Photovoltaic-battery powered grid connected system using multi-structural adaptive circular noise estimation control

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Abstract
The intermittent nature of renewable energy sources results in an interruptible and inadequate power. The integration of the battery energy storage to renewable energy sources provides reliable and continuous power to the loads. Further, the high penetration of renewable energy sources raises the power quality problems in the grid. This work deals with performance improvement of PV-battery energy storage based energy conversion system achieved through implementing a multi-structural adaptive circular noise estimation control for its grid connected mode. The control is developed for the grid side voltage source converter, which provides the power quality improvement and automated transition from grid connected mode to standalone mode or vice-versa. It provides multi-functional features such as harmonics extraction, DC offset elimination, and power quality improvement in PV-battery energy storage based energy conversion system even at nonlinear loading condition in grid connected mode. In standalone mode, the amplitude and waveform of load voltage are controlled sinusoidal by the voltage control. Performance of PV-battery energy storage based energy conversion system is studied to validate the acceptability of these controls according to the IEEE-519 standard.

KEYWORDS
multi-structural adaptive circular noise estimation, power quality, solar PV generation

1 | INTRODUCTION

The excessive use of conventional fuels, has led to environmental issues like global warming, green house effect etc. To overcome this issue, renewable energy resources (RESs) namely, solar PV (Photovoltaic), wind, hydro, fuel cell etc. are now being used as an alternative source of energy [1–2]. Recently, the installation of RES in the distribution network has increased exponentially. The major source of energy is through the solar PV generation almost 54% of total generation all over the world [3]. The generation of electrical energy based on the solar PV array is an environment friendly with easy installation [4]. Therefore, the solar PV technology in the grid-connected application is the most effective way to produce electricity for diversified purposes [5–6]. The grid interconnected systems with RESs are the desirable solution to meet the demand of energy in the distribution network. However, the energy generation from RES is a function of climate and meteorological conditions, which brings uncertainties in its operation [7–8]. Moreover, intermittency in the solar PV power generation has a considerable impact on power quality (PQ) of RES energy conversion systems. The battery energy storage (BES) equipped in RES to smoothen out the power fluctuations, deals with power imbalance between the source and loads. The integration of BES not only improves reliability, but it also enables the operation of the system in grid connected mode (GCM) and standalone mode (SAM) of operation. In a grid-tied system, the solar PV panel and BES both are connected near to local loads/ consumers rather than laying long transmission lines for feeding the power to local loads. In SAM, the BES integrated PV system works effectively by regulating the voltage and frequency across local loads and provides an uninterrupted power to these loads.

The high-level utilization of nonlinear loads such as switch-mode power supplies (SMPS), light emitting diode (LED)
drivers, electric drives and many other power electronic-based loads inject harmonics in the distribution network. These harmonics reduce power factor and affect the power quality at the grid. However, such systems must control the total harmonics distortion (THD) in its output below its prescribed limit according to the IEEE standard 519. Thus, it is necessary to have a robust control for harmonics compensation in the grid interfaced PV inverter to feed high-quality power to the grid in various operating situations [9].

To enhance the stability and efficiency of solar PV energy conversion system, the researchers have focussed on the grid connected systems. However, the grid outages are more common phenomena in remote areas. Hence, a system with a facility to work under both the grid connected and islanding conditions are more suitable. The grid interfaced PV system proposed in [10] works satisfactorily for elimination of power quality issues problems. However, the scenarios under the unavailability of the grid or the grid voltage violates the limits, the system fails to operate. In [7], the proposed PV battery-grid interfaced system works in GCM as well as SAM. During the grid outage condition, the battery is used to supply the critical loads. However, the power quality problems are not taken care in it. The grid connected solar inverter with compensation of harmonics, is presented in [9,11]. The grid disconnection and resynchronization conditions have not been presented in these attempts. Therefore, a continuous supply of power to the critical loads is not possible due to the outage of the grid.

An exhaustive literature review has been carried out on various controls to deal with issues related to PQ and to achieve the fast-dynamic response at varying dynamic conditions in the system. Many control schemes, namely synchronous reference frame (SRF) theory [11], and instantaneous reactive power (IRP) theory [12] have been proposed for improving the quality of power in the grid connected system. However, these above-mentioned control techniques have some disadvantages, such as SRF and IRP theories have inadequate performance at distorted grid voltage conditions and introduce a time delay during extraction of fundamental component due to multiple transformations. In SRF technique, due to the low-pass filter (LPF), the response of the system is deteriorated in the reference current generation. Besides these control methods, many adaptive control techniques have been proposed such as least mean fourth (LMF) [13] and adaptive noise cancellation (ANC) filter [14]. The LMF control has high steady-state error and high oscillations in the extracted fundamental components because of low convergence rate. This has negligible harmonics due to good harmonics rejection capability against high order frequency components [15]. To remove this drawback, Chilipi et al. [15] have proposed a multi structural ANC filter for the grid tied system. Moreover, some generalized integrator-based controls such as SOGI-FLL (Second Order Generalized Integrator-Frequency lock loop) [16], multi SOGI (MSOGI) [17] and third order integrator (TOGI) [18] are reported in the literature. These control algorithms have good dynamic performance and filtering capability, but the performance of the grid-connected system deteriorates when the DC-offset is present. Another control known as disturbance compensation through disturbance observer (DO) provides more strength against unknown disturbances. Many structures of DO have been reported in the literature [19–22]. Selvajyothi et al. [19] have proposed a composite observer with feed-forward loop to estimate a fundamental component of current and voltage in a single-phase inverter. An adaptive circular noise estimation (ACNE) based control is presented in [20] to reject the harmonics and the DC bias in fundamental voltage estimation, which is used in the grid synchronization. Performance of ACNE is better against higher-order harmonics, however, in the presence of low order harmonics, performance of the observer is adverse. Kim et al. [21] have presented a frequency adaptive based observer in permanent magnet synchronous machine to estimate the fundamental flux. The fundamental flux is estimated by the voltage and current observer-based flux model, which is realized with frequency adaptive observer and harmonics extractor (HE). This arrangement provides correct estimation of offset errors and disturbances. The frequency adaptive based observers have been identified in [20,22]. These observers estimate the distortion-free signal from the distorted input signal and provide a reasonable stability margin.

