has the same capability of simultaneously adjusting all the parameters of the power system: line impedance, transmission angle, and bus voltage magnitude [7]. Within the DPFC, the common DC link between the shunt and series converters is eliminated, which provides flexibility for independent placement of series and shunt converters. The DPFC uses the transmission line to exchange active power between converters at the third harmonic frequency [9]. Instead of one large three-phase converter, the DPFC uses multiple single-phase converters (D-FACTS concept [10]) as the series compensator. This concept not only reduces the rating of the components but also provides a high reliability because of the redundancy. The scheme of the DPFC in a simple two-bus System is shown in Fig.1.

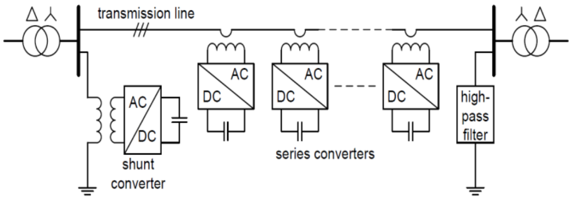


Fig.1: DPFC structure

As the series converters of the DPFC are single-phase, it gives DPFC the opportunity to control current in each phase independently, which implies that both negative and zero sequence unbalanced currents can be compensated. Additional controllers are supplemented to the existing DPFC controller. Their control principle is to monitor the negative and zero sequence currents through the transmission line and to force them to zero. The above literature does not deal with power quality improvement in Thirty Three bus system using DPFC. The objective of this work is to analyze the improvement in power quality due to the addition of DPFC in a thirty three bus system. Operating principle of DPFC is given in section II. Simulation results for thirty three bus system with and without DPFC are presented in section III and the work is concluded in section IV.

II. PRINCIPLE OF THE DPFC

A). Introduction of the DPFC

Multiple individual converters co-ordinate together and compose the DPFC, which is shown in Fig.1. The converters connected in series with the transmission lines are the series converters. They can inject a controllable voltage at the fundamental frequency; consequently they control the power flow through the line. The converter connected between the line and ground is the parallel 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. In a normal UPFC, there is active power exchange through the DC link that connects the series converter with the shunt converter. Since there is no common DC link between the shunt and series converters in the DPFC, Within the DPFC, the transmission line presents a common connection between the AC ports of the shunt and the series converters. Therefore, it is possible to exchange active power through the AC ports. The method is based on power theory of non-sinusoidal components. According to the Fourier analysis, 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 non-sinusoidal voltage and current is defined as the mean value of the product of voltage and current. [5] Since the integrals of all the cross product of terms with different frequencies are zero, the active power can be expressed by:

$$P = \sum_{n=1}^{\infty} V_n I_n \cos \phi_n \qquad (1)$$

Where n is the order of the harmonic frequency and ϕn is the angle between the current and voltage of the nth harmonic. Equation (1) shows that the active powers at different frequencies are independent from each other and the voltage or 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. [5] 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 a closed loop for the harmonic current. [5]

B). Control Principle of DPFC

The DPFC system consists of two types of converters, and each type of converter requires a different control scheme. The block diagram of the DPFC and its control is shown in Fig.2. The shunt converter is controlled to inject a constant third harmonic current into the transmission line, which is intended to supply active power for the series converters. The shunt converter extracts some active power from the grid at the fundamental frequency to maintain its DC voltage. The DC voltage of the shunt converter is controlled by the d component of the current at the fundamental frequency, and the q component is utilized for reactive power compensation. The series converters generate a voltage with controllable phase angle at fundamental frequency, and use the voltage at the 3rd harmonic frequency to absorb active power to maintain its DC voltages at a constant value. The power flow control function is realized by an outer control loop, the power flow control block. This block gets its reference signals from the system operator, and the control signals for DPFC series converters are sent remotely via wireless or PLC communication method. To control multiple converters, a DPFC consists of three types of controllers: central control, shunt control and series control, as shown in Figure 2.

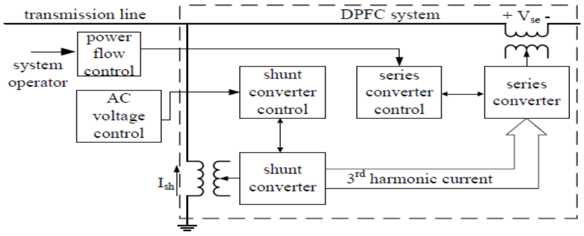


Fig.2. Block diagram representing the control mode of DPFC

The shunt and series control 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 listed:

- AC voltage control: The AC voltage 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, such as power flow control, low frequency power oscillation damping and balancing of asymmetrical components. 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.
- 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.
- 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.

III. SIMULATION RESULTS

3.1 Thirty Three Bus Systems without DPFC

The parameters given in Appendix-I are calculated by multiplying ohms per Km with the length of line. The pulse width of all inverters is calculated based on frequency. The Simulink model of thirty three bus system without DPFC is shown in Fig 3(a). Each feeder is represented as series impedance. Each load is represented as shunt impedance.

