A novel active current co-efficient extraction-based control for grid-tied solar photovoltaic system

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Abstract

In this paper, a novel active current co-efficient extraction (ACCE)-based control method is presented for a three-phase grid-interfaced voltage source inverter (VSI). Since the VSI performance largely depends on the reference current generation method, it is of significance to identify the active current co-efficient of the load current contaminated with harmonics, as it is a key governing factor that decides the shape of the compensating current. The proposed ACCE structure functions with minimal mathematical operators like product, sum, and integrators and thereby identifies the fundamental current with computational effectiveness. Besides, in comparison to existing prevalent state-of-the-art methods, the proposed ACCE structure is devoid of any low-pass filter and zero-crossing detector, and hence serves the following two distinctive purposes: (i) Ensures minimum steady-state oscillations and (ii) exhibits improved dynamic performance under disturbances in the grid and load. The proposed structure effectively confronts the various power quality challenges while injecting the active power into the utility grid. Further, the incremental-conductance-based maximum power point tracking algorithm is equipped to extract the maximum possible power from the photovoltaic array. Finally, the effectiveness of the proposed ACCE structure has been investigated through MATLAB/Simulink software studies followed by dSPACE-1104-based experimental setup.

1 | INTRODUCTION

The grid-interfaced voltage source inverter (VSI) together with the boost converter is capable of controlling the active power flow from solar photovoltaic (PV) towards the load as well as the grid if solar power is greater than the load demand. Additionally, the control algorithm of VSI can also be employed for multi-functionality operation like reactive power control, harmonic mitigation, power factor correction (PFC), and so forth [1]. The grid-interactive VSI operates as an active power filter (APF) and transfers the active power along with reactive power when the solar irradiance is available, whereas in the night time or when irradiance is zero, the VSI behaves as a power conditioning tool. Moreover, the integration of a solar PV system with the grid has several advantages like reduced burden on the grid and peak shaving, and so forth [2]. In this work, a double-stage grid-tied solar PV system is employed, which typically consists of incremental-conductance (InC)-based maximum power point tracking (MPPT) algorithm for DC-DC boost converter and active current co-efficient extraction (ACCE)-based control for three-phase VSI [3–5]. The double-stage system is very popular and highly reliable due to various reasons that are independent DC-link voltage control and isolation from the grid and so forth.

Effectively, a robust and precise control algorithm is also required for the smooth operation of the grid-interactive VSI. The main objective of this control algorithm is to inject the active and reactive power demanded by the load in presence of solar insolation and the remaining power if available is then supplied towards the grid. Further, if the solar PV power is not enough to fulfill the load demand, then the extra power is taken from the grid to serve the load requirement. Therefore, the following should be the responsibilities of the control algorithm: (1) DC-AC power conversion, (2) grid synchronisation, (3) power quality (PQ) improvement, (4) operate as power conditioner under zero irradiance, and (5) management of the...
power flow. Additionally, after completion of the overall process, the PQ issues of the main grid are resolved.

The control algorithms for VSI are several in numbers, in which some of the emerging algorithms are mentioned below: The fundamental current extraction-based control like orthogonal current decomposition control (OCDC) [6], leaky least-mean logarithmic fourth control [2], modified instantaneous symmetrical component theory [7], and improved generalised integrator-based control [8] has zero-crossing detector (ZCD) and low-pass filter (LPF) block-set along with a calculation of reactive current extraction block-set that introduces jitters and several complexities in the system. However, the proposed work has a calculation of the active current extraction that further improves the overall system complexity. Moreover, the control algorithm proposed in [9, 10] have LPF block-set, which further distorts the steady-state stability and creates more oscillation in the system.

This paper proposes a robust ACCE-based control, which is used for precise and fast detection of reference grid current. This algorithm is devoid of LPF, ZCD, and derivative term. As a result, the current estimation burden as well as the time taken to estimate the fundamental component of the current is relatively less. Moreover, for a high-frequency system, the ACCE control is highly suitable. The block diagram, mathematical expression, and description of the proposed ACCE control algorithm are presented in the following section.

Moreover, the effectiveness of the proposed ACCE control is first investigated by MATLAB/Simulink studies in the unbalanced, non-linear load case, and load perturbation case. Further, the merits of the ACCE is verified by hardware setup in a grid-to-load case and grid-to-load with VSI as a power conditioner, in which obtained hardware result fulfills the need of the proposed system and satisfies the IEEE-519 criteria. The main objectives and methodology of the proposed work are noted as follows:

1. A novel current controller based on the ACCE is devised to estimate the adequate reference grid current. The proposed ACCE structure is equipped with basic mathematical blocks to precisely identify the fundamental component of the load current contaminated with harmonics.
2. The proposed control algorithm is devoid of LPF, ZCD, and sample control and hold (SCH) in order to compute the compensating commands. Consequently, without any latency, the proposed control method extracts the fundamental component of the load current and ensures superior performance when exposed to perturbations in the grid voltage and load current.
3. The practicality and feasibility of the proposed ACCE structure are examined through dSPACE-1104-based laboratory setup under different operating scenarios.

