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Novel DSOGI-Based SRF Controller for Power Quality Enhancement in Three-Phase-Grid-Connected Dynamic Voltage Restorer Integrated With Photovoltaic System

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WHAT IS ALREADY KNOWN ON THIS TOPIC?

- *Many authors working on conventional controllers have provided numerous types of topologies and solutions for system efficiency enhancement under weak environment conditions.*

WHAT THIS STUDY ADDS ON THIS TOPIC?

- *This study adds utilization of a D-SOGI-based controller to enhance the grid synchronization along with DC link voltage regulation.*

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ABSTRACT

This paper presents a DSOGI-based SRF control methodology that regulates load voltages using a dynamic voltage restorer (DVR) with the integration of photovoltaic (PV) systems under severe grid voltage disturbances. The primary objective of the proposed controller is to provide a synchronization signal from the distorted grid voltages to the control methodology for the generation of reference signals. A DSOGI-based phase-locked loop has been employed over the conventional phase-locked loop in the proposed controller. The photovoltaic-based system has been attached to the dc link of the DVR for voltage regulation of DC link. Simulations under MATLAB/Simulink platform are conducted to analyze controller performance under severe grid conditions such as voltage sags, voltage swells, and voltage harmonics. Moreover, controller efficiency has been verified under sudden dual voltage sags. The analysis of the PV-based DVR with the proposed controller points towards the efficiency of the proposed controller in regulating load voltages for the normal operation of consumer loads. The total harmonic distortions have been reduced significantly, complying with the IEEE standards for power quality.
Index Terms—Adaptive controller, voltage quality, power quality, dynamic voltage restorer (DVR), voltage sags, voltage swells

I. INTRODUCTION

In the preceding decade, both electricity providers and consumers have increasingly turned their attention to the realm of power quality (PQ) [1]. This focus arises from the recognition that suboptimal power quality can stem from various factors, including voltage irregularities such as swells, sags, flickers, as well as oscillatory or impulsive transients. The cases such as transient discontinuities, high and multiple notches, and the appearance of harmonics can also be the focus for power quality issues. Moreover, advancements in sustainable energy technologies, encompassing microturbines, wind power, and photovoltaic (PV) solar energy systems, have underscored the necessity for meticulous monitoring of PQ phenomena, particularly within low-voltage microgrid infrastructures [2, 3]. A prevalent strategy involves the continual capture of disturbance waveforms facilitated by power monitoring sensors, a practice aimed at refining and fortifying power quality standards [4-7].

The significance of assessing the condition of electricity quality and analyzing the robustness of power grid network systems has escalated notably in recent times within academic and scientific discourse. Concurrently, there has been a mounting exigency for heightened quality standards and enhanced reliability within electrical networks [8-10]. Nevertheless, the advent of advanced controlled systems predicated on power electronics in recent years has precipitated an upsurge in interruptions experienced within power networks. Furthermore, external factors such as lightning strikes or abrupt activation of high-capacity rotating machinery can instigate sudden voltage fluctuations, posing additional challenges. Presently, prevalent power quality issues encompass voltage sags (resulting from short circuits), voltage overloads, voltage fluctuations, imbalance, and harmonics [2,8,11]. Consequently, international regulatory bodies have instituted stringent measures to address power quality concerns, imposing restrictions on consumers. As a consequence, the mitigation of harmonic components has emerged as a focal point in the operational challenges faced by electricity distributors.

With increasing emphasis placed on the restructuring of unregulated power networks and the integration of distributed generators within microgrid environments, there arises a necessity for the computation of estimated PQ indices in accordance with IEEE Standard 1459-2000 [10, 11]. Furthermore, a concerted exploration of PQ indices is warranted in light of burgeoning interest in nonconventional energy sources, including wind, solar, and fuel cells, which contribute substantial amounts of dynamic harmonic conditions alongside frequency deviations. The ascendancy of these renewable energy technologies underscores the imperative for comprehensive PQ assessment methodologies [5, 6] reflecting the evolving dynamics of contemporary power distribution systems. In recent years, the penetration of Solar PV systems has overwhelmed the power network as it increases the capacity of the conventional grid. Easy installation, lower cost, and higher efficiency have enriched the popularity of Solar PV utilization. Therefore, Solar PV integrated systems design and development is the major focus of researchers at the present time [12, 13]. Solar PV integrated systems for the advanced power grid can play a major role in the distribution system to achieve sustainable development goals. Therefore, numerous types of topologies and solutions related to Solar PV-based grid integrated systems have been developed and studied at the present scenarios. Wael S. Hassanein et al. [10] mentioned about the off grid-based hybrid nonconventional energy systems by the utilization of dynamic voltage restorer (DVR) for power quality mitigation. In this research, Solar PV, wind energy, and hydrogen-based fuel cells have been utilized to make the system hybrid. However, an energy storage component has been attached to the DC-link of the DVR to regulate the system stabilization. An ANN-based controller has been utilized here for the control of the DVR to enhance the efficiency. Mohamed I. et al. [11] focused on the integration and control of the DVR in a hybrid power system with PV/Wind for Egypt. In this research, an advanced cuckoo optimization technique has been utilized to achieve the optimal parameters specified for the PI controller to enhance the efficiency of the DVR. Shaila Shirke et al. [12] proposed a new control technique for the improved utilization of DC bus voltage for the improvement of DVR performance. In this research, the authors have utilized a repetitive controller for DC bus regulation, which also improves the transient response with steady zero error. Mishra S.K. et al. (2022) [13] mentioned the integration of renewable energy systems into the grid and utilization of DVR for the enhancement of power quality. The present research work includes P & O MPPT controller and an improved PLL-based SRF controller for system performance enhancement. In this literature, Rajkumar K. et al. [14], authors have developed a T-type DVR for the mitigation of power quality issues in a distribution system. The system developed under study has been utilized for performance analysis under various uncertainties and grid fluctuations. To improve power quality for a Solar PV integrated system, a DVR has been utilized in ref. [15], with an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller and an INC MPPT controller. This system under study explains the importance of DVR in grid-connected systems.

To enhance the performance and efficiency along with power quality in a grid-connected three-phase renewable energy system, grid synchronization is necessary to stabilize the system output. Therefore, to improve synchronization in a grid-connected system, various phase locked loop methodologies have been adopted. Improved PLL, SRF PLL, Modified PLL, Modified SRF PLL, SOGI PLL, and SOGI QSG PLL types are utilized for the grid-connected systems. In this paper, to improve the ability of PV-based DVR, D-SOGI-based modified SRF Controller has been utilized. This methodology has the ability to remove the ripples in the synchronization signals. Moreover, the present paper contributes in the following way:

- Implementation of the PV DVR for achieving the dual purpose of power quality improvement and utilization of renewable energies has been focused on.
- Integration of Photovoltaic system to DVR for the enhancement of DC link voltage regulation is obtained by the proposed controller.
- Utilization of a D-SOGI-based SRF controller to enhance the grid synchronization in the grid-connected PV system has been presented.

The present paper has been divided into several categories; section II describes the major literature related to the focus of the paper. Section III incorporates the structure of the present PV-based DVR system configuration. The design of the system has been presented in section IV, and the controllers like boost converter control, DVR control, DC link voltage control, and hysteresis current controller, are presented in section V. The analysis of simulation results for various power quality issues like voltage sags, swells, and harmonics has been discussed in section VI and finally, the research paper is concluded in section VII.