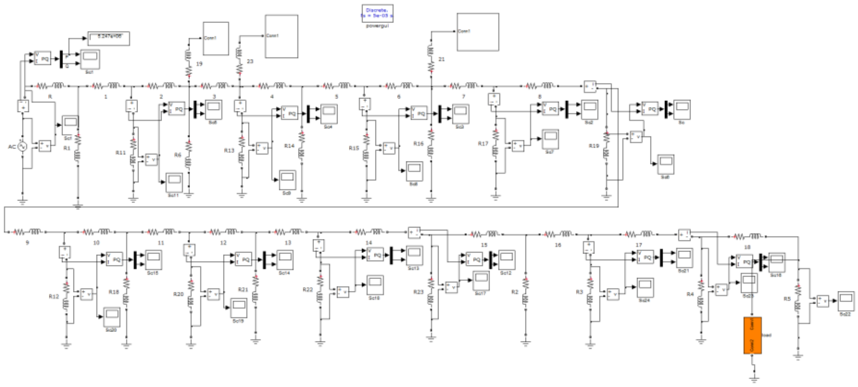
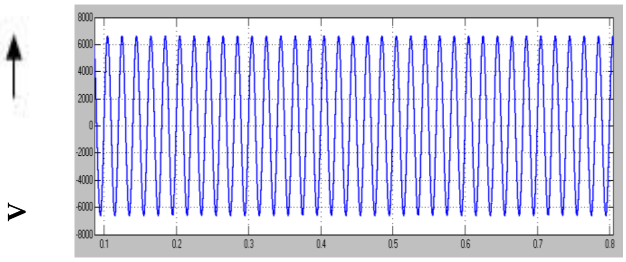


Fig 3(a) Model of 33 Bus system without DPFC

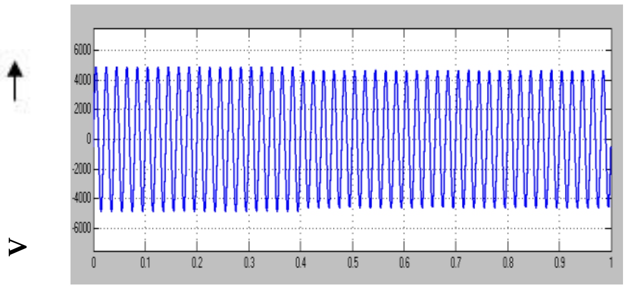
The source voltage is shown in Fig 3(b). The peak value is 6600V.



Time (s) →

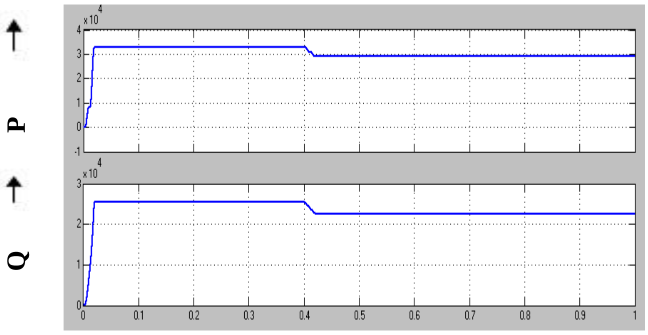
Fig 3(b) Source Voltage

The voltage, real power and reactive power at bus 5 are shown in Figs 3(c) & 3(d) respectively. The peak value of voltage is 4100V. Real power reduces to $2.99*10^4$W and Reactive power reduces to $2.28*10^4$MVAR.



Time (s) →

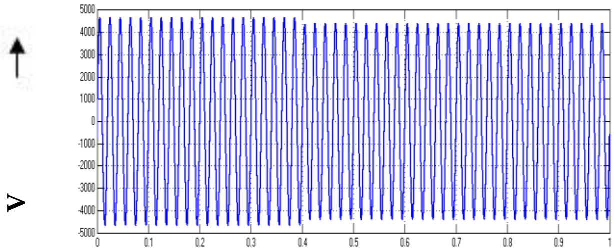
Fig 3(c) voltage at Bus -5



Time (s) →

Fig 3(d) Real & Reactive Power Bus-5

The voltage, real power and reactive power at bus 11 are shown in Figs 3(e) & 3(f) respectively. The voltage decreases from 4400V to 4200V. Real power reduces to $4.21*10^4$W and Reactive power reduces to $4.48*10^4$VAR.



