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A Modified Three-Phase Four-Wire UPQC Topology with Reduced DC-Link Voltage Rating

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Abstract: This paper introduces a new concept of optimal utilization of a unified power quality conditioner (UPQC). The series inverter of UPQC is controlled to perform simultaneous 1) voltage sag/swell compensation and 2) load reactive power sharing with the shunt inverter. The active power control approach is used to compensate voltage sag/swell and is integrated with theory of power angle control (PAC) of UPQC to coordinate the load reactive power between the two inverters. Since the series inverter simultaneously delivers active and reactive powers, this concept is named as UPQC. A detailed mathematical analysis, to extend the PAC approach for UPQC, is presented in this paper. MATLAB/SIMULINK-based simulation results are discussed to support the developed concept. Finally, the proposed concept is validated with a digital signal processor-based experimental study

Keywords: Active power filter (APF), power angle control (PAC), power quality, reactive power compensation, unified power quality conditioner (UPQC), voltage sag and swell compensation

I. INTRODUCTION

With the advent of power semiconductor switching devices, like thyristors, GTO's (Gate Turn off thyristors), IGBT's (Insulated Gate Bipolar Transistors) and many more devices, control of electric power has become a reality. Such power electronic controllers are widely used to feed electric power to electrical loads, such as adjustable speed drives (ASD's), furnaces, computer power supplies, HVDC systems etc[1]-[5].The power electronic devices due to their inherent non-linearity draw harmonic and reactive power from the supply. In three phase systems, they could also cause unbalance and draw excessive neutral currents. The injected harmonics, reactive power burden, unbalance, and excessive neutral currents cause low system efficiency and poor power factor. In addition to this, the power system is subjected to various transients like voltage sags, swells, flickers etc. These transients would affect the voltage at distribution levels. Excessive reactive power of loads would increase the generating capacity of generating stations and increase the transmission losses in lines. Hence supply of reactive power at the load ends becomes essential. Power Quality (PQ) has become an important issue since many loads at various distribution ends like adjustable speed drives, process industries, printers, domestic utilities, computers, microprocessor based equipments etc. have become intolerant to voltage fluctuations, harmonic content and interruptions In this paper, a UPQC topology with reduced dc-link voltage is proposed. The topology consists of capacitor in series with the interfacing inductor of the shunt active filter. The series capacitor enables reduction in dc-link voltage requirement of the shunt active filter and simultaneously[7] compensating the reactive power required by the load, so as to maintain unity power factor, without compromising its performance. This allows us to match the dc-link voltage requirements of the series and shunt active filters with a common dc-link capacitor. Further ,in this topology, the system neutral is connected to the negative terminal of the dc bus[5]. This will avoid the requirement of the fourth leg in VSI of the shunt active filter and enables independent control of each leg of the shunt VSI with single dc capacitor. The simulation studies are carried out using PSCAD simulator, and detailed results are presented in the paper. A prototype of three-phase UPQC is developed in the laboratory to verify the proposed concept, and the detailed results are presented in this paper.

II. LITERATURE SURVEY

The voltage injected in series with the load by series APF is made to follow a control law such that the sum of this injected voltage and the input voltage is sinusoidal[12]. Thus, if utility voltages are non-sinusoidal or unbalanced, due to the presence of other clients on the same grid, proper selection of magnitude and phase for the injected voltages will make the voltages at load end to be balanced and sinusoidal. The shunt APF acts as a current source and inject a compensating harmonic current in order to have sinusoidal, in-phase input current and the series APF acts as a voltage source and inject a compensating voltage in order to have sinusoidal load voltage[14]. The developments in the digital electronics, communications and in process control system have increased the number of sensitive loads that require ideal sinusoidal supply voltage for their proper operation. In order to meet limits proposed by standards it is necessary to include some sort of compensation. In the last few years, solutions based on combination of series active and shunt active filter have appeared. Its main purpose is to compensate for supply

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voltage and load current imperfections, such as sags, swells, interruptions, imbalance, flicker, voltage imbalance, harmonics, reactive currents, and current unbalance [10-15]. This combination of series and shunt APF is called as Unified Power Quality Conditioner (UPQC). In most of the articles control techniques suggested are complex requiring different kinds of transformations. The control technique presented here is very simple and does not require any transformation.

