Control of solar PV-integrated battery energy storage system for rural area application

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Abstract
The inaccessibility of a utility grid is the challenge for rural and remote areas. This work presents the application of solar photovoltaic (PV) integrated battery energy storage (BES) for rural area electrification. The addition of a BES at DC link, is realised by means of a DC–DC bidirectional converter. The BES is discharged/charged in accordance with the solar PV generation and load variations. This converter control also maintains the voltage for the maximum power point tracking (MPPT) with perturb and observe (P & O) control at the DC link. The voltage source converter (VSC) works by means of voltage control algorithm in a solar PV-BES system. The system manages the power for the load network with frequency and voltage regulation by the non-ideal discrete proportional and resonant controller (PR). The fundamental component from the load current, is acquired using an adaptive digital filter, which improves the power quality. The utilization of buck-boost converter with an optimum BES rating as related to the system, when it is linked directly at the VSC DC link. The system’s operations at steady state and dynamic circumstances i.e. solar insolation change and load variation, load disconnection, are authenticated with test results on a developed prototype.

1 INTRODUCTION

The global energy crises issue has led to the incredible technical development in the field of renewable energy resources (RESs) and revolutionised the power field for industrial applications. Due to enhanced use of this energy, annual saving for the users, is consistently increasing thereby saving precious foreign exchange for the nation. Due to reduced CO2 emission, major support is provided to deteriorating environmental conditions. These sources provide clean energy, reduce greenhouse gas emission drastically. The solar power is one of the most effective sources among other RESs due to various reasons like sustainability, economical, pollution free and easy to install. The microgrid is integrated by means of a battery energy storage (BES) and has gained popularity because it stores the energy at off-peak periods and provides the energy during the peak load demand [1]. The main cause of unreachability of electrical power supply system in remote villages is the low voltage and intermittent nature of electrical power supply coming from the available utility grid. The main reason of these circumstances is the misalliance of demand and supply in the distribution network. The off-grid solar PV-battery system is a best solution for the reliable and affordable source of electrical energy than convention sources [2]. The microgrid operates in a grid integrated mode or in autonomous mode. It is separated from the utility grid under the abnormal conditions like, grid outage and works in autonomous mode. The energy storage is desirable for the compensation of intermittency problem of RESs and makes the reliable operation of the system. The incorporation of solar photovoltaic (PV) based microgrid to the utility grid and energy management, are given in [3].

The maximum power point tracking (MPPT) schemes are developed and implemented due to the sporadic problem of the PV array. The essential part of the PV system is the tracking of the maximum power point of a PV array, and various MPP tracking techniques for the generation of solar power, are elaborated in [4], [5]. To maintain the power quality (PQ) level in the distribution network, is a difficult task because of an increase in power converters in residential, industrial and commercial premises. The PQ concerns and their mitigation approaches...
with numerous current control algorithms are reported in [6]. The PQ issues in realising for smart distribution grid and the description of technologies like demand side management, microgrid, feeder reconfiguration, advanced voltage control methods, are described in [7]. The battery selection is of higher rating, when its connection at the DC link is direct; however, in this system, the low rating battery is incorporated by the DC–DC bidirectional converter, which increases the battery life by eliminating the battery current’s second harmonic current. The battery discharging and charging are influenced by the DC–DC bidirectional converter, which increases the battery life by eliminating the battery current’s second harmonic current.

The RESs, BES and loads are necessary for the reliable performance of autonomous system. The BES smoothens the variable nature of RESs [10]. The voltage boosting and DC–AC conversion is implemented with novel boost inverter made by utilising the DC–DC buck-boost converter and DC–AC inverter [11]. Due to the variable nature of RESs, the BES acts as a critical element in an islanded microgrid and regulates the voltage and frequency. It also maintains the generation and balances in loads, thus improves the reliability of the system. Various control methods for power management of PV-BES islanded microgrid are reported in [12–14].

The proportional and resonant (PR) regulator eliminates the shortcomings of proportional and integrator (PI) controller, that is, steady-state error between AC quantities, which improves converter’s tracking performance. Performance of PR control depends on the accuracy of the resonant frequency. The PR controller with discretisation method is reported in [15], [16]. The application of stationary frame linear PI controllers has the major drawback of steady-state error for the regulation of AC quantities, whereas the PR controller is the attractive solution to eliminate the error [17]. The proliferation of nonlinear loads connected at consumer’s end, has introduced PQ issues and has hindered the performance of existing distribution network as in terms of poor power factor and generation of harmonics in utility grid voltage and current, which do not follow the IEEE-519 standard [18]. The accurate computation of harmonics and sequence components is necessary to observe the three phase system performance.