II. LITERATURE SURVEY

For the detailed discussion about the literature under the focused area of the paper and various major research contributions in the area of photovoltaic-based DVR have been listed in this table. Table I shows a clear analysis of the application, type of controller, and major advantages and disadvantages. Tuyen and Fujita in ref. [1] have mentioned about the harmonic current compensation in a grid-connected PV system based on IPR theory for efficiency improvement. However, the authors have not mentioned about the intelligent or adaptive controllers for the system. STF-based control approach for synchronization phase signal has been considered by Kashif et al. in ref. [2] for power quality improvement, without focusing on system efficiency enhancement under various voltage deviations. Combined Feed-Forward and Feed-Back control for DFIG-based system has been implemented in ref. [3] for the improvement of grid-connected DFIG system for power quality improvement. Authors have not mentioned the efficiency of the system under various dynamic grid conditions. Frequency-locked loop (FLL)-based modified reduced order generalized integrator (MROGI) has been applied for a clean energy generation system for power quality improvement in ref. [4]; however, adaptive or intelligent controller has not been considered for the performance enhancement of the system. Literature [5-8] has the focus on power quality improvement under nonlinear system conditions, but steps for enhancement of system performance have not been mentioned. For the elimination of voltage unbalances and voltage fluctuations under various conditions, refs. [9] and [10] have reported two different system topologies for performance enhancement. Authors of this research have not focused on performance enhancement of the system under severe disturbances of

TABLE I. LITERATURE RELATED TO PV-DVR AND CONTROLLER IMPLEMENTATION

Literature	Application System With DVR	Controller/Algorithm	Merits/Demerits
[1]	Harmonic current compensation in a grid connected PV system	IPR Control theory	Regulation of DC link for voltage balance and removal of loss. External power is necessary for the inverter to regulate dc link.
[2]	Power Quality enhancement	STF-based control approach for synchronization phase signal	Controller provides a dynamic response during load variation. Suitable for low-cost implementation.
[3]	DFIG based wind turbines	Combined Feed-Forward and Feed-Back control	Reactive power support without tripping, dc-link voltage balancing, fault current control has been mitigated.
[4]	Power management and power quality enhancement.	Frequency-locked loop (FLL) based modified reduced order generalized integrator (MROGI)	Clean energy generation and power quality enhancement
[5]	Harmonic current compensation in a grid connected PV system	Improvement of power quality by IRPT and SRF controller	Comparative study provides knowledge about various current techniques and their limitations
[6]	Grid interfaced photovoltaic system	A sixth-order generalized integrator for controller of DVR	Provides fast and accurate response in comparison to single second-order generalized integrator.
[7]	DC side voltage regulation and power quality improvement.	Linear active disturbance rejection control (LADRC)	Needs less nonlinear functions than ADRC.
[8]	Harmonic compensation by active filter	Cascade control system with PI and PID controllers	Harmonic voltage compensation purposes, sag and swell problems are not addressed.
[9]	Low voltage ride through system	Controller based on low voltage ride through capability controller	Voltage unbalances Voltage harmonics Power factor correction Outages
[10]	Cascaded multilevel inverter	Fuzzy based cascaded multilevel inverter (CMLI)	Voltage regulation and frequency synchronization is required.
[11]	Power quality improvement by HAPF	Conventional PID controller (CPIDC) based on PSO, GWO and hybrid PSO-GWO.	Harmonic voltage compensation purposes, sag and swell problems are not addressed.
[12]	200 kW grid-connected PV system	PLL-current regulator	Frequency synchronization.
[13]	Universal active power filter based on PV	Second-order generalized integrator in instantaneous power balance theory (IPBT)	Maximum power extraction and utilization.
[14]	Distributed generation	Synchronous reference frame (SRF) theory is implemented	Voltage unbalances Voltage harmonics Power factor correction Outages power quality enhancement
[15]	PV battery based DVR	d-q controller is implemented	Symmetrical and asymmetrical voltage sags scenarios have been regulated.
[16, 17]	Hybrid renewable energy system	ANN based controller Advanced cuckoo optimization	Implementation of ANN and cuckoo search optimization
[18]	Hybrid system	Advanced cuckoo optimization	Advanced cuckoo search algorithm is used for hybrid system
[19, 20]	Distribution system	Repetitive controller Improved PLL based SRF controller	Algorithm is used for distributed system for grid synchronization.

grid networks. Conventional PID Controller (CPIDC) based on PSO, GWO, and hybrid PSO-based optimization techniques have been applied for power quality improvement; however, the authors have not mentioned harmonic compensation of voltage signals and voltage deviations [11]. PLL-based current regulator is presented in ref. [12] for grid synchronization in a PV-based grid-connected system; the literature has not mentioned power quality or voltage quality [12]. Conventional Synchronous Reference Frame (SRF) Theory is implemented for power quality and voltage quality improvement in ref. [13]; however, this literature has not focused on the advanced controller for the system and voltage quality enhancement under severe weak grid conditions. Literature in Table I focuses on voltage and current fluctuations under various conditions [14-20]. However, the mentioned literature has not discussed the performance of the systems under severe fluctuations in weak environmental conditions [21-25]. Moreover, conventional controllers have been focused on system efficiency enhancement [26-32]. Therefore, the present paper has proposed an adaptive controller for the PV-based DVR system to analyze the performance.

III. STATE OF ART OF PV-DVR SYSTEM

In the proposed system, the integration of the Solar PV system occurs via the DC Link of the DVR into the distribution system. The three-phase, three-wire DVR is connected to the power network through series transformers. The system's source supplies power to diode rectifier-based nonlinear loads within the power network. The Solar PV system comprises both the PV source and a DC–DC boost converter, controlled by Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) methodology. Furthermore, the Solar PV system with the DC–DC boost converter is integrated with a 700V DC link capacitor. The major role of the DVR is to mitigate voltage disturbances within the power distribution network. The research paper under consideration introduces the integration of the Solar PV system with the DVR, aiming to regulate the DC link voltage and compensate for voltage disturbances, thereby stabilizing load voltages under various weak grid conditions. The depicted system is illustrated in Fig. 1.

IV. PV-BASED DVR SYSTEM ENGINEERING

A. Solar PV Design

Fig. 2 depicts the equivalent circuit of a photovoltaic cell and typically displays the equivalent circuit diagram of a diode model that is proportionate to the observed current and voltage characteristics module of the silicon photovoltaic. PV modules are actually just collections of solar cells. These modules may be used in solar power generating systems to generate energy by connecting them in series or parallel to form PV arrays. Fig. 3 depicts the PV array's comparable circuit. Fig. 2 presents supply I_{ph} as a representation of the cell's photocurrent. The inherent transformations of the cell are R_{sh} and R_s; series resistances are frequently disregarded in an effort to streamline the study.

$$I = I_{pv} - I_o[\exp\left(\frac{v + R_s I}{v_t a}\right) - 1] - \frac{v + R_s I}{R_p} \tag{1}$$

$$I_{pv} = \left(I_{PVn} + K_I \Delta_T\right)\frac{G}{G_n} \tag{2}$$

$$I = I_{pv}N_p - I_o\,N_p[\exp\left(\frac{v + R_s\left(\frac{N_s}{N_p}\right)I}{v_t a N_s}\right) - 1] - \frac{v + R_s\left(\frac{N_s}{N_p}\right)I}{R_p\left(\frac{N_s}{N_p}\right)} \tag{3}$$

