An Improved Adaptive Control Strategy in Grid-Tied PV System with Active Power Filter for Power Quality Enhancement

Babu, Narendra P.; Guerrero, Josep M.; Siano, Pierluigi; Peesapati, Rangababu; Panda, Gayadhar

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An Improved Adaptive Control Strategy in Grid-Tied PV System With Active Power Filter for Power Quality Enhancement

Narendra Babu P, Josep M. Guerrero, Fellow, IEEE, Pierluigi Siano, Senior Member, IEEE, Rangababu Peesapati, Member, IEEE, and Gayadhar Panda, Senior Member, IEEE

Abstract—This article investigates the power quality enhancement of a grid-tied photovoltaic (PV) distribution system by employing a fuzzy logic proportional–integrator–derivative multiple complex coefficient filter multiple second-order generalized integrator frequency-locked loop (FLPID-MCCF-MSOGI-FLL) hybrid control scheme based shunt active power filter. The MSOGI-FLL reference current generation strategy is implemented to mitigate the current harmonics by extracting the fundamental constituents (FCs) from the nonlinear load currents, whereas an MCCF is employed to separate the FC from the distorted grid voltages and eliminates the voltage harmonics during extremely polluted grid voltage condition. The main objective of using FLPID is to maintain the stable power between dc and ac sides by regulating the dc-link voltage constant under transient conditions. To track the maximum power from the PV panel under varying environmental condition, the particle swarm optimization based perturb and observe technique is used in this article. The comparative analysis is analyzed to check the effectiveness of the proposed hybrid control scheme with existing and adaptive control techniques in respect of power quality, better dc offset rejection, better FC and frequency extraction, and grid synchronization. The system with the proposed control scheme is simulated on MATLAB/Simulink and validated in a real-time field-programmable gate array platform under different test scenarios. In conclusion, the harmonic content of grid currents and voltages is found well within the IEEE-519 standard limits.

Index Terms—Active power filter (APF), fuzzy logic proportional–integrator–derivative (FLPID), maximum power point tracking (MPPT), multiple complex coefficient filter (MCCF), multiple second-order generalized integrator frequency-locked loop (MSOGI-FLL), particle swarm optimization (PSO), perturb and observe, photovoltaic (PV) system, power quality, total harmonic distortion (THD).

I. INTRODUCTION

INCREASING the power quality in a distribution network through the use of an advanced control has gained a lot of interest among power electronics/power system research community. Electrical distribution side is getting polluted due to increased proliferation of power electronics based household, commercial, as well as industrial nonlinear loads. These nonlinear loads feed harmonic currents leading to increased loss, harmonics, and voltage distortion, which in turn severely influence the quality of power and stability [1]. Traditionally passive filters have been employed to figure out the problems but at the cost, tuning and series-parallel resonance problem [2]. Thus to avoid these problems, active power filters (APFs) and moreover shunt types have been widely used as a viable solution [3]. Recently, power quality issues in the grid-tied system have been addressed by the use of more advanced APF technology [4], [5].

Along with the power quality improvement, pollution-free clean energy production is another key matter of concern. In this regard, integration of renewable energy sources such as photovoltaic (PV), and wind energy to grid-connected and a standalone system is growing exponentially. Solar PV power is pollution-free power generating resource widely used to meet the energy demand, which improves the reliability and power quality while reducing the burden on the central grid [6], [7]. With the decrease in manufacturing cost of the solar PV system, rooftop PV systems are also utilized in small-scale applications [8]–[13].

System performance can be improved through the injection of active and reactive components to it by implementing a suitable control strategy for the grid-tied APFs. Over the last two decades, several control topologies such as instantaneous reactive power [pq] theory [5], Fryze current compensation technique [6], synchronous reference frame (SRF) [7], and neural network (NN) technique [8] have been proposed for the elevation of quality power in grid-tied systems. However, the above control approaches have some drawbacks, such as pq theory has deficient performance in the existence of unbalance and distorted grid voltage conditions, and Fryze theory has inadequate performance during grid transient conditions. Due to low-pass filter (LPF), aggressive behavior of the system is deteriorated in the strategy of reference current generation evaluation in the SRF technique. In the neural network techniques, to find the
proper learning is tough. The above-mentioned controllers are well developed and well implemented by simulation as well as experimental. In order to defeat the above disadvantages, several control techniques have been proposed for the power quality improvement in grid interfacing systems such as extended Kalman filter [14], wavelet transform [15], and discrete-Fourier transform [16]. The drawback of the above controllers is by varying the system frequency, the system performance is affected by losing accuracy of the control. Besides these control techniques, several adaptive control techniques have been evolved in recent years, such as least mean fourth (LMF) [17], notch filter and variable step size least mean square (VLMS) [18]. The VLMS and LMF control scenarios have inadequate steady-state performance because of the low convergence rate. The notch filter is hard to execute in practical applications because of its ideal manners of magnitude and phase response. The improved linear sinusoidal tracer (ILST) control technique has inappropriate steady-state performance because of LPF.

