

Research Article

Suchismita Roy*, Pradeep Kumar Sahu and Satyaranjan Jena

Analysis and control strategy of standalone PV system with various reference frames

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Abstract: Renewable energy sources like solar power are the more convenient source of renewable energy. Nowadays, increasing the energy demand may create many disturbances in power system distribution. To overcome the necessity of power demand, all are focusing on generation of more energy from clean technologies with increased development in power distribution systems using the renewable energy sources. This work aims to propose a standalone PV system with an LCL filter, with two cascaded feedback control loops with an appropriate controller for three reference frame. This work concerns the topology for three reference frames such as synchronous, standalone, and natural reference frames with the respective controllers (PI and PR). The topology contains two cascaded feedback control loops such as DC-link voltage control loop (PI) cascaded with the internal current loop (PI and PR). These commonly used controllers are implemented in various well-known reference frames for the PV system and their steady-state performance is also evaluated in terms of total harmonic distortion. Finally, the simulation results from a two-stage 5.5 kW, 440 V (L–L), three-phase standalone PV system are provided to confirm the theoretical analysis and effectiveness of the control schemes.

Keywords: PV system, VSI, PI, PR controller, reference frames, voltage control loop, current control loop

1 Introduction

Nowadays, renewable energy sources are the leading energy source all over the world. The solar system is a more convenient source of renewable energy source. By increasing the demand for energy, many disturbances are created in power system distribution and grid integration. To overcome the necessity of power demand we focused on producing more energy from clean technologies with increased development of power distribution systems using renewable energy [1]. To fulfill the requirement, more energy should be generated from renewable energy sources like solar. Due to the lack of availability of conventional fossil fuels, such as coal and diesel, we focused on renewable energy sources such as solar energy. Solar is one of the leading renewable sources all over the world, due to their huge amount of power production with less pollution and clean environment features. Now we are focused on solar cell due to their one-time installation with long life properties with free energy sources. Among these renewable energy sources, solar system has the largest utilization nowadays. Another renewable energy source that gains such a way of maintaining and improving living standards without harming the environment is photovoltaic (PV) system, so the number of PV installations has an exponential growth, due to the governments and utility companies' policy that support the programs focusing on grid-connected PV systems [2,3].

When PV is connected to the utility system, it needs a power conditioning unit for interfacing. Since PV sources are DC in nature, we required a voltage source inverter (VSI) for DC/AC conversion. Due to the use of power electronics converter harmonics present in the system, disturbances (e.g., switch overheating, voltage drop, and wave destruction) are created in the system. It requires appropriate filter design for mitigating the total harmonic distortion entering the system. An LCL filter used at the output of the inverter can reduce levels of harmonic distortion with lower switching frequencies and less inductance [4–6]. Here many papers proposed a combined controller incorporating feedback controllers such as PI,

* **Corresponding author: Suchismita Roy**, School of Electrical Engineering, KIIT Deemed to be University, Bhubaneswar, India, e-mail: sroyfel@kiit.ac.in

Pradeep Kumar Sahu: School of Electrical Engineering, KIIT Deemed to be University, Bhubaneswar, India, e-mail: pksahu.nitrkl@gmail.com

Satyaranjan Jena: School of Electrical Engineering, KIIT Deemed to be University, Bhubaneswar, India, e-mail: srj.kiit@gmail.com

PR, and repetitive control for the three-phase (3-ph) grid-connected inverter with LCL filter [6,7].

In this work, the conventional controllers such as PI, PR, and repetitive control are applied to a standalone PV system with an LCL filter. Here the converter is based on a 3-ph VSI connected to the solar system. Now the challenges associated with the system are divided into few groups such as generation, conversion, and controlling of power such as active and reactive power flow with the quality of voltage and current profile. The PV system stability requires proper control strategy to interconnect with the domestic system due to the disturbances generated by power electronics devices or non linear load. Here the study proposed a constant AC voltage output without connecting any battery to the solar cell. Here VSI requires switching modulation techniques such as sinusoidal pulse width modulators (SPWM) to mitigate the lower level of harmonics [8,9]. The output voltage of VSI should maintain a constant value having low total harmonic distortions (THDs) for any type of load. The THD level should be within 5% as defined by the IEEE standard 1547 [10]. Hence, an appropriate controller should be applied for securing a fast dynamic response against large step load fluctuations. These control strategies require various control topologies such as internal current control topology and DC-link voltage control topology. Here the inner current control loop controls the system current which requires a proportional integral controller (PI) or proportional resonant converter (PR) for dynamic and system stability [11–14]. PI controllers have easy control of current and voltage with compensation of harmonics but some drawbacks like steady-state error and lower order harmonics are unable to be eliminated. The voltage control loop is used to maintain a constant dc link voltage and requires a PI controller. Control strategy includes three types of reference frames, namely, rotating, stationary, and natural reference frames. The accomplishment of these reference frames requires a control frame, such as dq , $\alpha\beta$, and abc frames [15–17]. These control frames requires desired transformation and measurement of voltage and current to accomplish these reference frames.

The control schemes used for the standalone PV system have two control loops. The outer control loop regulates the DC-link voltage whereas the inner control loop is used to enhance the transient performance. It is challenging to design both the control loops. The outer voltage loops are designed by taking its slow dynamics and the inner control loop by taking fast dynamics. The detailed design of both the control loops is briefly reported in the literature [18–20]. The application of these controllers

in different reference frames and their performances are highlighted in this article.

