Robust Control System for Mitigating Power Quality Issues in Solar-Based Dynamic Voltage Restorer Integrated with Battery Energy Storage

Ambati Supraja

Department of Electrical and Electronics Engineering
Malla Reddy Engineering College (Autonomous),
Secunderabad, Telangana, India.

T. Rajesh

Department of Electrical and Electronics Engineering
Malla Reddy Engineering College (Autonomous),
Secunderabad, Telangana, India.

P. Marimuthu

Department of Electrical and Electronics Engineering
Malla Reddy Engineering College (Autonomous),
Secunderabad, Telangana, India.

D. Chandra Sekhar

Department of Electrical and Electronics Engineering
Malla Reddy Engineering College (Autonomous),
Secunderabad, Telangana, India.

Abstract-The growing implementation of power electronics devices, ensuring power quality has become increasingly challenging. The effective compensation of non-sinusoidal, reactive, and harmonic components plays a pivotal role in maintaining power quality, relying heavily on the robustness of the control system. This research focuses on addressing voltage sag and voltage swell issues in power system networks using a solar-based dynamic voltage restorer (DVR). The integration of a series-connected DVR circuit with the SRF (Selective Harmonic Elimination) theory serves to improve power quality concerns. To achieve enhanced voltage stability and frequency regulation, a solar energy-integrated battery setup is adopted as an energy storage unit for the DVR circuit. A comprehensive evaluation of the proposed DVR control operation involves testing the devised algorithm under both balanced and unbalanced voltage sag and voltage swell scenarios. The system is meticulously modeled and simulated using MATLAB Simulink, enabling performance analysis under various conditions, including balanced and unbalanced voltage sag and voltage swell situations.

Keywords-Power Quality, Dynamic Voltage Restorer,Voltage Sag, Voltage Swell, Solar Energy System, Battery Energy Storage.

I. INTRODUCTION

Many electrical industrial plants, pharmacy industries, paper mills, and the manufacture of electronic component industries are equipped with sensitive loads [1-2]. These sensitive loads are much sensitive power distortions. On the other hand, concern to cost wise these sensitive loads are more economical [3]. Maintaining voltage stability and frequency regulations are two yet most important requirements at the customer end. In this aspect,improved power quality standards are highly noted. Voltage sag and voltage swell are the most frequentlyappearing power issues in industries. This voltage sag occurred mainly due to consistency in the switching operation of electronic devices, inrush currents a quick insertion of the large loads, high-end storms, and symmetrical or asymmetrical short circuit faults [4]. Voltage sag is defined as the decrease of the R.M.S value of the voltage from its threshold (nominal) voltage. A short duration of voltage sag that is up to 10ms (equivalent to 0.5 cycles) is permissible [5]. Voltage sag more than three cycles becauseitreduces the output voltage hence in industries the longer duration of voltage sag is not allowable because it can degrade the overplant economy.

Voltage swells occurbecause of the sudden turning off of large machines. Fast variations in load from full load to light load conditions voltage swells happen [6]-[7]. The amount of increase in R.M.S voltage from its specified threshold (nominal) value is referred to as voltage swells. The short increment of voltage can cause to damage sensitive equipment. Voltage swells severely impact the loads over the voltage sags. The influence of the voltage swelldepends on the voltage level and its duration.Atemporary rise in voltage of more than 110 percent is not permitted. The duration of the voltage swell over the three cycle'scauses to rise of the output voltage so it can severely impact the performance of the power system network [8].

If industries are constituted of solid-state devices the unbalances in voltages do not impact much. Most modern industries are composed of semiconductor devices so enhanced voltage regulation as per IEEE standards yet most required.However, for small-scale industries, several approaches are available to obtain power quality such as uninterrupted power supply, universal power supply program-based adjustable speed drives, and 1-phase power conditions [9]-[10]. For large-scale industries fly-wheel energy sources, static VARs, and DVR is highly preferred.

The main concern in employing DVR in industries is it efficiently absorbs or inserts (compensates) the voltages based on power system operating conditions [11]. The compensation of the reactive power by DVRdepends on the identification of the voltage drop or voltage rise at the reference voltage. Many well-known load voltage detecting methods are addressed in the kinds of literature [12]-[13] that are fast or discrete Fourier transform and Kalman and Extended KalmanFilter (EKF) based algorithms. TheKF-based algorithms efficiently predict the disturbance in source voltages for balanced voltage sag and swell. For unbalanced power quality issues,Synchronous Reference Frame (SRF)theory-based algorithms [14] identify the voltage abnormalities. In this paper, SRF theory is adopted to detect the voltage variations at grid voltages.