The main drawback of LMS technique is that the convergence rate depends upon the constant step size and is associated with the current weight value. The least mean square (LMS) algorithm is simple technique to find parameters for PQ event and not much effective for short time and time varying disturbances as it has low signal to noise ratio, whereas least mean forth method is better than LMS for PQ issues but its computational complexity is more, which results in poor steady-state response. The volterra LMS/forth filter is used to find sequence components, decaying DC and harmonics [19].

The coordinated control for RESs with BES in an islanded microgrid, is demonstrated in [20]. The active in power control of hybrid microgrid in remote islands and the analysis and implementation of voltage and frequency control methods in autonomous mode for hybrid microgrid with variability imposed by RESs, are given in [21], [22]. For the enhancement in PQ and the distribution network reliability, the microgrid must be realised in the grid integrated as well as in off-grid mode. The control technique for an inverter interfaced distribution generator for voltage and frequency variations, are shown in [23]. In this work, an adaptive digital filter is used to obtain the fundamental component of the load current, which is easy to implement as compared to the analog filters and results in sinusoidal point of common coupling (PCC) voltage at non-linear loads. The adjustable coefficients contribute for better steady-state and dynamic performance and, are detailed in [24]. The application of automatic parameter extraction method for dynamic battery model in off-grid solar PV system, is detailed in [25]. Due to continual demand on load side, the battery is used in the system. The power management approaches for the RESs with the BES, for the operation of system in the grid integrated mode as well as for an autonomous mode, are detailed in [26], [27].

The solar PV integrated BES island system’s basic features are elaborated as follows.

- A single stage structure of system for rural area is realised for the utilisation of peak solar power through a PV array by a simplified perturb and observe (P & O) MPP tracking approach, which is simple and easy to implement [4], whereas in a double stage structure supplementary boost converter is integrated in the system, which increases the losses and the cost of overall system. Hence, this topology is economical and efficient.
- The battery in conjunction with a bidirectional converter makes the charging and discharging process of BES under the off-peak and peak demand of load, respectively.
- The non-ideal PR controller with high tracking proficiency reduces steady-state errors between reference load voltages and sensed load voltages.
- The regulation of frequency and voltage, is achieved by the voltage control technique in autonomous mode.
- The dynamic response of digital filter is adaptable and load voltage total harmonic distortion (THD) is in prescribed limits [18].
- At night or non-accessibility of solar energy, the battery manages the load demand.

## 2 SYSTEM CONFIGURATION

The schematic connection for a solar photovoltaic battery based autonomous system is represented in Figure 1. The system comprises of a PV array connected directly at the DC link, wherein the VSC is also integrated. The P & O approach is used to acquire the maximum PV array power, which utilises inputs as, the PV current ($I_{pv}$) and voltage ($V_{pv}$). A battery is supplemented through a bidirectional DC–DC converter to the DC link, which manages the load levelling. The voltage across the DC link is maintained using this converter. The three phase nonlinear load encompasses, three phase diode bridge rectifier, connected in parallel arrangement with the series load consisting with inductance (L) and resistance (R). Terminals
of VSC are interconnected through the interfacing inductors \((L_f)\) across PCC, wherein, ripple filter \((R_f, C_f)\), and load are connected.

3  CONTROL APPROACH

The control approach of system consists of control for VSC voltage in autonomous mode and control for buck-boost converter.

3.1 Solar PV integrated BES system control

The control technique for solar PV integrated BES system for electrification of islanded remote area shown in Figure 2(a), is presented for the switching pulses generation for VSC, whereas the fundamental part extraction of ‘a’ phase by adaptive digital filter is presented in Figure 2(b). The phase load voltages are computed from sensed line load voltages of \((v_{La}, v_{Lb}, v_{Lc})\) as [6],

\[
\begin{bmatrix}
    v_{La} \\
    v_{Lb} \\
    v_{Lc}
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
    2 & 1 & 0 \\
    -1 & 1 & 0 \\
    -1 & -2 & 0
\end{bmatrix} \begin{bmatrix}
    v_{La,b} \\
    v_{Lb,c}
\end{bmatrix}.
\]

(1)

