PV source in SRF–Controlled DVR system for enhanced voltage sag and swell conditions

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***Abstract*—Power quality problems in today's distribution systems result from the growing use of delicate and essential equipment components, such as communication networks, process industries, and precise manufacturing processes. Transients, sags, swells, and other aberrations in the supply voltage's sinusoidal waveform impact this device's operation. The SRF approach uses a sequence component identification method rather than signal filtering. The control system can respond while maintaining stability and operating conditions, including extreme swells and sags. In order to generate the load voltage reference, these positive sequence components are converted into DQ coordinates. Voltage source inverter (VSI) switches use hysteresis voltage control to produce firing signals by comparing the reference voltages to the actual load voltages.**

The proposed DVR consists of a PV source as an energy storage device, a Voltage Source Inverter (VSI), a Hysteresis voltage control to generate switching pulses, an LC filter, and a series transformer. The proposed topology does not use P, PI, PID controllers, artificial intelligence, or fuzzy techniques for compensation. Developed Simulink model by different conditions like 20% sag and 70% swell in grid voltage and observed the mitigation of voltage by DVR and harmonic analysis.

***Index Terms*—Dynamic voltage restorer (DVR); voltage sag; voltage swell; harmonics; PV source; synchronous reference frame (SRF) technique**

I. INTRODUCTION

Among the sensitive loads susceptible to power-supply disruptions are producers of semiconductor devices, paper mills, medical equipment, and factory automation. In today's power networks, the growing demand for high power quality and voltage stability poses a severe danger and is a regularly occurring power-quality issue. Voltage sag and swell are now understood to have serious, expensive effects such as production loss and sensitive load tripping. Many electrical networks experience voltage sags due to line-to-ground faults caused by severe storms and lightning striking power lines. Short circuits at the beginning of the power transmission line, the parallel power distribution line connected to the point of standard coupling (PCC), high inrush currents associated with large machine starts, sudden changes in load, power transformer energization, and switching activities within the power system network are a few more factors that cause these disturbances. The brief decrease in the root mean square (RMS) voltage at a specific point in the electrical system below a predefined threshold is known as voltage sag. A brief fluctuation in the RMS voltage value between 10 and 90% of the nominal voltage occurs over some time greater than 0.5 power frequency cycles (10ms) but less than or equal to 60 seconds. People often need to understand the terminology used to describe the degree of voltage sag. IEEE 1159-2019 states that sag to 70% is acceptable, meaning that the line voltage is lowered to 70% rather than 70% of its standard value. A voltage dip of 70% indicates a voltage drop of 70% from the standard voltage of 100%. There will be a 30% drop or 30% residual voltage. Various circumstances, including sudden changes in load resistance and the shutdown of heavy loads, cause swells. During a voltage swell, the RMS voltage will momentarily rise above a designated level. Both voltage level and duration influence the voltage swell; its start threshold is 11%, and its duration spans 0.5 cycles (10ms) to 60 seconds. Often, the effects of a swell are more detrimental than those of sag [1]. Power supply equipment faults result from overvoltage problems, albeit the effects may be gradual and cumulative. The Synchronous Rotating Frame (SRF) uses Park's and Clark's transformations to determine swell and sag. The SRF, or Park's transformation, is limited to producing balanced three-phase sags. Different modules for recovering positive and negative sequence components from fundamental and harmonic waves simplified multiple SRF transforms [5–6].

II. LITERATURE REVIEW

In electrical networks, various types of custom power devices are used to resolve problems with power quality. Every device has advantages and disadvantages. The DVR is recommended since the SVC cannot regulate active power flow. Another factor is the DVR's larger energy capacity than SMES and UPS devices. In addition, the DVR is less expensive and smaller than the DSTATCOM and other power devices. Based on these considerations, the DVR is commonly regarded as an excellent custom power device for minimizing voltage sags, swell compensation, harmonics, and power factor correction. DVR is a modern and effective device for improving power quality [15], [16], [17]. The energy is stored in the battery after conversion from AC to DC by the uninterruptible power supply. After being transformed into AC, this stored DC is sent to the utilities. By using a double conversion procedure, it mitigates most power quality issues [18]. A solid-state transfer switch does not require an energy storage device for mitigation.

