RESEARCH ARTICLE OPEN ACCESS

Controlling Methods for Single-Phase to Three-Phase UPQC Applied in Single Wire Earth Return Distribution Grids

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Abstract:

Aim of this project is to simulate a Unified Power Quality Conditioner (UPQC), which can be connected in three-phase three-wire electrical power distribution system (EPDS) for performing the series-parallel power-line conditioning. Using a single to three-phase UPQC (UPQC 1Ph-to-3Ph), this uses for the applications in rural or remote areas in which, only EPDS with single wire earth return (SWER) are accessible to the consumer. Since the use of three-phase loads is increasing in these areas, it is difficult to access the three-phase distribution system. This UPQC employs a dual compensation strategy, such that the controlled quantities are always sinusoidal. Series converter is controlled to act as a sinusoidal current source whereas the parallel converter operates as a sinusoidal voltage source. The system can able to suppress grid voltage harmonics, as well as to compensate for other disturbances such as voltage sags. Thus, a 3P3W system with regulated and balanced sinusoidal voltages with low harmonic contents is provided for single and three-phase loads. Synchronous Reference Frame (SRF) based controllers are implemented to control the input currents and the output voltages of the UPQC.To reduce the THD further, ANN is replaced by PI in the above method. The present work studies the compensation principle and different control strategies based on PI & ANN controller. The control strategies are modeled using MATLAB/SIMULINK.

Keywords — **Unified power quality conditioner (UPQC), Dual Compensation Strategy, active power filter.**

I. INTRODUCTION

Unified power quality conditioner (UPQC) is one of the progressed forms of power conditioning device, which is a combination of back to back connected series APF (SAPF) and shunt active power filter (PAPF) attached to a common DC link voltage. This topology will facilitates this equipment to have a reduced dc-link voltage without reducing its compensation capability. This device is principally used in getting better the power quality.

The demand for power quality (PQ) improvement has been expanding in recent years, mainly because of the increase of nonlinear loads attached to the electrical power system causing distortions in the utility voltages at the point of common coupling[1]. Nowadays Power quality problems have received a great attention because of their impacts on both utilities and customers. Unified power quality conditioner is one of the best custom power device used to compensate both source and load side problems. In this paper, controller is used to compensate voltage sag and it is compared with neural network based controller. Other PQ problems, such as voltage sags/swells and voltage unbalances can also have effects on the proper operation of sensitive equipment causing defect. Furthermore, additional procedures should be taken under consideration in order to overcome PQ problems linked to harmonic currents generated by nonlinear loads, load unbalances and reactive power demanded by the load [8].

In agricultural or remote, electrical power distribution systems (EPDS) with single-wire earth return (SWER) have been frequently adopted as a solution for electrical power supplying. This is because of the fact that the reduction of costs in the distribution of energy to perform huge territorial extensions with low numerical densities is a vital condition [1], since lower establishment and maintenance costs are achieved [4]. Other choices are using energy distribution by the use of two conductors (phase-to-neutral) without earth return or maybe using two-phase systems (phase-to-phase).

Considering the above-mentioned alternatives, capital investments for the realization of SWER distribution grid facilities installations are even lower [7]. The demand for electrical energy in single-phase agricultural distribution grids has remarkably expanded in the last decades, both in cultivation and in farm animals, mainly because of the developing growth and modernization of the technologies used, as well as the rise in the automation of production processes. For example, the automation of irrigation, as well as the post-harvest agricultural processing involving seed selection and milling, ventilation and refrigeration, washing and packaging lines, with others.

The current system describes about the demand for power quality (PQ) improvement has been growing in recent times, mainly due to the increase of nonlinear loads attached to the electrical power system causing distortions in the utility voltages at the point of common coupling. Other PQ problems, such as voltage sags/swells and voltage unbalances may also have effects on the correct operation of sensitive equipment causing malfunction.

