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IMPROVING STABILITY AND RELIABILITY INPUT GRID VOLTAGE FOR REGULATION, FLC-BASED UPQC

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ABSTRACT
We provide fuzzy logic controller-based UPQC in this work to improve stability and reliability as well as power quality features. The usual features of a transformer less unified power quality conditioner are enhanced with this project (TL-UPQC). An enhanced control method is suggested in order to provide input grid voltage management and permit the exchange of reactive power between the system and the grid. A single converter may thereby change the voltage on both the load side and the input grid side. The input voltage and the input current now have a phase angle. This controls how the system behaves as an inductive or capacitive reactance. An extra ac voltage control loop has been created. Two exterior voltage loops have been modified to provide reference data to the inner current loop. The improved control strategy operates without the need for extra sensor circuits based on local data gathered by the TL-UPQC. The FLC-TL- UPQC system's traditional functions have been expanded, so features of system modeling and control design should be improved. Presenting a small-signal model that describes the dynamics of the powerstage and the controller. The proposed system is designed inMATLAB/SIMULINK environment andproved that simulation results are obtained better than conventional system.
Keywords: FLC, UPQC,STABILITY, RELIABILITY.

INTRODUCTION

Low voltage (LV) distribution ac networks currently have a HIGH penetration of small-scale distributed energy resources (DER). To address the rising need for power, a photovoltaic (PV) system, for instance, provides a dependable and clean source of electricity. While small-scale wind farms are linked with ac microgrids, large-scale wind power plants are commonly used in the transmission of electric electricity. Yet, the intermittent nature of renewable energy sources presents several difficulties for the utility grid's power quality. During the height of PV generation, reverse power flow may cause an abrupt voltage increase [1], [2]. By surpassing voltage flickering levels, the stochastic nature of wind active and reactive power causes concerns with power quality [3]. Voltage variation in the networkis a critical issue that causes system shutdown, loss of data, high losses,overheating of equipment and reduced lifetime.

Considerable work has been reported in the literature adopting the recent advancements of semiconductor technology to provide grid voltage support. A centralized distribution static synchronous compensator (D-STATCOM) that is connected to mediumvoltage (MV) distribution networks is widely employed to provide line voltage regulation due to its large dynamic range [4]-[6]. In [7], the behavior of a D- STATCOM as a controlled voltage source has been adopted to implement a generalized impedance control. Generally, a D-STATCOM can support the grid voltage by means of controlling the reactive power injection into the power system. However, installing a high rating D-STATCOM at MVlacks the capability of identifying local problems happening at the LV side and cannot guarantee a stable voltage profile for long distance loads. Since massive number of DER units are being installed at the residential or commercial side, power quality improvement techniques should be installed adjacent to these points. This will allow more units to join grid operation without affecting the upstream voltage.

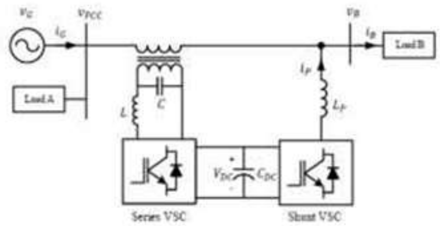


Fig. 1. Conventional UPQC topology.

A unified power quality conditioner (UPQC)is an effective solution since it can perform both series and parallel compensation in LV distribution networks. A conventional topology of a UPQC system is shown in Fig.
1. It consists of two voltage source converters (VSCs) and is mainly connected between the ac supply and critical nonlinearnloads. In a UPQC system, the shunt converter injects current into the grid to compensate for load current harmonics and reactive power consumption. On the other hand, the series converter injects voltage to mitigate voltage disturbances propagating in the network, such as flickering, voltage swells and voltage sags. The work reported in the literature mainly focused on developing control strategies to improve the conventional features of a UPQC system including active power control and minimum active power injection control [8]-[11]. In the latter, the injected voltage is controlled at an appropriate angle based on operational requirements. In other words, active reactive power control technique where the series converter delivers complex power can be achieved. Hence, the seriesconverter shares load reactive power withthe shunt converter under steady-state and transient conditions. This will enlarge thereactive power compensation range of thesystem, and optimum sizing can be realized. In [12], a data-driven based control methodology implementing adjustable phase angle for optimal operating point has been proposed.