In this work, a multifunctional PV-battery based energy conversion system (PVBECS) is implemented to provide continuous high-quality power to local nonlinear loads in the multimode operations. A MACNE algorithm facilities the reactive power compensation, harmonics and DC offset mitigation and unity power factor in PVBECS. The MACNE algorithm has the inherent property to follow the notch filter characteristics and state equations are estimated by keeping the limitation of low pass filtering method in filtering the DC-offset. This MACNE algorithm also has capability of selective harmonic elimination from the distorted signal. To achieve MPE, various MPE methods are presented in [23].

The simple perturb and observe (P&O) algorithm is selected for MPE of the PV array owing to ease of implementation. In this paper, a multifunctional VSC control is implemented in PVBECS for the power quality improvement. The main contributions of this work are summarised as follows.

• A multitasking PVBECS has automated transition between GCM and SAM thereby allowing uninterruptable power for local nonlinear loads.
• In GCM mode, the VSC works as an active power filter, which compensates the harmonics currents of the load. However, in SAM, the load voltage is maintained sinusoidal by the voltage control to provide efficient power transfer to local nonlinear loads. This feature enhances the utilization factor of the VSC, which reduces the payback period of the system.
• This MACNE algorithm is used in PVBECS for estimating fundamental component of the grid voltage and the load current. It has a DC offset elimination ability with good harmonics filtering and fast dynamic performance.
• The VSC control enhances the power quality of PVBECS and maintains THD of the grid current in GCM and the load voltage in SAM < 5% as per the IEEE 519 standard.
The combined function of power generation through a solar PV array and enhancement of power quality at supply side as well as load side, is achieved into a single system. Thus, this system has a better utilization with respect to conventional grid connected solar inverter system.

2 PV-BATTERY INTEGRATED GRID CONFIGURATION

Figure 1 shows a configuration of PVBECS, which is consisting of solar PV array, BES with a bi-directional DC–DC converter (BDC), a DC–DC boost converter (BC) and a single-phase grid. The solar PV array is interfaced to the DC link capacitor, $C_{dc}$ through a BC. A nonlinear load is realised by connecting series R-L load in parallel to single phase uncontrolled rectifier connected at the PCI (Point of Common interconnection). A R-C ripple filter is used to mitigate high frequency switching harmonics and an interfacing inductor is utilized to reject the high frequency current harmonics generated from the switching of VSC. The BES is connected to the DC link through a BDC. The DC link voltage is regulated at constant value by the control of BDC through charging and discharging the BES. When there is surplus power from the PV array, $V_{dc}$ increases, indicating the excess PV array power, $P_{PV}$ to be stored in the BES unit.

3 SYSTEM CONTROL STRATEGY

The control for PVBECS is designed in this section. Each power converter (VSC, BC and BDC) has its own control as illustrated in Figures 2–4. The control of VSC needs the reference grid current generation based on the operating modes (GCM and SAM) of the PVBECS.

3.1 Grid current control

In order to obtain a sinusoidal grid current, MACNE based control is used for switching of the VSC. The harmonics information and fundamental component from the harmonic rich load current are estimated using a MACNE algorithm. Various functionalities of the VSC control are attained by dissection of
control into four units, namely, an extraction of fundamental load current, the feed-forward component ($i_{PVFF}$) of the PV array power, unit templates ($u_p$ and $u_q$) and $V_{dc}$ control ($I_{Loss}$). The fundamental components ($i_L^{\alpha_f}$ and $i_L^{\beta_f}$) of the load current are determined by MACNE algorithm. Figure 3 presents a flowchart of VSC control, which is used for switching of VSC in GCM as well as SAM. The control methodology is described as follows.