III. GENERALIZED THEORY OF ACTIVE POWER FILTER

In this scheme, each node with message searches for possible path nodes to copy its message. Hence, possible path nodes of a node are considered. Using NSS, each node having message selects its path nodes to provide a sufficient level of end-to-end latency while examining its transmission effort. Here, it derives the CSS measure to permit CR-Networks nodes to decide which licensed channels should be used. The aim of CSS is to maximize spectrum utilization with minimum interference to primary system. Assume that there are M licensed channels with different bandwidth values and y denotes the bandwidth of channel c. Each CR-Networks node is also assumed to periodically sense a set of M licensed channels. Mi denotes the set including Ids of licensed channels that are periodically sensed by node i. suppose that channel c is periodically sensed by node i in each slot and channel c is idle during the time interval x called channel idle duration[10]. Here, it use the product of channel bandwidth y and the channel idle duration x, tc = xy, as a metric to examine the channel idleness. Furthermore, failures in the sensing of primary users are assumed to cause the collisions among the transmissions of primary users and CR-Networks nodes. The various nonlinear loads like Adjustable Speed Drives (ASD's), bulk rectifiers, furnaces, computer supplies, etc. draw non sinusoidal currents containing harmonics from the supply which in turn causes voltage harmonics. Harmonic currents cause increased power system losses, excessive heating in rotating machinery, interference with nearby communication circuits and control circuits etc. It has become imperative to maintain the sinusoidal nature of voltage and currents in the power system. Various international agencies like IEEE and IEC have issued standards, which put limits on various current and voltage harmonics. The limits for various current and voltage harmonics specified by IEEE-519 for various frequencies are given in Table1.

Table 1.IEEE 519 Voltage Limits

Bus Voltage	Minimum Individual Harmonic Components (%)	Maximum THD (%)
69 kV and below	3	5
115 kV to 161 kV	1.5	2.5
Above 161 kV	1	1.5

A. *Classifications of Active Power Filters*

Current Source Inverter (CSI) Active Power Filter (Fig 1) and Voltage Source Inverter Active Power Filter (VSI) (Fig.2) are two classifications in this category. Current Source Inverter behaves as a non-sinusoidal current source to meet the harmonic current requirement of the nonlinear loads. A diode is used in series with the self-commutating device (IGBT) for reverse voltage blocking. However, GTO-based configurations do not need the series diode, but they have restricted frequency of switching[8]. They are considered sufficiently reliable, but have higher losses and require higher values of parallel ac power capacitors. Moreover, they cannot be used in multilevel or multistep modes to improve performance in higher ratings.The other converter used as an AF is a voltage-fed PWM inverter structure, as shown in Fig.2. It has a self-supporting dc voltage bus with a large dc capacitor. It has become more dominant, since it is lighter, cheaper, and expandable to multilevel and multistep versions, to enhance the performance with lower switching frequencies. It is more popular in UPS-based applications, because in the presence of mains, the same Inverter bridge can be used as an AF to eliminate harmonics of critical nonlinear loads.

AF's can be classified based on the topology used as series or shunt filters, and unified power quality conditioners use a combination of both. Combinations of active series and passive shunt filtering are known as hybrid filters[15]. Fig 3 is an example of an active shunt filter, which is most widely used to eliminate current harmonics, reactive power compensation (also known as STATCOM), and balancing unbalanced currents.

