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# Modified instantaneous power theory control of dynamic voltage restorer powered by photovoltaic system

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## ABSTRACT

Power quality issues have become widespread due to nonlinear electronic converters and loads. Nonlinear components in the power system hamper the power quality, network efficiency and voltage regulation. The power quality issues like sag, swell, and voltage unbalance can be reduced by employing a dynamic voltage restorer (DVR). DVR provides the compensating power from a DC source to minimize the effect of sag, swell, and voltage unbalance. This article presents a power system with DVR using a photovoltaic system (PV) as a DC source instead of a conventional battery source. This article proposes a modified instantaneous power (PQ) control technique to generate the reference signal of load voltage to assure the DVR's superior performance. This modified technique uses an anti-aliasing filter to generate a reference signal. This proposed technique is tested under extreme power quality issues of 80% sag, 20% sag, 120% swell, 170% swell, and voltage unbalance. The DVR is modeled and simulated using MATLAB/Simulink. A comparison is made between the traditional and modified PQ methods from the obtained results. The analyzed results under severe power quality issues suggest that the proposed P-Q control technique is a preferable option for the DVR with PV as a DC power supply.

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## 1. INTRODUCTION

The extensive usage of nonlinear power electronic equipment and the incidence of faults will reduce the quality of the sinusoidal voltages and currents in the power system. Utilities and customers require a continuous sine waveform of voltage supply with stable frequency and balanced constant root mean square (RMS) value of supply voltage. The power system network's power quality can be maintained by eliminating or compensating for the issues with an efficient control technique. Power quality issues have become a key concern for customers and utilities [1]. Poor power quality can increase losses, equipment failure, and interference with nearby communication lines. The power system is configured to work within the permitted limits of electrical parameters. Any breach of these limits can lead to problems with power quality. Many research studies aim to improve the power quality by using filters like active, passive, and hybrid equipment or with custom power devices (CPD) [2], [3].

The system voltage is exposed to several power quality issues. These issues include sag, swell, unbalance, and harmonic distortion conditions of voltages [4], [5]. A voltage sag at the power frequency is the fall in RMS voltage or current over periods ranging from 0.5 cycles to 1 minute with a magnitude ranging between 0.1 and 0.9 pu [6], [7]. Voltage sags are generally associated with system failures caused by heavily loaded switching or large motor start-ups. Voltage sag is a hazardous voltage quality problem [1], [5], [8]. A swell is caused by an increase in RMS voltage or current between 1.1 and 1.8 pu for a duration ranging from 0.5 cycles to 1 minute at power frequency. Swells are associated with system disturbances but are not as regular as voltage sags. A swell can occur because of a temporary voltage rise in unfaulty phases during an SLG fault. Swells can also be caused by turning off a large load or switching on a large capacitor banks [9], [10]. DVR is a reasonable approach for limiting the impact of voltage sags and swells. Voltage unbalance exists when the 3-Φ voltages are not identical in magnitude and/or the phase differences between the three phases are explicitly not 120°. There are two ways to assess the degree of unbalance:

– The ratio of the maximum difference from three-phase average voltages to the average value of the three-phase voltages as (1).

$$V_{un} = \frac{\max\left(|V_{ab}-V_{avg}|,|V_{bc}-V_{avg}|,|V_{ca}-V_{avg}|\right)}{V_{avg}} \times 100 \tag{1}$$

where $V_{un}$ is the percentage of voltage unbalance; $V_{ab}$ , $V_{bc}$, $V_{ca}$ are phase-to-phase voltages; $V_{avg}$ is the average value of the 3-Φ voltages.

– The ratio of negative to positive sequence component of the voltage as (2):

$$V_{unf=\frac{V_2}{V_1}\times 100} \tag{2}$$

where $V_{unf}$ is the voltage unbalance factor; $V_2$ is positive sequence voltage; $V_1$ is negative sequence voltage.

The following are the primary reasons for voltage unbalance in power systems: i) Unbalanced loading in one phase of the three-phase system; ii) Untransposed overhead transmission lines; and iii) Failure of the fuse in one of the phases in the three-phase capacitor bank. These issues can be mitigated by using an active voltage conditioner (APC), distribution static synchronous compensation (D- STATCOM), or dynamic voltage restorer (DVR) [1], [3].

This article demonstrates the use of the PV system as the DC source for the DVR and the control of DVR by modified PQ control technique implementation for reference voltage generation to reduce distortions in the voltage and current parameters of the grid and load waveforms induced by extreme sag, swell, and unbalanced conditions. A MATLAB/Simulink model is developed for the power system with DVR powered by PV system along with the traditional PQ and modified PQ control technique for reference load voltage generation. The points of common coupling (PCC), load, DVR voltages, and currents obtained for traditional PQ and modified PQ are compared and analyzed to study the effectiveness of each technique.

## 2. DESCRIPTION OF DVR

### 2.1. Working of DVR

DVR is a series connected power electronic switching compensator that can be connected between grid and load to protect it from power quality issues like sag, swell and unbalance [9], [10]. The DVR's main feature is that it controls the load voltage by injecting 3-phase voltages with variable magnitude and angle in line with the supply voltage. The flow of real and reactive power between the compensator and the power system must be regulated to achieve the nominal operation of the power system with good power quality [11], [12]. DVR can effectively absorb excess energy from the system, preventing any power outages caused by system malfunctions. The DVR's basic structure is depicted in Figure 1(a).

### 2.2. DVR modeling

The DVR basic structure is represented with an electrical equivalent circuit, as shown in Figure 1(b).

$$V_{DVR} = V_L + Z_{TH} I_L - V_{TH} \tag{3}$$

Where $V_L$ is desired voltage magnitude of load, $Z_{TH}$ represents system impedance, $I_L$ for load current, and $V_{TH}$ is for the voltage of the system [5], [13], [14]. Mathematically $I_L$ is evaluated by (4).

$$I_L = \frac{P_L + jQ_L}{V_L} \tag{4}$$

Considering $V_L$ as a reference, then in (3) can be written as (5).

