Control of pico-hydro-PV-based distributed generation with battery support for off-grid electrification

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Abstract
This work presents the operation and control of a pico-hydro-solar photovoltaic (PV)-battery energy storage (BES)-based isolated renewable energy system (RES) feeding 3-phase 4-wire loads. For voltage regulation, to maintain frequency, and power quality improvement in this system, a 4-leg VSC is used. The BES is connected to the DC-link of the voltage source converter (VSC) through a bidirectional converter (BDC), which regulates the DC-link voltage and controls the charging and discharging current of the battery. An advanced perturb and observe (AP&O)-based MPPT control technique with drift free operation and capability to operate in the derated mode is adapted in this work. The VSC connected to PCC, injects or absorbs power from this system based on the difference of power between generation and the load. The modified complex co-efficient filter (MCCF)-based control technique monitors the power quality of this RES system and 4-leg VSC provides the source neutral current compensation. This control algorithm is used to extract the amplitude of the fundamental load current component with improved dynamic response, DC offset elimination and higher order harmonics removal capability. The ability of the presented control strategy for power quality improvement, power management, load balancing and neutral current compensation is reported in this work.

1 | INTRODUCTION

The prime focus of all the existing renewable energy systems (RES) using conventional energy sources is to provide electricity to locations near it. The energy demand of locations, which are far away from utility grids can be satisfied using decentralised/off grids [1]. These off-grid systems provide cost-effective power generation if they are energised by green energy sources such as wind, hydro, solar or any other renewable energy. The integration of many such sources to form an isolated system reduces the intermittency of such sources supplying power individually [2]. The smaller power capacity-based isolated systems and their integration have considerably increased in use [3]. This kind of system is suitable for operation in off-grid and grid-connected modes. In an off-grid mode, the system supplies power to a local consumer load and in case of excess power, a battery storage system (BES) is the only solution where it can be stored [4].

The demand of pico-hydro systems is huge as extracting energy to feed remote areas has become inevitable [5]. The changing speed in the flow of water, decreases the power generated and affects the isolated system frequency [6]. It can be controlled if the load is levelled between generation and consumption in this system [7]. Another alternative and cost-effective green energy, which can be integrated to a pico-hydro system, can be a solar PV array-based RES. This source is highly intermittent in nature and its power solely depends on weather conditions [8].

Moreover, a PV array produces variable DC voltage, which needs to be converted to stable AC output and requires a power converter [9]. The intermittency in PV generation, caused by changing weather conditions, requires an appropriate MPPT algorithm to bring out maximum power from the solar PV array. In recent years, various MPPT approaches for obtaining maximum power from a solar PV array using DC-DC power converters have been proposed in the literature.
Similarly, Killi et al. [16] have created adaptive P&O algorithms, such as the modified P&O [13], modified InC [14], and adaptive P&O [15] have recently been proposed to address these shortcomings in the classic P&O and InC approaches. Similarly, Killi et al. [16] have created an adaptive P&O algorithm that outperforms the traditional P&O approach in terms of tracking quality. Power flow regulation for RES can be achieved using a BES, as it can store power and provide power when it is needed by the system [17]. The power quality improvement is such systems must be carefully monitored in order to allow power sharing and seamless integration of such sources [18]. Furthermore, combining multiple renewable resources elevates losses during abrupt power fluctuations while lowering noise and volatility in these systems [19]. It is feasible to recover quickly from variation in power when a VSC is operated with the support of bidirectional converter-controlled BES.

