An Improved UPQC Controller to Provide Grid-Voltage Regulation

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ABSTRACT

In this paper presents an improved controller for the dual topology of the Unified Power Quality Conditioner (UPQC) extending its capability in power quality compensation, as well as in micro-grid applications. By the use of this controller, beyond the conventional UPQC power quality features including voltage sag/swell compensation, the iUPQC will also compensate reactive power support to regulate not only the load-bus voltage, but also the voltage at the grid-side bus. We can say, the iUPQC will work as a STATCOM at the grid side, while providing also the conventional UPQC compensations at the load terminal or micro-grid side. Experimental results are provided to verify the new functionality of the equipment.

KEYWORDS: *UPQC, Micro-grid, Power quality, STATCOM, Unified Power Quality Conditioner*

I. Introduction

Certainly, the devices which are used in power-electronics have brought about great technological improvements. However, the increasing number of load which are driven by power-electronic devices generally in the industry has brought about uncommon power quality problems. In contrast, the loads which are driven by power-electronic devices generally require ideal sinusoidal supply voltage for function properly, whereas they are the most responsible ones for abnormal harmonic currents level in the distribution system. In this scenario, the devices can mitigate these drawbacks have been developed over the years. the solutions which is involve in this flexible compensator, known as the Unified Power Quality Conditioner (UPQC) [1] [2] [3] [4] [5] [6] [7] and the Static Synchronous Compensator (STATCOM) [8] [9] [10] [11] [12] [13].In the power circuit of a UPQC consists of a combination of a shunt active filter and a series active filter connected in a back-to-back configuration. This combination allows the simultaneous compensation of the load current and the supply voltage, so that the compensated current drawn from the grid and supply voltage delivered to the load are compensated to keep balanced and sinusoidal. The topology of the Unified Power Quality Conditioner – the iUPQC – was presented in[14] [15] [16] [17] [18] [19],where the shunt active filter behaves as an ac-voltage source and the series one as an ac-current source, both at the fundamental frequency This is a key point to design a better control gains, as well as to optimize the LCL filter of the power converters, which allows improving significantly the overall performance of the compensator [20].

The Static Synchronous Compensator (STATCOM) has been used widely in transmission networks to regulate the voltage with the help of dynamic reactive-power compensation. Nowadays, the STATCOM is largely used for voltage regulation [9], while the UPQC and the iUPQC have been selected as solution for more specific applications [21]. Moreover, these last ones are used only in specific cases, where their relatively high costs are justified by the power quality improvement it can provide, which would be not possible by using conventional solutions. By joining the extra functionality like a STATCOM in the iUPQC device, then the applications of this can be used in wide scenario, particularly in case of distributed generation in smart grids and as the coupling device in grid-tied micro-grid. In [16] the performance of the iUPQC and the UPQC were compared when working as unified power quality conditioners. The main difference between these compensators is the sort of source emulated by the series and shunt power converters. In the UPQC, the series converter is controlled as a non-sinusoidal voltage source and the shunt one as a non-sinusoidal current source. Hence, in practical the UPQC controller has to determine and synthesize accurately the harmonic voltage and current to be compensated. On the another side, in the iUPQC approach the series converter behaves as controlled, sinusoidal, current source and the shunt converter as a controlled, sinusoidal, voltage source. This means that it is not necessary to find out the harmonic voltage and current to be compensated, since the harmonic voltages develop naturally across the series current source and the harmonic currents flow naturally into the shunt voltage source.

In the power converters devices, as the switching frequency has been increasing, the power rate capability is reduced. Therefore, the iUPQC offers better solutions if compare with the UPQC in case of high-power applications, since the iUPQC compensating references are pure sinusoidal waveform at the fundamental frequency. Moreover, the UPQC has higher switching losses due its higher switching frequency.

In this paper proposes an improved controller which expands the iUPQC functionalities. This modified version of iUPQC controller includes all functionalities of those previous ones, including the voltage regulation at the load-side bus, and also providing voltage regulation at the grid-side bus, like a STATCOM to the grid. Experimental results are provided to validate the new controller design. Paper has been prepared in five sections. After this introduction, in section I, the iUPQC applicability is explained as well as the novel feature of the proposed controller. Section III presents the proposed controller and an analysis of the power flow in steady state. Finally, section IV provides the experimental results and section V the conclusions.