The article is organized as follows. The system configuration and its modeling are presented in Section 2, followed by the complete knowledge of the various reference frames is focused in Section 3. The description of the convectional controllers used in PV system to improve the power quality is discussed in Section 4. The simulation results are then presented in Section 4 to highlight the features of the various control schemes which were implemented in various reference frames.

2 System description

The proposed PV system consists of a PV array, DC–DC converter, DC link capacitor, bridge inverter, and LCL filter. The detailed components of the PV system are discussed below.

The PV array consists of several PV modules assembled in series and parallel combinations of several solar cells. The equivalent circuit of the PV array consists of a PV current source, a parallel diode, a series resistance, and a parallel resistance. There are 16 modules that are connected in series producing an open-circuit voltage of 337.6 V and 3 strings in parallel for 17.78 A short-circuit current in the PV array. The power generated by the PV module is dependent on several external factors like solar irradiance and ambient temperature.

The next component of the proposed system consists of DC–DC converter which boosts up the voltage level as required by the bridge inverter as shown in Figure 1. The PV panel produces the power which is variable in nature and it changes with atmospheric condition. So, to maximize the power extracted from PV panel at a maximum

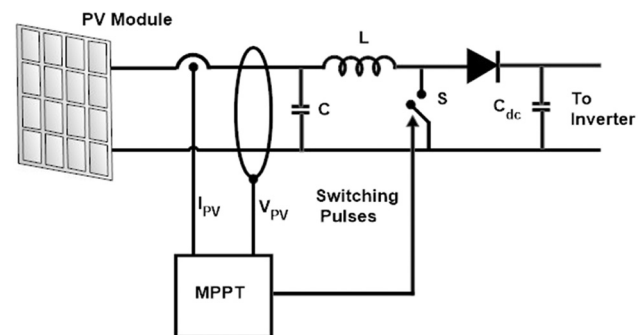


Figure 1: Solar system integrated with DC-EDC converter with maximum power point tracking (MPPT) technique.

peak voltage of 320.5 V and maximum peak current of 16.14 A, MPPT algorithm is used. The MPPT controller generates the gate pulses required by boost converter in order to produce the DC voltage required by bridge inverter. The detailed description of the sliding mode control based MPPT algorithm used in this work is given in our article [21].

The 3-ph bridge inverter consists of six switches which can be IGBT or MOSFET. The control pulses for these switches are generated by SPWM modulators. The inverter controller is designed to regulate the power supplied by the inverter in order to ensure that the DC-link voltage does not drop below the minimum required voltage for the inverter to be able to supply the peak output voltage. Different inverter controllers like PI, PR, hysteresis, and deadbeat controller can be designed for various reference frames of control. The proper controller can be designed to improve the dynamic response and voltage regulation of the system. The bridge inverter under study may produce higher order switching harmonics which causes losses and instability of the system. So, the LCL filter can be designed to obtain a cleaner output with reduced THDs. The LCL filter can mitigate the switching harmonics produced by bridge inverter and produces sinusoidal voltage required by the load.

current loop and DC-link voltage control loop. Here the internal current loop regulates the circulating current in the whole system whereas the external voltage loop controls the DC-link voltage. It offers constant DC voltage with ripple-free dc output for balancing the power flow to the system. While the current control loop is accountable for power quality profile and current limitation, harmonics mitigation and system dynamics are the important features of the current loop controller. The DC-link voltage controller is designed in such a way that it balances the power flow and regulates the DC-link voltage for stabilizing the system. The control of converter input side DC voltage control is based on a DC-link voltage loop controller which is connected to an inner power loop instead of the current control loop. In this manner, the current is injected into the system and also indirectly controlled. Here the article demonstrates three types of reference frames, namely, stationary reference, rotating reference, and natural reference frames. Here the rotating reference frame used “dq” control frame, while the stationary reference frame is based on the “ $\alpha\beta$ ” control frame, and, finally, natural reference frame is based on “abc” control frame. These control frames are accomplished by the use of different controllers such as PI, PR, deadbeat, etc.

3 Control scheme for standalone PV system

The control strategy applied to VSI mainly consists of two control loops as shown in Figure 2, such as internal

4 Overview of various reference frames

The power quality of the solar PV system can be enhanced by using a high-performance current control scheme. The proposed scheme is achieved by the use of feedback current

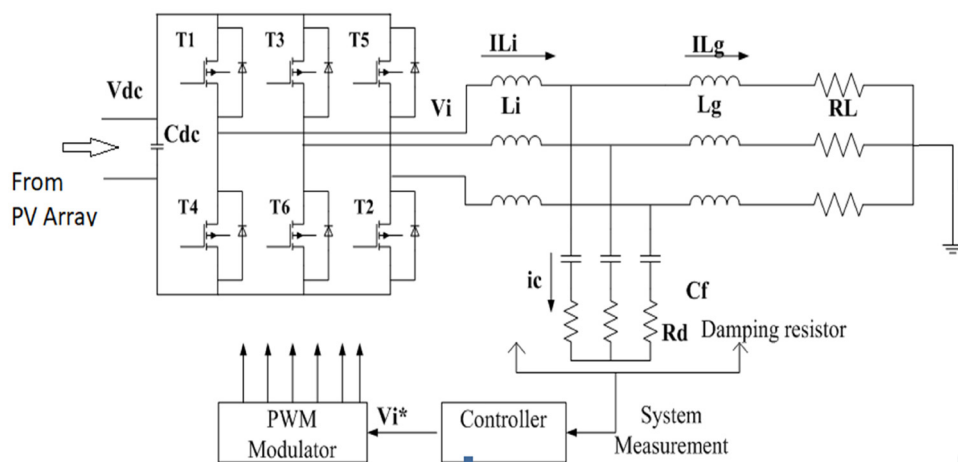


Figure 2: Standalone PV system with its control scheme.

control loop with desired reference frame. The main objective of the current control loop is to improve the transient performance of the system with less harmonics component. The various reference frames using which anyone can implement the proper control schemes are discussed below.