This paper follows the given flow: Section 2 describes the system description of the presented system with controller uses. Section 3 provides the mathematical modelling, block diagram and description of the ACCE-based control algorithm. Section 4 presents the complete simulation approach of the proposed algorithm and presented system. In Section 5, the verification of simulation studies is investigated by hardware setup using dSPACE-1104. Finally, the conclusion of the presented work is shown followed by future work in Section 6.

### 2 SYSTEM DESCRIPTION

The complete schematic diagram of the dual-stage grid-tied solar PV system is depicted in Figure 1. Three-phase unbalanced, linear/non-linear loads are connected with the utility grid via a point of common coupling (PCC). Here, \( R_{Ga} \), \( L_{Ga} \), \( R_{Gb} \), \( L_{Gb} \), \( R_{Gc} \), and \( L_{Gc} \) are line resistances and line inductances of phases a, b, and c, respectively. Interfacing inductor \( L_{f}, L_{g} \) is used to interface the VSI to the PCC, which neglects the ripples from the grid current. A DC-DC boost converter is used to regulate the DC-link voltage. As proposed, the work is a double-stage grid-tied solar PV system, so the burden on ACCE will be less as compared to a single-stage solar PV system. The first stage is used to boost the PV voltage to the DC-link voltage level with the MPPT algorithm to extract the maximum power from the solar PV under adverse environmental conditions. Moreover, the second stage is used to transfer the solar power to PCC and for grid synchronisation. Additionally, the sensor circuit, amplification circuit, dSPACE-1104 controller, delay circuit and gate driver circuit is used for the overall operation. The dSPACE-1104 controller has very fast convergence capabilities with various ports like analog to digital converter (ADC), digital to analog converter, digital input/outputs (I/Os) master, slave I/Os pulse width modulation (PWM), Universal Asynchronous Receiver/Transmitter (UART), and so forth. The flexibility of dSPACE is further increased as this controller works in the MATLAB/Simulink environment [13].

### 3 CONTROL ALGORITHM

The design of this control algorithm having two different parts: InC-based MPPT algorithm for DC-DC basic boost converter and ACCE-based control for three-phase VSI. The InC-based MPPT algorithm is taken from [6], whereas the ACCE-based control is devised in this paper. The ACCE control has minimal mathematical block-set, so ACCE is a highly preferable control algorithm to implement for hardware setup.

First, the sensed line-to-line voltages \( V_{abc} \), \( V_{ab} \) helps to calculate the phase voltages of each phase \( V_{Gabc} \), which is further converted to terminal voltage \( V_{Gabcd} \) through bandpass filter (BPF). This phase voltage \( V_{Gabcd} \) is further used to calculate the unit template of each phase \( w_{pab}, w_{phb}, w_{phc} \). BPF is used to minimise the harmonics from the source voltage during voltage distortion/unbalance. The BPF is a mathematical operation of Clarke transformation, transfer function (TF), and Inverse Clarke transformation [14].

Additionally, unit templates \( w_{pab}, w_{phb}, w_{phc} \) along with three-phase sensed load currents \( i_{f,ab}, i_{f,bc}, i_{f,ca} \) are used to extract the...
co-efficient of respective active current ($i_{Lpa}$, $i_{Lpb}$, $i_{Lpc}$). Now, the total active current co-efficient gain ($i_{Lpabc}$) is calculated with the help of extracted active current co-efficient. Meanwhile, for DC-link voltage regulation, measured DC-link voltage ($V_{DC}$) is subtracted from reference DC-link voltage ($V_{DC*}$), which is further used to compute DC-link current gain ($i_D$). Further, the DC-link current gain and total active current co-efficient gain is used to calculate the reference current gain ($i_R$). Moreover, this reference current gain is multiplied with unit templates to generate reference grid current ($i_{Ga*}$, $i_{Gb*}$, $i_{Gc*}$) of the respective phase. However, gate pulses for VSI are generated with the help of the hysteresis current controller by comparing actual grid currents with reference currents. Extensively, the control algorithm is modified in such a way that the slow dynamic responses and steady-state oscillation of the overall system are mitigated.

Moreover, the control technique is simplified as the reactive current extraction is not required. In addition to that, ZCD and LPF are also eliminated from the control technique that further improves the PQ of the overall system. The complete flow of the proposed control algorithm is linked as unit templates calculation, active current co-efficient extraction, estimation of current gain component, and calculation of reference grid currents.