To avoid the shortcomings, few adaptive reference current generation techniques have been implemented for grid-tied renewable energy systems. Considering the voltage distortion and unbalance grid conditions, pure sinusoidal signals injection into the utility grid is necessary. Therefore, the fundamental constituent (FC) separation is required under grid abnormal conditions. In [19], Gude and Chu discussed the mitigation of multiple delayed signals by employing prefilters under unfavorable grid conditions. In [20], Chilipi et al. discussed multipurpose control scheme based on an adaptive notch filter for grid interfaced inverter. In [21], Li et al. discussed complex vector filter in three-phase grid synchronization systems. Although, the above controllers are failed to separate the fundamental constituent (FC) if considering the dc component and interharmonics in signal. To defeat the above disadvantages, few adaptive control topologies have been introduced in cited work as third-order filter, second-order generalized integrator (SOGI), dual SOGI (DSOGI) [22], second-order SOGI (SO-SOGI) [23], and improved SOGI (ISOGI) [24]. The above controllers are suitable for dc offset rejection; however, if considering the lower frequency dc offset rejection, the performance of the controllers is compromised. In [25], Xiaqiang et al. proposed a multiple complex coefficient filter (MCCF)-based PLL control algorithm under polluted and unbalanced grid voltage conditions. In [26], Prakash et al. proposed an MCCF-SOGI-based control topology for current and voltage harmonic rejection. This controller has been employed to separate the FCs from extremely polluted grid voltages and load currents. In [27], Rodriguez et al. proposed a multiresonant frequency adaptive synchronization method for grid-connected converter control under grid voltage polluted and unbalanced conditions. The above controllers have been implemented for grid synchronization, frequency variation conditions. However, they have not been considered dc offset rejection and both current and voltage harmonic rejection. Moreover, they have been used existing PI controller to regulating the dc bus voltage. The behavior of the existing PI control method has not acceptable under grid and load transient conditions. In [28]–[32], an adaptive fuzzy-neural fractional-order-based terminal sliding controller, fuzzy super twisting sliding mode control, self-controlled double hidden layer (DHL) output feedback NN, full-controlled NN with a DHL recurrent neural network (RNN), and adaptive dynamic terminal sliding mode controller using a DHL–RNN to control the microgyroscope and grid-tied inverter are proposed. However, these control schemes have been implemented for the quality of power enrichment. The drawbacks of the above control schemes are not suitable for fundamental component extraction of the load currents and grid voltages, grid synchronization, and dc offset rejection. Moreover, they are not considered the renewable power generation system applications.

To bypass the cited work limitations, an adaptive hybrid control technique is employed based on the reference current generator, fundamental constituent extraction (FCE) of distorted grid voltages and dc-link bus controller. The multiple second-order generalized integrator frequency-locked loop (MSOGI-FLL) control scheme is executed to separate the FCs from three-phase load currents. Additionally, an MCCF is executed to take out the FCs from the extremely deformed grid voltages. Moreover, it is also used for grid synchronization. In addition, fuzzy tuned proportional–integral–differential (PID) adaptive dc-link voltage controller is absorbed in the suggested control scheme to keeping the balanced power between dc and ac sides by regulating the dc bus voltage constant. The two-stage PV dc–dc power conversion using hybrid P&O combined with particle swarm optimization (PSO)-based MPPT algorithm is adopted to extract the available peak PV power [33]. The hybrid MPP algorithm is executed in view of obtaining accurate global power tracking performance under varying irradiance conditions. The proposed hybrid control algorithm incorporates an adaptive frequency control topology, which is used to estimate the system frequency under varying frequency condition. Improved flexibility, adaptive in nature, easy implementation, optimal switching operation of inverter to get swift, and low computational burden are the few remarkable advantages of the proposed control technique. The hybrid control algorithm is examined under several test cases, such as balanced, unbalanced, polluted grid voltages, load removed, dynamic load and varying irradiation levels. The results obtained from simulation are further validated experimentally in the laboratory designed prototype using Virtex-7 VC707 controller. Distinctive characteristics of the proposed article are as follows.

1) The MSOGI-FLL reference current generation strategy is implemented to mitigate the current harmonics by extracting the FC from the nonlinear load currents.
2) The MCCF, as an ideal filter not imposing any delay in the system, is employed to separate the FCs from the extremely polluted grid voltages. Moreover, it is also used for grid synchronization.
3) A fuzzy tuned PID adaptive dc-link control algorithm is included in the control scheme to preserve the balanced power between dc and ac terminals by keeping the dc terminal voltage constant.
4) The feedforward constituent of the PV system is also included in the control scheme, which improves the system dynamic performance by minimizing oscillations during the dynamic load condition, as well as irradiation changing conditions.
Fig. 1. Proposed system’s schematic diagram.

5) Compared to the proposed control scheme with conventional control schemes performs very well in terms of harmonic mitigation, dc offset rejection, fundamental component extraction, and grid synchronization.

6) The proposed control algorithm is well suitable to mitigate the current and voltage harmonics from the extremely polluted load current and grid voltages, better dc offset rejection and grid synchronization.