4.1 Synchronous rotating reference frame

The synchronous rotating reference frame is also called as “dq” control frame. Here in this reference frame, “dq” are the control variables, such as the direct axis and quadrature axis parameter as shown in Figure 3. Since the direct axis and quadrature axis are the DC parameters, control is much easier with better control performance. Hence, PI controller is used for the “dq” control frame. PI controller has the salient properties such as controlling DC parameters like DC voltage or DC current in a easy manner with harmonics compensating properties. For the accomplishment of the control reference frame, some transformations are carried out such as abc to dq transformation. This transformation is accomplished with the value of phase angle (theta angle) which is extracted from phase-locked loop (PLL). By choosing the appropriate K_p and K_i value of the PI controller and

also with the use of an appropriate LCL filter, the whole system will work with minimum THD and better power quality.

In this control reference frame, the voltage error is generated by comparing the feedback dc link voltage (V_{dc}) with its reference value (V_{dc}^*). Then, the error voltage signal is passed through PI controller, in which reference current signal (I_d^* , I_q^*) is generated for the inner current control loop. The reference current signal in this frame is dc in nature as shown in Figure 4.

4.2 Stationary reference frame

The reference current signal (I_d^* , I_q^*) is compared with feedback current (I_i)_{abc} which is tracked from inverter side inductor L_i . Since I_d^* and I_q^* is DC in nature, it is fastly converted to I_α^* and I_β^* with the help of Clarke transformation. But we want two-phase AC system I_α^* and I_β^* from (I_i)_{abc} and hence we used fast Clarke transformation to convert (I_i)_{abc} to I_α and I_β . Then, the error signal generated from the comparator is passed through PR controller in stationary reference frame, because the control variable is two-phase ac, which generate the reference voltage output V_α^* and V_β^* , then the reference voltage

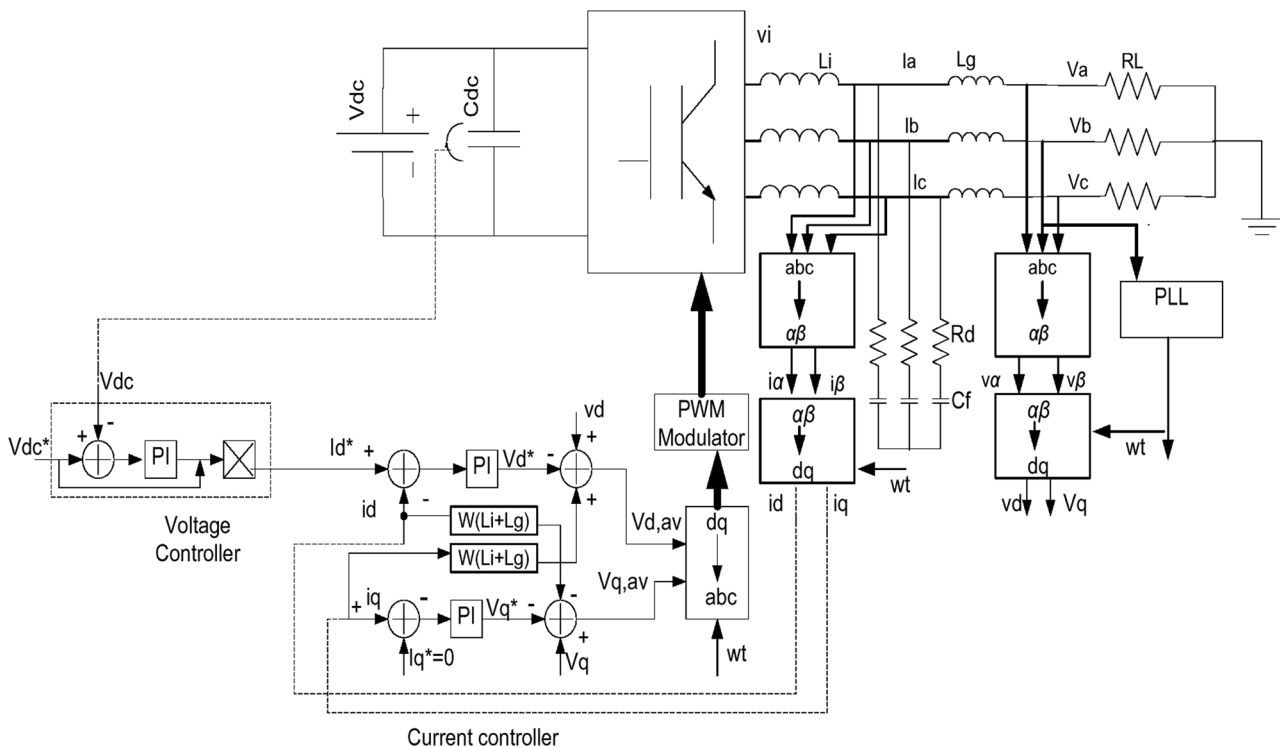


Figure 3: Standalone PV system with its control scheme in dq reference frame.