II. PROBLEM DEFINITION

Power quality has different meanings. According to institute of electrical and electronics engineer (IEEE) standard describe power quality as "the concept of powering and grounding sensitive electronic equipment in a manner suitable for the appliances". There are variety of power quality problems linked to power systems according to time such as long continuation variations, short continuation variations and other few disturbances. All electrical appliances are demand to break down or mal-function during exposed to one or more power quality problems. The quality of electrical power supply is a set of parameters that describe the method of electric power transmission to the user under normal working conditions, work out the continuity of supply and indicate the supply voltage. Power quality phenomena can be split into two types, a quality of voltage or current (frequency or power factor) isn't exactly equal to its formal and desired value. The minor deviations are called voltage variations or current variations. When the voltage or current deviates moderately from its natural or ideal wave shape. These unusual deviations are called events. Power quality events are the phenomena which can lead to tripping of equipment, to disturbance of the production or of plant operation, or threaten power system operation. This includes disturbances, under voltages, overvoltage, phase angle jumps and three phase unbalance. Therefore to give protection to equipment from damage and to stay away from malfunctioning of equipment all of the parameters of power quality must be in recommended limits. The quality of power must satisfy the national and international standards. The particular power quality problems are given below.

Voltage variations can be of two types like short duration voltage variation and long duration voltage variation. Short duration voltage variations occur for time period of lower than 1min [8]. And long duration voltage variations are for greater than 1min. Short duration voltage variations are due to switching on of loads that need high starting current. Short duration voltage variations can be of three types like voltage sag, voltage swell and interruption [4]. The range of short voltage variations can be from few seconds to 1min. Power quality problem can be detected from symptoms like flickering of lamps, communication interface, overheated elements of devices, usual dropouts of sensitive equipments and frequent blackouts etc. These can be due to any fault, quick switching on or shutting down of load and occasional loose connections wiring. These forms of voltage variations include voltage sags, voltage swells and interruptions.

Several procedures have been adopted to mitigate PQ problems that can be carried out by means of active power-line conditioners, such as unified power quality conditioners (UPQCs), shunt, series and hybrid active power filters (APFs) and dynamic voltage restorers. This thesis introduces dual topology of unified power quality conditioner. This custom power device is similar to the conventional unified power quality conditioner only dissimilarity of the controlled signal is used. In dual unified power quality conditioner, the shunt filter controlled as a sinusoidal voltage source, and series filter controlled as a sinusoidal current source. The conventional UPQC has the drawbacks of complex harmonic extraction of the grid voltage and the load involving complex calculations, voltage and current references with harmonic contents demanding a huge bandwidth control, and the leakage inductance of the series connection transformer affecting the voltage compensation generated by the series filter [8].

Furthermore, further procedures need to be taken under consideration as a way to overcome PQ problems associated with harmonic currents generated by nonlinear loads, load unbalances and reactive power demanded by the load. But it has disadvantages like PQ problems similar to voltage sags/swells and voltage unbalances may also affect the proper operation of unstable equipment causing fault and Harmonic currents or load unbalances [2]. Thus, for overcoming utility PQ problems, UPQCs have been employed according to the various concepts and solutions [4] comprising single-phase systems or in three-phase applications, considering three-phase three-wire (3P3W) systems or three-phase four-wire (3P4W) systems . Accordingly, in most UPQC-based applications, the series and parallel APFs are measured as non-sinusoidal sources by using non-sinusoidal references to regulate voltage and current quantities [7].

It is widely known that non-sinusoidal references are difficult to be synthesized by PWM converters and require an additional power so as to achieve excellent performance in APF or UPQC applications. On the other hand, sinusoidal control references have been used in applications involving uninterruptible power supply (UPS) systems such that in the standby operation condition the UPS system acts similarly to a UPQC operating the series-parallel power compensation. In the present application, the series converter is controlled to work as a sinusoidal current source instead of a non-sinusoidal voltage source, although inside the parallel conditioning the parallel converter is controlled to operate as a sinusoidal voltage source rather than a non-sinusoidal current source. In addition, this dual compensation strategy has further been tested in UPQC applications Thus, different from the conventional conditioning strategy, that uses non-sinusoidal control references, the dual compensating strategy uses most effective sinusoidal references to control the pulse width modulation (PWM) converters. As a result, the formation of the control references is simpler to achieve, allow the use of simpler algorithms to attain this aim, synchronous Reference Frame based controllers (d-q-0-axes) are implemented to control the input current [5]. It can neutralize harmonic currents, load unbalances and reactive power of the load, while the load voltages are fixed. On the other hand, UPQC systems can perform, simultaneously, the series-parallel active power-line compensation by using both series and parallel APFs [2].