II. SYSTEM DESCRIPTION

Fig. 1 shows the proposed schematic diagram for PV integrated grid system. The proposed system has three-phase utility grid, which is connected to nonlinear, linear, and domestic loads. The PV systems are connected to utility grid via boost converter and voltage source inverter (VSI). The hybrid MPP technique is used to generate pulsewidth modulation (PWM) signal to boost converter to improve the voltage profile of the PV system. The fuzzy logic proportional–integrator–derivative (FLPID) feedback controller is used to maintain dc bus voltage at its reference voltage [10], [24], [34]. The MSOGI-QSG-PLL control scheme is employed to compute the three-phase reference currents. The block diagram of the complex coefficient filter (CCF) is shown in Fig. 2. The MCCF is designed to separate the FCs from extremely polluted grid voltages and it is tuned to 50 Hz fundamental frequency, which is worked on converted voltages (V_{saβ}). The MCCF is used to eliminate harmonics as well as negative sequence constituents from the highly distorted grid voltages. The MCCF is used to generate fundamental positive constituents [25], which are expressed as follows:

$$V_{sa} = 0.8165[V_{sa} - (0.5 \ast V_{sb}) - (0.5 \ast V_{sc})]$$

$$V_{sb} = 0.8165[(0.866 \ast V_{sb}) - (0.866 \ast V_{sc})]$$

where $V_{sa}$ and $V_{sb}$ are the $\alpha\beta$ coordinates of grid voltages [5]. The resultant grid voltage can be expressed as follows:

$$V_{sa\beta} = V_{h\alpha\beta} + V_{h\alpha\beta} + V_{h\alpha\beta} \quad (2)$$

where “h” represents the order of harmonics.

The MCCF is designed to separate the FCs from the extremely polluted grid voltages and it is tuned to 50 Hz fundamental frequency, which is worked on converted voltages (V_{saβ}). The MCCF is used to eliminate harmonics as well as negative sequence constituents from the highly distorted grid voltages. The MCCF is used to generate fundamental positive constituents [25], which are expressed as follows:

$$V_{sa}^+ = \sqrt{\frac{2}{3}}[V_{sa}^+ + V_{sa}]$$

$$V_{sb}^+ = \sqrt{\frac{2}{3}}[-0.5 \ast V_{sa}^+ + 0.866 \ast V_{sb} + V_{sa}]$$

$$V_{sc}^+ = \sqrt{\frac{2}{3}}[-0.5 \ast V_{sa}^+ - 0.866 \ast V_{sb}^+ + V_{sa}]$$

The block diagram of the complex coefficient filter (CCF) structure is shown in Fig. 2. The MCCF incorporates a series of CCFs; every CCF is implemented to separate particular selective harmonics from grid voltages. The transfer function of CCF [25] is expressed as follows:

$$CCF_s = \frac{\omega_r}{s - jn\omega_0 + \omega_r} \quad (4)$$

III. PROPOSED CONTROL ALGORITHM

The proposed hybrid control scheme, as shown in Fig. 1, incorporates FLPID, MCCF, and MSOGI-QSG-PLL control algorithms. This combination achieves to separate the better FCs from the extremely polluted grid voltages as well as load currents. The MCCF technique is used to separate the FCs from the nonlinear currents consequently generates the three-phase reference currents. The FLPID voltage controller is used to keeping the stable power at the VSI output [10], [24], [33]. The mathematical modeling of FLPID-MCCF-MSOGI-QSG-PLL is expressed as in further sections.
where “n” is the order of harmonic, ω₀ is the fundamental frequency, and ωᵣ is the bandwidth of the filter. The above equation is executed on α, β constituent of voltage, which is obtained from (1) and (2), as shown in Fig. 2. Compare to the conventional filters, MCCF is the most efficient to distinguish between positive and negative sequence constituents of a selective harmonics.

The transient response study of MCCF is as follows. Fig. 2(a) represents the fundamental positive and negative constituents extraction and harmonic components extraction from the highly polluted grid voltages. The state-space equations of the grid voltages if considering the positive sequence extraction [25] are expressed as follows:

\[
\begin{align*}
V_{sa f}^+ &= \omega_r V_{sa} - \omega_r V_{sa f}^+ - \omega_0 V_{sb}^+ \\
V_{sb f}^+ &= \omega_r V_{sb} - \omega_r V_{sb f}^+ + \omega_0 V_{sa}^+
\end{align*}
\]

where \( V_{sa} \) and \( V_{sb} \) are the α and β constituents of grid voltage, respectively, and \( V_{sa f}^+ \) and \( V_{sb f}^+ \) are the fundamental α, β positive sequence constituents of grid voltage, respectively. The above system’s state-space model can be written as

\[
\begin{align*}
\dot{X}(t) &= AX(t) + Bu(t) \\
y(t) &= CX(t) + Du(t)
\end{align*}
\]

where \( X(t) = [V_{sa f}^+, V_{sb f}^+] \), \( u(t) = [V_{sa}, V_{sb}], D = 0, C = [I_2] \), and

\[
A = \begin{bmatrix}
-\omega_r & -\omega_0 \\
\omega_0 & -\omega_r
\end{bmatrix} \quad B = \begin{bmatrix}
\omega_r & 0 \\
0 & \omega_r
\end{bmatrix}.
\]

The state-space model of (7) is expressed as

\[
\phi(s) = C[sI - A]^{-1}B + D.
\]

Substituting A–D values in (8), we get

\[
\phi(s) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix}
s & 0 \\
0 & s
\end{bmatrix} \begin{bmatrix}
-\omega_r & -\omega_0 \\
\omega_0 & -\omega_r
\end{bmatrix}^{-1} \begin{bmatrix}
\omega_r & 0 \\
0 & \omega_r
\end{bmatrix} + 0
\]

\[
\phi(s) = \omega_r \left[ \frac{\omega_0}{(s+\omega_r)^2 + \omega_0^2} \right] = \omega_r \left[ \frac{\omega_0}{(s+\omega_r)^2 + \omega_0^2} \right] = \omega_r \left[ \frac{\omega_0}{(s+\omega_r)^2 + \omega_0^2} \right].
\]