A conventional UPQC toplogy requires a series transformer to reduce the voltage stress of the converter as indicated in Fig. 1. Nevertheless, transformers are bulky, increase cost and limit the power density of the converter. In addition, achieving a fast- dynamic response at the output voltage can be challenging [13]. The structure of a single-phase UPQC system can be a full-bridge, a three-leg, or a half-bridge topology [8]. A single-phase transformerless full- bridge UPQC topology has been proposed in [14], [15], where circulating current has been addressed. Adopting full-bridge topology requires a high number of switches which leads to high losses and low efficiency. A single-phase three-leg transformerless UPQC topology requires six switches; therefore, it can attain higher efficiency and power density [16], [17]. However, the shared leg introduces leakage current into the system and decoupling the operation between the series and parallel converters becomes essential. In general, most proposed conventional TL-UPQC topologies are able to provide a stable and sinusoidal voltage across loads connected to its output terminal, e.g. load B in Fig. 1.Nonetheless, loads that are connected to the input grid voltage directly are still exposedto voltage variations in the network, e.g. load A in Fig. 1. Thereby, an additional compensator is still required to be installed at the point of common coupling (PCC). A three-phase improved topology of UPQC (iUPQC) that includes the functionality of reactive power injection for input grid voltage regulation has been proposed in [18] where instantaneous reactive power theory (P-Q) control methodology has been adopted. This control methodology requires an extra current sensor at the load side. It is worth mentioning that system modeling for stability studies of a UPQC system to provide input grid voltage regulation in addition to output voltage regulation has not been developed yet in the literature. Also, the effect of the grid impedance has not beenconsidered in the design process.

PROPOSED SYSTEMCONFIGA RATION

A transformerless UPQC (TL-UPQC) system adopting half-bridge topology has been proposed in [13], [19], [20]. The system proved to successfully support critical loads against long and short durationvoltage variations with fast dynamic response. It is important to highlight thatonly the load side voltage power quality issues have been mitigated while input grid voltage regulation has not been introduced or studied for the TL-UPQC system yet. This paper extends the features of the TL- UPQC system offered in [13], [19], [20]. The paper presents an enhanced control strategy to expand the functions of a TL- UPQC system to include input grid voltage regulation. The TL-UPQC will be able to support loads that are connected to the grid side voltage besides its ability to support critical loads that are connected to the load side voltage, i.e. sustain the voltage across critical loads and general loads at the same time as depicted in Fig. 2. A comparison between reported TL-UPQC topologies in the literature is provided in Table I. The work in this paper presents a comprehensive study implementing three control loops and their coordination. Theoretical analysis considering the grid impedance, mathematical models and stability analysis for the proposed comprehensive system are presented with experimental justifications. Controller design guidelines for the proposed system to achieve a specific performance is provided as well.

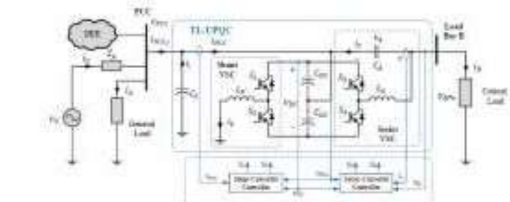


Fig. 2. TL-UPQC topology for low voltage distribution network.

Fig. 2 shows the detailed structure of a single-phase TL-UPQC connected to the PCC at a LV distribution network. The TL- UPQC consists of two half-bridge bi- directional VSCs. The topology is formed by one shunt converter and one seriesconverter. Both converters share a common dc link. A shunt filter capacitor Cf is added to the system to act as a low impedance for the high frequency components introduced by the converter. This will minimize the switching harmonics injected by the shunt converter into the grid. The TL-UPQC topology offers the following features,