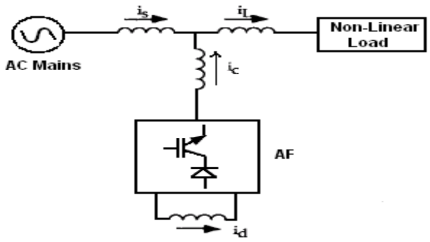

Fig .1 Current fed type AF

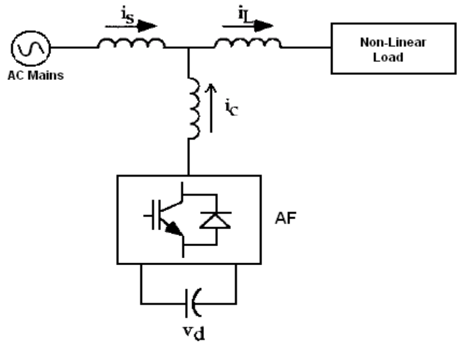

Fig .2 Voltage fed type AF

It is mainly used at the load end, because current harmonics are injected by nonlinear loads. It injects equal compensating currents, opposite in phase, to cancel harmonics and/or reactive components of the nonlinear load current at the point of connection. It can also be used as a static VAR generator (STATCON) in the power

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system network for stabilizing and improving the voltage profile. Fig .4 shows the basic block of a stand-alone active series filter. It is connected before the load in series with the mains, using a matching transformer, to eliminate voltage harmonics, and to balance and regulate the terminal voltage of the load or line. It has been used to reduce negative-sequence voltage and regulate the voltage on three-phase systems. It can be installed by electric utilities to compensate voltage harmonics and to damp out harmonic propagation caused by resonance with line impedances and passive shunt compensators. Fig .5 shows the hybrid filter, which is a combination of an active series filter and passive shunt filter. It is quite popular because the solid-state devices used in the active series part can be of reduced size and cost (about 5% of the load size) and a major part of the hybrid filter is made of the passive shunt L–C filter used to eliminate lower order harmonics. It has the capability of reducing voltage and current harmonics at a reasonable cost.

