Power Quality Improvement by Multilevel Inverter Based on UPQC

M. Sravanthi[1] B. Linganna[2] P. V. Samrat[3]
[1,2]Assistant Professor [3]M.E. Student
[1]Joginpally B R Engineering College, Moinabad, India
[2]Jagruti Institute of Engineering & Technology, Ibrahimpatnam, India
[3]University College of Engineering, Osmania University, Amberpet, India

Abstract— This paper aims at the development of multilevel inverter (MLI) based unified power quality conditioner (UPQC) for power quality improvement in 13 Bus system. In this paper, a 9-level based UPQC system is developed to maintain the system voltage and current profile at the grid as well as the load. The power quality of the proposed systems is progressed by controlling the MLI switches using a firefly algorithm (FFA) based pulse width modulation (PWM) scheme. The synchronization of UPQC with proposed 13 bus system is done with same FFA algorithm. The simulation and experimental results of the proposed system are clearly presented, which indicates that proposed FFA-PWM can facilitate the seamless control, over 9-level UPQC converter when power system instability is detected and it also improves the power quality in the system within the standard limit.

Key words: Multilevel Inverter (MLI), Unified Power Quality Conditioner (UPQC), Firefly Algorithm (FFA)

I. Introduction

The rapid demand for active and reactive power control raises the development of FACTS devices. Many researchers demonstrated the ability of the power electronic technology based FACTS devices in power system operation and security enhancement, which is explained in Ambati et al (1), Dizdarevic et al (2) and Muljadi et al. (3). Because they can control most parameters related to the operation of transmission systems with a quick response. FACTS devices are used to control the system oscillation within the stable limit. Unified power quality, control was widely studied by many researchers as an eventual method to improve power quality of electrical distribution system. The function of unified power quality conditioner is to compensate supply voltage flicker/imbalance, reactive power, negative-sequence current, and harmonics (4). In other words, the UPQC has the capability of improving power quality at the point of installation of power distribution systems or industrial power systems. Therefore, the UPQC is expected to be one of the most powerful solutions for large capacity loads sensitive to supply voltage flicker/imbalance. The UPQC consisting of the combination of a series active power filter (APF) and shunt APF can also compensate the voltage interruption if it has some energy storage or battery in the DC link. The shunt APF is usually connected across the loads to compensate for all current-related problems such as the reactive power compensation, power factor improvement, current harmonic compensation, and load unbalance compensation, whereas the series APF is connected in a series with the line through series transformers. It acts as controlled voltage source and can compensate all voltage related problems, such as voltage harmonics, voltage sag, voltage swell, flicker, etc. In this paper a new control algorithm called a firefly algorithm (FFA) for the UPQC system is optimized without measuring transformer voltage, load and filter current, so that system performance is improved. Since, finding the optimal location of performance is improved. Since, finding the optimal location of FACTS controller and its control are more complex, because a loading parameter with respect to reactive power flowing through the lines is computed to decide the optimal location for the placement of UPQC and real and reactive components of system functions are taken as input variables to control the UPQC converter devices. This is not directly compatible with the FACTS device control given in terms of complex variables and relations, which is explained in Meng Ji and MagnusEgested (5). In order to control and stabilize the complex system, various features such as monitoring, control and operation functions are optimized using Fire Fly Algorithm (FFA) control. In Wen and Smedley (6). MLI has been proposed for the control of three phase motor drive. This multi-level inverter has improved the power quality and the results are presented in Mikhail et al. (7) .The proposed control technique has been evaluated and tested under non-ideal mains voltage and unbalanced load conditions using Matlab/Simulink software. The proposed method is also validated through experimental study. The main focus of this paper is to realize new MLI based Unified Power Quality Conditioning (MLI-UPQC).

System for 225 kW power systems. The coordinated control of this MLI-UPQC can be ensured by Fire Fly Algorithm (FFA) control. The paper is organized as follows: section 2; presents MLI- converter functional features; section 3 elaborates the Fire Fly Algorithm for coordinated control WFs; sections 4 bring the experimental and simulation validation results. Finally a section 5 concludes the recommendations.

