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Investigation and Performance of PI Volt/Var Controller for Photovoltaic Inverters in Distribution Networks

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***Abstract*–The increasing share of the distributed solar photovoltaic (PV) presents many challenges for the electric power system's volt-var control (VVC). In this paper,a smart grid inverter control method to support the distribution system's larger penetration and deployment of PV generationsis studied and developed. The entire system (PV inverter model and distribution feeder) is realized and improved to secure the direct solar PV system generations using the proportional-integration (PI) controller. PI controller parameters are adapted to stabilize the system, meet the transient and steady-state performances' specifications, adapt well with the system, and concurrently achieve low steady-state error (SSE). Based on the local bus information, a solid implementation of voltage control limits within the acceptable bounds by inverter's absorbing or injecting reactive power (Q) is described. Comprehensive simulation work is completed, and simulation results are given. The obtained results have shown that the applied control method can be successfully implemented, and the achieved outcomes met the accepted boundaries of ANSI standards (5 percent from the reference voltage value).**

Index Terms–Distribution Feeder, Proportional-Integration Controller, Steady State Error, Volt-Var Control.

INTRODUCTIONS

The installed capacity of PV distributed generation is worldwide rising rapidly, driven by the increases in electricity prices, reduction in PV system cost and sustainability awareness [1]. Nonetheless, rapid penetration of PVs in the distribution network causes many difficulties in voltage regulation and brings technical challenges due to transient change either in load or weather conditions, leading to reduced power quality [2]. However, power distribution utilities should provide the quality of service, as the ANSI standards stated that delivered voltage to the residential loads, under normal conditions, must remain within 5% of the reference voltage value [3]. Optimal control and PV system allocating and sizing methods improve power quality management, reduce power system losses and handle transient fluctuations in solar generation nature [4]. A recommended solution in the unbalanced distribution system is to complete a sensitivity analysis and reconfigure the distribution network by interchanging PV interconnections and loads due to the random distribution [5]. Such an expensive and complicated process requires changing or swapping distribution lines to improve the volt/var management in the distribution system. Furthermore, several controlling techniques have been proposed to mitigate reduced power quality [2]-[5] which can be employed by the utility itself or the owners of the distributed PV generation.

Recently, technological approaches have led to research on the benefits of using distributed energy resources in voltage regulation in distribution systems [6]. For example, smart PV inverter has emerged as effective solutions in control algorithmic method and provides faster and continuous VVC capability. However, the traditional power flow in the distribution network is configured as a unidirectional system along with the conventional VVC systems and traditional regulating devices such as switched capacitors and distributed tap changer transformers to regulate the voltage. For instance, unacceptable voltage rise or drop happens during high output power generation at the terminals of PV terminals and light loads condition or at a sudden loss in the generation, which significantly affects power quality at the end of the distribution feeder. Furthermore, a major obstacle in integrating PV systems into the distribution network is the fluctuation in voltage magnitude due to the bi-directional flow of power along the distribution feeder. Moreover, distributed energy resources deployment raises unprecedented deterioration in power quality due to the widespread use of commercial control strategies in the inverter technology. A traditional method is to use a voltage regulator or lower/raise the on-load tap changer setpoint in the power transformer at the primary transmission substations. In fact, these solutions cannot ensure the regulation in voltage profile magnitude throughout the feeder within the acceptable limits (±5% voltage regulation). In addition, other connected feeders to the same power transformer might be impacted by this action adversely. Instead, the utility can support the distribution grid by reducing the resistance of line power cables in medium and low voltage by increasing line conductor sizing to reduce its losses. In Japan, the PV system control reduces its active output power when the measured voltage at the common coupling point exceeds the accepted limit. The disadvantage of this scenario is that it will cause solar energy spilling. Economically, it does not attract the PV panel owners. For instance, in the National Energy Grid of Germany, where the updating of grid codes or the development of new controllers is much slower than the increase in the installed capacity of PV systems, this practice led to high costs.