The generation of reference load voltages are described as follows.

\[
v_{La}^* = V_{pm} \sin (\omega t),
\]

\[
v_{Lb}^* = V_{pm} \sin \left(\omega t - \frac{2\pi}{3}\right),
\]

\[
v_{Lc}^* = V_{pm} \sin \left(\omega t + \frac{2\pi}{3}\right),
\]

\]

(2)

where \(V_{pm}\) is the reference amplitude of peak voltage and \(\omega\) is frequency. \(v_{La}, v_{Lb}, v_{Lc}\) that is, sensed load voltages are compared with reference load voltages and results

\[
v_{La,e} \left( p \right) = v_{La}^* - v_{La,b} \left( p \right) = v_{Lb}^* - v_{Lb,c} \left( p \right) = v_{Lc}^* - v_{Lc,a}.
\]

(3)

The digital non-ideal proportional resonant controllers (PR) are fed with these errors and reference load currents are produced. The digital non-ideal PR controllers minimise the steady-state error in reference and sensed load voltages (AC quantities) [15], [16].

\[
T_{La}(z), T_{Lb}(z), T_{Lc}(z),
\]

which are transfer functions for non-ideal discrete PR controllers of phases ‘a’, ‘b’ and ‘c’, respectively, are computed as [15], [16].
Transfer functions of non-ideal PR controllers are modified as,

\[ T_{L,a}(\zeta) = \frac{\hat{i}_{L,a}}{v_{L,a}} = \begin{bmatrix} k_{pL,a}^{+} \\ k_{iL,a} * 2 * \omega_c * \frac{1 + \left( \frac{T_i * k_1}{\zeta - 1} \right) \left\{ (2 * \omega_c) + \omega^2 * \left( \frac{T_i * k_1 * \zeta}{\zeta - 1} \right) \right\}}{1 + \left( \frac{T_i * k_1}{\zeta - 1} \right) \left\{ (2 * \omega_c) + \omega^2 * \left( \frac{T_i * k_1 * \zeta}{\zeta - 1} \right) \right\}} \end{bmatrix}, \]  

(4)

\[ T_{L,b}(\zeta) = \frac{\hat{i}_{L,b}}{v_{L,b}} = \begin{bmatrix} k_{pL,b}^{+} \\ k_{iL,b} * 2 * \omega_c * \frac{1 + \left( \frac{T_i * k_1}{\zeta - 1} \right) \left\{ (2 * \omega_c) + \omega^2 * \left( \frac{T_i * k_1 * \zeta}{\zeta - 1} \right) \right\}}{1 + \left( \frac{T_i * k_1}{\zeta - 1} \right) \left\{ (2 * \omega_c) + \omega^2 * \left( \frac{T_i * k_1 * \zeta}{\zeta - 1} \right) \right\}} \end{bmatrix}, \]  

(5)

\[ T_{L,c}(\zeta) = \frac{\hat{i}_{L,c}}{v_{L,c}} = \begin{bmatrix} k_{pL,c}^{+} \\ k_{iL,c} * 2 * \omega_c * \frac{1 + \left( \frac{T_i * k_1}{\zeta - 1} \right) \left\{ (2 * \omega_c) + \omega^2 * \left( \frac{T_i * k_1 * \zeta}{\zeta - 1} \right) \right\}}{1 + \left( \frac{T_i * k_1}{\zeta - 1} \right) \left\{ (2 * \omega_c) + \omega^2 * \left( \frac{T_i * k_1 * \zeta}{\zeta - 1} \right) \right\}} \end{bmatrix}, \]  

(6)
where \( k_{ppr} \) and \( k_{pr} \) are proportional and integral gains for PR controller, correspondingly. \( \omega \) is the bandwidth around \( \omega \). The digital filter is used to calculate fundamental constituent of load current of phase ‘a’ \( (i_{f,a}) \), as depicted in Figure 2(b).

