Design of Two Feeder Three Phase Four Wire Distribution System Utilizing Multi Converter UPQC with Fuzzy Logic Controller

Chandra Babu PADUCHURI, Subhransu Sekhar DASH, Subramani CHINNAMUTHU

Department of Electrical and Electronics Engineering, Faculty of Engineering and Technology, SRM University, SRM Nagar, Kattankulathur, 603 203 Chennai, India

paduchuri.chandrababu@gmail.com, munu_dash_2k@yahoo.com, csmsrm@gmail.com

Abstract. *This paper proposes the instantaneous p-q theory based fuzzy logic controller (FLC) for multi-converter unified power quality conditioner (MC-UPQC) to mitigate power quality issues in two feeders three-phase four-wire distribution systems. The proposed system is extended system of the existing one feeder three-phase four-wire distribution system, which is operated with UPQC. This system is employed with three voltage source converters, which are connected commonly to two feeder distribution systems. The performance of this proposed system used to compensate voltage sag, neutral current mitigation and compensation of voltage and current harmonics under linear and nonlinear load conditions. The neutral current flowing in series transformers is zero in the implementation of the proposed system. The simulation performance analysis is carried out using MATLAB.*

Keywords

Fuzzy logic controller, instantaneous p–q theory, MC-UPQC, power quality, VSC.

1. Introduction

Modern days power systems are complicated networks with hundreds of generating stations and load centers being interconnected through power transmission lines. A few years back, the main concern of consumers of electricity was the reliability of supply. The transmission systems compound the problem further as they are exposed to the vagaries of mother nature. Power quality variations are classified as either disturbance or steady state variations. The disturbances pertained be due to abnormalities in the system such as, Voltage/currents due to a fault or some abnormal operations. A steady state variation refers to a rms deviation from the nominal quantities/harmonics.

In reality the power electronics devices are connected to the power distribution system to increase the reliability and supplied quality power to the consumers. The family of Custom Power Devices (CPD) are Distribution Statcom (DSTATCOM), Dynamic Voltage Restorer (DVR), Unified Power Quality Conditioner (UPQC). CPD can provide an integrated solution for the problems faced by the utilities and power distributors. It can improve in terms of reduced interruptions, voltage variation, load balancing, power factor correction, harmonic free voltage to consumers and voltage regulation. Among these, the UPQC alone can inject unbalanced, distorted voltages/currents; individually and also simultaneously in a dual control mode. This leads to the performance functions of load compensations and voltage control at the same time. Due to the development in recent years many power quality conditioners are proposed with the help of power electronics converters.

A new structure of three-phase four-wire (3P4W) distribution system utilizing UPQC to balance the unbalanced load currents, neutral current compensation using PI control technique is reported in [1]. Design of UPQC with minimization of DC link voltage for the improvement of power quality using FLC alone, along with PI controller and its comparison is reported in [2]. When the system is connected to 3P4W, the improvement of power quality issues like voltage, current unbalance, distortions, reactive power demanded by the load using UPQC is reported in [5], [6], [7], [8], [9], [10].

MC-UPQC consisting of three VSC's connected to the system for simultaneous compensation of voltage and current imperfection is proposed in [11], [12], [13], [8]. One feeder 3P4W distribution system can be provided the neutral conductor along with the three power lines from the generation station [8], [9], [10] to improve the unbalanced voltage and current by using PI controller. A new control strategy of 3P4W UPQC for power quality improvement is reported in [14], [15], [16], [17], to the control of shunt APF with a simple scheme based on the real component of fundamental load current ($I \cos \Phi$) to reduce the number of current sensors is applied. The above scheme also used to evaluate in terms of power factor correction, source neutral current mitigation, load balancing, mitigation of voltage and current harmonics with linear and non-linear loads.

To compensate the voltage/current unbalance there are many control techniques are available. However most of these reported controller are not compensated load and shunt neutral currents. The transformer neutral current have some distortions, it is not equal to zero while all operating conditions were not discussed in [1]. To achieve this, the proposed system to compensate the neutral current by using four leg voltage source converters in shunt.

This work proposes the instantaneous p–q theory based controller for two feeder 3P4W system fed UPQC. Here series transformer's neutral wire is connected to load as a fourth wire of 3P4W systems. The new control system has been modeled with FLC for above mentioned power quality problems of two feeders 3P4W. The system consists of two-series converters and one shunt back to back converter with common DC-link capacitor in order to maintain the voltage.

2. Proposed System Description

The MC-UPQC is connected to the distribution side to make the source and load voltage free from any distortions. The single line diagram of MC-UPQC for the proposed control scheme of two feeder 3P4W systems is shown in Fig. 1.

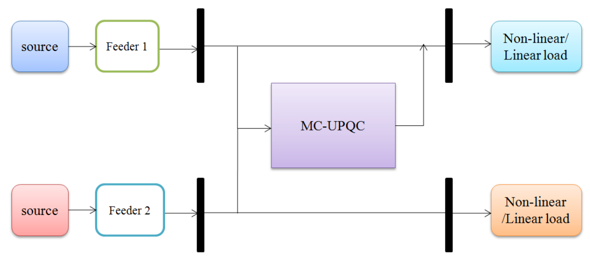


Fig. 1: Single line diagram of MC-UPQC.

At the same time, the reactive current drawn from the source should be similar to that of the currents at source side that would be in phase with utility voltages. A schematic of the proposed two feeder 3P4W distribution system is connected to MC-UPQCis shown in Fig. 2.

The schematic circuit consists of two-series converter having three-legged VSC, one shunt converter with four-legged VSC. The two feeders are connected the two different substations that are supplying the linear/non-linear loads. The active filters are connected in both shunt & series in order to eliminate the harmonic currents. However, the shunt filters are preferred more than series filters due to greater ease of protection. While considering to controlling the voltage sources in which three linear transformers connected in series along with two-series inverter.

If any neutral current is found to be present, it would flow through the fourth wire of the series transformer neutral point. The four-leg VSI based shunt active filter topology [3], [4], [10] is used to compensate the negative sequence of the source current, load balancing, power factor correction as well as to eliminate the harmonics in source currents. This result in the current at transformer neutral point will be zero. The proposed scheme can also be used to compensate the power quality problems related to different types of faults that occurs in the two feeders (L-G, L-L, L-L-G, L-L-L, L-L-G and without faults).