This study primarily develops and investigates the solar PV VVC, which falls within the locally based control method. However, the optimal power flow (OPF) is excluded in this paper among the PV inverters because of the long-term expected to determine the communication delay and the OPF [7]. On the other hand, voltage measurements within the local VAR control value are considered at the local bus. Usually, a constant reference voltage value is assumed in the local PV inverters algorithms, which effectively responds to the voltage deviation relatively faster and relies on the feeder's full topologies for the optimal selection of PV inverter control parameters. Nonetheless, it is challenging to achieve dynamic stability in designing of solar PV inverter local control (LC) method [8]. Inverter's LC approaches among distributed generations and the inappropriate adaptation of control parameters increase tap changer triggers, leading to instability issues and voltage oscillation [9]. Unfortunately, modern LC methods lack analytical characterization and do not discuss parameters selection. While securing convergence in changing operating conditions and external disturbance, a significant difficulty with the LC is the inherent inability to achieve a low SSE level [10]. Consequently, control stability and low SSE are crucial to ensure distribution feeder security and will not offset the operation or adversely affect other voltage regulating devices. In this journal, the solar PV inverter VVC intends to manage, as a function of voltage magnitude, the Q absorption/injection using the PI controller at the inverter terminals to achieve an accomplished implementation. Distinctly, the proposed control strategy is easily performed, faster response to sudden change, and does not require communication or cooperation between the distributed inverters with ensuring system stability and reduced SSE. Furthermore, the accumulative side outcomes of the improved scheme are clearly observed at the distribution feeder terminals (grid side). PV inverters absorb or inject Q in order to regulate voltage in a distribution feeder. Consequently, the aim is to achieve an accomplished implementation of VVC using the PI controller to preserve the accepted bounds of voltage by Q absorption or injection, which response to the sudden external disturbances, simple to implement and faster in the distribution system with ensuring low SSE and system stability. This analysis objective provided through a comprehensive simulation works at essentially no extra investment cost on the PV panel owners, and this control will mitigate voltage violation due to the intermittent nature of solar energy and sudden change in generation and load.

Previous studies extended in the following points on this topic: 1) Simulation studies completed in great detail of various capacities of PV system connected in the distribution feeder. The simulations were performed using SIMULINK/MATLAB, professionally developed for simulating, analyzing, and modeling. 2) Control parameters and updated transfer function are developed to eliminate undesired oscillatory behavior present in the control path and help to stabilize the system. 3) The PV inverters' Q capability was modeled accurately because Q generation and absorption capability are limited at the most during peak PV power generation times, precisely as mostly needed by the system. The rest of this paper is structured as follows: The Methodology and Method explained in Section 2. This part sets forth complete system modeling and PV controller scheme. The Results and Discussion are presented in Section 3; Illustrative simulation results and findings from SIMULINK are stated. Finally, comprehensive remarks of the conclusion and system implementation are given in Section 4.

METHOD AND METHODOLOGY

This sectionexamines the envisioned practical implementation of the solar PV inverter PI control methodology to improve power quality management in the distribution feeder and illustrates the grid-tied inverter modeling using SIMULINK/MATLAB software. In the grid-tied PV systems, PV inverters are used to interface the power control in the distribution network. As an important point, the controller design shall maintain efficient operation and ensure the utility power quality requirements [1]-[3].

I. System Modelling Procedures

The state-of-the-art and newly introduced local control strategy is embedded into the grid-tied Volt/var control process. The details of the complete system (PV inverter and the distribution feeder) are modeled using SIMULINK tools which run in MATLAB environments. In this model, the distributed solar PV generations are developed to source dc power supply using Soltech1 STH 215 P PV modules[11].

PV modules were connected in a series-parallel configuration; sets of PV modules are connected in parallel, each of them consisting of another set of modules connected in series to form a PV array and formed with a large unit of the solar cells. Two solar PV generators are connected with the distribution system; 1) PV generator-1 compensates electrical power system losses in addition to power system generation. 2) PV generator-2 is mainly connected to examine the response of the proposed controller of the PV inverter with the sudden change in power generation or the extra power generation at the load side where the sampling time of the simulation is run at 2.5 µs. Solar PV modules generate 725 dc output voltage, and PV inverters convert it into 537.4 peak ac voltage at nominal frequency equals 50 Hz. The inverter's output power is connected with the grid. Besides that, LC filters are applied to conduct the smart PV system with the network to eliminate the undesired harmonics [12]-[13].

The output voltage of solar cells is a function of the photocurrent and solar irradiation is the source of the photocurrent level during the operation where the PV current and voltage were developed by considering parallel branched and series modules of the PV array. Simulink toolbox implements an array of PV block, a five-parameter model using a shunt resistance, diode, series resistance and light generated current source are used to represent I-V characteristics, temperature, and irradiance of the PV module. Also, the Pulse Width Modulator (PWM) generator generates pulses using two-level topology for carrier-based PWM converters. It controls the inverter switching devices (IGBT) of 3 arms (three-phase bridge). The modulating signal, also called reference signal (U_{ref}), is compared with a symmetrical triangle carrier. When the modulating signal is greater than the carrier signal, the pulse of the upper switching device is low, and the pulse of the lower switching device is high vice versa. In addition, the Phase-Locked Loop (PLL) is a closed-loop control system that tracks and adjusts the phase and frequency of sinusoidal waveforms of three-phase system by using an internal frequency oscillator. However, the internal oscillator frequency is adjusted by the control system to keep the phase difference to zero where Park transformation in a rotating reference frame is performed by the abc to dq_0 block. Finally, the distribution feeder V-I Bus blocks are built to store and read the data.