However, the direct connection of BES to the DC-link affects the life of the battery since it produces a second harmonic component. To eliminate such situations in this work, BES is used to support the capacitor voltage of the DC-link using a bidirectional converter (BDC) [20]. Generally any pico-hydro system located remotely, feeds power to single-phase loads. To serve this purpose, single-phase machines are mostly employed. However, if the power requirement is higher, a three-phase machine is needed to satisfy the consumer demand. Hence, an isolated system is required with a four-wire distribution system, where separate three single-phase consumer loads can be connected with a common neutral. In this work, the solar PV array with PMSG-based hydro generation is integrated together to form an isolated system feeding three-phase 4-wire loads. Major setbacks experienced by an isolated systems are voltage imbalances, dynamic and steady-state oscillations, and the presence of DC offset in load currents [21]. To eliminate these flaws, an effective control mechanism is required. For reference source current extraction and solving such difficulties, there are numerous control techniques available in the literature. Several filtering strategies have been reported to address these concerns. In [22-24], a band-pass filter (BPF)-based control is reported. This filter has efficiency to block DC offset. However, it causes delays and induces high oscillations in the fundamental components of load currents during dynamic changes. A high pass filter (HPF) [25] is used to solve the DC offset presence by passing the output signal through a LPF and subtracting its output from the original input current. However, depending on the LPF order, the filtering performance of the control technique decreases. A notch filter (NF)-based PLL control technique has heavy filtering but it has poor DC-offset removal characteristics [26]. The main objective of this work is to utilise MCCF-based control to provide switching pulses to IGBT switches of VSC, which efficiently reduces DC offset disturbances in the extracted fundamental load component of current. This control improves the system performance by eliminating distortions due to harmonics, and tackles imbalances in the load. Following are the major highlights of this work:

- The operation of an isolated hydro-PV-BES supported three-phase 4-wire hybrid system is found capable of operating in remote locations where grid connection is not feasible is proposed in this work.
- The BDC-based BES enables a bidirectional power flow and DC-link voltage control in the system. It protects the battery from the presence of second harmonic current.
- An advanced AP&O-based MPPT technique with derating capability for overcharge protection of BES and drift-free operation is presented.
- A voltage source converter (VSC) is used for generating reference source current, frequency, DC offset elimination, provides control of frequency and voltage of this system.
- A detail comparative performance of the MCCF-PLL-based VSC control with their conventional counter parts is reported in this work.

2 | SYSTEM CONFIGURATION

The configuration of the presented system contains the solar PV array and PMSG-based pico hydro system with BES support, as shown in Figure 1. The primary aim of this system is to feed the consumer loads in remote areas. The IGBT-based 4-leg VSC is made used to regulate the terminal voltage, frequency and to provide neutral current compensation. The output of the solar PV array is also connected to the DC-link capacitor of the VSC. Hence, the PV array and BES-based DC sources combined together, are coupled to the point of common coupling (PCC). These coupled energy sources can inject active power to the system for supplying power to the load. Moreover, in case of excess power in, it can absorb power for storing in a BES.

3 | CONTROL STRATEGY OF VSC

The structure of the control technique using MCCF is provided in Figure 2(a). It is used to generate reference source currents and the details of this technique for reference source current generation, are given in this section.
3.1 | MCCF-based control

The positive sequence component matching the fundamental frequency is obtained using a complex bandpass filter (CBF) in the MCCF structure. Figure 2(b) shows the structure of CBF. The current components in the $\alpha\beta$ frame are estimated corresponding to fundamental frequencies using this CBF structure. The transfer function of the CBF filter is obtained as follows:

$$\text{CBF}(s) = \frac{s - j\alpha_n}{s - j\alpha_n + \omega_p}$$

Here, the LPF block of the MCCF filter’s transfer function is given by $\omega_p/(s + \omega_p)$ where the cutoff frequency is given by $\omega_p$. The MCCF filter’s dynamic performance and DC offset rejection abilities are determined by the cutoff frequency. This filter’s output signal can be written as follows:

$$i_{\alpha}^\prime(s) = i_{\alpha}^\prime(s) - i_{\alpha,dc}^\prime(s)$$

$$i_{\alpha}^\prime(s) = (1 - \frac{\omega_p}{s + \omega_p})i_{\alpha}^\prime(s) + \frac{\omega_p}{s + \omega_p}i_{\alpha}^\prime(s)$$

$$i_{\beta}^\prime(s) = (1 - \frac{\omega_p}{s + \omega_p})i_{\beta}^\prime(s) + \frac{\omega_p}{s + \omega_p}\text{CBF}(s)i_{\beta}^\prime(s)$$

The MCCF filter’s transfer function, that is the ratio of current signals $i_{\alpha}^\prime$ to $i_{\beta}^\prime$, can be determined using the aforementioned formulae,

$$\frac{i_{\alpha}^\prime(s)}{i_{\beta}^\prime(s)} = \frac{s}{s + \omega_p(1 - \text{CBF}(s))}$$

To achieve the necessary performance, the LPF cutoff frequency is set to $\omega_p = 2\times15 \text{ rad/sec}$ and $\omega_c$, and the reference frequency is set to $\omega_u = 2\times50 \text{ rad/sec}$. The preceding section includes a comparative Bode diagram based on this control.