It connects to a healthy feeder and disconnects the faulty feeder in case of a power quality disruption [19]. Since UPS needs to operate constantly, whether or not there is a power quality issue, DVR is more economical and efficient than UPS. As a shunt controller, DSTATCOM requires a transformer with a high-power rating that can handle high shunt injection currents to reduce voltage sag, swell, or interruption [21]. The literature review presents a variety of DVR topologies. Direct converter-based DVRs are described in [6] and [7], where the AC supply side provides the power needed for compensation. AC/AC direct converters produce the compensatory voltage to mitigate voltage sag and swell. PV sources are used by DVRs based on energy storage devices to store DC power. A voltage source inverter (VSI) produces the compensating voltage from the DC power in the PV source. Since the compensating voltage is produced from the DC power in the PV source, these topologies may eliminate all voltage sag, swell, and outages. Using DVR based on energy storage devices, the Cuckoo search algorithm is employed [22] to reduce power quality issues. In order to improve the capabilities of DVRs, the Zero Active Power Tracking Technique is presented in [23], [24]. It combines the synchronous reference frame method with a hysteresis voltage control loop. In [25], the Harris Hawks Optimization Algorithm is used to improve the DVR control system. A discrete time-based control technique is used for quick transient voltage sag correction in DVR [26]. In [27], power quality is improved using an adaptive Neuro-fuzzy control method based on soft computing. In [28], a novel recurrent compensatory micro fuzzy neural network controller is utilized to enhance the transient responses of the DC-link voltage and the three-phase load voltage under sudden grid voltage distortion conditions. A predictive space vector transformation with a proportional resonant controller is presented for DVR-based power quality enhancement by [29]. Both line current and supply side voltages are detected to create the compensatory voltage [30]. It presents an improved instantaneous reactive power theory-based management of DVR for correcting excessive sag and swell.

However, the proposed control technique only detects supply-side voltage to create compensatory voltage. Moreover, for voltage sag and swell compensations, the mentioned DVR topologies use specific control loops, algorithms, intelligent controllers, P controllers, PI controllers, or PID controllers. However, no algorithm, PI controller, current measurement, artificial intelligence, Neuro, or fuzzy approach compensates for the suggested topology. The suggested topology involves calculating the supply-side voltage and converting it into DQ0 values. The project's main objective is to improve injection capabilities by controlling the DVR. The energy storage device's size limits the DVR's injecting capabilities and the control algorithm. Thus, an energy storage study is carried out when a PV source is used as the energy storage device. The thesis focuses on three power quality issues: 1) voltage sag, 2) voltage swell, and 3) harmonics.

III. MATERIALS AND METHODOLOGY

This project suggests using SRF to regulate DVRs. A time-domain approach for recognizing the positive sequence component of grid voltage is the foundation for the proposed detection method. The SRF approach is based on a sequence component detection methodology that does not use signal filtering or adaptive mechanisms such as PI controllers. The result is reduced computing time, which allows the control system to respond while maintaining reasonable stability and a wide variety of operating situations, including severe swells and sags. Furthermore, this control system achieves virtually zero tracking error under all abnormal operating conditions. The control system is validated by simulation.

3.1 DYNAMIC VOLTAGE RESTORER (DVR):

To restore the load side voltage to the correct amplitude and waveform, injecting compensation voltage with the desired magnitude and frequency is essential. Injecting up to 50% of the standard voltage is possible [16], but only briefly (0.1 seconds). Most voltage sags, nevertheless, are far smaller than 50%.