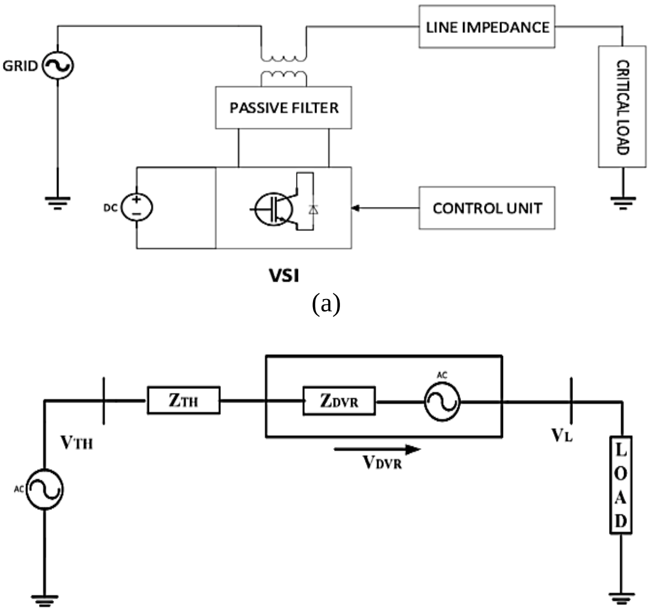
$$V_{DVR}\angle\alpha = V_L\angle 0 + Z_{TH} I_L \angle(\beta - \theta) + V_{TH}\angle\delta \tag{5}$$

where $\alpha$ is phase angle of desired voltage magnitude, $\beta$ is phase angle of system impedance, $\delta$ is angle of system voltage, and $\theta$ is power angle of load [5].

$$\theta = \tan^{-1}\frac{Q_L}{P_L} \tag{6}$$

The injected complex power of DVR is written as (7).

$$S_{DVR} = V_{DVR}\, I_L^{\,*} \tag{7}$$



(a)

(b)

Figure 1. Representation of DVR: (a) structure and (b) equivalent circuit

### 2.3. DVR control

DVR control consists of three stages [15], [16]: (1) Identification of voltage level (sag/swell) in the system; (2) Comparison of instantaneous values with a reference value; and (3) Generation of PWM signals for power electronics switches of the voltage source inverter (VSI) to provide DVR compensating voltages that can inject/absorb the appropriate power, to regulate parameters like magnitude, frequency, and phase shift using various compensation schemes [16], [17]. The inverter control strategy has two types of control: linear and nonlinear [18]–[20]. This article focuses on mitigating power quality problems by using a DVR supplied by the photovoltaic (PV) system instead of a conventional DC power supply with modified PQ control technique to generate a voltage reference signal.

## 3. MODELLING OF PQ CONTROL TECHNIQUE

### 3.1. Traditional PQ control theory

Akagi [21], [22] proposed the “Instantaneous Power Theory” or “Instantaneous Reactive Power Theory” based on the “Instant Value Principle” in 1983. The Clarke Transformation is used in the Instantaneous Power Principle, and the 3-Φ voltages are represented as:

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{9}$$

The zero-sequence current component is not existing in a 3-Φ system of three wires; therefore, the output will be contributed only by the $\alpha - \beta$ components [23], [24]. Instant active power in a three-phase circuit in the $\alpha - \beta$ coordinate system can be written as (10).

$$p = v_\alpha i_\alpha + v_\beta i_\beta = \bar{p} + \tilde{p} \tag{10}$$

$\bar{p}$ is an average value of the instantaneous real power. This parameter is the important required component and refers to the source's real power transmitted to the load. $\tilde{p}$ is alternating instantaneous real power exchanged between load and source [5], [7]. Instantaneous reactive power is written as (11).

$$q = v_\beta i_\alpha - v_\alpha i_\beta = \tilde{q} + \bar{q} \tag{11}$$

$\bar{q}$ is the average value of instantaneous reactive power. $\tilde{q}$ is the alternating instantaneous reactive power exchanged between load and source. Instantaneous zero-sequence power is written as (12).

$$p_0 = v_0 i_0 = \widetilde{p_0} + \overline{p_0} \tag{12}$$

$\overline{p_0}$ is the mean value of instantaneous zero-sequence real power. This value is associated with the real power transmitted between load and source through the zero-sequence voltage and current components. $\widetilde{p_0}$ is the instantaneous alternating active power with zero-sequence component.

The fluctuating active and reacting power are objectionable as they result from the system's harmonics [25]. The average reactive power is disagreeable in several circumstances [26]. The oscillating active and reactive power can be calculated by filtering the total active and reactive power. This theory is utilized for generating an instantaneous reactive power compensator, which detects the instantaneous reactive power without time delay and compensates it [27]–[29].

### 3.2. Proposed PQ theory-based control technique

In this proposed PQ technique, reference load voltage ($V_L^*$) is generated to compare with the actual load voltage ($V_L$). To generate $V_L^*$, point of common coupling voltage ($V_{PCC}$) and load current ($I_L$) are used as inputs for the controller, then filtered by an anti-aliasing filter with a cut-off frequency 60 Hz. Following that, the filtered signals transformed from a-b-c to $\alpha\beta$ to produce $V_\alpha$ , $V_\beta$ , $I_\alpha$ and $I_\beta$ which are used to calculate real power ($p$) and reactive power ($q$). After that $V_{\alpha\beta}^*$ calculated by (13) and (14).

$$V_\alpha^* = \frac{(p \times I_\alpha) - (q \times I_\beta)}{I_\alpha^2 + I_\beta^2} \tag{13}$$

$$V_\beta^* = \frac{(p \times I_\beta) + (q \times I_\alpha)}{I_\alpha^2 + I_\beta^2} \tag{14}$$

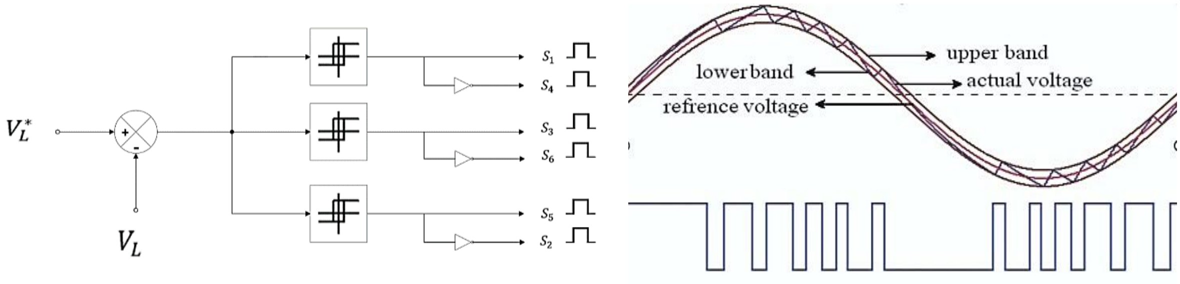
Then $V_{\alpha\beta}^*$ transformed back to a-b-c to generate $V_L^+$ from as (15).

$$V_L^+ = V_{PCC} - V_L^- \tag{15}$$

From the (13), (14), and (15) $V_L^*$ is generated.