### 3.1 Unit templates calculation

The line-to-line voltages ($V_{ab}$, $V_{bc}$) sensed from PCC are first used to estimate the phase voltages of the grid ($V_{Ga}$, $V_{Gb}$, $V_{Gc}$) or ($V_{Gabc}$) as represented in Equation (1). Additionally, this grid
voltage passes through BPF to reduce the distortion present in
the voltage signal. The formula for Clarke transformation and
inverse Clarke transformation used in BPF is equated in Equa-
tions (2) and (3), respectively [15]:

\[
V_{Ga} = \frac{2V_{ab} + V_{bc}}{3}; \quad V_{Gb} = \frac{-V_{ab} - V_{bc}}{3};
\]

\[
V_G = \frac{-(V_{ab} - 2V_{bc})}{3};
\]

\[
V_G = \sqrt{\frac{2}{3}} \left[ V_{Ga} - \frac{1}{2} V_{Gb} - \frac{1}{2} V_G \right]; \quad V_G = \sqrt{\frac{I}{2}} \left[ V_{Gb} - V_{Ga} \right]
\]

\[
r_{Ga} = \sqrt{\frac{2}{3}} \left[ V_{Ga} \right]; \quad r_{Gb} = \sqrt{\frac{2}{3}} \left[ -\frac{1}{2} V_G + \sqrt{\frac{3}{2}} V_G \right];
\]

\[
r_{Gc} = \sqrt{\frac{2}{3}} \left[ -\frac{1}{2} V_G - \sqrt{\frac{3}{2}} V_G \right]
\]

Subsequently, the TF of a BPF is the same as mentioned in [14] and is given in Equation (4), where \( k = \sqrt{2} \times (2 \times n \times f) \times T_s \), \( f \) is grid frequency and \( T_s \) is a sampling period. Moreover, the amplitude of the voltage at PCC \((v_G)\) is calculated as given in Equation (5):

\[
T.F. = \frac{k(\zeta - 1)}{\zeta^2 + (k - 2) \times \zeta + \left( 1 - k + \frac{k^2}{2} \right)}
\]

\[
r_G = \sqrt{\frac{2}{3}} \left( r_{Ga}^2 + r_{Gb}^2 + r_{Gc}^2 \right)
\]

Further, phase voltages of the grid and amplitude of the PCC voltage are used to calculate the in-phase signal of the unit vector template \((w_{pa}, w_{pb}, w_{pc})\) as represented in Equation (6). Here, in this control algorithm, only the active component of the unit template is enough to extract the active current co-efficient:

\[
w_{pa} = \frac{r_{Ga}}{V_G}; \quad w_{pb} = \frac{r_{Gb}}{V_G}; \quad w_{pc} = \frac{r_{Gc}}{V_G}
\]

### 3.2 Active current co-efficient extraction

The concept of obtaining active current co-efficient \((i_{Lpa}, i_{Lpb}, i_{Lpc})\) is highlighted by grey colour and is applied after getting the unit templates \((w_{pa}, w_{pb}, w_{pc})\) along with the three-phase sensed load currents \((i_{Lpa}, i_{Lpb}, i_{Lpc})\) of each phase as shown in Figure 2.

The expression of active current co-efficient for the respective phases \((i_{Lpa}, i_{Lpb}, i_{Lpc})\) similar to OCDC [6] is represented in Equations (7) to (9). More specifically, Equation (7) is for phase ‘a’, Equation (8) is for phase ‘b’, and Equation (9) is for phase ‘c’. Moreover, the ACCE is better than OCDC because in this control algorithm, ZCD circuit, SCH circuit, and the reactive component for reference current generation are eliminated so that overall system complexity is reduced and the convergence time for generating gate pulse is minimised:

\[
i_{Lpa} = \frac{1}{n} \int_0^{n} (\dot{i}_{Lpa} \times w_{pa}) dt
\]

\[
i_{Lpb} = \frac{1}{n} \int_0^{n} (w_{pa} \times \dot{i}_{Lpb}) dt
\]

\[
i_{Lpc} = \frac{1}{n} \int_0^{n} (w_{pa} \times \dot{i}_{Lpc}) dt
\]

### 3.3 Estimation of current gain component

Now, the estimation of total active current co-efficient gain \((i_{Labc})\) is represented in Equation (10), which is a simple mathematical operation:

\[
i_{Labc} = \frac{i_{Lpa} + i_{Lpb} + i_{Lpc}}{3}
\]

Additionally, the estimation of DC gain \((i_D)\) is used to regulate the DC-link voltage at a particular given reference value as expressed in Equation (11). In Equation (11), ‘\(i_D(n+1)\)’ is the new value of the current gain, whereas ‘\(i_D(n)\)’ is the previous value of the current gain. Here, ‘\(k_{pd}\)’ is proportional constant and ‘\(k_{id}\)’ is an integral constant of the proportional-integral (PI) controller. The error in voltage \((V_e)\) is obtained after subtraction of sensed DC-link voltage \((V_{DC})\) from DC-link reference voltage \((V_{DC^*})\):

\[
i_D(n + 1) = i_D(n) + k_{pd}[V_e(n + 1) - V_e(n)] + k_{id}[V_e(n + 1) - V_e(n)];
\]

where \(V_e = V_{DC^*} - V_{DC}\)