II. Equipment Applicability

In order to clarify the applicability of improved iUPQC controller, Fig. 1 depicts an electrical system with two buses in spotlight bus A and bus B. Bus A is critical bus of the power system that supplies sensitive loads and serves as point of coupling of a micro-grid. Bus B is a bus of the micro-grid where non-linear loads are connected, which requires premium-quality power supply. The voltages at bus A and bus B must be regulated in order to supply properly the sensitive loads and the non-linear loads. The effects caused by the harmonic currents drawn by the non-linear loads should be mitigated, avoiding harmonic voltage propagation to bus A.

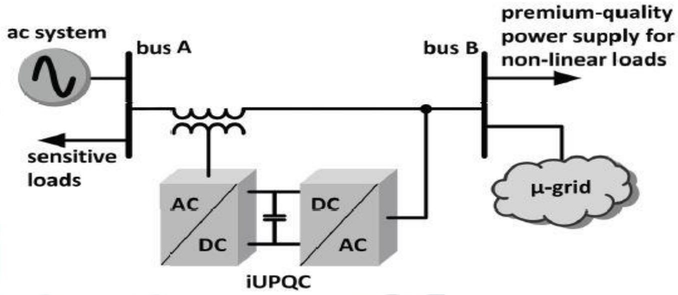

Figure 1 Example of applicability of iUPQC

The use of a STATCOM to guarantee the voltage regulation at bus A is not enough, because the harmonic currents drawn by the non-linear loads are not mitigated. On the other hand, a UPQC or an iUPQC between bus A and bus B can compensate the harmonic currents of the non-linear loads and compensate the voltage at bus B, in terms of voltage harmonics, unbalance and sag/swell. Nevertheless, this is still not enough to guarantee the voltage regulation at bus A. Hence, to achieve all the desired goals, a STATCOM at bus A and a UPQC (or an iUPQC) between bus A and B should be employed. However, the costs of this solution would be unreasonably high. An attractive solution would be the use of a modified iUPQC controller to provide also reactive power support to the bus A, beside all those functionalities of this equipment, as presented in [16] and [18]. Note that the modified iUPQC serves as an intertie between buses A and B. Moreover, the micro-grid connected to the bus B could be a complex system comprising distributed generation, energy management system and other control systems involving micro-grid, as well as smart grid concepts [22].In summary, the modified iUPQC can provide the following functionalities.

- "Smart" circuit breaker as an intertie between the grid and the micro-grid.
- Energy and power flow control between the grid and the micro-grid (imposed by a tertiary control layer for the micro-grid).
- Reactive power support at bus A of the power system.
- Voltage/frequency support at bus B of the micro-grid.

- Harmonic voltage and current isolation between bus A and bus B (simultaneous grid- voltage and load-current active-filtering capability).
- Voltage and current imbalance compensation.

The functionalities (d) to (f) listed above were extensively explained and verified through simulations and experimental analysis [14] [15] [16] [17] [1 8], whereas the functionality (c) comprises the original contribution of the present work. Fig. 2 depicts in details the connections and measurements of the iUPQC between bus A and bus B.