### 3.3. Hysteresis voltage control

The voltage source inverter has entirely controllable switches. The four most common switches are IGBT, GTO, MOSFET, and IGCT. For DVR converters, since it is simple to monitor and suitable for power quality improvement applications, the IGBT switch is selected. The hysteresis controller is primarily equipped with two voltage inputs, one from the supply side and the other from the transformer, which is a voltage injected by a dynamic DVR. The controller compares these two signals and sets the switching pattern according to these signals [6], [28], [29]. The hysteresis voltage control theory is based on error signal generation by comparing the real voltage (measured) and reference voltage signals; therefore, this error signal initiates the hysteresis comparator switching pulses for the inverter [11]. Figure 2(a) and Figure 2(b) show the hysteresis voltage controller and its switching pattern.



(a) (b)

Figure 2. Hysteresis voltage and switching pattern control (a) hysteresis voltage control and (b) hysteresis switching pattern control

## 4. SIMULATION CIRCUIT AND RESULTS

### 4.1. Power system with photovoltaic (PV) system as DC power supply for DVR

Figure 3(a) shows DVR powered with the PV system. Besides the component of the traditional topology (DVR with constant DC source), the DVR with PV system, a step-up converter, and maximum power point tracking control (MPPT). The power provided by the PV system is affected by input parameters of temperature and irradiance [3]. The PV system has nonlinear characteristics, with a maximum power point (MPP) at a precise operating point. The voltage and current characteristics of PV system is presented in Figure 3(b). As solar irradiation and temperature affect the PV system's maximum power operating point, the operating point is changed continuously. Hence, MPP tracker should be employed to monitor the changes in input parameters and identify the maximum operating point. There are many MPPT methods, but the most common algorithm is perturb and observe (P&O) is implemented because of its simplicity in its fundamental structure.

### 4.2. PV system operation

When the PV array's operating voltage is agitated in a particular direction and $dP/dV > 0$, it is known that the perturbation has shifted the operating point of PV array nearer to MPP. Following that, the Perturb and Observe algorithm would remain to perturb the voltage of PV system in the same direction. If $dP/dV < 0$, the operating point is pushed away from the MPP, and then the perturbation direction is reversed [3], [4]. If the perturbation oscillates and $dP/dV = 0$, the maximum operating point is achieved. Figure 3(c) shows the flowchart of the P&O method utilized for MPPT of PV system.

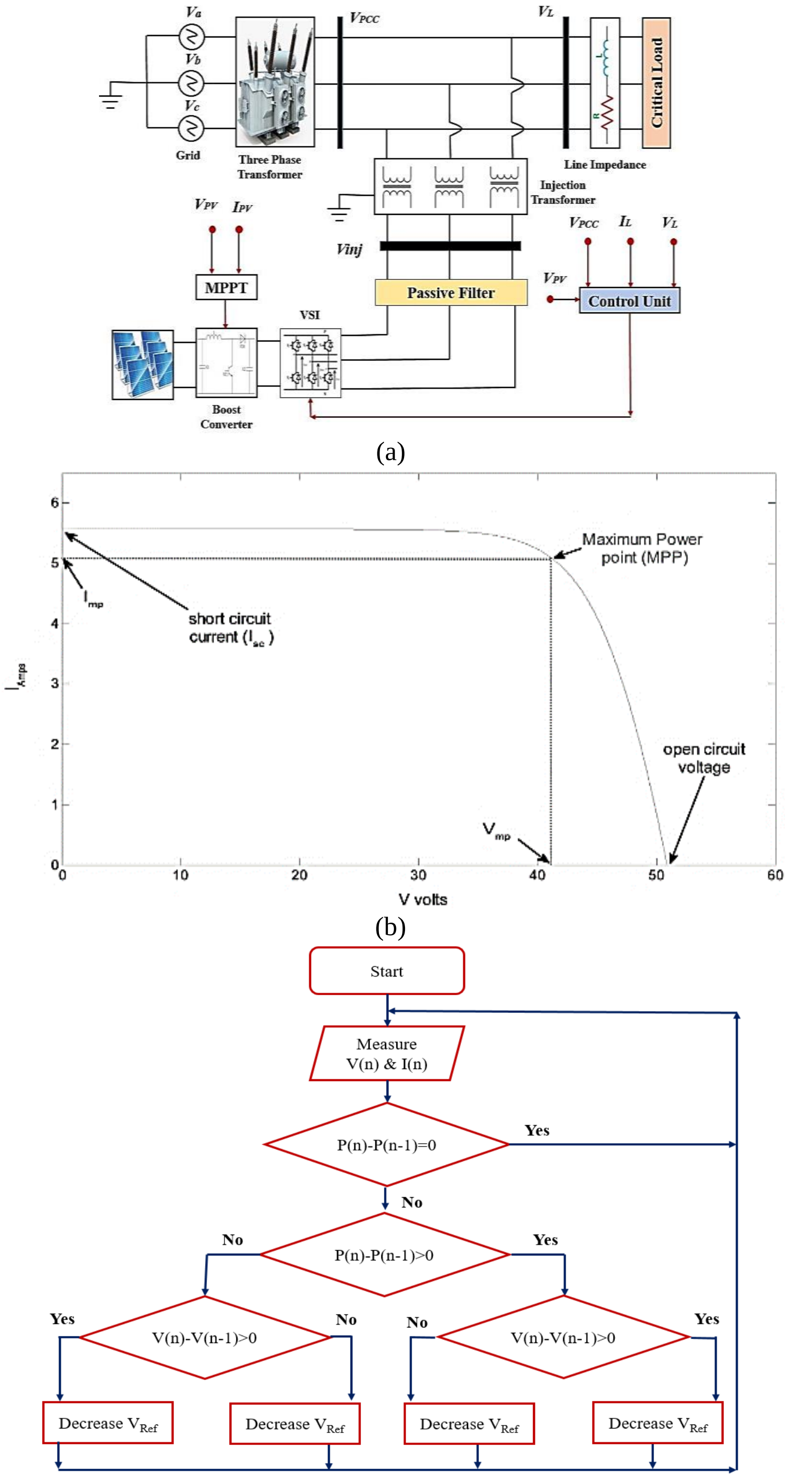
### 4.3. Control techniques

Power quality (PQ) theory-based control is a cutting-edge approach in the field of power systems that focuses on maintaining and improving the quality of electrical power. By utilizing advanced algorithms and control techniques, PQ theory-based control aims to mitigate power quality issues such as voltage sags, harmonics, flicker, and unbalanced loads. This control methodology relies on real-time monitoring of power signals and the analysis of various power quality parameters. With the help of sophisticated sensors and measurement devices, the system can detect deviations in voltage, current, and frequency, allowing for prompt corrective actions. PQ theory-based control algorithms are designed to dynamically adjust power system parameters, such as voltage regulation, reactive power compensation, and harmonic filtering, to ensure optimal power quality at all times. By implementing PQ theory-based control strategies, power system operators can minimize disruptions, protect sensitive equipment, and enhance the overall reliability and efficiency of the electrical grid. This innovative control approach holds tremendous potential for the future of power systems, paving the way for a more stable and high-quality electrical infrastructure. PQ theory-based control technique is implemented to control the DVR for injection of compensation power based on the power quality issue of sag, swell, and unbalanced conditions by generating the voltage reference signal. This section presents the proposed modified PQ theory-based control technique.