Time (s) →

Fig 3(e) voltage at Bus-11

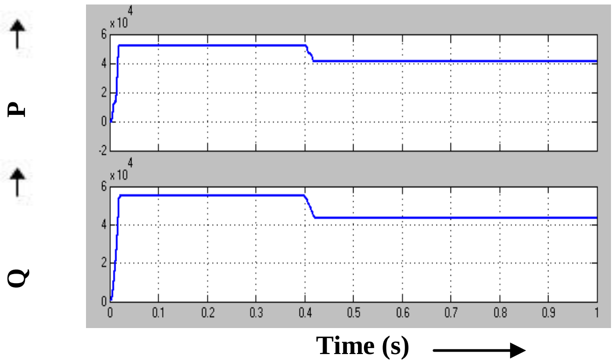


Fig 3(f) Real & Reactive Power at Bus-11

The voltage, real power and reactive power at bus 17 are shown in Figs 3(g) & 3(h) respectively. The voltage reduces to 3958V. Real power reduces to 2.64*10^4W and Reactive power reduces to 2.73*10^4VAR.

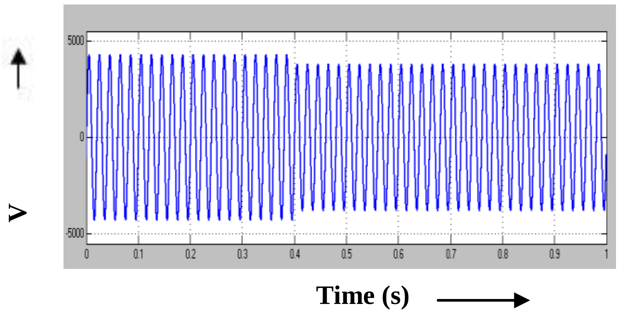


Fig 3(g) Voltage at Bus-17

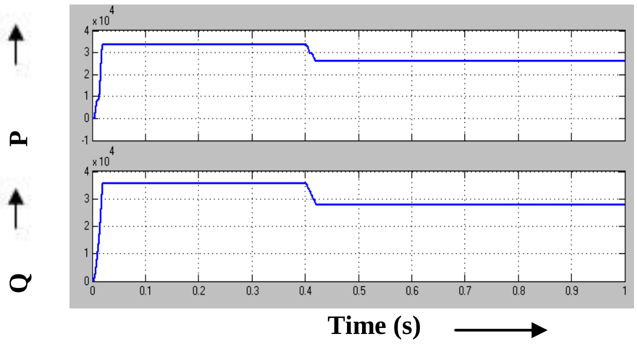
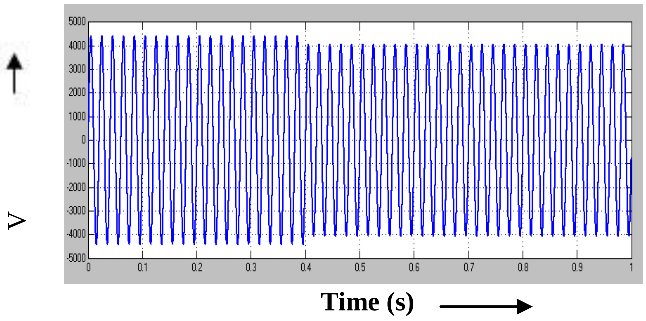
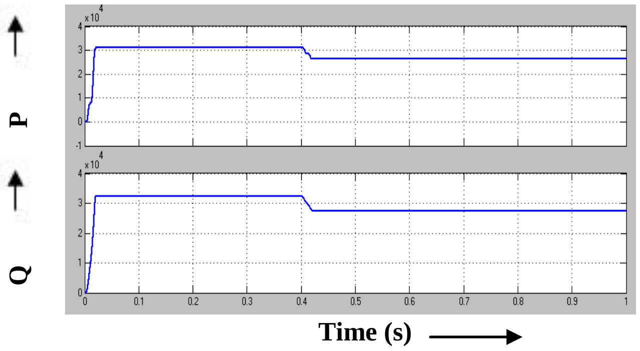


Fig 3(h) Real & Reactive Power at Bus-17

The voltage, real power and reactive power at bus 27 are shown in Figs 3(i) & 3(j) respectively. The peak value of voltage is 4000V. Real and Reactive power are reduced to 2.61*10^4W and 2.68*10^4VAR respectively.



3(i) Voltage at Bus-27



3(j) Real & Reactive Power at Bus-27

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The voltage, real power and reactive power at bus 29 are shown in Figs 3(k) & 3(l) respectively. The voltage reduces to 4000V. Real and Reactive power are reduced to $2.73*10^4$W and $3.31*10^4$VAR respectively.