II. MLI Topology for UPQC Application

This paper also presents a new nine level inverter topology for UPQC application and is shown in Fig.1 and Fig. 2. To achieve the 9-level, the traditional cascaded inverter topologies need 20 power switches and 24 switches in diode clamped arrangement. But, the proposed nine level inverter has only seven IGBT switches in the power circuit. Input V_{dc} is divided into four levels using DC link capacitors of each $V_{dc}/4$ magnitudes. Four identical reference signals that are identical to each other with an offset that is equivalent to the amplitude of the triangular carrier signal were used to generate the PWM signals from the DC supply voltage. The operation of nine level inverter topology switching sequences is presented in Table 1.Single line diagram of the proposed 13 bus wind energy system is shown in Figure 1. In this, four wind generators are connected in bus numbers 1, 4, 7 and 8 which are generator buses and remaining are considered as a load buses. Experimental data of the 225kW WFs are utilized to identify the weak transmission lines of the buses based on the continuation power flow (CPF) algorithm to place the FACTs controller.

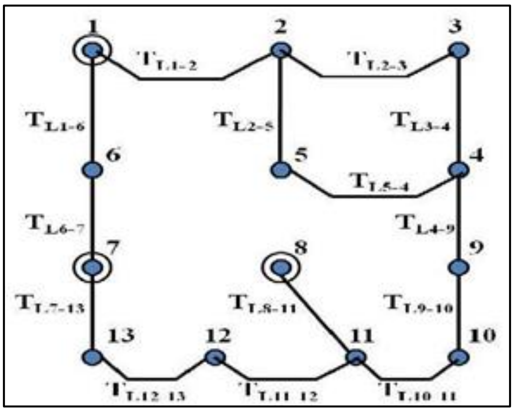


Fig. 1: Single Line Diagram of Proposed 13 Bus Systems

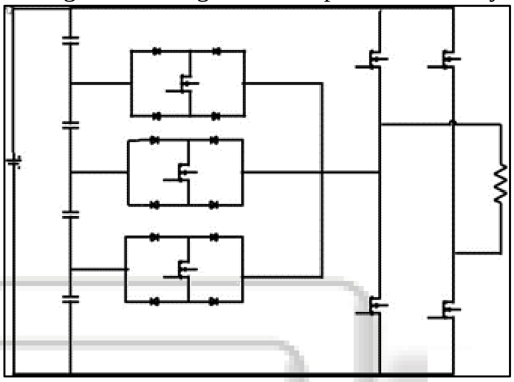


Fig. 2: Proposed 9-Level MLI for UPQC System

The proposed 9-level inverter has four voltage divider capacitors such as C_1, C_2, C_3 & C_4 respectively as shown in Fig.2. These capacitor dividers provide the nine voltage levels by controlling the seven IGBT switches with flow control diodes, which are presented in Table 1.The 9-level has been achieved by operating the power switches at nine different modes. In the first mode, the nine level inverter operated at maximum positive voltage ie. V_{dc} by operating the switches S_1=>S_4. Voltage level has been reduced to the three fourth at the second mode of operation by activating the switches in the following sequence D_1=>S_5=> D_2 => S_4. Similarly in the other modes the output voltage levels have been changed by selecting the capacitive voltage divider arrangement, using the power switches as presented in Table 1.

Mode	Switching sequence	Voltage level
1	S_1& S_4	$^{+V}$dc
2	D_1, S_5, D_2& S_4	$+3V_{dc}/4$
3	D_5, S_6, D_6& S_4	$+V_{dc}/2$
4	D_9, S_7, D_{10}& S_4	$+V_{dc}/4$
5	S_3& S_4	$V_{dc}=0$
6	S_2, D_3, S_5& D_4	$-V_{dc}/4$
7	S_2, D_7, S_6& D_8	$-V_{dc}/2$
8	S_2, D_{11}, S_7& D_{12}	$-3V_{dc}/4$
9	S_2& S_3	$-V_{dc}$