#### 4.3.1. Proposed P-Q theory-based control technique

By the sampling theorem, a signal can only be rebuilt properly from its samples when it is band limited. Practically, no signal is entirely band-limited; instead, signals have frequency spectra that combine low and high-frequency noise components. All signals with a frequency range higher than ($\omega_{s/2}$) cause aliasing when a signal is sampled at a sampling frequency ($\omega_s$). Therefore, it is required to first band-limit the signal x(t) to some appropriate frequency $\omega_m$ by employing the low-pass filter so that most of the signal's energy is maintained to prevent the aliasing mistakes brought on by the undesirable high-frequency signals.

The anti-aliasing filter is a low-pass filter used to band-limit a signal before sampling. Unlike the traditional PQ theory-based control technique, the proposed control technique filter ‘ $V_{PCC}$‘ and ‘ $I_L$ ‘ using antialiasing filters. Anti-aliasing filters are the additional components of the existing PQ control technique. Because $V_{PV}$ impacts the system voltage, its value must be used in the computation of the reference voltage, as shown in Figure 4.



(a)

(b)

(c)

Figure 3. Proposed system, (a) power system with DVR powered with PV system, (b) I-V characteristics of the solar cell, and (c) flowchart of P&O method for MPPT

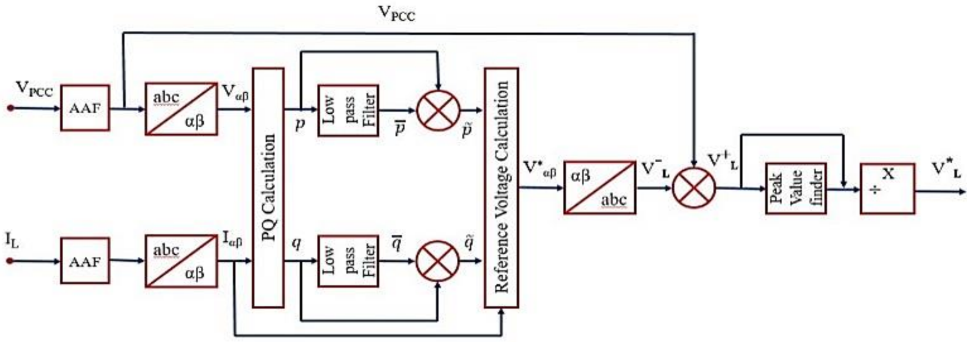


Figure 4. Proposed P-Q theory-based control technique

## 5. SYSTEM PARAMETERS

The modified PQ control considers a power system with a grid of 230.94 V, 60 Hz connected to a resistive load of 1000 W at nominal voltage. An Injection transformer of 10kVA with a transformation ratio of 1:1 is selected. Filters, voltage source inverters, and PV systems are considered in the system. The parameters of these components are tabulated in Table 1.

Table 1. System parameters

| System/Component | Parameter | Value | System/Component | Parameter | Value |
|---|---|---|---|---|---|
| Grid | Voltage | 230.94 V | Energy Storage | Type | IGBT |
| | Frequency | 60 Hz | | Voltage | Battery |
| Load | Voltage | 230.94 V | PV System | Maximum power | 213.15 W |
| | Type | Resistive | | Parallel strings | 1 |
| | Power | 1000 W | | series-connected modules per string | 10 |
| Injection Transformer | Ratio | 1:1 | | Cells per module | 60 |
| | Nominal Power | 10 kVA | | Open circuit voltage $V_{oc}$ | 36.3 V |
| Passive Filter | Inductor | 3 mH | | Short circuit current $I_{sc}$ | 7.84 A |
| | Capacitor | 100 µF | | Voltage at MPPT | 29 V |
| Inverter | Number of bridges | 3 | | Current at MPPT | 7.35 A |
| | Power electronic device | IGBT | | | |

## 6. SIMULATED CASES

The DVR's power system network with PV as a DC power supply is modeled in MATLAB/Simulink. Different power quality issues of sag, swell and unbalanced conditions are implemented to test the efficacy of the modified PQ. A comparison is made between the traditional PQ and modified PQ control for the voltage and current waveform obtained at PCC, load, and compensation. The power quality issues considered are 80% sag, 20% sag, 120% swell, 170% swell in one phase, and a voltage unbalance. Simulations are carried out for all above mentioned cases for both traditional PQ and proposed PQ. PCC, load, DVR voltages, and currents are studied for each case. The waveforms for each case are shown and discussed in the following section.

### 6.1. Simulation results

### 6.1.1. One phase 80% sag with traditional PQ

Figure 5 compares the voltage and current of PCC, Load and injected values for traditional and proposed PQ control at 0.8PU value of grid voltage. In this case, phase “a” of the grid voltage sags by 20% of the nominal value, implying that the remaining voltage is 80% (0.8 p.u) of the nominal value. As illustrated in Figure 5(a), the DVR responds appropriately to the issue and injects the corresponding voltage amount to compensate for sag in one phase of the load voltage. It can be observed that one phase in the PCC has 0.8PU voltage. To compensate for this voltage, DVR injects the required amount of power from the PV system with the traditional PQ method. The resultant waveform of voltage and current at load showed many distortions.

### 6.1.2. One phase 80% sag with proposed PQ

As illustrated in Figure 5(b), the DVR responds appropriately to the issue of 80% sag and injects the appropriate voltage to compensate for the 80% sag in one phase of the load voltage. DVR starts injecting instantaneously, resulting in better compensation when compared to the traditional PQ. At PCC, the sag is compensated, and the nominal value of 1PU voltage is obtained.

### 6.1.3. One phase 20% sag with traditional PQ

Figure 6 compares the voltage and current of PCC, Load and injected values for traditional and proposed PQ control at 0.2PU value of grid voltage. In this case, the grid voltage sags by 80% of the nominal value, implying that the remaining voltage is 20% (0.2 p.u) of the nominal value. Despite the severity of the fault, the DVR responds appropriately to the issue and injects a proportional amount of voltage to compensate for the sag in one phase of the voltage, as illustrated in Figure 6(a). Even after compensation from the DVR with a PV system under traditional PQ control, the load voltage and currents have large distortion.