a) Transformerless – no transformer in between the VSC and the grid. It leads high efficiency and cost effective.
b) Low common-mode (CM) voltage – since the transformer is absent, CM voltage and leakage current become significant. The topology can maintain low CM voltage since the potential difference between the ac and dc grounds is clamped [21].
c) Mitigates harmonics of nonlinear loads and provides reactive power to linear loads connected to the load bus.
d) Protects critical loads against voltage flickering, and voltage disturbances with fastdynamic response.
e) Allows amplitude voltage variation control to achieve energy saving at the load bus [22]. While, TL-UPQC is intended to be installed at a LV distribution network, its functions can be maximized to include the following,
f) Provides reactive power compensation to achieve input grid voltage regulation to the loads connected to the PCC.
g) Improves the PCC voltage profile andeventually improve the voltage quality of theupstream voltage.
h) Eliminates the need to install a D- STATCOM at the PCC and copes with the new distributed nature of a microgrid grid tomitigate power quality issues elevated at LVdistribution networks. i) Relies on means of locally collected information and does not require additional sensors.

TABLE I
COMPARISON BETWEEN SINGLE-PHASE TL-UPQC TOPOLOGIES

Topology	Number of Switches	Number of Sensors	Voltage stress across switches	Isolation	Current Quality	Output Voltage Profile	Input Grid Voltage Profile
Full-bridge [14], [15]	8	5	Low	Not required	Improved	Improved	Low
Three-leg [16], [17]	6	5	Low	Not required	Improved	Improved	Low
Half-bridge [18], [19], [20]	4	5	High	Not required	Improved	Improved	Low
Proposed solution	4	5	High	Not required	Improved	Improved	Improved

To illustrate the operation of the TL-UPQC, Fig. 3 shows the equivalent circuit of the system which consists of a controlled current-source to model the shunt converter and a controlled voltage-source to model the series

converter? In a typical TL-UPQC system, the shunt converter injects current harmonics and reactive current iP to compensate the distorted current of the nonlinear load iB connected to bus B. This will shape the input current $iPCC$ to be sinusoidal and in-phase with the PCC voltage. The grid current (t) will carry the apparent power demand of the PCC load that is quantified by the PCC load current(t). It will also carry the active power demand consumed by the load connected to the load bus in addition to the necessary active power required to maintain the dc linkvoltage and compensate for converter losses.The enhanced control methodology proposed in this paper contains an additional control degree of freedom. If reactive power compensation is needed at the grid side, a phase angle θ is created between $vPCC$ &
$iPCC$ as depicted in Fig. 3. The active and reactive power at the PCC can be expressed as follows,

$$P_{PCC} = V_{PCC} I_{PCC} \cos\theta \ \& \ Q_{PCC} = V_{PCC} I_{PCC} \sin\theta \qquad (1)$$

Where $VPCC$ is the steady-state rms value ofthe PCC voltage, $IPCC$is the steady-state rms value of the feeder current, and θ is the PCC current displacement angle withrespect to its voltage. By controlling the phase angle θ, the TL-UPQC will be able to operate in three reactive power compensation modes. The phasor diagrams shown in Fig. 4 illustrate the operation ofthe three modes: a) power factor correction (PFC) mode in which no reactive power compensation is needed at the grid side, b) capacitive mode in which reactive power is being injected to the grid and c) inductive mode in which reactive power is being absorbed from the grid. $IPCC'$,' and $VPCC'$ represent the steady-state values before enabling grid reactive power compensation.

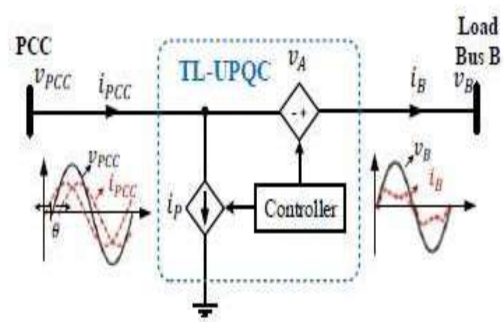


Fig. 3. Equivalent circuit model of a TL-UPQC system.