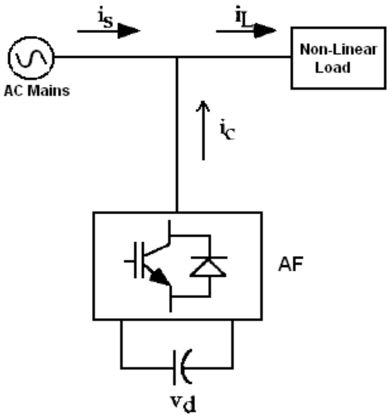


Fig .3 Shunt-type AF

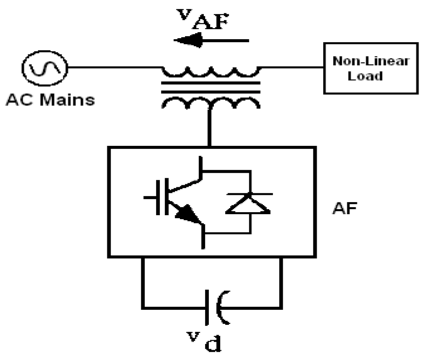


Fig .4 Series-type AF

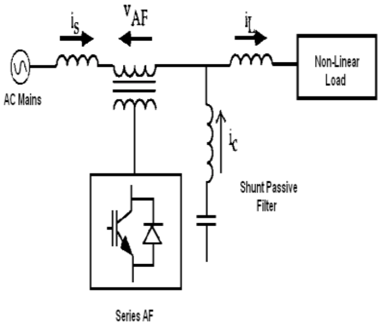


Fig .5 Hybrid filter

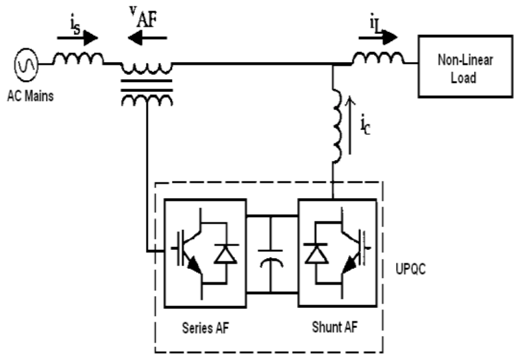


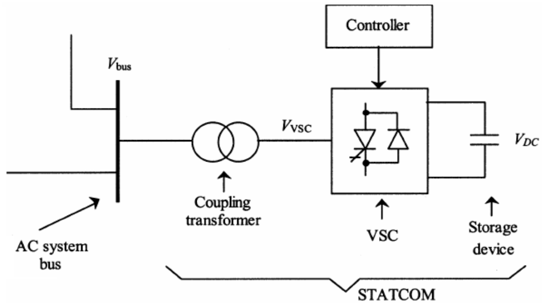
Fig .6 Unified Power Quality Conditioner

Fig .6 shows a unified power quality conditioner (also known as a universal AF), which is a combination of active shunt and active series filters. The dc-link storage element (either inductor or dc-bus capacitor) is shared between two current-source or voltage-source bridges operating as active series and active shunt compensators. It is used in single-phase as well as three-phase configurations. It is considered an ideal AF, which eliminates voltage and current harmonics and is capable of giving clean power to critical and harmonic-prone loads, such as computers, medical equipment, etc. It can balance and regulate terminal voltage and eliminate negative-sequence currents. Its main drawbacks are its large cost and control complexity because of the large number of solid-state devices involved.

IV. UNIFIED POWER QUALITY CONDITIONER (UPQC)

A. *Distributed Static Compensator (DSTATCOM)*

The Distributed Static Compensator (DSTATCOM) is a voltage source inverter based static compensator shown in Fig. 4.1 that is used for the correction of bus voltage sags. Connection (shunt) to the distribution network is via a standard power distribution transformer. The DSTATCOM is capable of generating continuously variable inductive or capacitive shunt compensation at a level up its maximum MVA rating. The DSTATCOM continuously checks the line waveform with respect to a reference ac signal, and therefore, it can provide the correct amount of leading or lagging reactive current compensation to reduce the amount of voltage fluctuations.



B. *Dynamic Voltage Restorer (DVR)*

The DVR mitigates voltage sags by injecting a compensating voltage into the power system in synchronous real time. The DVR is a high-speed switching

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power electronic converter that consists of an energy storage system that feeds three independent single-phase pulse width modulated (PWM) inverters. As shown in Fig. 4.2 the energy storage system for the DVR is a dc capacitor bank, which is interfaced to the PWM inverters by using a boost converter (dc to dc). The boost converter regulates the voltage across the dc link capacitor that serves as a common voltage source for the PWM inverters. The three voltage source single-phase PWM inverters (dc to ac) synthesize the appropriate voltage waveform as determined by the DVR's digital control system. This compensating voltage waveform is injected into the power system through three single-phase series injection transformers. The DVR control system compares the input voltage to an adaptive reference signal and injects voltage so that the output voltage remains within specifications.

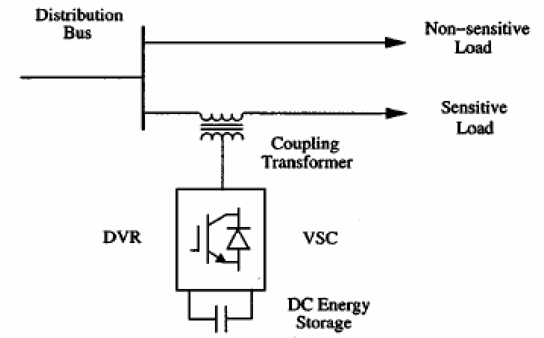

Fig 7. Schematic representation of the DVR

C. *Unified Power Quality Conditioner (UPQC)*

The Unified Power Quality Conditioner (UPQC) is a more complete solution for the power quality problem. The basic structure of this equipment is shown in shown in Fig 4.4. In this figure, the UPQC is an association of a series and shunt active filter based on two converters with common dc link. The series converter has the function to compensate for the harmonic components (Including unbalances) present in the source voltages in such a way that the voltage on the load is sinusoidal and balanced.