3.2 | Fundamental current extraction using MCCF

The MCCF-based filter is used to find the fundamental fixed frame $\alpha\beta$ currents ($i^\alpha$ & $i^\beta$) from three-phase sensed load currents. This control obtains error free and accurate amplitude currents in the $\alpha\beta$ frame.
The governing equations of this control for the current amplitude estimation and harmonics elimination based on the structure shown in Figure 2 are given here. The three-phase input load currents to the control are given as follows:

\[
\begin{align*}
    i_{La} &= I_m \sin(\omega t + \varphi) \\
    i_{Lb} &= I_m \sin(\omega t + \varphi - 120^\circ) \\
    i_{Lc} &= I_m \sin(\omega t + \varphi + 120^\circ)
\end{align*}
\]

(6)

Here, \(I_m\) is the amplitude of the input current signal, \(\omega\) is the input frequency, and \(\varphi\) the phase angle deviation from the ideal condition. To obtain \(\alpha\beta\) components of load currents, the above three-phase currents can be transformed as follows:

\[
\begin{bmatrix}
    i_n \\
    i_\beta
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
    1 & -1 & 0 \\
    0 & \sqrt{3} & 0 \\
    1 & -1 & 0
\end{bmatrix} \begin{bmatrix}
    i_{La} \\
    i_{Lb} \\
    i_{Lc}
\end{bmatrix}
\]

(7)

The current signals in the \(\alpha\beta\) rotating frame are derived as follows:

\[
\begin{align*}
    i_n &= I_m \sin(\omega t + \varphi) \\
    i_\beta &= I_m \sin(\omega t + \varphi - 90^\circ)
\end{align*}
\]

(8)

The technique for generating harmonic free reference source currents using the MCCF control technique is given in Figure 2. The current components are changed from rotating the \(\alpha\beta\) frame into the dq frame as follows:

\[
\begin{bmatrix}
    I_{dl} \\
    I_{ql}
\end{bmatrix} = \begin{bmatrix}
    \cos \theta & \sin \theta \\
    -\sin \theta & \cos \theta
\end{bmatrix} \begin{bmatrix}
    i_n \\
    i_\beta
\end{bmatrix}
\]

(9)

The error \(V_{te}\) in the PCC voltage is obtained from the reference voltage \(V^*_t\) as follows:

\[
V_{te}(n) = V^*_t(n) - V_t(n)
\]

(10)

The reactive component current \(I_{qq}\) is determined from the error in the terminal voltage \(V_{te}\) as follows:

\[
I_{qq}(n) = I_{qq}(n-1) + k_{pv}\{V_{te}(n) - V_{te}(n-1)\} + k_{iv}V_{te}(n)
\]

(11)

where \(k_{pv}\) and \(k_{iv}\) are the voltage PI controller’s proportional and integral gains, respectively. Similarly, the reference value of frequency, \(f^*\) is compared with measured system frequency to create a frequency error value \(f_e\) as follows:

\[
f_e(n) = f^*(n) - f(n)
\]

(12)

After determination of frequency error, this output is used to determine the \(I_{df}\) component using a PI controller, which further controls the frequency as follows:

\[
I_{df}(n) = I_{df}(n-1) + k_{pf}\{f_e(n) - f_e(n-1)\} + k_{df}f_e(n)
\]

(13)

By subtracting the load current component from the d-axis component, the net d-axis source component of the generator current is calculated as follows:

\[
I_{ds} = I_{df} - I_{dl}
\]

(14)