For feeder one, the source side voltages, load voltage, voltage injected by the series APF and DC link voltage between two inverters are represented by V_{s1}, V_{l1}, $V_{inj-se1}$ and V_{dc} are respectively. The current on the source side, load side, shunt current, neutral current on the load side, shunt neutral current and transformer neutral currents are represented by I_{s1}, I_{l1}, I_{sh1}, I_{ln}, I_{sh-n} and I_{sr-n} respectively. Similarly in feeder two, the source voltage, injected voltage, load voltage, source current, load current and transformer neutral current are represented by V_{s2}, V_{inj2}, V_{l2}, I_{s2}, I_{l2} and I_{sr-n2} respectively.

3. Control Strategy for the MC-UPQC

The proposed control strategy aims to generate reference signals for both shunt and series APF of the MC-UPQC. The function of series APF is to eliminate harmonics and for compensating reactive power, supply voltage in both feeders. Whereas the shunt APF functions to eliminate the supply current harmonics, distortions and also to compensate the unbalance, negative sequence current, reactive power, neutral current, thereby maintaining the transformer neutral current as zero during entire operating conditions.

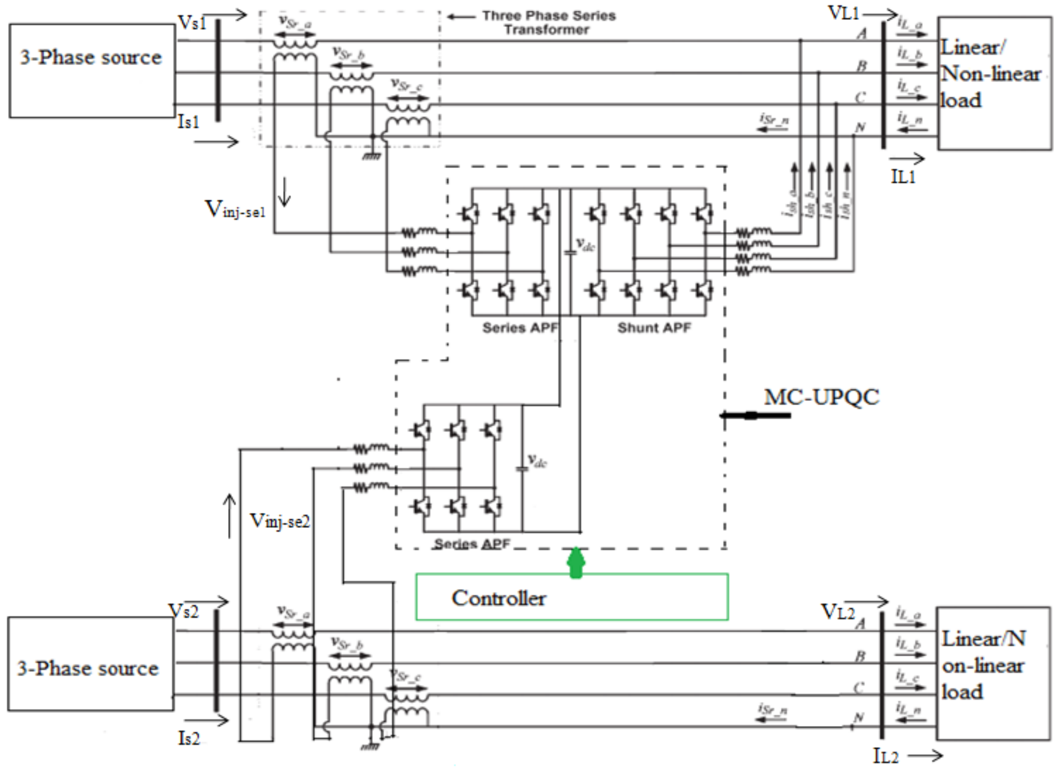
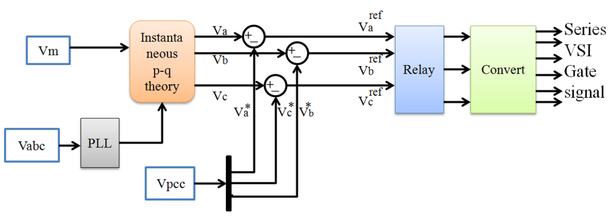


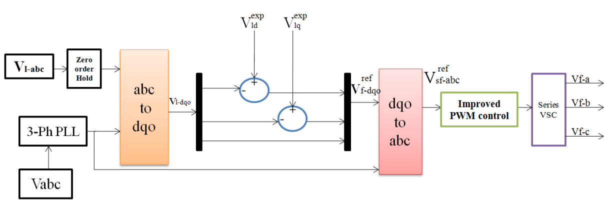
Fig. 2: The schematic of the proposed two feeder 3P4W distribution system is connected to MC-UPQC.

3.1. The Control Scheme of the Series APF's

If the supply voltage is distorted from its original value in feeder one, the phase- locked loop (PLL) is used to accomplish synchronization to bring back to its original supply voltage. The control algorithm for series APF's of two feeders is shown in Fig. 3.



(a)



(b)

Fig. 3: Control algorithm for series APF for (a) feeder one (b) feeder two.

When any distorted supply voltages are sensed by PLL it generates two quadrature unit vectors namely, the sine and cosine outputs are used to compute the 120 ° phase displacement for each phase. The instantaneous p–q theory is expanded from the concept of single phase p-q theory [5], [6], [10], [18] and the corresponding voltage equations are mentioned below in Eq. (1), Eq. (2) and Eq. (3). TThe voltages found at the point of common coupling were added to the Eq. (1), Eq. (2) and Eq. (3) and it is given to the relay. The relay output after getting compared with the reference voltages are given to convert a block to generate a gate signal for the series inverter. According to the expanded theory, the phase angle of each phase voltage and currents can be extracted as a three independent two phase system is charitable by $\Pi/2$ lead or lag, this can be applied for three-phase balanced system as well as an unbalanced system also. The control block diagram is shown in Fig. 3(a).