### 6.1.4. One phase 20% sag with proposed PQ

In this case, phase “a” is subjected to 20% (0.2 p.u) of the nominal value. Under this severe sag condition, the DVR responds spontaneously to the issue and injects voltage to compensate for the sag in one phase of the voltage, as illustrated in Figure 6(b). The distortion level is much less when compared to the voltage and current waveforms under traditional PQ.

### 6.1.5. one phase 120% swell with traditional PQ

Figure 7 compares the voltage and current of PCC, Load and injected values for traditional and proposed PQ at 1.2 PU value of grid voltage. In this case, phase “a” of the grid voltage swells by 20% of the nominal value, inferring that the voltage on the system is 120% (1.2 p.u) of the nominal value. As illustrated in Figure 7(a), the DVR responds appropriately to the issue and eliminates the swell from phase a of the load voltage. With traditional PQ, the waveforms of voltage and current are more distorted.

### 6.1.6. one phase 120% swell with proposed PQ

As illustrated in Figure 7(b), the DVR responds instantaneously to the power quality issue and eliminates the swell from phase “a” of the load voltage, leading to the voltage value of 1 PU. With a 1.2 PU value of grid voltage in phase “a” and controlled by the proposed PQ control shows an efficient effect on the compensation of grid voltage to the nominal value of 1PU.

### 6.1.7. One phase 170% swell with traditional PQ

Figure 8 compares the voltage and current of PCC, Load and injected values for traditional and proposed PQ control at 1.7PU value of grid voltage. In this case, phase “a” of the grid voltage swells by 70% of the nominal value, inferring that the existing voltage is 170% (1.7 p.u) of the nominal value. Under this extreme swell condition, the DVR responds appropriately to the issue and eliminates the swell from phase a of the load voltage, as illustrated in Figure 8(a). under this situation, the voltage and current waveforms have more distortion with the control of traditional PQ.

### 6.1.8. One phase 170% swell with proposed PQ

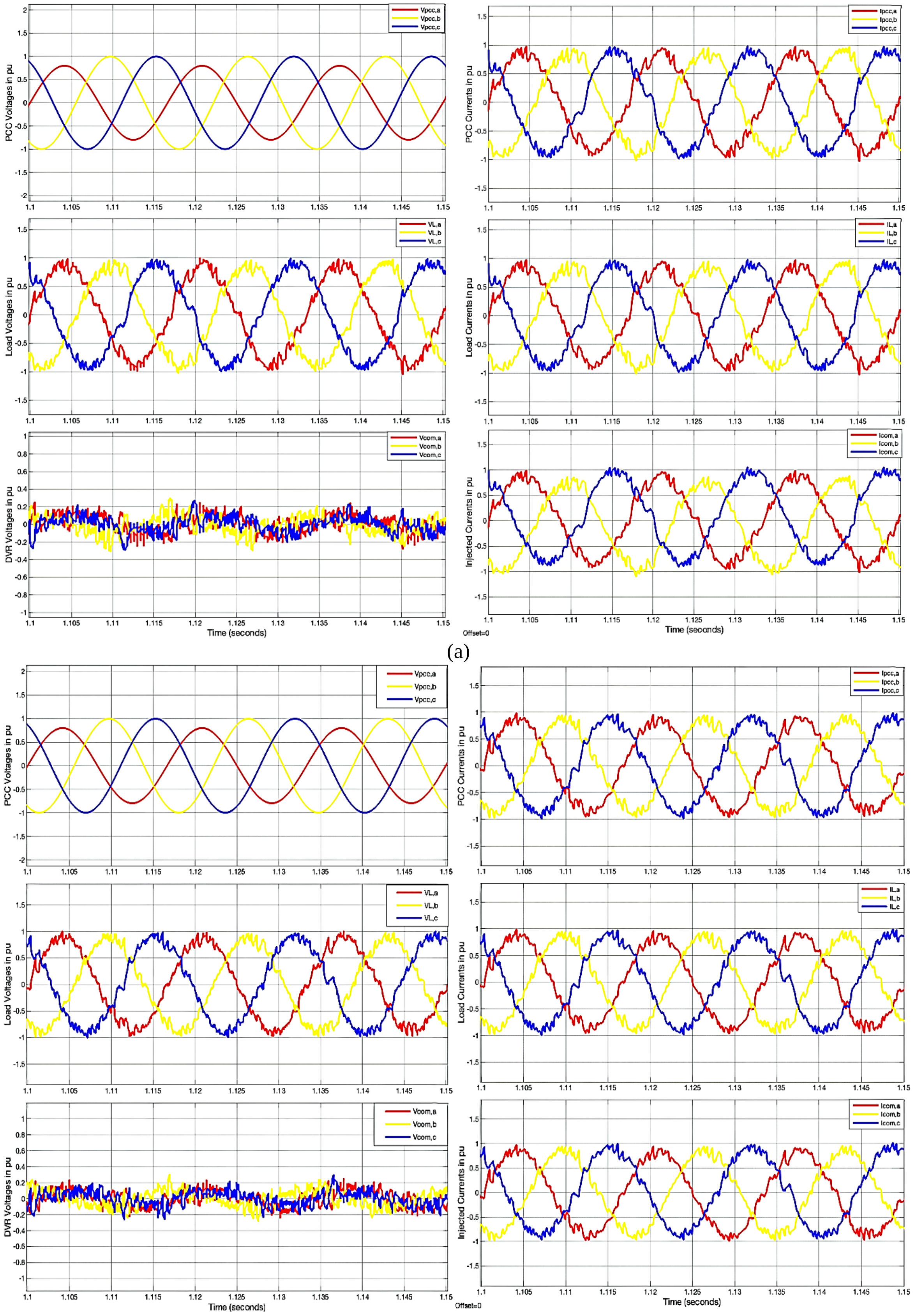
Under severe conditions of 170% swell in one phase with the proposed PQ, the voltage and current waveforms have better sinusoidal forms than the traditional PQ control. The waveform of voltages and currents for PCC, Load, and DVR are shown in Figure 8(b).

### 6.1.9. Voltage unbalance with traditional PQ

Figure 9 compares the voltage and current of PCC, Load and injected values for traditional and proposed PQ control at unbalance grid voltage. Figure 9(a) shows an unbalanced grid voltage at the input of PCC. while compensating with traditional PQ the voltage and current waveforms have distortions. Though it compensates well by balancing the grid voltage, there are still distortions in the load current.