Similarly, the q-axis component of the generator current is obtained by subtracting the component of the q-axis \(I_{qv}\) from the \(I_{ql}\) component as follows:

\[
I_{qs} = I_{qv} - I_{ql}
\]

(15)

Thus, reference of hydro generator currents are obtained as follows:

\[
\begin{bmatrix}
    I_{ds} \\
    I_{qs}
\end{bmatrix} = \begin{bmatrix}
    \cos \left( \theta - \frac{2\pi}{3} \right) & -\sin \left( \theta - \frac{2\pi}{3} \right) \\
    \cos \left( \theta + \frac{2\pi}{3} \right) & -\sin \left( \theta + \frac{2\pi}{3} \right)
\end{bmatrix} \begin{bmatrix}
    I_d^* \\
    I_q^*
\end{bmatrix}
\]

(16)

The generated reference source currents are utilised to track and create pulses for the VSC’s four legs. To make switching pulses for the VSC’s IGBTs, the generated reference source currents are compared with generator source currents using a hysteresis current controller. The switching pulse to fourth leg is generated in such a way that the source neutral current is reduced to zero.

### 3.3 | Comparative performance of MCCF control

Based on the transfer function in (5), a Bode diagram in comparison with other state-of-the-art techniques are given in Figure 3. The comparative Bode plot shows that the MCCF filter only passes a positive sequence of fundamental components, where as other filters like BPF [23], HPF [25] and NF [26] have low attenuation towards higher and lower frequencies. However, all these techniques indicate that they have good capability to allow fundamental frequency. The phase plot of the MCCF filter exactly passes through 0° at 50 Hz showing that it has zero phase shift at fundamental frequency.

The harmonic elimination and DC offset removal ability of the MCCF-based control in comparison with NF [26] are shown in Figure 4(a). It can be observed in this figure that the non-linear input load current has a marginal DC offset. However, the presence of the DC offset and harmonics are not present in the output in-phase reference source current generated by the MCCF control. In contrast to the MCCF
control, the NF control has shown no capability to remove the DC offset and it is clearly reflected in the in-phase reference source current generation in Figure 4. The comparative performance of the MCCF control with already reported filtering techniques like BPF [23], HPF [25] and NF [26]-based controls is studied in detail.

Simulated performance for determination for the component of the d-axis of the fundamental current (I_{dl}) during the steady state and dynamic load change using these control techniques is given in Figure 4(b). The response in the above figure demonstrates that the MCCF-based control has less oscillations and fast settling during the steady state and dynamic performances. The error for this control is observed to be less as compared to that of the existing control algorithms. The comparative performance of MCCF-based control with existing techniques is shown in Table 1. As per this chart, the comparative performance and superior capability of this control for DC offset rejection and the accurate estimation of fundamental amplitude of load current are demonstrated.

### 3.4 Bidirectional converter

The bidirectional converter (BDC) is used to control the DC-link voltage of VSC, as shown in Figure 5. The buck-boost operation of BDC helps to control the DC-link voltage of VSC. This controller uses the DC-link voltage error processed through a PI controller to estimate the battery reference current. This reference current is compared with the sensed battery current to create necessary switching signals to the switches of BDC. It also provides power balance by controlling the operation of BES. The derating mechanism is adapted in MPPT of the PV array further to protect the BES from overcharging.

The operational duty ratio of the selected BDC is obtained as follows:

$$\text{Duty} = \frac{V_{dc} - V_{bat}}{V_{dc}} = \frac{400 - 240}{400} = 0.4 \quad (17)$$

After calculating the duty ratio, the inductor L_b for BDC can be estimated as follows:

$$L_b = \frac{V_{bat} \times \text{Duty}}{\Delta V_{\text{L}_b} \times f_{sw}} = \frac{0.4 \times 240}{5 \times 0.2 \times 20 \times 10^3} = 4.8mH \quad (18)$$