II. Investigation Methodology and Controlling Method

This study investigates and develops system-interactive control to enhance larger solar PV deployment and penetration and reduce voltage fluctuation. The control system is developed to support the feeder voltage profile and secure the distributed solar PV direct generation, especially at the end of the feeder, as far as from the substation. Moreover, the impedance is lowest at the substation and increases as far away from it. Accordingly, by recognizing distribution system impedances and losses, an undervoltage effect will be experienced at the load bus [14].

This work shows that a smart PV system substitutes the drop in load bus voltage due to power losses and impedances. To study the impacts of PV on load bus voltage, assuming a PV inverter output is connected to the secondary circuit of a distribution feeder. Using Thevenin theorem, the effect changes across the common coupling point of the interconnection with the load bus in voltage magnitude (ΔV_{pv}) is:

$$\Delta V_{pv} = \left(\frac{RP - QX}{V_{pv}}\right) \tag{1}$$

Equation (1) shows the necessary factors influencing in power injection from the PV inverters that determine the impacts on the magnitude of the load bus voltage. Where ΔV_{pv}expresses the change in, per unit, voltage magnitude, and $V_{pv}$is the nominal load bus voltage. In addition, the ΔV_{pv} depends upon the reactive and active power injection from the PV inverter. In this paper, a grid-tied PV system connected to the load bus substitute the drop in V_{pv} due to distribution system impedance losses. However, the PV inverter's main three control parts are controller system, IGBT and filters [15], where PWM generates switching signals to keep the voltage within correct limits among IGBT switchings for the inverter operation. The output of smart PV inverters passes through the LC filters in order to eliminate higher-order harmonic components [13]. It is a second-order filter, simply designed, and it works mostly without problems. LC filters modeling equations:

$$Q_C = (0.5 \, * \, P_{inv}) \tag{2}$$

$$L = \frac{(0.1 * V_{base}^2)}{(2\pi L f P_{min})} \tag{3}$$

At each period, the MPPT function determines P. Also, based on the generated P in every period, the inverter losses should be considered and the Q injection or absorption is recomputed to achieve the desired controlling at the load bus and support voltage profile, especially at the end of substation feeders. Nevertheless, improper selection of the control system and its parameters could cause variation and instability at the connection point (busbar) [16]. Consequently, the inverter capability is determined by [14] as below, which reflects its current limitation:

$$S = Q^2 + P^2 \tag{4}$$

Simply, the extra Q generation is achieved by supplying the relevant amounts of current component *90°* out of phase and employing the reference of *dq* theory. Basically, PV inverters start absorbing Q when the measured load bus voltage (*LBV*) value crosses the reference of *LBV* (V_{ref}), in a bitV_{ref} is lower the *LBV* magnitude. Vice versa, the inverters are directed to support the mitigation of low voltage occurring by supplying Q when *LBV* drops below theV_{ref} and beyond [17].

III. Adaptive Volt-Var Control Strategy

The proportional and integration (PI) system is widely applied in control systems because of the reduced parameters number to be tuned and it is a special case of the PID controller, the derivative (D) of the error is not used to meet the criteria of the design of PV system [18]. Therefore, the PI controller provides a control signal proportional to the calculated voltage difference (*ΔV*) between the measured signal and the reference signal represented in proportional step, and to the integral of the calculated error (integral step). In other words, it sums the proportional error with the integral of the error [19]. Voltage sampled signals are transformed into *dq0* from the three axes *abc* frame using the Transformation of Park method as shown in equation (5). In addition, Park transformation is implemented with 50 Hz from a PLL block during employing the synchronized signals in the balanced three-phase distribution feeder.

$$\begin{matrix} V_d \\ V_q \\ V_0 \end{matrix} = \frac{2}{3}\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \times \begin{bmatrix} \cos(w_f t) & \cos(w_f t - \frac{2\pi}{3}) & \cos(w_f t + \frac{2\pi}{3}) \\ -\sin(w_f t) & -\sin(w_f t - \frac{2\pi}{3}) & -\sin(w_f t + \frac{2\pi}{3}) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \quad (5)$$