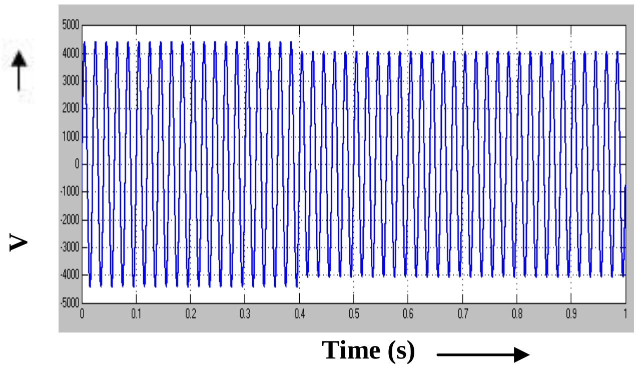


Fig 3(k) Voltage at Bus-29

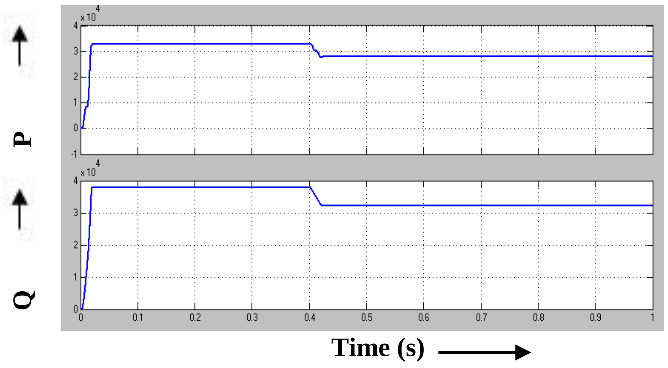
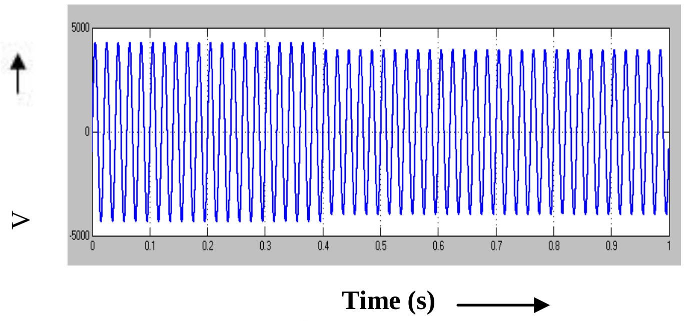
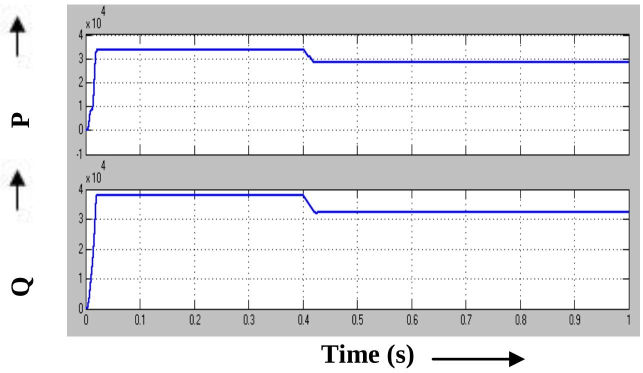


Fig 3(l) Real & Reactive Power at Bus-29



3(m) Voltage at Bus-33

The voltage, real power and reactive power at bus 33 are shown in Figs 3(m) & 3(n) respectively. The peak value of voltage is 4250V. Real and Reactive power are reduced to $2.91*10^4$W and $3.24*10^4$VAR respectively. It is observed that the voltage decreases at various buses due to the addition of extra load.



3(n) Real & Reactive Power at Bus-33

3.2 Thirty three bus system with DPFC

The circuit model of thirty three bus system with DPFC is shown in Fig 4(a).

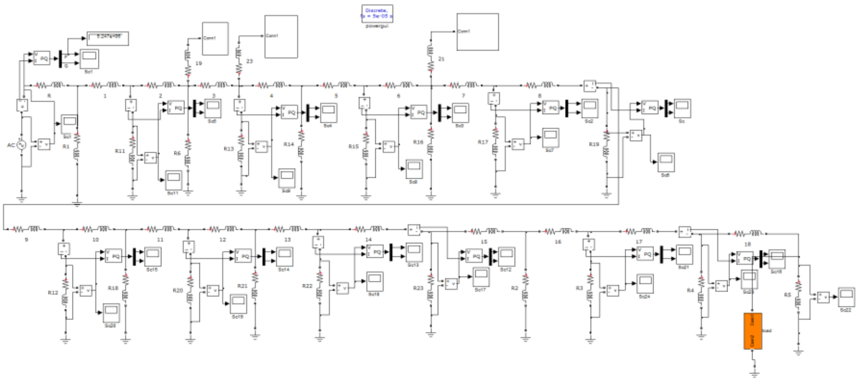


Fig 4(a) 33-bus system with DPFC

The STATCOM system is shown in Fig 4(b) and source voltage is shown in Fig 4(c).