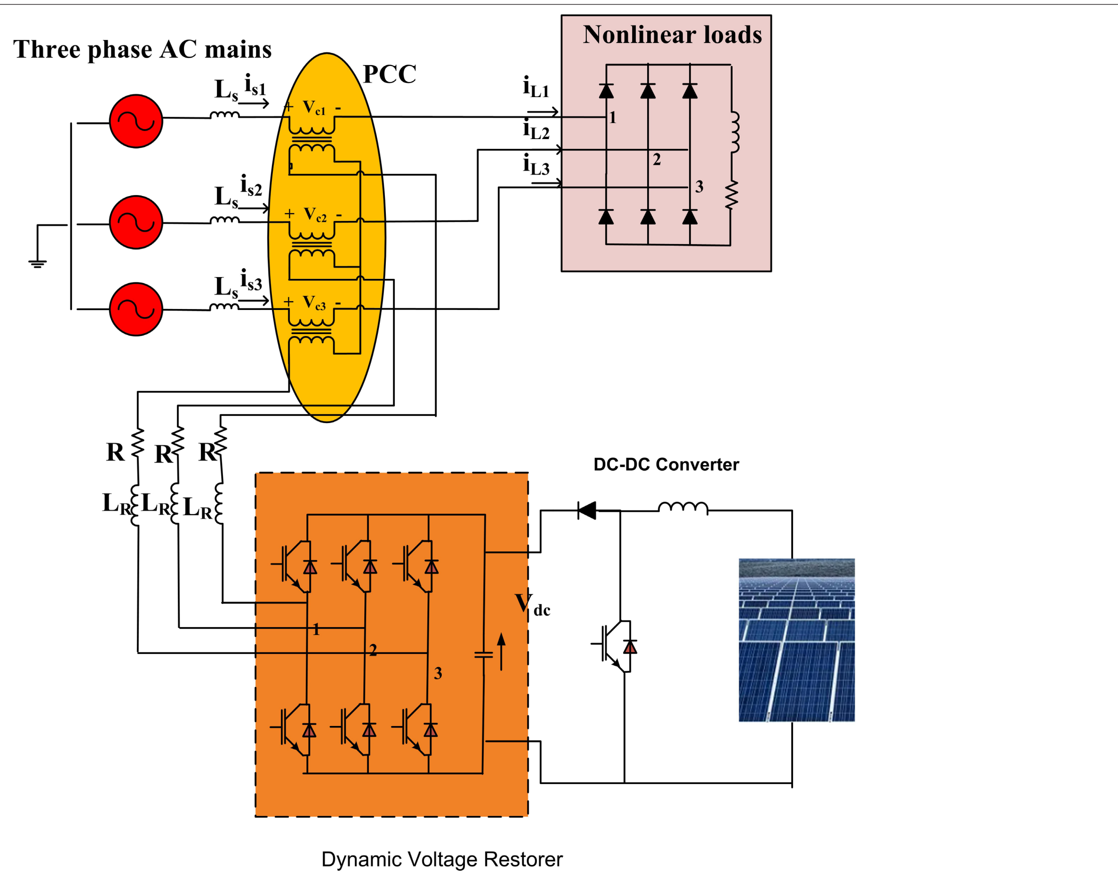

Fig. 1. Structure of the PV-DVR configuration.

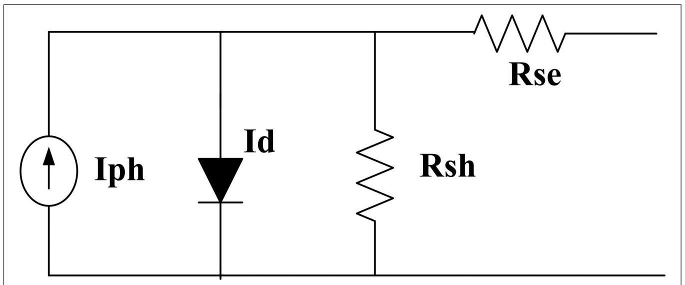

Fig. 2. Configuration of a PV cell.

The regulation of the DC-link capacitor within the PV-based DVR serves multiple functions for the series inverter and Solar PV array. When determining the magnitude of the DC-link voltage, it is crucial to ensure that it is twice the peak value of the phase voltage within the three-phase distribution system [11]. Hence, the magnitude of the DC-bus voltage is expressed as follows:

$$V_{dc} = \frac{2\sqrt{2}V_L}{\sqrt{3}m} = \frac{2\sqrt{2}\times 415}{\sqrt{3}.1} = 677.692 \tag{4}$$

With a depth of modulation (m) set at 1 and denoting the line voltage as V_line, it has been established that the minimum necessary V_dc is 677.7 V, resulting in the selection of 700 V for the DC-bus.

Considering the power regulation of a PV-based DVR system and the specified DC link voltage requirement, the rating for the DC-bus capacitor has been established. The assessment of the DC-bus capacitor rating can be conducted [12, 13] using the subsequent equation.

$$C_{dc} = \frac{3ka.V_{sa}.I_{sh}.t}{\frac{1}{2}\left(V_{dc}^2 - V_{dc\_min}^2\right)} = \frac{3\times 0.1\times 1.5\times 235.8\times 20\times 0.03}{\frac{1}{2}\left(700^2 - 677.692^2\right)} = 4143.094\ \mu F \tag{5}$$

In the equation, "k" represents the factor accounting for energy variation during dynamic conditions, while the overloading factor is denoted as "a". "t" signifies the minimum duration necessary to reach a steady-state value following a disturbance.

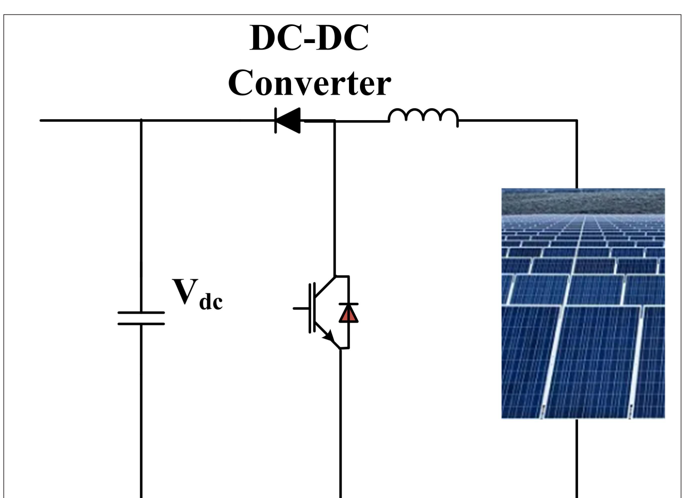

Fig. 3. DC–DC boost converter design.

V. CONTROL STRATEGIES FOR THE PV-BASED DYNAMIC VOLTAGE RESTORER

The control strategy required for PV-based DVR includes various types of control structures for necessary steps to enhance power quality. This overall control structure includes control of the boost converter, reference voltage generation, Phase locked loop, and hysteresis current controller. This section explains in detail all controllers that are implemented for the system.

A. Control of Boost Converter

The regulation and maintenance of dc-bus voltage is accomplished by a dc-voltage controller, ensuring the power balance of the PV system. However, this controller lacks the necessary speed to prevent sudden voltage oscillations. This issue arises from the slower response of the voltage control loop compared to the loop of current control, directly impacting the quality of current injected into the grid. To address this, implement a Feed-forward Current Loop (FFCL) is utilized in this paper. Feed-forward Current Loop enhances the speed of the dc-voltage controller, facilitating rapid power balance adjustment for PV-DVR systems. Working alongside a reference current generation technique for series DVR converters, FFCL ensures proper current amplitude regulation. Consequently, it allows for an estimation of the active current injected into the grid. Additionally, FFCL enables swift computation for generating input current references, even amidst dynamic variations in the dc-bus voltage.

The active power achieved by the SPV system is given by

$$P_{pv} = v_{pv}.i_{pv} = V_{dc}.i_{pv} \tag{6}$$

Assuming DVR series inverter currents and grid voltage to be balanced, the active power (P_{ap}) injected into the grid is represented as

$$P_{ap} = 3V_{frms}.I_{frms} = \frac{3V_{fpk}.I_{fpk}}{2} \tag{7}$$

where V_{frms} and I_{frms} represents the rms value of fundamental grid voltages and fundamental rms currents, respectively. And V_{fpk} , I_{fpk} are fundamental voltage and current peak amplitude.

Considering the PV system operates in ideal conditions and neglecting all the system losses, the power produced by the PV system is the injected active power to the grid. The peak amplitude of fundamental current I_{fpk} can be given as:

$$I_{fpk} = \frac{2v_{pv}.i_{pv}}{3V_{fpk}} \tag{8}$$

The other detailed designs are provided in ref. [15]. In the boost converter, the P&O-based MPPT algorithm is chosen; power is determined by tracking the maximum power through adjustments in the voltage obtained from the PV cells. The flowchart depicted in Fig. 4 illustrates the P&O algorithm [19]. Initially, the voltage and current are calculated, and then power is computed by multiplying the voltage and current values. Here, the current power is denoted as P_{now}, while the previous power is denoted as P_{old}. There are two conditions: first, if the current power exceeds the previous power; and second, if the current power is less than the previous power. In the first condition, when the current power surpasses the previous power, and the current voltage (V_{now}) exceeds the previous voltage (V_{old}), the Pulse Width Modulation (PWM)