Figure 1 shows the methodology used to investigate the effects of the control strategy. V_{ref} is compared with *dq* voltage. Then, the difference generates the voltage error values. This comparison process fed the controller for the desired regulation. The PI control system outputs are expressed in the time domain as shown below:

$$ma = K_I \int \Delta V \, dt \; + \; \Delta V K_P \quad (6)$$

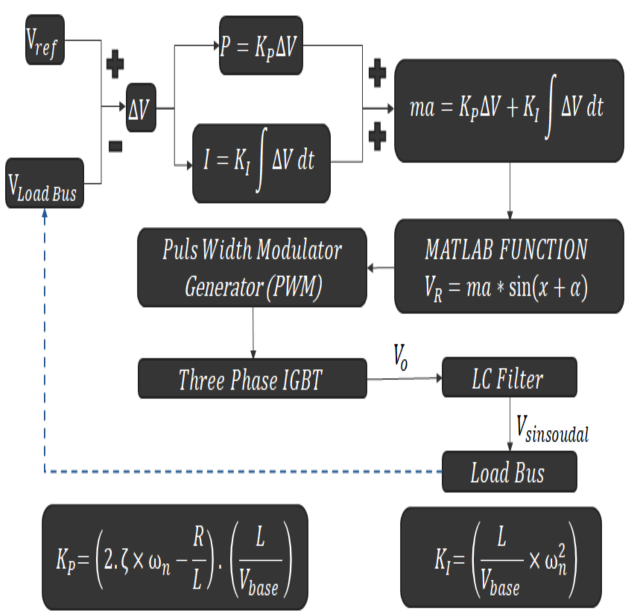


FIGURE 1
BLOCK DIAGRAM OF THE CONTROL CLOSED LOOP..

Where *ma* and *ΔV* represent the output of the controller and the error, respectively. K_I and K_P are tuned, and also denote the integral and proportional parameters (gains) [20]. One of the significant characteristics of the PI controller is the capability to rise the time response of the inverters output voltage and eliminate the steady-state error [21]-[22]. Upon summation, a control signal is generated where the PI controller keeps the error signal value at the minimum. Consequently, the system keeps the output voltage equal/near the V_{ref}as close as possible. Finally, the output voltage of the inverters can be controlled and stabilized. In PI controller, having a derived transfer function using the Laplace transform makes it easier for the system to define the closed-loop function, which is derived and designed completely inside the SIMULINK using MATLAB algorithms [23]. Further, PI controller parameters adapting is satisfied using the following equations that make the control system stable using the below equations:

$$\omega_n = \left(0.2 \times \frac{f_{PWM}}{\zeta}\right) \quad (7)$$

$$f_{PWM} = (33 \times f) \quad (8)$$

$$K_I = \left(\omega_n^2 \times \frac{L}{V_{base}}\right) \quad (9)$$

$$K_P = \left(\frac{L}{V_{base}}\right).\left(\omega_n - \frac{R}{L} \times 2.\zeta\right) \quad (10)$$

Where$w_n$and ζ are the parameters used in the response of PI controller determination. The control loop factor w_n is the undamped natural frequency and ζ is the damping ratio. The value of ζ is set to 0.707, where this value occurs in the step response with reasonable overshoot and fast settling time [22]. The corresponding transfer output function of the PI controller is given by:

$$ma = K_I . T_s\left(\frac{1}{z-1}\right).\left(V_{ref} - V_{load\ bus}\right) + K_P\left(b.V_{ref} - V_{load\ bus}\right) \quad (11)$$

It is considered that(0 <*ma* < 1) where *ma* > 1 value causes overmodulation and results in higher output voltages with more extra harmonics in the output waveform of the inverters. Consequently, *ma*value is kept below 1 in the PI control system. In addition, $T_s$is sampling time and*b*is setpoint weight. Where the value of *b*is set to 0.65 and $T_s$is 2.5 μs. MATLAB functions are used as an interface between the input of the PWM and PI controller output. The functions represent the inputs to the PWM as a three-phase reference waveform with a unity power factor, as shown in the following equations:

$$R = ma \times \sin(w_f) \quad (12)$$

$$Y = ma \times \sin\left(w_f - \frac{2\pi}{3}\right) \quad (13)$$

$$B = ma \times \sin\left(w_f + \frac{2\pi}{3}\right) \quad (14)$$

Where also, w_f is the voltage frequency. The above equations are used and sampled in the voltage regulation process in the voltage control scheme. Finally, the output voltage of PV inverter is within the accepted bounds and in phase within the ANSI standards as considered in this journal. The Q power is fed to or absorbed from the grid, PLL function blocks ensure that the grid-tied PV controller generates V_{ref} in phase with V_{grid}. Accordingly, the output signal is fed to the PWM generator to generate PV inverter switching signals. Therefore, the PWM modulates the switching signal of the inverter's switches to shape the output voltage as close to sinusoidal waves [23], as shown in figure 2. Additionally, the amplitude of the inverter output waveform is proportional to the varying control signal output and the dc input voltage. However, the frequency of the triangular wave signal, the carrier signal, establishes the inverter switching frequencies. A control variable (*ma*), PI controller output, is responsible for the rms value of the inverter output voltage.