$$V_a = V_m \sin(wt), \tag{1}$$

$$V_b = V_m \sin(wt - 120°), \tag{2}$$

$$V_c = V_m \sin(wt + 120°). \tag{3}$$

The series controller is connected in feeder two, leads to mitigate voltage sag, swell, voltage distortions such as harmonics and interruption. The control algorithm for the series VSC block diagram is shown in Fig. 3(b). The series VSC is designed by using modified Synchronous reference frame (MSRF) theory with improved PWM generator in the proposed scheme. The series VSC is based on the unit vector template by expanding from the concept of MSRF theory. According to this theory, this can also be applicable for both three-phase balanced and unbalanced system. The three-phase load voltages are transformed into load synchronous reference voltages using Eq. (4):

$$\begin{bmatrix} v_{l-d} \\ v_{l-q} \\ v_{l-0} \end{bmatrix} = \begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} \begin{bmatrix} v_{l-a} \\ v_{l-b} \\ v_{l-c} \end{bmatrix}, \tag{4}$$

where:

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin wt & \sin\left(wt - \frac{2\pi}{3}\right) & \sin\left(wt + \frac{2\pi}{3}\right) \\ \cos wt & \cos\left(wt - \frac{2\pi}{3}\right) & \cos\left(wt + \frac{2\pi}{3}\right) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}. \tag{5}$$

According to series control objective, it is that the load voltage must be kept sinusoidal with constant amplitude as far as the supply voltage is concerned. The expected load Synchronous reference dq0 voltages are subtracted with the V_{l-dq0} in Eq. (6) obtained from Eq. (4). AAgain the compensation reference feeder dq0 voltages are transformed back to the synchronous reference feeder voltages using Eq. (7):

$$\begin{bmatrix} v_{f-d}^{ref} \\ v_{f-q}^{ref} \\ v_{f-0}^{ref} \end{bmatrix} = \begin{bmatrix} v_{l-d} \\ v_{l-q} \\ v_{l-0} \end{bmatrix} \begin{bmatrix} v_{l-d}^{ref} \\ v_{l-q}^{ref} \\ v_{l-0}^{ref} \end{bmatrix}, \tag{6}$$

$$\begin{bmatrix} v_{sf-a}^{ref} \\ v_{sf-b}^{ref} \\ v_{sf-c}^{ref} \end{bmatrix} = \begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix}^{-1} \begin{bmatrix} v_{f-d}^{ref} \\ v_{f-q}^{ref} \\ v_{f-0}^{ref} \end{bmatrix}. \tag{7}$$

The compensated synchronous reference abc voltages were forwarded to improve the operation of PWM generator. The output of the PWM generator is directly given to control part of series VSC as shown in Fig. 3(b). However, even the source voltage is distorting the series control objective have to be maintained. The improved PWM generates switching the signal such that the voltage at PCC becomes the desired sinusoidal reference voltage. Due to the series transformer across the injected voltage which cancel out the harmonics present in the supply and load voltage with the help of ripple filter, thereby making them free-from distortion.

3.2. The Control Scheme of the Shunt APF's

It consists of the generation of three-phase reference supply currents; due to the non-linear load on the 3P4W system connected to the source side by which currents are unbalanced. The proposed control system is compensating these unbalanced source currents on the source side by expanding the concept of modified p–q theory [1]. The control algorithms for the shunt APF block diagram are shown in Fig. 4.

On the load side the three-phase load currents are different due to fundamental load active and reactive power. To overcome this unequal load power demand from the source side, the fundamental three-phase active powers can be perfectly balanced; by the following method the unequal load power should be correctly redistributed between source, MC-UPQC and load such that the three-phase load from the source would be linear and equal loads.

The power obtained from the dc-link capacitor through the series inverter and switching losses will decrease the average value of dc bus voltage. In this dc-bus voltage all other distortions like unbalance conditions, sudden changes in load current can result in oscillations, if the transient response of the dc-link capacitor voltage is very slow. In order to overcome from this error between desired capacitor voltage and measured values, at FLC is installed. The output control signal is applied to the current control system in shunt VSI, which stabilizes the dc capacitor voltage by receiving required power from the source.

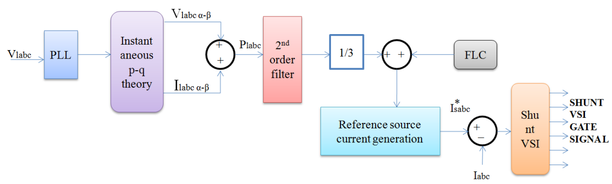


Fig. 4: Control algorithms for the shunt APF block diagram.

The three-phase load instantaneous p–q theory voltage and current can be added to get the active power estimation. The reference source current generation is extracted by the per phase fundamental active power estimation which is added to FLC output, the three-phase source currents were compared to the reference currents through which generates the appropriate shunt gate signals to be given for shunt VSI:

$$P_{labc} = V_{labc\alpha-\beta} + I_{labc\alpha-\beta}. \tag{8}$$

4. Fuzzy Logic Controller

Fuzzy Logic Control (FLC) system is composed of the following four principal components.

- Fuzzification,
- knowledge base,
- inference engine or decision making logic,

- de-fuzzification.

The output from the database and the rules of the knowledge base which were used to get the inference relation B mentioned in the Eq. (9). The input and output variables of controlled system or data bus contains a description of fuzzy sets:

$$\begin{aligned} &B^{(p)} = \\ &\text{if } X_1 \text{ is } F_1 \text{ and } X_2 \text{ is } F_2, \ldots, X_n \text{ is } F_n \\ &\text{then } Y \text{ is } C^{(p)}, \end{aligned} \tag{9}$$

where X_1, X_2, $\ldots$, X_n is the input variables vector, Y is the output or control variable, n is the number of fuzzy variables ($N = 5$), F_1, F_2, $\ldots$, F_n is the fuzzy sets, $P = 1, 2, 3, \ldots, N$, N is the number of rules ($N = 5$).

From the given rule base the fuzzy controller has to compute necessary specific input signal conditions, which can determine its effective control action. To design an FLC, the plant control is inferred from the two input state variables, namely error dc capacitor voltage (V_{dc}) and change in reference dc capacitor voltage error (ΔV_{dc}) in Eq. (10):

$$v_{e\ fuzzy} = v_{dc} - v_{dc}^{ref}. \tag{10}$$

The proposed structure of a complete FLC is given in Fig. 5. The Fuzzy control rules are designed for a fuzzy set of the control input in each combination of fuzzy sets for V_{dc} and ΔV_{dc} through which a very small amount of real loss is required for voltage regulation taken as the output from the FLC. The per phase fundamental active power estimation is added with Eq. (10) and it is forwarded to the reference source current generation.