The inverse Laplace transformation matrix of (10) is given by

\[
\phi(t) = \omega_r \left[ \begin{array}{c}
e^{-\omega_r t}\cos(\omega_0 t) & -e^{-\omega_r t}\sin(\omega_0 t) \\
e^{-\omega_r t}\sin(\omega_0 t) & e^{-\omega_r t}\cos(\omega_0 t)
\end{array} \right].
\]

\[
\phi(t) = \omega_r e^{-\omega_r t} \left[ \begin{array}{c}
\cos(\omega_0 t) & -\sin(\omega_0 t) \\
\sin(\omega_0 t) & \cos(\omega_0 t)
\end{array} \right].
\]

Initial input’s \( X(0) \) state-space transient response model is expressed as

\[
X(t) = \phi(t) \times X(0).
\]

Fig. 3. Control diagram of the FLPID-MSOGI-QSG-FLL technique.

Substituting \( \phi(t) \) in (13), we get

\[
X(t) = \omega_r e^{-\omega_r t} \left[ \begin{array}{c}
\cos(\omega_0 t) & -\sin(\omega_0 t) \\
\sin(\omega_0 t) & \cos(\omega_0 t)
\end{array} \right] \times (0).
\]

The transient response of MCCF mainly depends upon the bandwidth (\( \omega_r \)) of the MCCF, which is clearly observed from (14).

B. MSOGI-QSG-FL Control Algorithm

Fig. 4 displays the MSOGI-QSG-FL control scenario. The control scenario of VSI incorporates the in-phase unit templates \( u_{a}, u_{b}, \) and \( u_{c} \), estimation of peak voltages of point of common coupling (PCC) (\( V_{p} \)), dc voltage regulator loss components \( (I_{loss}) \), PV feedforward components \( (I_{pvff}) \), zero-crossing detection (ZCD) and sampling & holding (S&H) circuits, fundamental amplitude of load currents \( (I_{ap}, I_{bp}, \) and \( I_{cp}) \), estimation of reference currents \( (I_{ar}, I_{br}, \) and \( I_{cr}) \), and PWM generation for the APF inverter. Fig. 3 displays the overall circuit of the reference current generation control scenario.

The terminal voltage amplitude is estimated by using phase voltages \( (V_{sa}, V_{sb}, \) and \( V_{sc}) \) of the utility grid. By sensing the line voltages \( (V_{sab}, V_{sbc}) \) of the utility grid, phase voltages...
are calculated [27] by using the following equation:
\[
\begin{align*}
V_{sa} &= \frac{2}{3}(2V_{sab} + V_{sbc}) \\
V_{sb} &= \frac{2}{3}(-V_{sab} + V_{sbc}) \\
V_{sc} &= \frac{2}{3}(-V_{sab} - 2V_{sbc}) \\
\end{align*}
\] (15)
The estimation of peak terminal voltage \(V_t\) is calculated by
\[
V_t = \sqrt{\frac{2}{3}(V_{sa}^2 + V_{sb}^2 + V_{sc}^2)}. \\
\] (16)
The estimation of in-phase unit templates is calculated by using
\[
u_a = \frac{V_{sa}}{V_t} \quad u_b = \frac{V_{sb}}{V_t} \quad u_c = \frac{V_{sc}}{V_t}.
\] (17)
The estimation of PV feedforward compensation is calculated by using the estimated PV power \(P_{pv}\) and peak terminal voltage [10], [17], [24]
\[
I_{pvff} = \frac{2}{3} \frac{P_{pv}}{V_t} \\
\] (18)
By varying the load at PCC and variation in PV power, the grid currents have some oscillations. So, the PV feed-forward compensation is used to eliminate the oscillations in grid currents. Estimation of fundamental load current amplitude: the MSOGI-QSG-FLL control scenario is implemented by a combination of selective and adaptive filters. The FLL is designed to track the system frequency during transient cases, as shown in Fig. 4. The SOGI-QSG control technique is used to extract selective harmonic constituents from the load currents with multiplying estimated FLL frequency using several coefficients. Fig. 4 displays the internal design of MSOGI-QSG-FLL. The MSOGI-QSG-FLL controller comprises four SOGI-QSGs; each one is designed for fundamental, 3rd, 5th, and 7th harmonics. The in-phase and quadrature constituents transfer functions of load currents are expressed as follows:
\[
D_s = \frac{I_d(s)}{I_{in}(s)} = \frac{n\omega_s s}{s^2 + n\omega_s s + \omega^2} \\
Q_s = \frac{I_q(s)}{I_{in}(s)} = \frac{n\omega^2}{s^2 + n\omega s + \omega^2}.
\] (19) (20)
Tuning of MCCF coefficients
\[
\text{settling time}(t_s) = \frac{4}{\xi \pi n} \\
\] (21)
where \(\xi\) is the damping coefficient and \(\omega\) is the FLL estimated frequency.
The SOGI-QSG bandpass filter gives gain to \(h\)th harmonics with fundamental frequency as
\[
|D(j\omega)| = \frac{2 \xi + h}{\sqrt{(1 - h^2)^2 + (2 \xi h)^2}} \] (22)
where \(h = 1, 3, 5, 7\) and \(\xi\) value range between 0 and 1. The above equation can be simplified as follows:
\[
|D(j\omega)| = \frac{2 \xi + h}{h}. \\
\] (23)
The damping factor gains are taken as 1/3 for third harmonic, 1/5 for fifth harmonic, and 1/7 for seventh harmonic. The gain of harmonic frequency \((K_f)\) is taken as 3 for third harmonic, 5 for fifth harmonic, and 7 for seventh harmonic.
The in-phase and quadrature constituents transfer functions of SOGI-QSG are given in (19) and (20). The generalized equation for MSOGI-QSG-FLL is expressed as follows:
\[
\begin{align*}
\left\{L_d(s) = IL \frac{1}{D_1(s)} \left[1 - \frac{D_3(s)}{1 - D_3(s)}\frac{D_1(s)}{1 - D_1(s)}\right]\right\} \\
\left\{L_q(s) = IL \frac{1}{Q_1(s)} \left[1 - \frac{Q_3(s)}{1 - Q_3(s)}\frac{Q_1(s)}{1 - Q_1(s)}\right]\right\}
\end{align*}
\] (24) (25)
The quadrature constituents \((I_{aq1}, I_{bq1}, I_{cql1})\) of load currents are given to ZCD and S&H circuit, which calculates fundamental active load currents by using in-phase unit templates
\[
I_{load} = \frac{I_{ap} + I_{bp} + I_{cp}}{3}
\] (26) where \(I_{load}\) is the per phase weight of load currents
\[
I_{net} = I_{load} - I_{pvff} + I_{loss}
\] (27) where \(I_{net}\) is the net weight of load current, \(I_{pvff}\) is the PV feedforward compensation, and \(I_{loss}\) is the loss components of dc bus regulator
\[
I_{ar} = I_{net} * u_a \quad I_{br} = I_{net} * u_b \quad I_{cr} = I_{net} * u_c
\] (28) where \(I_{ar}, I_{br}, I_{cr}\) are the three-phase reference currents. The grid sensed and controller calculated currents are given to hysteresis current controller. The error between the currents controller develops PWM signals, which are given to APF inverter. Consequently, the VSI generates three-phase compensating currents, which injects to the utility grid for power quality improvement at the distribution side.