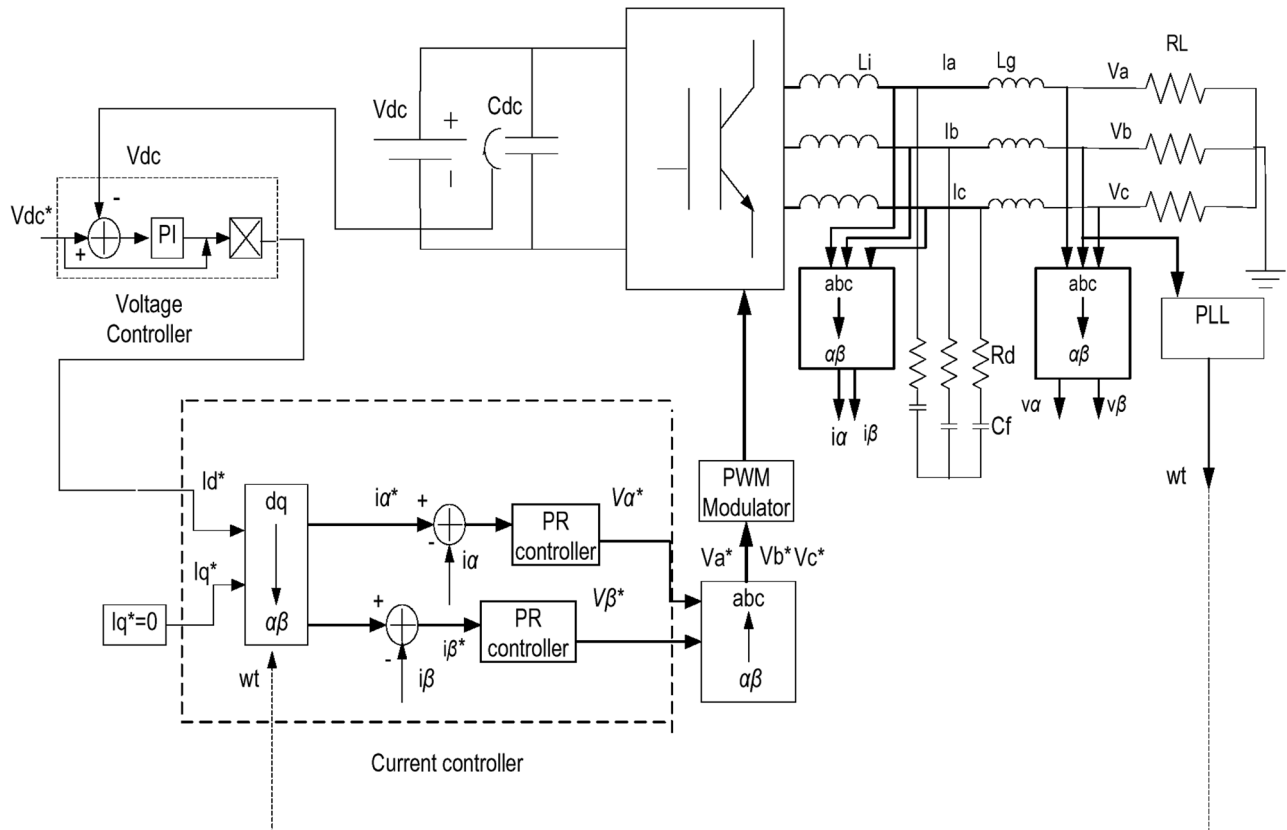


Figure 4: Standalone PV system with its control scheme in α - β reference frame.

signal is converted to V_a^* and V_b^* and V_c^* with the help of Clarke transformation. The reference voltage signal is compared with a triangular carrier signal called as SPWM modulation, which generates switching state of inverter bridge switches. In this way the current control loop and also the entire system works.

4.3 Natural reference frame

The natural reference frame is otherwise called as “abc” control frame.

Here in this reference of abc are the control variables. Here in the concern topology, the 3-ph such as a, b, and c phase parameters like voltage and current are controlled individually as shown in Figure 5. In other words, each 3-ph (a, b, and c phase) parameter is controlled individually. abc phases are alternating in nature with individual phase control in the scheme, and due to this reason control is much more complicated.

For achieving the topology, PR controller is used. Here the transformation from one frame to another frame is not required. Due to high tracking response, a deadbeat

controller is used in the natural reference frame. Due to high gain at the resonance frequency and elimination of steady-state error, PR controller is used in the natural reference frame. For an appropriate choice of controller parameter, we get desired output with less ripple and better power quality is achieved.

5 State space model of LCL filter with 3-ph inverter

Let us take the single-phase system as shown in Figure 6. The standard form of state space model is as follows:

$$\begin{aligned}\dot{x} &= Ax + Bu \\ y &= Cx + Du.\end{aligned}\quad (1)$$

Where x = state vector, y = output vector, u = control vector and “ A , B , C , D ” are the system matrix.