The overall transfer function filter \( (T(z)) \) is described as [24],

\[
T(z) = \frac{\eta_4}{\eta_4} + \begin{bmatrix}
\frac{-\eta_2 + \eta_3 + \eta_2^2 - \eta_2}{1 - \eta_1 \eta_3 + \eta_2 \eta_3^2} - \eta_1 \\
- \eta_2 + \eta_3 + \eta_2^2 - \eta_2
\end{bmatrix}
\]

\[
i_{f,a}(p) = \eta_4 \left[ i_{f,a}(p) + \{ T(z) \} i_{f,a}(p) \right],
\]

\[
i_{f,a}(p) = \eta_4 \left[ i_{f,a}(p) + \{ T(z) \} i_{f,a}(p) \right],
\]

Similarly fundamental constituents of phases ‘b’, ‘c’ load currents \( (i_{f,b} \) and \( i_{f,c} \)) are calculated. The fundamental current constituents from \( (i_{f,a}, i_{f,b}, i_{f,c}) \) from sensed load currents \( (i_{f,a}, i_{f,b}, i_{f,c}) \) are acquired using an adaptive digital filtering transfer function [25], so that load voltage profile is improved. The reference currents \( (i_{f,a}, i_{f,b}, i_{f,c}) \) in comparison to \( (i_{f,a}, i_{f,b}, i_{f,c}) \) result in current errors,

\[
i_{rel,a} = i_{f,a} - i_{f,b} - i_{f,c} = i_{f,b} - i_{f,a} - i_{f,c} = i_{f,c} - i_{f,a}
\]

These errors are given to hysteresis controller for switching pulses of VSC in voltage control.

### 3.2 DC–DC bidirectional converter control

The DC link voltage and current control of BES are regulated by the bidirectional converter as depicted in Figure 3. The converter has two switches \( S_7 \) and \( S_8 \), where \( S_7 \) operates in buck mode during the battery charging process, while the boost mode is implemented with \( S_8 \) in discharging mode. The current for the BES is positive while discharging and negative while the charging, \( V_{dc} \) is obtained using P & O method for MPP tracking of the PV array is compared with sensed DC voltage \( (V_{dc}) \) and this comparison results in an error signal, which is set as input for to the proportional and integral \( (PI) \) regulator.

\[
V_{dc}(p) = V_{dc}^e(p) - V_{dc}(p).
\]
The $I_{bat}^*$ regulator’s output acts as battery reference current.

$$I_{bat}^*(p + 1) = I_{bat}^*(p) + k_{pdc}V_{dc}(p + 1) + k_{idc}\{V_{dc}(p + 1) - V_{dc}(p)\},$$  \hspace{1em} (19)$$

where, $k_{pdc}$ and $k_{idc}$ are gains for PI$_a$, correspondingly.

The subtraction of sensed BES current ($I_{bat}$) with $I_{bat}^*$, results in an error, which is supplied to PI$_b$ and is calculated as,

$$I_{bate}(p) = I_{bat}^*(p) - I_{bat}(p).$$  \hspace{1em} (20)$$

The $I_{bate}$ is set as PI$_b$ regulator’s input, whereas its output is calculated as,

$$I_{er}^*(p + 1) = I_{er}^*(p) + k_{pbat}I_{bate}(p + 1) + k_{ibat}\{I_{bate}(p + 1) - I_{bate}(p)\},$$  \hspace{1em} (21)$$

where $k_{pbat}$ and $k_{ibat}$ are gains for the proportional and integral parts of PI$_b$, correspondingly.

The duty cycle, that is, $I_{er}^*$, is supplied to pulse width modulator for formation of switching logics for bidirectional converter.

4.1 Internal signals of adaptive digital filter for fundamental component extraction from load current and its comparison with conventional SOGI control

The internal signals of digital filter to obtain fundamental current component are represented in Figure 5(a), which improves the voltage profile at load side and the performance of system. There is no phase shift observed in between $i_{La}$ and $i_{fat}$. Figure 5(b) presents the Bode plot of digital filter and it is observed from the magnitude plot that this control technique furnishes at zero db axes and zero phase shift at fundamental frequency. Therefore, $i_{fat}$ is in-phase with $i_{La}^*$.

In comparison to conventional control, like second order generalised integrator (SOGI) control, this control technique is better in harmonics rejection capability. Thus, PCC voltage profile is found better with adaptive digital controller as compared to SOGI control. The comparison of digital filter with a conventional controller, that is, second order generalised integrator (SOGI) algorithm under disconnection and connection of phase ‘a’ load is shown in Figure 5(c), which shows that the digital filter control has faster dynamic response as compared to the conventional SOGI control. The load removal effects on $i_{fat}$ shows that digital filter’s control approach converges fast, that
is, reaches zero in a cycle as compared to SOGI control. Thus the digital filter based control has better performance as compared to the existing conventional controller, that is, SOGI.