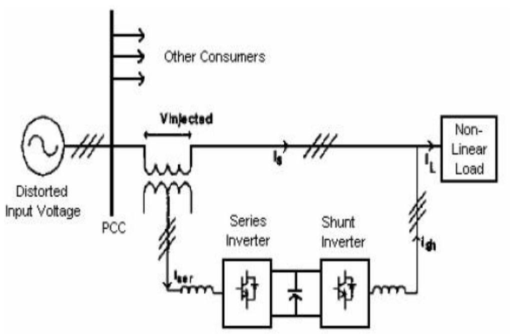

Fig 8 Basic Block Diagram of UPQC

The shunt active filter has the function of eliminating the harmonic components of nonlinear loads in such a way that the source current is sinusoidal and balanced. This equipment is a good solution for the case when the voltage source presents distortion and a harmonic sensitive load is close to a nonlinear load as shown in Fig 4.4.To provide a balance, distortion-free, and constant magnitude power to sensitive load and, at the same time, to restrict the harmonic, unbalance, and reactive power demanded by the load and hence to make the overall power distribution system more healthy, the unified power quality conditioner(UPQC) is one of the best solutions.A unified power quality conditioner (UPQC) is a device that is similar in construction to a unified power flow conditioner (UPFC). The UPQC, like a UPFC, employs two voltage source inverters (VSIs) that are connected to a common dc energy storage capacitor. One of these two VSIs is connected in series with the ac line while the other is connected in the shunt with the same line. A UPFC is employed in a power transmission system to perform shunt and series compensation at the same time. Similarly a UPQC can also perform both the tasks in a power distribution system. A power distribution system, on the other hand, may contain unbalance, distortion and even dc components. Therefore a UPQC must operate under this environment while providing shunt or series compensation. Generally, a 3P4W distribution system is realized by providing a neutral conductor along with three power conductors from generation station or by utilizing a three-phase Δ-Y transformer at distribution level. Fig. 10 shows a 3P4W network in which the neutral conductor is provided from the generating station itself, where Fig. 11 shows a 3P4W distribution network considering, a Δ-Y transformer. Assume a plant site where three-phase three-wire UPQC is already installed to protect a sensitive load and to restrict any entry of distortion from load side toward utility, as shown in Fig..7. If we want to upgrade the system now from 3P3W to 3P4W due to installation of some single-phase loads and if the distribution transformer is close to the plant under consideration, utility would provide the neutral conductor from this transformer without major cost involvement. In certain cases, this may be a costly solution because the distribution transformer may not be situated in close vicinity.

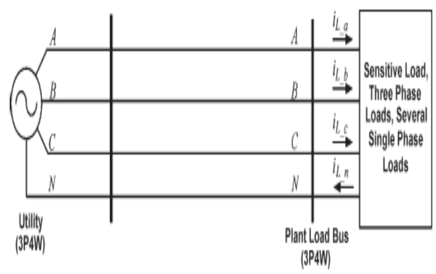

Fig. 9 3P4W distribution system: neutral provided from generation station

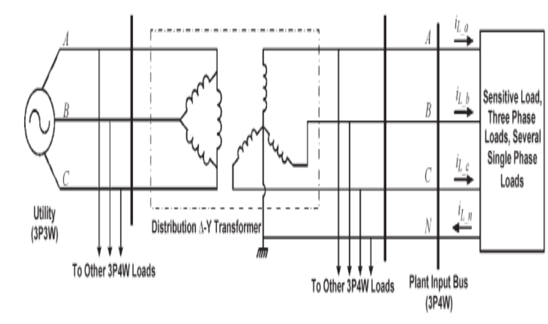

Fig. 10 3P4W distribution system: neutral provided from Δ-Y transformer

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Recently, the utility service providers are putting more and more restrictions on current total harmonic distortion (THD) limits, drawn by nonlinear loads, to control the power distribution systems harmonic pollution. At the same time, the use of sophisticated equipment/load has increased significantly, and it needs clean power for its operation. Therefore, in future distribution systems and plant/load centers, application of UPQC would be common.