II. DVR TOPOLOGY

The Figure 1 represents the basic structure of the DVR for a power system. The DVR is a series-connected FACTS device. This circuit is basically composed of energy storage elements, a converter, filters, and a transformer.DVR can operate in different modes to restore the voltage to a nominal level. The main operating modes of a DVR are:

a. Voltage Injection Mode: In this mode, the DVR injects a voltage waveform in series with the supply voltage. The injected voltage is of the opposite phase to the sag/swell and helps to compensate for the voltage deviation, restoring the load voltage to its nominal value.

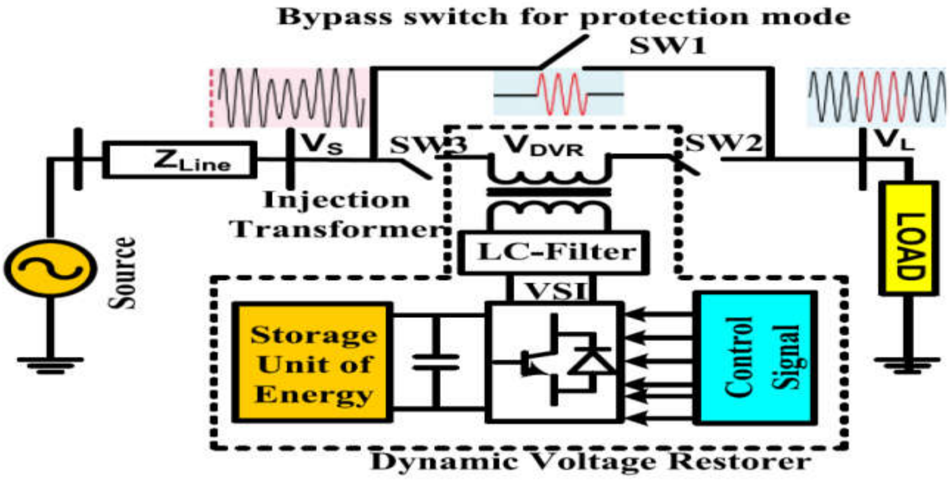

Figure 1. Power system network with DVR circuit

b. Voltage Compensation Mode: This mode involves injecting a voltage that is proportional to the magnitude of the voltage sag/swell. The DVR attempts to maintain the load voltage at the desired level by providing a compensating voltage. The compensation voltage is typically generated by a voltage source inverter within the DVR[19]-[20].

c. Voltage Source Mode: In certain situations, the DVR can operate in a voltage source mode, where it acts as an independent voltage source, generating the entire load voltage. This mode is often used when the supply voltage is severely distorted or when there's a complete outage.

d. Voltage Balancing Mode: In cases where there are multiple phases in a distribution system and voltage imbalances occur, the DVR can operate to balance the phase voltages by injecting appropriate voltages in each phase.
e. Harmonic Compensation Mode: Some DVRs are equipped with the capability to mitigate harmonic distortion in addition to voltage sags and swells. They inject harmonic currents to cancel out the harmonic components in the supply voltage.

The operating mode selected depends on the severity of the voltage disturbance, the capabilities of the DVR, and the desired level of compensation required to maintain the load voltage within acceptable limits.

III. PROPOSED SOLAR-BASED DVR CONFIGURATION

The primary goal of a DVR is to provide a stable and reliable voltage supply to sensitive loads during grid voltage disturbances, mitigating their impact on equipment and processes. To achieve this solar and battery energy sources integrated as energy storage units.