4.2  Response for system at load variation

Figure 6 presents the response of system at load perturbation. At $t = 2.1s$, as the load increases, the magnitude of BES charging current is reduced, thus the load demand is met by BES. The BES charging current increases again, when the load demand is decreased at $t = 2.2s$. The sinusoidal load phase voltages ($v_{Labc}$) are well maintained at load variation. There is no change in solar PV power at load variation, therefore, the PV current remains constant. However, at varying load, DC link voltage is maintained to MPPT value.

4.3  Response for standalone system at solar irradiance change

Figure 7 depicts the response of system at solar insolation change. The solar insolation is decreased at $t = 1.3s$, so due to a decrease in the solar power, the PV current is also decreased. Thus, the BES charging current is reduced and load demand remains constant and is accomplished by the BES. However, at solar irradiance alteration, no variation is observed in the DC link voltage and load voltages $v_{Labc}$, which shows that PCC voltage profile is well maintained.

4.4  VSC operation for solar PV-BES system on non-accessibility of solar power

The behaviour of solar PV-BES system, when solar insolation is reduced to zero at $t = 1.5s$, is presented in Figure 8. The BES current is positive, which shows that BES comes to the
4.5 Response of controller on load disconnection

The behaviour of the solar PV-BES system at load disconnection is shown in Figure 9. The BES charging current is increased under load disconnection at \( t = 1.8 \) s. As no variation in solar power, therefore, the PV power and PV current are constant. The DC link voltage is regulated to the MPPT value. The load voltages are sinusoidal and balanced at the load removal. Hence, the system has satisfactory performance at load disconnection.

4.6 Comparison of control technique based on adaptive digital filter and PR controller with conventional control based on PI controller and without digital filter

The harmonic spectra of load voltage without adaptive digital filter and with conventional PI controller are shown in Figure 10(a), whereas \( v_{La,b} \) with adaptive digital filter and nonideal PR controller is demonstrated in Figure 10(b) for the nonlinear load current as depicted in Figure 10(c). Figure 10(a) demonstrates that in the voltage control approach, when the sensed load current is subtracted from the reference load current, the THD of PCC voltage is 3.94%. However, PCC voltage THD is reduced to 1.87% as shown in Figure 10(b), when a fundamental part of nonlinear load current obtained through adaptive digital filter is compared with the reference load current. Thus, harmonics in PCC voltages are within prescribed limits and per the standard IEEE-519. The nonlinear load current has THD of 27.54% as depicted in Figure 10(c). Figure 11(a) shows the steady-state error between \( v_{La,b} \) and \( v_{La,b} \) is not zero with a conventional PI controller, whereas Figure 11(b) depicts that the steady-state error is zero by utilising the non-ideal PR controller. Figure 11(c) shows the Bode plot of the conventional
controller and digital non-ideal PR controller. The performance of conventional PI controller is good for DC quantities in comparison to AC quantities. This non-ideal PR controller has finite gain at fundamental frequency, hence it eliminates the steady-state error between two AC quantities. An adaptive digital filter with digital non-ideal PR controller’s comparison with other conventional control techniques is depicted in Table 1.

5 | EXPERIMENTAL RESULTS

To validate the practicability of system, a developed prototype as shown in Figure 12(a) is utilised, to perform the tests.

The solar simulator is utilised to obtain the PV power. The control of system is implemented by an OPAL-RT (OP4510). The opto-couplers give the optical isolation between the power circuit and the pulses obtained from the output of power circuit and the pulses obtained from the output of OPAL-RT. The current and voltage sensors based on the Hall Effect, that is, LA-55P and LV-25 are utilised for perceiving the signals $v_{Lab}$, $v_{Lbc}$, $v_{La}$, $v_{Lb}$, $v_{Lc}$, $I_{dc}$, $I_{bat}$ and $I_{pv}$. The digital storage oscilloscope and power analyser are used for obtaining the experimental results for the operation system for steady-state as well as various dynamic scenarios. Figure 12(b) demonstrates the block diagram of hardware connection of the developed prototype. The constituents of hardware connection comprise of solar PV array simulator, bidirectional converter, three leg VSC, interfacing inductors, ripple filter and nonlinear load. The sensed signals through Hall-Effect sensors are sent to OP4510 via analog to digital converters (ADCs). The output of ADC are the signals given to control algorithm, which is loaded in field programmable gate array (FPGA). Therefore, switching pulses generated for bidirectional converter and VSC are provided to optocouplers via digital inputs and outputs DIO. The system’s parameters for prototype are specified in Table A.1 of Appendix.