The 3P4W topology that can be realized from 3P3W system is shown in the Fig. 10. This system has all the advantages of general UPQC, in addition to easy expansion of 3P3W system to 3P4W system. Thus, this topology may play an important role in the future 3P4W distribution system for more advanced UPQC-based plant/load center installation, where utilities would be having an additional option to realize a 3P4W system just by providing a 3P3W supply.

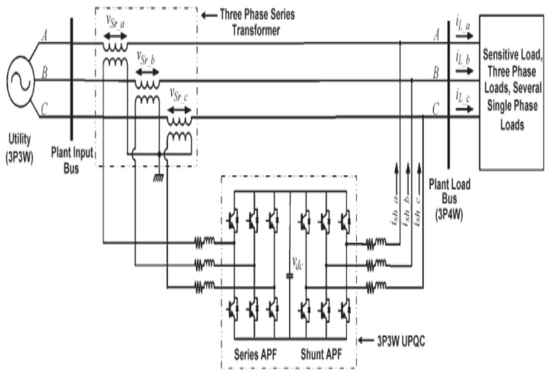

Fig. 11 3P3W UPQC structure

As shown in Fig. 11. the UPQC should necessarily consist of three-phase series transformer in order to connect one of the inverters in the series with the line to function as a controlled voltage source.

If we could use the neutral of three-phase series transformer to connect a neutral wire to realize the 3P4W system, then 3P4W system can easily be achieved from a 3P3W system (Fig.10). The neutral current, present if any, would flow through this fourth wire toward transformer neutral point.

This neutral current can be compensated by using a split capacitor topology or a four-leg voltage-source inverter (VSI) topology for a shunt inverter. The four-leg VSI topology requires one additional leg as compared to the split capacitor because the split capacitor topology essentially needs two capacitors and an extra control loop to maintain a zero voltage error difference between both the capacitor voltages, resulting in a more complex control loop to maintain the dc bus voltage at constant level.

The four-leg VSI topology is considered to compensate the neutral current flowing toward the transformer neutral point. A fourth leg is added on the existing 3P3W UPQC, such that the transformer neutral point will be at neutral point will be at virtual zero potential.

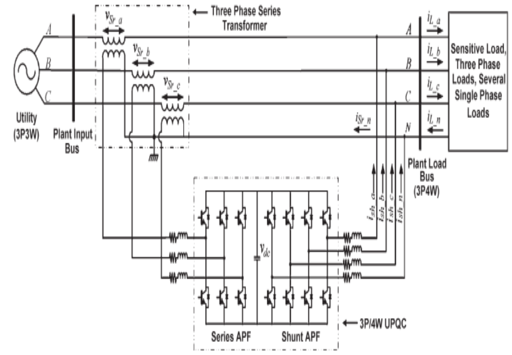

Fig. 12. 3P4W UPQC structure

V. MATLAB/SIMULINK RESULTS

Unified power quality conditioning system (UPQC) consists of three VSCs in which two VSCs are connected in series to the two feeders and one VSC is connected in parallel to load end of the first feeder. These three VSCs connected back to back through a common dc-link capacitor. Each of the VSCs in Fig. 7.5 is realized by a three-phase converter with a commutation reactor and high-pass output filter. The commutation reactor and high-pass output filter are connected to prevent the flow of switching harmonics into the power supply.