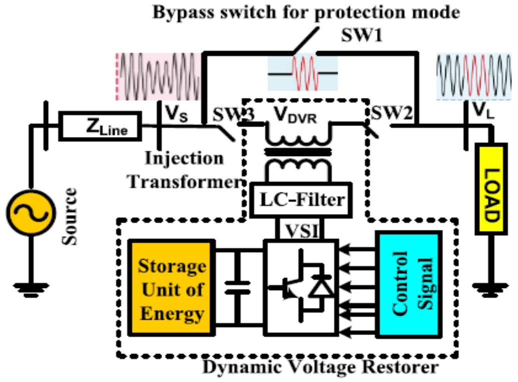

FIGURE 1. Basic circuit of power system with DVR.

The DVR is believed to be the regulating apparatus. DVRs might be valuable tools for end consumers who experience unintentional power quality disruptions [29] [30]. Fig.3.1.1 depicts a simple DVR power system circuit and a control circuit to inject compensated voltage and keep the voltage at the correct level. DVRs are often mounted on a vital feeder, providing the necessary reactive power internally, while DC energy storage supplies the active power.

3.1.1 CONTROL STRATEGIES AND ALGORITHMS OF DVR: The primary focus of the DVR's control system is voltage disturbance detection. In particular, when dealing with delicate loads, the detection system must be swift enough to precisely detect the voltage disturbance and evaluate the DVR's performance. Several techniques, including RMS, Peak Value, DFT, Fourier Transform, Wavelet Transform, Windowed Fast FT, ABC to SRF axis translation, KF (PLL), and SRF, have been proposed to detect voltage disturbances.

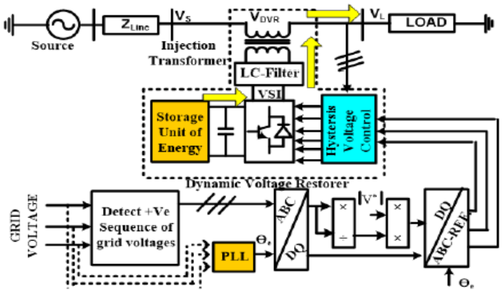

FIGURE 2. Schematic diagram of the proposed system with DVR.

The suggested setup includes a three-phase load, an injection transformer, a supply (grid) voltage with grid impedance, and the DVR system. The DVR system consists of a harmonic passive filter and a voltage source inverter (VSI) driven by a DC power source with a DC link capacitor. In this system, a three-phase load is taken into account.

3.2 ENERGY STORAGE UNIT:

A DVR system's energy storage system (ESS) and DC-link capacitor are two crucial parts that provide the active power needed to fend against protracted outages. The DC link capacitor, an energy storage device, produces high-power, short-duration pulses to provide dynamic responsiveness. ESS in a DVR typically comprises a battery, including the energy and power density, life cycle count, and discharge durations of standard capacitors and batteries. Here, we use renewable energy, i.e., Solar, to compensate for the drop. The DC solar energy is converted to AC and injected to compensate for maximum voltage. It is employed to enhance the power quality of on-grid photovoltaic systems. Preserve the transmission of a constant voltage across the grid. Lower the voltage and drop across the grid. PV source should be used in an effectual control approach to meet the grid's load requirement. To provide PV-fed DVR configuration based on VSI that integrates PV panels. A precise detection technique and effective voltage sag, surge, and interruption compensation are offered to increase the DVR controller's effectiveness. The SRF method is provided to enhance the VSI-DVR's control performance. By (1) detecting start/stop locations of voltage disturbances, (2) reducing transients, (3) mitigating voltage disturbances, and (4) reducing injected voltage THD, it performs the other two standard DVR systems. Thus, the power quality of the output voltage is improved. Integration of the PV panel is recommended for the proposed VSI-DVR. Because (1) Sunshine reduces the energy limitations of batteries as a freely accessible source; (2) Solar power recharging provides a valuable alternative for DVR

3.3. SYNCHRONOUS REFERENCE FRAME ALGORITHM:

Symmetrical components, or positive and negative sequence components, appear in the system voltages that impact the load voltages during abnormal operating situations. The proposed control system aims to distinguish the positive sequence components from the system voltage based on the appearance of harmful sequence components using the suggested detection approach. The reference of load voltages is created by converting these positive sequence components into SRF coordinates.

