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Multi-Level Inverter Topologies Based UPQC Applied to Distribution Systems for Power Quality Improvement

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***Abstract*: At distribution side most type of loads connected are non-linear types. These loads adversely affect the power quality of the system. If not rectified at times they may distort the sine wave at source side. This paper presents a power quality conditioner which is designed using multi-level inverter (MLI). The advantage that the proposed MLI has over conventional one is that it requires less number of components as compared to the conventional. Also it improves the utility profile by improving harmonic content at output side. The proposed MLI based Unified power Quality Conditioner (UPQC) improves the grid profile at non-linear loading by prohibiting the propagation of high content harmonic load current at source side. The proposed topology has inherent active filtering capability by virtue of which there has been seen a good mitigation of power quality issues at point of common coupling.**

Comparative analysis of the proposed topology with the conventional MLI is also presented. The comparison of results is also presented in terms of linear and non-linear loading in a UPQC compensated distribution system.

Keywords*: Unified power Quality Conditioner, *Multilevel Inverter, Harmonic distortion, Neutral point clamped, Cascaded inverter.

I. INTRODUCTION

THE good quality of power (PQ) is always an essential requirement of supply system since poor quality causes adverse effect to the sensitive equipments. Various devices and control have been reported to improve the quality of utility. The problem has been growing in recent years due to poor quality, specifically owing to the rise in nonlinear loads connected to the system. The prominent affect is the utility voltage distortions at the point of common coupling (PCC). Many more are voltage swell/sag, unbalanced voltages and load and/or source current harmonics affecting the appropriate operation of sensitive devices. The power demanded by the load has to be conditioned in order to upgrade the system performance at all adverse conditions. There have been numerous events reported in literature which witnesses the presence of voltage and current quality issues causing complete failure in the grid. Also in deregulated market structure this is the right of consumer to get good quality of power since they pay for it. Moreover the presence of PQ issues brings abnormalities in sensitive loads at various levels of distribution system. Owing to this abundant of research work is done in order to mitigate PQ issues Power electronics conditioners are the preferred choice for this since these devices can control the output voltage of the system by controlling the switching of the semiconductor switches. The precisely controlled and designed such devices are combinely termed as custom power conditioners which includes filters both active (APF) and passive, series, parallel and hybrid APF whose study and implementation is sited in [1]. Another popular CPD used for voltage regulation and harmonic mitigation is dynamic voltage restorers [2]. D-Statcom [3] is also one such CPD installed at distribution system for current and / or voltage harmonic mitigation. The problem with the mentioned CPD is they can mitigate one or two issues at a time and can provide series or shunt compensation only. Above all UPQC can simultaneously compensate shunt and series power providing voltage and /or current conditioning simultaneously. Hence in overcoming utility PQ issues, UPQCs are the best choice which is available with numerous concept and control [4], [5]. UPQC [6]–[8] are the combination of back to back series-shunt APF connected through dc-link capacitor. The series APF act as a current source sinusoid ally while parallel as voltage source converter hence it can simultaneously mitigate current as well as voltage based PQ problems in a way of providing series and parallel power conditioning. The comparison table which the above CPD can employed for mitigating PQ issues is presented in Table 1.

The use of multi-level inverters (MLI) in designing control of UPQC has not been explored much. Broadly MLI are of two types; separately energized DC source and common DC source connected MLI. In separately type cascaded is the popular one and in common DC source type neutral point clamped (NPC) is popularly used.

In this paper various both cascaded and NPCMLI topology with different level has been presented in designing the UPQC control.

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Also the modified cascaded having reduced component count and good harmonic profile as compared to the conventional one is also employed in designing the UPQC.

The results are obtained when the proposed UPQC topology are connected to distribution system with both balanced and unbalanced linear as well as non-linear loadings.

Table-1 Comparative analysis of different CPD for mitigating PQ parameters.