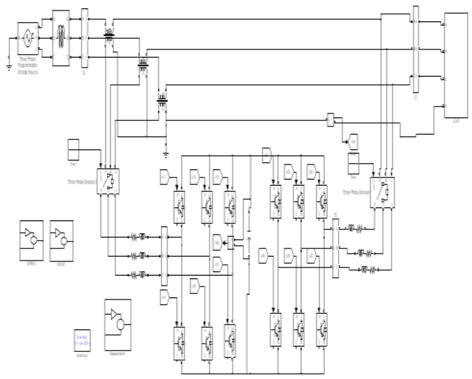

Fig. 12. Simulink block diagram of UPQC

The purpose of UPQC is to regulate the load voltages against voltage sags, voltage swells and disturbances in the in the system and to compensate the reactive and harmonic components of nonlinear load currents.

A. *Implementation of VSCs*

The structure of VSC is shown in the Fig. 7.6

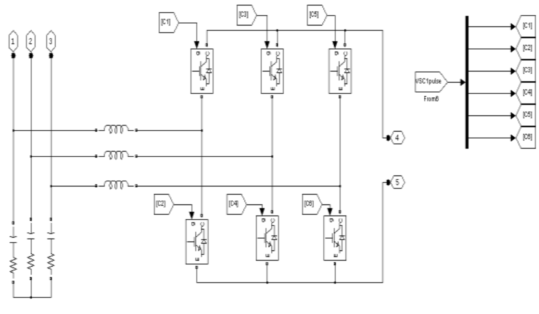

Fig. 13.Simulink block diagram of VSCs

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In the internal structure of UPQC three VSCs are present. Out of three VSCs, two VSCs are operating as voltage controllers and one VSC is operating as current controller. Each VSC consists of six switches (IGBTs) are present.

B. *Implementation of Series Transformer*

The UPQC should necessarily consist of two three-phase series transformer in order to connect of the two VSCs in series with the lines to function as a controlled voltage sources.

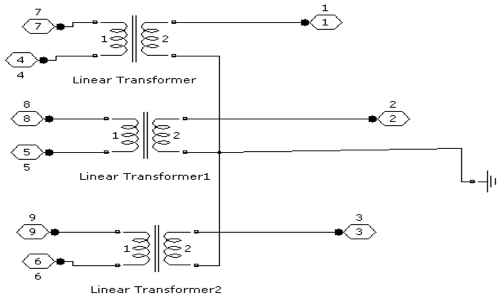

Fig. 14. Simulink diagram of three-phase series transformer

C. *Implementation of Shunt and Series Controllers*

The Simulink block diagram of shunt controller is shown in the Fig. 7.8.

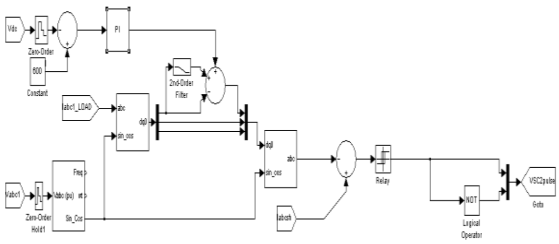

Fig. 15.Simulink block diagram of shunt controller

The switching control strategy used for shunt VSC is hysteris current control. The purpose of this shunt controller is that to compensate reactive and harmonic component of load L1 current. In this block the load current is detected and then transformed into the synchronous *dq*0 frame. A low pass filter is used to extract the harmonics. The PI contoller is used to regulate the dc-link capacitor voltage.