III. DUAL COMPENSATION PRINCIPLE

In this, the power supply is believed to be a single-phase, three-wire system. The two active filters are composed of two 3-leg voltage source inverters (VSI). Functionally, the series filter is used to compensate for the voltage distortions although the shunt filter is needed to arrange reactive power and counteract the harmonic current injected by the load. Also, the voltage of the DC link capacitor is composed to a desired value by the shunt active filter. There can be negative and zero sequence components in the transfer when a voltage disturbance occurs. Unified power quality conditioners are viable compensation devices which are used to make sure that delivered power meets all required standards and specifications at the point of installation. The UPQC is a custom power device which joins the series and shunt active filters, attached back-to-back on dc side and dividing a common DC capacitor [2]. This dual performance makes the UPQC as one of the most proper devices that could solve the issues of both consumers as well as of utility.

UPQC, thus may help to extend voltage profile and hence the overall energy of power distribution system. UPQC is composed of two IGBT based Voltage Source Converters (VSC) which are connected to a common DC energy storage capacitor and an inductor and also consists of two filter banks. One of these two VSCs is attached in series with the feeder and the other is connected in parallel to a similar feeder [11]. The series compensator is regulated in PWM voltage controlled mode. Whenever the supply voltage undergoes sag and then series converter injects correct voltage with supply. The series filter suppresses and isolates voltage based distortions, although the shunt filter cancels current-based distortions. The UPQC, thus, is expected as one of the most powerful solutions to large capability sensitive loads to voltage flicker/imbalance. UPQC maintains load end voltage at the graded quality even in the presence of supply voltage sag. The voltage injected by UPQC to conserve the load end voltage at the desired value is taken from a similar dc link, thus no additional link voltage support is required for for the series compensator [7]. It is composed of a series voltage-source converter attached in series with the AC line and acts as a voltage source to decrease voltage distortions. It is used to eliminate supply voltage flickers or imbalance from the load terminal voltage and forces the shunt branch to absorb current harmonics generated by the nonlinear load. Control of series converter output voltage is usually performed by pulse-width modulation (PWM).

The gate pulses needed for converter are generated by fundamental input voltage reference signal [8]. It is composed of a voltage-source converter connected in shunt with the same AC line and acts as a current source to cancel current distortions, improve reactive current of load, and recover the power factor. The gate pulses needed for converter are generated by fundamental input current reference signal. It further consists of a transformer. These are implemented to inject the compensation voltages and currents, and for purpose of electrical isolation of UPQC bridge converters. The shunt active filter is responsible for power factor correction and compensation of load current harmonics and unbalances. Also, it handles constant average voltage across the DC storage capacitor. The series active filter compensation goals are achieved by injecting voltages in series with the supply voltages such that the load voltages are balanced and undistorted, and their magnitudes are maintained at the desired level. This voltage injection is provided by dc storage capacitor. The control scheme of the shunt active power filter must depend on the current reference waveform for each phase of the inverter, maintain dc voltage constant, and achieve inverter gating signals [10].

It is a voltage-source converter attached in series with the AC line and performs a voltage source to mitigate voltage distortions. It is used to get rid of supply voltage flickers or imbalance from the load terminal voltage and forces the shunt branch to take in current harmonics generated by the nonlinear load. Control of the series converter output voltage is usually performed the use of sinusoidal pulse-width modulation (SPWM). The gate pulses needed for converter are generated by the comparison of a fundamental voltage reference signal with a high-frequency triangular waveform [5].

