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A novel MVVR controlled solar-PV fed MF-DVR for compensation of islanding and PQ issues in utility-grid integrated distribution system

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ABSTRACT

The depletion of fossil fuels, planning of new industries, and increased population are considered significant motivations for the expansion of new power generation in line with the requisite load demand. In recent days, the solar-PV-based distribution generation is the most suitable power generation in a utility-grid-integrated distribution system. The main intention of this work is to present the effective DG scheme; it delivers the required active power during sudden interruptions, grid-islanding, and sudden block-outs. And also enhancing the voltage stability during voltage-harmonics, voltage sags/swells, and unsymmetrical fault conditions occurred in the utility-grid integrated distribution system through solar-PV fed multi-functional dynamic-voltage restorer (MF-DVR) device. The effective compensation performance of MF-DVR relies on viable reference voltage signals, which are produced by well-known control schemes reported in literature studies. But these regular schemes have reported that the major problems are highlighted and have been eliminated by proposing the novel modified voltage vector reference (MVVR) control scheme. The proposed MVVR controller perfectly produces the unique reference voltage signals for delivering a feasible switching pattern to the MF-DVR device. In this work, the design and performance of the proposed MVVR-controlled solar-PV-fed MF-DVR have been verified to enhance power quality and grid-islanding issues through MATLAB/Simulation software tool. The extracted simulation findings are presented with appealing interpretations complying with IEEE-519/2022 standards.

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1. INTRODUCTION

The electric-power system (EPS) is the centralized system consisting of complex sections such as electrical power generation, power transmission through high-power transformers, and a distribution system for delivering energy to end-level consumers. That delivers electric power to various load apparatus like households, industrial, and commercial loads for a substantial area through a utility-grid integrated distribution system [1]. Due to increased population, the establishments of new industries, and depletion of fossil fuels, are considered as major motivations for expansion of new power-generation plants in line with the requisite load demand. To manage the requisite load demand, nearly 35 to 45 million rupees have been spent on newly installed generation plants along with the expansion of transmission facilities [2]. Major initiatives have been undertaken across the world to encourage the adoption of newly installed power generation through renewable energy sources (RES), which are interfaced between the utility grid and the secondary distribution system through the distribution generation (DG) scheme [3]. It is noted that the DG scheme provides vital advantages such as reliable power transfer, maximizing the grid capacity, reduced transmission cost and losses, maximum power efficiency, and so on [4]-[8]. It is best suited for alternative energy generation, and also acts as an energy backup for delivering uninterrupted power to end-level consumers during sudden power interruptions, power failures, sudden power block-outs, and grid-islanding, and so on.

The DG scheme utilizes several micro-energy sources such as solar-PV, wind-turbine energy, biomass, and tidal energy. Among several renewable energies, the solar-PV is the reliable and most appropriate energy source because of low maintenance, natural nature, greater operating life, virtuous [9]-[11]. During these DG operations, the energy generated from solar-PV is directly integrated to the point of common coupling (PCC) of the distribution system by means of a power-conditioning technique with a suitable control structure for energy management. Therefore, the solar-PV fed DG scheme is highly dependent on significant aspects such as continuous power support, reliable power control, greater power transfer capacity, and well-complying with power-quality (PQ) limitations [12].

The PQ is the most substantial and notable key specification in the present utility-grid integrated distribution system for delivering the standard and quality power to end-user consumers, complying with grid-code guidelines. Due to the presence of critical PQ issues, the utility-grid specifications like source voltage, current, and frequency are proliferated, therefore affecting the entire load apparatus has been identified as a major problem. These PQ issues are highly influencing the utility-grid voltage by injecting the voltage harmonics, voltage sags-swells, and faults, which increase the subversive power-pollution and degrade the overall functioning of end-user consumer loads at the PCC of the utility-grid system [13]-[15]. Moreover, the grid-islanding issues are also creating serious impacts on the utility-grid system, which is influencing the continuous delivery of electric power to end-user consumer loads in line with the peak load demands.

In this manner, the main objective is not only limited to compensation of severe PQ issues but also regulating the grid-islanding issues by employing the desirable custom-power technology (CPT) by many power-system control engineers and various research teams [16]-[19]. The CPT utilizes the various compensation devices for compensation of severe voltage relevant PQ issues and restoring the utility-grid specifications as linear, fundamental frequency and sinusoidal wave-shapes, balanced system with the help of requisite identification and classification methods [20], [21]. Zhang *et al.* [20] explored the various custom-power devices for enhancing the power quality in the distribution networks by employing advanced techniques. Chawda *et al.* [21] presented the role and analytical operation of various custom power devices for the mitigation of severe PQ issues in the DG systems. There are multiple CPT devices that can be conveniently available to handle specific PQ challenges, resulting in the distribution system being sinusoidal in form, evenly balanced, and uniform, and having fundamental characteristics. Swain *et al.* [22] presented the significant elimination of harmonic distortions in the utility grid and also regulating the energy demand issues for improving the micro-grid performance by using a shunt active power filter operated with feasible SHAF control schemes. The results in [23], [24] presented that solar-PV-based FC-TCR and SVC are used for compensation of power-demand shortages, current relevant PQ concerns in the modern distribution system establish the improved performance of the grid-integrated distribution network. Abas *et al.* [25] explored the unique power-quality improvement technique by adopting the dynamic-voltage restorer (DVR) for the mitigation of several voltage-related power-quality issues. Kumar *et al.* [26] presented the feasible compensation of voltage sags-swell concerns by using DVR, along with attaining the enhanced power-quality characteristics in the power-system network.

According to the problem identification, the DVR is the best and suitable CPT device for compensation of all voltage-related PQ issues because of its favorable merits such as flexible operation, compact size, inexpensive, and rapid response to voltage-related and power-related issues [27]. The presented solar-PV DG scheme delivers the required active power during grid islanding, along with enhancing the voltage stability during power-quality deterioration through a DVR named as multi-functional dynamic-voltage restorer (MF-DVR) device with a feasible control scheme. From various recent literature reviews, the synchronous reference frame (SRF) [28]-[31] is the most regular control scheme for the generation of a voltage reference signal for voltage compensation is explored by Singh and Singh in [32]. But, the regular SRF control scheme has substantial problems identified and is also not recommended due to technical limitations such as sophisticated transformations and mathematical calculations, high transient delay in the reference signal, which degrades the compensation performance and efficiency. These critical technical limitations in the regular SRF control scheme have been eliminated by proposing the novel modified voltage vector reference (MVVR) control scheme. The proposed MVVR controller perfectly produces the unique reference voltage signals for delivering a feasible switching pattern to the MF-DVR device. In this work, the design and performance of the proposed MVVR-controlled solar-PV-fed MF-DVR have been verified under enhancing power-quality in voltage compensation mode and grid-islanding issues in DG mode through MATLAB/Simulation software tool. The extracted simulation findings are presented with appealing interpretations complying with IEEE-519/2022 standards.