The dynamic equation of the system is given by

$$V_L = L \frac{dI_L}{dt}, \quad (2)$$

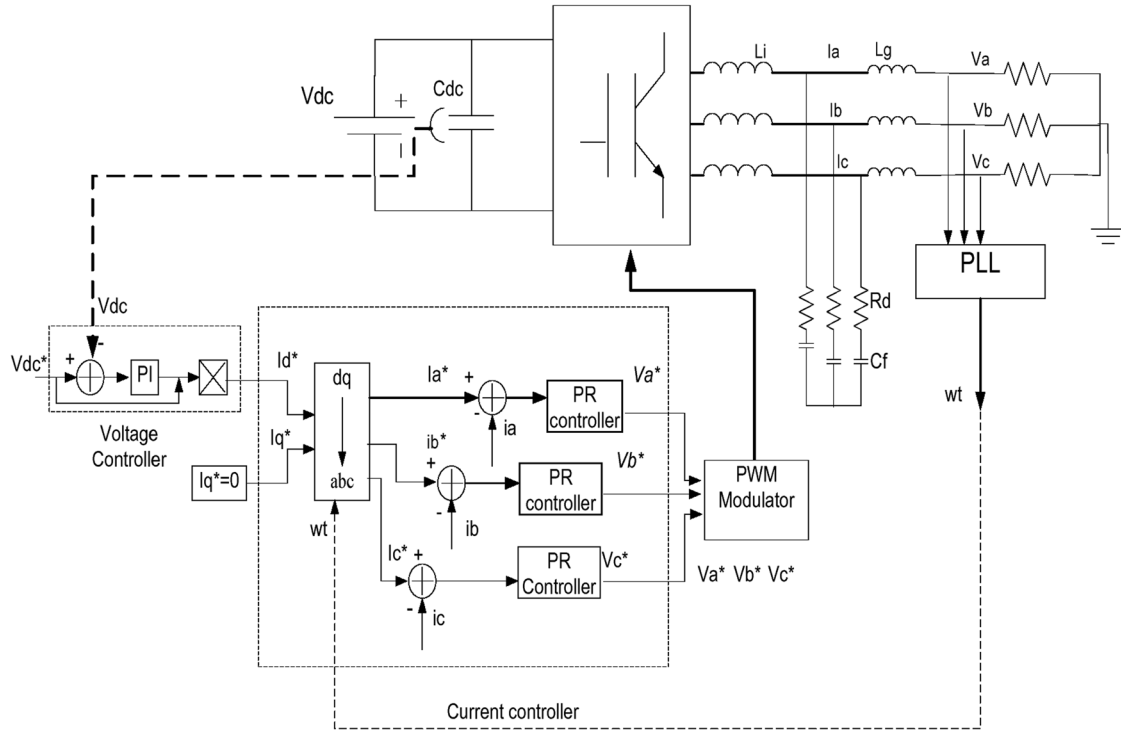


Figure 5: Standalone PV system with its control scheme in abc reference frame.

$$I_C = C \frac{dV_C}{dt}.$$

(3) Finally, the dynamic state model for 3-ph system is written as

The state-variables of the system are

$$\dot{x}_1 = \frac{V_i - V_{cf} - R_i I_{Li} - R_d (I_{Li} - I_{Lg})}{L_i}, \quad (4)$$

$$V_{Lg} = V_c - R_L I_{Lg} - R_g I_{Lg} + R_d (I_{Li} - I_{Lg}), \quad (5)$$

$$\dot{x}_2 = \frac{V_c - R_L I_{Lg} - R_g I_{Lg} + R_d (I_{Li} - I_{Lg})}{L_g}, \quad (6)$$

$$\dot{x}_3 = \frac{I_{Li} - I_{Lg}}{C_f}. \quad (7)$$

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix}_{ABC} = \begin{bmatrix} \frac{-R_i + R_d}{L_i} & \frac{R_d}{L_i} & -\frac{1}{L_i} \\ \frac{R_f}{L_g} & -\frac{(R_f + R_L + R_g)}{L_g} & \frac{1}{L_g} \\ \frac{1}{C_f} & -\frac{1}{C_f} & 0 \end{bmatrix}_{ABC} \begin{bmatrix} I_{Li} \\ I_{Lg} \\ V_{cf} \end{bmatrix}_{ABC} + \begin{bmatrix} \frac{1}{L_i} \\ 0 \\ 0 \end{bmatrix}_{ABC} [V_i]. \quad (8)$$

The maximum allowable current for the filter is

$$I_{\max} = \frac{P_n \sqrt{2}}{3V_{ph}}. \quad (9)$$

The ripple current for the LCL filter is given by

$$\Delta I_{\max} = (1-5\%) I_{\max}, \quad (10)$$

$$L_i = \frac{0.49 \times V_{dc}}{3 \Delta I_{L \max} F_{sw}}. \quad (11)$$

The designed value of grid-side inductance and the damping resistor of LCL filter is shown in equations (12) and (13).

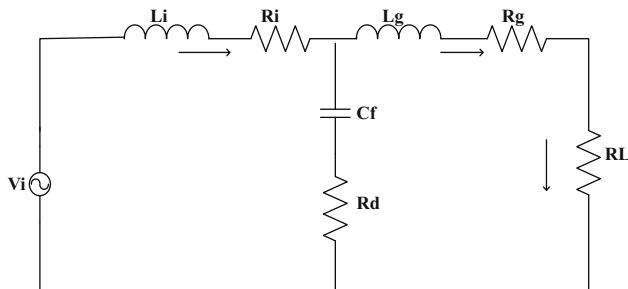


Figure 6: LCL filter with 3-ph inverter output.

$$L_g = \frac{1 + \sqrt{\frac{1}{K_a^2}}}{C_f \omega_{sw}^2}, \quad (12)$$

$$R_d = \frac{1}{3\omega_{res} C_f}. \quad (13)$$

The resonant frequency of the LCL filter is

$$\omega_{res} = \sqrt{\frac{L_i + L_g}{L_i L_g C_f}}. \quad (14)$$

Finally, the resonant frequency is in this given range for better filtering.