Parameters	APF	DVR	STATCOM	SVC	UPQC
Reactive power	Yes		Yes	Yes	Yes
Active power	Yes	Yes	Yes	Yes	Yes
Voltage stability	Yes		Yes	Yes	Yes
Voltage Flicker	Yes		Yes	Yes	Yes
Harmonic reduction					Yes
Power flow					Yes
Oscillation damping		Yes	Yes	Yes	Yes

II. UNIFIED POWER QUALITY CONDITIONER

The superiority of UPQC converter lies in the fact that it can simultaneously mitigate both voltage as well as current related PQ abnormalities. This is because it employs dual scheme of compensation, which means it is a combine effort of both series as well as shunt converters. The schematic of the UPQC as mentioned in figure 1 is comprised of series and shunt interlinked via DC-link capacitor. One side of the converter is connected to the source which has to be protected against load harmonic or PQ problems. Other side is connected to the load which generates the PQ issues.

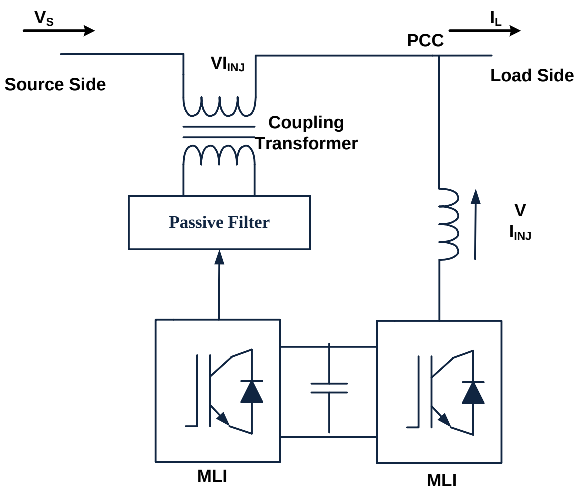

Fig. 1. Schematic diagram of Grid connected UPQC system

UPQC is a very versatile controller which can be easily customized as per the requirement for mitigating PQ issues. Broadly they could be UPQC-L/UPQC-R in which left or right converter are shunted, UPQC-Q for reactive power injection, UPQC-P for real power injection, UPQC-S which could inject both active and reactive power and many more like multi-converter based, modular, interline or distributed etc. All these classification are application oriented.

In this work a new type of UPQC is proposed in which in place of voltage or current source converter as in case of conventional UPQC topology, multilevel inverters are used to control the output at PCC.

In literature not much research are sited and which are sited it is not tested for loading conditions. Here three topologies for MLI are used namely 5-level neutral point (NPC) inverter, 5-level cascaded (CHB) MLI and 11-level modified CHBMLI. All the above mentioned MLI are used to design series and shunt converters for UPQC. Their results are compared for linear and non-linear loading.

III. MULTILEVEL INVERTERS

As the name suggest there are multiple level of output voltage retrieved by many DC-voltage sources. Moreover voltage quality at output is enhanced because of the increased voltage levels, so the cost and quality of the filter can be reduced. To obtain higher power, the basic concept of a MLI is to use semiconductor switches in series with many lower level voltage dc-sources to do power conversion by blending a step waveform like rectangular one for output voltage. To energies the MLI RES, batteries and capacitors are applicable for compound dc-voltage sources. Owing to the benefits obtained from MLI a lot of research work has been done to design various topologies as per the need. Some of which are classified in figure 2.

Now-a-days there has been popularity in hybrid type of topologies; as they are specifically designed to overcome the limitations possess by conventional topologies.