3.1.1 MACNE algorithm

This control structure is designed for eliminating the harmonics and DC offset from the input signal. The block diagram of MACNE algorithm is demonstrated in Figure 4. This MACNE algorithm is pertinent tool to extract the fundamental component from the load current. The state variables of MACNE algorithm [20] are given as,

$$
\frac{d}{dt} \begin{bmatrix} i_{L^{\alpha_f}} \\ i_{L^{\beta_f}} \end{bmatrix} = \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} \begin{bmatrix} i_{L^{\alpha_f}} \\ i_{L^{\beta_f}} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} \begin{bmatrix} D \\ \tau_{offset} \end{bmatrix} = A \begin{bmatrix} i_{L^{\alpha_f}} \\ i_{L^{\beta_f}} \end{bmatrix} + B \begin{bmatrix} D \\ \tau_{offset} \end{bmatrix},
$$

(1)

$$
Z = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ i_{L^{\alpha_f}} \\ i_{L^{\beta_f}} \\ D \end{bmatrix} = C \begin{bmatrix} 0 \\ j\omega \\ \frac{\omega_n}{\beta_1} j\omega \\ \frac{\omega_n}{\beta_2} j\omega \\ \frac{\omega_n}{\beta_3} j\omega \end{bmatrix} = \begin{bmatrix} 0 \\ \omega_n j\omega \\ \frac{\omega_n}{\beta_1} j\omega \\ \frac{\omega_n}{\beta_2} j\omega \\ \frac{\omega_n}{\beta_3} j\omega \end{bmatrix},
$$

(2)

The derivative of '$D$' is defined in Equation (1) considered as null and derivative of $i_{L}$ is same as derivative of $i_{L^{\alpha_f}}$. $\omega$ represents as fundamental frequency and corresponding to derivative of $\theta$. By considering A and C in Equations (1) and (2), it
determines the observability of state equation. Corresponding state equation is observable, because the rank of $O_i$ is equal to full column rank as shown from Equation (3). According to the Luenberger observer [21] state equations are given as,

$$\text{rank}(O_i) = \text{rank} \begin{bmatrix} C \\ CA \\ CA^2 \end{bmatrix} = 3$$ (3)

$$\frac{d}{dt} \begin{bmatrix} \dot{i}_L \\ \dot{i}_L \\ \dot{i}_L \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 \\ \omega & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}^{-1} \begin{bmatrix} \chi_1 \\ \chi_2 \\ \chi_3 \end{bmatrix} \{\dot{i}_L - (D + \phi)\}$$ (4)

where “$\dot{\cdot}$” over the state variable defines the estimated value.

In Equation (5), the derivative operator “$d/dt$” is replaced with the Laplace operator “$s$” and expressed the state variables with respect to “$\dot{i}_L$” as shown,

$$\begin{bmatrix} \dot{i}_L \\ \dot{i}_L \\ \dot{i}_L \end{bmatrix} = \begin{bmatrix} s\chi_1 & \omega & \chi_1 \\ \omega - \chi_2 & \chi_2 \\ 0 & \chi_3 \end{bmatrix}^{-1} + \begin{bmatrix} \chi_1 \dot{i}_L \\ \chi_2 \dot{i}_L \\ \chi_3 \dot{i}_L \end{bmatrix}$$ (5)

If $\omega_2$ is considered equal to fundamental frequency, then the subsequent gain tuning is attained. The pole placement technique [20] is used for tuning of observer gains ($\chi_1, \chi_2$ and $\chi_3$). The transfer functions [20] of ACNF are given as,

$$\frac{\gamma_{\alpha i}}{\dot{i}_L} = G_{\alpha i}(s) = \frac{2\gamma_1 \omega}{s^2 + 2\gamma_1 \omega s + \omega^2}$$ (6)

$$\frac{\gamma_{\beta i}}{\dot{i}_L} = G_{\beta i}(s) = \frac{2\gamma_1 \omega}{s^2 + 2\gamma_1 \omega s + \omega^2} (s + \omega)$$ (7)

$$\frac{D}{\dot{i}_L} = G_{NS}(s) = \frac{(\gamma^2 + \omega^2)}{s^2 + 2\gamma_1 \omega s + \omega^2} \cdot \frac{\omega_1}{s + \omega_1}$$ (8)

It is illustrated that the second order band-pass filter (BPF) defined as $G_{\alpha i}(s)$ is applied to input for eliminating harmonic components from the input signal. Further, a notch filter cascaded with a low pass filter (LPF) is defined as $G_{NS}(s)$, which is used to remove the DC bias component. A band stop frequency and cut-off frequency of $G_{NS}(s)$ are synchronized to $\omega$. It is employed to eliminate the distortion and filter out low order harmonics from the signal, a harmonic extractor (HE) is implemented as illustrated in Figure 4(c). The transfer function (TF) from the calculated harmonic, $\Phi_h$ to error signal is achieved as,

$$\frac{\dot{\phi}_h}{\dot{\epsilon}} = \alpha_i(s) = \frac{2\gamma_1 \omega s}{s^2 + h^2 \omega}$$ (9)

where $h$ represents the order of harmonic.

Figure 4(a) shows the structure of MACNE algorithm, which includes the harmonic extractor (HE) in parallel with ACNF [20]. The input of HE is interfaced loop is subtracted from the input signal to cancel the harmonics. The transfer function from $\dot{i}_L$ to fundamental frequency component ($\dot{i}_f^2$), $TF_{ACNF}(\dot{i}_f)$, can be achieved [21] as,

$$\frac{\dot{i}_f}{\dot{i}_L} = TF_{ACNF} = \frac{2\gamma_1 \omega}{s^2 + 2\gamma_1 \omega s + \omega^2} \sum \alpha_i(s)$$ (10)

A sample and hold logic with zero-crossing detector is utilized to extract peak value ($\hat{\dot{i}}_f$) of in-phase active fundamental load component extracted from load current.