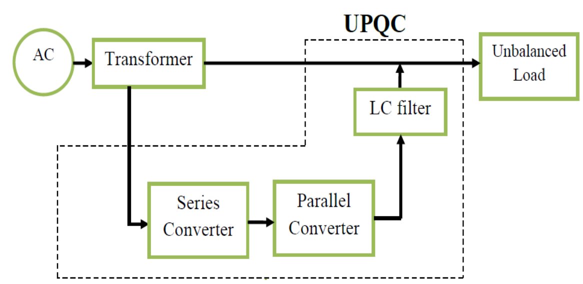


Fig. 1: Block diagram of UPQC

IV. CONTROL REFERENCES OF SERIES & PARALLEL CONVERTERS

Three phase p-q theory and synchronous reference frame method or three-phase d-q theory is most generally used time-domain control techniques for UPQC. These modes transfer the voltage and current signals in ABC frame to stationary reference frame (p-q theory) or synchronously rotating frame (d-q theory) to free the fundamental and harmonic quantities [13]. In p-q theory, spontaneous active and reactive powers are computed, while, the d-q theory deals with the current independent of the supply voltage. The curious feature of these theories is that the real and reactive powers linked to fundamental components (p-q theory), and the fundamental component in distorted voltage or current (d-q theory), are dc quantities.

These quantities can easily be extracted using a low pass filter or a high-pass filter. Due to the dc signal extraction, filtering of signals in the α-β reference frame is insensitive to any phase shift errors introduced by LPF. However, the cut-off frequency of these LPF or HPF can affect the dynamic appearance of the controller [5]. The original three-phase p-q theory exhibits limitations when the supply voltages are distorted and/or unbalanced. To overcome these limitations, the original p-q theory has been altered and generally referred as p-q-r [5]. Furthermore, both three-phase p-q and three-phase d-q theories have been altered such that the advantages offered by these methods are widen for single-phase APFs including single-phase UPQC systems.

Synchronous Reference Frame (SRF) based controller (d-q-o axes) is used to regulate the input currents and output voltages of the UPQC for speed control and to differ the system operation using PI controller. The PI controller leads to reduction in the steady state errors when continuous control references (V and I) into the SRF based controller is permitted [1]. Here, a-b-c to d-q transformation is called as Park's transformation. 3 phase PLL suffers with utility voltage disturbances such as harmonics or unbalances, STF is used in conjunction with the 3 phase PLL scheme. The system is very strong since the controller deals mainly with the d-q quantities. The conventional SRF method may be used to extract the harmonics contained in the supply voltages or currents. For current harmonic compensation, the distorted currents are first transmitted into two-phase stationary coordinates using α−β transformation. After that, the stationary frame quantities are transmitted into synchronous rotating frames using cosine and sine functions from the phase-locked loop (PLL). The conventional SRF algorithm is also known as d-q method.

The proposed SRF control method uses d-q-0 transformation equations, filters, and the modified PLL algorithm. This approach is simple and easy to implement and offers reduced current measurement. Therefore, it can run efficiently in DSP platforms. Hence, the proposed modified PLL algorithm intensively improves the appearance of the UPQC under unbalanced and distorted load conditions. Artificial Neural Networks are relatively electronic models based on the neural structure of the brain. The brain basically learns from experiences [3]. It is natural proof that are beyond the scope of current computers are indeed solvable by small energy efficient packages. This brain modeling also promises a less technical way to develop machine solutions. The ANN is made up of interconnecting artificial neurons. It is essentially a cluster of suitably interconnected nonlinear elements of very simple form that possess the ability to learn [15]. ANN takes data samples rather than entire data sets to arrive at solutions, which saves both time and money. ANNs are considered fairly simple mathematical models to enhance existing data analysis technologies.