2. METHOD

The model block diagram of solar-PV fed MF-DVR for DG operations and PQ enhancement is depicted in Figure 1. The proposed DG scheme consists of solar-PV arrays followed by a DC-DC boost converter interfaced to series series-connected voltage-source converter (VSC) with a line-interfacing filter controlled by the proposed controller with gate-drive circuitry. It is fed by a three-phase utility-grid voltage source of $V_{gs.abc}$ (V) with a current of $I_{gs.abc}$ (A) connected to the load bus through source impedance of $Z_{gs.abc}$ (Ω) driving the sensitive load with a load voltage of $V_{SL.abc}$ (V), with a load current of $I_{SL.abc}$ (A), respectively.

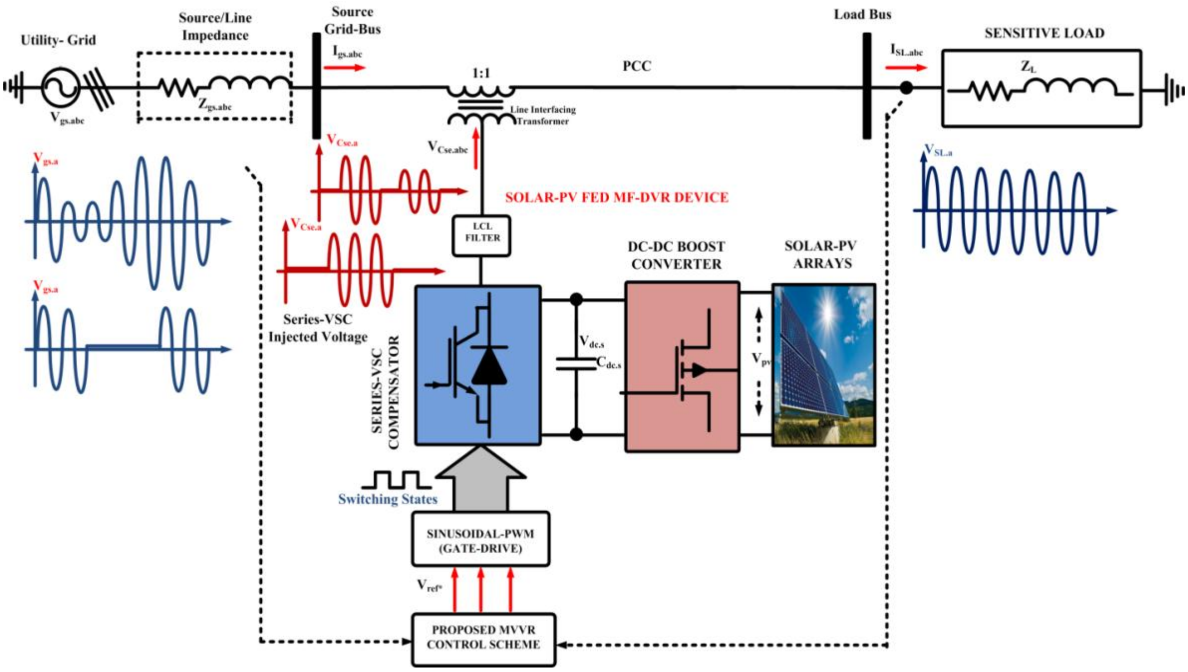


Figure 1. Model block diagram of solar-PV fed MF-DVR for DG operations and PQ enhancement

The superlative solar-PV fed MF-DVR device has a stronger capability for continuous active power support to local end-user loads during grid-islanding mode, sudden power block-outs, and so on. Along with DG operations, the MF-DVR acts as a series active power filter (SeAPF) for compensation of all voltage-related issues for enhancing the power quality, load balancing, and ensuring voltage stability in a utility-grid integrated distribution system. The design and functioning of the proposed MF-DVR device have similar features related to basic SeAPF by utilizing a single 3-level VSC module integrated to the PCC of the utility-grid integrated distribution system via a 1:1 line-interfacing transformer. The VSC of MF-DVR acts as a multi-functioning module which is powered by a common DC-link capacitor ($C_{dc.s}$) followed by solar-PV energy.

In DG mode, any grid-islanding issues are detected, then the solar-PV system is directly delivering energy to the common DC-link capacitor, followed by a DC-DC boost converter along with an INC-MPPT controller for regulating the solar-PV power under varying conditions. The energy generated from solar-PV has been directly delivered to end-level consumers for active-power regulation under grid-islanding mode by using the available VSC in the MF-DVR device. This proposed DG system reduces the utilization of an additional inverter/converter model for compensation of grid-islanding issues in the distribution system, which helps to reduce the initial cost, occupancy, and size of the compensation device. This can be attained by transition VSC of MF-DVR as a grid-forming state by allowing the DG to regulate the islanded utility-grid characteristics, ensuring the stable voltage and power support to end-user consumer loads with respect to load demand.

Similarly, when any voltage-relevant issues such as voltage harmonics, voltage sags, swells, or faults have occurred, affecting the overall functioning of end-user consumer loads at the PCC of the utility-grid system due to subversive power-pollution, discontinuous power-flow. In this mode, the VSC of MF-DVR transitions into PQ enhancement mode for compensation of all voltage-relevant PQ issues, as an in-phase voltage compensation principle that injects the requisite compensation voltage of $V_{Cse.abc}$ (V) into the PCC of the distribution system. The injected voltage restores the utility-grid specifications as linear, fundamental frequency, and sinusoidal wave shapes, a balanced system, and so on. The injected voltage is varied based on the type of voltage issues by sensing through detection devices, and the presented notches during compensation are eliminated by using LCL filters, which help to continuously load voltage regulation in the distribution system. It is noted that, as per IEEE/IEC regulations, the proposed MF-DVR device has been recognized for DG operations and compensation of voltage-related issues in a utility-grid integrated distribution system by employing a newly proposed MVVR control scheme.