Figure 5 shows the Bode plot of MACNE algorithm [21]. It demonstrates the frequency response of the MACNE algorithm, its magnitude gains attenuate at $3\omega, 5\omega$ and $7\omega$. The trade-off relation between the calculation burden and filtering performance is considered in the selection of the number of HE with an input signal of inner feedback signal ‘i’ and output of HE.

### 3.1.2 Assessment of unit template and PCI voltage

The MACNE algorithm (from Figure 4) is used to estimate the in-phase, $v_{\alpha g}$ and quadrature phase grid voltage $v_{\beta g}$ of the grid voltage. The amplitude of terminal voltage, $V_t$ is calculated as follows,

$$V_t = \sqrt{(v_{\alpha g}^2 + v_{\beta g}^2)}$$ (11)

The ration of quadrature and in-phase voltages ($v_{\alpha g}$ and $v_{\beta g}$) with $V_t$ gives the in phase and quadrature phase unit templates ($\alpha_p$ and $\beta_p$) as,

$$\frac{\alpha_p}{\beta_p} = \frac{v_{\alpha g}}{v_{\beta g}} = \frac{v_{\beta g}}{V_t}$$ (12)
3.1.3 | Estimation of DC loss component

To avoid the interruption in the operation of the PVBECS, the DC link loss component \( I_{\text{loss}} \) is added to the peak value of reference grid current \( I_{\text{gref}} \) in the absence of a battery. To maintain the DC link voltage, the PI controller is used to compensate for the error between the reference DC link voltage \( V_{\text{dc}} \) and \( V_{\text{dc}} \). The output of the PI controller is defined as \( I_{\text{dcr}} \) which is utilized in the grid current control to regulate \( V_{\text{dc}} \).

The governing equation is defined as,

\[
I_{\text{loss}} = [k_{\text{pdc}} + (K_{\text{dc}}/s)] (V_{\text{dc}} - V_{\text{dc}})
\]  

(13)

The DC link loss component is considered as zero in the estimation of reference grid current when the battery is present in the system.

3.1.4 | Calculation of feed-forward term of solar PV power

The dynamic performance of PVBECS is enhanced by using solar PV array power feed-forward term \( I_{\text{PVFF}} \). The \( I_{\text{PVFF}} \) is calculated as,

\[
I_{\text{PVFF}} = \frac{2P_{\text{pv}}}{V_{\text{f}}}
\]  

(14)

3.1.5 | Reference Grid Current Estimation in Current Control Mode (CCM)

The MACNE algorithm is implemented to estimate the active in-phase and quadrature phase fundamental component \( f_x, f_y \) of load current. The amplitude of fundamental in-phase complement is considered as \( I_{\text{f}} \). The amplitude of net reference grid current is estimated as,

\[
I_{\text{gref}} = I_{\text{d}} - I_{\text{PVFF}} + I_{\text{Loss}}
\]  

(15)

The sinusoidal reference grid is estimated as,

\[
i_{\text{gref}} = I_{\text{gref}} \times u_{\phi}
\]  

(16)

The reference current and sensed grid current are compared, and the calculated error is fed to the hysteresis current controller to generate the pulses for switching the VSC for VSC in GCM.

3.1.6 | Control in standalone mode

When the islanding condition occurs, the VSC must identify it and it must change its mode to standalone voltage mode operation. The PVBECS is cut-off from the grid and in islanding, the VSC regulates the constant voltage across the local loads. At the instant of transition from GCM to SAM, the VSC starts functioning in voltage control mode (VCM) as illustrated in Figure 2. In SAM, the instantaneous phase for reference load voltage is estimated at 50 Hz frequency independently. The reference voltage \( V_{\text{ref}} \) is compared with the sensed load voltage to maintain the voltage across the local loads.

3.2 | Mode selection control

The mode selection control is depicted in Figure 2, which selects the mode (Mode 1: GCM or Mode 2: SAM) in which the system should work. Three inputs are given to the mode selection control. The inputs are defined as, \( \theta_{g} \) magnitude of \( f_x \), \( \theta_{s} \) phase difference of phase angle \( \Delta \theta_{g} = \theta_{g} - \theta_{t} \). The PES \( \theta_{g} \) signal output of this mode selection control and that output signal are used to disconnect or reconnect the grid of the PV-BES system and its logic is selected as given:

\[
\Delta \theta_{g} = \begin{cases} 1 & \text{when } V_{\text{fmin}} < n_{\text{e}} < V_{\text{fmax}} \text{ : Case 1} \\ f_{\text{gmin}} < f_{\text{e}} < f_{\text{gmax}} \text{ : Case 2} \\ \theta_{\text{min}} < \Delta \theta_{e} < \theta_{\text{max}} \text{ : Case 3} \\ 0 & \text{Otherwise.} \end{cases}
\]  

(17)