A. Power Flow Analysis

Fig. 5 shows a block diagram of the powerflow in a TL-UPQC system. The amount ofgrid active and reactive power transferred from the grid to the PCC bus can be expressed by,

$$P_G = \frac{V_G V_{PCC}}{Z_g} \cos(-\delta + \emptyset_g) - \frac{V_{PCC}^2}{Z_g} \cos(\emptyset_g) \qquad (2)$$

$$Q_G = \frac{V_G V_{PCC}}{Z_g} \sin(-\delta + \emptyset_g) - \frac{V_{PCC}^2}{Z_g} \sin(\emptyset_g) \qquad (3)$$

Where Zg represents the grid impedance with a displacement angle of $\emptyset g$. A linear load represents the load connected to thePCC. The load active and reactive power aregiven as follows,

$$P_A = \frac{V_{PCC}^2}{Z_A} \cos(\emptyset_A) \ \& \ Q_A = \frac{V_{PCC}^2}{Z_A} \sin(\emptyset_A) \qquad (4)$$

where ZA is the load impedance connected to the PCC with a displacement angle of $\emptyset A$.The nonlinear load connected to the TL- UPQC system in this study is chosen to be dimmable LED lamps, due to their extreme sensitivity to voltage flickering and their nonlinear characteristics [23]. The TL- UPQC system will compensate for the load harmonics, the LED lamps is assumed to be seen as a resistive load from the grid point of view. The amount of active powerconsumed by this critical load is given by,

$$P_B = \frac{V_B^2}{R_B} \qquad (5)$$

where, RB is the equivalent fictitious resistance of the LEDs and VB is the output

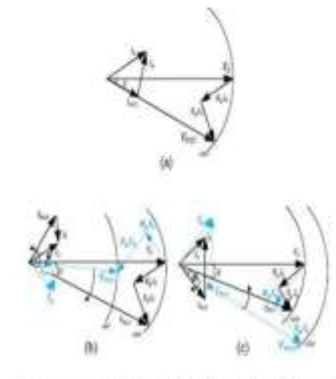


Fig. 4. Phasor diagrams of (a) PFC mode (b) capacitive mode (c) inductive mode.

rms voltage maintained by the TL-UPQCsystem across the load bus.

The power going through the shuntconverter $P1$, assuming no losses in theconverter, is used to charge up the dc link capacitor and maintain the dc link voltage by compensating for the power needed by the series converter $P2$. The indicator is the dc link voltage reached steady-state, in other words, a constant value. At system equilibrium, the input power $PPCC\ (t)$ equals the output power $PB\ (t)$. From which, the following equation can be found,

$$\frac{V_G V_{PCC}}{Z_g}\cos(-\delta+\emptyset_g) - \frac{V_{PCC}^2}{Z_g}\cos(\emptyset_g) = \frac{V_B^2}{R_B} + \frac{V_{PCC}^2}{Z_A}$$

Consequently, the power angle δ can be obtained. The TLUPQC system regulates thePCC voltage by injecting/absorbing reactive power $QPCC\ (t)$ into/from the grid. Thus, the amount of reactive power needed by

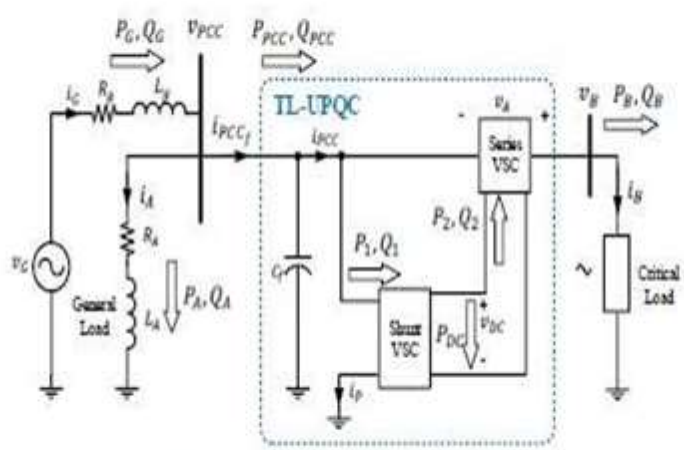


Fig. 5. A block diagram of power flow in a TL-UPQC system.