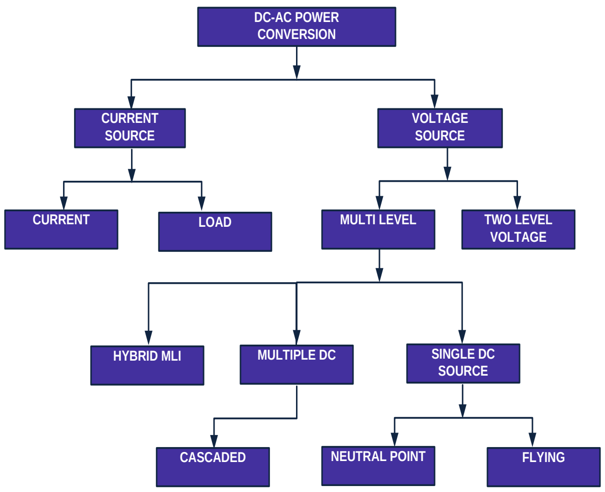

Fig.2. Topologies of multilevel Inverters

This section presents the comparative results for NPCMLI, CHBMLI and modified CHB to improve the performance efficiency especially harmonic reduction in output voltages and current as presented in fig. 3 in comparison to the conventional topologies also to make it cost efficient by reducing the component count at higher level of MLIs as shown in Table 2.

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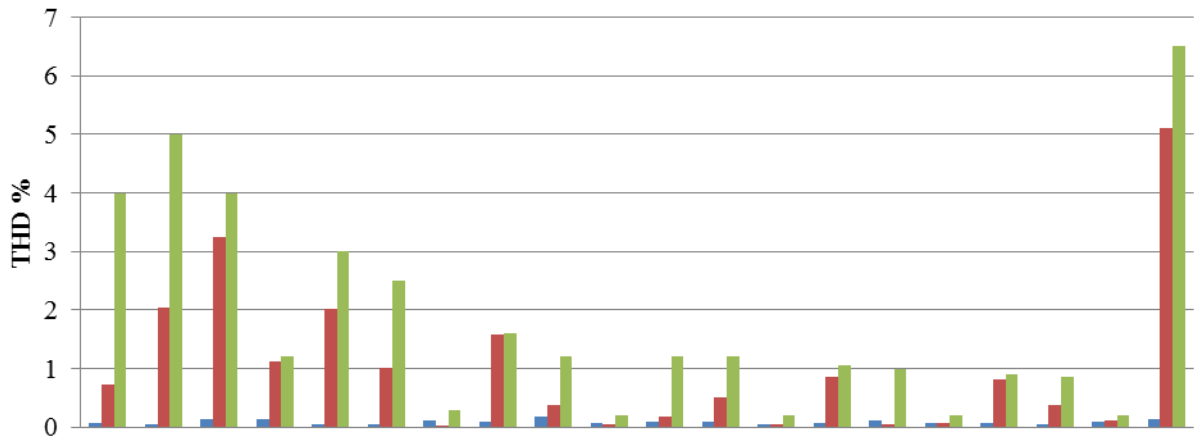

Harmonics order	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	40
Modified CHB	0.08	0.05	0.13	0.13	0.05	0.05	0.12	0.09	0.18	0.07	0.09	0.09	0.06	0.07	0.11	0.07	0.08	0.06	0.1	0.67
CHB	0.73	2.04	3.25	1.12	2.02	1.02	0.2	1.58	0.38	0.04	1.9	0.51	0.04	0.87	0.06	0.08	0.82	0.38	0.12	5.11
NPC	4	5	4	1.2	3	2.5	0.3	1.6	1.2	0.2	1.2	1.2	0.2	1.06	1	0.2	0.91	0.87	0.2	6.5

Fig.3.Output voltage harmonic comparison for various MLI topologies using VF PWM

Table 2 comparison of the component requirement for various MLI topologies

Parameters	Eleven level topology: m=11 Inverter type			
	FC	**NPC**	**CHB**	**Modified CHB**
Switching devices	20	20	20	8
Diodes	20	20	20	0
Clamping Diode	0	90	0	0
Capacitor balance	45	0	0	0
DC bus	10	10	5	3

Fig.3. compares the THD % upto 40 th order of harmonics for various topologies. The graph plotted is for R-loading and the switching of the IGBTs are controlled by employing high switching frequency based Pulse width modulation (PWM) technique. From the graph it is evident that the proposed reduced count CHB can reduce THD for a wide range of frequency including fundamental frequency ranging from low harmonic to higher harmonic content. On the other hand conventional topologies can control THD at higher level but fails at low level including fundamental component.