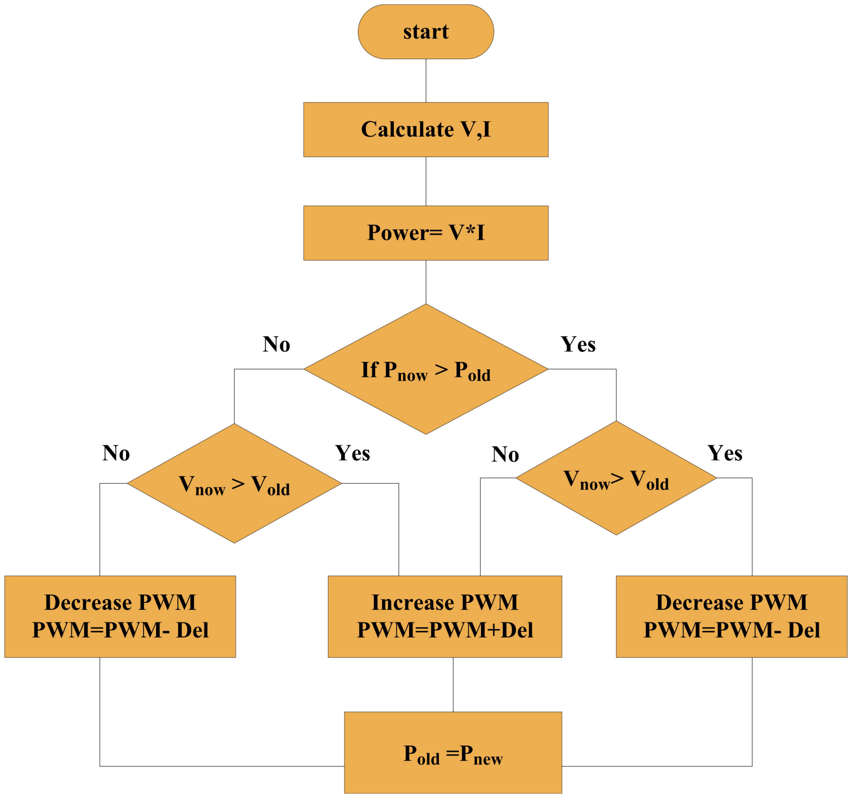

Fig. 4. Implementation of perturb and observe algorithm for MPPT of a PV cell.

is decreased by subtracting a delta value from it. Conversely, if the current voltage is less than the previous voltage, the PWM is increased by adding a delta value to it. In the second condition, when the current power is less than the previous power, and the current voltage is less than the previous voltage, the PWM is increased by adding a delta to it. Conversely, if the current voltage exceeds the previous voltage, the PWM is decreased by subtracting a delta from it. An increase in PWM leads to the maximum power point shifting towards the forward direction, while a decrease causes it to move backward. This perturbation process continues until the current power matches the previous power, at which point the perturbation ceases [20].

B. Control Method of Dynamic Voltage Restorer

The strategy for DVR includes the reference signal generation, Phase Locked Loop, and hysteresis current controller. This section includes a novel SRF controller for accurate reference signal generation. The three-phase voltage signal is converted to the d-q frame by the utilization of Clarke transformations as per the representation below.

$$\begin{bmatrix} V_{sd} \\ V_{sq} \\ V_{s0} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \tag{10}$$

The acquired rotating frame components $d-q$ terms of three-phase grid voltages are presented and additionally broken down into two components, which can be expressed as:

$$V_{sd} = \bar{V}_{sd} + \tilde{V}_{sd} \tag{11}$$

$$V_{sq} = \bar{V}_{sq} + \tilde{V}_{sq} \tag{12}$$

$$V_{cd}^{*} = \bar{V_d} - \tilde{V}_{sd} \tag{13}$$

$$V_{cq}^{*} = \bar{V_q} - \tilde{V}_{sq} \tag{14}$$

The source voltages are divided into direct and quadrature components, which are classified into two distinct categories: voltage direct current (DC) components $(\bar{V}_{sd}, \bar{V}_{sq})$ and voltage oscillating components $(\tilde{V}_{sd}, \tilde{V}_{sq})$, as detailed in Equations (11) and (12) respectively. Equations (13) and (14) delineate the direct and quadrature axis signals of the reference voltage. The significance of noticeable oscillating components within both direct and quadrature voltage signals contributes to voltage perturbations. Mitigating grid voltage distortions necessitates the subtraction of these oscillating components from the DC voltage signals. Effective regulation of voltage in the DC link capacitor of DVR is essential for maintaining load voltages at a regulated level. However, fluctuations in the voltages of the DC link can hinder the DVR's ability to adequately compensate for grid voltage disturbances. To address this issue, a DC link voltage controller based on a Second-Order Generalized Integrator Phase-Locked Loop (SOGI-PLL) is employed, as detailed in Section 3.2. Furthermore, the proposed method incorporates a Proportional-Integral (PI) controller in conjunction with a self-supported capacitor for regulating the DC link voltage. The voltage loss of the PI controller has been presented as:

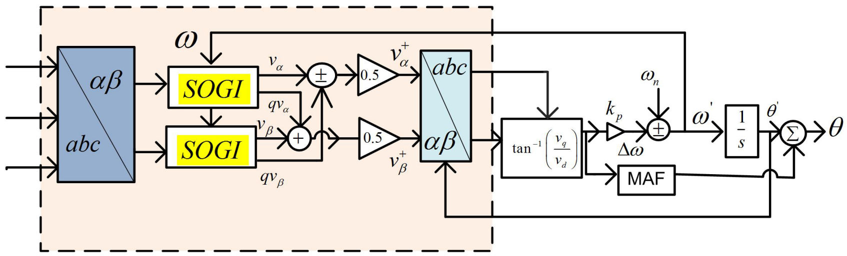

Fig. 5. DSOGI structure for proposed PLL.

$$v_{dc\_loss(n)} = v_{dc\_loss(n-1)} + K_p(v_{d\_e(n)} - v_{d\_e(n-1)}) + K_i * v_{d\_e(n)} \quad (15)$$

where $v_{d\_e(n)} = V_{dc}^{*} - V_{dc}$ is the error evaluated between the reference DC link voltage and the sensed real DC link voltage. K_p and K_i are the gains of proportional and integral gain respectively.

The variances observed in the load terminal voltages are detected and their amplitudes assessed, juxtaposed with the reference load voltage via the utilization of the PI controller. Consequently, the PI controller's output yields the reactive component of the voltage, expressed as follows:

$$v_{q\_re(n)} = v_{q\_re(n-1)} + K_p(v_{t\_e(n)} - v_{t\_e(n-1)}) + K_i v_{t\_e(n)} \quad (16)$$

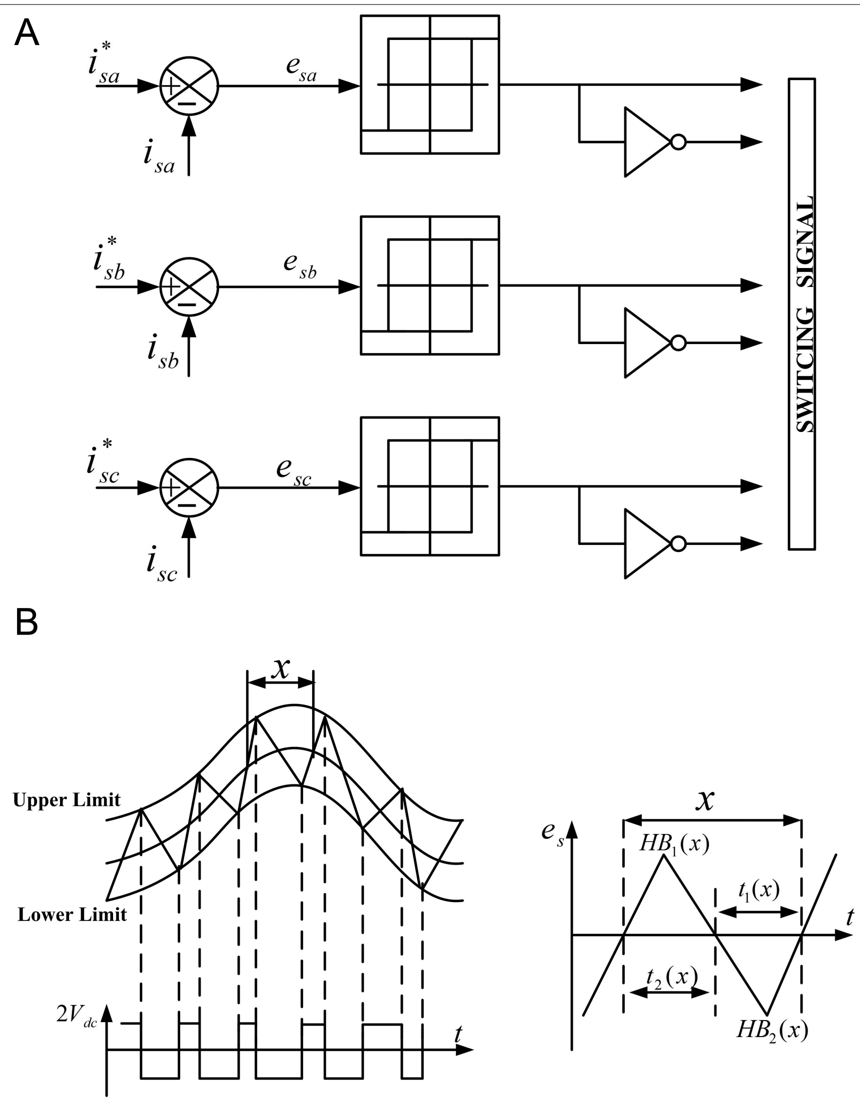

Fig. 6. Hysteresis current controller: (a) hysteresis controller diagram, (b) hysteresis band, and (c) error generated through the band.