5.1 | Steady-state response for control based on adaptive digital filter and non-ideal PR controller and its comparison with conventional PI control

The waveforms of $v_{Lab}$, $v_{Lbc}$, $v_{La}$, $v_{Lb}$, $v_{Lc}$, $v_{dc}$, $v_{Ls}$, $i_{La}$, $i_{Lc}$ and $V_{dc}$ are represented in Figures 13(a)–(c). $V_{dc}$ is maintained to MPP tracking value. Figures 14(a)–(d) demonstrate the system’s response at steady-state scenario with the non-ideal digital PR controller. Figures 14(a) and (b) present power of the load power of VSC and $i_{Lc}$. Figures 14(c) and (d) present VSC current of phase ‘c’, that is, $i_{Lc}$. Figures 15(a)–(c) show response of system with non-ideal digital PR controller. Figure 15(a) presents the THD of nonlinear load current, that is, $i_{Lc}$ is 27.9 %. The BES voltage and the BES current are shown in Figure 15(b). Figure 15(c) demonstrates the harmonic

![Figure 10](image-url) | Harmonic analysis. (a) $v_{Lab}$ without digital filter technique and with conventional PI controller; (b) $v_{Lab}$ with digital filter technique and non-ideal PR controller; (c) $i_{Lc}$, nonlinear load current
FIGURE 11  Comparison of conventional PI controller with non-ideal PR controller; (a) $v_{La}, v_{La}^*$ without digital filter technique and with conventional PI controller; (b) $v_{La}, v_{La}^*$ with digital filter technique and non-ideal PR controller; (c) Bode plot of conventional PI controller with digital non-ideal PR controller

| Parameter                        | Adaptive Digital Control with Non-Ideal PR Controller | Conventional SOGI Control with Non-Ideal PR Controller | Without Adaptive Digital Control with Conventional PI Controller |
|----------------------------------|------------------------------------------------------|--------------------------------------------------------|---------------------------------------------------------------|
| Performance under load removal   | Fundamental load current component reaches zero within a cycle | Fundamental load current component reaches to zero in 5 cycles | No fundamental part component extraction                      |
| PCC voltage THD                  | Low                                                  | Medium                                                 | Medium                                                       |
| Computation burden               | Less                                                 | High                                                   | Less                                                         |
| Dynamic response                 | Fast                                                 | Slow                                                   | Slow                                                         |
| Steady-state error               | Zero                                                 | Zero                                                   | Is not zero                                                  |
FIGURE 12  Block diagram of hardware connection and experimental setup. (a) Block diagram of hardware connection; (b) experimental setup
spectrum of $v_{Lab}$ without digital filter technique and with PI controller. The THD of PCC voltage is 3.5 %, when there is no digital controller is used in the voltage control and the PI controller regulates the voltage to 211 V. The harmonic spectrum of $v_{Lab}$ with adaptive digital filter technique and with digital PR controller is presented in Figure 15(d). A 2.6% THD for load voltage is observed, hence, there is reduction in THD of PCC voltage.
voltage by utilising the adaptive digital filter, and non-ideal PR controller has regulated the voltage to the required value, that is, 220 V. Thus, PR controller reduces the steady-state error to zero.

Figure 16(a) depicts that steady-state error between the reference PCC voltage and sensed PCC voltage is not zero with a conventional PI regulator, whereas Figure 16(b) demonstrates that steady-state error is zero with a discrete non-ideal PR controller. Thus, with the implementation of a digital filter control and non-ideal PR controller, the harmonics of load current are filtered, which improves the power quality of voltage profile at PCC and reduces the steady-state error between two AC quantities, that is, reference PCC voltages and sensed PCC voltages. The system’s steady-state and dynamic responses are better with digital controller and non-ideal PR controller as compared to the conventional controllers.

5.2 | Dynamic performance at perturbation in load

The waveforms of $V_{pv}$, $I_{pv}$, $I_{La}$ and $I_{bat}$ are shown in Figure 17(a) for a rise and a reduction in the load demand. As the load is increased, the battery’s charging current is reduced to fulfil the load demand, whereas on a decrease in the load demand,
5.3 Response at solar irradiance change

The maximum power tracking is observed near to 100% for insolation levels of 500W/m² and 1000W/m² as depicted in Figures 18(a) and (b). In this system, $V_{dc}$, $I_{pp}$, $I_{La}$ and $I_{bat}$ waveforms for solar insolation change, are illustrated in Figure 19. The fall in solar irradiance results in a reduction in $I_{pv}$.