the TL-UPQC system to accomplish voltage regulation can be found using the following equation,

$$Q_{PCC}(t) = \frac{V_G V_{PCC}}{Z_g}\sin(-\delta+\emptyset_g) - \frac{V_{PCC}^2}{Z_g}\sin(\emptyset_g)$$

$$-\frac{V_{PCC}^2}{Z_A}\sin(\emptyset_A) \qquad (7)$$

B. Enhanced Controller Strategy and

Implementation

Shunt Converter Enhanced ControlMethodology Fig. 6 shows the shunt converter circuit of the TL-UPQC that isresponsible of regulating the input grid voltage under the proposed enhanced controlmethodology. A current source is connected to the dc link voltage to model the power required by the series converter to maintain the output voltage. The shunt converter's control block diagram is depicted in Fig. 7, which involves three controllers. Two voltage control loops and one current controlloop can be described as follows,

a) Dc link voltage controller – maintains thedc link voltage between the two VSCs.
b) Ac voltage controller – provides input voltage regulation to the PCC bus through means of reactive power injection.
c) Input current controller – shapes the PCC current to operate in three modes (PFC, capacitive and inductive mode).

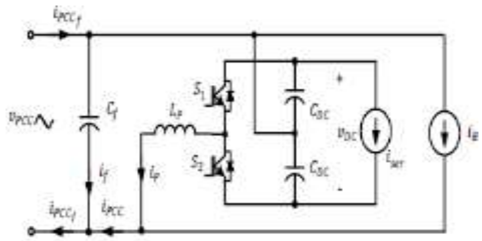


Fig. 6. Half-bridge inverter configuration of the shunt converter.

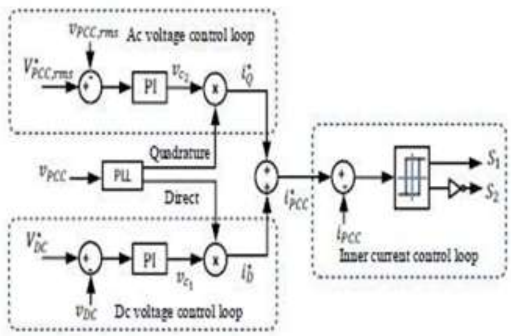


Fig. 7. Shunt converter control block diagram.

If neglecting the load current iB in Fig. 6 thesystem is a simple PFC when no reactive power support is required. This is the defaultoperating mode of the TL-UPQC system. In order to provide input grid voltage support, the system will operate in either the inductive or the capacitive mode, hence controlling the phase angle θ of the PCC current. The phase angle θ is governed by the amount of reactive power needed to regulate the PCC voltage. It will also take role to define the absorption of active power. So that the system is decoupled, $iPCC$ (t) is converted into the d-q axis,

$$I_D = I_{PCC} \cos\theta \quad \& \; I_Q = I_{PCC} \sin\theta \qquad (8)$$

where,

$$I_{PCC} = \sqrt{I_D^2 + I_Q^2} \qquad (9)$$

$IPCC$ represents the steady state rms values of the PCC current, while ID and IQ represent the direct and quadraturecomponents of the PCC current respectively.The dc voltage control loop is a PI controller, which is used to fix the dc link voltage and determine the direct component of the injected current. The ac voltage control loop is also a PI controller that is used to regulate the PCC voltage andgenerate the quadrature component of the PCC current. The inner current control loop is a hysteresis controller that shapes the shunt inductor current by comparing it to its reference signal. Since the shunt converter circuit is connected in parallel to the source and considering the load current to be constant, the PCC current ripple is the same as the inductor current ripple. Therefore, a reference signal for the PCC current can be formed with specified upper and lower bands to guide the inductor current following the reference. The reference current signal is generated by the two outer voltage loops and phase locked loop (PLL) as follows,