The other advantage modified CHB has over NPC and CHB is that to generate 11-level voltage they require 20 switching devices as compare to the 8 in modified one. Also other components like capacitor balancer, clamping diode, diodes etc. are not required which reduces the cost of designing the MLI at higher level with better performance efficiency and simple design. The only disadvantage this topology possesses is that it requires separate DC-sources for individual bridge units.

IV. MLI BASED UPQC

MLI based UPQC is not evident much since the complication is to control two converters with PWM technique and synchronize to give desired output. MLI topologies based UPQC upto three-level [9] and five-level [10] are available in literature. In this paper an 11-level CHB with low component requirement topology is proposed to design UPQC. In basic configuration of UPQC the series converter is connected to source through a coupling-transformer while parallel one is shunted to the load side as shown in fig.4.

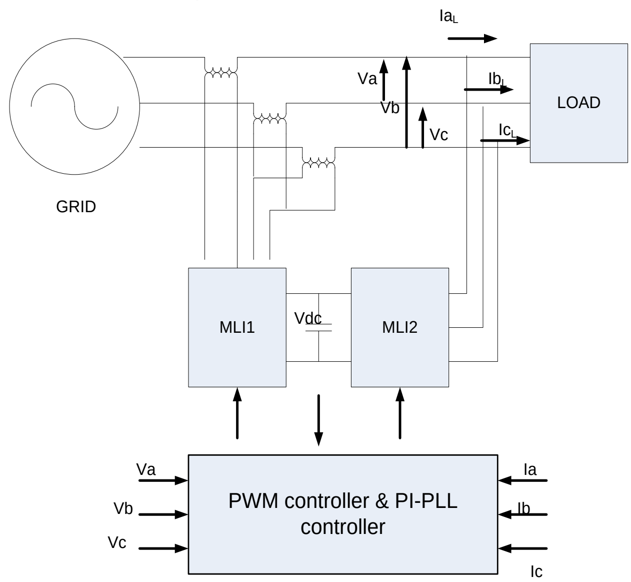

Fig.4. Basic configuration of UPQC

The series APF performs the function of current source while the parallel performs the function of voltage-source. In this work APF is replaced by MLI. The switching pulses are generated using variable frequency based PWM. The two MLIs are synchronized using PI controller and PLL. The synchronous reference frame signals are obtained using grid voltage reference signals to generate control for PI. The work has been done to test the performance of the UPQC with 5-level NPCMLI, 5-level CHBMLI and 11-level modified CHB.

As the level of MLI increases there is a tremendous reduction in THD percentage hence PQ of the system is enhanced. Hence this work is presented using 11-level MLI to improve the performance of the UPQC at various loading conditions.

The simulation results are obtained for grid connected MLI-UPQC for balanced linear loading and non-linear loading. The simulation results for all the operating conditions are presented in the next section.

V. RESULT AND DISCUSSION

The MATLAB simulation model has been developed using Simulink platform. Firstly MLI has been designed and performed the simulation for static load. Three MLIS are designed whose simulation results are shown in subsection A. the designed MLI are than used to model the dual compensating UPQC controller. The results for MLI-UPQC are presented in subsection B.

A. Simulation results for MLIs

The three topologies has been studied to design the MLI; 5-level NPC, 5-level CHB and 11-level modified CHB. The respective comparison of THD is presented fig.3.