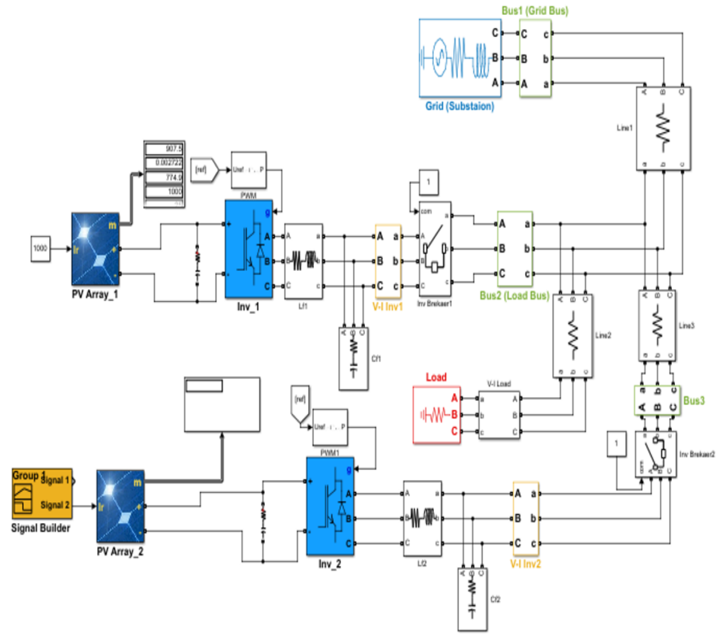


FIGURE 2
PV SYSTEMS MODEL USING SIMULINK.

SIMULATION RESULTS

In this section, simulation results were filtered and analyzed to obtain a sensible and accurate representation of the distribution feeder's grid-tied PV inverter control strategy modeled in high detail. The PI controller represents the base scenario where the inverters are regulating the load bus voltage. Accordingly, two scenarios within four systems of different PV array capacities (53 kW, 0.106 MW, 0.533 MW, and 1.066 MW) are studied and their PI controlling parameters are tabulated in Table I. Hence, the design of the controller and power stage is discussed in the previous sections.

TABLE I
PV SYSTEM LOAD POWER, LOAD BUS VOLTAGE AND MAXIMUM ERROR READINGS

System Capacity	K_I (*N.m.rad^{-1}*)	K_P (*N.m.s.rad^{-1}x10^{-3}*)	PV(kW)	P_{LOAD}(kW)	Q_{LOAD}(kVAR)	LBV (V_{ref}=537.4 V)			
						V_{min}(V)	V_{max}(V)	$Error_{max}$(%)1st scenario	$Error_{max}$(%)2nd scenario
53 kW	3.313	9.660	53.3	53	30	536.5	538.8	0.2	0.2
0.106 MW	0.166	4.840	106	98.5	56.5	536	540	0.48	0.26
0.533 MW	0.329	0.960	533	475	275	534	540	0.63	0.50
1.066 MW	0.165	0.480	1066	940	542	537	546	1.6	0.57

To understand, investigate and study the effect of PV penetration in the distribution system; the PV inverter's support and response with the extra generation or the sudden supply shortage, a second PV system (PV Array_2) is added and simulated, as seen in Figure 2. PV Array_2 considered with a variable irradiance input, the step change in the irradiance input to the inverter refelcts the sudden change in the delivered power to the distributon feeder. However, Figure 3 shows the two different scenarios; First one, step change of irradiance is [1000-0] within 3 seconds and the second scenario, three steps change in the irradiance [1000-200] within 6 seconds, then a stable condition for 2 seconds, showing the PI controller's desired functionality.