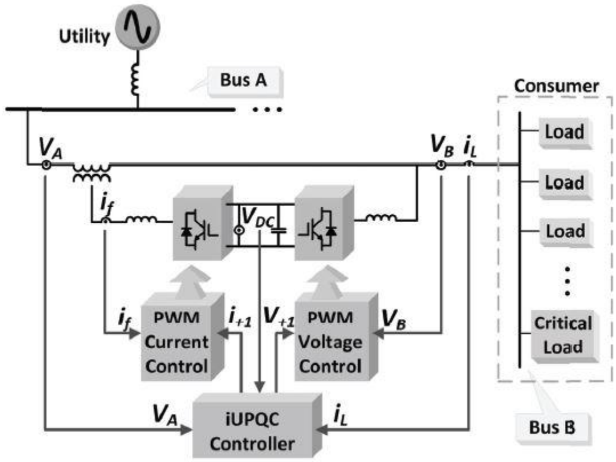

Figure 2 A modified iUPQC configuration

According to the standard iUPQC controller, the shunt converter imposes a controlled, sinusoidal voltage at bus B, which corresponds to the preceding functionality (d). As a result, the shunt converter has no further degree of freedom in terms of compensating active- or reactive-power variables to expand its functionality. On the other hand, the series converter of a conventional iUPQC uses only an active-power control variable, p in order to synthesize a fundamental, sinusoidal current drawn from the bus A, corresponding to the active power demanded by bus B. If the dc ink of the iUPQC has no large energy storage system or even no energy source, the control variable ̄also serves as an additional active-power reference to the series converter to keep the energy inside the dc link of the iUPQC balanced. In this case, the losses in the iUPQC and the active power supplied by the shunt converter must be quickly compensated in the form of an additional active power injected by the series converter into the bus B. The iUPQC can serve as (a) “smart” circuit breaker and as (b) Power flow controller between the grid and the micro-grid only if the compensating active- and reactive-power references of the series converter can be set arbitrarily. In this case, it is necessary to provide an energy source (or large energy storage) associated to the dc link of the iUPQC. The last degree of freedom is represented by a reactive-power control variable, q, for the series converter of the iUPQC. During this method, the iUPQC will provide reactive-power compensation like a STATCOM to the bus A of the grid. As it will be confirmed, this functionality can be added into the controller without degrading all other functionalities of the iUPQC.

III. Improved Iupqc Controller

Fig. 2 depicts the iUPQC hardware and the measured units of a three-phase three-wire system that are used in the controller. Fig. 3 shows the proposed controller. The controller inputs are the voltages at bus A and B, the current demanded by bus B, the current demanded by bus B, i_L and the voltage v_{DC} of the common dc link. The outputs are the shunt-voltage reference and the series -current reference to the PWM controllers. The voltage and current PWM controllers can be as simple as those employed in [18], or be improved further to better deal with voltage and current imbalance and harmonics [23] [24] [25]. Firstly, the simplified Clark transformation is applied to the measured variables. As example of this transformation, the grid voltage in α β-reference frame can be calculated as:

$$\begin{bmatrix} V_{A\_\alpha} \\ V_{A\_\beta} \end{bmatrix} = \begin{bmatrix} 1 & 1/2 \\ 0 & \sqrt{3}/_2 \end{bmatrix} \begin{bmatrix} V_{A\_ab} \\ V_{A\_bc} \end{bmatrix} \quad (1)$$

The shunt converter imposes the voltage at bus B. Thus, it is necessary to synthesize sinusoidal voltages with nominal amplitude and frequency. Consequently, the signals sent to the PWM controller are the Phase-Locked-Loop (PLL) outputs with amplitude equal to 1 pu. There are many possible PLL algorithms which could be used in this case, as verified. In the original iUPQC approach as presented in [14], the shunt-converter voltage reference can be either the PLL outputs or the fundamental positive-sequence component V_{A+1} of the grid voltage (bus A in Fig. 2).The use of V_{A+1} in the controller is useful to minimize the circulating power through the series and shunt converters, under normal operation, while the amplitude of the grid voltage is within an acceptable range of magnitude. However, this is not the case here, in the modified iUPQC controller, since now the grid voltage will be also regulated by the modified iUPQC. In other words, both buses will be regulated independently to track their reference values. The series converter synthesizes the current drawn from the grid bus (bus A). In the original approach of iUPQC, this current is calculated through the average active power required by the loads, P_L plus the power P_{LOSS}. The load active power can be estimated by:

$$P_L = V_{+1\_\alpha} \cdot i_{L\_\alpha} + V_{+1\_\beta} \cdot i_{L\_\beta} \quad (2)$$

Where i_{L_α}, i_{L_β} are the load currents, and V_{+1_α}, V_{+1_β} are the voltage references for the shunt converter. A low pass filter is used to obtain the average active power (P_L). The losses in the power converters and the circulating power to provide energy balance inside the iUPQC are calculated indirectly from the measurement of the dc-link voltage. In other words, the power signal P_{LOSS} is determined by a proportional-integral controller (PI block in Fig. 3), by comparing the measured dc voltage, V_{DC}, with its reference value. The additional control loop to provide voltage regulation like a STATCOM at the grid bus is represented by the control signal in Fig. 3. This control signal is obtained through a PI controller, in which the input variable is the error between the reference value and the actual aggregate voltage of the grid bus, given by:

$$V_{col} = \sqrt{(V_{A+1\_\alpha}^2 + V_{A+1\_\beta}^2)} \quad (3)$$

The sum of the power signals P_L and P_{LOSS} composes the active-power control variable for the series converter of the iUPQC. P described in section II. Likewise, $Q_{STATCOM}$ is the reactive power control variable q. Thus, the current references i_{L_α} and i_{L_β} of the series converter are determined by:

$$\begin{bmatrix} i_{+1\_\alpha} \\ i_{+1\_\beta} \end{bmatrix} = \frac{1}{V_{A\_\alpha}{}^2 + V_{A\_\beta}{}^2} \begin{bmatrix} V_{A+1\_\alpha} & V_{A+1\_\beta} \\ V_{A+1\_\beta} & -V_{A+1\_\alpha} \end{bmatrix} \begin{bmatrix} P_L + P_{LOSS} \\ Q_{STATCOM} \end{bmatrix}$$

(4)

The following procedure, based on the average power flow, is useful for estimating the power ratings of the iUPQC converters. For combined series-shunt power conditioners, as the UPQC and the iUPQC, only the voltage sag /swell disturbance and the power factor compensation of the load produce a circulating average power through the power conditioners [34], [35].According to Fig. 4, the compensation of a voltage sag/swell disturbance at bus B causes a positive-sequence voltage at the coupling-transformer the ($V_{series} \neq 0$). Since $V_A \neq V_B$. Moreover V_{series} and i_{P_B} in the coupling transformer leads to circulating active power, P_{inner} , in the iUPQC. Additionally, the compensation factor increase the current supplied by the shunt converter. The following analysis is valid for an iUPQC acting like a conventional UPQC or including the extra-compensation like a STATCOM. Firstly, the circulating power will be calculated when the iUPQC is operating just like a conventional UPQC. Afterward, the equations will include the STATCOM functionality to the grid bus A. In both cases, it will be assumed that the iUPQC controller is able to force the shunt converter of the iUPQC to generate fundamental voltage always in phase with the grid voltage at bus A. For simplicity, the losses in the iUPQC will be neglected.

For the first case, the following average powers in steady state can be determined.

$$S_A = P_B \quad (5)$$

$$Q_{shunt} = -Q_B \quad (6)$$

$$Q_{series} = Q_A = 0 \text{ var} \quad (7)$$

$$P_{series} = P_{shunt} \quad (8)$$

Where S_A and Q_A are the apparent and reactive power injected in the bus A; P_B and Q_B are the active and reactive power injected to bus B. P_{shunt} and Q_{shunt} are the active and reactive power drained by the shunt converter. P_{series} And Q_{series} are the active and reactive power supplied by the series converter. Equations (5) and (6) are derived from the constraint of keeping unitary the power factor at bus A.

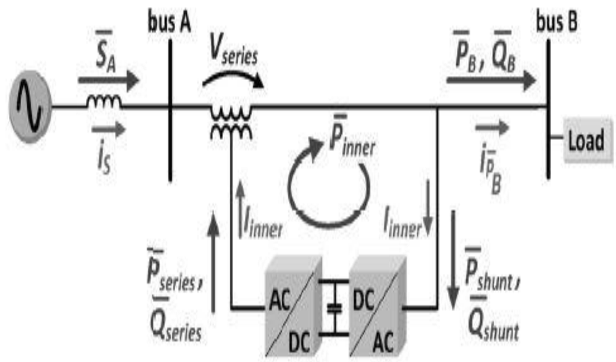

Figure 3 iUPQC Power flow in steady-state

In this case, the current passing through the series converter is responsible only for supplying the load active power, that is, it is in phase (or counter-phase) with the voltages V_A and V_B. Thus, (7) can be stated. Consequently, the coherence of the power flow is ensured through (8). If a voltage sag or swell occurs P_{series} and P_{shunt}, be zero, and thus an inner-loop current (I_{inner}) will appear. The series and shunt converters and circulating active power (P_{inner}) flows inside the equipment. It is convenient to define the following sag/swell considering V_N as the nominal voltage,

$$k_{sag\,/swell} = \frac{VA}{V_N} \quad (9)$$

From (5) and considering that the voltage at bus B is kept regulated, $V_B = V_N$, it follows that

$$\sqrt{3}.k_{sag\,/swell}.V_N.i_s = \sqrt{3}.V_N.i_{P_B}$$

$$i_s = \frac{i_{P_B}}{k_{sag\,/swell}} = i_{P_B} + I_{inner} \quad (10)$$

$$I_{inner} = i_{P_B}\left(\frac{1}{k_{sag/swell}} - 1\right) \quad (11)$$

The circulating power is given by,

$$P_{inner} = P_{series} = P_{shunt} = 3(V_B - V_A)\,(i_{P_B} + I_{inner}) \quad (12)$$