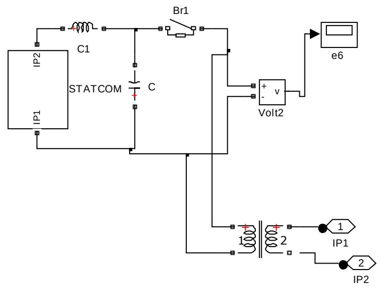


Fig 4(b) STATCOM system

The Peak value of voltage is 6600V

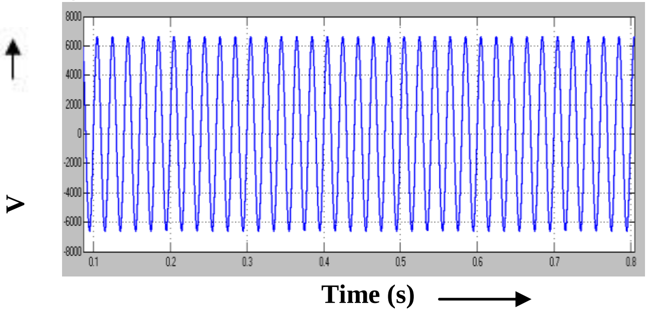


Fig 4(c) Sending end voltage

The voltages, real and reactive powers at bus 5 are shown in Figs 4(d) & 4(e) respectively. The peak value of voltage is 4400V, Real and Reactive power are reduced to $3.15*10^4$W and $2.34*10^4$VAR respectively.

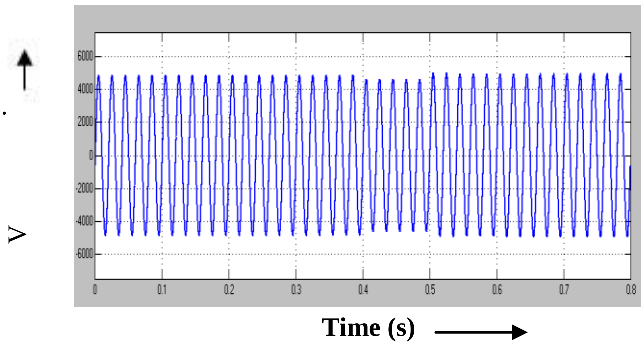


Fig 4(d) Voltage at Bus -5

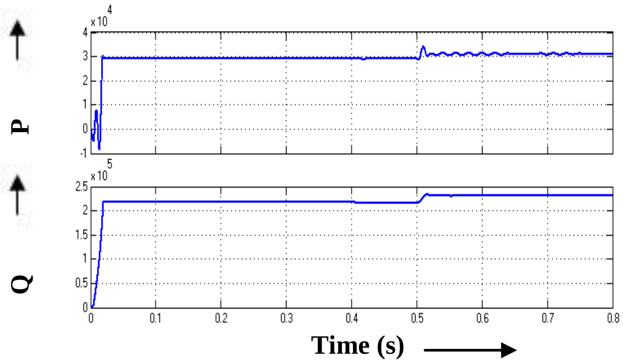


Fig 4(e) Real & Reactive power at Bus-5

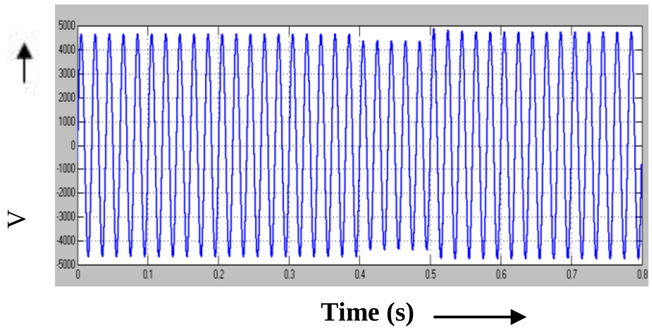


Fig4 (f) Voltage at Bus-11

The bus voltage, real and reactive powers at bus 11 are shown in Figs 4(f) & 4(g) respectively. The Peak value is 4820V, Real and Reactive powers are reduced to $4.40*10^4$W and $4.5*10^4$VAR respectively.

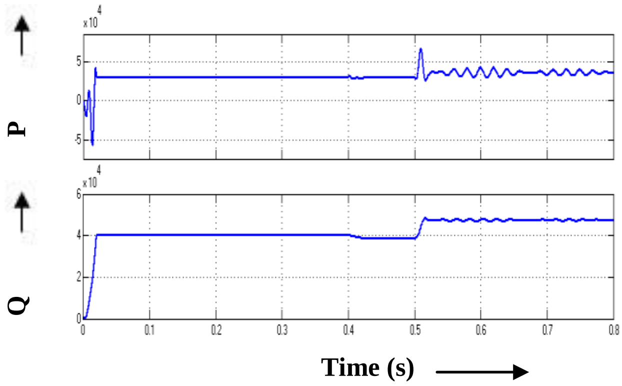


Fig 4 (g) Real & Reactive Power at Bus-11

The series converter is shown in Fig 4(h). The voltages, real and reactive power at bus 17 are shown in Figs 4(i) & 4(j) respectively.

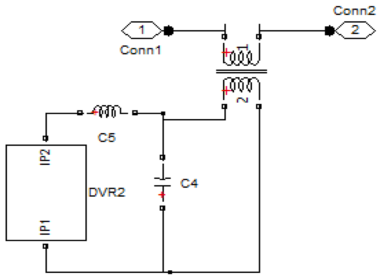


Fig 4(h) DVR system

The peak value of voltage is 4750V, Real and Reactive power are reduced to $2.74*10^4$W and $4.78*10^4$VAR respectively.