1. Simulation results for 5-level NPC.

The design parameter for 5-level NPC-MLI is given in Table 3. The output voltage waveform is shown in fig. 5

Table 3 System parameters for 5-level NPC-MLI

Parameter	Values
Effective nominal voltage of the utility (RMS) VS	415 V
Nominal utility grid frequency fS	50Hz
Switching frequency of the converters fch	30khz
inductance of filter	100e-3 H
Series resistance converter	0.01 ohms
Capacitances of the parallel filters	1000e-6F
Resistances of the converter filter	0.01 ohms
dc-bus voltage Vdc	500V
PI gains	Kp = 0.04; Ki = 500

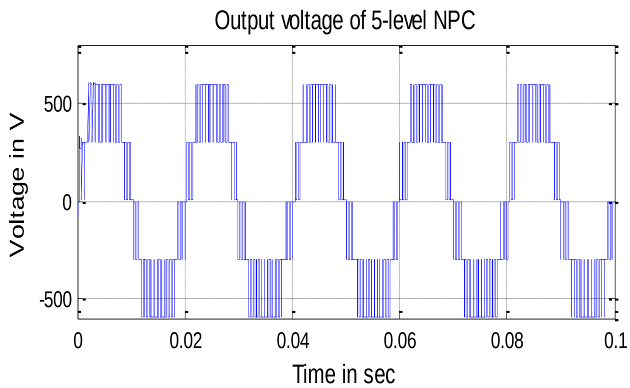

Fig.5. Output Voltage of 5-level single phase NPC-MLI.

2. Simulation results for 5-level CHB.

The design parameter for 5-level CHB-MLI is same as Table 3. The output voltage waveform is shown in fig. 6.

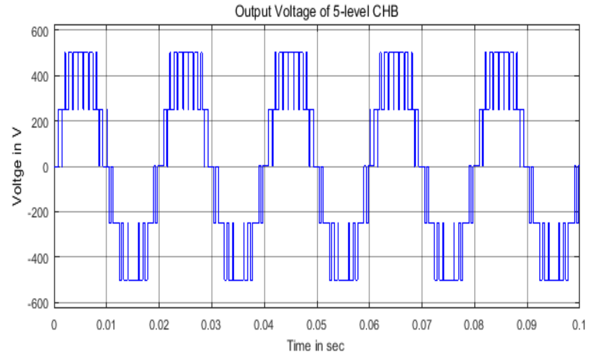

Fig.6. Output Voltage of 5-level single phase CHB-MLI.

3. Simulation results for 11-level modified CHBMLI

The design parameter for 5-level CHB-MLI is same as Table 4. The output voltage waveform is shown in fig. 7.

Table 4 System parameters for 11-level CHB-MLI

Parameter	Values
Effective nominal voltage of the utility (RMS) VS	415 V
Nominal utility grid frequency fS	50Hz
Switching frequency of the converters fch	10khz
inductance of filter	1e-3 H &
Series resistance converter	0.01 ohms
Capacitances of the parallel filters	1e-6 F
Resistances of the converter filter	0.01 ohms
dc-bus voltage Vdc	500V
PI gains	Kp = 0.04; Ki = 500

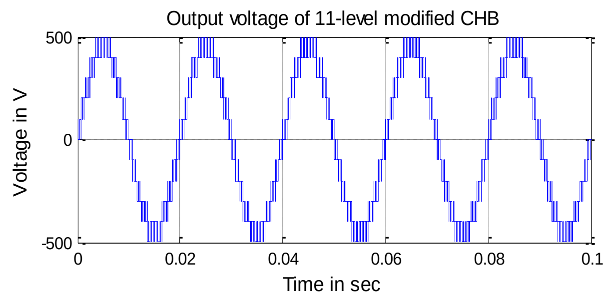

Fig.7. Output Voltage of 11-level single phase CHB-MLI.

B. Simulation results for MLI-UPQC

The three topologies have been studied to design the MLI-UPQC; 5-level NPC-UPQC, 5-level CHB-UPQC and 11-level modified CHB-UPQC. The performance of the systems are tested for two types of loading one is balanced linear loading and another is balanced non-linear loading.