3. PROPOSED MVVR CONTROL SCHEME

The block diagram of the newly proposed MVVR control scheme for the MF-DVR device is shown in Figure 2. The effective operation and robust performance of the proposed MF-DVR device rely on a suitable reference control scheme. The proposed MVVR control scheme is best suited for the extraction of voltage vector reference signals among the traditional SRF controller reported in [28]. The generated reference signal has a fast dynamic response due to low transient delay, simple transformations, and mathematical calculations, and improves the compensation efficiency and performance. This voltage vector reference signal utilizes the unit-vector template, which helps to produce the feasible switching states to the VSC of the MF-DVR device by using gate-drive circuitry. When any voltage-relevant PQ issues occur, the sensor in the MVVR controller calculates the changes in the rate of amplitude and phase-coordinates of the sensitive load voltage of the distribution system. The calculated load voltages are evaluated for producing synchronized vector notations with an angle rotated with in the phase-locked loop (PLL) for generation of précised frequency signal with noise cancellation and signal demodulation features. The sensed sensitive load voltage is represented as (1).

$$
\begin{aligned}
V_{SL.a} &= V_{gs.a} \sin(\theta_s) \\
V_{SL.b} &= V_{gs.b}\, sin\left(\theta_s - {}^{2\pi}/_{3}\right) \\
V_{SL.c} &= V_{gs.c}\, sin\left(\theta_s + {}^{2\pi}/_{3}\right)
\end{aligned} \tag{1}
$$

The sensitive load voltage is simply forwarded to unit-vector template, it produces the non-complex unit vector signals are extracted as phase-angle coordinates of load voltage as described in (2).

$$
\Delta V^{+}_{ugs.abc} = \left\{\frac{2}{3}\left(V^2_{ugs.a} + V^2_{ugs.b} + V^2_{ugs.c}\right)\right\}^{1/2} \tag{2}
$$

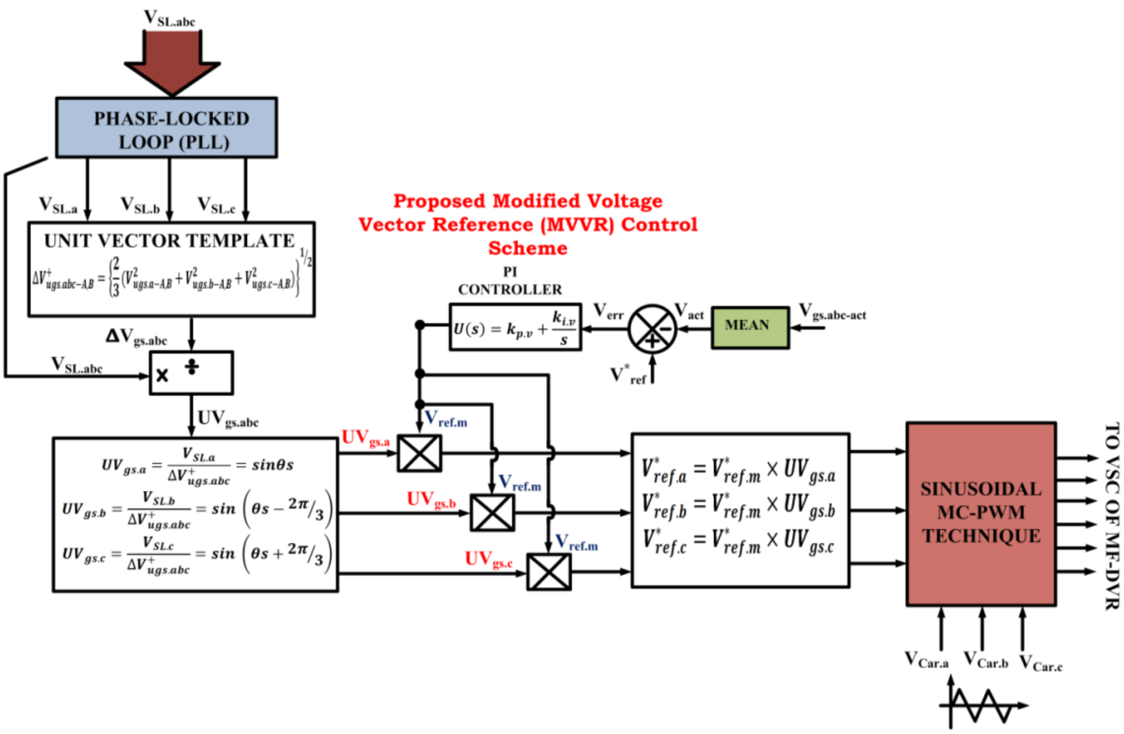


Figure 2. Block diagram of newly proposed MVVR control scheme for MF-DVR device

The resultant non-complex unit vector signals are represented by (3). These signals are used to extract the phase angle.

$$UV_{gs.a} = \frac{V_{SL.a}}{\Delta V^{+}_{ugs.abc}} = \frac{V_{gs.a}\sin(\theta_s)}{\left\{\frac{2}{3}(V^2_{ugs.a}+V^2_{ugs.b}+V^2_{ugs.c})\right\}^{1/2}} = sin\theta s$$
$$UV_{gs.b} = \frac{V_{SL.b}}{\Delta V^{+}_{ugs.abc}} = \frac{V_{gs.b}\sin(\theta_s - 2\pi/3)}{\left\{\frac{2}{3}(V^2_{ugs.a}+V^2_{ugs.b}+V^2_{ugs.c})\right\}^{1/2}} = sin\left(\theta s - 2\pi/3\right)$$
$$UV_{gs.c} = \frac{V_{SL.c}}{\Delta V^{+}_{ugs.abc}} = \frac{V_{gs.b}\sin(\theta_s + 2\pi/3)}{\left\{\frac{2}{3}(V^2_{ugs.a}+V^2_{ugs.b}+V^2_{ugs.c})\right\}^{1/2}} = sin\left(\theta s + 2\pi/3\right) \quad (3)$$

On other side, the actual voltage calculated from mean value (V_{act}) of utility-grid voltage is differentiated with reference set voltage (V^*_{ref}), it delivers some error sequences. These error sequences in voltage are regulated by using proportional-integral (PI) controller with proper tuning of gain values (($K_{p.v}, K_{i.v}$) using Ziegler-Nichols (ZN) method. It is the heuristic method for determining the initial values of PI controller for tuning the parameters to attain précised transfer function mathematical model of the system. The significant PI controller minimizes the error sequences and produces the final reference voltage magnitude value ($V^*_{ref.m}$) at n^th^ notation, as magnitude is stated as (4) and (5).