### 3.4 Calculation of the reference grid current

Here, the calculation of the reference grid current \((i_{Ga^*}, i_{Gb^*}, i_{Gc^*})\) in the ACCE control algorithm only requires the active
TABLE 1 Simulation and hardware parameters of the adopted system

| Circuit parameters       | Simulation values (unit) | Hardware values (unit) |
|--------------------------|--------------------------|------------------------|
| Grid voltage (L-L)       | 415 V                    | 80 V                   |
| Grid frequency           | 50 Hz                    | 50 Hz                  |
| Grid impedance           | $R_{Ga} = 0.25 \, \Omega$ | $R_{Ga} = 0.05 \, \Omega$ |
|                          | $L_{Ga} = 0.5 \, \text{mH}$ | $L_{Ga} = 0.1 \, \text{mH}$ |
| Interfacing inductor     | 2.5 mH                   | 2.2 mH                 |
| Switching frequency      | 5 kHz                    | 5 kHz                  |
| DC filter capacitor ($C_d$) | 3000 $\mu$F            | 4700 $\mu$F            |
| DC link voltage ($V_{DC}$) | 735 V                    | 130 V                  |
| Switching frequency of boost converter | 10 kHz                  | 10 kHz                 |
| Inductor for boost       | 4 mH                     | 5 mH                   |
| Solar photovoltaic (PV) voltage ($V_{PV}$) | 360 V                    | 60 V                   |
| 3-$\phi$ rectifier load | $R_L = 25 \, \Omega$     | $R_L = 17 \, \Omega$   |
|                          | $L_L = 50 \, \text{mH}$  | $L_L = 80 \, \text{mH}$ |
| 1-$\phi$ rectifier load | $R_L = 80 \, \Omega$     | NIL                    |
|                          | $L_L = 70 \, \text{mH}$  |                        |

component of the current and unit template as represented in Equation (13). Therefore, reference grid currents are estimated after multiplying the unit template of the respective phase with reference current gain. Finally, estimated reference grid current, as well as sensed grid current ($i_{Ga}$, $i_{Gb}$, $i_{Gc}$) are compared to obtain the error, which further passes through a hysteresis band of ± 0.02 for generating the high-frequency switching gate pulse for upper switches of every leg of the three-phase VSI. Additionally, the switching gate pulses for lower switches of three-phase VSI are obtained by using the NOT-gate as shown in Figure 2:

$$
\begin{align*}
    i_{Ga}^* &= i_R \times W_{pa}; \\
    i_{Gb}^* &= i_R \times W_{pb}; \\
    i_{Gc}^* &= i_R \times W_{pc}
\end{align*}
$$

(13)

4 | SIMULATION APPROACH

The MATLAB/Simulink studies are presented in this section. The simulation results are described in six case studies in which case study-I is for non-linear and unbalanced load, case study-II is for load perturbation, case study-III is for change in irradiance, case study-IV is for comparison study, case study-V is for voltage distortion/unbalance scheme, and case study-VI is conducted under exposure to sudden voltage deviations. The simulation parameters used in this proposed work is given in Table 1. The responses of the simulation system are presented by the three-phase grid voltage ($V_{abc}$), three-phase grid current ($I_{abc}$), three-phase load current ($I_{Labc}$), inverter current ($I_{L}$) of phase ‘a’, DC-link voltage ($V_{DC}$), active power by the grid and solar PV, reactive power of grid ($Q_G$), and power factor (PF). Further, the fast Fourier transform (FFT) analysis of the given signal is observed for verification. Finally, the response of reference current gain ($i_R$) versus time (s) is obtained for showing the comparison between several control algorithms that are discussed in the respective case study.

4.1 | Case study-I: Non-linear and unbalanced load

In this case study, the response of the proposed system is illustrated for time $t = 0.0-0.3$ s as shown in Figure 3 where for 0.0–0.1 s, the grid is used to feed the load so as the grid current is inclusive of harmonics during this period. In the next period 0.1–0.2 s, the inverter is used as a power conditioner to filter out the harmonics from the source current, as VSI is injecting only the reactive power in this period. Further, from 0.2 to 0.3 s, the VSI is used for injecting the reactive power as well as the active power. The reactive power is produced by the VSI and DC-link capacitor, whereas the active power is generated through solar PV with the MPPT technique so that the maximum power is harvested from the PV arrays. Shifting from normal to power conditioning operation is shown by the dotted line at 0.1 s, whereas shifting from power conditioning operation to VSI as APF operation is shown by the dashed line at 0.2 s. Moreover, for the unbalanced load, a single-phase rectifier with non-linear load is connected to two terminals of the three-phase system.