Table 1: Switching Table for Modified 9-Level Inverter

In the MLI-UPQC scheme, the active power is exchanged via series MLI converters through a DC link and it is noted that the sum of the active power outputted from VSIs to the transmission lines should be zero when the losses of the converter circuits are ignored. The injection voltage magnitude and the phase angle are controlled by a combination of the series connected MLI-VSIs. It also maintains the fundamental frequency for controlling the DC link voltage at a desired level. The common DC link is represented by a bidirectional link for active power exchange between the voltage sources. The placement of UPQC in a transmission line as a power injection model and the power injection model of an MLI-UPQC is shown in the Fig.2. The power injections at buses are summarized and expressed in the Equations (1) – (4).

$$P_{inj,i} = \sum_{n=j,k} V_i V_{se_{in}} b_{in} \cos\left(\theta_i - \theta_{se_{in}}\right) \quad (1)$$

$$Q_{inj,i} = -\sum_{n=j,k} V_i V_{se_{in}} b_{in} \cos\left(\theta_i - \theta_{se_{in}}\right) \quad (2)$$

$$P_{inj,n} = -V_n V_{se_{in}} b_{in} \sin\left(\theta_n - \theta_{se_{in}}\right) \quad (3)$$

$$Q_{inj,n} = V_n Vse_{in} b_{in} \cos\left(\theta_n - \theta_{se_{in}}\right) \quad (4)$$

III. Optimal Placement of MLI-UPQC System using the Continual Power Flow Method

The optimal placement of various FACTS devices is an important problem in power systems operation for secure operation. In the past, most researchers had utilized dynamic considerations for the placement of the FACTS devices, as these devices have been utilized mainly to improve the stability of the power system networks. In the present research, the MLI-UPQC is considered from a static point of view to reduce the total system transmission loss and enhance the stability of the system. Hence, a new method based on the reliability analysis approach, as described below, has been suggested for placement of the FACTS devices. When the FACTS devices are included in the system, it will modify the power flow between two transmission lines. Therefore, MLI-UPQC device should be placed on the most sensitive lines. A more flexible formulation of the problem can be accomplished by stating the problem in a manner of the continual power flow method (CPF). From the CPF programming with optimal placement of FACTS devices constraints is given in Equation (5). Minimize {F, S_P}

$$Xij = XT.line + Xmli \text{ and } Qi = Qmli \quad (5)$$

F is the number of objectives (to be optimized), S_P the system sensitive index by reliability analysis and $X_{T.line}$ - reactance of transmission line. The above formulation is meant for simultaneously optimizing the objective functions and if there is no conflict between the objective functions, a solution can then be found where simultaneous optimization of several objective functions is possible. Hence the proposed MLI-UPQC converter has been implemented in transmission line T_{L7-13} between Bus 7 to 13 and line T_{L8-11} between buses 8 to 11.

This will control the real and reactive power injection to the grid. It also maintains the voltage profile of the system under critical loading conditions. Implementation of proposed MLI-UPQC will control the real and reactive power injection to transmission lines and also maintains the voltage profile and its power quality under critical loading conditions. The performance analysis is presented in Table 2.

The coordinated operation of the MLI-PQC converter and WFs parameters are periodically monitored and controlled by FFA and presentedTableis3.

Bus Number	Bus voltage magnitude (V_1) (Volts) without MLI-UPQC	Bus voltage magnitude (V_2) (Volts) with MLI-UPQC	Difference in voltage magnitude (Volts) $\|V\|=\|V_1-V_2\|$	Bus voltage angle with indices (- sign)
1	664.1362	664.1362	0	0.0000
2	653.5449	659.3342	5.7893	5.3533
3	651.4521	651.4521	0	7.5319
4	664.1439	664.1362	0.0077	9.2851
5	660.4789	661.5898	1.1109	14.1708
6	660.3109	662.4954	2.1845	11.0623
7	655.6725	659.4959	3.8234	12.8660
8	596.3234	653.6342	57.3108	11.8183
9	669.1294	673.6297	4.5003	14.0535
10	653.1297	653.0475	0.0822	15.6506
11	584.9427	651.4863	66.5436	14.0535
12	654.9336	658.4129	3.4793	15.1025
13	590.0346	661.5898	71.5552	15.1025