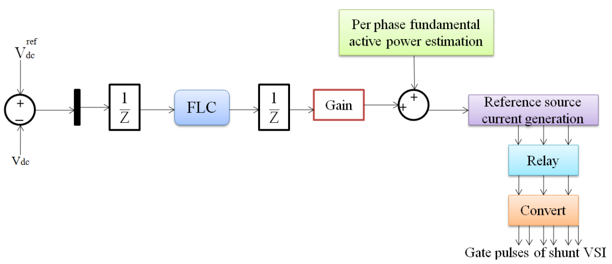


Fig. 5: Proposed structure of a complete Fuzzy logic controller.

The p–q theory based currents are directly given to relay that is sensed to control the signals of shunt VSC circuit as shown in Fig. 5.

In this paper, instead of using conventional (PI) controller mentioned in references a FLC is being used for its transient response to make MC-UPQC very fast in reducing the total harmonic distortions on source and load side voltages as well as currents on both the feeders. Here five labels of fuzzy subsets; negative large (NL), negative medium (NM), zero (ZR), positive medium (PM), positive large (PL). The control rule base table is shown in Tab. 1. In which the row and column represent the error and its changes respectively.

Tab. 1: Rule based for voltage control.

	ΔV→	**Input 2**				
↓V		NL	NM	ZR	PM	PL
Input 1	NL	NL	NL	NM	NM	ZR
	NM	NL	NM	NM	ZR	PM
	ZR	NM	NM	ZR	PM	PM
	PM	NM	ZR	PM	PM	PL
	PL	ZR	PM	PM	PL	PL

5. Simulation Results And Discussion

In order to justify the strategies of new control scheme discussed above, a Matlab based simulation designed as the system described in Fig. 2, and then the results are compared with a conventional system. It is observed from the results that the proposed new control scheme gives the better simulation results that the conventional system. The designed model of an MC-UPQC system connected with two feeders is realized using the MATLAB/Simulink software environment as shown in Fig. 6.

The three-phase rectifier load is turned on at time $t = 0.1$ s, to realize voltage harmonics in source voltage. The three-phase rectifier load mentioned in the design is a combination of linear and non-linear loads, where non-linear load considered being on the distribution side of feeder one, is a three-phase diode bridge rectifier with R-L load. At this time the shunt APF is connected to maintain the dc-link voltage as constant with respect to set reference value. Immediately the FLC discards load disturbance continuously without overshoot and also with a negligible steady state error.

The voltage is limited by its maximal admissible value, by a saturation function and by making the performance of a fuzzy control system in its adaptive nature. The controller is able to realize in different control scheme for each input state. The performance of the MC-UPQC connected between two feeder systems is used to voltage/current balancing, harmonic mitigation, source voltage/current compensation, power factor correction for both linear and nonlinear loads as well as maintaining the transformer neutral current as zero during all operating conditions. The control algorithm for shunt and series APF simulation diagram are shown in Fig. 7 and Fig. 8.

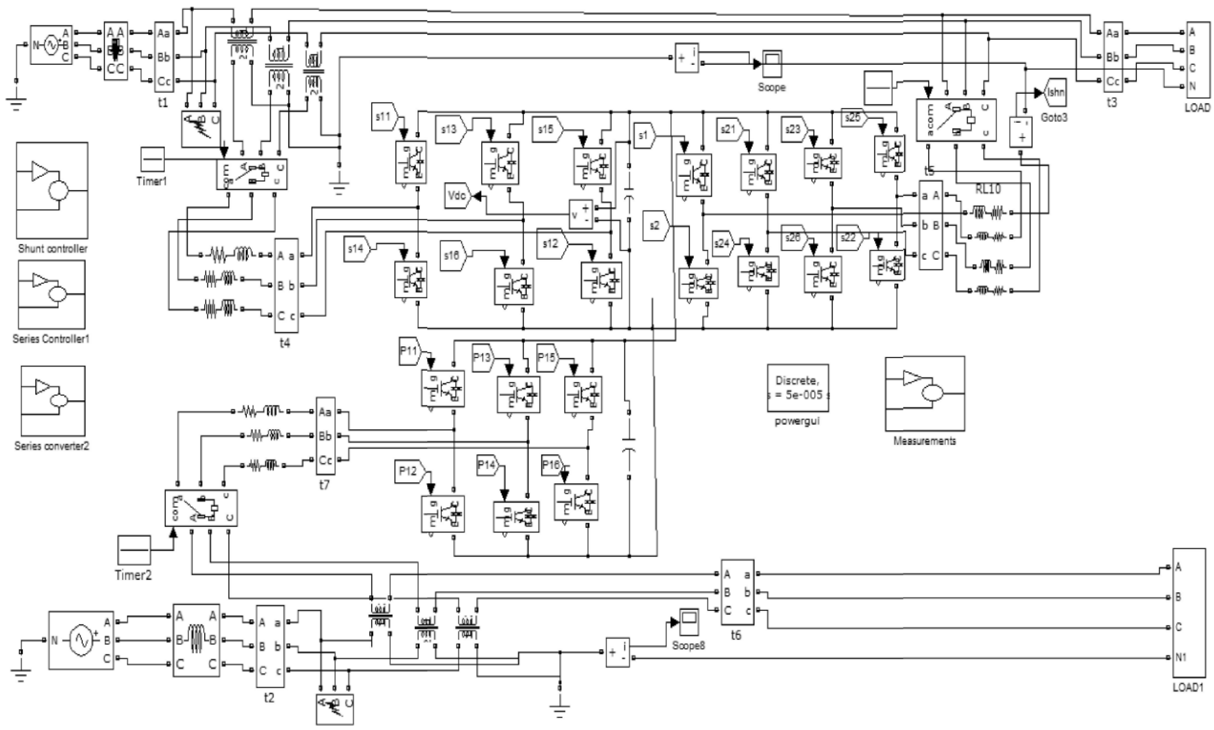
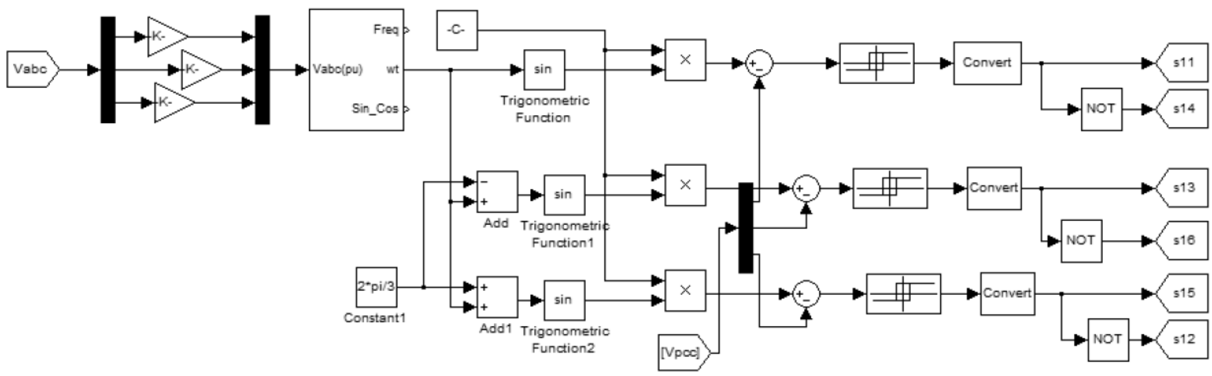
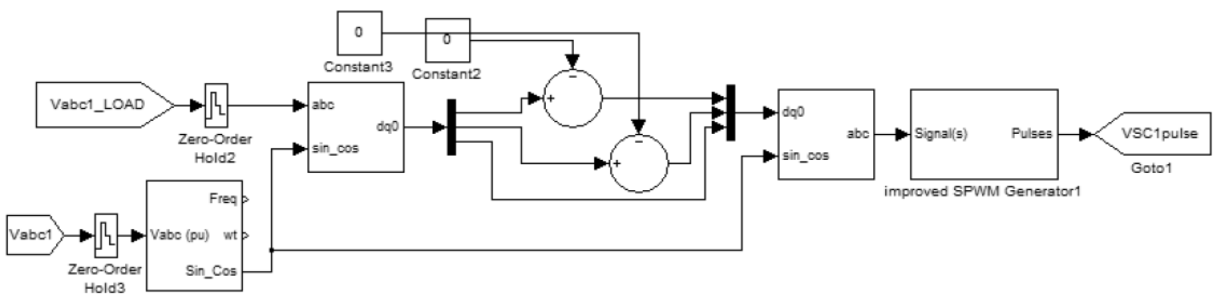