Further, the FFT analysis of the grid current is observed for different conditions during 0.0–0.3 s in which the first case is for normal condition (grid and load) during 0.02–0.08 s as shown in Figure 4, whereas the second case during 0.12–0.18 s is obtained for the VSI as power conditioner as shown in Figure 5. The total harmonic distortion (THD) for both cases are noted as 22.60% and 2.23%, respectively.
**FIGURE 4** Fast Fourier transform (FFT) analysis of grid current phase ‘$a$’ during time 0.02–0.08 s

**FIGURE 5** FFT analysis of grid current phase ‘$a$’ during time 0.12–0.18 s
In theoretical, the THD of three-phase non-linear (three-phase diode bridge rectifier) load is given as 31% as in [16] for resistive-inductive (RL) load. In this work, the THD is measured as 22.60% for an inductive load of 50 mH and a resistive load of 25 Ω. The FFT analysis shows the presence of sub-harmonics in the graph, which is due to the load unbalancing and load non-linearity. The even harmonics are present due to load unbalancing, whereas the presence of odd harmonics is due to non-linear load.

4.2 Case study-II: Load perturbation

The study shown in Figure 6 confirms the improved response of the proposed control during the load perturbation. For the period 0.3–0.4 s, the load current, as well as the grid current, is more but at the instant of 0.4 s; the load is perturbed so the load current and grid current is low from 0.4 to 0.5 s; whereas at instant 0.5 s, again the load is perturbing to the normal one, which is shown from 0.5 to 0.6 s. The perturbation from high to low load is shown by the dotted line at 0.4 s, whereas perturbation from low to normal load is shown by the dashed line at instant 0.5 s. The DC-link voltage ($V_{DC}$) is obtained nearly constant during the load perturbation [17], whereas active power (kW) obtained from the grid is decreased at 0.4 s and increased at 0.5 s.

4.3 Case study-III: Change in solar irradiance

This case study presents the response of the system during change in the solar insolation. The solar irradiance changing time to time corresponds to an atmospheric condition of the sun, partial shading on the solar PV array, and so forth [18]. So the change in solar irradiance affects the decrease of solar PV power ($P_{PV}$) due to the reduction in the PV current. Simultaneously, the active power supplied by the grid ($P_{G}$) increases according to the load demand. The case study for verification of change in solar irradiance is simulated from 0.6 to 0.9 s as shown in Figure 7.

The response of solar PV power is shown by blue colour, whereas the response of the grid active power is shown by red colour in the active power (kW) block of Figure 7. The change in solar irradiance is placed at an instant of 0.7 s from 1000 to 400 W/m² shown by a dotted line. Whereas at the instant of 0.8 s
again, solar irradiance is varied from 400 to 1000 W/m² shown by the dashed line. The DC-link voltage is obtained approximately constant during a change in solar irradiance and clearly stated through the response, and there is a slightly small oscillation during a change in reactive power ($Q_G$) and PF. The other responses of change in a solar irradiance case study are identical during the simulation period.

4.4 Case study-IV: A comparison study

In this section, a comparison study between different conventional control, algorithms are investigated with the proposed ACCE control technique. The comparison study for this control algorithm is verified only during a change in solar irradiance due to the presence of more dynamic response and oscillations. To investigate this case study, weight component from two conventional control algorithms like synchronous reference frame theory [18, 19] and harmonics, and HRCCD [12] along with the proposed ACCE were extracted as shown in Figure 8. The solar irradiance is changed from 1000 to 400 W/m² at 0.7 s, whereas at 0.8 s, it is changed from 400 to 1000 W/m² shown by the dotted and dashed lines, respectively. Corresponding to the change in solar irradiance, the extracted weight component should be updated instantly for better performance, but in several control algorithms, extracted weight component was in ramp or parabola shape rather than an instant change. So the shown responses stated clearly that the proposed ACCE has better performance than the conventional current extraction-based control algorithms.

4.5 Case study-V: Under grid voltage distortion

In this case study, the effectiveness of the proposed control scheme is analysed for the voltage distortion scheme. For voltage distortion/unbalance, two voltage sources of small value (1.05 and 1.1 p.u.) are added in series with the grid voltage, also fifth- and seventh-order harmonics are introduced in the system. The distortion/unbalance in voltage is shown as $V_{abc}$ (V) in Figure 9. It is visible from the response that the
distortion/unbalance is available in the three-phase grid voltage ($V_{Gabc}$). The results are captured for 0 to 0.3 s where for 0 to 0.1 s, the grid is used to feed the load so the grid current is inclusive of harmonics during this period. In the next period of 0.1 to 0.2 s, the inverter is used as a power conditioner to filter out the harmonics from the source current, as VSI is injecting only the reactive power in this period. Further, from 0.2 to 0.3 s, the VSI is used for injecting the reactive power as well as the active power at PCC. Voltage distortion/unbalance can be filtered out from the grid current ($I_{Gabc}$) with the use of
FIGURE 10 Simulation result under sudden voltage deviations

BPF in the proposed control technique, and the explanation of BPF is discussed in the previous section. Further, responses to this scheme state that the proposed control algorithm is suitable with voltage distortion/unbalance scheme.