Table 2: Voltage Profile of Proposed WES with and Without MLI-UPQC

110 KV wind feeder Line (TL7-13) readings				225 KV grid feeder (TL8-11) readings			
Hrs	Amps	KW P_{ij}	kVAR Q_{ij}	Hrs	Amps	KW P_{lk}	KVAR Q_{lk}
1	290	50	6	1	266	98	22
2	292	51	6	2	258	95	26
3	294	51	6	3	264	97	26
4	298	51	5	4	267	98	27
5	323	56	7	5	217	78	24
6	329	56	5	6	270	98	26
7	273	76	2	7	282	100	25
8	398	66	6	8	404	142	28
9	471	74	5	9	344	119	18
10	473	77	6	10	322	110	15
11	454	70	3	11	454	158	18
12	509	79	5	12	390	137	18
13	451	74	5	13	348	125	12
14	429	68	5	14	351	128	18
15	441	73	1	15	364	128	24
16	483	77	5	16	392	130	31
17	455	70	3	17	439	147	37
18	385	62	6	18	440	155	30
19	350	56	0	19	323	112	25
20	466	75	1	20	407	144	30
21	405	67	3	21	361	131	27
22	363	61	0	22	398	147	29
23	369	62	3	23	410	151	30
24	332	57	0	24	406	135	28

Table 3: Weak Transmission Link Data for FFA Input

IV. FIREFLY ALGORITHM BASED CONTROLLER

Firefly (FFA) is novel nature-inspired algorithm metaheuristic algorithm that solves the continuous multi-objective optimization problems based on the social behavior of fireflies. It is proven to be a very efficient technique to search for the Pareto optimal set with superior success rates and efficiency compared with the PSO and GA for both continuous and discrete problems. In FFA, two important issues arise, namely, the variation in light intensity I and the Formulation of the attractiveness ß. In the simplest form and considering a fixed light absorption coefficient γ, light intensity I, which varies with distance r, can be expressed as

$$I(r) = I_o \exp(-\gamma r^2) \quad (6)$$

Where I_0 is the light intensity at r = 0. Considering the firefly's attractiveness as proportional to the light intensity seen by adjacent fireflies, the attractiveness ß can be expressed as

$$\beta(r) = \beta_o \exp(-\gamma r^2) (7)$$

Wher e ß 0 is the attractiveness at r = 0. The distance between any two fireflies i and j at x i respectively, can be calculated using the Euclidean

$$rij = \|x_i - x_j\| = \sqrt{\sum_{d \in D}(x_{i,d} - x_{j,d})^2} (8)$$

Where a is the randomization parameter and ξ i is a vector of random numbers with Gaussian or uniform distributions.

A. *Pseudo Code for Fire Fly Algorithm*

Objective function f(x), $X=(x_1\ldots\ldots x_d)^T$
Generate initial population of fire flies Xi (i=1,2…n)
Light intensity I_i at X_i is determined by f (X_i)
Define light absorption coefficient
While (t<MaxGeneration)
For i=1: n all n fireflies
For j=1: i all n fireflies
If Jib> Ii Move firefly I towards j in d-dimensions; end if
Attractiveness varies with distance r via
Evaluate new solutions and update light intensity
End for j
End for i
Rank the fireflies and find the current best End while
Post process results and visualization

1) *Step 1: Initialization*

- Maximum generation as 1000; j=1to P, P the number of training pairs used
- Select Xi; i=1 to 100 population and Ii=1;
- Initialize premise parameter matrix {ai bi ci} for input voltage and current

2) *Step 2: Estimating the Flies Level*

- Equation (26) is used to estimate the distance between the fire flies generated from the input.
- Propagate change of error measure for each iteration.
- Calculate the overall error measure with respect to each premise parameter
- Update premise parameters
  [ai bi ci] = ∂ E[ai bi ci]
  [ai bi ci] new = [ai bi ci] + [ai bi ci]
- Based on the errors or difference in voltage levels the MLI-UPQC system output has been adjusted by varying the duty cycle of the converter from the equation (9).