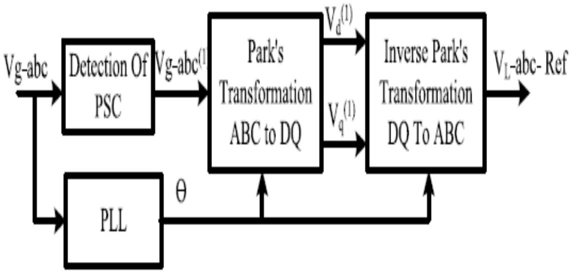

Fig.3: Synchronous reference frame (SRF) method

The reference and actual load voltages are compared using hysteresis voltage control to create voltage source inverter (VSI) switching signals. The suggested detection method helps find positive sequence components instantly and continuously, and load voltage fluctuations can be compensated. It also helps adjust the voltage amplitude to the required level with the correct duration of compensation. The control system consists of a voltage controller and a method for generating reference signals. The SRF approach is adopted in the reference signal-generating process. The SRF technique features a phase-locked loop (PLL) and Park transformation. It also includes a peak finder methodology and a method for detecting positive sequence components.

3.4 HYSTERESIS VOLTAGE CONTROLLER:

A hysteresis voltage controller produces the voltage source inverter's switching signals. Its features include effective dynamic response, excellent precision, low cost, and simple implementation, making it superior to conventional controllers like PWM and SVPWM. The hysteresis control approach overcomes the drawbacks of traditional systems, such as switching losses with high switching frequency electromagnetic interference difficulties owing to higher-order harmonics and a decrease in available voltage. The actual load voltages and the produced voltage references are contrasted. In hysteresis control, a reference voltage signal corresponds to the desired voltage level at the standard coupling (PCC) point. The DVR continuously monitors the actual voltage and compares it with the reference.

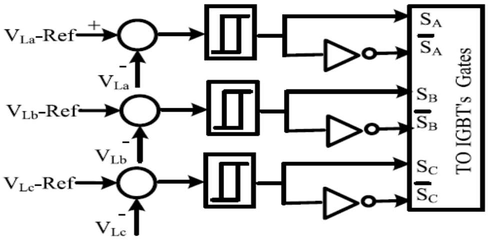

Fig. 4: Hysteresis voltage controller.

The Fig. 4 illustrates how the hysteresis band handles the difference between the reference and absolute voltage values, resulting in the ring signals of inverter IGBT switches.

IV. SIMULATION RESULTS

The Simulink simulates the DVR based on the control strategy. The SRF method is shown in the figures below.