4.6 Case study-VI: Under sudden voltage deviations

The case study shown in Figure 10 is to analyse the effectiveness of the proposed control algorithm under sudden voltage deviations. In practice, it shows the capability of the control algorithm to respond satisfactorily during sag and swell in the voltage profile. For this analysis, a programmable voltage source is taken and for a fixed time duration, the magnitude of the voltage is reduced to 0.8 p.u. from the original voltage level and again raised to 1.2 p.u. from the default voltage condition. The change in the grid voltage is shown from the voltage block ($V_{abc}$) from 0.9 to 1.4 s. The decrement in voltage is shown at 1.0 s and again normal at 1.1 s, whereas increment in the voltage is shown at 1.2 s and again normal at 1.3 s.

Moreover, change in the three-phase grid current is visible according to the increment and decrement in the three-phase grid voltage. Further, the DC-link voltage shows minor oscillation despite decrement and increment in the three-phase grid voltage. Finally, it is analysed that the proposed control algorithm is effective under sudden voltage sag and swell.

Further, Table 2 considers the comparative analysis between the conventional control algorithm and the proposed control technique. Various features are listed for comparison, which are presented in tabular form with detailed explanation. The common and essential features related to this research work are THD, sampling time, number of LPFs, calculation work, the method used for the grid synchronisation, and so forth. So from the presented comparative analysis, it is concluded that the proposed ACCE control technique is suitable for the grid-tied solar PV system.

The simulation results can be concluded here that the proposed ACCE control technique is working properly with satisfactory results. It also provides a better dynamic response under instant change or transient situation with less computational work. Therefore, from the conclusion, it is clear that
## TABLE 2  Comparative analysis

| Features                                      | Synchronous reference frame (SRF) [20] | Reactive current component detection and character of triangle function (CTF) [12, 21] | Orthogonal current decomposition contro [6] | Proposed active current co-efficient extraction |
|-----------------------------------------------|----------------------------------------|--------------------------------------------------------------------------------------|-----------------------------------------------|------------------------------------------------|
| Total harmonic distortion (THD; %) in grid current | 4.17%                                  | 3.20%                                                                                | 2.35%                                         | 2.23%                                          |
| Sampling time                                 | 55 µs                                  | 40 µs                                                                                | 35 µs                                         | 30 µs                                          |
| Filter used                                   | 2 low-pass filter (LPF)                | 6 LPF                                                                                | No LPF                                        | No LPF                                         |
| Precision                                     | Low                                    | Moderate                                                                             | High                                          | High                                           |
| Complication                                  | High                                   | High                                                                                 | Moderate                                      | Low                                           |
| Calculation work                              | More                                   | More                                                                                 | Less                                          | Very less                                      |
| Grid synchronisation method                   | SRF-based phase locked loop (PLL)     | Unit vector template                                                                  | Unit vector template                          | Unit vector template                           |
| Use of grid voltage                           | Ideal only                             | Ideal and non-ideal                                                                  | Ideal and non-ideal                           | Ideal and non-ideal                           |
| Strengths                                     | Easy control                           | PLL-less control                                                                     | PLL-less control with fast dynamic response   | PLL-less control with very-fast dynamic response |
| Weaknesses                                    | Work with PLL, passive filter and non-uniform criteria creates delay                  | Uses of various numeric filter that creates time delay, complex current detection algorithm | Active and reactive current detection algorithm creates time delay | Integrator is used that should be handled delicately while hardware work |

the proposed ACCE can be utilised for multifunctional grid-tied VSI for serving the functions of power conditioning, active power injection, reactive power compensation, load balancing, harmonic mitigation, and PFC.

## 5  HARDWARE APPROACH

A down-scaled hardware prototype study of the proposed system is taken to match the simulation results using dSPACE-1104 controller. The multi-functional three-phase VSI uses a three-power insulated-gate bipolar transistor (IGBT) module, and for the DC-DC boost converter, a module of IGBT with an inbuilt power diode is used [21]. These power modules are operating on a high power-rating, having less conduction loss, high switching frequency, and highly effective for hardware. Each IGBTs are connected with the snubber circuit, gate driver circuit, and delay circuit. A snubber circuit is used for \( \frac{dv}{dt} \) protection, while a gate driver circuit is used for amplification and isolation determination; a delay circuit is used to protect IGBTs from short-through [22].