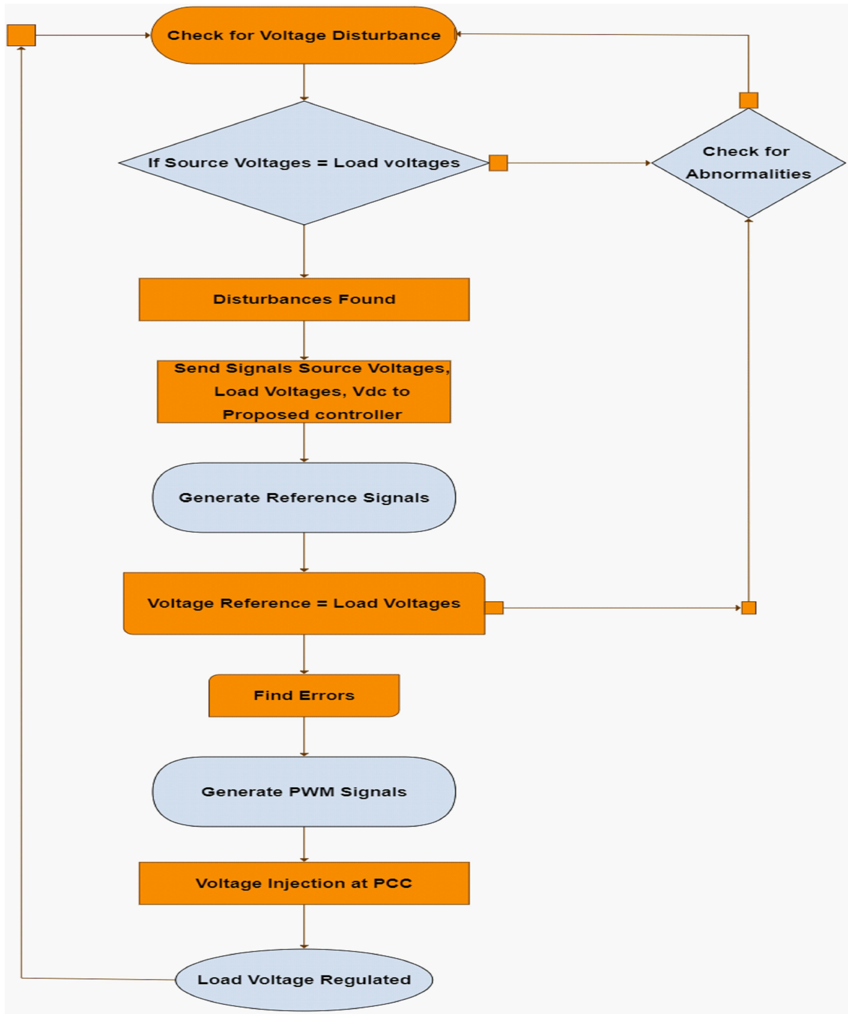

Fig. 7. Flowchart for working of the proposed system.

where $v_{t\_e(n)} = v_{Lt}^{*} - v_{Lt(n)}$ denotes evaluated error between reference load voltage and sensed real load voltage, K_p and K_i are the proportional and integral gains, respectively, of the PI controller.

The voltage signals generated for reference utilization play a pivotal role in compensating for grid voltage disturbances affecting the load voltages of consumers. The obtained voltage signals in a two-frame reference undergo a conversion process to be transformed into a 3-phase components voltage in stationary frame. This transformation is achieved through the method of following inverse Park's transformation method, delineated in Equation (17). In this Equation, Va,Vb and Vc represents the Phase voltages.

TABLE II. SIMULATION PARAMETERS FOR PV-DVR

Parameters	Value
Source voltage	380 V
Frequency	50 Hz
Source inductance	1.5 Ω, 0.5 mH
Filter coupling inductance	1.8 Ω, 1.5 mH
Non linear load	Diode bridge rectifier, 60 Ω, 20 mH
DC link voltage	720 V
PI controller gains	Proportional gain = 90, Integral gain = 3.27

$$\begin{bmatrix} V_{ca}^{*} \\ V_{cb}^{*} \\ V_{cc}^{*} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} V_{sd}^{*} \\ V_{sq}^{*} \\ V_0 \end{bmatrix} \tag{17}$$

C. DSOGI-PLL Controller

Numerous active filtering methods are documented in the survey by researchers alongside the SRF-based control methodology, renowned for its simple utilization and enhanced efficiency. Nevertheless, the efficacy of this SRF methodology diminishes considerably in the face of weak voltage conditions and current perturbations. The present research focuses on a novel SRF methodology [16] reported by an advanced Phase-Locked Loop

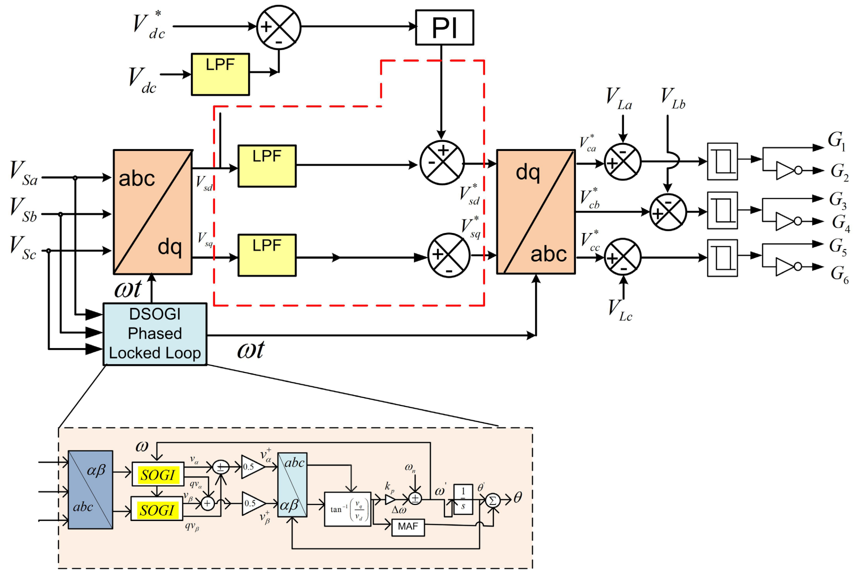

Fig. 8. Proposed controller for PV-DVR.