$$i_{PCC}^*(t) = i_D^*(t) + i_Q^*(t) \qquad (10)$$

$$i_{PCC}(t) \le i_{PCC}^*(t) - \frac{\Delta I_{pcc}}{2} \qquad (11)$$

$$i_{PCC}(t) \ge i_{PCC}^*(t) + \frac{\Delta I_{pcc}}{2} \qquad (12)$$

Series Converter Control Methodology

Fig. 8 shows the half-bridge configurationof the series converter circuit of the TL-UPQC. One controller is formalized in the series converter which represents the fourth controller in the system as follows, 4) Load bus voltage controller – maintains the outputvoltage to be sinusoidal and constant amplitude. The controller strategy adopted for the load bus voltage controller is boundary control with second order switching surface. In boundary control, the switching trajectory is used to predict the moves of voltages and currents of passive components. These predictions ensure a veryfast dynamic response to any external disturbance. Fig. 9 indicates the switching trajectories of the series converter system fora resistive load on the state plane ($vA - iL$), which have been obtained solving the state- space equations of the system. The solid lines represent the on-state trajectory, while the dotted lines represent the off-state trajectory. The figure shows that the system operating points are realized following the switching trajectories with a defined reference voltage band. The switching criteria of $S3$ and $S4$ is governed by,

$$v_B(t) - v_{B,min} - \left[\frac{k_A}{\frac{v_{DC}}{2} - v_B + v_{PCC}}\right] i_C^2(t) \leq 0 \qquad (13)$$

$$\& \; i_C(t) \leq 0 \qquad (14)$$

$$v_B(t) - v_{B,max} + \left[\frac{k_A}{\frac{v_{DC}}{2} + v_B - v_{PCC}}\right] i_C^2(t) \geq 0 \qquad (15)$$

$$\& \; i_C(t) \geq 0 \qquad (16)$$

k_A represents a constant value and is calculated as follows,

$$k_A = \frac{L_A}{2C_A} \qquad (17)$$

vB, and vB,ax are minimum boundary andmaximum boundary of reference signal, respectively.

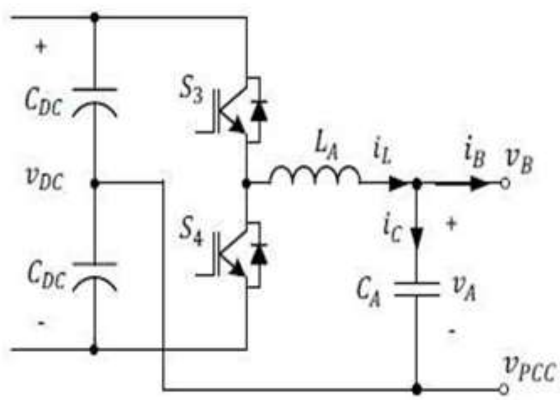


Fig. 8. Half-bridge inverter configuration of the series converter.

SIMULATION RESULTS

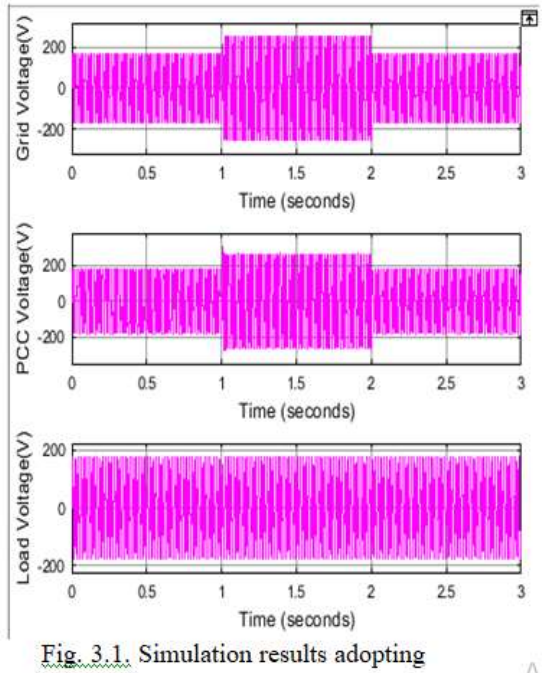


Fig. 3.1. Simulation results adopting conventional TL-UPQC system under random voltage variations in the network