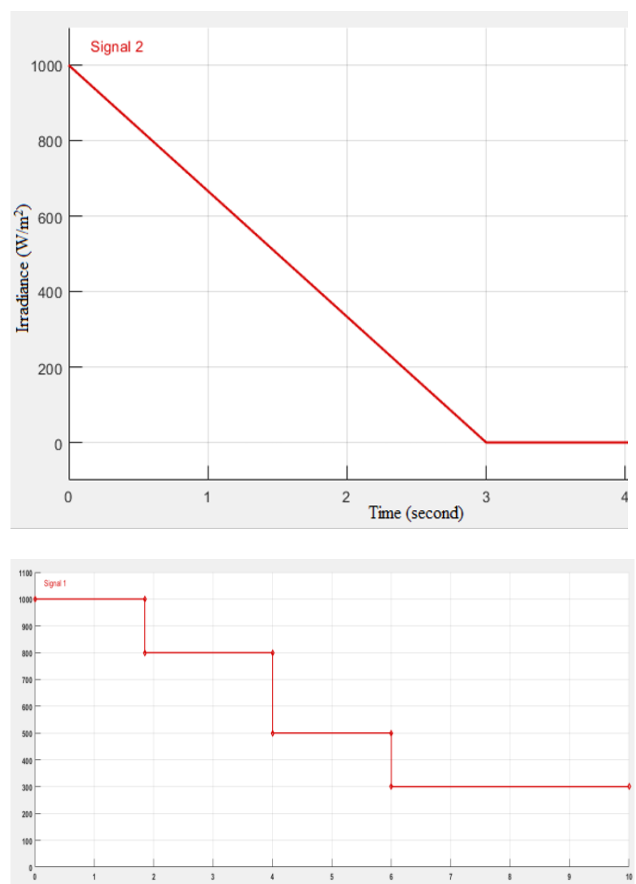
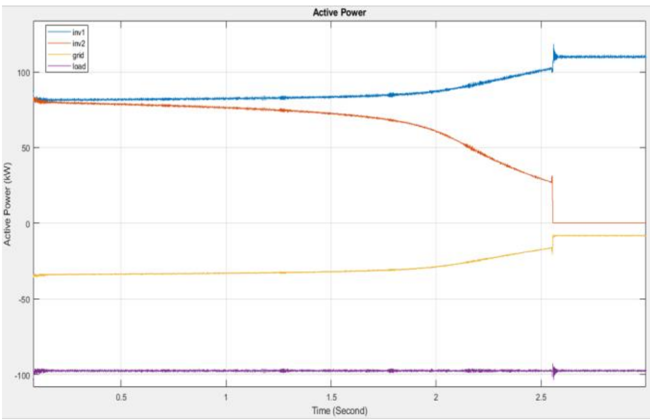


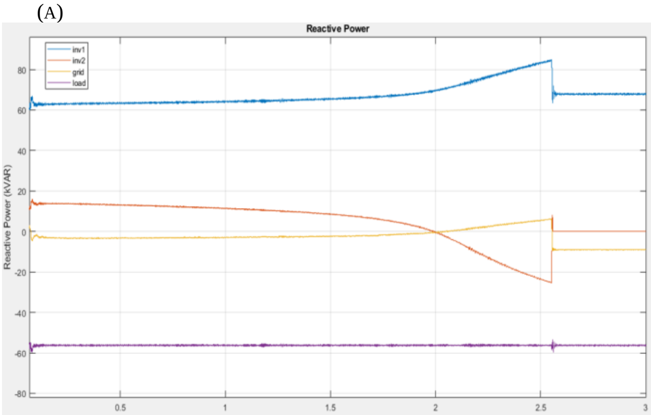
FIGURE 3
SCENARIO1 AND SCENARIO2

I. First Scenario:Irradiance Input Step change is [1000-0] W/m2 within 3 seconds

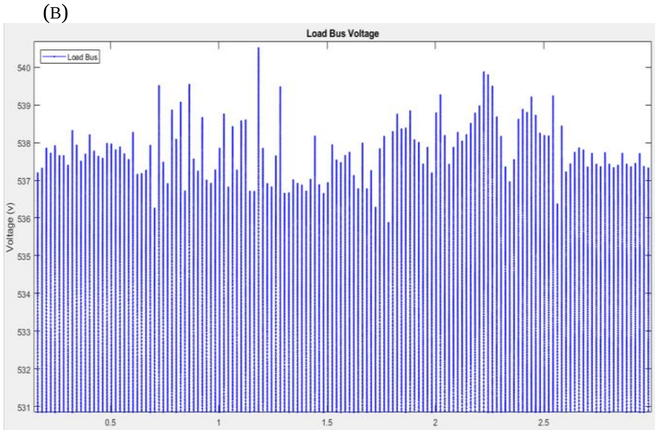
Four systems (53 kW, 0.106 MW, and 0.533 MW, and 1.066 MW) are modeled and selective simulation results of one system (0.106 MW) are provided in this part. In this model, grid loads are designed to consume (Q=56.5kVAR and P=98.5kW). Both solar PV inverters are connected to the distribution feeder to support the voltage profile, as shown in Figure 1. Hence, simulation results of the remaining systems are added at the end of this section. Figure 4 shows load bus voltage, PV inverters, grid and load active and reactive power and PI controller output readings.