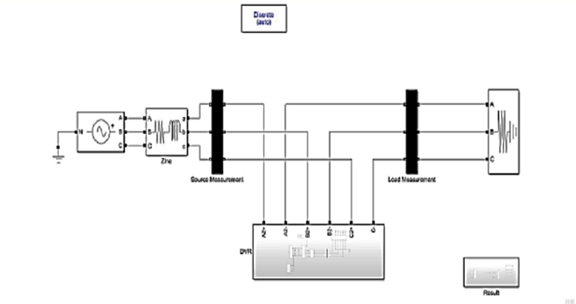

Fig.5: Simulink model of proposed system

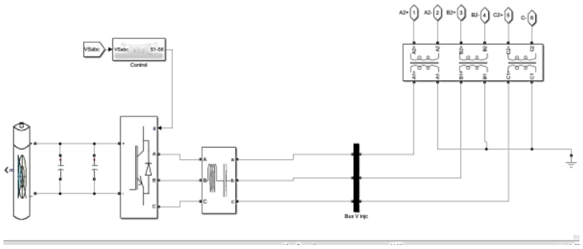

Fig.6: Configuration of DVR with battery source

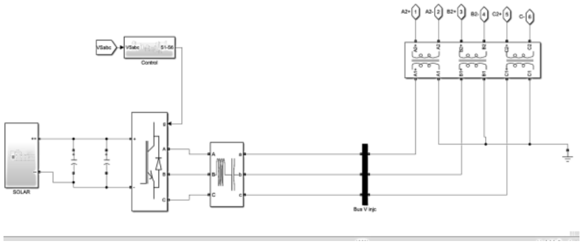

Fig.7: Configuration of DVR with PV source

V. RESULTS AND DISCUSSIONS

4.1 BATTERY-FED DVR VOLTAGE

CASE 1: 20% SAG

Figure 8 shows the grid voltage with a severe 20% sag in the grid voltage from 0.8 seconds, together with the load voltage and compensated voltage regulated by the SRF technique. In this case, the load voltage wave distortion is relatively low. It is noticeable that the SRF technique responds so quickly that the moment of injecting compensating voltage approaches the instant of 0.8 sec.

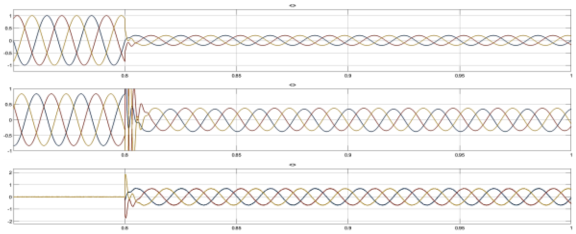

Figure 8: Simulation results of (a) grid voltages, (b) load voltage, and (c) Battery DVR voltages under 3ϕ grid voltage sag of 20%.

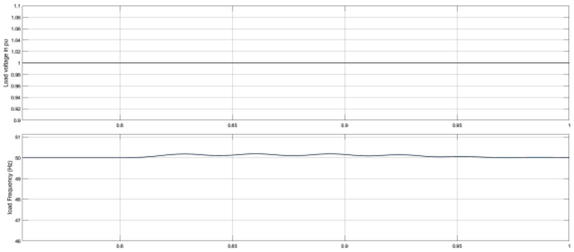

Figure 9: [Upper] per unit load voltage, [lower] Load frequency under 3ϕ grid voltage sag of 20%.

Figure 9 shows the load voltage per unit and frequency for the SRF technique, with 20% voltage sag. The data indicates that the SRF technique is quick enough to detect any sag and immediately correct the voltage. The SRF method shows no slight frequency deviation from the nominal value of 50 Hz**,** suggesting that the controller keeps the system stable.

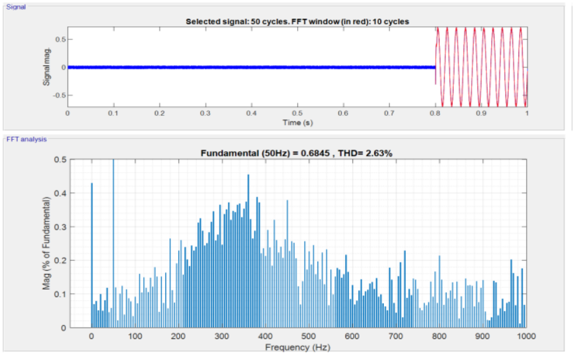

Figure 10: THD analysis of source voltage of DVR with Battery under Harmonics compensation scheme

Figure 10 shows the FFT analysis for the DVR with the battery. The waveform of Injecting voltage has a total harmonic distortion (THD) value of 2.63%, which is very low. The fundamental (50 Hz) is 0.6845 at the time of disturbance.