The PES signal \( \Delta \theta_{g} \) is high (\( \Delta \theta_{g} = 1 \)) only when all defined cases in Equation (17), are satisfied, else \( \Delta \theta_{g} \) is fixed to its low value (\( \Delta \theta_{g} = 0 \)). Where \( \Delta \theta_{e} = \theta_{e} - \theta_{t} \) is the phase error of \( \theta_{g} \) and \( \theta_{t} \). Mode selection of the load voltage phase angle \( \theta_{L} \) for the estimation of \( V_{\text{L}} \) is described as,

\[
\theta_{L}(k) = \begin{cases} \theta_{L}(k-1) + \frac{K_{\theta} + \frac{K_{I} \Delta \theta_{e}}{s}}{T_{i}} \Delta \theta_{e} & \text{if } V_{\text{fmin}} < n_{\text{e}} < V_{\text{fmax}} \text{ and } f_{\text{gmin}} < f_{\text{e}} < f_{\text{gmax}} \text{ : Case 3} \\ \theta_{L}(k-1) & \text{otherwise} \end{cases}
\]  

(18)

where proportional and integral gains of the PI controller are defined as \( K_{\theta} \) and \( K_{I} \) respectively. From Equation (18), first two cases are satisfied, \( \Delta \theta_{e} \) is compensated via a PI controller and its output is added with \( \theta_{e} \), and the output is utilized to estimate \( V_{\text{L}} \) (Reference Load Voltage). As \( \Delta \theta_{e} \) reduces to zero and all cases (as defined in Equation (18)) are satisfied \( \Delta \theta_{g} = 1 \), the operating mode of the system is decided as per the state value of \( \Delta \theta_{g} \) which is shown in Figure 2 and its logic is decided as follows:

\[
\Delta \theta_{g} = \begin{cases} 1 & \text{For Mode } -1 \text{ : Grid Connected Mode.} \\ 0 & \text{For Mode } -2 \text{ : Islanding Mode.} \end{cases}
\]  

(19)

3.3 | Bidirectional DC–DC converter control

The BDC is utilized as an interconnection between \( V_{\text{dc}} \) and BES. The BDC control loop consists of two loops i.e. the DC link voltage controller as an outer loop and an inductor current...
control as an inner loop, respectively. In the outer voltage control loop, the reference DC link voltage, \( V_{\text{dcr}} \) and sensed \( V_{\text{dc}} \) are compared and the resultant error is fed to the PI controller (with proportional gain \( K_{\text{pi}} \) and integral gain \( K_{\text{ii}} \)). The output of the voltage control loop is expressed as,

\[
I_{\text{bat}}^* = (K_{\text{pi}} + K_{\text{ii}}/s) \times (V_{\text{dcr}} - V_{\text{dc}}) \quad (20)
\]

The inner current loop has utilized a PI controller (with proportional gain \( K_{\text{pv}} \) and integral gain \( K_{\text{iv}} \)) to reduce the error between \( I_{\text{bat}}^* \) (reference BES current) and sensed BES current, \( I_{\text{bat}} \) and it generates the pulses for DBC by using pulse width modulation (PWM) generator as follows.

\[
d = (K_{\text{pv}} + K_{\text{iv}}/s) \times (I_{\text{bat}} - I_{\text{bat}}^*) \quad (21)
\]

### 3.4 Boost converter control

The BC is utilized to interface between DC link voltage \( V_{\text{dc}} \) and the solar PV array. The BC is utilized to extract the maximum power (MP) of the solar PV array via Perturb and Observe (P&O) MPPT algorithm. A duty cycle of BC is generated by a PWM based voltage controller as illustrated in Figure 2. The equations of P&O algorithm [23] are defined as,

\[
\begin{align*}
\text{if } \Delta I_{\text{PV}} = 0, & \quad \delta_{\text{new}} = \delta_{\text{old}} \\
\text{else if } \Delta I_{\text{PV}} > 0, & \quad \begin{cases} 
\text{if } \Delta I_{\text{PV}} > 0, & \quad \delta_{\text{new}} = \delta_{\text{old}} - \Delta f_{\text{fi}} \\
\text{else} & \quad \delta_{\text{new}} = \delta_{\text{old}} + \Delta f_{\text{fi}}
\end{cases} \\
\text{else,} & \quad \begin{cases} 
\text{if } \Delta I_{\text{PV}} > 0, & \quad \delta_{\text{new}} = \delta_{\text{old}} + \Delta f_{\text{fi}} \\
\text{else} & \quad \delta_{\text{new}} = \delta_{\text{old}} - \Delta f_{\text{fi}}
\end{cases}
\end{align*}
\]

### 4 RESULTS AND DISCUSSION

To test the effectiveness of controls, an experimental setup of a PVBECS is developed in the laboratory as shown in Fig. 6. The implemented control of power converters is realized in DSP (Digital Signal Processor-dSPACE-1202) control unit with MATLAB interface. The dynamic and steady state performances of controls at various operational conditions are presented to demonstrate performance of a PVBECS in following subsections. Parameters of PVBECS are given in Table 1 and Appendix A.