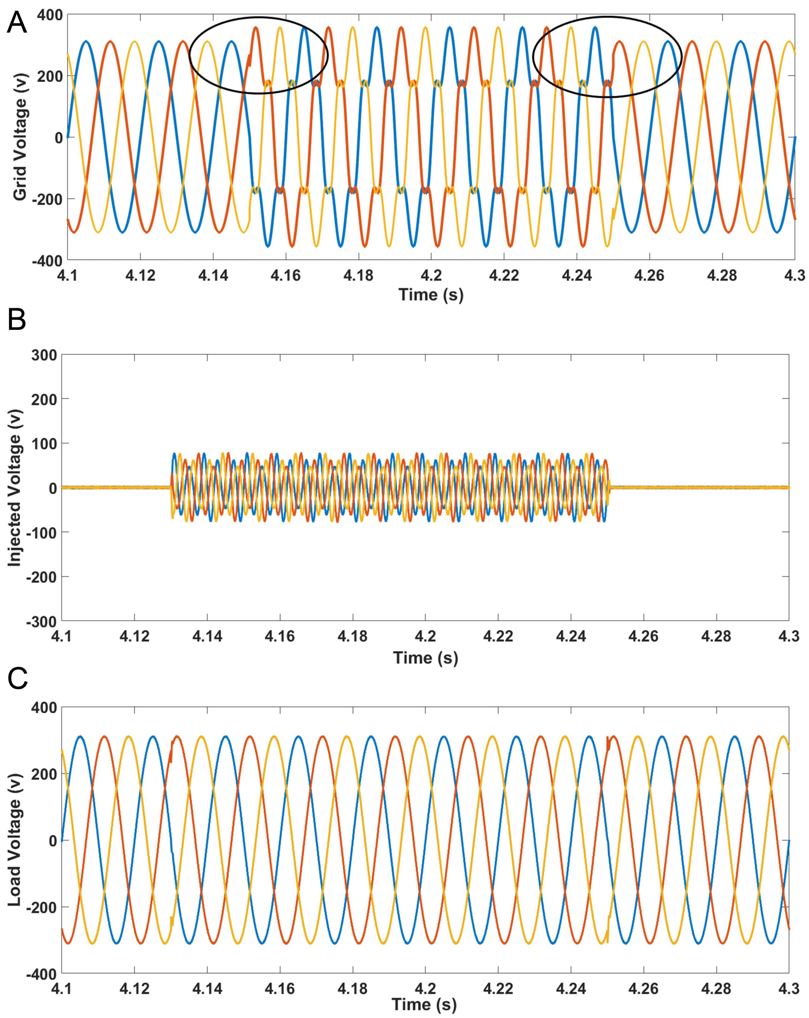

Fig. 9. Source voltage harmonics elimination: (A) Source voltage with harmonics, (B) compensation signals from DVR, and (C) regulated load voltages.

(PLL) implementation. The depicted DSOGI SRF methodology for the Photovoltaic-DVR is illustrated in Fig. 5. The incorporation of Phase-Locked Loop algorithms serves a dual purpose: facilitating accurate phase identification of grid voltages and evaluating fundamental components of PV-based DVR voltage signals. Diverse PLL mechanisms are integrated with methodologies to enhance the efficacy of custom power devices. However, traditional PLL strategies exhibit diminished effectiveness when confronted with severely weak grid voltage scenarios, such as voltage sags and swells.

To adapt the harness of the transient response of the standard PLL, neglecting the presence of disturbance or power quality issues rejection capability, the proposed PLL (DSOGI) has been utilized. A quasi-type-1 (QT1) methodology has been utilized by replacing a PI controller. The fundamental QT1 utilizes a moving-average filter (MAF) as illustrated in Fig. 5, where MAF stabilizes the dynamic performance of the proposed PLL technique. The presence of the MAF increases the synchronization timing in the QT1 structure control loop. To overcome this issue and enhance the efficiency of the overall system, MAF is employed in the Feed-Forward sequence of the QT1 technique. In a type-2 system, phase and frequency jumps neglecting experience of steady-state error, much like the conventional QT1 structure. The complete proposed controller diagram is presented in Fig. 8.

In SOGI PLL, the first order filter can be defined as:

$$\text{Low Pass Filter} = \frac{\omega_p}{s+\omega_p} \tag{18}$$

where ω_p represents cut-off frequency. The ω_p is selected as $k_{\omega n}/2$ (where, ω_n is minimal grid frequency). The window-length of the MAF is also needs to be identified for the proposed system. The rich harmonic contamination of the grid voltage signals should be taken into consideration when selecting its window-length ($T\omega$) [15]. Given that the negative sequence component of the fundamental frequency is separated before the PLL control loop.

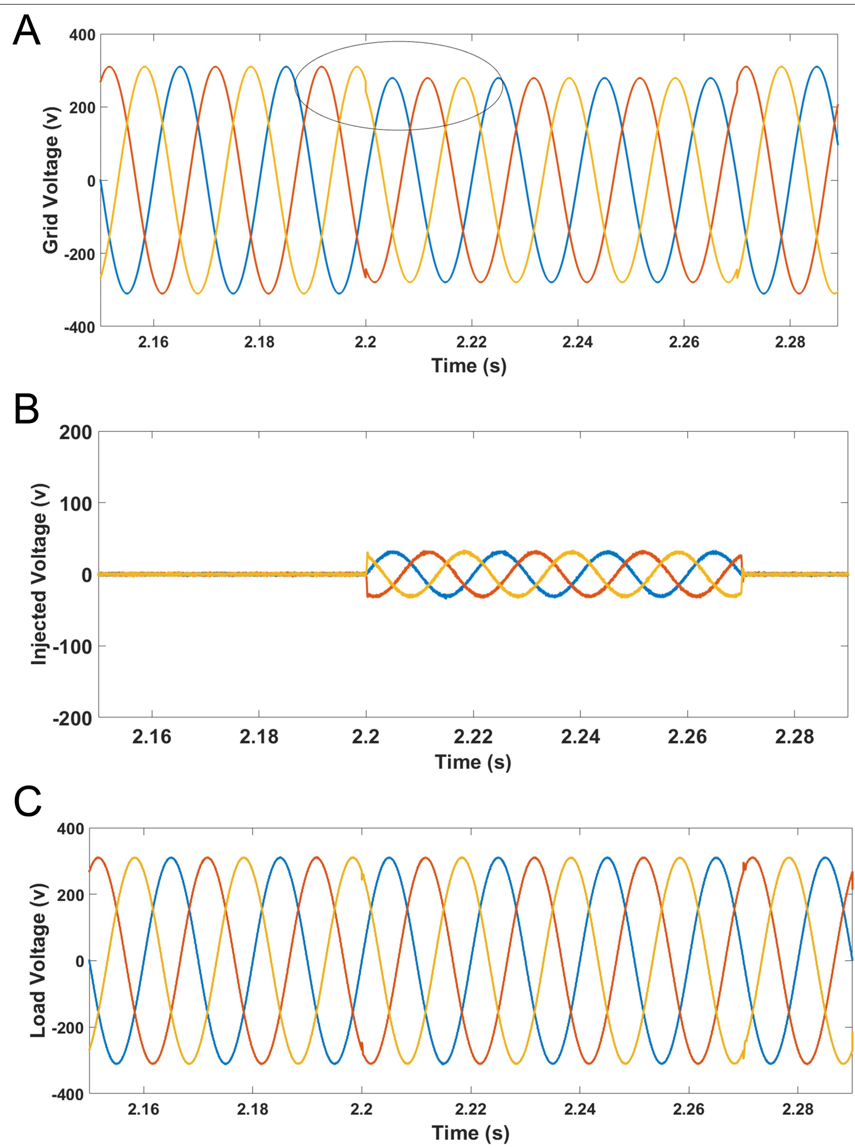

Fig. 10. Source voltage sags elimination: (A) Source voltage with sags, (B) compensation signals from DVR, and (c) regulated load voltages.