C. FLPID Voltage Controller

The conventional PI controller has been failed to stable the dc bus voltage during grid and load transient conditions. To bypass the shortcoming, a fuzzy tuned PID adaptive control scheme is designed to calculate the PID gains adaptively during transient conditions. The control diagram of the FLPID is shown in Fig. 5.
The mathematical modeling of FLPID controller [10], [24], [34] is discussed as follows:

\[ G_c(s) = k_p + \frac{k_i}{s} + k_d(s) \]  

(29)

\[ G_c(s) = k_p \left( 1 + \frac{1}{\frac{1}{s}} + \frac{k_d}{k_p}(s) \right). \]  

(30)

The PID controller’s discrete-time equivalent equation is

\[ u_k = k_p * e(k) + k_i T_s \sum_{i=1}^{n} e(i) + \frac{k_d}{T_s} e(k) - e(k-1) \]  

(31)

where \( e(k) \) is the error voltage obtained from the actual and reference dc voltage, \( u_k \) is the control signal, and \( T_s \) is the sampling time.

The mathematical analysis of fuzzy gain scheduling for PID controller is expressed as follows:

\[
\left\{
\begin{array}{l}
k'_p = \frac{k_{p\text{max}} - k_{p\text{min}}}{k_{p\text{max}} - k_{p\text{min}}} k_p \\
k'_d = \frac{k_{d\text{max}} - k_{d\text{min}}}{k_{d\text{max}} - k_{d\text{min}}} k_d \\
\end{array}
\right.
\]

(32)

The defuzzification yields are obtained by using the following:

\[
\left\{
\begin{array}{l}
k_p = \frac{\sum_{i=1}^{m} \mu_i k'_p}{\sum_{i=1}^{m} \mu_i} \\
k_d = \frac{\sum_{i=1}^{m} \mu_i k'_d}{\sum_{i=1}^{m} \mu_i} \\
\end{array}
\right.
\]

(33)

The PID controller’s gains are obtained by using the following:

\[
\left\{
\begin{array}{l}
k_p = (k_{p\text{max}} - k_{p\text{min}}) k'_p + k_{p\text{min}} \\
k_i = \frac{k^2}{\alpha k_d} \\
k_d = (k_{d\text{max}} - k_{d\text{min}}) k'_d + k_{d\text{min}}. \\
\end{array}
\right.
\]

(34)

IV. RESULTS AND DISCUSSIONS

The model of the proposed control scenario is developed on MATLAB/Simulink platform. The proposed system is implemented on several conditions, such as steady state, dynamic load, load removed, grid voltage unbalanced, variable solar irradiation level, and distorted grid voltage conditions. The data for designing the system are displayed in Table I. Table II lists the harmonic analysis of individual harmonic during various test cases.