CASE 2: 70% SWELL**:** Figure 11 shows the simulation results for a severe 70% swell controlled by the SRF technique for grid, load, and compensation voltage. The load voltage displays a favorable voltage profile with reduced distortion and no swell sections in any of the phases, and the SRF technique initiates the compensating voltage at precisely 1.1 seconds.

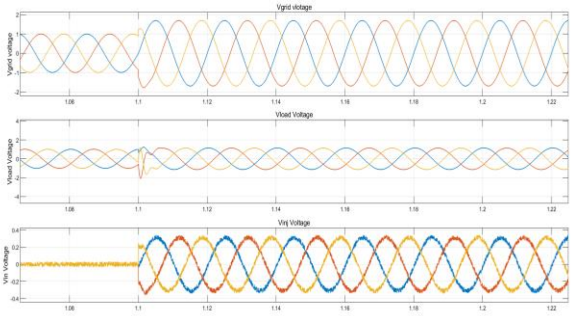

Figure 11: Simulation results of (a) grid voltages, (b) load voltage, and (c) Battery DVR voltages under 3ϕ grid voltage swell of 70%.

Figure 12 illustrates the SRF method per unit load voltage and frequency. According to the SRF technique, the load voltage has no swell and steady features, which indicates that in conditions of 70% swell, the SRF has the lowest frequency fluctuation, as demonstrated by the SRF technique. SRF has shown quick and efficient control of the features of load frequency.

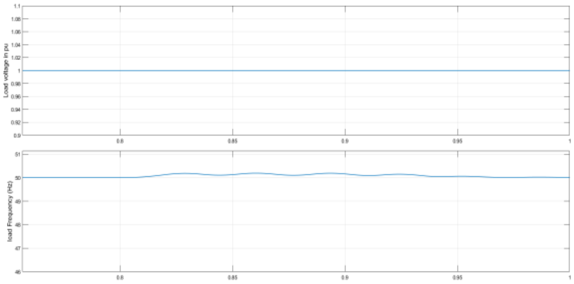

Figure 12: [Upper] per unit load voltage, [lower] Load frequency under 3ϕ grid voltage swell of 70%.

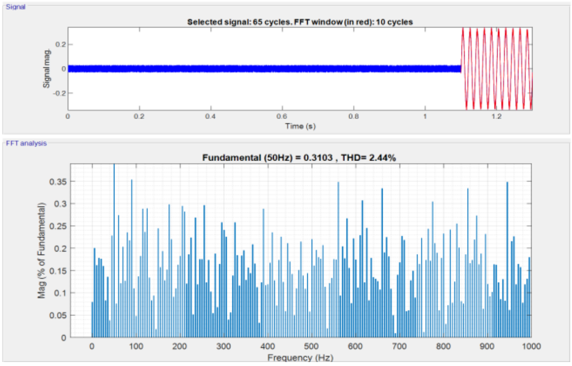

Figure 13: THD analysis of source voltage of DVR with Battery under Harmonics compensation scheme

Figure 13 shows the FFT analysis for the DVR with the battery. The waveform of Injecting voltage has a total harmonic distortion (THD) value of 2.44%, which is very low. The fundamental (50 Hz) is 0.3103 at the time of disturbance.

4.2 PV SOURCE FED DVR VOLTAGE

CASE 1: 20% SAG

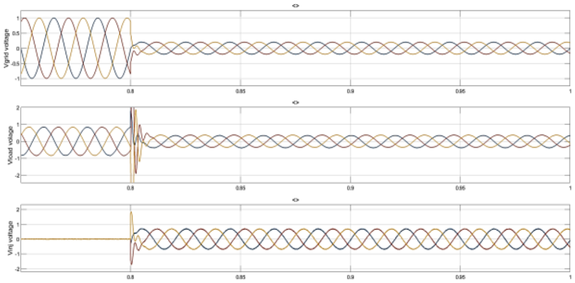

Figure 14: Simulation results of (a) grid voltages, (b) load voltage, and (c) PV-fed DVR voltages under 3ϕ grid voltage sag of 20%.