The design parameters are same for all the topologies the parameters that changes are the MLI parameters which have been discussed in previous section. Hence the design parameters for MLI-UPQC is given in Table 5

Table 4 System parameters for MLI-UPQC

Parameter	Values
Effective nominal voltage of the utility (line to neutral))	Vs a , b , c = 127 V
Nominal utility grid frequency	fs = 60 Hz
Series filter inductance and capacitance	11H, 28e-6H
Inductance, resistance and Capacitances of the parallel	13e-6H, 10 ohm, 50e-6F
Transformation ratio of the series coupling transformers	n = 1
dc-bus voltage	Vd c = 400 V
dc-bus capacitance	Cd c = 9400 μF
Balanced linear loading	R=17 K ohm
Balanced non- linear loading	three phase full wave rectifier connected R=17 ohm

1. Simulation results for 5-level NPC-UPQC.

The system has been designed for three phase distribution system. In the designed UPQC series converter is connected across the source via coupling-transformer and the parallel converter is shunted across the load side. The simulation results are obtained for linear and non-linear loading. The output voltage and current waveforms are presented in fig. 8 and 9 for source side as well as load side respectively for the linear loading. In case of non-linear loading the output waveforms are presented in fig. 10 and 11 source as well as load side respectively. Form the output waveforms it is evident that UPQC designed by employing MLI is capable of maintain source quality as per the grid profile. Though load current THD are high since it is the characteristic of load connected in case of non-linear load, but load voltage THD is sufficiently low as compared to the system without UPQC connected which has been shown in Table. 6.