### 3.5 MPPT control strategy

The maximum power from a PV array is extracted using the analytical perturb and observe (AP&O)-based MPPT algorithm and its flowchart is shown in Figure 6. It also has a drift management loop that works during both insolation climb and reductions. The P&O algorithm has been explored previously in a number of attempts. However, here a slightly advanced AP&O algorithm with a derating mechanism is used. In this technique, voltage perturbation is carried out first and based on that the values of current and previous operational power are determined. If the current PV power is greater than the prior power at the disturbed voltage, the voltage perturbation’s direction is preserved. Once the maximum power has been taken from the PV array, the VSC and BES determine the amount of power to be delivered or absorbed from the system based on the DC-link voltage and frequency control loop.
The hardware prototype of the presented system is setup in the laboratory. A DSP (dSPACE DS1202), is utilised for the processing of signals. The bidirectional converter is implemented with the help of a DC–DC converter using one leg consisting of two IGBTs. The test results feeding 3-phase 4-wire loads for various conditions such as unbalanced loads, disconnection of one-phase, disconnection of two-phases (single-phasing) etc. are demonstrated. Moreover, the active power management with voltage and frequency control is observed along with variations in parameters such as generator voltages and currents ($V_{ab}$, $V_{abc}$, $V_{sca}$) and ($i_{a}$, $i_{b}$, $i_{c}$), the THD of source voltages ($P_{ab}$ THD, $P_{abc}$ THD, $P_{sca}$ THD), generated power of each phase ($P_{g}$), converter currents ($i_{ca}$, $i_{cb}$, $i_{cc}$), harmonic spectra of source currents ($i_{abc}$ THD), load currents ($i_{La}$, $i_{Lb}$, $i_{Lc}$), harmonic spectra of load currents ($i_{Labc}$ THD), load neutral current ($i_{Ln}$), source-neutral current ($i_{sa}$), and load powers ($P_{L}$).
4.1 | Performance at disconnection of the load on one-phase

Figure 7 and Figure 8 show the operation of this isolated system when the load is disconnected for one phase. In Figures 7a and 7b, the performance of hydro generator parameters, such as the three-phase current’s waveforms, three phase line voltages, source-neutral current waveform, generated three-phase hydropower, and the corresponding harmonic spectra of individual source currents and load current waveforms during this condition, are shown. In Figures 7c and 7d, the load parameters such as individual phase load powers when one phase is disconnected, the load neutral current waveform and the respective load current’s total harmonic distortion (THD) are shown. The current waveforms of the 4-leg VSC with power flow from solar PV-BES-coupled VSC to PCC are also shown in Figure 7d. As seen from these figures, the hydro system is producing a total power of 2.5 kW. The connected two-phase loads are consuming 0.777 kW of power. The net power produced from hydro and SPV sources amounts to a 4.1 kW; hence the battery should be able to absorb the rest of the power. The compensation of the source neutral current is performed by the fourth leg of the VSC despite the load neutral current being around 3.7 A. The THDs of all line-line voltages at PCC and line currents are less than 5% well within the IEEE standards [27]. Moreover, the terminal voltage and frequency are maintained constant despite the removal of the single phase of the load. In Figure 8a, the power absorbed by BES during this non-linear loaded condition is around 3 kW. This agrees with the above discussion regarding the excess power to be fed to BES.

Moreover, it also proves the power management capability of this system. Figure 8b to 8d show the dynamic performance during the same non-linear loading condition. Despite losing one phase of the load connected, the terminal voltage and frequency are maintained constant as seen from Figure 8b. The ‘a’ phase line to the neutral voltage is still sinusoidal as the same phase load is disconnected as seen in Figure 8c. The fourth leg of VSC always eliminates the source neutral current despite the increase in the neutral load current as seen in Figure 8d.

4.2 | Performance when two phases of the non-linear load are disconnected

In Figure 9, the performance of this system captured by the power quality analyser reading the load connected between

| TABLE 1 | Comparative control chart |

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<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>DC offset rejection</td>
<td>Medium</td>
<td>Medium</td>
<td>Poor</td>
<td>Excellent</td>
</tr>
<tr>
<td>Filtering order</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Accuracy</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
<td>Best</td>
</tr>
<tr>
<td>Steady-state oscillations</td>
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<td>Moderate</td>
<td>Less</td>
<td>Less</td>
</tr>
<tr>
<td>Settling time</td>
<td>Slow</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Fast</td>
</tr>
<tr>
<td>Dynamic response</td>
<td>Poor</td>
<td>Poor</td>
<td>Moderate</td>
<td>Best</td>
</tr>
<tr>
<td>Oscillations in I_dL</td>
<td>High</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Abbreviations: BPF, band-pass filter; HPF, high pass filter; MCCF, modified complex coefficient filter; NF, notch filter.