Both solar and battery sources are responsible for delivering energy to the DC link capacitor. The output voltage of the inverter contains harmonics that can be avoided by the LC filters. The required voltage is injected into the power system network with series series-connected transformer. The schematic diagram of solar based DVR circuit is depicted in Figure2.

$$V_{inj}=V_{s\text{-}presag}-V_{s\text{-}postsag}$$

$$V_{inj}=[V_{s}{}^{2}{}_{\text{-}presag}+V^{2}{}_{s\text{-}postsag}-2V^{2}{}_{s\text{-}postsag}V^{2}{}_{s\text{-}postsag}\cos\left(\theta_{s\text{-}postsag}-\theta_{s\text{-}postsag}\right)]^{1/2}$$

The required power is determined as

$$P_{inj}=\sqrt{3}*V_{inj}*I_{L}+\cos(\theta_{L}+\theta_{inj})$$

The injected active power from energy storage to load is determined as $P_{dvr}=3(V_s-V_L)\ ILcos\varphi$

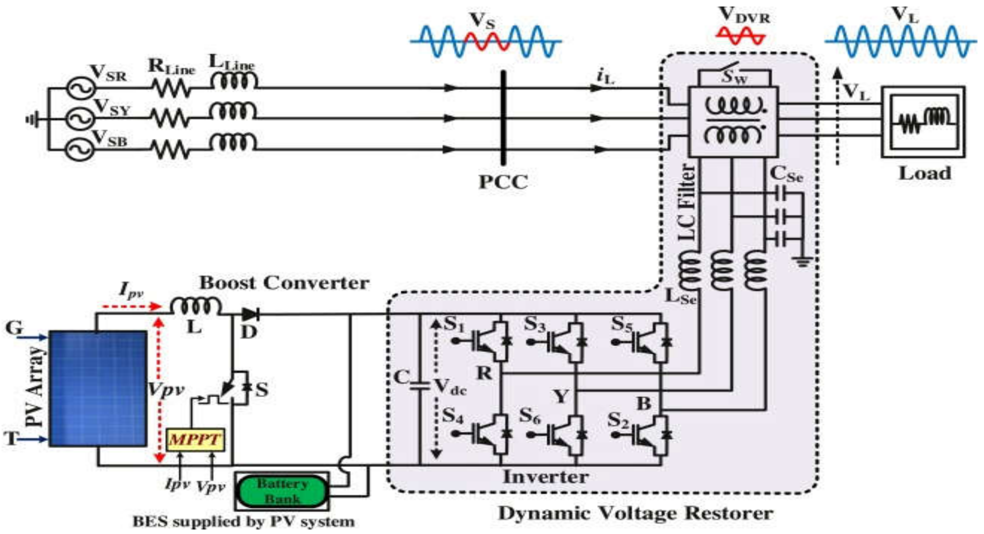

Figure 2. Power system network with solar-based DVR circuit

III. CONTROL SCHEME

Synchronous Reference Frame (SRF) theory is a control strategy commonly used in power electronics applications, including Dynamic Voltage Restorers (DVRs), to achieve effective compensation during voltage sags, swells, and other disturbances. A MATLAB circuit diagram of SRF theory-based DVR control is depicted in Figure3.

The SRF theory transforms the three-phase voltages and currents into a rotating reference frame known as the dq frame. This transformation simplifies the analysis of the system by separating the active and reactive power components. DVR control generates a reference frame based on the nominal voltage frequency. This reference frame is synchronized with the grid voltage and rotates at the same frequency. The transformed dq voltages are monitored to detect voltage sags, swells, or disturbances. Deviations from the nominal values in the reference frame signal the occurrence of a disturbance. When a disturbance is detected, the DVR calculates the required compensating voltages in the dq frame. These compensating voltages are then transformed into the three-phase abc frame and injected into the system to mitigate the disturbance [15]-[17].

3.1 Method for storing energy in batteries

When RES power output is insufficient, battery energy storage systems are used to meet load demands. The equation (1) is used to estimate and establish the battery energy storage system capacity under the conditions of the system's required power demand as follows.

$$\text{Battery } y^{b}=\frac{ad^{*}\times P^{*}{}_{j}}{\varepsilon^{*}{}_{j}\times\varepsilon^{*}{}_{B}\times DOD^{*}} \qquad (1)$$

ad^{*} = Autonomy Day,

$\varepsilon^{*}{}_{B}$= Battery efficiency,

$\varepsilon^{*}{}_{j}$=Efficiency of an inverter,

$P^{*}{}_{j}$= Demand power,

DOD^{*} = depth of discharge rate of the battery.