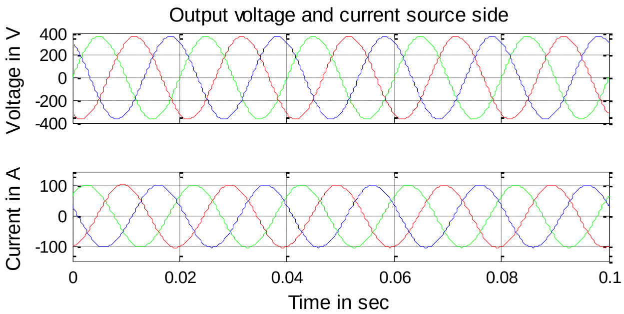

Fig.8. Output Waveforms of 5-level NPC-UPQC source side for linear loading

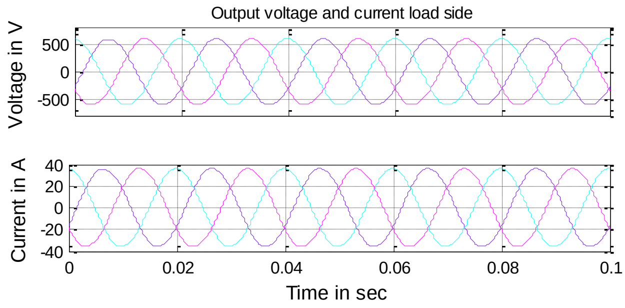

Fig.9. Output Waveforms of 5-level NPC-UPQC load side for linear loading

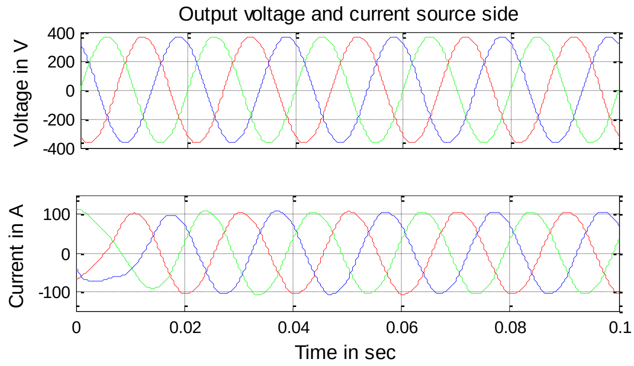

Fig.10. Output Waveforms of 5-level NPC-UPQC source side for non-linear loading

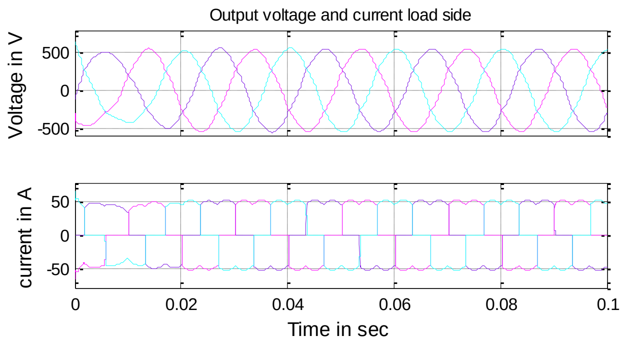

Fig.11. Output Waveforms of 5-level NPC-UPQC load side for non-linear loading

2. Simulation results for 5-level CHB-UPQC.

The output voltage and current waveforms for 5-level CHB-MLI are presented in fig. 12 and 13 for source side as well as load side respectively for the linear loading. In case of non-linear loading the output waveforms are presented in fig. 14 and 15 source as well as load side respectively. The results of CHB-MLI 5-level are compatible with5-level NPC-MLI. Not much difference is noticed.

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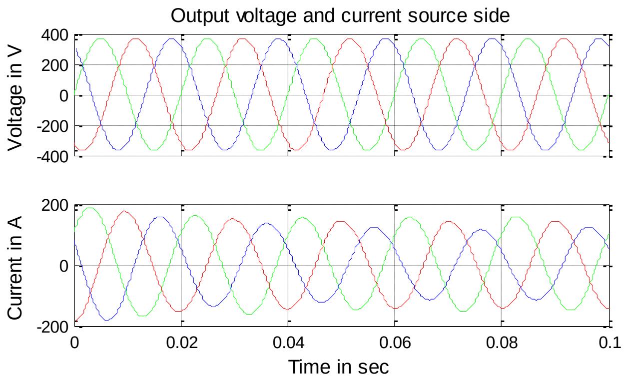

Fig.12. Output Waveforms of 5-level CHB-UPQC source side for linear loading

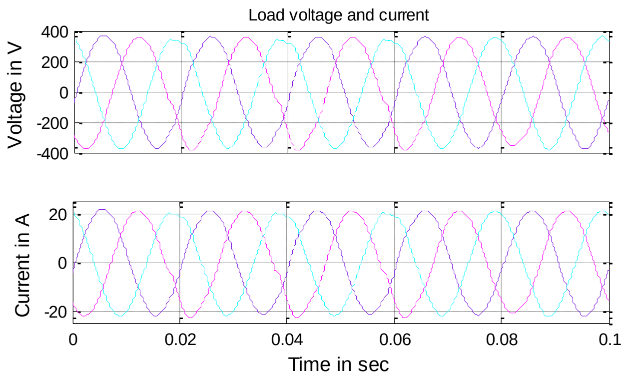

Fig.13. Output Waveforms of 5-level CHB-UPQC load side for linear loading.

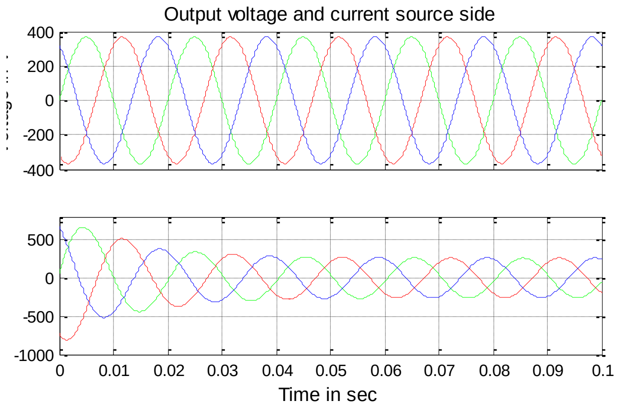

Fig.14. Output Waveforms of 5-level CHB-UPQC source side for non-linear loading.