6 Conventional current control schemes

The feedback current control schemes are used to enhance the power quality issues like harmonics compensation and dynamic or transient performance. The conventional controllers like PI and PR control schemes are commonly used in the solar PV system. The brief description of these controllers is highlighted in Sections 6.1 and 6.2

6.1 PI current control scheme

Since PI controller is a linear control system, its main advantage is that it has easy filtering and controlling properties. Since it has better properties to control DC quantities rather than AC quantities, the transfer function is given as

$$G_c(s) = \begin{bmatrix} K_p + \frac{K_i}{s} & 0 \\ 0 & K_p + \frac{K_i}{s} \end{bmatrix}. \quad (15)$$

The stationary reference frame is otherwise called as “ $\alpha\beta$ ” control frame. Here in the reference frame, “ $\alpha\beta$ ” are the control variables. Otherwise, $\alpha\beta$ are called Clarke variables used in Clarke transformation. Since $\alpha\beta$ are the AC (alternating in nature) quantities, the controlling is complicated. For the accomplishment of this reference frame first, three reference phases (a, b, and c phases) are converted to two-phase system (α and β phase), which are alternating in nature. Due to the disadvantages of the PI controller, instead of this PI controller, the PR controller is used. PR controller has certain properties; the PR controller has infinity gain at resonance frequency

with the elimination of steady-state error. Due to this, the PR controller is used for controlling AC quantities. To avoid the complexity of abc reference frame, it is converted to a new reference frame $\alpha\beta$. By choosing the appropriate K_p , K_i , and resonance frequency values of the PR controller and also use of appropriate LCL filter, the whole system is going to work with minimum THD with better power quality.

6.2 PR current control schemes

Since PR controller is a linear control, it has infinite gain at resonant frequency, due to which steady state error is eliminated. It is used for AC quantities due to its frequency term present on its transfer function. Transfer function is given as

$$G_c(s) = K_p + \frac{2K_i s}{s^2 + \omega_0^2}. \quad (16)$$

Since the transfer function has infinite gain at resonance frequency, to make the system gain finite, a cut-off frequency of ω_{cut} is added in the transfer function. Let the new transfer function be given as

$$G_c(s) = K_p + \frac{2K_i \omega_{cut} s}{s^2 + 2\omega_{cut} s + \omega_0^2}, \quad (17)$$

where K_p and K_i are gain constants, $\omega_0 (= 2 \times \pi \times 50 \text{ rad/s})$, is the grid frequency, and ω_{cut} is the cut off frequency.

7 Result

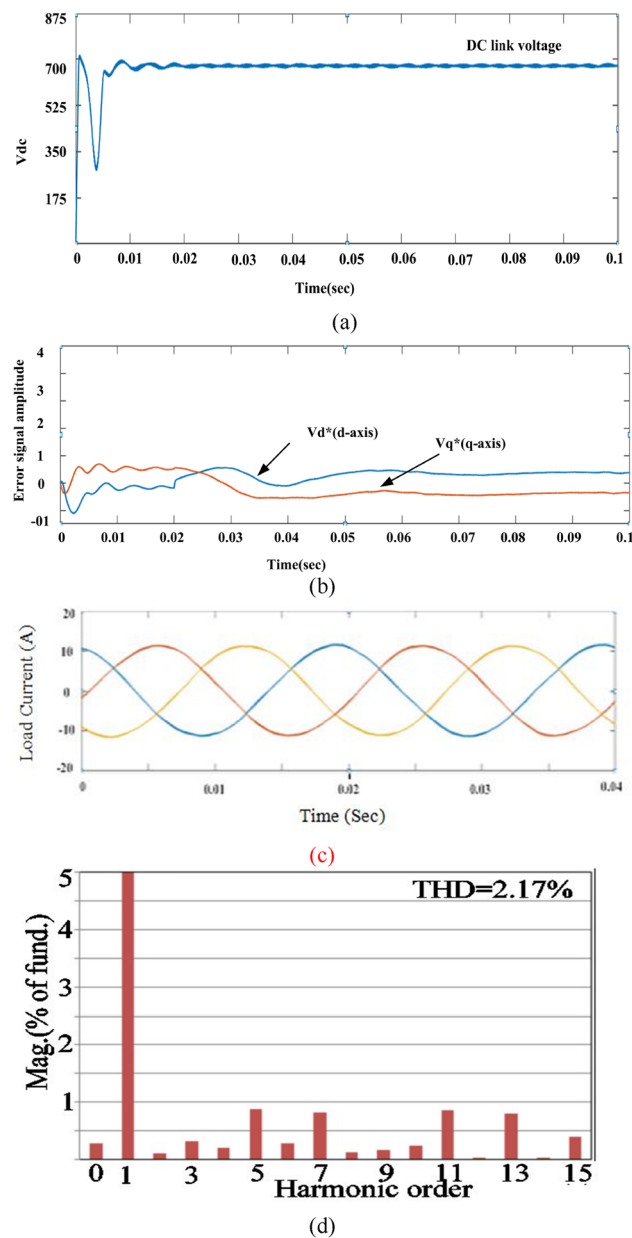
After theoretical analysis, the simulation study for the above 3-phase standalone PV system has been carried out in the MATLAB 18b platform.