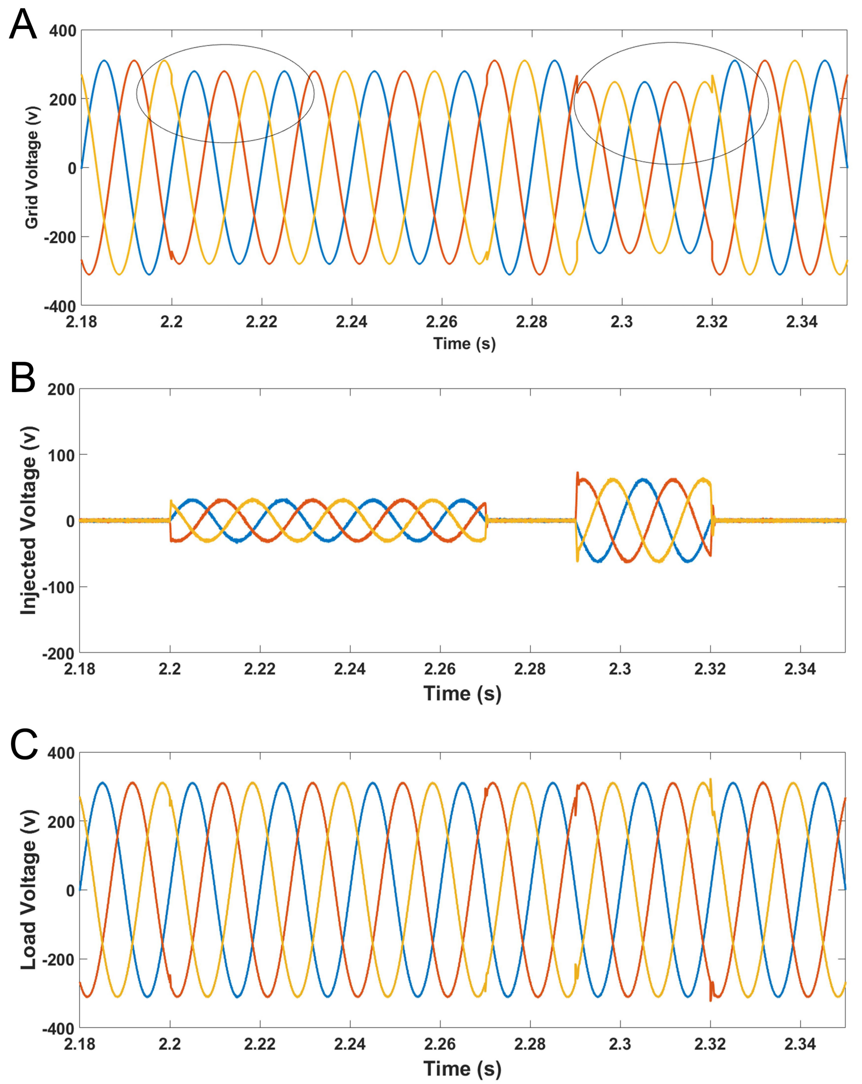

Fig. 11. Source voltage dual sags elimination: (A) Source voltage with dual sags, (B) compensation signals from DVR, and (C) regulated load voltages.

The specification of the cut-off frequency of the LPF and the $T\omega$ of the MAF helps the controller parameter (k_p) to adjust accordingly. k_p can be designed by utilizing the equations below.

The transfer function presented in an open-loop condition can be denoted as:

$$H(s)_{ol} = \frac{\Delta\theta^{+}(s)}{\theta_e(s)} = \left(\frac{LPF(s)}{(1 - LPF(s).MAF(s)}\right)\left(MAF(s) + \frac{k_p}{s}\right) \tag{19}$$

The transfer function for tracking error per each phase:

$$H_e(s) = \frac{\theta_e(s)\Delta\theta^{+}(s)}{\Delta\theta_i(s)} = \left(\frac{1}{(1 + H_{ol}(s)}\right) \tag{20}$$

The change in settling time of $G_e(s)$ considering 2% of evaluation, as a function of k_p presented for in-phase and frequency jump scenarios, as seen in Fig. 4. The value of k_p, which in both cases is 90, results in the optimal settling time.

D. Hysteresis Controller for PV-DVR

According to the reference voltage signals, corrections have been created. To assess the inaccuracy, the real load voltages are compared to the reference voltage signals. The hysteresis controller has been used to generate three HC switching signals using the collected errors. However, for the DVR to function, six gating signals are needed, as presented in Fig. 6(a). Three further gating pulses for the DVR are produced by inverting the acquired HC1, HC2, and HC3. As a result, the created pulses activated the DVR's switches. The hysteresis band and error signals are presented in Fig. 6(b).

VI. RESULTS ANALYSIS AND DISCUSSION

The working of the proposed controller for the elimination of power quality issues has been achieved by the proposed PV DVR. Therefore, stepwise iteration of the proposed control strategies has been explained by the flowchart illustrated here in Fig. 7. Simulation of the proposed model has been achieved by adopting MATLAB/Simulink platform. The system parameters are illustrated in Table I.

TABLE III. COMPARISION FOR THD% FOR CONVENTIONAL CONTROLLER AND PROPOSED CONTROLLER

Grid Voltage		THD %					
		Without Compensation Va	After Compensation Va	Without Compensation Vb	After Compensation Vb	Without Compensation Vc	After Compensation Vc
380 V	Conventional-based SRF controller	30.31	4.0	30.2	5.01	30.21	4.95
380 V	DSOGI-based SRF controller	30.31	2.01	30.2	2.0	30.21	1.98

A. Simulation Results for Dynamic Voltage Restorer Operation

Source voltage with high distortions like voltage sags, voltage swells, and injection of harmonics is introduced to the distribution network in the presence of severe grid voltage fluctuations. The occurrence of any kind of voltage disturbance will affect the load operation and aging subsequently. Therefore, the controller proposed in this research paper for the Solar PV-based DVR has shown its performance under various conditions of the grid with simulation parameters in Table II. The cases are discussed below for validation of the proposed controller.

Case 1: Voltage Harmonic Case for SPV-Based DVR

The grid voltage with harmonics due to disturbances will also affect the load behavior during abnormal operation. In the

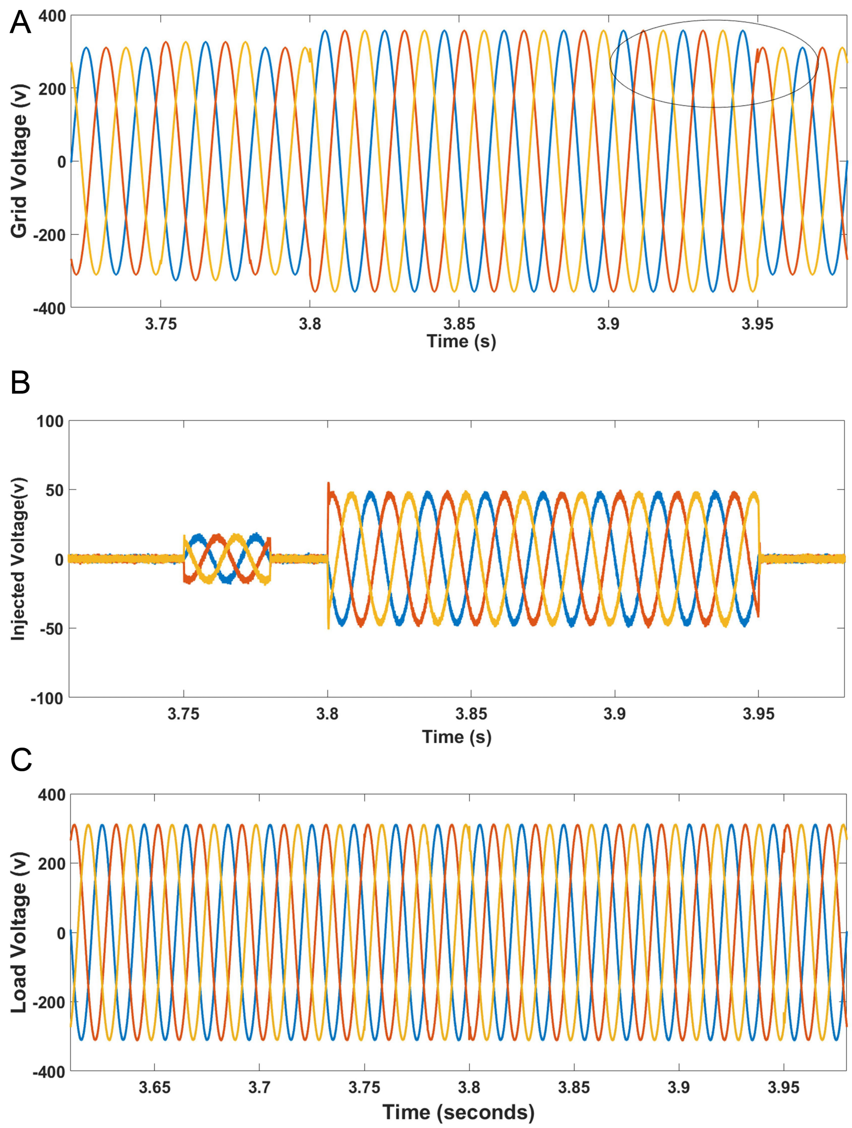

Fig. 12. Source voltage swells elimination: (A) Source voltage with swells, (B) compensation signals from DVR, and (C) regulated load voltages.

presnted Fig. 9(a), it is noticed that the grid voltages have harmonics present in the voltage waveform. To remove the harmonics in the load voltages and provide balanced voltages, the proposed controller for the SPV-based DVR has generated the compensation signals as presented in Fig. 9(b). The regulated load voltages are presented in Fig. 9(c).