$$V_{err} = V^*_{ref} - V_{act} \quad (4)$$

$$V^*_{ref.m} = K_{p.v} \times \left(V_{err\,(n)} - V_{err\,(n-1)}\right) + K_{i.v} \times \left(V_{err\,(n)}\right) \quad (5)$$

The generated solar-PV power from solar-PV system under DG operating mode is described as (6).

$$I_m = I_{L.pv} - I_o\left[exp\left(\frac{V_{pv}+I_{pv}*R_{se}}{\eta V_T}\right) - 1\right] - \left[\frac{V_{pv}+I_{pv}*R_{se}}{R_{sh}}\right]$$
$$P_{pv} = V_{pv} \times I_{pv} \quad (6)$$

Where I_m is total DG current (A), I_{pv} is solar-PV current (A), V_{pv} is solar-PV voltage (V), I_o is reverse-saturation of diode's current (A), $I_{L.pv}$ is solar-PV irradiance light current (A), R_{se} is series resistance (Ω), R_{sh} is shunt resistance (Ω), V_T is thermal voltage (V), and η is ideality index.

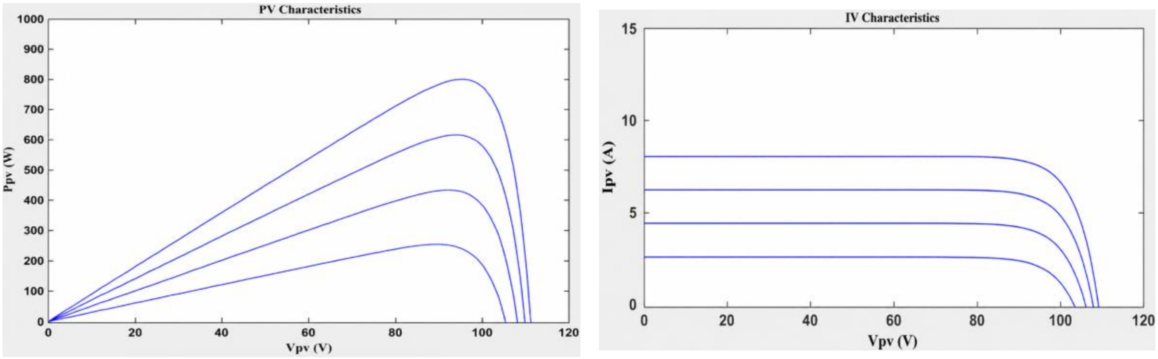
Figure 3 shows the solar PV performances, where Figure 3(a) illustrates the PV characteristics and Figure 3(b) illustrates the I–V characteristics. The generated solar-PV power is managed by a front-end DC-DC boost converter with the incremental-conductance (INC) maximum-power point tracker (MPPT) algorithm. The INC-MPPT algorithm extracts the feasible direction of solar-PV system working on various perturbations of possible curve slopes of solar-PV voltage $V_{pv.dg}$ and PV current $I_{pv.dg}$, it may be either right or left and either positive or negative of the maximum peak point and/or zero slope at maximum peak point is described as (7).

$$\left.\begin{array}{ll} \frac{\Delta I_{pv}}{\Delta V_{pv}} = -\frac{I_{pv}}{V_{pv}}; & at\ MPP \\ \frac{\Delta I_{pv}}{\Delta V_{pv}} < -\frac{I_{pv}}{V_{pv}}; & right\ of\ MPP \\ \frac{\Delta I_{pv}}{\Delta V_{pv}} > -\frac{I_{pv}}{V_{pv}}; & left\ of\ MPP \end{array}\right\} \quad (7)$$

From the resultant non-complex unit vector signals ($UV_{gs.abc}$) and the reference voltage magnitude ($V^*_{ref.m}$) are multiplied for generation of final reference voltage vector signal ($V^*_{ref.abc}$) to VSC of MF-DVR device, it is described as (8).

$$V^*_{ref.a} = V^*_{ref.m} \times UV_{gs.a}$$
$$V^*_{ref.b} = V^*_{ref.m} \times UV_{gs.b}$$
$$V^*_{ref.c} = V^*_{ref.m} \times UV_{gs.c} \quad (8)$$

Finally, the generated reference voltage vector signal is forwarded to sinusoidal multi-carrier pulse-width modulation (SMC-PWM) with certain triangular multi-carrier signals helps to produce the feasible switching states to VSC of MF-DVR device for both DG operations and all PQ enhancement modes. The pulsation index of the VSC of MF-DVR is automatically set during the compensation based on the reference voltage generated by the proposed MVVR control scheme, and the switching or carrier frequency is selected as an odd multiple of the utility-grid supply frequency for better harmonic reduction, better filter size, and low ripple content. The feasible switching states help to operate the VSC of MF-DVR as direct voltage injection, which restores the utility-grid specifications in the distribution system as linear, fundamental frequency, and sinusoidal wave shapes, a balanced system, and so on. The schematic model diagram of the newly proposed MVVR-controlled MF-DVR device for DG operations and PQ enhancement in the utility-grid integrated distribution system is depicted in Figure 4.



(a) (d)

Figure 3. Solar-PV performance: (a) PV characteristics and (b) IV characteristics