From (11) and (12) it follows that

$$P_{inner} = 3(V_A - V_N)\left(\frac{P_B}{3V_N}\frac{1}{k_{sag/swell}}\right) \quad (13)$$

$$P_{inner} = P_{series} = P_{shunt} = \frac{1-k_{sag/swell}}{k_{sag/swell}}P_B \quad (14)$$

Thus, (14) demonstrates that P_{inner} depends on the active power of the load and the sag/swell voltage disturbance. In order to verify the effect on the power rate of the series and shunt converters, a full load system $S_B = \sqrt{(P_B^2 + Q_B^2)} = 1$pu with power factor ranging from 0 to 1 was considered the sag/swell voltage disturbance at bus A ranging $k_{sag/swell}$ from 0.5 to 1.5.In this way, the power rating of the series and shunt converter are obtained through (6), (7), (8), and (14). Fig. 5 depicts the apparent power of the series and shunt power converters. In these figures, the axis and the power factor (PF) axis are used to evaluate the power flow in the series and shunt power converters according to the sag/swell voltage disturbance and the load power consumption, respectively. The power flow in the series converter indicates that a high power is required in case of sag voltage disturbance with high active power load consumption. In this situation, an increased P_{inner} arises and high rated power converters are necessary to ensure the disturbance compensation. Moreover, in case of compensating sag/swell voltage disturbance with high reactive power load consumption, only the shunt converter has high power demand, since P_{inner} decreases. It is important to highlight that, for each PF value, the amplitude of the apparent power is the same for capacitive or inductive loads. In other words, Fig. 5 is the same for Q_B capacitive or inductive. If the iUPQC performs all original UPQC functionalities together with the STATCOM functionality, the voltage at bus A is also regulated with the same phase and magnitude, that is, $V_A = V_B = V_N$ and then the positive sequence of the at the coupling transformer is zero ($V_{series} = 0$) Thus, in steady state the power flow is determined by,

$$S_A = P_B + jQ_{STATCOM} \quad (15)$$

$$Q_{STATCOM} + Q_{series} = Q_{shunt} + Q_B \quad (16)$$

$$Q_{series} = 0 \text{ var} \quad (17)$$

$$P_{series} = P_{inner} = 0\text{W} \quad (18)$$

Where $Q_{STATCOM}$ is the reactive power that provides voltage regulation at bus A. Ideally, the STATCOM functionality mitigates the inner-loop active power flow (P_{inner}) and the power flow in the series converter is zero. Consequently, if the series converter is properly designed along with the coupling transformer to synthesize the controlled currents I_{+1_α} and I_{+1_β}, as shown in Fig. 3, then a lower power converter can be employed. Contrarily, the shunt converter still has to provide the full reactive power of the load and also to drain the reactive power injected by the series converter to regulate the voltage at bus A.

IV. Experimental Results

The improved iUPQC controller as shown in Fig. 3 was verified in a 5 kVA prototype, In order to verify all the power quality issues described in this paper, the iUPQC was connected to a grid with a voltage sag system, as depicted in Fig. 6. The voltage sag system was composed by an inductor (L_S), a resistor (R_{SAG}) and a breaker (S_{SAG}). To cause a voltage sag at bus A, S_{SAG} is closed.