Additionally, dSPACE-1104 controller, three-phase grid, grid impedance, interfacing inductor, DC-link capacitor, LEM-make sensor card, and three-phase uncontrolled rectifier with variable RL load are used to realise the overall grid-interfaced PV system. The dSPACE controller is used for providing the accurate switching gate pulses for the VSI and DC-DC boost converter. For the need of the three-phase grid, a three-phase autotransformer is used to supply the load and DC-link capacitor through VSI to get charged during the night when solar irradiance is zero. The interfacing inductor is used to interface the three-phase VSI with the grid. The DC-link capacitor is used to provide the demand for the reactive power and filtering the voltage ripple from the output of the boost converter. LEM-make sensor card having ‘Hall effect’ current and voltage transducers are used to sense the required signal for better operation of the control algorithm in a closed loop. Moreover, the sensed value is provided to the dSPACE controller for further operation of the control algorithm. The three-phase uncontrolled rectifier with variable RL load is used to realise the effect of non-linear load in the system. It also helps to investigate the overall system performance under non-linear loading [23]. The overall hardware parameters of the presented system for the proposed ACCE control algorithm is given in Table 1.

Further, the proposed ACCE control algorithm is developed in MATLAB/Simulink environment along with real-time interface (RTI) block-set of dSPACE-1104 controller. Moreover, for measuring the experimental results ‘Tektronix’-make digital storage oscilloscope (DSO) is used, which has four channels for measurement. Additionally, the power measurement facility and harmonic analysis option are available in this DSO. Moreover, the steady-state performance of the proposed ACCE control approach is verified with the help of results having grid voltage of phase ‘a’ \((V_{Ga})\), grid current of phase ‘a’ \((I_{Ga})\), load current of phase ‘a’ \((I_{La})\), inverter compensating current of phase ‘a’ \((I_{Ia})\), DC-link voltage \((V_{DC})\), and power of grid \((P_{Ga})\). Besides, the reactive power of the grid \((Q_{G})\), the true PF of the grid (PF), and the phase angle between the grid voltage and current are also termed in these results. Now, from the results, it is observed that the hardware results are almost equivalent to simulation results.
The hardware results are shown in different sub-sections as different case studies to differentiate the operation and working of the proposed control algorithm.

5.1 Steady-state performance analysis

The steady-state performance analysis is shown in this section for non-linear load where Figure 11(a) shows the hardware results for normal case (grid and non-linear load is connected during this time) that is without compensation. Here, the grid voltage of phase ‘a’ ($V_{Ga}$) is sinusoidal, the grid current of phase ‘a’ ($I_{Ga}$) and load current of phase ‘a’ ($I_{La}$) are the same because of zero compensation current at this time. Further, immediately after switching on the VSI, the grid current of phase ‘a’ ($I_{Ga}$) turns out to be sinusoidal as shown in Figure 11(b). The inverter compensating current of phase ‘a’ ($I_{Ia}$) shows some compensation current. Here, the three-phase VSI works as a power conditioner. Additionally, Figure 11(c) shows the unity PF by showing grid voltage and current in the same altitude, whereas the load current and inverter compensating current are the same. Moreover, the stability of the DC-link voltage is shown in (CH4) of Figure 11(d) where the DC-link voltage is always constant during the operation of three-phase VSI with the proposed control technique.

5.2 Dynamic performance analysis

The proposed ACCE controller is further taken to analyse the dynamic performance during a sudden change of the load or load perturbation (increment and decrement). The increment and decrement of the load correspond to the change of load current as well as grid current. For analysing the sudden change of the load, the response of DC-link voltage ($V_{DC}$) is taken into account along with the grid current ($I_{Ga}$) and the load current ($I_{La}$). Here, the DC-link voltage shows a small disturbance at the instant of the load perturbation, then immediately regulates to the predefined DC-link value as shown in Figures 12 (a) to (d).

5.3 Power flow management

The management of power flow is necessary to control the injection of the PV power into the grid as well to fulfil the demand of the active and reactive power by the non-linear load. Effectively, the active power demand of load (159 W/phase) is fully taken by the main grid, whereas the reactive power demand of load (42.1 VAr/phase) is compensated by three-phase VSI to (22.5 VAr/phase) and further supplied by the grid as shown in Figures 13(a) and (b). Further, the PF between the grid volt-
5.4 Harmonic mitigation capability

Hardware result with harmonic spectral analysis of the grid current of phase ‘a’ ($I_{ga}$) during the normal case (grid and current is corrected from 0.90 to 0.99. In Figure 13(a), results before compensation with power measurement is shown, whereas results during grid current compensation along with power measurement are shown in Figure 13(b).
Hardware comparison study showing grid current of phase ‘a’ (IGa) in CH2, load current of phase ‘a’ (ILa) in CH3, DC-link voltage (VDC) in CH4: (a) reactive current component detection control algorithm, and (b) proposed ACCE control technique.