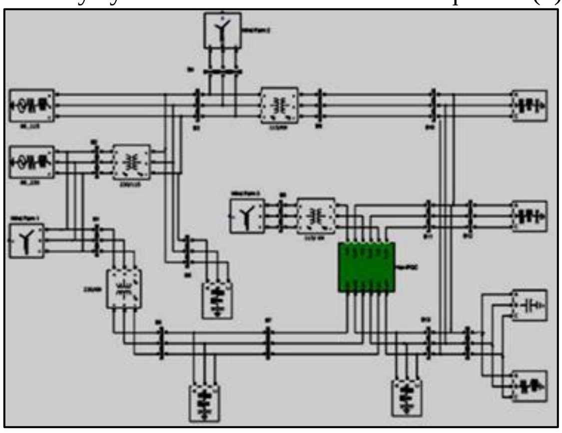


Fig. 3: Simulink Model of Proposed 13 Bus WFs

Intelligent control logics like PSO and FFA are implemented to verify and improve the performance of the MLI-UPQC system. The comparative results are presented in Table 4.

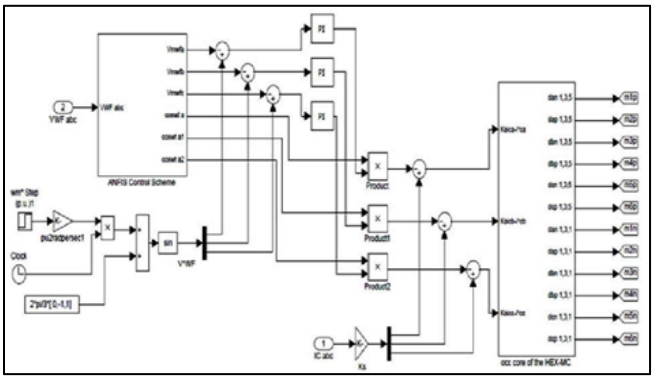


Fig. 4: Proposed FFA controller for MLI-UPQC system in MATLAB

Parameters	MLI-UPQC with PSO		MLI-UPQC with FFA	
Location of the Line	7-11	8-13	7-11	8-13
V_{inj} (V) during load isturbance	29.63	56.83	62.37	58.25
θ_{inj}(rad)	1.0877	0.9819	0.9750	0.859
Total line losses (KW)	6.639	5.135	2.948	4.963
Simulation time (Sec)	25	30	24	25
No. of Iterations	24	28	25	28

Table 4: Comparisons of MLI-UPQC with PSO AND FFA Controller

PWM pulses from the FFA controller are given in Fig. 5. The duty ratio to the MLI-UPQC inverters is changed from 30% to 65% for compensating the transmission line voltage, real and reactive powers. The dynamic behavior of the controller is verified by creating a load disturbance during 2 Sec. To 3 Sec. and voltage magnitude below 580V is detected. The proposed MLI-UPQC is designed to compensate nearly 150V in the disturbance in the system and to maintain the system voltage level more than 650V within few seconds. The results of the above mentioned criteria are validated through simulation. A FireFly Algorithm (FFA) Scheme is designed in such a way to accomplish some specific task. In this paper, there are seven different agents have been declared and each agent has some sub agents as shown in Fig.4. In this FFA system, each fly has unique objectives and responsibilities. In this MLI-UPQC system, seven agents are working towards achieving the overall goal of WFs, which is to secure WFs and grid under critical or power outages. Objectives and responsibilities of each agent will be discussed in the next section. Simulation result as shown in Fig. 6 illustrates the voltage disturbance in the system at bus 11 due to the critical loading condition. This voltage disturbance is cleared out and voltage quality is maintained within the few seconds with the help of FFA based MLI-UPQC system. The same is achieved in the hardware implementation of the MLI-UPQC system and the results are presented in Fig. 10. This simulation result shows that voltage stability waveforms of the 13 bus system voltage and power quality controlled by the FFA based MLI UPQC system which is exactly matched with the experimental data of the 225kW system. During critical load condition, FFA system brings proposed system stability into the limit within few seconds. It shows the effectiveness of the FFA system in coordinated control operation over the 13 bus systems. The experimental data of the 225kV system are given in Table 5 which shows the real and reactive power control values at the UPQC connected 110kV and 225 KV feeder line.