The battery's capacity to generate enough energy to meet the requirement on all days is known as autonomy day. The surplus energy from RES is used to charge the battery. The power of the battery is displayed in equation (2)

$$b^{*}{}_{P}= p^{*}{}_{PV}(t) + p^{*}{}_{WT}(t) - \frac{\boldsymbol{P}^{*}{}_{I}(t)}{\varepsilon^{*}{}_{i}} \ (2)$$

$P^{*}{}_{I}(t)$ = Demand for system load,

$b^{*}{}_{P}$ = Battery power.

An important battery feature known as the State of Charge (SOC) is linked to RES's inability to produce enough energy and excessive power production.

3.2 Photovoltaic Voltage System

The anticipated power is provided by the PV module using a mixture of series and parallel cells. It is possible to depict the correlation between the output current and voltage as

$$I^{*}{}_{PV} = N^{*}{}_{P}I^{*}{}_{G} - N^{*}{}_{P}I^{*}{}_{S}\left(exp\left[\frac{q^{*}}{AKT_{C}}\left(\frac{v^{*}{}_{PV}}{N^{*}{}_{S}}+\frac{R_{S}I^{*}{}_{PV}}{N^{*}{}_{P}}\right)\right]-1\right) \ (3)$$

Photocurrent I* G is created by solar irradiation, as demonstrated below:

$$I^{*}{}_{G} = \left(I^{*}{}_{SC} + k_{I}\left(T_{C} - T_{ref}\right)\right)\frac{S}{1000}(4)$$

According to the correlation shown below, I* S is the saturation current of a PV cell that changes with temperature:

$$I^{*}{}_{S} = I^{*}{}_{rs}\left[\frac{T_{C}}{T_{ref}}\right]^{3} exp\left[\frac{q^{*}E_{g}}{AK}\left(\frac{1}{T_{ref}}-\frac{1}{T_{C}}\right)\right](5)$$

A PLL is often used to generate the synchronized reference frame. It ensures the reference frame remains aligned with the grid voltage despite frequency variations or phase shifts. Using Synchronous Reference Frame theory and appropriate control algorithms, DVRs can effectively detect and compensate for voltage disturbances,

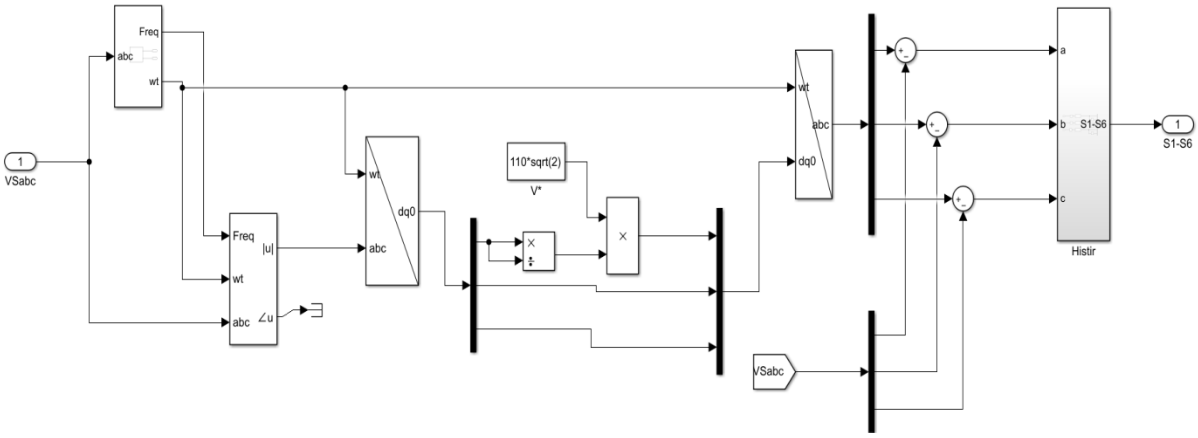

Figure 3. SRF theory-based control scheme for DVR

ensuring a stable and high-quality power supply to sensitive loads. This technique enables the DVR to respond quickly to voltage variations and provide seamless compensation during power quality issues [18]-[20].

IV. SIMULATION RESULTS

The performance of the proposed solar-based DVR control schemehas tested and investigated in power system network under balanced and unbalanced operating scenarios with 20% voltage sag and 70% voltage swell.

Case 1: Balanced Sag and Swell conditions

The equal dip or rise in 3-phase grid voltages is generally referred to as balanced sag or swell conditions. This is occurred under symmetrical (L-L-L or L-L-L-G) fault conditions.