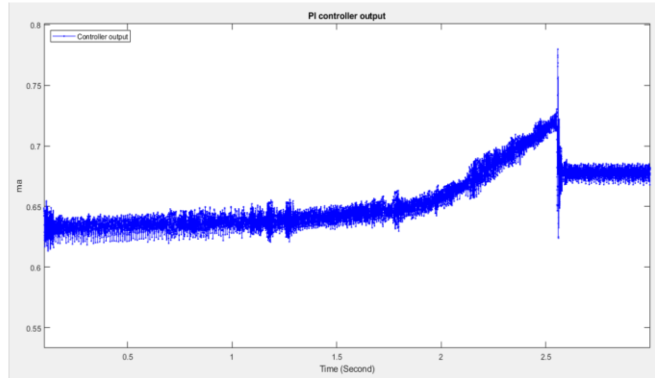
(A)



(B)



(C)



(D)

FIGURE 4
SIMULATION RESULTS OF LOAD BUS READINGS: (A)P (KW) (B)Q (KVAR) (C)LBV (V) (D)PI CONTROLLER OUTPUT (MA).

The delivered power to the load and voltage magnitude at the load bus were maintained and kept within the accepted limits during the sudden change in the PV_2 irradiance input during the step change, as required in this proposal. Initially, at PV_2 maximum generation, PV_2 delivered extra power than load needs, so PV_1 inverter absorbed Q to reduce the increase in LBV magnitude. Likewise, at the step-change, the reduction in PV_2 inverter output was offset by PV_1 inverter and grid supply, where PV_1 compensated the reduction in LBV magnitude by Q injection. Table II shows the performance of the PV inverted controlling system against the step-change in the power supply. Successfully, the control system achieved stability in load bus parameters and low SSE.

TABLE II
PV SYSTEMS, GRID AND LOAD READINGS

Time (Second)	PV_2 W/m²	PV_2 (kVAR)	PV_1 (kVAR)	Grid (kVAR)	PV_1 (kW)	PV_2 (kW)	Grid (kW)	ma	LBV (V)	Load (kVAR)	Load (kW)
0	1000	16	62	-3.4	80.5	83	-35.3	0.620	537.3	-56.5	-98.5
0.5	833.3	12.87	63.11	-3.02	81.35	78.16	-33.44	0.636	537.9		
1	666.6	11.36	64.17	-3	82.47	76.81	-33.02	0.639	537.6		
1.5	500	8.58	65.78	-2.42	84.05	72.81	-32.25	0.649	536.9		
2	333.3	-0.51	69.77	-0.52	87.8	60.37	-28.78	0.656	538.8		
2.5	166.6	-23.58	83.48	5.40	101.4	29.09	-17.37	0.715	538.2		

II. Scenario 2: Three stpes-change in the irradiance [1000-200] within 6 seconds.

In this scenario, three steps change in the irradiance [1000-200] within 6 seconds to examine PV inverter behavior during the stable condition for each step within 2 seconds. Same like the first scenario, four systems (53 kW, 0.106 MW, and 0.533 MW, and 1.066 MW) are modeled and selective simulation results of one system (1.066 MW) are provided in this part. In this model, grid loads are designed to consume (Q=540kVAR and P=940kW). Both solar PV inverters are connected to the distribution feeder to support the voltage profile as shown in Figure 2. Hence, simulation results of the remaining systems are added at the end of this section. Figure 5 shows load bus voltage, PV inverters, grid and load active and reactive power and PI controller output readings.