### 6.1.10. Voltage unbalance with proposed PQ

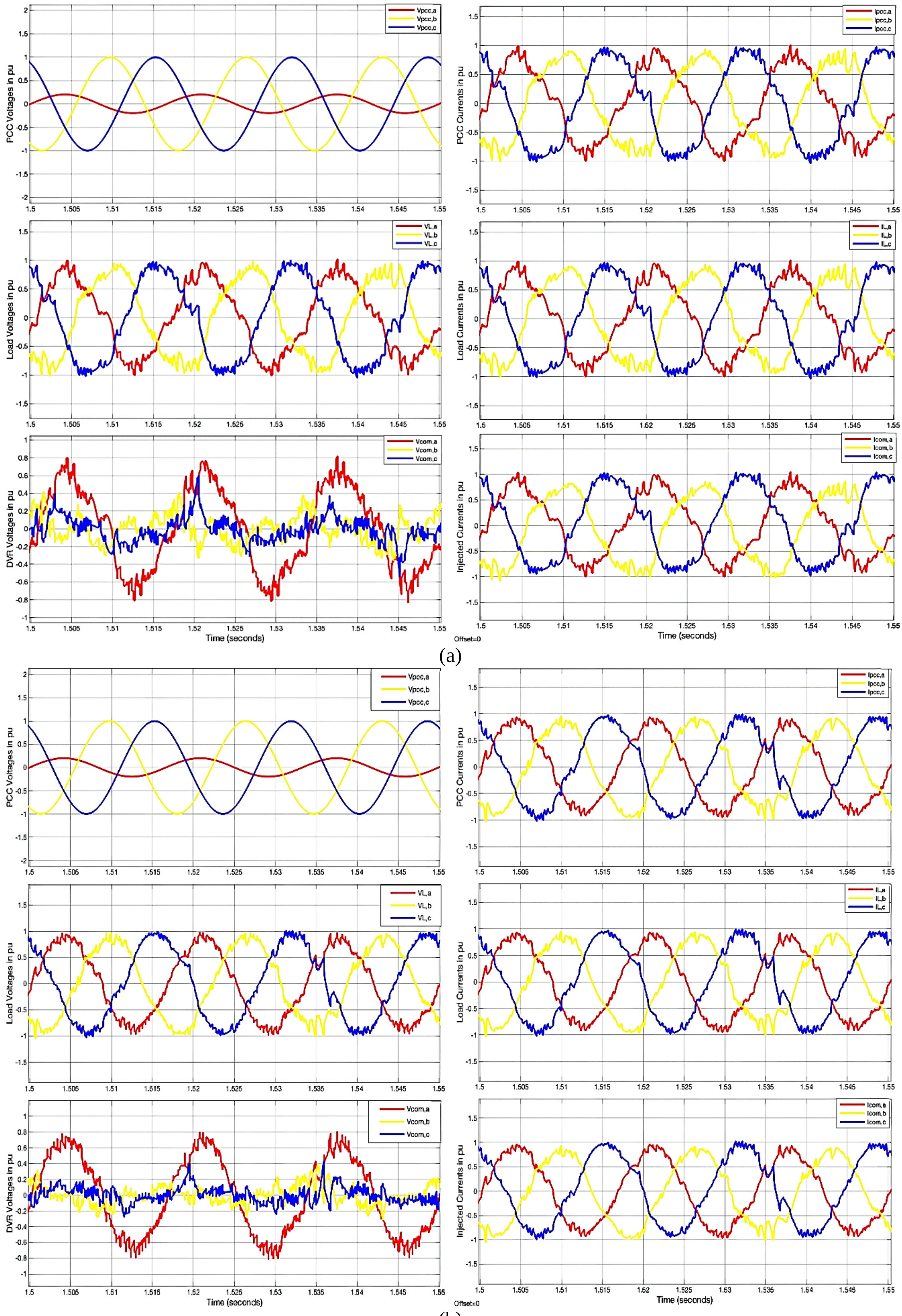
Figure 9(b) shows an unbalanced grid voltage while the load voltage is balanced due to the appropriate response of the DVR. The proposed PQ has shown better performance in balancing the load voltage with low distortion than the traditional PQ method. In all the cases, the proposed modified PQ control technique with an anti-aliasing filter under extreme conditions effectively compensates for power and improves power quality compared to the traditional PQ technique. Whereas, there are still few distortions in the load current, which must be eliminated using perfect filters.



(a)

(b)

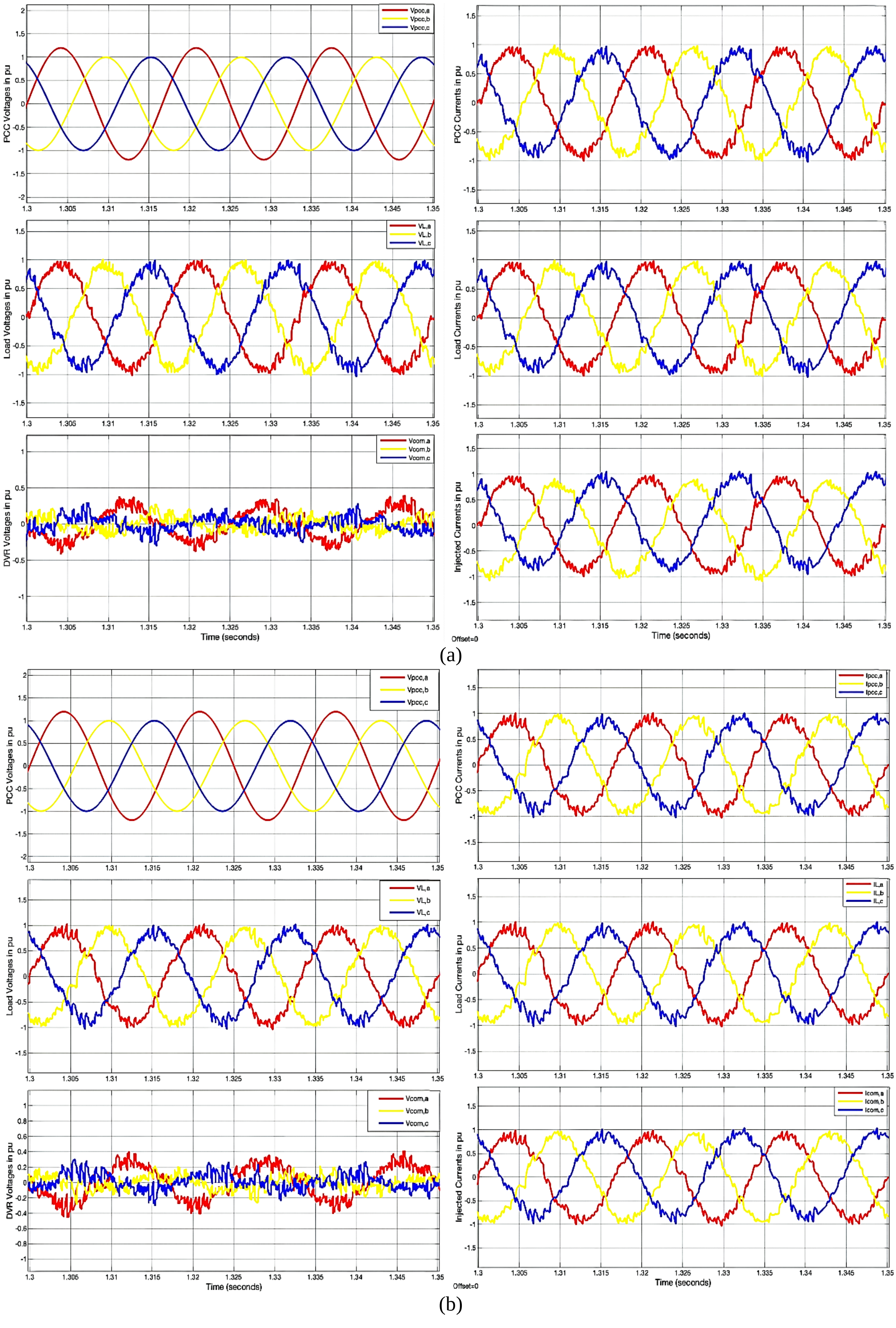
Figure 5. PCC, Load, DVR voltages and currents with sag of 80% in one phase, (a) with traditional PQ control method and (b) with proposed PQ control method