Scenario 1: 20% balanced voltage sag

In this scenario,a 20% decrease in balanced 3-phase grid voltage is considered from 0.8 seconds. The obtained simulation results in this operating condition are represented in Figure 4. From the simulation responses it can be observed that at grid voltages distortion time (after 0.8secs). At this time the DVR can be operated in boost mode andinject the voltage into the power system network in a series manner to compensatefor the corresponding 20% grid voltage sags. Hencethe load voltage balances at 1.0p.u. Even 20% variations in balanced sag grid voltages also constant load voltage are supplied to the load.

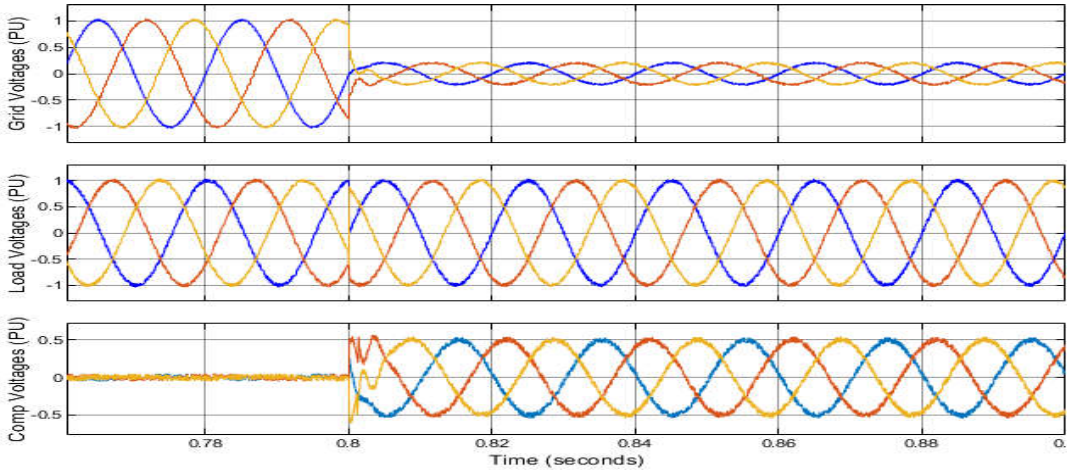

Figure 4. Simulation responses of grid, load, and DVR compensated voltages under 20% balanced sag in 3-phase grid voltages.

Scenario 2: 70% balanced voltage swell

In this scenario 70% rise in balanced 3-phase grid voltage (1.7p. u) is considered from 1.1secs. The obtained simulation results in this operating condition are depicted in Figure 5. From the simulation responses it can be confirmedthat at grid voltages distortion time (after 1.1secs). At this time the DVR can be initiated as in buck mode and absorb the increased grid voltage from the power system network tocompensate for the corresponding 70% grid voltage swell.Thus,load voltage balances at 1.0p.u. Even 70% variations balanced swell in grid voltages also constant load voltage is supplied to the load.

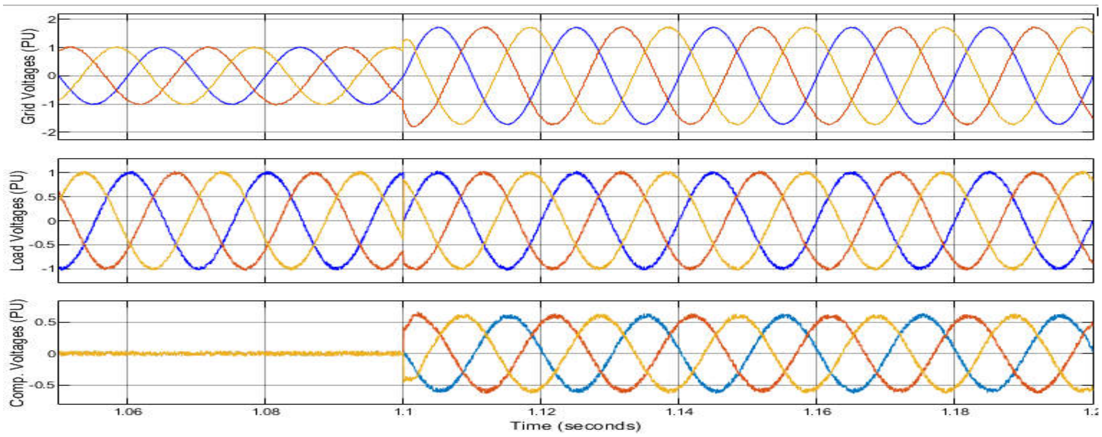

Figure 5. Simulation responses of grid, load, and DVR compensated voltages under 70% balanced swell in 3-phase grid voltages.