A. Simulation Results Under Balanced Voltage Supply, Load Removed, and Dynamic Load Conditions

Fig. 6 shows that the system is running under balanced supply voltage, load removed, and dynamic load conditions. From 0 to 0.08 s shows the grid balanced supply voltage condition. To examining the controller dynamic performance, phase “a” load is removed, which is shown in Fig. 6 from 0.08 to 0.15 s. During 0.15–0.2 s, the proposed system is working under dynamic load condition. The performance of the proposed controller is found good under balanced supply voltage, load removed, and dynamic load conditions. Fig. 6 includes three-phase grid voltages (\( V_{abc} \)), grid currents (\( I_{abc} \)), three-phase load currents (\( I_{Labc} \)), \( \alpha, \beta \) coordinates of MCCF (\( V_{abc} \)), FCE of the MCCF (\( V_{abcf} \)), error current of phase “a” load current (\( e_a \)), quadrature component of the load currents (\( I_{qabc} \)), in-phase component of the phase load currents (\( I_{pabc} \)), unit vector template voltage (\( V_t \)), in-phase unit templates (\( u_{abc} \)), net load current (\( I_{net} \)), estimated load current (\( I_{Labc} \)), three-phase reference currents (\( I_{rabc} \)), three-phase compensating currents (\( I_{fabc} \)), estimated PLL frequency (\( f \)), dc-link voltage (\( V_{dc} \)), and total harmonic distortion (THD) analysis of grid current with APF under the
TABLE II
PERCENTAGE OF INDIVIDUAL HARMONIC COMPONENTS OF THE PROPOSED SYSTEM (NOTE: BF: BEFORE FILTER AND AF: AFTER FILTER)

<table>
<thead>
<tr>
<th>Test Cases (TC)</th>
<th>5th (%)</th>
<th>7th (%)</th>
<th>11th (%)</th>
<th>13th (%)</th>
<th>17th (%)</th>
<th>19th (%)</th>
<th>23rd (%)</th>
<th>25th (%)</th>
<th>29th (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I_dq</td>
<td>I_dq</td>
<td>I_dq</td>
<td>I_dq</td>
<td>I_dq</td>
<td>I_dq</td>
<td>I_dq</td>
<td>I_dq</td>
<td>I_dq</td>
</tr>
<tr>
<td>TC1 BF</td>
<td>0.26</td>
<td>22.56</td>
<td>0.13</td>
<td>11.35</td>
<td>0.11</td>
<td>8.97</td>
<td>0.08</td>
<td>6.5</td>
<td>0.07</td>
</tr>
<tr>
<td>TC1 AF</td>
<td>0.04</td>
<td>2.02</td>
<td>0.02</td>
<td>1.01</td>
<td>0.01</td>
<td>0.84</td>
<td>0.00</td>
<td>0.62</td>
<td>0.00</td>
</tr>
<tr>
<td>TC2 BF</td>
<td>0.00</td>
<td>0.15</td>
<td>0.01</td>
<td>0.14</td>
<td>0.00</td>
<td>0.10</td>
<td>0.00</td>
<td>0.09</td>
<td>0.00</td>
</tr>
<tr>
<td>TC2 AF</td>
<td>0.00</td>
<td>0.02</td>
<td>0.01</td>
<td>0.08</td>
<td>0.00</td>
<td>0.03</td>
<td>0.00</td>
<td>0.03</td>
<td>0.00</td>
</tr>
<tr>
<td>TC3 BF</td>
<td>0.26</td>
<td>22.51</td>
<td>0.13</td>
<td>11.36</td>
<td>0.11</td>
<td>8.91</td>
<td>0.08</td>
<td>6.50</td>
<td>0.07</td>
</tr>
<tr>
<td>TC3 AF</td>
<td>0.04</td>
<td>2.25</td>
<td>0.02</td>
<td>1.14</td>
<td>0.01</td>
<td>0.81</td>
<td>0.00</td>
<td>0.64</td>
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<tr>
<td>TC4 BF</td>
<td>0.26</td>
<td>22.11</td>
<td>0.13</td>
<td>11.65</td>
<td>0.11</td>
<td>8.62</td>
<td>0.08</td>
<td>6.97</td>
<td>0.07</td>
</tr>
<tr>
<td>TC4 AF</td>
<td>0.04</td>
<td>2.01</td>
<td>0.02</td>
<td>1.12</td>
<td>0.01</td>
<td>0.79</td>
<td>0.00</td>
<td>0.63</td>
<td>0.00</td>
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<tr>
<td>TC5 BF</td>
<td>18.52</td>
<td>22.53</td>
<td>18.40</td>
<td>11.36</td>
<td>0.11</td>
<td>8.95</td>
<td>0.08</td>
<td>6.52</td>
<td>0.07</td>
</tr>
<tr>
<td>TC5 AF</td>
<td>0.04</td>
<td>2.09</td>
<td>0.02</td>
<td>1.10</td>
<td>0.01</td>
<td>0.83</td>
<td>0.00</td>
<td>0.60</td>
<td>0.00</td>
</tr>
<tr>
<td>TC6 BF</td>
<td>0.26</td>
<td>22.55</td>
<td>0.13</td>
<td>11.34</td>
<td>0.11</td>
<td>8.94</td>
<td>0.08</td>
<td>6.54</td>
<td>0.07</td>
</tr>
<tr>
<td>TC6 AF</td>
<td>0.04</td>
<td>2.08</td>
<td>0.02</td>
<td>1.05</td>
<td>0.01</td>
<td>0.83</td>
<td>0.00</td>
<td>0.62</td>
<td>0.00</td>
</tr>
</tbody>
</table>

above-mentioned conditions. In these conditions, the grid currents and voltages THD are found well within the IEEE-519 standard limits.