#### 4.1 Steady state performance of PVBECS

Figures 7–9 depict performance of PVBECS in steady state. Figures 7(a–d) show the waveforms of the grid current (\( i_g \)), PV current (\( I_{\text{PV}} \)), load current (\( i_L \)) and VSC current (\( i_{\text{VSC}} \)), respectively. The grid voltage and grid current are 180° phase shifted and have maintained unity power factor operation as demonstrated in Figure 7(a). The waveform of \( I_{\text{PV}} \) and \( V_{\text{PV}} \) of PV panel are presented in Figure 7(b) and the PV array generates 2.1 kW, out of which, 1.4 kW (in Figure 8(a)) is fed to the grid. The BES unit is connected to \( V_{\text{dc}} \) through BDC and BES voltage \( (V_{\text{bat}}) \) is 247.2 V, which is demonstrated in Figure 8(b).

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**TABLE 1** Specification of component for developed hardware phototype

| Component                      | Specification                        |
|-------------------------------|--------------------------------------|
| Solar PV panel                | PV simulator AMETEK make ETS600 x 17DPVF |
| Current sensor                | LA55-p                                |
| Voltage sensor                | LV25-P                                |
| Real-time controller          | dSPACE-1202 micro Lab Box             |
| Battery                       | Lead acid (240 V, 42 Ah)              |
| VSC                           | IGBT switch module (SKM200GB12T4):    |
|                               | 200 A, 1200 V                         |

---

**FIGURE 7** Steady state performance of PVBECS while feeding power to grid (a) \( E_{g}, i_{g} \) (b) \( V_{\text{PV}}, i_{\text{PV}} \) (c) \( V_{\text{L}}, i_{\text{L}} \) (d) \( v_{\text{vsc}}, i_{\text{vsc}} \)
FIGURE 8  Steady state performance of PVBECS while feeding power to
grid (a) grid power (b) \( I_{bat} \), \( V_{bat} \) (c) Load power and (d) VSC power

FIGURE 9  Steady state performance of PVECS while feeding power to
grid (a) battery power (b) harmonic spectrum of \( i_L \) (c) harmonic spectrum of \( v_g \) and (d) harmonic spectrum

Power) of the system, respectively. The excess solar PV array
power (\( P_{bat} = (P_{PV} - P_g - P_L) = 248 \) W) is stored in the BES after
supplying \( P_g \) to the grid and fulfilling the load demand as pre-
sented in Figure 9(a). The harmonic spectra of \( i_L \), \( i_g \), and \( v_g \) are
represented in Figure 9(b–d). The THD (Total Harmonic Dis-
tortion) of the load current is 28%. The high harmonics con-
tent in load current is due to the presence of nonlinear load.
However, the THD of the grid current \( i_g \) is maintained at 3.6%,
which satisfies the IEEE-519 standard.

4.2  Response of PVBECS in SAM

The implemented control is also tested in SAM. In this mode,
the grid is disconnected, and the BES maintains the \( V_{dc} \) by
storing the excess power as shown in Figures 10 and 11. Here,
\( n_L \) is maintained constant (Figure 11(a)) and THD of \( v_L \) is 3.7%
even at the nonlinear load (Figure 10(c)). The implemented
control in this mode not only maintains low THD in the load
disconnection but it also maintains power equilibrium in PVBECS,
which shows the multimode features of the controller and the
excess power is fed to BES (which has been injecting into
the grid in previous mode of operation). Here, \( n_L \) and \( i_L \) are
maintained constant during SAM of operation. This shows the
effectiveness of the implemented control.

4.3  Performance at varying solar insolation

Figure 12(a–b) illustrate the response of the system at varying
solar isolation from 1000 to 600 W/m\(^2\). To maintain the power
equilibrium in the system, the BES is combined with the solar
PV energy conversion system. The P&O based voltage con-
trol method is implemented in the system to achieve maximum
power from the PV array with the high efficiency. As solar PV
array irradiation is varied from 1000 to 600 W/m\(^2\) there is a
decremental change in solar PV power \( P_{PV} \). But the value of
grid power \(P_g\) and load power \(P_L\) are fixed. Hence solar PV array is unable to fulfill the load demand, so that the deficient load power is supplied by the discharging of BES unit. The state of charge (SOC) of the BES controls within the defined limits (upper (80%) and lower (20%)). In this dynamic condition, the VSC control has maintained the power quality by containing the grid current sinusoidal and achieves power equilibrium in the system. Figure 13(a–b) show the \(P-V\) and \(I-V\) characteristics of the PV array at 1000 and 600 W/m², respectively.

### 4.4 Performance at grid outage condition

Figure 14(a–b) represent the dynamic performance of the PVBECS in mode transition from GCM to SAM. The grid voltage \(v_g\), grid phase angle \(\theta_g\), load phase angle \(\theta_L\) and load voltage \(v_L\) of the PVBECS are illustrated in Figure 14(a). In the GCM \(v_g\) and \(v_L\) are same in magnitude and its phase angles \(\theta_g\) and \(\theta_L\) are also synchronized. When the magnitude of \(v_g\) decreases below the set level, this interrupts the case 1 (from Equation (17)) that is \(V_t\) goes less than \(V_{tmin}\), the mode is shifted from the GCM to SAM. Thus, the synchronization signal \(S_z = 0\) goes to zero and the system starts working in SAM as demonstrated in Figure 14(b). The voltage control is used to maintain the \(v_L\) across the load in SAM. The grid angle \(\theta_g\) and load angle \(\theta_L\) are out of synchronism due to the grid disconnection now.