Case 2: Voltage Sag Case for SPV-Based DVR

In the case of voltage sags in the grid voltage, the amplitude of the 3-phase voltages will be lowered up to 20–30% from the original amplitude of the source voltage. In Fig. 10(a), it is clearly noticed that the voltage sag appears from 2.10 s to 2.15 s in the grid voltage. The utilization of the control algorithm as proposed in this research work has the efficiency to compensate for the voltage sags and provide regulated voltage to the loads connected to this power network. Therefore, from Fig. 10(c), it is observed that the load voltage is regulated by the proposed control algorithm with compensation signals in Fig. 10(b). To analyze the system performance with the proposed controller, a sudden dual sag case is also considered here for verification.

Case 3: Voltage Swell Case for SPV-Based DVR

The source grid voltage will experience voltage swell conditions during a sudden increase in voltage amplitude up to 20–30%. In the given Fig. 11(a), the grid voltages with a sudden swell is presented, where approximately 20% swell has been noticed. Therefore, to provide regulated power supply to the loads, the proposed controller of the SPV-based DVR has generated a compensated signal as given in Fig. 11(b). In Fig. 11(c), the regulated voltage for the load voltage has been presented.

In research work, Table III represents the comparison of the total harmonic distortions for the conventional SRF control methodology and the proposed SOGI-based SRF controller. It is noticeable that the THD% has been significantly reduced for the proposed controller in comparison to the conventional SRF controller as presented in Fig. 13. The DC link voltage has been regulated to 710 V as presented in Fig. 12(c). The integrated PV system characteristic has been presented in Fig. 14.

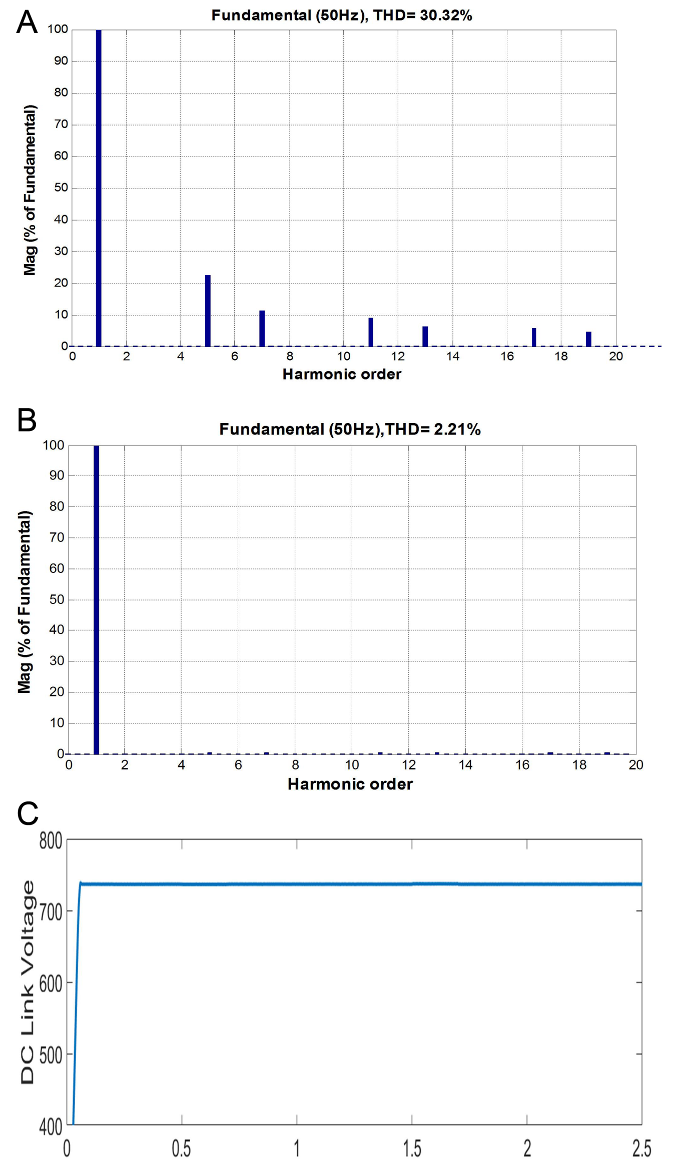

Fig. 13. Harmonic analysis: (A) THD before compensation, (B) THD after compensation, and (C) regulated DC link voltage.

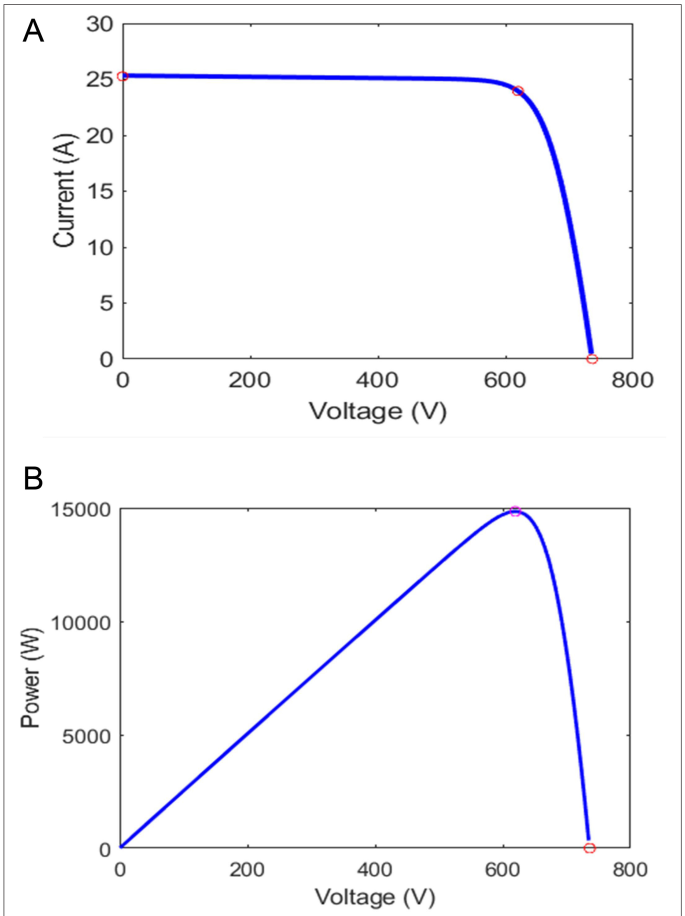

Fig. 14. PV system characteristics: (A) *I–V* characteristics of a PV system and (B) PV characteristics of a PV system.

VII. CONCLUSION

This paper illustrates the adoption of advanced controller methodologies to achieve regulated load voltages under dynamic grid conditions in a PV-based DVR system. Unpredictable conditions like voltage harmonics, voltage sags, dual sags, voltage swells are desired to be eliminated by the PV-based DVR system. Integration of the PV system with DVR , stabilizes the DC link of the system. Therefore, in this paper, a novel SRF controller with DSOGI PLL has been employed for the improvement of power quality. The novel SRF controller is able to generate suitable reference signals, and DSOGI PLL provides synchronization signals to the controller under dynamic conditions. The model has been validated under severe grid conditions like voltage harmonics, voltage sags, dual sags, voltage swells on the simulation platform. The results are analyzed minutely, justifying the satisfactory performance of the PV-DVR system.

Availability of Data and Materials: The data that support the findings of this study are available on request from the corresponding author.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – R.M., I.N.; Design – R.M., I.N.; Supervision – I.N.; Resources – R.M., I.N.; Materials – R.M.; Data Collection and/or Processing – R.M., I.N.; Analysis and/or Interpretation – R.M., I.N.; Literature Search – R.M.; Writing – R.M.; Critical Review – R.M., I.N.

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