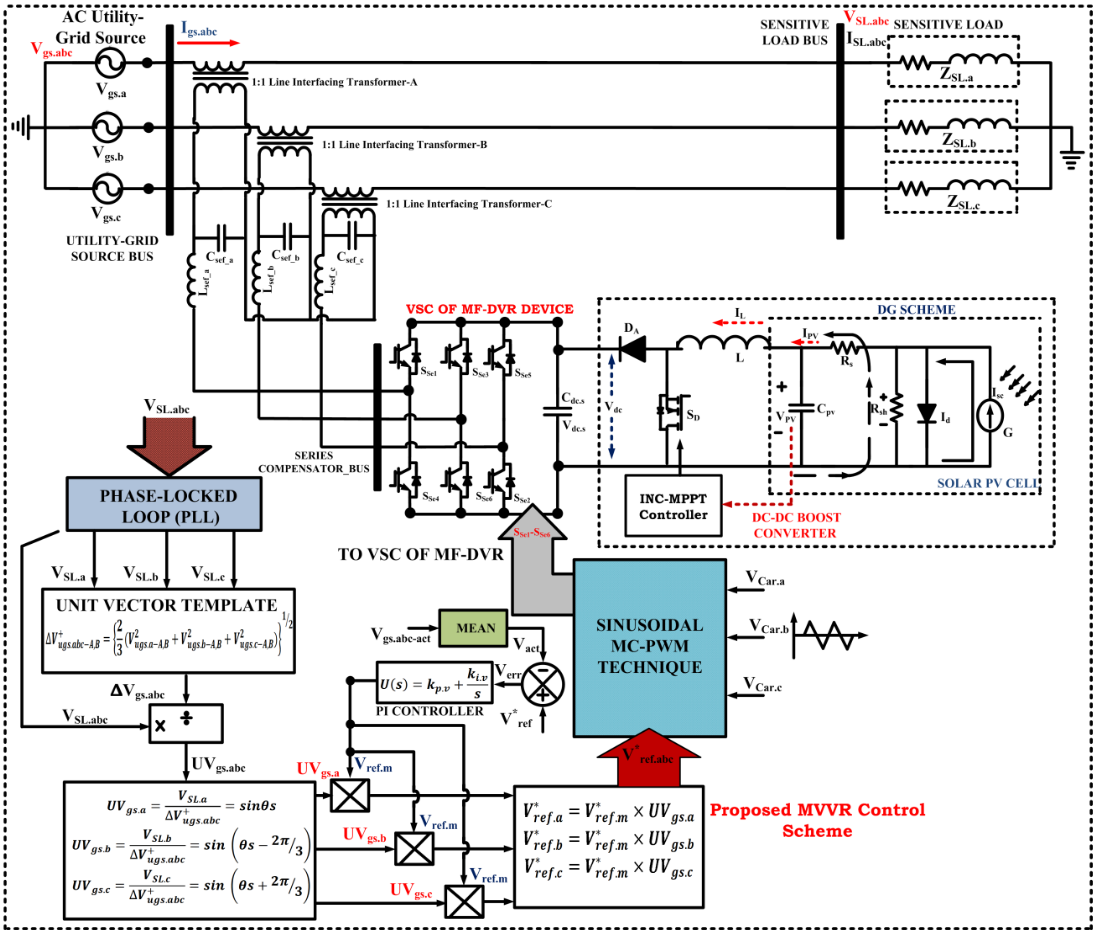


Figure 4. Schematic model diagram of newly proposed MVVR controlled solar-PV fed MF-DVR device for DG operations and PQ enhancement in utility-grid integrated distribution system

4. RESULTS AND DISCUSSION

4.1. Compensation of voltage relevant PQ issues in utility-grid integrated distribution system using newly proposed MVVR controlled solar-PV fed MF-DVR device

The design and performance of the proposed MVVR-controlled solar-PV-fed MF-DVR have been verified under enhancing power-quality in voltage compensation mode and grid-islanding issues in DG mode through MATLAB/Simulation software tool. The MATLAB/Simulink specifications are illustrated in Table 1. The simulation results of compensation of voltage-relevant PQ issues in a utility-grid integrated distribution system using a newly proposed MVVR-controlled solar-PV-fed MF-DVR device is presented in Figure 5 (see Appendix). The distribution system is powered by a three-phase utility-grid voltage source of 415 Vrms, 50 Hz source frequency is shown in Figure 5(a). In this case, some of voltage voltage-relevant issues, such as voltage harmonics, voltage sag, and voltage are occurred and affect the overall functioning of sensitive loads at the PCC of the utility-grid system due to subversive power pollution, discontinuous power-flow. The occurred voltage relevant issues are compensated by employing a VSC of an MF-DVR device, which is integrated as a series connection at the PCC of the distribution system via 1:1 line-interfaced transformers. For better compensation, the newly proposed MVVR control scheme extracts the suitable reference voltage signal; it can produce the feasible switching states to the VSC of the MF-DVR device for enhancing PQ through sinusoidal multi-carrier pulse-width modulation (SMC-PWM) with certain triangular multi-carrier signals.

Table 1. MATLAB/Simulink specifications

S. No	Simulation parameters	Values
1	Utility-grid source voltage	$V_{gs.abc}$-415 V, F_{gs}-50 Hz
2	Source/line impedance	$R_{gs.abc}$-0.1 Ω, $L_{gs.abc}$-0.9 mH
3	Sensitive load impedance	$R_{SL.abc}$-20 Ω, $L_{SL.abc}$-30 mH
4	DC-link capacitor	$V_{dc.s}$-880 V, $C_{dc.s}$-1500 µF
5	MF-DVR VSC's filter	$R_{fs.abc}$-1 Ω, $C_{fs.abc}$-100 µF
6	Solar-PV DG system	$V_{pv.dg}$-440 V, $I_{pv.dg}$-25 A, $P_{pv.dg}$-11 kW
7	DC-DC boost converter	L-1 mH, $C_{dc.s}$-1500 µF
8	PI controller	$K_{p.v}$-1, $K_{i.v}$-0.1
9	PWM frequency	F_{sw}-5000 Hz

In this way, the time instant before t-0.05 sec is treated as a pre-distorted condition, as a healthy condition, representing that the utility-grid voltage source is maintained as a constant voltage of 340 V. During the instant 0.05 sec < t < 0.15 sec, the PCC of the distribution system has been distorted and harmonized due to the presence of 5th, 7th harmonics, affecting the performance of the critical load, as depicted in Figure 5(a). Therefore, the VSC of MF-DVR is transitioned as a series-APF for compensation of voltage harmonics as an in-phase voltage compensation principle, which injects the requisite compensation voltage with phase-angle correction into the PCC of the distribution system. The injected voltage with a certain phase-angle restores the critical-load voltage as a harmonic-free, maintained as linear, fundamental frequency, sinusoidal wave-shapes and balanced as shown in Figures 5(b) and 5(c). During this harmonic compensation, the solar-PV voltage, current, and active power are not utilized much because the DC-link capacitor supported the DC-link voltage of 880 V, as shown in Figures 5(d)-5(g). The THD spectrum of utility-grid source voltage during voltage harmonics is measured as 20.62% and the THD spectrum of critical load voltage during compensation of voltage harmonics is measured as 0.43%, which is well within the IEEE-519/2022 standards as depicted in Figures 5(h) and 5(i).