### 4.5 Performance at grid recovery

The dynamic performance of PVBECS in mode change from SAM to GCM is depicted in Figure 15. The waveform of grid voltage \(v_g\), load voltage \(v_L\), grid phase angle and load phase angle are presented in Figure 15(a). The system operates in SAM initially and as the grid is recovered back, the system commands to transfer its mode from SAM to GCM. For the grid reconnection, the phase minimization control is used to control the phase error between the load voltage and the grid voltage. Now, the phase error, \(\Delta\theta_{es}\) reduces near to zero by using a PI controller as illustrated in Figure 2. When all defining conditions as per Equation (15) are satisfied, \(S_z\) (synchronization signal) goes high \(S_z = 1\). At that instant, the system changes its mode.
from SAM to GCM and system starts operating in GCM. After the reconnection of the grid into the system, the grid current $i_g$ is reappeared as shown in Figure 15(c). The uninterpretable power is supplied to the load, which is connected to the system. This performance shows the effectiveness of the implemented control against the mode transition.

### 4.6 Performance at solar PV generation mode to active power filter mode

Figure 16(a) demonstrates the waveforms of PVBECS at sudden mode change from the PV array generation mode to APF mode. During moon time, the power of PV array goes to zero, while the utility grid appears, so the PV array coupled VSC performs as a shunt APF and retains the BES unit in floating mode. Therefore, the grid is always present to feed the power to the load in low or zero PV array insolation.

At zero irradiation, $I_{PV}$ is reduced to zero and sudden phase reversal of $i_g$ is observed. During the outage of PV array power, if the grid is also not present, the BES unit starts discharging to the supply the loads in the system. However, at regain of the utility, the load demand is supplied by the grid and BES unit stops discharging. Figure 16(b) depicts the response of PVBECS after reappearing the PV array power. Now the power demand of the load is shifted from the grid to the PV array. Due to it, the phase reversal of the grid current is occurred at mode transition as shown in Figure 16(b). In this situation, VSC performs the task of active power transfer along with reactive power compensation. The PV array is operated at MPPT point by using P&O algorithm. The power supplied to the load is continuous during this mode transition. Moreover, $V_{dc}$ is regulated at constant
FIGURE 16 System dynamic performance (a) PV-VSC mode to APF mode (b) APF mode to PV-VSC mode

value (360 V). In these mode transitions, the power quality of PVBECS is maintained within the IEEE 519 standard.

5 EFFECTIVENESS OF CONTROL

A control algorithm of PVBECS is developed in MATLAB/Simulink platform and simulation results are used to demonstrate the effectiveness of control at the distorted grid voltage and load disturbance conditions.

5.1 Performance of controller at grid voltage distortion and load disturbance

In Figure 17(a), the effectiveness of the control is presented by considering the voltage distortion in the source voltage, $v_g$, at 0.6 s. A MACNE based VSC control processes the grid voltage, $v_g$, and generates the pure sinusoidal in-phase and quadrature-phase voltage components ($v_{\alpha g}$ and $v_{\beta g}$) even under the presence of the voltage distortion. These components ($v_{\alpha g}$ and $v_{\beta g}$) are utilized in the estimation of unit templates ($u_{\alpha}$ and $u_{\beta}$ in

FIGURE 17 Simulated performance of the PVBECS under the distortion and of load variation
5.2 Performance of control algorithms at presence of DC-offset

Figure 18 demonstrates the comparative analysis of MACNE algorithm with SOGI-FLL, TOGI and frequency adaptive disturbance observer (FADO) controls based on the DC offset rejection. An offset is added in the grid voltage, \( v_\text{g} \) at 0.4 s, as shown in Figure 18. With MACNE algorithm control, the generated in-phase and quadrature phase components \( v_{\alpha g} \) and \( v_{\beta g} \) of \( v_\text{g} \) are sinusoidal as shown in Figure 18(a). The DC offset is eliminated from the grid voltage, \( v_\text{g} \) by using a MACNE algorithm. However, in the performance of SOGI-FLL, the DC offset is presented in the quadrature grid voltage \( v_{\beta g} \). From Figure 18(d), it shows that FADO also has not capability to remove DC-offset error. It reflects in the extracted in-phase and quadrature phase components \( v_{\alpha g} \) and \( v_{\beta g} \) of the grid voltage.

In comparison of SOGI-FLL and FADO, the TOGI removes the DC offset error from \( v_\text{g} \) as presented in Figure 18(d). The extracted in-phase and quadrature phase components \( v_{\alpha g} \) and \( v_{\beta g} \) are further used in the generation of unit templates. The Lissajous pattern of signals obtained from MACNE algorithm is presented to show the phase difference between the \( v_{\alpha g} \) and \( v_{\beta g} \) in Figure 19. This pattern consists of \( v_{\alpha g} \) on x-axis and \( v_{\beta g} \) on y-axis, respectively, which constitutes a circle of a constant radius on their plane that shows these signals \( v_{\alpha g} \) and \( v_{\beta g} \) are 90° phase shifted in the presence of DC-offset in the grid voltage.