Figure 14 shows the load voltage, compensated voltage controlled by the SRF method and the grid voltage with 20% sag in the grid voltage from 0.8 seconds. The load voltage wave distortion in this instance is relatively minor. The SRF technique reacts so fast that the injection of compensatory voltage occurs almost precisely at 0.8 seconds.

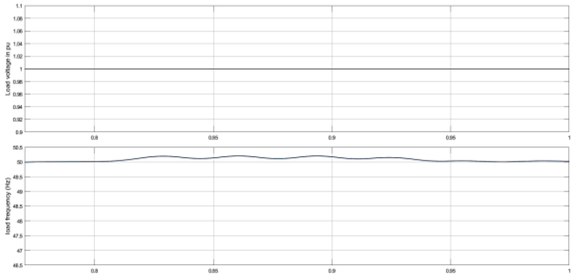

Figure 15: [Upper] per unit load voltage, [lower] Load frequency under 3ϕ grid voltage sag of 20%.

Figure 15 displays the load voltage per unit and frequency for the SRF method, with 20% voltage sag. The data suggests the SRF technique is fast enough to identify any sag and promptly adjust the voltage. The SRF approach indicates minimal frequency variation from the nominal value of 50 Hz, indicating that the controller is effectively maintaining system stability.

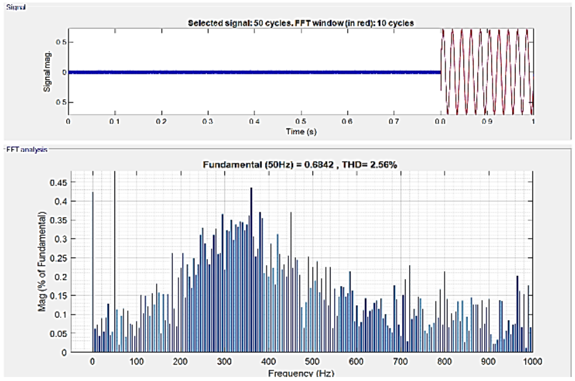

Figure 16: THD analysis of PV source voltage of DVR under Harmonics compensation scheme

Figure 16 shows the FFT analysis for the DVR with the battery. The waveform of Injecting voltage has a total harmonic distortion (THD) value of 2.56%, which is very low. The fundamental (50 Hz) is 0.6842 at the time of disturbance.

CASE 2: 70% Swell: Under 3ϕ grid voltage, the swell is 70%. Figure 17 displays the simulation results for a severe 70% swell managed using the SRF approach for grid, load, and compensation voltage. The load voltage has a favorable voltage profile with less distortion and no swell sections in any phase, and the SRF technique starts the compensating voltage at precisely 1.1 sec.

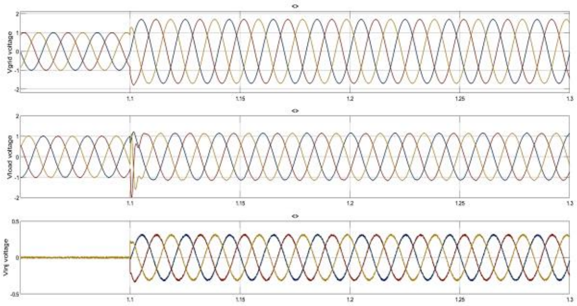

Figure 17: Simulation results of (a) grid voltages, (b) load voltage, and (c)PV- fed DVR voltages

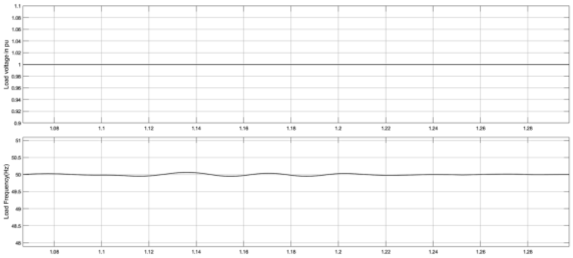

Figure 18: [Upper] per unit load voltage, [lower] Load frequency under 3ϕ grid voltage swell of 70%.