**FIGURE 5** Controller of the bidirectional converter (BDC)

**FIGURE 6** AP&O-based MPPT control technique
two phases is shown. The hydro generator line voltages at PCC and their currents including the neutral current waveform is seen in Figure 9a. Despite the non-linear single-phase loading as seen in Figure 9b, the source voltages are sinusoidal. The neutral source current is compensated as seen in Figure 9d, as the fourth leg VSC current is almost equal in magnitude to the load neutral current of 4.2 A. The hydro-generator power is 2.48 kW, and the PV array generates around 1.6 kW. Hence the total generation is 4.08 kW as observed in Figure 9a, but the connected load between two phases is only consuming 0.35 kW as seen from Figure 9c. Hence, rest of the excess power should be used to charge the BES.

The PV-BES-coupled VSC uses 2.07 kW power, and it is the difference between the generated power from the hydro generator and the power consumed by the load. The improvement in power quality is achieved since the THDs of all line-line voltages at PCC and line currents are less than 5%,
within the IEEE standards [27]. Moreover, the terminal voltage and frequency are maintained constant despite the two phase of the 3-phase 4-wire load are disconnected. Figure 10a shows that the battery voltage and power and as discussed previously, the battery is charging from the extra power. Moreover, during this loading, the PCC terminal voltage and frequency quickly settle down to its nominal value as seen in Figure 10b. From Figure 10c, when two phases are disconnected then the line to the neutral voltage of ‘a’ phase is still sinusoidal. Moreover, the source neutral current of the hydro-generator is also compensated as it is always maintained near to zero as seen in Figure 10d. This figure also shows that the increase in the load neutral current is balanced by the fourth leg VSC current.

4.3 | Performance at the No-load condition

At the no-load condition, the entire power generation in this system is utilised for charging the BES. As viewed in Figure 11a, the hydro system is generating 2.5 kW of power and since the connected PV array is generating almost 1.6 kW of power, the net generated power is 4.1 kW. However, there is no power consumption in the load due to the no-load condition. Moreover, the entire power generated in the system is fed to the BES. It is seen from Figure 11d that BES is charging with a power of 3.83 kW. During this no-load condition, the voltage and frequency are maintained constant. The system power quality is not affected as the generator source current THDs are within 5%, which is well with the IEEE-519 standard [27]. Moreover, the waveforms of the hydro generator source currents are observed to be the same as the compensator’s currents of VSC.

4.4 | Performance at varying solar insolation

The suggested AP&O- based approach achieves the MPPT efficiency as shown in Figure 12. The tracking effectiveness
of the AP&O MPPT technique has been evaluated at two distinct levels of solar insolation (1000 W/m² and 500 W/m²). As shown in Figure 12 (a–b), tracking efficiencies of over 99 percent have been obtained at both levels. As a result, the suggested MPPT approach has attained true MPP under variable insolation, demonstrating its efficacy and resilience in tracking behaviour. Figure 12 depicts the behaviour of a PV system with BES and its behaviour using dynamic fluctuations in solar insolation. The PV voltage ($V_{PV}$), which has only slightly changed as observed from Figure 12c. In Figure 12c, the dynamic variations in PV performance, such as current ($I_{PV}$), voltage ($V_{PV}$), PV power ($P_{PV}$), and BES, are illustrated for different amounts of solar insolation and back.

The battery overcharging is limited to 300 V SOC, after which the BES switches to the floating mode and the PV
array is derated until the BES voltage falls below the specified limit, protecting it from overcharging. Figure 12(d) depicts its dynamic performance. In this diagram, the surplus power should charge the BES when the load is suddenly removed, but the battery current is lowered to practically zero and the PV array output is derated to preserve the hybrid system’s active power balance.