Fig. 6: Simulation circuit diagram of two feeder three phase four wire distribution system with MC-UPQC.



(a) feeder one



(b) feeder two

Fig. 7: Simulation circuit diagram for series APF.

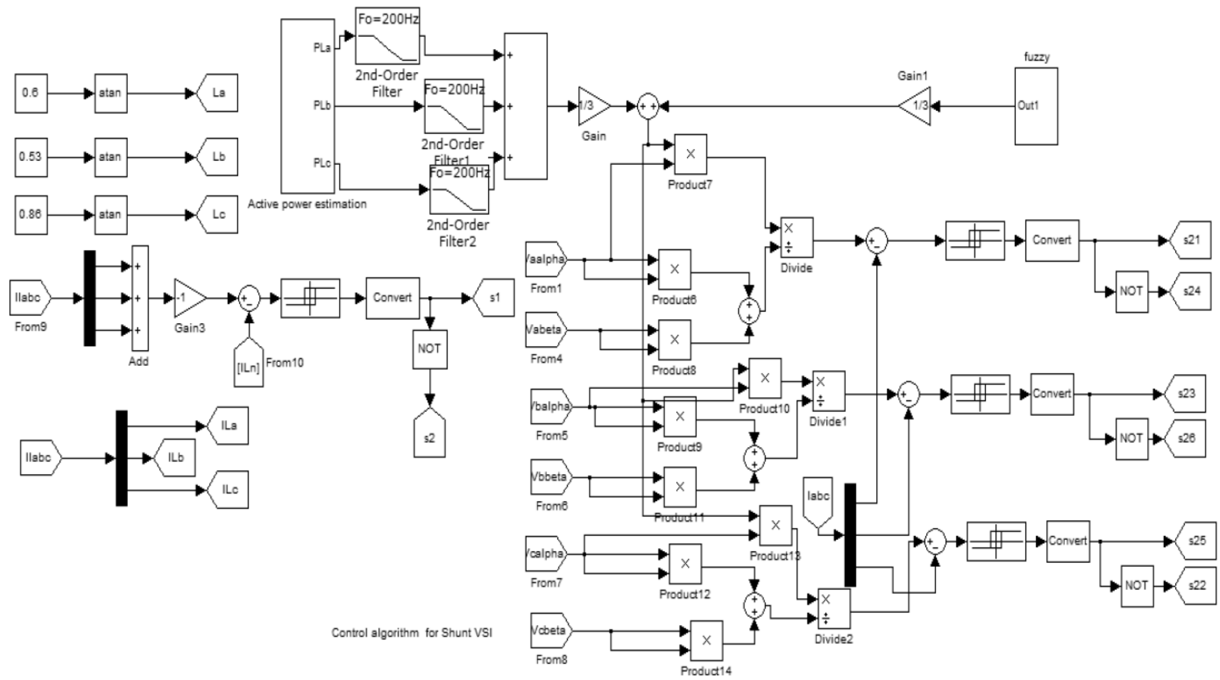


Fig. 8: Simulation circuit diagram for shunt APF.

5.1. Performance Analysis of MC-UPQC Connected to Feeder One

The performance of the MC-UPQC connected to feeder one with proposed new control techniques simulation results were presented in Fig. 9, Fig. 10, Fig. 11, Fig. 12 and Fig. 13.

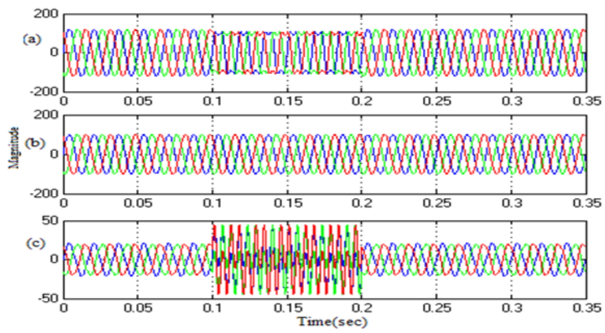


Fig. 9: Simulation results in feeder one; (a) source voltage, (b) load voltage, (c) injected voltage.