(a)

(b)

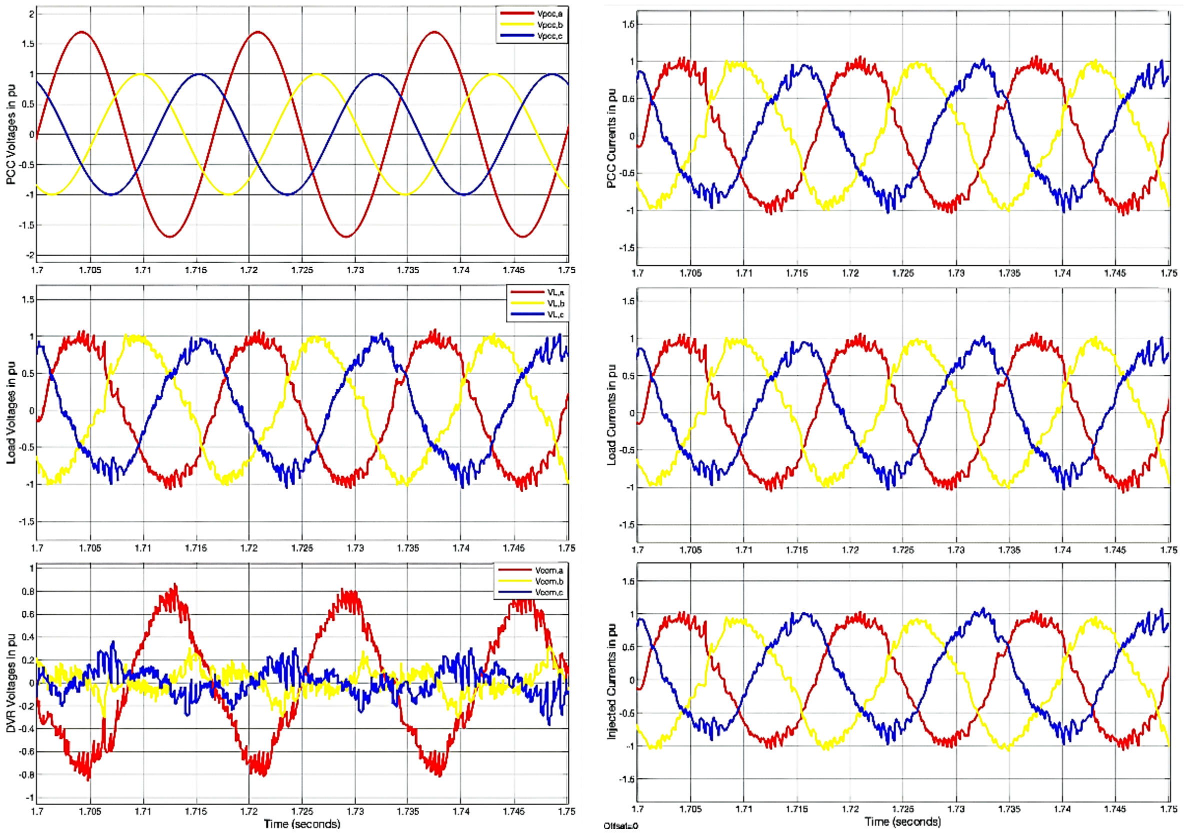
Figure 6. PCC, Load, DVR voltages and currents with sag of 20% in one phase, (a) with traditional PQ control method and (b) with proposed PQ control method



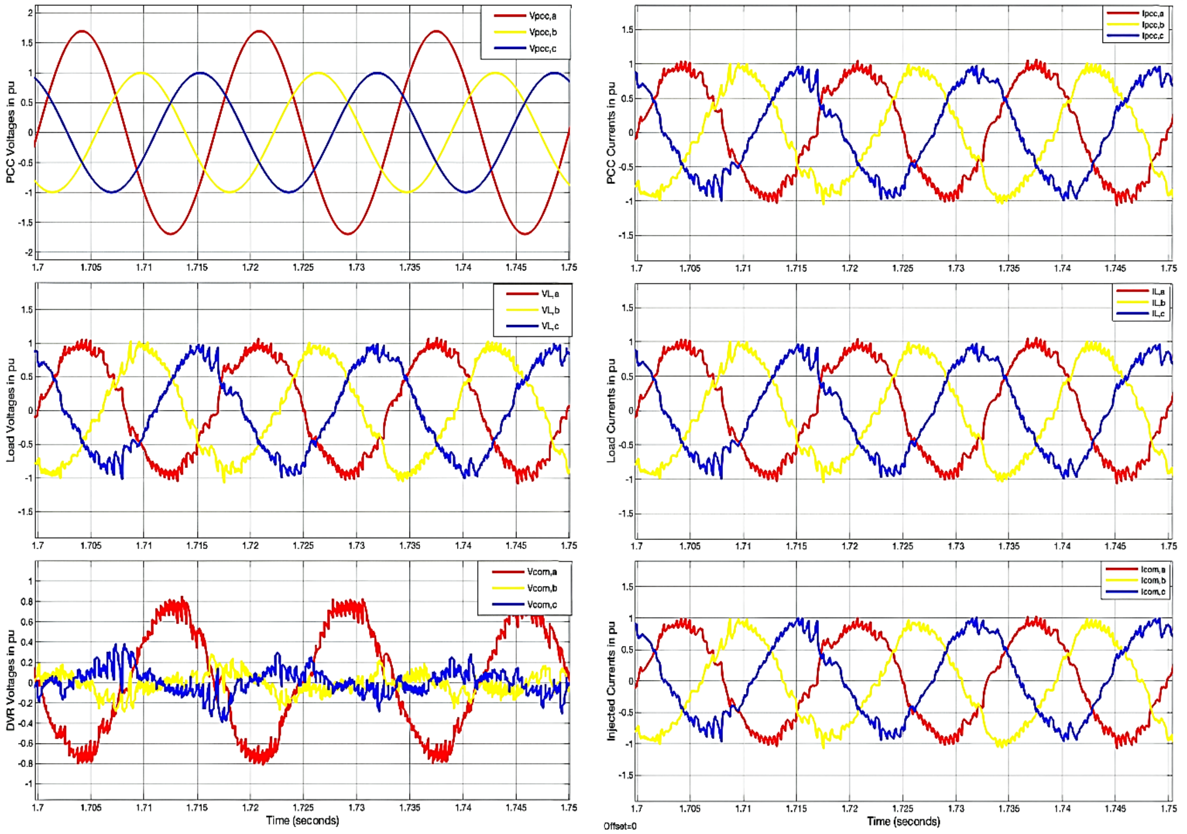
(a)