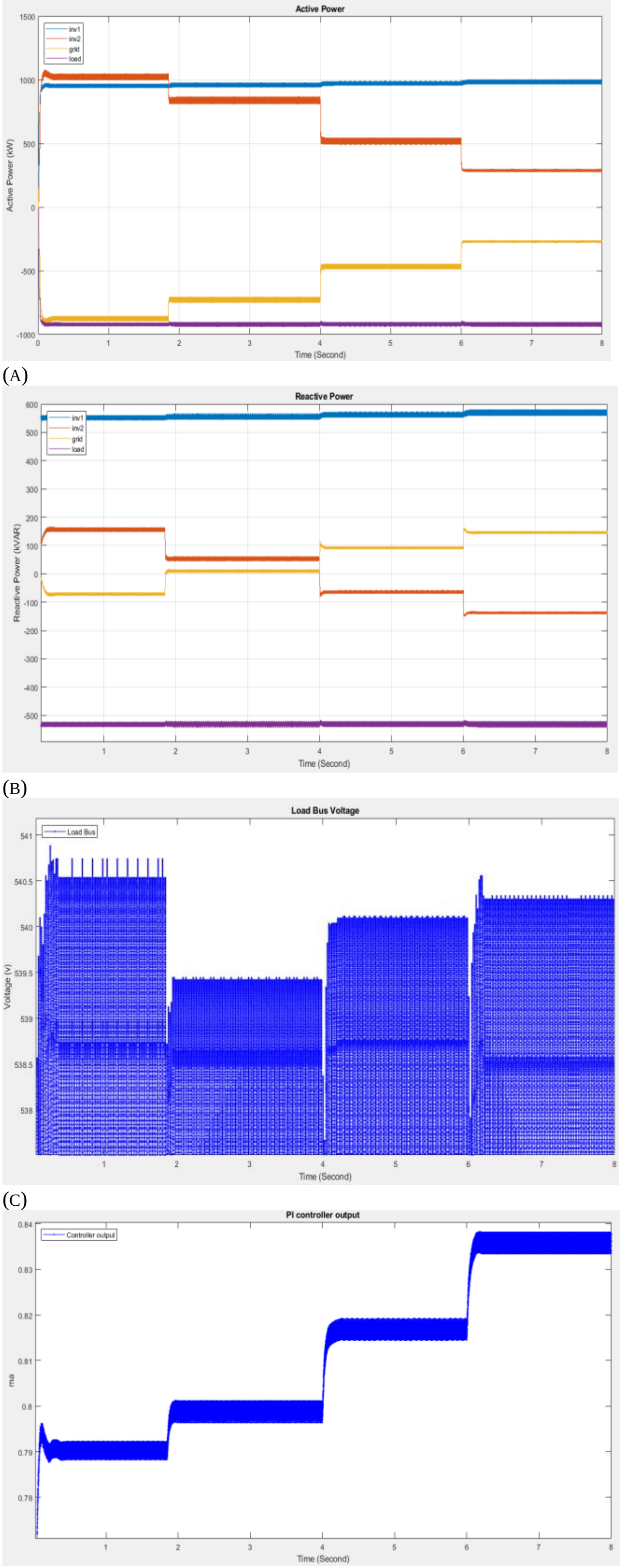


FIGURE 5
SIMULATION RESULTS OF LOAD BUS READINGS: (A)P (KW) (B)Q (KVAR) (C)LBV (V) (D)PI CONTROLLER OUTPUT (MA).

The highest model contribution in power-sharing is clearly in the 1.066 MW capacity with a bigger influence on load bus voltage magnitude, the reduction in PV_2 power contribution is disturbing voltage magnitude and adversely affects the power quality at the load bus. However, as an achieved target of this work, the implemented control system offsets the loss, regulates voltages and eliminates the steady-state error, as shown in the final simulation results in Table III.

TABLE III
PV SYSTEMS, GRID AND LOAD READINGS

Time (Second)	PV_2 W/m^2	PV_2 (kVAR)	PV_1 (kVAR)	Grid (kVAR)	PV_1 (kW)	PV_2 (kW)	Grid (kW)	ma	LBV (V)	Load (kVAR)	Load (kW)
0-2	1000	160	545	-72	950	1000	-870	0.639	537.6	-540	-940
2-4	800	55	555	10	960	800	-730	0.649	536.9		
4-6	500	-64	565	92	980	500	-465	0.656	538.8		
6-8	300	-138	575	146	1000	300	-270	0.715	538.2		

CONCLUSION

In this study, a real-time control simulation in the PV system voltage and wevar scheme addressed two significant issues of the conventional VVC ways. Firstly, the proposed PI control system enables to achieve high accuracy in the setpoint tracking and control stability. Secondly, the PI control system dynamic self-adaption mitigates operating conditions or the side effect under large-scale external disturbances. Moreover, the proposed VVC operation is compatible with the integration standards and compatible with utility practices. The study focused on mitigating voltage fluctuation via Q compensating by smart PV inverters. The satisfactory performance is demonstrated in two scenarios of four different PV system capacities in the distribution feeder, showing great properties and approving the PI controller's desired functionality.

In the future work, an actual implementation and studying of the real effects of the proposed control system on distribution system performance will be interesting. Moreover, it would be more interesting to study how and if the proposed control integrated into conventional VVC systems that including load tap changers and capacitor banks.

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