5.3 Comparative steady of MACNE algorithm with other control algorithms

Figure 20 demonstrates a comparative analysis of MACNE algorithm with FADO, TOGI, SOGI-FLL, ACNE and LMF based control schemes at varying load condition. Performance of PVBECS is considered for both steady-state and dynamic
**FIGURE 20** Comparative results of MACNE algorithm with existing control algorithms

**TABLE 2** Comparison of various prevailing state-of-art control methods

| Control                  | Structure                        | Behaviour                                                                 | DC offset removal | Oscillation | Convergence rate | Amplitude tracking | Complexity |
|--------------------------|----------------------------------|---------------------------------------------------------------------------|-------------------|-------------|------------------|---------------------|------------|
| LMF                      | Adaptive filter                  | High oscillation present in the estimated amplitude of fundamental component | No                | High        | 0.025 s          | Poor                | Low        |
| SOGI-FLL                 | Generalized integrator           | Poor dynamic response and incapable to eliminate DC offset present in the input signal | No                | Medium      | 0.20 s           | Medium              | Low        |
| TOGI                     | Third order integrator           | Extracted amplitude contains fluctuations under the existence of DC offset | Yes               | Less        | 0.16 s           | Good                | Medium     |
| Frequency-adaptive disturbance observer (FADO) | Adaptive                        | Good dynamic performance, However, it requires additional quadrature signal generator/transformation for orthogonal signal generation in single phase application. This leads high complexity | No                | Less        | 0.16 s           | Good                | Medium     |
| ACNE                     | Adaptive                         | It has poor lower-order harmonics elimination capabilities under non-ideal condition | Yes               | high        | 0.018 s          | Medium              | Low        |
| Proposed control         | Multi structural adaptive observer | It has a better dynamic performance as better lower and higher order harmonics elimination and DC offset removal capability | Yes               | Less        | 0.012 s          | Better              | Medium     |
conditions. Figure 20 demonstrates the waveforms of the peak fundamental component of load current ($I_d$) and an error $e$ during disconnection and reconnection of load. Therefore, it is observed that the proposed MACNE Algorithm provides smooth and oscillation-free operation during the extraction of the fundamental component of load current. As and when the load is disconnected then oscillations and the error are observed in other control schemes during the estimation of fundamental component of the load current. Similarly, during load reconnection condition, due to the close convergence, performance of MACNE algorithm is detected to be better as compared to other controls. Table 2 depicts a comparative study of MACNE algorithm with existing control schemes. It clearly shows superior characteristics of MACNE algorithm with existing control schemes.

6 CONCLUSION

To maintain the power quality in PVBECS, the VSC control technique is an optimum solution that results in a pollution-free power at the end users. The effectiveness of the VSC control is validated on a developed prototype in the laboratory. The MACNE based current control is realized for the VSC to compute the reference current in GCM. The MACNE algorithm has also been used for harmonics mitigation, DC-offset rejection and for extraction of fundamental component of the grid voltage and the load current. Simulated performance validates the superiority of MACNE algorithm compared to other control methods. Test results have satisfactorily shown the effectiveness of the VSC control at load and grid-side perturbations. The BDC has maintained the DC link voltage constant by charging/discharging of BES. In standalone operating mode, the solar PV array coupled with BES supports the local loads, which has been validated from test results. The reliability of power equilibrium in the system is confirmed under adverse power generating situations. Under all operating conditions, the implemented VSC control is operating satisfactorily and it has maintained the grid current THD within the prescribed range i.e. $<$5%. Hence, PQ improvement is achieved in the system in accordance with the standard IEEE-519.

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APPENDIX A

Experimental parameters

Solar PV simulator-PV Power: 2.2 kW, PV voltage \((V_{PV}) = 300\) V and PV current \((I_{PV}) = 7\) A.

BDC parameter—\(K_{pv} = 0.12, K_{iv} = 0.02, K_{pi} = 0.08, K_{ii} = 0.01\) and inductor \(L_{db} = 2.5\) mH.

Battery rating—240 V, 42 Ah, \(SOC_{max} = 80\%\), \(SOC_{min} = 30\%\).

Grid side parameters—\(V_g = 220\) V and \(f_g = 50\) Hz.

Ripple filter \(= (R_{rf} = 5\) Ω; \(C_{rf} = 10\) μF).

Interfacing inductor: \(L_{db} = 4\) mH; \(f_{g_{min}} = 49.7\) Hz; \(f_{g_{max}} = 50.3\) Hz; \(V_{t_{max}} = 0.88\) pu V; \(V_{t_{max}} = 1.1\) pu; \(\theta_{min} = 2^\circ\); \(f_r = 2 \times \pi \times 50\)

VSC Rating: IGBT switch module (SKM200GB12T4): 200 A, 1200 V, \(V_{DC} = 360\) V and \(C_{dc} = 2200\) μF.

Controller parameters—MACNE Algorithm \(\xi = 0.7\) and \(\xi_1 = 50\); Mode selection algorithm- \(K^p = 0.03\) and \(K^i_1 = 0.002\).