Table 1: Specification of the system parameter

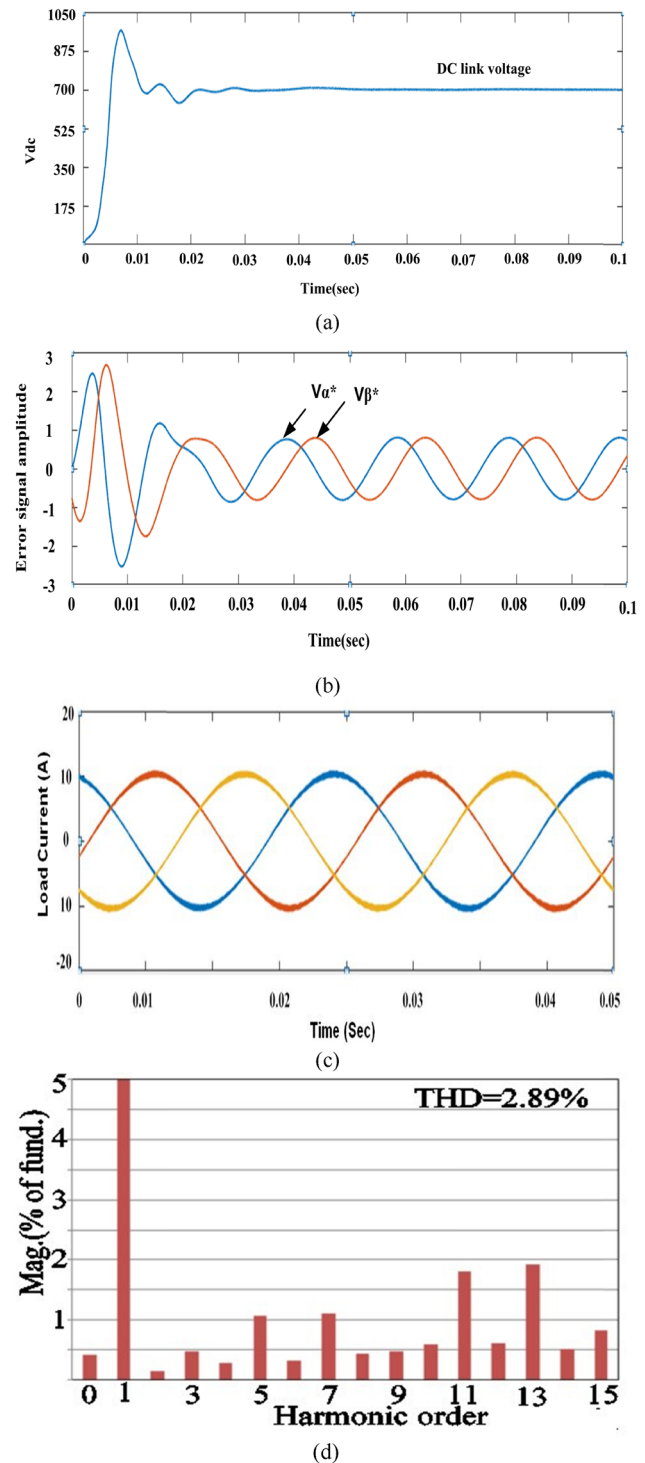
Parameter	Value
P_{pv}	5.5 kW
V_{dc}	700 V
V_{L-L}	440 V
L_i	1.9 mH
L_g	2.8 mH
C_f	5.35 μ F
f_{sw}	10 kHz
f_0	50 Hz
C_1	4 nF
C_2	4 nF
C_{dc}	2,200 μ F

Table 2: Specification of the controller parameters

Reference frame	Outer voltage control loop parameter	Inner current control loop parameter
dq control	$K_p = 0.1$ $K_i = 1$ (PI)	$K_p = 0.091$ $K_i = 0.12$ (PI)
$\alpha\beta$ control	$K_p = 0.1$ $\omega = 50$ rad	$K_p = 0.091$ $K_i = 0.12$ (PI)
abc control	$K_p = 0.1$ $\omega = 50$ rad	$K_p = 0.091$ $K_i = 0.12$ (PI)

**Figure 7:** Results for synchronous reference frame: (a) DC-link voltage, (b) error signal, (c) inverter output current, and (d) THD of output current.

This simulation was realized through 5.5 kW PV system and output voltage and frequency of 440 V (L-L) and 50 Hz, respectively. The load for this test is taken as 20 Ω . The detailed plant parameters are given in Table 1,

**Figure 8:** Results for stationary reference frame: (a) DC-link voltage, (b) error signal, (c) inverter output current, and (d) THD of output current.

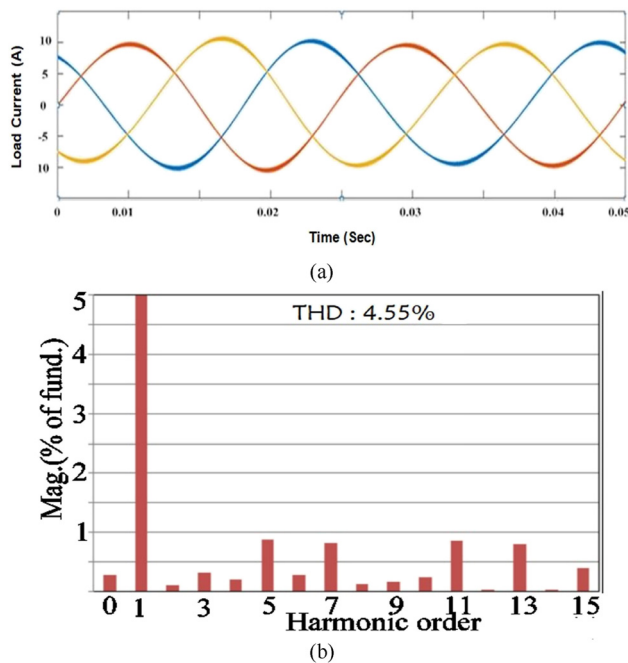


Figure 9: Results for natural reference frame: (a) inverter output current and (b) THD of output current.