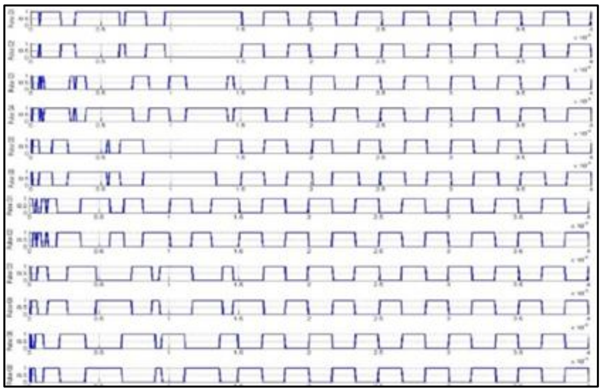


Fig. 5: PWM Signals to the Proposed MLI-UPQC during Fault using MATLAB Simulation

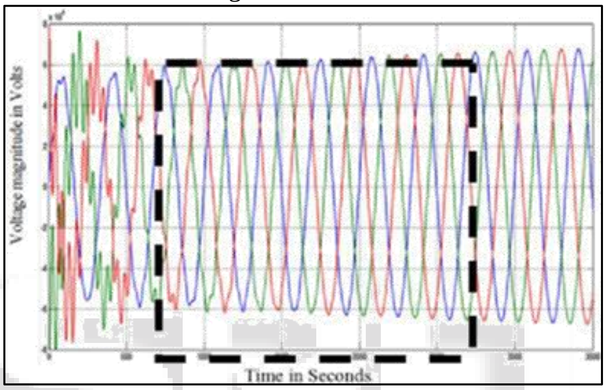


Fig. 6: Simulation Output of the MLI-UPQC Voltage Waveforms at Bus 11

V. RESULTS AND DISCUSSION

The various data have been collected from the 13 bus and 225kV power system. Measured parameters are presented in Table 5. Analysis of the system gave an idea to select weak bus for locating the MLI-UPQC system. Finally the implementation FFA system coordinated all the tasks assigned for the improvement of power quality and system stability enhancement. The proposed MLI-UPQC system implementation model has been simulated using MATLAB software and validated through experimental data. The simulation model of the proposed MLI-UPQC system for the 225KW Wind Farm system is developed in Matlab Simulink environment. It is observed that implementation of MLI-UPQC with FFA system controls the reactive power and improves the real power flow. Table 5 illustrates the real and reactive power injection between the transmission lines T_{L7-13} and T_{L8-11} using MLI-UPQC system with the FFA control scheme and corresponding waveform are given in Fig. 7 and Fig. 8

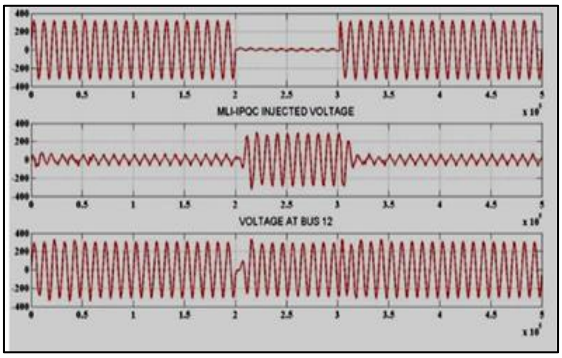


Fig. 7: Output Voltage Waveform at $T_{L7\text{-}13}$ with MLI-UPQC under Load Disturbance