B. Simulation Results Under Unbalanced Grid Voltages Condition

To verify the potency of the hybrid control technique under grid transient conditions, the system is working under grid unstable voltages state. The grid and controller performance characteristics are included in Fig. 7, which shows the waveforms of $V_{sabc}$, $I_{sabc}$, $V_{abc}$, $I_{abc}$, $V_{sabc}$, $I_{abc}$, and THD analysis of grid current with APF. In this test case, the proposed control topology is well verified and the grid currents and voltages THDs are found well within IEEE-519 standard limits.

C. Simulation Results Under Polluted Grid Voltages Condition

Fig. 8 shows the operation of the system under distorted grid voltages condition. In this condition, the MCCF is employed to take out the FCs from the extremely polluted grid voltages. The waveforms of $V_{sabc}$, $I_{sabc}$, $I_{abc}$, $V_{sabc}$, estimated FLL frequency ($\omega$), $V_{dc}$, and harmonic spectra of grid current with APF are included in Fig. 8. In this condition, the proposed control performance is well justified. The grid currents and voltages THDs are found well within IEEE-519 standard limits.

D. Simulation Results Under Change in Irradiation Level Condition

Fig. 9 displays the different irradiation level condition of the PV system. The waveforms of PV system characteristics are as follows: irradiation level ($G$), voltage of the PV ($V_{pv}$), current of the PV ($I_{pv}$), $V_{dc}$, and dc bus current ($I_{pv}$). The waveforms of the grid system are $V_{sabc}$, $I_{sabc}$, load currents ($I_{abc}$), FCE of grid voltages $V_{abc}$, $I_{abc}$, $I_{abc}$, $V_{abc}$, estimated THD analysis of grid current with APF. In this condition, the control scheme performance is well justified. The grid currents and voltages THDs are found well within IEEE-519 standard limits.

Fig. 7. Simulation results under unbalanced grid voltages state condition.

Fig. 8. Simulation characteristics under polluted grid voltage condition.
E. Real-Time Experimental Results

The overall system is examined on field-programmable gate array (FPGA) hardware-in-the-loop. The control circuit of the system is converted to FPGA Xilinx blocks using FPGA system generator software to generate the VHDL code for experimental platform. This code is dumped into the Virtex-7 interface kit via master computer for PWM generation purpose. The suggested system’s real-time setup is shown in Fig. 10. The components used for the experimental platform are as follows: 1.5-kW PV simulator (SAS12010) system, three-phase insulated gate bipolar transistor (IGBT) (25RSB120)-based voltages source converter, filter inductor (L_{apf}), diode-based rectifier circuit (acts as nonlinear load), WT 1800 power quality analyzer, HE025T01 Hall-effect current sensor, LV-25 voltage sensor, three-phase resistive and inductive loads, three-phase autotransformer, FPGA interface kit, master computer, and scope carder. The system parameters taken for simulation and experimental platform are shown in Table I. To estimate the efficiency of the system performance of the FLFID-MCCF-MSOGF-FLL controller in the APF system, the prototype laboratory hardware platform is implemented on 230-V grid supply. Case 1: Performance of the system under a balanced supply voltage condition, an exhibition of the proposed FLFID-MCCF-MSOGF-FLL scheme in APF is implemented in the experimental platform. The outcomes of this condition are shown in Figs. 11–13. In this condition, the grid and APF outcomes with the proposed scheme behavior are well justified consequently improves the system dynamic performance. Case 2: System’s performance during load removed condition. To justify the system aggressive behavior during load dynamic conditions, phase a nonlinear current is removed. The outcomes of this condition are shown in Figs. 14–16. Case 3: System’s performance during dynamic load condition. In this condition, an extra load is added to the system. The PV and grid system are giving the power to the load equally. After adding an extra constant load, the grid is giving more power to the load. That is why, the grid current is increased slightly, which is observed in Fig. 17. The outcomes of this condition are shown in Figs. 17–19. In this condition, the grid and APF outcomes with the proposed scheme behavior are found satisfactory. Similarly, to justify the system aggressive behavior under grid dynamic...
Fig. 14. Grid and load characteristics during load removed condition.

Fig. 15. Control characteristics during load removed condition.

Fig. 16. Reference, filter generated currents, frequency, and dc bus voltage during load removed condition.

Fig. 17. Grid and load characteristics during dynamic load condition.

Fig. 18. Control characteristics during dynamic load condition.

Fig. 19. Reference, filter generated currents, frequency, and dc bus voltage during dynamic load condition.

Fig. 20. Grid and load characteristics during unbalanced grid voltages condition.

Fig. 21. Control characteristics during unbalanced grid voltages condition.

Fig. 22. Reference, filter generated currents, frequency, and dc bus voltage during unbalanced grid voltages condition.