4.5 | Comparative performance of MCCF control

Figure 13 shows the comparative dynamic and steady-state responses of the MCCF-based control with conventional controls such as BPF [23] and HPF [25]. Figure 13 also shows that the MCCF-based control has the lowest oscillations while estimating the fundamental component of the load current. During the dynamic load change, the performance of the MCCF-based control is also observed to have smooth transition. As shown in the simulated results and Table 1, the rest of the algorithms have oscillation problems while estimating the fundamental component of the load current except NF [26]. However, this control fails to eliminate the DC offset present in load currents.

5 | CONCLUSION

An implementation of the presented system has been successfully carried out using the MCCF-based control. The experimental validations for various loading conditions of this system on the prototype developed in laboratory are presented successfully. The ease of implementation of the system for fundamental component extraction, removing harmonics and its effectiveness are clearly visible in the test results. The THDs of voltages at PCC and the currents of the hydro-generator are always observed to be less than 5% in compliance with the IEEE-519 standard [27]. The solar PV system and BES coupled to PCC via VSC are able to support the isolated system during dynamic load fluctuations by exchanging active power. The suggested AP&O MPPT control scheme provides fast dynamic performance subjected to changes in solar irradiance. Such isolated systems are highly beneficial for supplying power to remote areas where the availability of the grid is impossible.
FIGURE 11  Test result of system at the No-Load condition
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DATA AVAILABILITY STATEMENT
Data openly available in a public repository that does not issue DOIs.

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REFERENCES

APPENDICES

A. DC-link voltage

\[
V_{dc} = \frac{2\sqrt{2} \times \left(\frac{V_{dc}}{\sqrt{3}}\right)}{m_s} = \frac{2\sqrt{2} \times \left(\frac{220}{\sqrt{3}}\right)}{3} = 359.258V
\]

Selected value is 400 V for optimum operation.

B. DC-link capacitor

\[
C_{dc} = \frac{I_{dc}}{2\omega_s \Delta V_{dc}} = \frac{10.25}{2 \times 2 \times \pi \times 50 \times \left(0.02 \times 400\right)} = 2039.17\mu F
\]

where,

\[
I_{dc} = \frac{P_{dc}}{V_{dc}} = \frac{4100}{400} = 10.25A
\]

Selected value is 2700 µF for optimum operation.

C. Interfacing inductors
\[ L_f = \frac{\left(\sqrt{3}/2\right) \times m_a \times V_{dc}}{6 \times f_{c,pp}} = \frac{\left(\sqrt{3}/2\right) \times 1 \times 400}{6 \times 1.2 \times 10^3 \times 0.1 \times 10.25} = 4.69mH \]

**D. Design of BES**

\[ Ab = \frac{(P_{gen} - P_{load}) \times t(brs)}{V_{bat}} = \frac{(4100 - 0) \times 3}{240} = 51.25Ab \]

**E. Prime mover characteristics**

The DC motor behaves as a prime mover in the developed prototype instead of the speed governor used in the conventional hydro scheme. The frequency control at VSC is used for frequency control instead of a speed governor at the turbine in order to make the system frequency independent of the mechanical inertia of the turbine generator system. Moreover, the turbine characteristic of such system is given as \( T_{sh} = k_1 - k_2 \times \omega_m \).

**F. Frequency controller**

\( K_{pf} = 0.45, K_{if} = 0.005 \) Controller parameters: \( K_1 = 4, K_2 = 5, \omega_g = 314.16 \text{ rad/sec} \).

**G. Sampling time and PI parameters**

\( T_s = 30 \mu s, K_{pv} = 0.02, K_{iv} = 0.15, \) BDC PI Controller: \( K_{pbdc} = 0.1, K_{ibdc} = 0.025. \)

**H. Solar PV**

\( P_{pv} = 1.6 \text{ kW}, V_{pv} = 405 \text{ V}, I_{pv} = 4 \text{ A} \) (at insolation of 1000 W/m²).

**I. Hydro generator and Ripple Filter**

3.7 kW, 220 V Star-connected, ripple filters \( C_f = 10 \mu F, R_f = 5 \Omega. \)