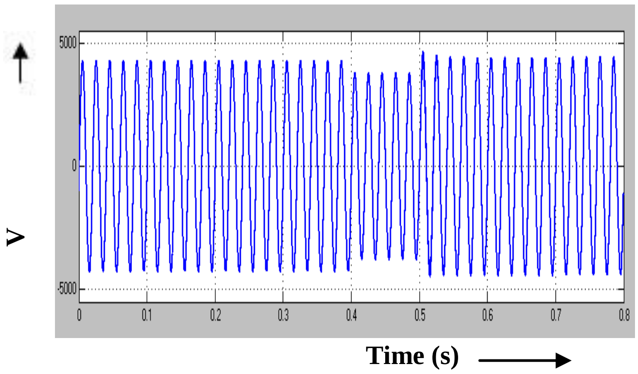


Fig 4(i) Voltage at Bus-17

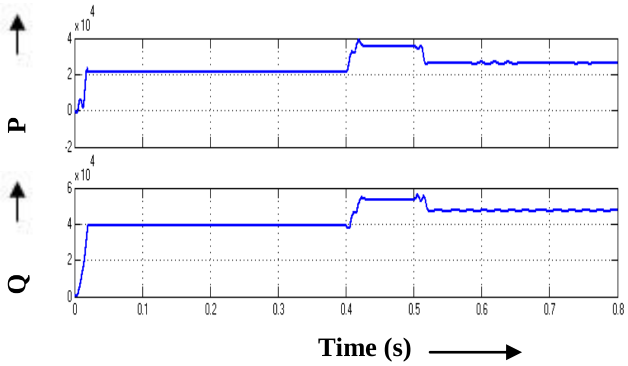


Fig 4(j) Real & Reactive Power at Bus-17

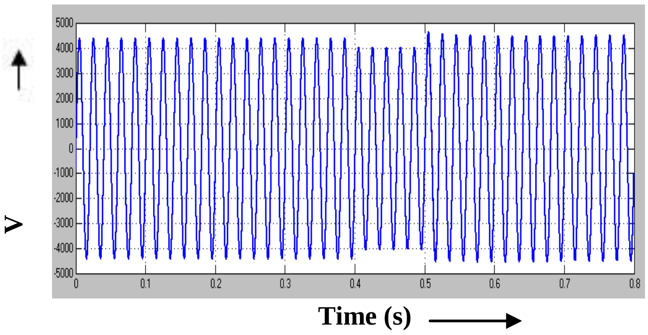


Fig 4(k) Voltage at Bus-27

The voltage, real and reactive powers at bus 27 are shown in Fig 4(k) & 4(l) respectively. The peak value of voltage is 4830V, Real and Reactive power are reduced to 2.71*10^{4}W and 6.13*10^{4}VAR respectively.

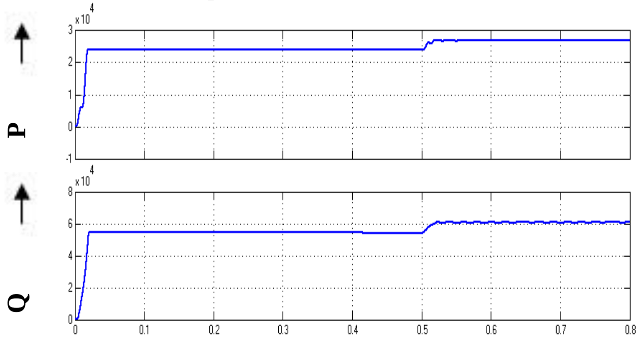


Fig 4(l) Real & Reactive Power at Bus -27

The voltages, real and reactive power at bus 29 are shown in Figs 4(m) & 4(n) respectively. The peak voltage value is 4910V, Real and Reactive power are reduced to 0.283MW and 0.589MVAR respectively.