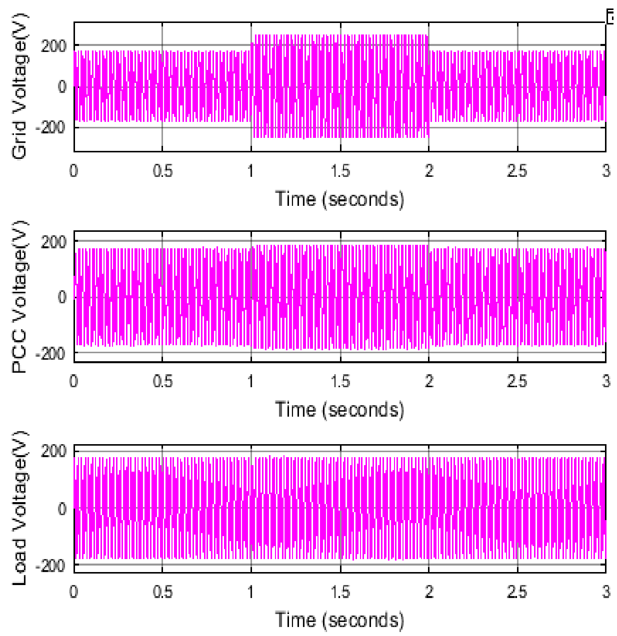
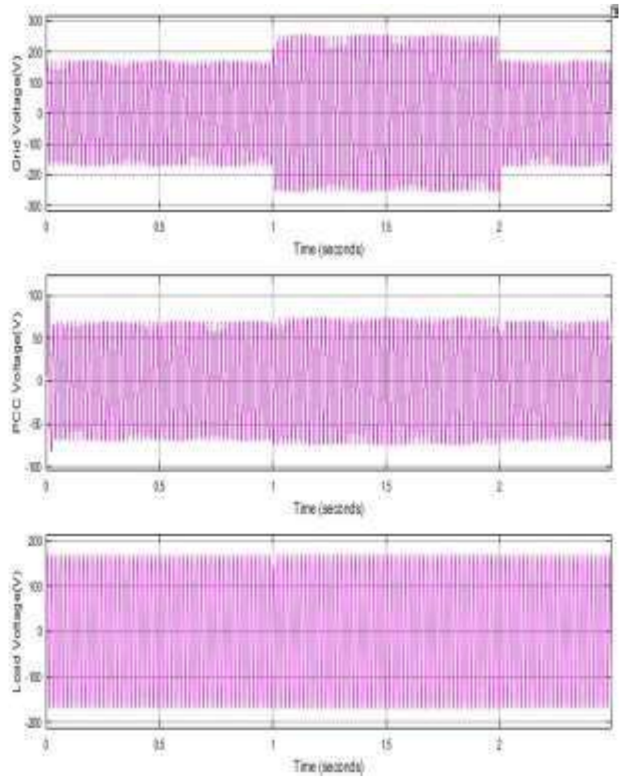


Fig. 3.2. Simulation results adopting proposed solution under random voltagevariations in the network.



3.3Simulation results of proposed fuzzylogic system

CONCLUSION

In this project we propose fuzzy logic controller based UPQC to enhance stability and reliability along with power quality feature. In order to enable the injection and absorption of reactive power into and from the input grid in low voltage distribution networks, the project expands the control strategy of a TL-UPQC system. The TL- UPQC was able to improve the voltage profile of the input grid and filter out harmonic components produced by nonlinear loads by using the proposed enhanced control technique. It was also able to quickly compensate for voltage changes across sensitive loads. Small signal models were used in a rigorous stability analysis andcontrol design requirements that were given.The simulation results verified the system's ability to provide linear and nonlinear sensitive loads simultaneously while regulating voltage at the PCC. The technology was able to lower the grid current, load bus voltage, and total harmonic distortion of the PCC voltage. In the event of voltage sags and swells, the system was capable of supplying a consistent voltage with constant amplitude to the loads connected to the PCC. The adoption of a half bridge architecture will result in increased voltage stress across semiconductor switches, it should be highlighted. Fuzzy logic controller based UPQC is simulated inMATLAB/SIMULINK environments andproposed system obtained better resultscompare to conventional Pi controller.

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