Case 2: Unbalanced Sag and Swell conditions

The dip or rise in 3-phase grid voltages in any phase of the grid voltages in an unbalanced manner is generally referred to as balanced sag or swell conditions. This type of issueoccurred under asymmetrical (L-G or L-L-G) fault conditions.

Scenario 1: 20% unbalanced voltage sag

In this scenario, a 20% decrease in unbalanced 3-phase grid voltage is considered from 2.0 seconds. The obtained simulation results in this operating condition are configured in Figure 6. From the simulation responses it can be observed that at grid voltage distortion time (after 2.0secs), the DVR can be operated as in boost mode and compensating the corresponding 20% grid voltage sag to make load voltage balance at 1.0 p.u. Even 20% variations in unbalanced sag grid voltages also constant load voltage are supplied to the load.

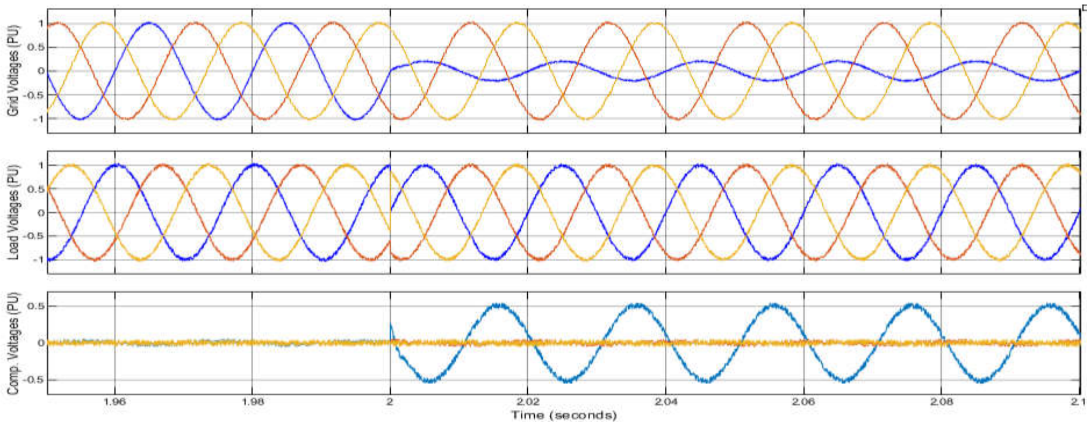

Figure 6. Simulation responses of grid, load, and DVR compensated voltages under 20% unbalanced sag in grid voltage.

Scenario 2: 70% unbalanced voltages swell

In this scenario, a 70% increase in unbalanced 3-phase grid voltage is considered from 2.3 seconds. The obtained simulation results in this operating condition are mentioned in Figure 7. From the simulation responses it can be clear that at grid voltage distortion time (after 2.3secs), the DVR can be operated as in buck mode and compensating the corresponding 70% grid voltage swell to make load voltage balance at 1.0 p.u. Even 70% variations in unbalanced swell grid voltages also constant load voltage are supplied to the load.