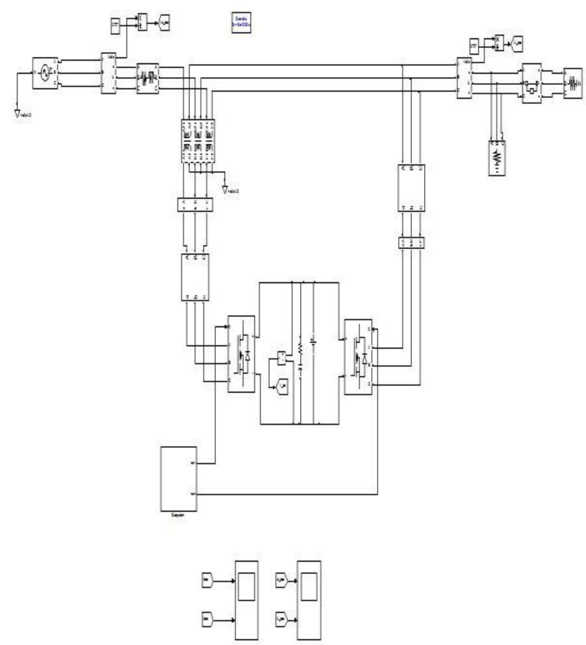

Figure 4 Simulation Model

At first, the source voltage regulation was tested with no load connected to bus B. In this case, the iUPQC behaves as a STATCOM and the breaker S_{SAG} is closed to cause the voltage sag. To verify the grid voltage regulation, the control of the $Q_{STATCOM}$ variable is enabled to compose the equation (4) at instant t = 0s.In this experimental case $L_S = 10mH$, and R_{SAG} =7.5Ω.Before the $Q_{STATCOM}$ variable is enable, only the dc link and the voltage at bus B are regulated, and there is 7.5. Before the $Q_{STATCOM}$ variable is enabled, only the dc link and voltage at bus B are regulated, and there is voltage sag at bus A, as shown in Fig8. After t = 0s, the iUPQC start to draw reactive power from bus A, increasing the voltage value until the reference value. As can be seen in Fig8, the load voltage at bus B is maintained regulated during all the time, and the grid- voltage regulation of bus A has a fast response. Next experimental case was carried out to verify the iUPQC performance during the connection of non-linear load with the iUPQC already in operation. The load is three phase diode rectifier with a series RL load at the dc link (R = 45Ω and L = 22mH) and the circuit breaker is S_{SAG} is permanently closed, with aL_s = 10mH and a R_{SAG} = 15Ω. In this way, the voltage sag disturbance is increased due to the load connection. In this Fig7 is possible to verify that the iUPQC is able to regulate the voltage at both side of the iUPQC can perform all power quality compensation as mentioned before, including the grid voltage regulation. It is important to highlight that the grid voltage regulation is also achieved by means of the improved iUPQC controller as introduced in section III. Finally the same procedure was performed with the connection of a two phase diode rectifier in order to better verify the mitigation of power quality issues. The diode rectifier has the same cd load(R = 45Ω and L = 22mH) and the same voltage sag (L_s = 10mH and a R_{SAG} = 15Ω).Fig 9 depicts the transitory response of the load connection. Despite the two phase load current, after the load connection at t = 0s, the three phase current drained from the grid has a reduced unbalanced component. Likewise, the unbalance in the voltage at bus A is negligible. Unfortunately, the voltage at bus B has higher unbalance content. These components could be mitigated if the shunt compensator works as an ideal voltage source. i.e. if the filter inductor could be eliminated. In this case the unbalanced current of the load could be supplied by the shunt converter and the voltage at the bus B could be exactly the voltage synthesized by the shunt converter. Therefore, without filter inductor there would be no unbalance voltage drop in it and the voltage at bus B would remain balanced. However, in a practical case, this inductor cannot be eliminated, and an improved PWM control to compensate voltage unbalances, as mentioned in section III, is necessary.

V. Conclusion

Here the Fig 5 and Fig 6 shows the simulation result of UPQC when PI controller and ANN controller are used respectively. The output waveform of load voltage in Fig. 6 is more sinusoidal and less harmonics in output.