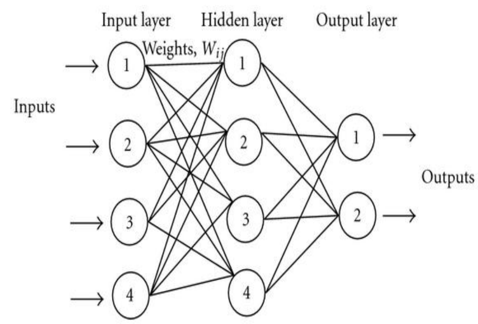


Fig. 2: Block diagram of ANN

V. MATHEMATICAL MODEL

The single-phase current reference used to control the SAPF is obtained in the synchronous reference frame d-q. Thus, the load are measured and transformed from the three-phase stationary reference frame (abc-axes) to the two-phase stationary reference frame using the Clarke transformation. Then, by means of the Park transformation, the stationary current quantities of the reference frame are transformed to the synchronous reference frame (d-q axes). In the rotating frame, the coordinates of the unit vector $sin(\theta)$ and $cos(\theta)$ and are obtained using the PLL system presented in [14], in which θ is the estimated phase-angle of the grid voltage. Once a 1 Ph-to-3 Ph system is being treated, the amplitude of the single-phase input/grid reference current (i^*cs) must be properly adjusted to ensure that the average single-phase input power (*Ps*) is equivalent to the average three-phase output power (*PL*). Since the single-phase system is connected to the grid, it should be considered the presence of voltage ripples at 120Hz on the dc-bus of the UPQC-1Ph-to-3Ph. This ripple may result in the appearance of the 120Hz harmonic in the series converter current reference (*i*cs*), since this current contains information of dc-bus controller current *(idc)*. Therefore, one way of attenuating the signal amplitude at this unwanted frequency would be used an LPF in the dc-bus voltage control loop. Nevertheless its use could interfere with the dynamics of the control making it slower. For this reason, it was opted to use only one LPF after the sum of the dc-bus controller current *(idc)*. To improve the dynamic filtering response, a moving average filter (MAF) [11] was used, acting as LPF. The MAF is characterized by being an easy-to-implement filter capable of rejecting the multiple frequency components of the cutoff frequency, which is defined as the inverse of the integration period (*T*) or by the fundamental component period. Furthermore, if there are unbalanced load currents, a fundamental negative sequence component will also appear in the synchronous reference frame at the 120Hz frequency, i.e., *T/2* of the fundamental component period. Consequently, it becomes necessary that the cutoff frequency of the moving average filter be 120Hz [12].

A. Series Converter Modeling

The modeling is accomplished considering that all involved inductances and resistances. By means of Fig 1 the equations that represent the system are given by (1) and (2)

usab_PWM= vLfsa+vRfsa+vCab-vRfsb-vLfsb (1)

usbc_PWM= vLfsb+vRfsb+vCbc-vRfsc-vLfsc (2)

Where usab_PWM and usbc_PWM are the respective PWM voltages at the 3-Leg series converter terminals. Considering the voltages of the PWM series converter in the d-q axes, the state-space equation is given by

$$\dot{x}sdq(t)=Asdqxsdq(t)+Bsdqusdq(t)+Fsdqwsdq(t) \quad (3)$$

Where $\dot{x}sdq(t)=\begin{bmatrix} disd/dt \\ disq/dt \end{bmatrix}$, $xsdq(t)=\begin{bmatrix} isd \\ isq \end{bmatrix}$,

$$usdq=\begin{bmatrix} usd\_PWM \\ usq\_PWM \end{bmatrix}$$

$$wsdq(t)=\begin{bmatrix} vsd \\ vcq \end{bmatrix}, Asdq=\begin{bmatrix} \frac{-Rfs}{Lfs} & \omega \\ -\omega & \frac{-Rfs}{Lfs} \end{bmatrix}$$

$$Bsdq=\frac{1}{3Lfs}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, Fsdq=\frac{1}{3Lfs}\begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}$$

Thereby, based on (3), the series converter average model

$$\frac{ics(d,q)(s)}{ics*(d,q)(s)} = \frac{X1(Kps(d,q)s+Kis(d,q))}{Leqs^2+(Req+X1\,Kps(d,q))s+X1Kis(d,q)} \quad (4)$$