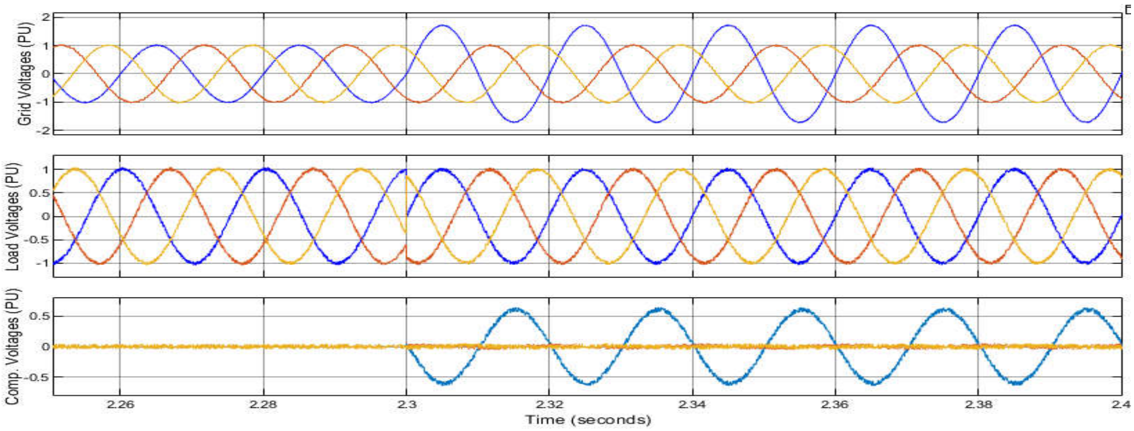

Figure 7. Simulation responses of grid, load, and DVR compensated voltages under 70% unbalanced swell in grid voltage.

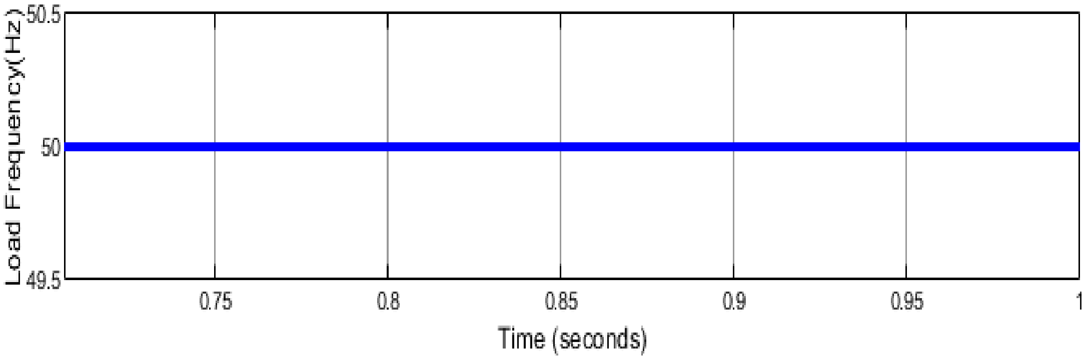

Figure 8.Frequency response under balanced Sag and Swell conditions

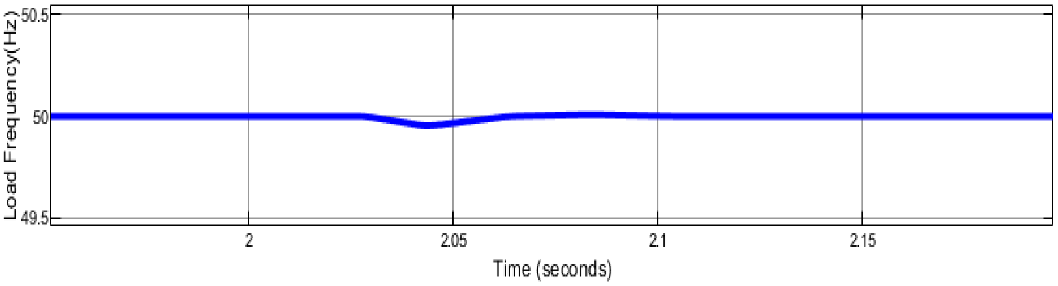

Figure 9. Frequency response under unbalanced sag and Swell conditions

As can be inspected from the frequency responses that are from Figure 8 and Figure 9 it is evident that the proposed DVR control scheme provides more robust frequency responses for both balanced and unbalanced voltage sag and swell conditions. For balanced and unbalanced three-phase voltage conditions, the frequency is restored to 50Hz very quickly by employing the proposed solar-based DVR control approach.

V. CONCLUSION

This paper investigates the mitigation of the voltage sag and swells in the power system network with solar-based DVR control. For the fast and efficient operation of DVR control, SRF theory is employed. The SRF theory detects the changes in grid voltages very quickly and operates to DVR immediately.From simulation outputs, it is proven that the proposed DVR control operates well and exhibits more transient and steady-state responses for severe impact voltage sag and voltage swells, even for balanced and unbalanced conditions.

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