Fig. 23. Grid and load characteristics during polluted grid voltages condition.
conditions, several grid perturbation conditions have been created and validated in the experimental platform. Case 4: System’s performance during unbalanced grid voltages condition. This is a very rare condition in the practical systems. However, it may due to the faults occur in the system. In the experimental validation, the magnitudes of the grid voltages are changed by using the three single-phase variac. The proposed control scheme balances the grid currents during the grid unbalanced voltage condition, which is observed in Fig. 20. Therefore, control scheme for the system can control the output currents of the grid interfacing VSI in the absence of negative sequence constituent. The outcomes of this condition are shown in Figs. 20–22. In this condition, the grid and APF outcomes obtained by using the proposed scheme behavior are found satisfactory. Case 5: System’s performance during polluted grid voltages condition. In this condition, we have manually
TABLE III
COMPARISON OF THE PROPOSED CONTROLLER WITH A GROUP OF ADAPTIVE CONTROL SCHEMES (NOTE: NP: NOT PERFORMED)

<table>
<thead>
<tr>
<th>Features</th>
<th>LMF</th>
<th>LMS</th>
<th>SOGI</th>
<th>DSOGI</th>
<th>SO-SOGI</th>
<th>ISOGI</th>
<th>MCCF</th>
<th>MCCF-SOGI</th>
<th>MSOGI</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oscillations</td>
<td>less</td>
<td>less</td>
<td>less</td>
<td>less</td>
<td>less</td>
<td>less</td>
<td>less</td>
<td>less</td>
<td>less</td>
<td>less</td>
</tr>
<tr>
<td>Complexity</td>
<td>medium</td>
<td>medium</td>
<td>low</td>
<td>medium</td>
<td>low</td>
<td>medium</td>
<td>low</td>
<td>medium</td>
<td>medium</td>
<td>medium</td>
</tr>
<tr>
<td>Amplitude tracking</td>
<td>no</td>
<td>no</td>
<td>low</td>
<td>medium</td>
<td>medium</td>
<td>medium</td>
<td>good</td>
<td>good</td>
<td>better</td>
<td>better</td>
</tr>
<tr>
<td>Frequency tracking</td>
<td>no</td>
<td>no</td>
<td>medium</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>no</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>DC offset rejection</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>medium</td>
<td>medium</td>
<td>medium</td>
<td>no</td>
<td>no</td>
<td>NP</td>
<td>better</td>
</tr>
<tr>
<td>Accuracy</td>
<td>good</td>
<td>good</td>
<td>medium</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>THD of grid currents</td>
<td>less</td>
<td>less</td>
<td>medium</td>
<td>less</td>
<td>less</td>
<td>less</td>
<td>na</td>
<td>less</td>
<td>NP</td>
<td>better</td>
</tr>
<tr>
<td>THD of grid voltages</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>yes</td>
<td>na</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Voltage and current</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
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<tr>
<td>Steady state performance</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
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<tr>
<td>Dynamic performance</td>
<td>good</td>
<td>good</td>
<td>medium</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
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<td>good</td>
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<tr>
<td>Harmonic elimination ability</td>
<td>good</td>
<td>good</td>
<td>medium</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
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<td>na</td>
<td>na</td>
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<td>na</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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</tr>
<tr>
<td>Sampling time</td>
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<td>50μs</td>
<td>50μs</td>
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<td>50μs</td>
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<td>50μs</td>
<td>50μs</td>
</tr>
</tbody>
</table>

F. Comparison of the Proposed Hybrid Algorithm With Conventional Techniques

Comparison of the proposed hybrid control algorithm with conventional control schemes (IRP, SRF, ADALINE, and Fryze) is analyzed through the THD analysis of grid current, which is shown in Fig. 32(a)–(d). Fig. 32(e) shows that the stability performance of the MSOGI-FLL algorithm with SOGI, SO-SOGI, DSOGI, and ISOGI control schemes is investigated via Bode diagram. Fig. 32(e) shows that the Bode magnitude plot of $I_{q1}(s)$ lies below for low frequencies, which represents (blue line) and gives the good dc offset mitigation ability compared with the above-mentioned adaptive control schemes. The proposed control topology is found good performance than the conventional and adaptive control schemes. Comparison table of the proposed control scheme with existing and few adaptive control techniques is shown in Table III. The comparison table shows the effectiveness of the proposed hybrid control scheme in terms of various characteristics. The proposed control scheme is found good under various characteristics than the existing control algorithms, which is observed from Table III.

V. Conclusion

Upon observing the negative consequences of harmonics presented into the transmission system, an APF with proposed FLPID-MCCF-MSOGI-FLL reference current generation scheme has been underlined in this article. To destroy the voltage and current harmonics in a grid-tied PV system, the APF along with adaptive current control technique is an optimal solution that results in a pollution-free power at the end users. The MSOGI-FLL reference current controller is used for APF to compute three-phase reference currents. The FLPID feedback controller is employed to maintain constant the voltage of the dc bus without any ripple at dc bus terminals. The MCCF is executed to eliminate the voltage harmonics from highly polluted grid voltages. The simulated outcomes of the proposed control strategy are found satisfactory and the THD of grid voltages and currents are maintained well within limits of IEEE-519 standard. Prototype laboratory experimental results have also shown that the effectiveness of the proposed control scheme is competent and robust during load- and grid-side perturbations.
The THD of injected grid currents obtained from experimental set-up remain within IEEE-519 standard. The comparison of the proposed system with existing and few adaptive control techniques is performed by using fast Fourier transform and stability analysis. The proposed technique gives the better performance than the existing techniques in terms of dc offset rejection, grid synchronization, harmonic rejection, and FC extraction.

REFERENCES