The time instant before t-0.2 sec is treated as a pre-sag condition, as a healthy condition represents that the utility-grid voltage source is maintained as a constant voltage of 340 V. The voltage sag has occurred in the time instant of 0.2 sec < t < 0.35 sec; the PCC of the distribution system voltage is decreased by 55% due to a sudden-sag issue, which affects the voltage of the sensitive load is decreased to 186 V, as depicted in Figure 5(a). Therefore, the MVVR-controlled VSC of solar-PV-fed MF-DVR is transitioned as a series voltage-restorer for compensation of voltage sag, as in-phase voltage compensation principle, which injects the requisite compensation voltage with a certain phase-angle of +154 V into the PCC of the distribution system, is shown in Figure 5(b). The injected voltage helps to restore the critical-load voltage is maintained as a linear, fundamental frequency, sinusoidal wave shape and balanced with a value of 340 V, as shown in Figure 5(c). The voltage-sag compensation has been initiated by energizing the DC-link capacitor through INC-MPPT controlled DG, which consists of extracting maximum power from the solar-PV system, as solar-PV DG voltage of 880 V with a solar-PV injected current of 7.2 A and the injected solar-PV power of 6.3 kW is depicted in Figures 5(d)-5(f). Also, during this time instant, the utility-grid source power has been decreased to 4.8 kW, and the solar-PV DG system injected the requisite active power of 5.2 kW to achieve the sensitive load power of 10 kW, as shown in Figure 5(g).

The time instant before t-0.5 sec is treated as a pre-swell condition, as a healthy condition represents that the utility-grid voltage source is maintained as a constant voltage of 340 V. The voltage sag has occurred in the time instant of 0.5 sec < t < 0.65 sec, the PCC of the distribution system voltage is increased by 55% due to a sudden swell, which affects the voltage of the sensitive load is increasing it to 525 V, as depicted in Figure 5(a). Therefore, the MVVR-controlled VSC of solar-PV-fed MF-DVR is transitioned as a series voltage-restorer for compensation of voltage swell, as an in-phase voltage compensation principle, which injects the requisite compensation voltage with a certain phase-angle of -185 V into the PCC of the distribution system, as shown in Figure 5(b). The injected voltage helps to restore the critical-load voltage is maintained as a linear, fundamental frequency, sinusoidal wave shape and balanced with a value of 340 V, as shown in Figure 5(c). The voltage-sag compensation has been initiated by energizing the DC-link capacitor through INC-MPPT controlled DG, which consists of extracting maximum power from the solar-PV system, as solar-PV DG voltage of 880 V with a solar-PV extracted current of -5.5 A and the extracted solar-PV power of -4.8 kW is depicted in Figures 5(d)-5(f). Also, during this time instant, the utility-grid source power has been increased to 13.6 kW, and the solar-PV DG system extracted the unwanted active power of -3.6 kW to achieve the sensitive load power of 10 kW, as shown in Figure 5(g).

4.2. Compensation of grid-islanding issues in utility-grid integrated distribution system using newly proposed MVVR controlled solar-PV fed MF-DVR device

The simulation results of compensation of grid-islanding issues in a utility-grid integrated distribution system using a newly proposed MVVR-controlled solar-PV-fed MF-DVR device is presented in Figure 6. The distribution system is powered by a three-phase utility-grid voltage source of 415 Vrms, 50 Hz source frequency is shown in Figure 6(a). In this case, grid-islanding issues like sudden voltage interruptions have occurred, which affect the uninterrupted power to sensitive loads at the PCC of the utility-grid system due to discontinuous power flow. The sudden voltage-interruptions under grid-islanding are compensated by employing a VSC of the MF-DVR device and integrated as a series-connection at the PCC of the distribution system via 1:1 line-interfaced transformers. This can be attained by transition VSC of MF-DVR as a grid-forming state by allowing the DG to regulate the islanded utility-grid characteristics, ensuring the stable voltage and power support to sensitive load apparatus with respect to the requisite load demand. For better compensation, the newly proposed MVVR control scheme extracts the suitable reference voltage signal; it can produce the feasible switching states to the VSC of the MF-DVR device for mitigation of grid-islanding issues through sinusoidal multi-carrier pulse-width modulation (SMC-PWM) with certain triangular multi-carrier signals.

The time instant before t-1 sec is treated as a pre-islanding/interrupted condition, as a healthy condition represents that the utility-grid voltage source is maintained as a constant voltage of 340 V. The sudden voltage interruptions under grid-islanding have occurred in the time instant of 1 sec < t < 1.3 sec, the PCC of the distribution system voltage is decreased due to sudden-voltage interruptions, which affects the voltage of the sensitive load is decreased to 0V because of and is depicted in Figure 6(a). Therefore, the MVVR-controlled VSC of solar-PV-fed MF-DVR is transitioned as a grid-forming state for compensation of sudden voltage interruptions, as in-phase voltage compensation principle, which injects the requisite compensation voltage with a certain phase-angle of +340 V into the PCC of the distribution system, as shown in Figure 6(b). The injected voltage helps to restore the critical-load voltage is maintained as a linear, fundamental frequency, sinusoidal wave-shape and balanced with a value of 340 V, as shown in Figure 6(c). The sudden voltage interruptions are compensated has been initiated by energizing the DC-link capacitor through INC-MPPT controlled DG, which consists of extracting maximum power from the solar-PV system as solar-PV DG voltage of 880 V with a solar-PV injected current of 12.5 A, and the injected solar-PV power of 11 kW is depicted in Figures 6(d) to 6(f). Also, during this time instant, the utility-grid source power has been completely decreased to 0 kW, and the solar-PV DG system injected the requisite active power of 10 kW to achieve the sensitive load power of 10 kW, as shown in Figure 6(g). The THD spectrum comparisons and graphical representation of utility-grid source voltage and the sensitive load voltage under various signatures are presented in Table 2 and Figure 7. Among various compensation signatures, the newly proposed MVVR-controlled MF-DVR device furnishes better compensation features with a low THD value, compared to a regular SRF-controlled MF-DVR device.