At time $t = 0.1$ s, the shunt APF is turned on which injects the compensating currents to realize the balanced source current free from distortions. The compensated source, load and injected currents are shown in Fig. 11. The THD seems to be reduced for compensated source current from 2.31 % to 2.28 %, whereas the shunt neutral current from 90.94 % to 90.90 % and load current from 12.15 % to 12.12 % respectively. The harmonic spectra of the source, load and injected currents

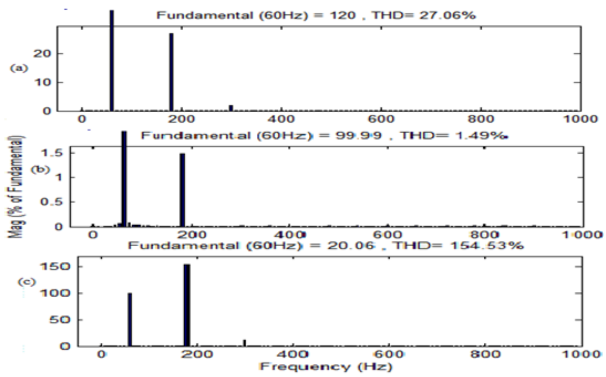


Fig. 10: Harmonic spectra of (a) source voltage, (b) load voltage and (c) injected voltage.

are shown in Fig. 12. Due to unbalanced load condition the load neutral current (25 A) that may follow towards the transformer neutral point. The load, injected shunt neutral current, dc-link capacitor voltage, transformer neutral current and harmonic spectra are shown in Fig. 13 (a)–(e) respectively. In this waveform we can see that transformer neutral current is without any distortions, with reduced THD from 0.24 % to 0.21 % and the dc-link capacitor voltage is maintained constant without any distortions.

The series APF is turned on at time $t = 0.2$ s, the injected voltage, source, and load voltage profile are shown in Fig. 9. The harmonic spectra of the source, load, and injected voltages are also shown in Fig. 10. It is observed that in the mentioned time the THD value has reduced for source voltage from 27.08 % to 27.05 %,

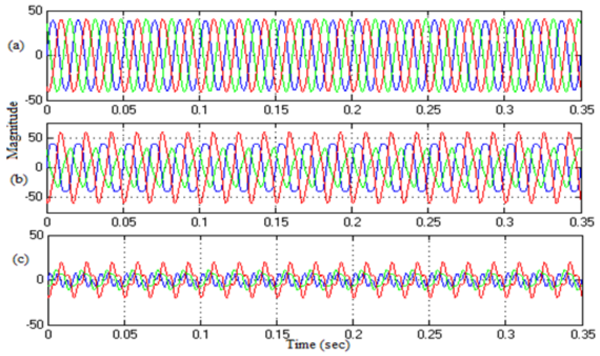


Fig. 11: Simulation results of (a) compensated source currents, (b) load currents, (c) injected currents.

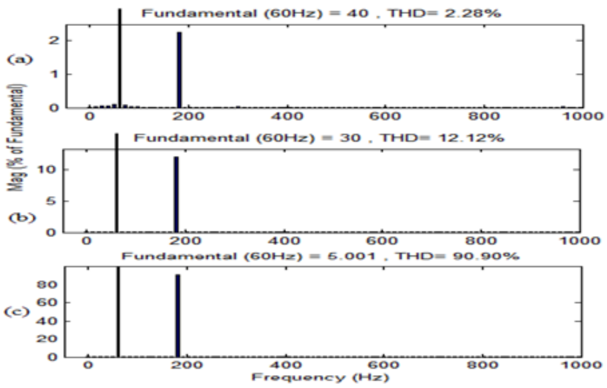


Fig. 12: Harmonic spectra of (a) compensated source currents, (b) load currents and (c) injected currents.

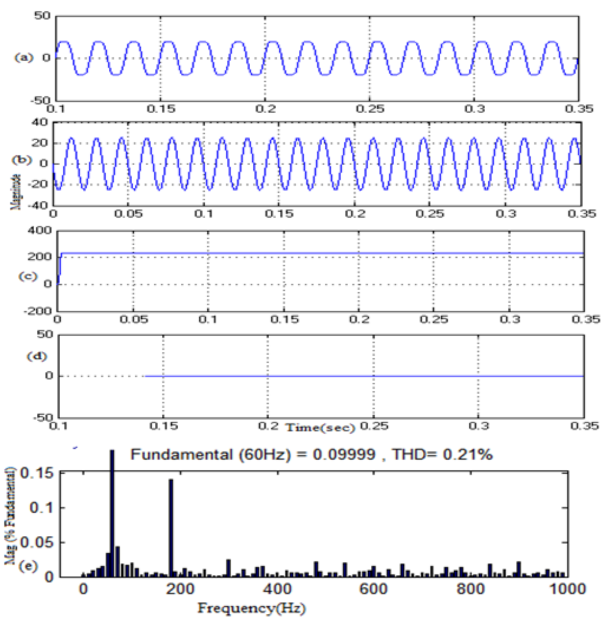


Fig. 13: Simulation results of (a) load neutral current, (b) injected shunt neutral current, (c) dc-link capacitor voltage, (d) transformer neutral current and (e) harmonic spectra for transformer neutral current.

load voltage from 1.51 % to 1.48 % and injected voltage from 154.56 % to 154.47 %.

5.2. Performance Analysis of MC-UPQC Connected to Feeder Two

The performance of MC-UPQC under new control scheme connected to feeder two is done to improve the source voltage and load current from distortion using MSRF based control techniques incorporated with FLC techniques..

The simulation results are shown in Fig. 14, Fig. 15, Fig. 16. At time $t = 0.25$ s, the series APF is turned on, the series APF gets starts compensating for the source voltages harmonics immediately by injecting out the phase harmonic voltages thus by making the source and load voltage free from distortions. The source voltage, source current, injected voltage and load voltage simulations, harmonic spectra are shown in Fig. 14, Fig. 15 respectively.

In feeder one, it is observed that source voltages are having distortions from 0.1 to 0.2 s along with injected voltage also. The source voltage in feeder one is distorted with THD value of 27.08 %. To compensate this distorted voltage in feeder one it is extended to feeder two with a new control scheme incorporated in the MC-UPQC results in reduced THD value of 0.19 %. The feeder two load current and transformer load neutral simulations, harmonic spectra are shown in Fig. 16.