**TABLE 3** Summary of obtained results

| Circuit elements                        | Obtained results for three-phase system |
|-----------------------------------------|----------------------------------------|
| Grid voltage along with THD             | 80 V, 2.8%                             |
| (VGa, VGb, VGc)                         |                                        |
| Grid current along with THD             | Phase ‘a’ - 3.137 A, 3.71%             |
| (IGa, IGb, IGc)                         | Phase ‘b’ - 3.131 A, 3.68%             |
| Load current along with THD             | Phase ‘c’ - 3.144 A, 3.73%             |
| (ILa, ILb, ILc)                         |                                        |
| Compensating current by                 | Phase ‘a’ - 1.24 A,                   |
| voltage source inverter (VSI)           | Phase ‘b’ - 1.23 A,                   |
| (IIa, IIb, IIc)                         | Phase ‘c’ - 1.25 A                    |
| Per phase power (normal case)           | 159 W, 42.1 VAr                       |
| Power factor (PF; normal case)          | 0.906                                  |
| (VSI with proposed control)             |                                        |
| PF                                      | 0.990                                  |
| The voltage level at DC link            | 130 V                                  |

Further, this section shows the hardware comparison study between the conventional current extractions-based control like HRCCD and the proposed ACCE control technique. It is already known that the hardware implementation for HRCCD control algorithm is difficult due to more computational work. In addition to that, the hardware results show more oscillations in the responses.

The comparison study of both control algorithms is verified during load perturbation with sudden change so that it shows dynamic response and oscillations during change. From Figure 15(a), it is clear that the HRCCD control have more oscillations in the grid current than the proposed ACCE control of Figure 15(b). The load current profiles in both cases are the same. On the other hand, the DC-link voltage of HRCCD has less transient response than the proposed ACCE. Therefore, from the hardware comparison study, it is justified that the proposed ACCE control is more suitable for the grid-tied solar PV system.

5.5 Hardware comparison study

5.6 Under utility grid voltage disturbances

In this section, the effectiveness of the proposed control algorithm is analysed with distortions in the grid voltage. The distortion in the grid voltage is shown in Figures 16(a) and (b). Figure 16(a) shows the sinusoidal grid current even during the voltage distortions. Besides, the load current is the same, and the inverter compensating current have some change in the response, which is clearly visible from Figure 16(a). This is mainly to compensate for the effect of voltage distortion from the system. In Figure 16(b), the DC-link voltage is shown along with the inverter compensating current, grid current, and voltage distortion. The DC-link voltage is stable during the voltage distortion response as witnessed in Figure 16(b).

5.7 Performance under voltage sag and swell

In this case, the response of the proposed control algorithm is confirmed under sudden voltage sag and swell. The corresponding experimental results are illustrated in Figures 17(a) and (b). Following the sudden voltage sag, swell, the grid, load current...
FIGURE 15  Hardware results with harmonic analysis for grid current of phase 'a' (I_Ga): (a) Before VSI operation, and (b) VSI with a proposed ACCE control technique

FIGURE 16  Hardware results for the voltage distortion scheme: (a) V_Ga in CH1 (50.0 V), I_Ga in CH2 (5.00 A), I_La in CH3 (5.00 A), and I_L in CH4 (5.00 A), and (b) V_Ga in CH1 (50.0 V), I_Ga in CH2 (5.00 A), I_L in CH3 (5.00 A), and V_DC in CH4 (50.0 V)

FIGURE 17  Hardware results under voltage sag scheme showing grid voltage of phase 'a' (V_Ga) in CH1 (50.0 V), grid current of phase 'a' (I_Ga) in CH2 (1.00 A), load current of phase 'a' (I_La) in CH3 (5.00 A), and DC-link voltage (V_DC) in CH4 (50.0 V): (a) Voltage reduced to 0.8 p.u. from normal three-phase grid voltage (1 p.u.) and (b) voltage from 0.8 p.u. to normal three-phase grid voltage (1 p.u.)
magnitude changes and reach to a new level corresponding to the grid voltage. Besides, the DC-link voltage is kept constant to its reference value of 130 V under the voltage change confirming the merits of the proposed controller.

6 | CONCLUSION

In this work, the ACCE control algorithm is used for extracting the active current co-efficient to generate the reference grid currents for a three-phase grid-interfaced VSI-based PV system. The performance of steady-state condition and transient behaviour of the presented system are also investigated. Moreover, several MATLAB/Simulink results and hardware results are also given to show the operation of VSI as an APF. Additionally, the power-sharing results along with the load perturbation are shown with simulation results. Further, it is also clearly stated that the grid current is in phase with the grid voltage and approximately free from harmonics when VSI works as an APF or power conditioner. The solar PV power injection to the PCC stated the active power transfer capability of three-phase VSI. Effectively, the THD value of grid current is under 5% and satisfies the IEEE-519 criteria. Mathematical modelling for the ACCE control algorithm is represented, which further shows the reliability of the proposed system. Finally, from the study, it is clear that the computation speed of the proposed control is very fast, highly balanced, trustworthy, and helpful to solve various PQ issues.

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