(b)

Figure 7. PCC, Load, DVR voltages and currents with swell of 120% in one phase: (a) with traditional PQ control method and (b) with traditional PQ control method

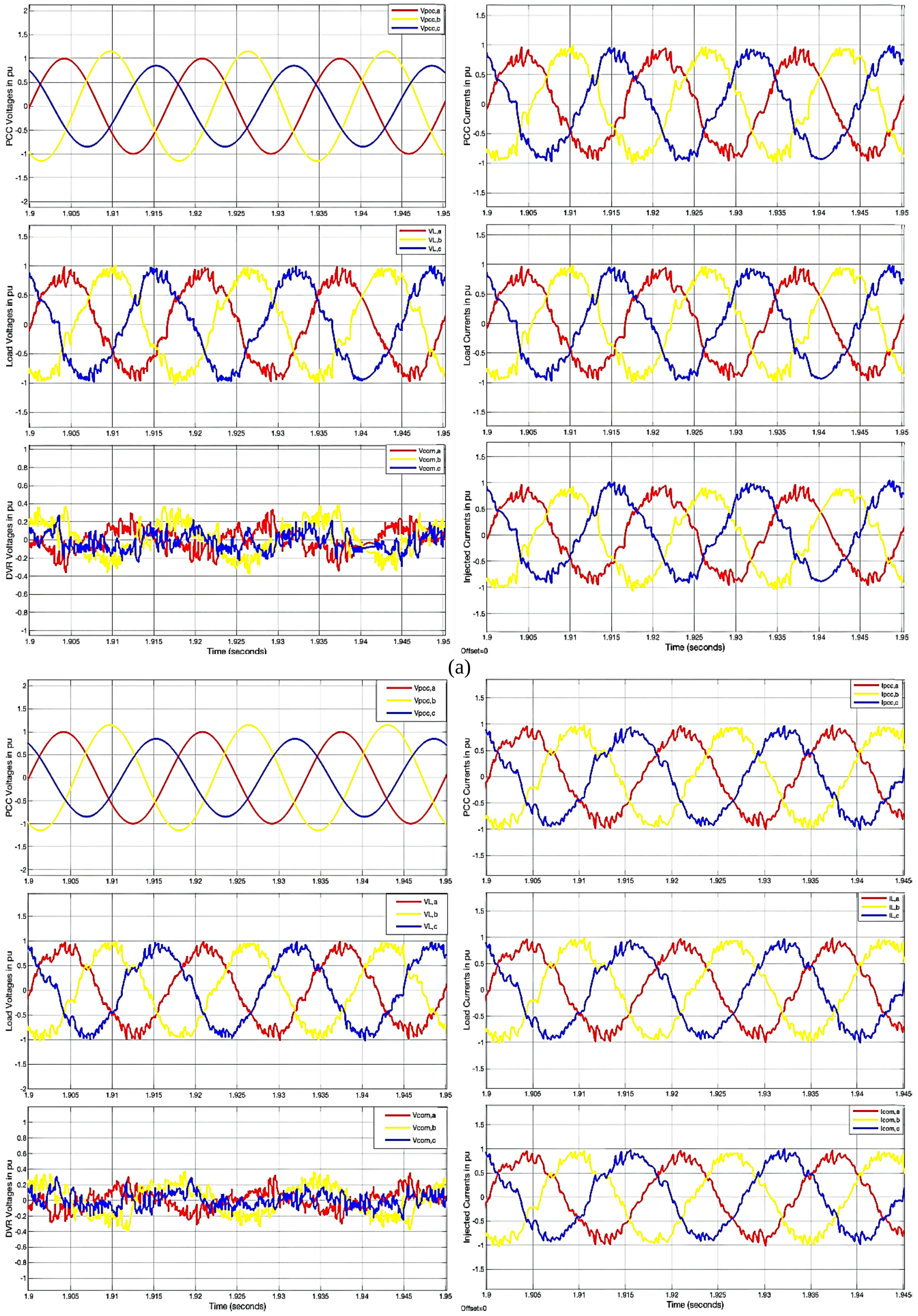


(a)



(b)

Figure 8. PCC, Load, DVR voltages and currents with swell of 170% in one phase, (a) with traditional PQ control method and (b) with proposed PQ control method



(a)

(b)

Figure 9. PCC, Load, DVR voltages and currents under unbalance grid voltage (a) with traditional PQ control method and (b) with proposed PQ control method

## 7. CONCLUSION

A power system network with a terminal voltage of 230.94 V, 60 Hz is connected to a load of 1000 W, and with a DVR with a PV system as a DC source is connected at point of common coupling to mitigate the power quality issues of 80% sag, 20% sag, 120% swell, 170% swell, and voltage unbalance. To generate the Voltage reference signal, the proposed modified PQ with an anti-aliasing filter has shown better performance in compensating for the load voltages and currents. With the traditional PQ control theory, the obtained waveforms of PCC voltage, load voltage, DVR voltage, PCC current, load current, and injected current are highly distorted. Whereas with the implementation of the modified PQ the distortion was reduced and can be observed in a waveform for the considered network at different extreme power quality issues of sag, swell, and unbalanced conditions. It can be observed that the proposed technique effectively reduces the distortion to a large extent but still consists of harmonic distortions at extreme conditions. This research work can be extended with more advanced filters and controllers like DQ control technique with evolutionary algorithms to compensate accurately.

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