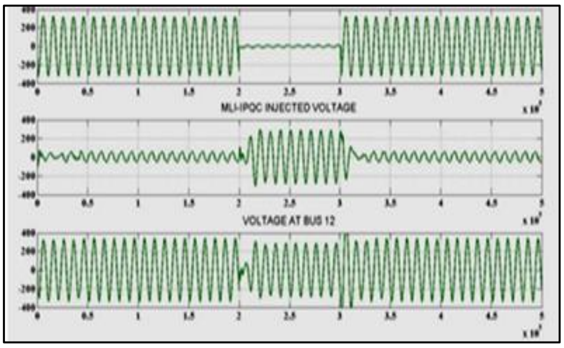
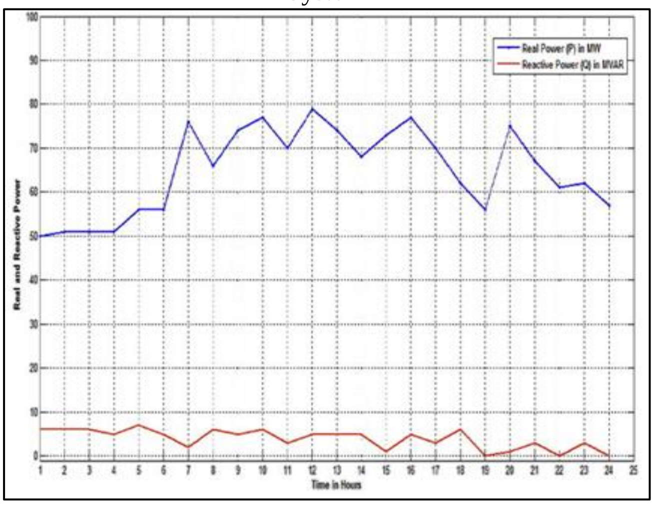


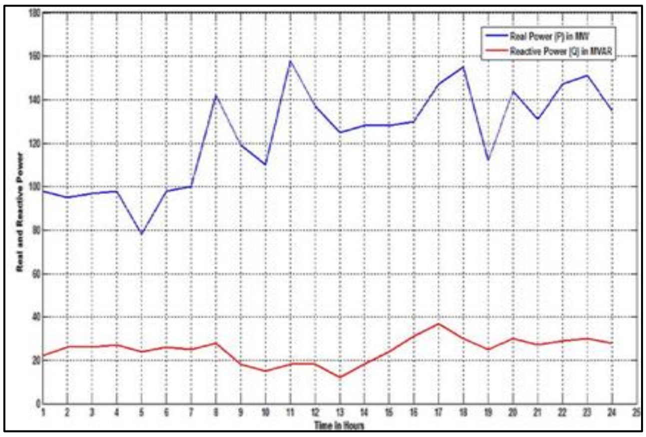
Fig.8 Output Voltage waveform at $T_{L8\text{-}11}$ with MLI-UPQC under Load Disturbance

Parameters	MLI-UPQC with PSO		MLI-UPQC with FFA	
Location of the Line	7-11	8-13	7-11	8-13
V_{inj} (V) during load isturbance	29.63	56.83	62.37	58.25
θ_{inj}(rad)	1.0877	0.9819	0.9750	0.859
Total line losses (KW)	6.639	5.135	2.948	4.963
Simulation time (Sec)	25	30	24	25
No. of Iterations	24	28	25	28