The Simulink block diagram of series controller is shown in the Fig. 14

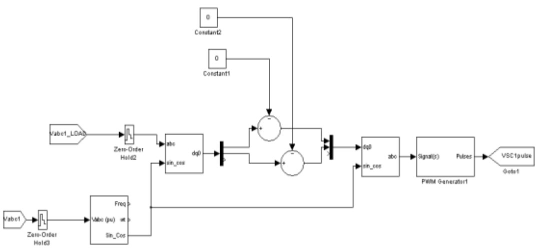

Fig. 16. Simulink block diagram of series controller

D. *SIMULATION RESULTS*

The simulation results with the modified topology are shown in Figs. In this topology, the value of the capacitor (Cf) in the shunt active filter branch is chosen to be 65 μF, and total dc bus voltage is maintained at 560 V. The voltage across the series capacitor in phase-a (vcfa) and the phase-a load voltage (vla) are shown in Fig. From this figure, it is clear that the voltage across the capacitor is in phase opposition to the terminal voltage. According to (16), the voltage across the capacitor adds to the dc-link voltage and injects the required compensation currents into the PCC.

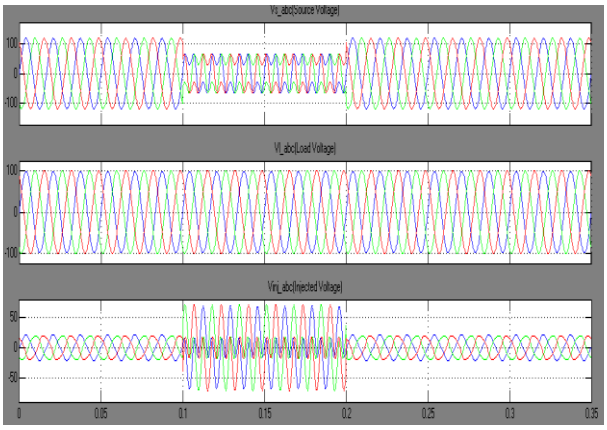

Fig 17. Simulation results using conventional topology. Terminal voltages with sag, DVR-injected voltages, and load voltages after compensation.

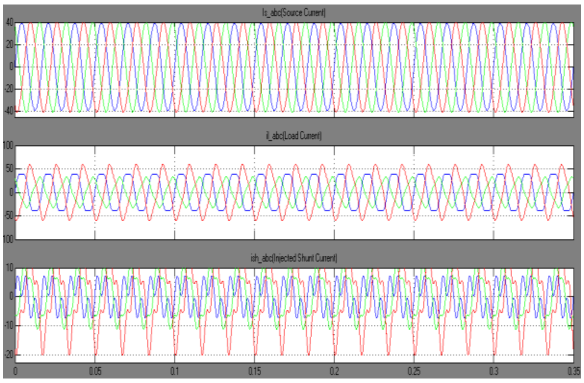

Fig 18.Simulation results using conventional topology. Shunt active filter currents

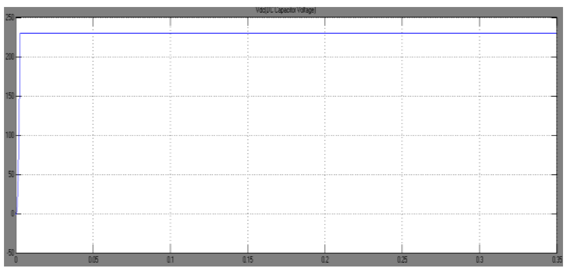

Fig 19.Simulation results using conventional topology. DC capacitor voltage

VI. CONCLUSION

A modified UPQC topology for three-phase four-wire system has been proposed in this paper, which has the

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capability to compensate the load at a lower dc-link voltage under non stiff source. Design of the filter parameters for the series and shunt active filters is explained in detail. The proposed method is validated through simulation and experimental studies in a three-phase distribution system with neutral-clamped UPQC topology (conventional). The proposed modified topology gives the advantages of both the conventional neutral-clamped topology and the four-leg topology. Detailed comparative studies are made for the conventional and modified topologies. From the study, it is found that the modified topology has less average switching frequency, less THDs in the source currents, and load voltages with reduced dc-link voltage as compared to the conventional UPQC topology.

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