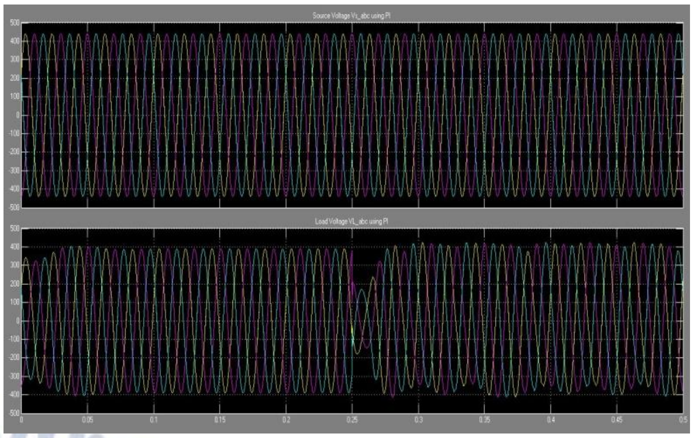

Figure 5 Source & Load Voltage without load using PI controller

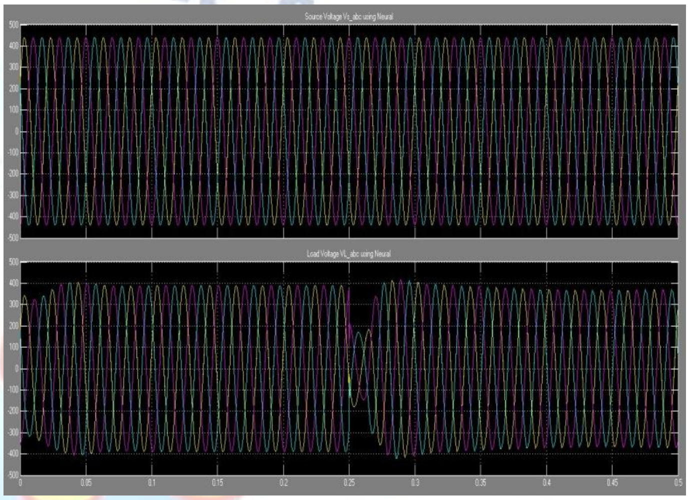

Figure 6 Source & Load Voltage without load using NN controller

Here we connect the load with UPQC by closing the circuit breaker and Fig 7 and Fig 8 shows the simulation result of UPQC when PI controller and ANN controller are used respectively. In Fig 7 the load voltage contain more harmonics compare to the Fig 8 load voltage waveform. So concluded that by using the ANN controller in UPQC can be reduced the harmonics compare to the PI controller.

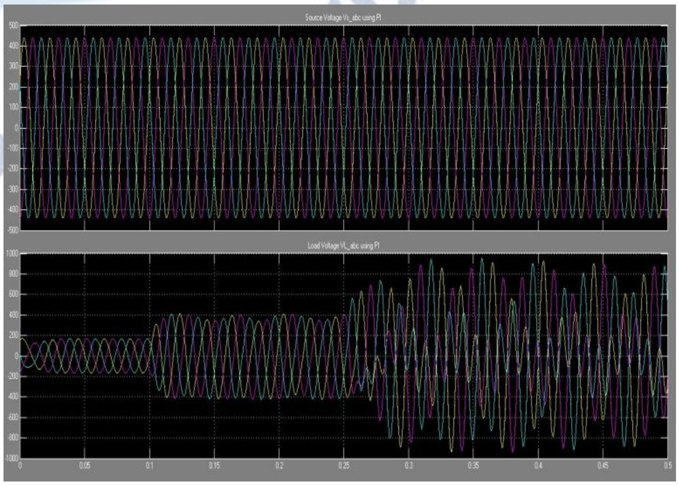

Figure 7 Source and Load Voltage with load using PI controller

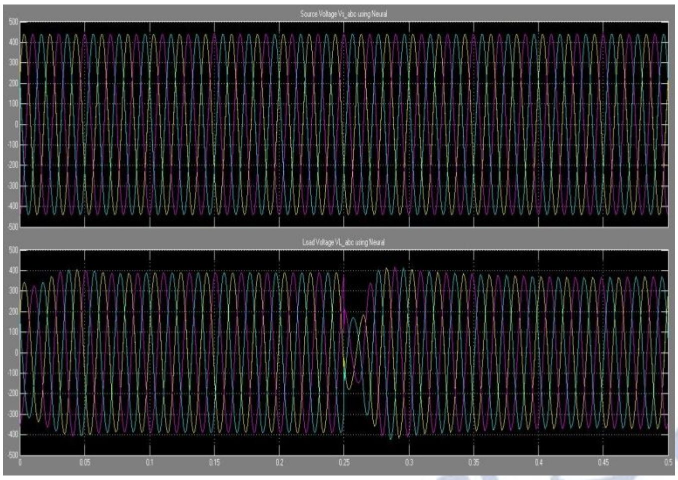

Figure 8 Source and Load Voltage with load using NN controller

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