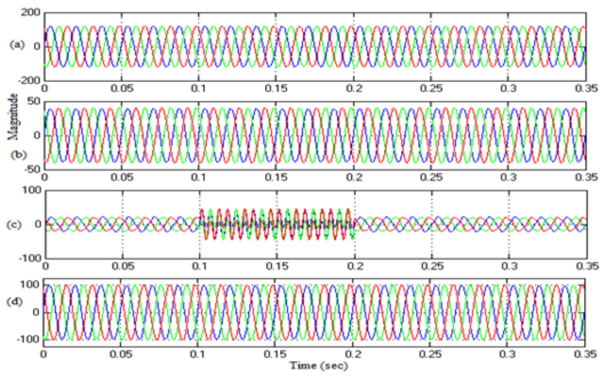


Fig. 14: Results of feeder two (a) source voltages, (b) source current, (c) injected voltage and (d) load voltage.

The comparison between conventional and new control scheme with reduced THD values are mentioned in Tab. 2. From the results it is observed that the proposed new control scheme gives better results even under the system is subjected to different types of faults like L-G, L-L, L-L-G, L -L-L and without faults. The harmonic spectra of different types of faults are listed in Tab. 3. The system with and without controller, the load neutral and shunt neutral having 25 A is verified. Not only these currents were compensated but also load neutral current flowing in the fourth wire of transformer neutral point is also maintained zero during all the operating conditions.

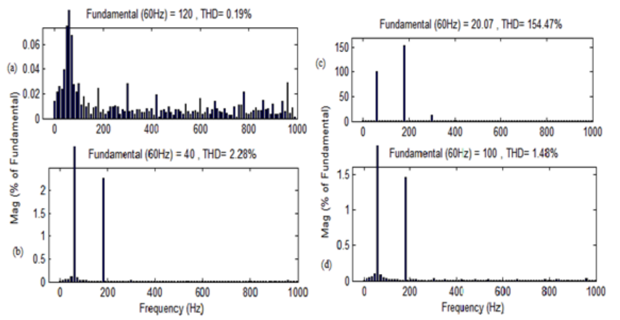


Fig. 15: THD Results of Feeder two (a) source voltage, (b) source current, (c) injected voltage and (d) load voltage by using Fuzzy Logic Controller.

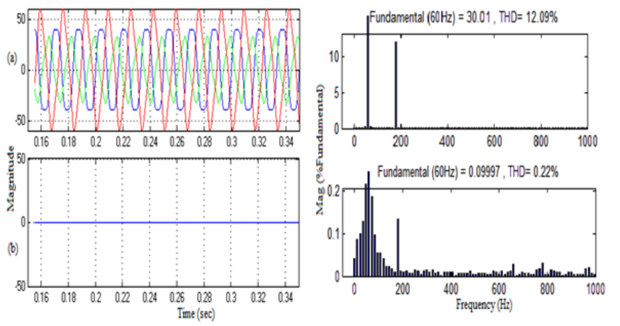


Fig. 16: Simulation results and THD value of (a) feeder two load current, (b) transformer load neutral current.

Tab. 2: % THD values comparison between existing system and proposed control strategy.

Voltage/ Current	Existing System [1]	Proposed Controller
Feeder 1	Considered	Considered
Source Voltage	27.08	**27.05**
Load Voltage	1.51	**1.48**
Injected Voltage	154.56	**154.47**
Source Current	2.31	**2.28**
Load Current	12.15	**12.12**
Shunt Current	90.94	**90.90**
Neutral Current	0.24	**0.21**
Feeder 2	Not Considered	Considered
Source Voltage	Not Considered	**0.19**
Load Voltage	Not Considered	1.48
Injected Voltage	Not Considered	154.47
Source Current	Not Considered	2.28
Load Current	Not Considered	**12.09**
Neutral Current	Not Considered	0.21

Tab. 3: % THD values comparison between different types of loads.

Voltage/ Current	L-G	L-L	L-L-G	L-L-L	Without faults
Feeder 1	**Considered**				
Source Voltage	7.16	34.54	11.02	683.34	18.04
Load Voltage	1.51	1.51	1.52	1.51	1.50
Injected Voltage	1.53	32.00	1.60	31.02	38.70
Source Current	2.31	2.31	2.32	2.31	2.30
Load Current	12.15	12.15	12.16	12.15	12.14
Shunt Current	90.93	90.93	90.96	90.93	90.92
Neutral Current	0.24	0.24	0.25	0.26	0.23
Feeder 2	**Considered**				
Source Voltage	35.42	54.19	54.00	28492.8	27.08
Load Voltage	1.51	1.51	1.52	1.51	1.50
Injected Voltage	1.53	32.00	1.60	31.02	38.70
Source Current	2.31	2.31	2.32	2.31	2.30

6. Conclusion

In this paper, the proposed control topology for two feeders three-phase four-wire system utilizing MC-UPQC is validated extensively under various operating conditions and compared with a conventional controller. The main advantages found from the proposed system compared to the conventional system are to compensate the power quality issues, such as the load voltage, load currents balancing, voltage and current harmonics mitigation. The source, load voltage and source, neutral currents with its harmonic levels are maintained according to IEEE 1159-1995 std., under all the operating conditions. Moreover, the transformer load neutral current is compensated, and it is found to be zero without any distortions in the load side. The effect of series converter is to eliminate the distortions on the supply side voltages due to unbalanced load conditions; the effect of shunt converter is not only to compensate the neutral current it also to make the current balanced on the source side, when they act individually. The proposed transient response of DC-link capacitor voltage is very fast when compare with the PI controller.

References

[1] KHADKIKAR, V. and A. CHANDRA. A Novel Structure for Three-Phase Four-Wire Distribution System Utilizing Unified Power Quality Conditioner (UPQC). *IEEE Transactions on Industry Applications*. 2009, vol. 45, iss. 5, pp. 1897–1902. ISSN 0093–9994. DOI: 10.1109/TIA.2009.2027147.

[2] RAMA RAO, R. V. D. and S. S. DASH. Design of UPQC with minimization of DC link voltage for the improvement of power quality by Fuzzy logic controller. *International Journal on Electrical & Power Engineering*. 2011, vol. 2, iss. 1, pp. 36–42. ISSN 2158-7574.

[3] SINGH, B., K. AL-HADDAD and A. CHANDRA. A review of active power filters for power quality improvement. *IEEE Transactions on Industrial Electronics*. 1999, vol. 46, iss. 5, pp. 960–971. ISSN 0278-0046. DOI: 10.1109/41.793345.