5.4 System operation at non-accessibility of PV power

Figure 20 illustrates the system’s performance, when there is no accessibility of the PV power. When $I_{pv}$ is decreased to zero, the battery operates in discharging mode and it provides active power to load. $V_{dc}$ is constant for these changes, and load side demand is maintained.

5.5 Response of controller at load removal and insertion

The removal and insertion of load of phase a as $i_{La}$ with the with the waveforms of $V_{dc}$, $I_{pp}$, $I_{bat}$ and $I_{La}$ waveforms for solar insolation change, are illustrated in Figure 19. The BES charging current is increased in magnitude as the load is disconnected, whereas at the load connection, $I_{bat}$ is reduced. The PCC voltages $V_{dc}$ are sinusoidal and balanced at load disconnection and connection of the load.
6 | CONCLUSION

The voltage regulation technique of solar PV-BES system for off-grid electrification in rural/remote areas, has been demonstrated by test results for variety of scenarios like solar insolation variation, load changes and load disconnection. The power is provided to the load in this system. The load management has been retained by the charge/discharge process of the BES linked through a DC–DC converter in buck/boost modes during base load/ uttermost load demands, accordingly. This converter also regulates the DC link voltage. The utilisation of digital filter in system alleviates the harmonics in the load voltage. The discrete non-ideal PR control in voltage control has sustained the voltage and frequency for nonlinear loads connected in the system. The load voltage THD is observed below than 5% and has been perceived as described in the IEEE 519 standard.

The performance of solar PV-BES system for rural/remote areas has been found satisfactory for various types of scenarios under steady-state and dynamic conditions.

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## APPENDIX A

| **Parameter** | **Simulation Value** | **Experimental Value** |
|---------------|----------------------|------------------------|
| $R_f$, $C_f$  | $5 \Omega$, $10 \mu F$ | $5 \Omega$, $10 \mu F$ |
| Interfacing inductor ($L_f$) | $5 \text{ mH}$ | $5 \text{ mH}$ |
| $V_{bat}$, Ampere hour (Ah) | $240 \text{ V}$, $21 \text{ Ah}$ | $240 \text{ V}$, $21 \text{ Ah}$ |
| $L_b$ | $6 \text{ mH}$ | $6 \text{ mH}$ |
| Solar power ($P_{pv}$) | $2.9 \text{ kW}$ | $1.365 \text{ kW}$ |
| Open circuit voltage ($V_{oc}$) | $32.9 \text{ V}$ | $418 \text{ V}$ |
| Short circuit current ($I_{sc}$) | $8.21 \text{ A}$ | $4 \text{ A}$ |
| MPP voltage ($V_{mp}$) and current ($I_{mp}$) | $26.3 \text{ V}$, $7.61 \text{ A}$ | $360 \text{ V}$, $3.79 \text{ A}$ |
| $N_{ss}$, $N_{pp}$, $R_{ss}$ and $R_{pp}$ | $14$, $1$, $221 \Omega$, $415.405 \Omega$ | $60 \Omega$, $0.2 \text{ H}$ |
| $R$, $L$ (Load) | $100 \Omega$, $0.2 \text{ H}$ | $1.2$, $0.02$ |
| Filter coefficients $\eta_1$, $\eta_2$, $\eta_3$, $\eta_4$ | $0.01$, $0.997$, $1.99$, $0.5$ | $0.01$, $0.997$, $1.99$, $0.5$ |
| Switching frequency | $10 \text{ kHz}$ | $10 \text{ kHz}$ |
| Gains of voltage controller ($k_{ppv}$, $k_{pv}$) | $1$, $0.4$ | $1.2$, $0.02$ |
| $V_d^*$ and DC link capacitance $C_d$ | $360 \text{ V}$, $3 \text{ mF}$ | $360 \text{ V}$, $3 \text{ mF}$ |
| $V_d$ control gains: $k_{pd}$, $k_{id}$ | $2.7$, $0.7$ | $0.15$, $0.005$ |
| $I_{bat}$ control gains: $k_{pbat}$, $k_{ibat}$ | $0.23$, $0.5$ | $0.1$, $0.003$ |