Where $X_1=\frac{(k_{pwm}V_{DC})}{2}$

B. Parallel Converter Modeling

The modeling is accomplished considering that all involved inductances, resistances and capacitances are identical.

$$L_{fpa} = L_{fpb} = L_{fpc} = L_{fpn} = L_{fp}\ ;\ R_{fpa} = R_{fpb} = R_{fpc} = R_{fpn} = RL_{fp} \text{ and } C_{fpa} = C_{fpb} = C_{fpc} = C_{fpn} = C_{fp}$$

The equations that represent the system are given by (5), (6), and (7) as follows:

$$u_{pan\_pwm} = R_{fpa}.\,i_{ia} + L_{fpa}\frac{d\,i_{ia}}{dt} + V_{La} + L_{fpn}\frac{d\,i_{cn}}{dt} + R_{fpn}.\,i_{cn} \quad (5)$$

$$u_{pbn\_pwm} = R_{fpb}.\,i_{ib} + L_{fpb}\frac{d\,i_{ib}}{dt} + V_{Lb} + L_{fpn}\frac{d\,i_{cn}}{dt} + R_{fpn}.\,i_{cn} \quad (6)$$

$$u_{pcn\_pwm} = R_{fpc}.\,i_{ic} + L_{fpc}\frac{d\,i_{ic}}{dt} + V_{Lc} + L_{fpn}\frac{d\,i_{cn}}{dt} + R_{fpn}.\,i_{cn} \quad (7)$$

Where u_{pan_pwm} , u_{pbn_pwm} and u_{pcn_pwm} are the respective PWM voltages at the terminals a, b, and c of the 4- Leg parallel converter. The capacitor currents of the output filters (i_{cfpa}, i_{cfpb} and i_{cfpc}) are given by:

$$i_{cfpa}=C_{fpa}\frac{dV_{La}}{dt} = i_{ia} - i_{ca} \quad (8)$$

$$i_{cfpb}=C_{fpb}\frac{dV_{Lb}}{dt} = i_{ib} - i_{cb} \quad (9)$$

$$i_{cfpc}=C_{fpc}\frac{dV_{Lc}}{dt} = i_{ic} - i_{cc} \quad (10)$$

Where i_{ia}, i_{ib} and i_{cc} are the currents of the inductors, and *ica, icb* and *icc* are the output currents of the parallel converter.

VI. RESPONSE OF SIMULINK MODEL

The Simulink developed by Math Works, is a data flow graphical programming language tool for modeling, simulating and analyzing multi domain dynamic systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries. It offers tight integration with the rest of the MATLAB environment and can either drive MATLAB or be scripted from it. Simulink is widely used in control theory and digital signal processing for multi domain simulation and Model-Based Design. From the MATLAB model it was possible to build and test UPQC systems and to optimize their performance before implementation on the actual equipment. This allowed faster development and the opportunity to investigate control. For the purpose of controller design, model verification and evaluation were modeled in MATLAB using SIMULINK. Fig 2 shows the MATLAB Simulation of Dual unified power quality conditioner. Having series and shunt active power filters with IGBTs.