[4] QUINN, C. A. and N. MOHAN. Active filtering of harmonic currents in three-phase, four-wire systems with three-phase and single-phase nonlinear loads. In: *Applied Power Electronics Conference and Exposition, 1992. APEC '92. Conference Proceedings 1992., 7th Annual*. Boston: IEEE, 1992, pp. 829–836. DOI: 10.1109/APEC.1992.228328.

[5] CORREA, J. M., S. CHAKRABORTY, M. G. SIMOES and F. A. FARRET. A single phase high frequency AC microgrid with an unified power quality conditioner. In: *38th IAS Annual Meeting. Conference Record of the Industry Applications Conference, 2003*. Salt Lake City: IEEE, 2003, pp. 956–962. ISBN 0-7803-7883-0. DOI: 10.1109/IAS.2003.1257652.

[6] KHADKIKAR, V., A. CHANDRA, A. O. BARRY and T. D. NGUYEN. Application of UPQC to protect a sensitive load on a polluted distribution network. In: *IEEE Power Engineering Society General Meeting*. Montreal: IEEE, 2006, pp. 6–12. ISBN 978-1-4244-0493-2. DOI: 10.1109/PES.2006.1709522.

[7] KHADKIKAR, V., A. CHANDRA, A. O. BARRY and T. D. NGUYEN. Conceptual Study of Unified Power Quality Conditioner (UPQC). In: *IEEE International Symposium on Industrial Electronics*. Montreal: IEEE, 2006, pp. 1088–1093. ISBN 1-4244-0496-7. DOI: 10.1109/ISIE.2006.295788.

[8] AREDES, M., K. HEUMANN and E. H. WATANABE. An universal active power line conditioner. *IEEE Transactions on Power Delivery*. 1998, vol. 13, iss. 2, pp. 545–551. ISSN 0885-8977. DOI: 10.1109/61.660927.

[9] FARANDA, R. and I. VALADE. UPQC compensation strategy and design aimed at reducing losses. In: *Proceedings of the IEEE International Symposium on Industrial Electronics, (ISIE 2002)*. L'Aquila: IEEE, 2002, pp. 1264–1270. ISBN 0-7803-7369-3. DOI: 10.1109/ISIE.2002.1025971.

[10] CHEN, G., Y. CHEN and K. M. SMEDLEY. Three-phase four-leg active power quality conditioner without references calculation. In: *Nineteenth Annual IEEE Applied Power Electronics Conference and Exposition (APEC '04)*. Anaheim: IEEE, 2004, pp. 587–593. ISBN 0-7803-8269-2. DOI: 10.1109/APEC.2004.1295866.

[11] MOHAMMADI, H. R., A. Y. VARJANI and H. MOKHTARI. Multiconverter Unified Power-Quality Conditioning System: MC-UPQC. *IEEE Transactions on Power Delivery*. 2009, vol. 24, iss. 3, pp. 1679–1686. ISSN 0885-8977. DOI: 10.1109/TPWRD.2009.2016822.

[12] FUJITA, H. and H. AKAGI. The unified power quality conditioner: The integration of series and shunt active filters. In: *27th Annual IEEE Power Electronics Specialists Conference (PESC '96)*. Baveno: IEEE, 1996, pp. 494–501. ISBN 0-7803-3500-7. DOI: 10.1109/PESC.1996.548626.

[13] GHOSH, A. and G. LEDWICH. A unified power quality conditioner (UPQC) for simultaneous voltage and current compensation. *Electric Power Systems Research*. 2001, vol. 59, iss. 1, pp. 55–63. ISSN 0378-7796. DOI: 10.1016/S0378-7796(01)00141-9.

[14] PAL, Y., A. SWARUP and B. SINGH. A novel control strategy of three-phase, Four-wire UPQC for power quality improvement. *Journal of Electrical Engineering & Technology*. 2012, vol. 7, no. 1, pp. 1–8. ISSN 1975-0102. DOI: 10.5370/JEET.2012.7.1.1.

[15] GUNTHER, E. W. and H. MEHTA. A survey of distribution system power quality. *IEEE Transactions on Power Delivery*. 1995, vol. 10, iss. 1, pp. 322–329. ISSN 0885-8977. DOI: 10.1109/61.368382.

[16] DUGAN, R. C., M. F. MCGRANAGHAN and H.W. BEATY. *Electric Power System Quality*. 3rd edition. New York: McGraw-Hill Companies, 2012. ISBN 978-0071761550.

[17] FUCHS, E. and M. A. S. MAUSOUM. *Power Quality in Power Systems and Electrical Machines*. London: Elsevier Academic Press, 2008. ISBN 978-0123695369.

[18] HAQUE, M. T. Single-phase PQ theory. In: *IEEE 33rd Annual Power Electronics Specialists Conference (PESC 02)*. Cairns: IEEE, 2002, pp. 1815–1820. ISBN 0-7803-7262-X. DOI: 10.1109/PSEC.2002.1023074.

About Authors

Chandra Babu PADUCHURI was born in 1987. He received B.Tech from JNTU-K and M.Tech from SRM UNIVERSITY Chennai in 2006 and 2012 respectively. He is currently pursuing his research at SRM University. His area of Interests includes Power

System operation, Control & Power Electronic Converters, Drives and FACTS, DSP. He has published 8 international conference papers.

Subhransu Sekhar DASH was born in 1972. He received A.M.I.E graduation from I.E (India). The M.E Degree from U.C.E, Burla and Ph.D. degree in Electrical Engineering from Anna University, Chennai in 1994, 1996 and 2006 respectively. He has published more number of Papers in National and International reputed Journals. He is presently working as Professor and HOD (EEE) in SRM Engineering College, SRM University, Chennai, India and his areas of interests include FACTS, Power System Operation, Control & Stability, Power Electronics Drives and Intelligent Controlling Techniques.

Subramani CHINNAMUTHU was born in 1976. was born in 1976. He received B.E graduation from Bharathiar University, M.E degree from Anna University, Chennai in 2004 and 2006 respectively. He was completed his Ph.D. degree in Electrical and Electronics Engineering from SRM University in 2012. He is presently working as Assistant professor in the Department of EEE at SRM University. He has published 20 Papers in referred International Journals and more than 40 papers in International/National Conference. He is having 15 years of teaching and industrial experience. His areas of interest are power system stability, power system control and FACTS, electrical machine design.