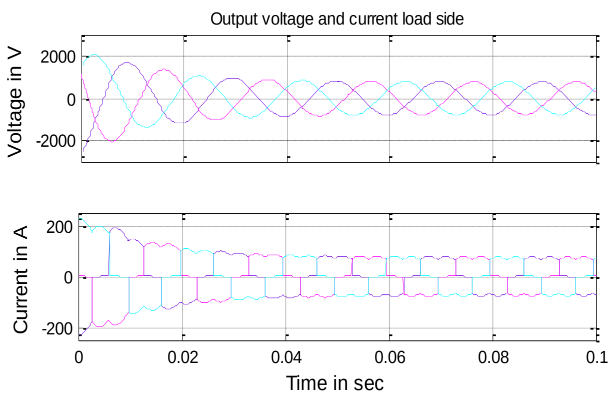

Fig.15. Output Waveforms of 5-level CHB-UPQC load side for non-linear loading.

3. Simulation results for 11-level modified CHB-UPQC.

The output voltage and current waveforms for 11-level modified CHB-MLI are more or less same as 5-level NPC and CHB based UPQC presented in previous section. Form the output waveforms it is evident that UPQC designed by employing 11-level MLI is capable of maintain source quality as per the grid profile far better than 5-level NPC and CHB. Table % and ^ presents the THD analysis for the proposed MLI based UPQC under various topologies of MLI and various loading conditions. The results for THD of voltages and currents are presented which shows that the though load THDs are very high but MLI based UPQC successfully eliminate the source harmonics and maintains the grid code power quality.

Table 5 THD analysis for voltages

Loading condition	**Phase A**	**Phas e B**	**Phase C**	**Phas e A**	**Phase B**	**Phas e C**
	Linear voltage	loading	Load	Non-linear Load		loading
Source voltage	0.1	0.1	0.1	0.1	0.1	0.1
5-level NPC-UPQC	0.01	0.0	0.0	15.4	12	14.7
5-level CHB-UPQC	0.01	0.0	0.01	14	13.7	11.7
11-level CHB-UPQC	0.01	0.01	0.01	2	3.1	1.7

Table 6 THD analysis for currents

Loading condition	**Phase A**	**Phas e B**	**Phase C**	**Phas e A**	**Phase B**	**Phas e C**
	Linear current	loading	Source	Non-linear loading Load current		
Source current	1.1	0.9	1	28	28	28
5-level NPC-UPQC	6.75	9	7	29.01	29.32	28.9
5-level CHB-UPQC	5.4	6	7.11	26.4	23.7	26.7
11-level CHB-UPQC	2.5	3.21	3.8	25.05	24.8	22.3

VI. CONCLUSION

A versatile topology of UPQC is presented in this paper based on MLI. Not of much work is available in literature for MLI-UPQC. Here successful implementation of MLI for designing UPQC has been evident for various loading conditions for three phase distribution system. In distribution system most of the loads are non-linear and they affect adversely the grid profile by injecting harmonics to the system. If these harmonics are not filtered out at time may distort the supply system and can damage the voltage sensitive devices. Hence the proposed UPQC-MLI is capable of eliminating source harmonics and can regulate the voltage at the same time.

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Dr Yogendra Kumar has pursued his Ph.D from Indian Institute of Technology, Roorkee in 2006. Presently he is Professor in the Department of Electrical Engineering, since 1992 in MANIT, Bhopal, India. His expertise is in Power System Application of Evolutionary Techniques in Advanced Power System. He is having more than 100 research papers published in various reputed journals and conferences. He had guided approximate 35 Mtech thesis and 15 Phd thesis.