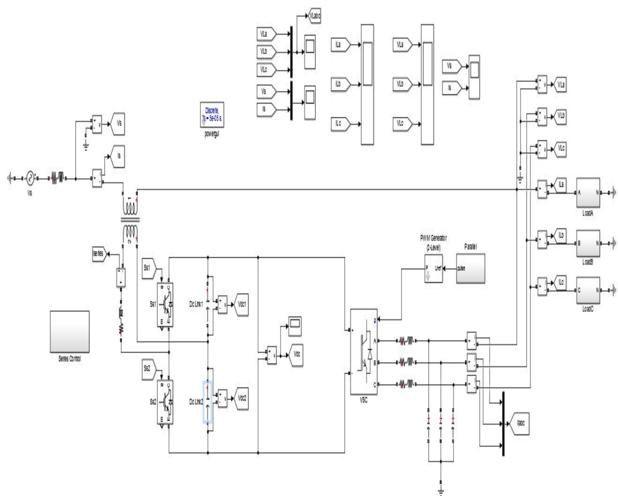


Fig. 3: Simulation of Dual UPQC

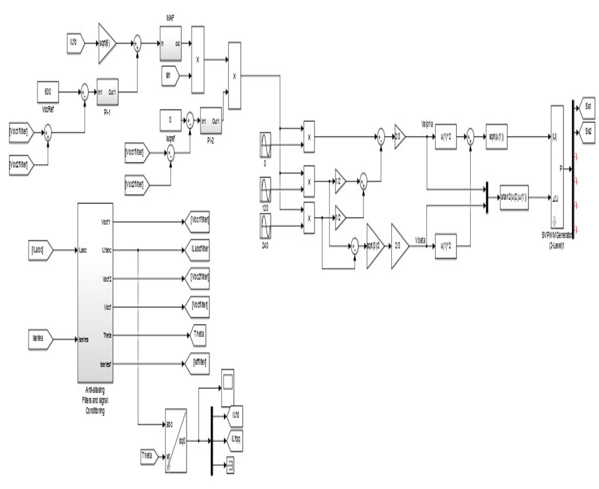


Fig. 4: Series PWM inverter

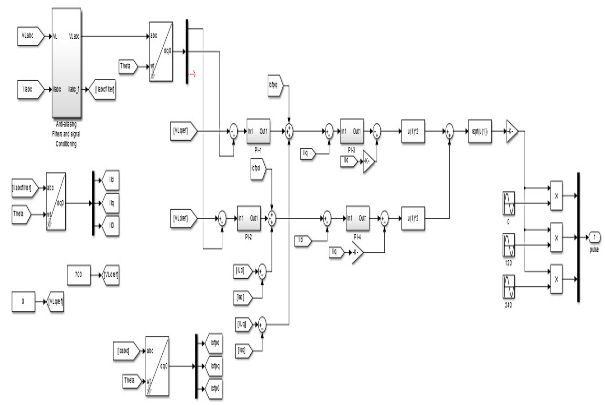


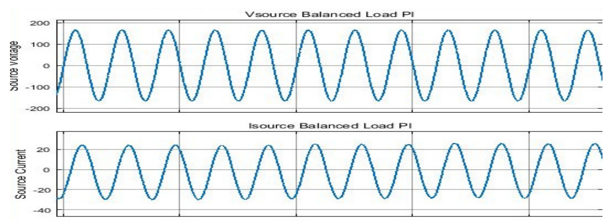
Fig. 5: Parallel PWM inverter

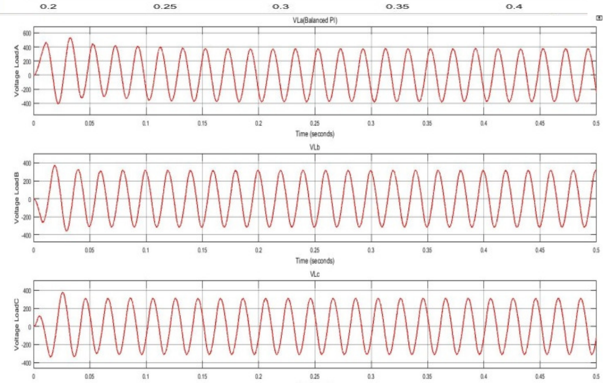
VII. SIMULATON RESULTS

The model is simulated using MATLAB. The simulation result of the system is shown in figures below:

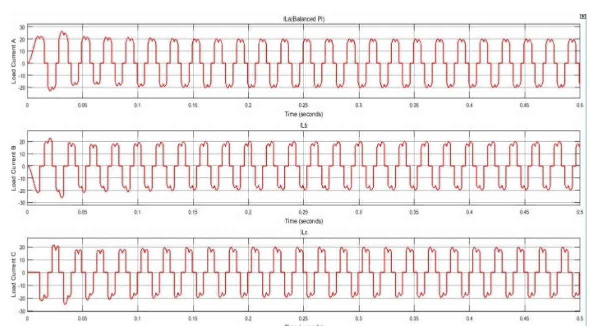
C. *During Balanced Load Condition (PI Controller)*