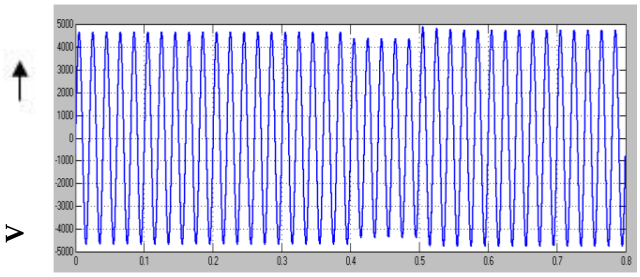


Fig 4(m) Output Voltage at Bus-29

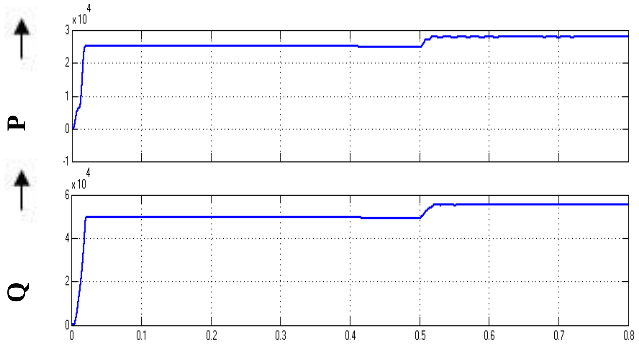


Fig 4(n) Real & Reactive Power at Bus-29

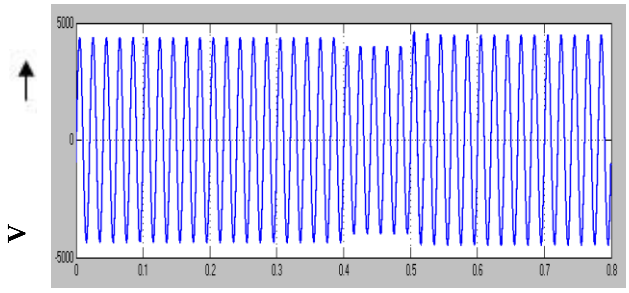


Fig 4(o) Output Voltage at Bus-33

The voltages, real and reactive power at bus 33 are shown in Figs 4(o) & 4(p) respectively. The peak voltage value is 4860V, Real and Reactive power are reduced to 3.01*10^4W and 4.61*10^4VAR respectively.

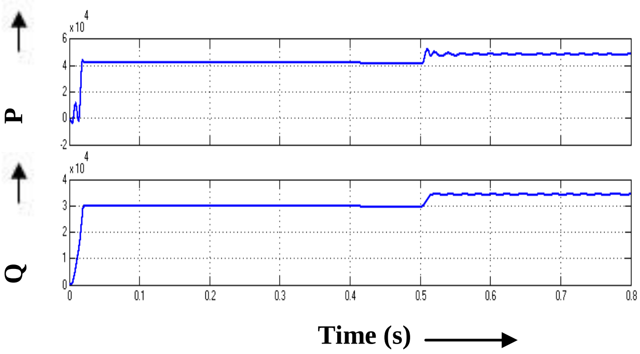


Fig 4(p) Real & Reactive Power at Bus-33

In the above wave forms, it is observed the voltage reaches normal value following the change in load, due to the addition of series converters and shunt converters. The buses 5, 11, 17, 27, 29 & 33 are selected, since they are nearer to the multiple DVRs introduced.

BUS NO	**Power factor without DPFC**	**Real power (10^5 W) Without dpfc**	**Real power (10^5 W) With dpfc**	**Reactive power (10^5VAR) Without dpfc**	**Reactive power (10^5VAR) With dpfc**	**Power factor with DPFC**
BUS-1	0.648	0.421	0.598	0.448	0.604	0.703
BUS-2	0.720	0.337	0.618	0.324	0.563	0.739
BUS-3	0.897	0.475	0.493	0.234	0.241	0.899
BUS-4	0.790	0.321	0.389	0.249	0.253	0.838
BUS-5	**0.795**	**0.299**	**0.315**	**0.228**	**0.234**	**0.802**
BUS-6	0.622	0.258	0.339	0.324	0.343	0.702
BUS-7	0.689	0.264	0.341	0.277	0.298	0.736
BUS-8	0.678	0.289	0.353	0.313	0.324	0.739
BUS-9	0.613	0.273	0.338	0.351	0.321	0.721
BUS-10	0.619	0.253	0.315	0.321	0.340	0.679
BUS-11	**0.684**	**0.421**	**0.440**	**0.448**	**0.450**	**0.699**
BUS-12	0.714	0.331	0.529	0.324	0.502	0.725
BUS-13	0.899	0.475	0.485	0.231	0.535	0.903
BUS-14	0.844	0.384	0.394	0.244	0.547	0.850
BUS-15	0.794	0.293	0.303	0.224	0.537	0.804
BUS-16	0.619	0.258	0.268	0.327	0.486	0.634
BUS-17	**0.695**	**0.264**	**0.274**	**0.273**	**0.478**	**0.708**
BUS-18	0.678	0.289	0.299	0.313	0.489	0.691
BUS-19	0.620	0.278	0.288	0.351	0.471	0.634
BUS-20	0.615	0.254	0.264	0.325	0.532	0.631
BUS-21	0.692	0.423	0.433	0.441	0.534	0.701
BUS-22	0.711	0.332	0.342	0.328	0.567	0.722

BUS-23	0.897	0.471	0.481	0.232	0.543	0.901
BUS-24	0.803	0.325	0.335	0.241	0.531	0.812
BUS-25	0.791	0.293	0.303	0.226	0.524	0.802
BUS-26	0.622	0.257	0.267	0.323	0.647	0.637
BUS-27	**0.697**	**0.261**	**0.271**	**0.268**	**0.613**	**0.711**
BUS-28	0.671	0.289	0.299	0.319	0.622	0.684
BUS-29	**0.636**	**0.273**	**0.283**	**0.331**	**0.589**	**0.650**
BUS-30	0.621	0.253	0.263	0.319	0.576	0.636
BUS-31	0.700	0.264	0.274	0.269	0.469	0.714
BUS-32	0.650	0.281	0.291	0.328	0.464	0.664
BUS-33	**0.668**	**0.291**	**0.301**	**0.324**	**0.461**	**0.681**