Table 5: Real and Reactive Power Data of the Proposed System



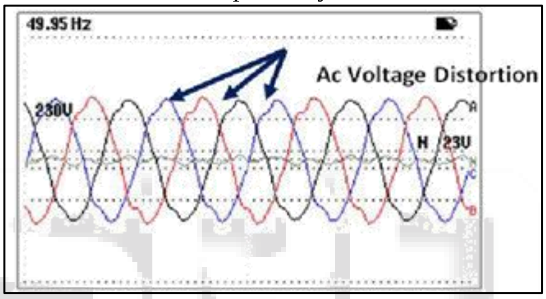
(a) 110kV Feeder Line



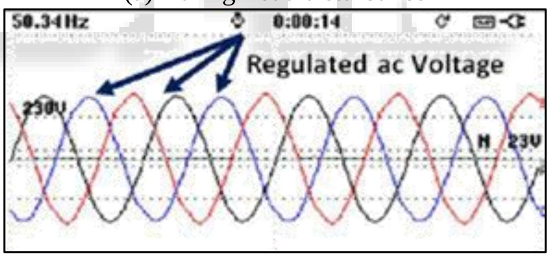
(b) 230kV Feeder Line

Fig. 9: Real and Reactive Power

Average real power and reactive power injection to the 13 bus systems are experimented and indicated in Fig.9. It shows that average real and reactive power flow in the 110kV feeder line is about 75MW and 6MVAR respectively. Similarly, real and reactive power flow in the 225 kV feeder line is about 140MW and 23MVAR respectively.



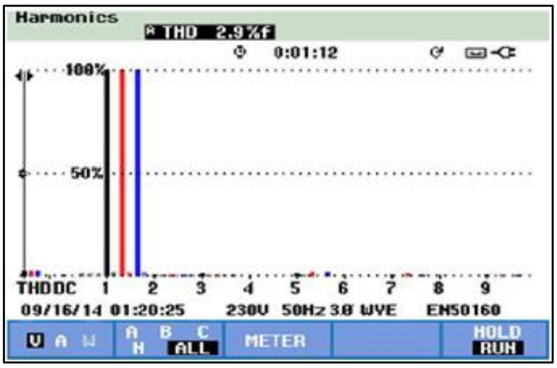
(a) During Load disturbance



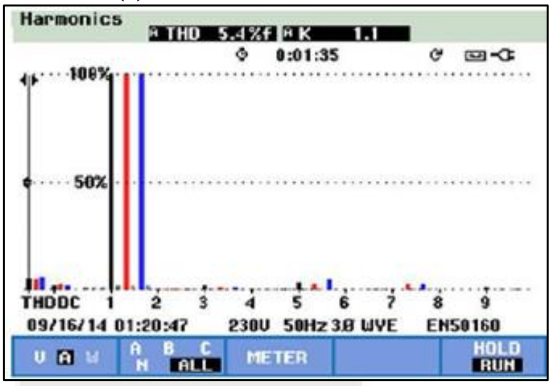
(b) Voltage regulation under MLI-UPQC with FFA Control

Fig. 10 Proposed MLI-UPQC functional waveforms from the simulation and experimental results, it is observed that implementation of MLI-UPQC with FFA scheme improves the quality and shape of the voltage at the load/grid as shown in Fig. 10. The proposed system also progresses the real and reactive power injection to grid by adjusting the output voltage level of the MLI-UPQCs inverter.

Hence the power quality and its control have been easily done using MLI-UPQC with intelligent FFA control strategy. The proposed system also progresses the real and reactive power injection to grid by adjusting the output voltage level of the MLI-UPQCs inverter. The Total Harmonic Distortion (THD) of the MLI-UPQC current signal is very low in the transmission line $T_{L7\text{-}13}$ and $T_{L8\text{-}11}$ which are shown in Fig.11. . Hence the power quality and power flow has been easily done using MLI-UPQC with the intelligent FFA control.



(a) Transmission lines TL7-13



(b) Transmission Lines TL8-11

Fig. 11: Current THD Spectrum

VI. Conclusion

The proposed 13 bus 225kW system has been modeled using MATLAB simulation. The specification of MLI-UPQC system is selected based on the experimental study and it is used for the simulation validation. The simulation and experimental study are carried for the various balanced and unbalanced loads. The effectiveness of the FFA control logic is verified and validated through the simulation and experimental results. The experimental and simulation results are clearly presented. The proposed MLI UPQC with FFA scheme provides better coordinated control to the power system parameters and maintains the system stability by controlling the reactive power and improves the real power flow in the wind farms. It also brings the system stability within few seconds when the load disturbance or power outage happens.

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