(a) Source voltage (b) Source Current



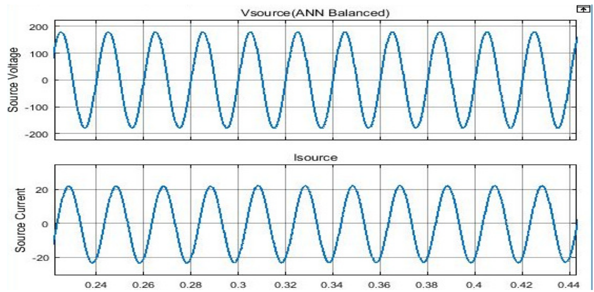


(a) Load voltages

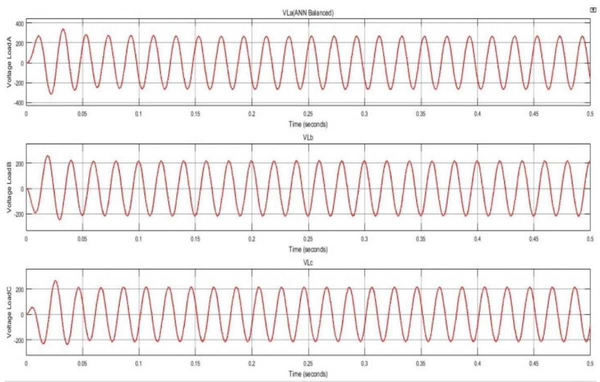


(a) Load currents

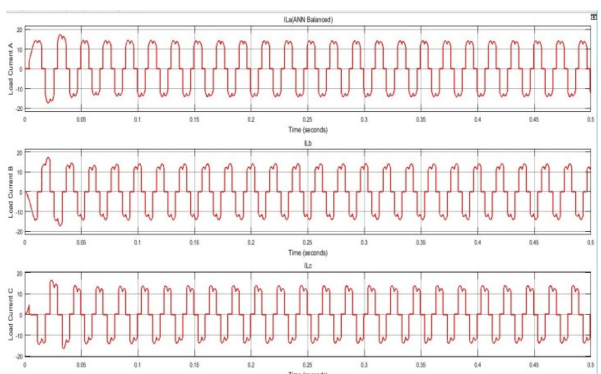
D. During Balanced Load Condition (ANN Controller)



(a) Source voltage (b) Source Current



(a) Load voltage



(a) Load Current

VIII. CONCLUSIONS

This project aims the Mat Lab based implementation of UPQC, which can be used in three-phase three-wire (3P3W), as well as three-phase four-wire (3P4W) distribution systems. An UPQC is able to protect the distribution system from various disturbances like voltage variations, transients, distortions and harmonics at the load at DC-link voltage by using Synchronous reference frame (SRF) control strategy for series and shunt converters. This method is validated through MATLAB simulation. Recent rapid interest in renewable energy generation is imposing new challenges to accommodate these sources into existing transmission/distribution system while keeping the power quality indices within tolerable limits. Thus UPQC improves both voltage- and current-related power quality problems at the same time. The recommended Dual unified power quality was able to satisfy the nonlinear load currents and also ensure the sinusoidal voltage for the load in all three phases. The control also had a great performance during the load steps and voltage disturbances at the source. The main benefit of the proposed control in relation to other expected schemes were the utilization of sinusoidal references for both series and shunt active filter controls without the need for complex calculations or coordinate transformations. It minimizes the total harmonic content in load voltages to maintain the power quality. THD's are lesser in the implemented ANN controller compared to strategies without UPQC and with UPQC using PI controller.

TABLE I
THD of Source Current during Balanced Load

Source Current	Without UPQC (%)	With UPQC	
		PI(%)	ANN(%)
I_s	28.56	5.64	0.14

TABLE III
THD of Source Current during Unbalanced Load

Source Current	Without UPQC (%)	With UPQC	
		PI(%)	ANN(%)
I_s	28.56	5.58	0.22

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