Table 2. THD spectrum comparisons and graphical representation of utility-grid source voltage, sensitive load voltage under various compensation signatures

THD (%)	Utility-grid source voltage	Sensitive load voltage
Without MF-DVR		20.62%
With regular SRF controlled MF-DVR device [28]	20.62%	0.58%
With newly proposed MVVR controlled MF-DVR device		0.43%

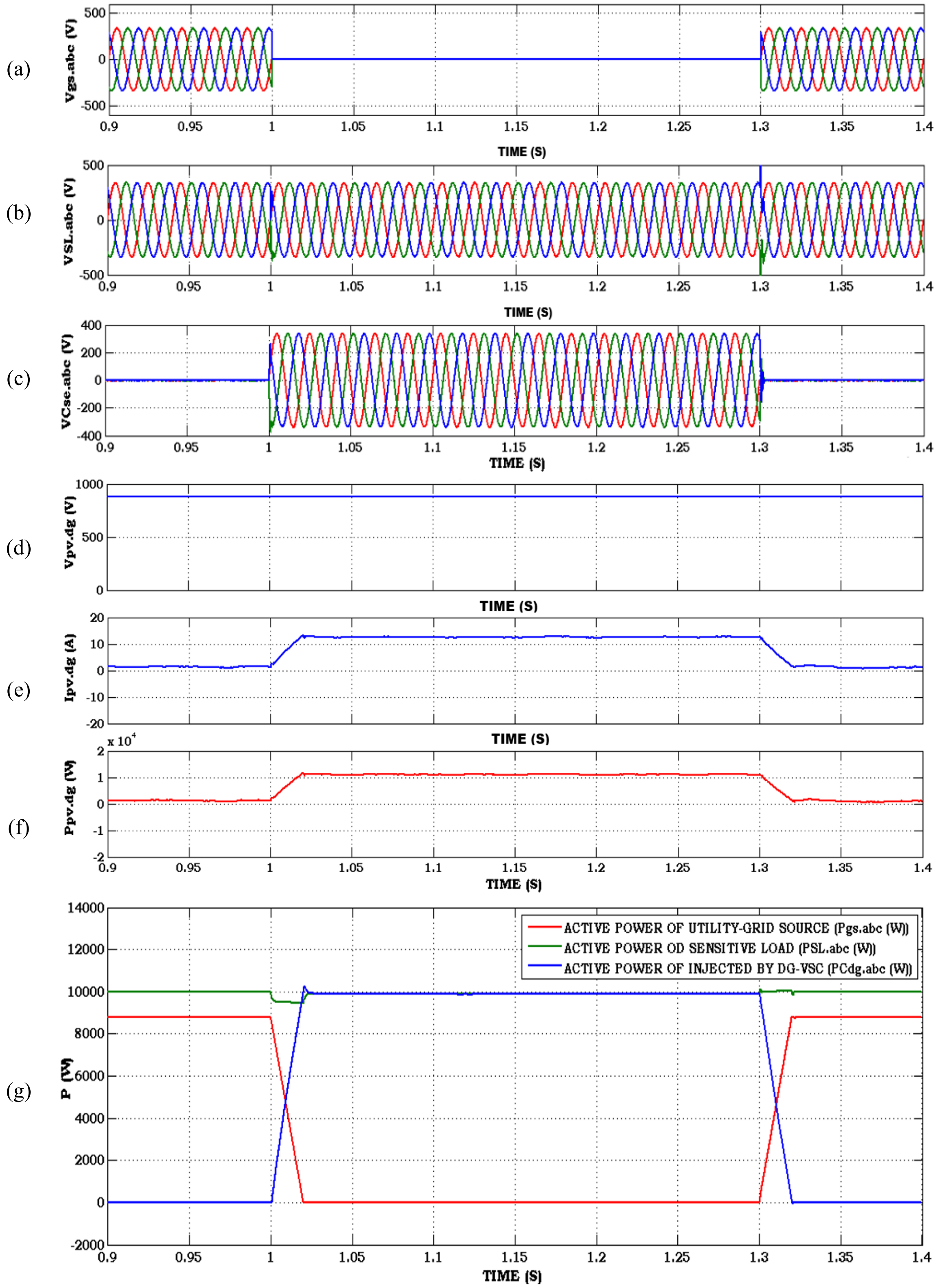


Figure 6. Simulated results of grid-islanding issues in utility-grid integrated distribution system using newly proposed MVVR controlled solar-PV fed MF-DVR device: (a) utility-grid voltage source, (b) sensitive load voltage, (c) series VSC injected voltage, (d) solar-PV DG voltage, (e) solar-PV DG injected current, (f) solar-PV DG power, and (g) active power

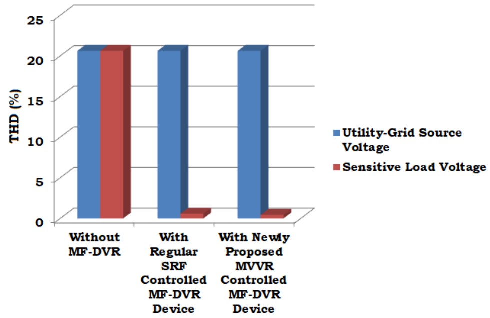


Figure 7. Graphical representation of THD spectrum under various compensation signatures

5. CONCLUSION

The superlative design and performance of the solar-PV fed MF-DVR device act as a unique DG integration scheme; it has stronger capability for continuous active power support, reliable power control, and greater power transfer to sensitive load apparatus during grid-islanding mode under sudden voltage interruptions. It delivers required active power during grid islanding, along with enhancing the voltage stability by using available VSC module in MF-DVR device for DG operations, installed with initial cost, low occupancy, and compact size are the substantial merits. Also, the solar-PV fed MF-DVR compensates all voltage relevant PQ issues for enhancing the power-quality, load balancing, and ensuring voltage stability in the utility-grid integrated distribution system. The effective operation and robust performance of the proposed solar-PV fed MF-DVR device under steady-state conditions through the newly proposed MVVR control scheme; it has a fast dynamic response due to low transient delay, simple transformations, and low mathematical calculations, which improves the compensation efficiency over the regular SRF control scheme. The THD spectrum of utility-grid source voltage during voltage harmonics is measured as 20.62% and the THD spectrum of critical load voltage during compensation of voltage harmonics in regular SRF and proposed MVVR controlled MF-DVR is measured as 0.58% and 0.43%, which is well within the IEEE-519/2022 standards. Further, the performance of the proposed solar-PV fed MF-DVR device under varying irradiance conditions during grid-islanding mode under long-voltage interruptions has been considered as the future research scope of the work.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Durgam Rajababu		✓		✓		✓	✓	✓		✓	✓	✓	✓	
Md Mujahid Irfan	✓		✓	✓	✓	✓	✓			✓	✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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APPENDIX