Figure 18 displays the load voltage per unit and frequency for the SRF approach with a 70% voltage swell. The data shows that no swell was observed while employing the SRF technique, suggesting that it is fast enough to identify any swell and instantly adjust the voltage.

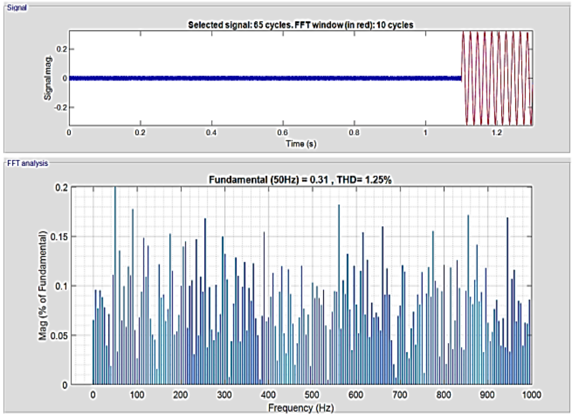

Figure 19: THD analysis of PV source voltage of DVR under Harmonics compensation scheme

Figure 19 shows the FFT analysis for the DVR with the battery. The waveform of Injecting voltage has a total harmonic distortion (THD) value of 1.25%, which is very low. The fundamental (50 Hz) is 0.31 at the time of disturbance.

4.3 COMPARATIVE ANALYSIS OF %THD ANALYSIS OF BATTERY FED BY DVR AND PV FED BY DVR

Scenarios	% THD of the Source voltage of DVR with Battery	% THD of the source voltage of DVR with PV Source
20% SAG	2.63	2.56
70% SWELL	2.44	1.24

Table 1: Comparative analysis of % THD analysis of battery fed by DVR and PV fed by DVR

The PV-fed DVR shows superior performance, particularly in the case of voltage swell, where it achieves a notably lower % THD (1.24%) than the battery-fed DVR (2.44%). The PV-based DVR is more effective at mitigating harmonics and stabilizing the voltage during high-voltage conditions. Its dynamic response to voltage variations makes it an excellent choice for environments where voltage swell is expected. On the other hand, during 20% voltage sag, the performance of both systems is closely matched, with the PV-based DVR having a slight edge (2.56% vs. 2.63% THD). It indicates that while both batteries and systems are suitable for sag conditions, the system still offers a minor advantage in terms of harmonic distortion.

VI. CONCLUSION

The simulation results proposed that the DVR method, which uses an energy storage device as the PV source, can mitigate voltage sag, swell, and harmonics by using the SRF method. The control is effortless, robust, and simple since a voltage source inverter with just six IGBT switches is used for a three-phase system. Various topologies were proposed in the literature to reduce voltage sag, swell, and interruption utilizing DVR; nevertheless, all developed controllers such as P, PI, PID, fuzzy logic, or neural network controllers. However, the proposed model is proven to mitigate voltage sag, swell, and harmonics; no controller is needed.

The proposed method generated the hysteresis voltage control, firing pulses required for producing compensating voltage to reduce the sag and swell without a controller, just by employing the SRF approach. The simulation results proved that the proposed system compensates for 20% voltage sag and 70% voltage swell without needing controllers using a DVR based on an energy storage device. Harmonics are analyzed with PV-fed DVR and battery-fed DVR compensating voltages. Due to harmonic reduction, a PV-based DVR system is recommended for frequent or significant voltage swell scenarios (1.24% vs. 2.44% THD). Both systems perform similarly for voltage sag conditions (2.56% vs. 2.63% THD), though the PV-based DVR still significantly improves harmonic suppression**.**

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