IV. CONCLUSION

The IEEE thirty three bus radial distribution system was successfully modeled and simulated. The results of case studies with and without DPFC for thirty three bus radial systems were presented. Lines and loads were modeled as constant impedances. The series converters of DPFC were added towards the far end of the distribution system. It is observed that the DPFC was capable of improving the voltage profile at load bus apart from enhancing the real and reactive power transfer, which was evident from the simulation results. The advantages of DPFC system was improved voltage profile and power factor. The disadvantage of DPFC was the requirement of multiple inverters, shunt capacitors and series transformers. The scope of this work was the modeling and simulation of IEEE thirty three bus radial distribution system. The Simulation studies on fifty bus system will be carried out in future.

Appendix-I: Parameters used for simulation voltage and frequency; 440V, 50 Hz.

Bus No	VOLTAGE	LOAD IMPEDANCE	
		RESISTANCE	INDUCTANCE
Bus 1	6.6kv	-	-
Bus 2		10Ω	50mH
Bus 3		25Ω	40mH
Bus 4	6.6kv	-	-
Bus 5	-	85Ω	110mH
Bus 6	-	95Ω	125mH
Bus 7	-	125 Ω	180mH
Bus 8	6.6 kv	-	-
Bus 9	-	135 Ω	167mH
Bus 10	-	58 Ω	127mH
Bus 11	-	100 Ω	100mH
Bus 12	6.6 kv	-	-
Bus 13	-	48 Ω	100mH
Bus 14	-	67 Ω	97mH
Bus 15	6.6 Kv	-	_
Bus 16	-	33 Ω	65mH
Bus 17	-	78 Ω	125mH
Bus 18	6.6 kv	-	-
Bus 19	-	120Ω	150mH
Bus 20	-	120Ω	168mH
Bus 21	-	125Ω	130mH
Bus 22	-	25Ω	90mH
Bus 23	-	110 Ω	138mH
Bus 24	6.6 kv	-	-
Bus 25	-	10Ω	100mH
Bus 26	-	10Ω	100mH

Bus 27	**6.6 kv**	**-**	**-**
Bus 28	**-**	**10Ω**	**10Ω**
Bus 29	**-**	**89Ω**	**89Ω**
Bus 30	**-**	**115Ω**	**115Ω**
Bus 31	**-**	**125Ω**	**125Ω**
Bus 32	**-**	**120Ω**	**120Ω**
Bus 33	**-**	**110 Ω**	**110 Ω**

Bus No	**LINE IMPEDANCE**	
	RESISTANCE	**INDUCTANCE**
Bus 1-2	**8 Ω**	**30mH**
Bus 2-5	**3Ω**	**38mH**
Bus 5-7	**6 Ω**	**40mH**
Bus 3-1	**13 Ω**	**37mH**
Bus 4-2	**15Ω**	**30mH**
Bus 6-2	**23 Ω**	**26mH**
Bus 6-7	**45 Ω**	**56mH**
Bus 13-4	**54 Ω**	**63mH**
Bus 12-4	**43Ω**	**100mH**
Bus 12-16	**36Ω**	**113mH**
Bus 16-17	**24 Ω**	**55mH**
Bus 17-10	**36 Ω**	**85mH**
Bus 10-9	**78 Ω**	**125mH**
Bus 9-11	**85 Ω**	**79mH**
Bus 10-6	**96 Ω**	**150mH**
Bus 6-9	**110 Ω**	**138mH**
Bus 6-28	**108Ω**	**124mH**
Bus 15-14	**89 Ω**	**119mH**
Bus 18-19	**76Ω**	**106mH**
Bus 19-20	**79 Ω**	**98mH**
Bus 20-10	**86 Ω**	**110mH**
Bus 22-21	**55Ω**	**103mH**
Bus 21-10	**40 Ω**	**75mH**
Bus 27-28	**55Ω**	**69mH**
Bus 28-30	**64Ω**	**78mH**
Bus 27-30	**81 Ω**	**93mH**
Bus 15-18	**112 Ω**	**97mH**
Bus 15-23	**106Ω**	**136mH**
Bus 23-24	**93Ω**	**131mH**
Bus 24-22	**89 Ω**	**124mH**
Bus 24-25	**40 Ω**	**75mH**
Bus 25-26	**55Ω**	**69mH**
Bus 28-27	**64Ω**	**78mH**
Bus 27-29	**81 Ω**	**93mH**
Bus 29-30	**112 Ω**	**97mH**
Bus 30-31	**93Ω**	**131mH**
Bus 31-32	**89 Ω**	**124mH**
Bus 32-33	**112 Ω**	**97mH**

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