while controller parameters are shown in Table 2. The parameters of the controller are designed to obtain better performance. The capacitor used as the DC-link is taken as $2,200\ \mu\text{F}$ with rated voltage of 700 V. The conventional controllers such as the PI and PR controllers are applied on the standalone PV system to improve the power quality issues. These controllers are implemented in all the reference frames and then performances of the controllers are evaluated.

First, a conventional PI current controller is used to improve the dynamic performance of the system.

The simulation and waveforms of the DC-bus voltage are shown in Figure 7(a). The performance of the outer DC-link controller can be evaluated by its error voltage which is shown in Figure 7(b). Figure 7(c) shows the inverter output current. The performance of the inner

Table 3: Comparison of THD of load current for different reference frames

Type of reference frames		Load current THD (%)
Synchronous reference frame	PI	2.17
	PR	3.87
Stationary reference frame	PI	5.43
	PR	2.89
Natural reference frame	PI	6.29
	PR	4.55

Table 4: Distinguished characteristics of the control structures in past literature

Sl no.	Reference frame	Implementation	Controller	Number of feedback	Control parameter	Filter type	Modulation scheme	Real time application
1	3-ph, dq [22]	Analog/digital	Classic and PI	Dual-loop	Voltage and current	LC	PWM	DG, PV, and UPS
2	Single-phase, dq [23]	Analog	PR	Single-loop	Current	LCL	PWM	PV
3	3-ph, $\alpha\beta$ [24]	Digital	PR	Single-loop	Current	L	PWM	General
4	Single-phase, $\alpha\beta$ [25]	Analog	PR	Dual-loop	Current	LCL	SPWM	General
5	3-ph, abc [26]	Analog/digital	PI	Dual-loop	Voltage and current	L	PWM	DG and PV
6	Single-phase, abc [27]	Digital	PI and PR	Dual-loop	Current	LCL	PWM	Micro inverter

current control can be evaluated on the basis of THD of inverter output current which lies within the standards as defined by IEEE 1547. The harmonics spectrum of the inverter current is shown in Figure 7(d).

Similarly, a conventional current controller called PR controller is applied to the PV system on the stationary reference frame for better results.

The simulation and waveforms of the DC-bus voltage for this reference frame are shown in Figure 8(a). Then, the error DC voltage of the outer control scheme is shown in Figure 8(b). From the results, the tremendous performance of this control loop is confirmed. Then, the performance of the inner current loop is evaluated. Figure 8(c) and (d) shows the THD of inverter output current which is within IEEE standard.

Finally, PR controller is applied for standalone PV system in the natural reference frames. Here three PR current controllers are used for the 3-ph of the inverter output current. Figure 9(a) shows the performance of the controller in abc natural reference frame. The THD of the output inverter current is shown in Figure 9(b). The inverter output current has a THD of 4.55% which ensures the performance of the controller. This THD level also lies within the standards defined by IEEE 1547. The detailed comparison of the performance of different control schemes in the various reference frames is highlighted in Table 3.

In this work, various control strategies in different reference frames were briefly studied and analyzed thoroughly. The most important and desired characteristics are presented in the Table 4. Different articles have been reviewed and presented in this table and all the control schemes can be successfully implemented in standalone PV system.

8 Conclusion

The filter design and the implementation of controller schemes in various reference frames for 3-ph VSI has been investigated to provide high power quality issues for the standalone PV systems. Here a third-order low-pass filter was designed for the inverter to eliminate the switching frequency harmonics of output voltage and current. To enhance the power quality of the overall system, both voltage and current control loops have been designed for the standalone PV system in various reference frames like synchronous reference frame (dq), stationary reference frame ($\alpha\beta$), and abc reference frames. These control schemes are implemented in the PV system

for regulating active and reactive powers of the system. Conventional controllers like PI and PR controllers are used as the voltage and current loop controllers and these are implemented in various reference frames. A comparative analysis was carried out among all the abovementioned controllers. From the results, it is concluded that the PI controller has tremendous performance in terms of current THD which is 2.17% whereas the PR controller is suitable for both stationary reference frames ($\alpha\beta$) and abc reference frames with a current THD of 2.89 and 4.55%, respectively. All the THD levels of different controllers in various reference frames are within the IEEE standards 1547.

The proposed controller has three control loops, a PLL to maintain the desired frequency, a voltage control loop for regulating the output voltage, and the inverter inductor current loop for improving the dynamic performance of the system. The simulation results have been successfully shown with their proposed standalone topology. The designed parameter of the LCL filter has efficiently attenuated the generated harmonics due to the switching of the inverter. The above-mentioned topology is based on a standalone PV system with 3-ph VSI. Additionally, different advanced control scheme can be used to integrate the PV system with local load which reduce the size of the harmonics filter.

Conflict of interest: Authors state no conflict of interest.

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