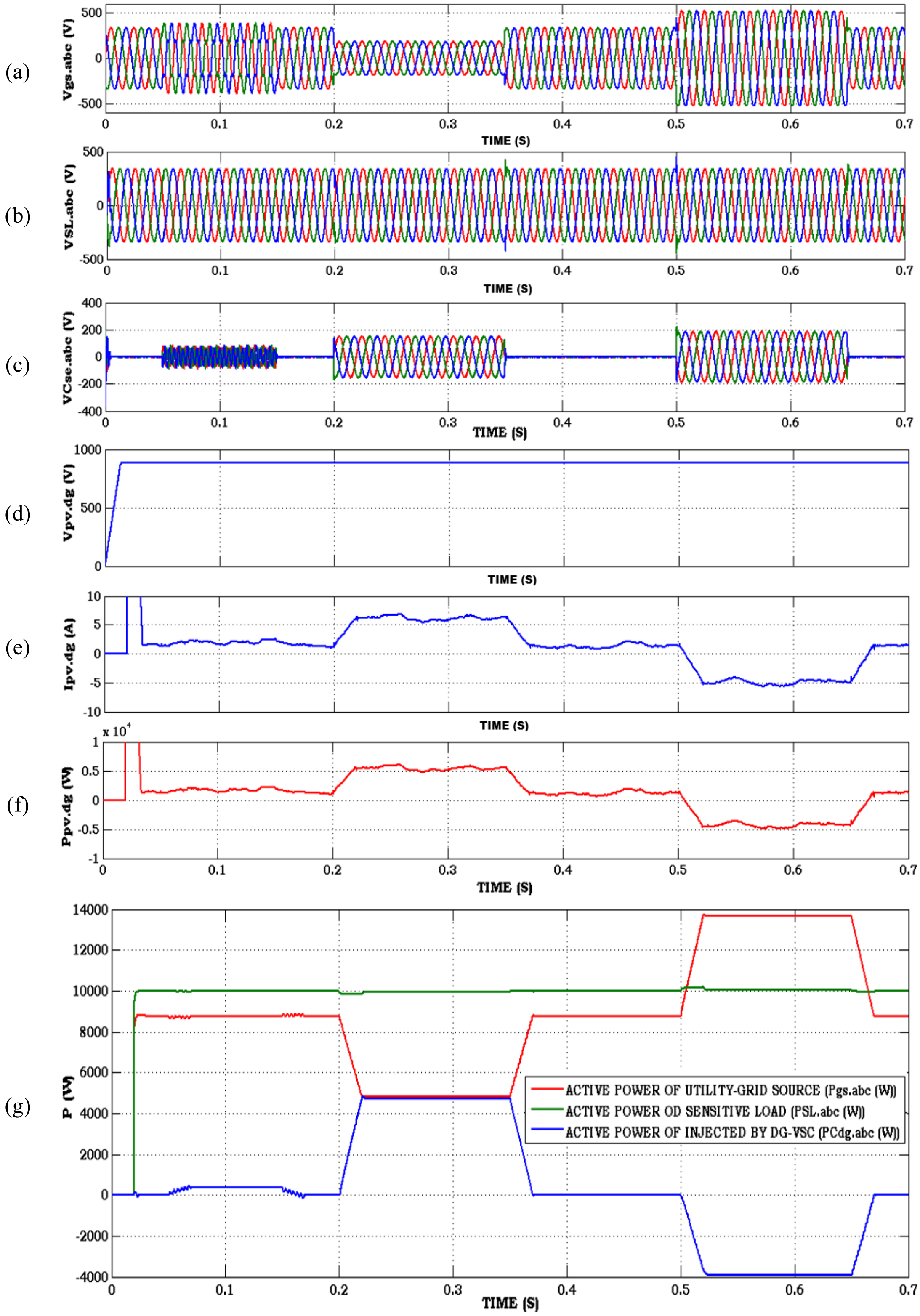

Figure 5. Simulated results of compensation of voltage relevant PQ issues in utility-grid integrated distribution system using newly proposed MVVR controlled solar-PV fed MF-DVR device: (a) utility-grid voltage source, (b) sensitive load voltage, (c) series VSC injected voltage, (d) solar-PV DG voltage, (e) solar-PV DG injected current, (f) solar-PV DG power, and (g) active power

(h)

(i)

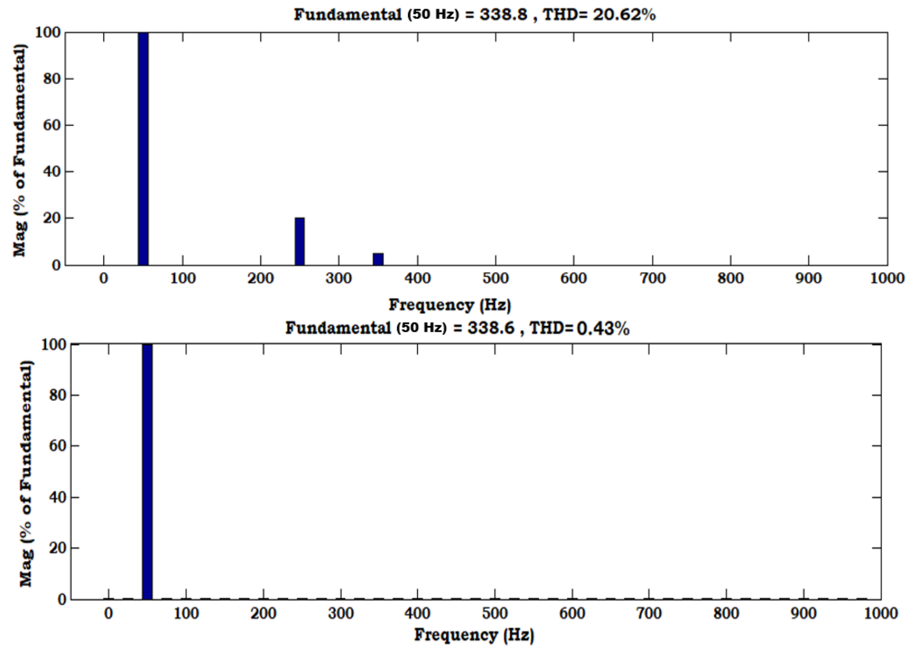

Figure 5. Simulated results of compensation of voltage relevant PQ issues in utility-grid integrated distribution system using newly proposed MVVR controlled solar-PV fed MF-DVR device: (h) THD spectrum of utility-grid source voltage and (i) THD spectrum of sensitive load voltage (continued)

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