

Research Paper

Modified sliding mode control for seamless integration of P.V. energy in A. C. grid

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ABSTRACT

Solar energy is a potentially abundant and reliable source of renewable energy. While it can undoubtedly increase grid reliability and efficiency, the inverted voltage generated from P.V. sources may introduce distortion into the A.C. grid. The proposed control mechanism, modified sliding mode control (MSMC), can seamlessly integrate the inverter output generated by obtaining D.C. voltage from the boost converter linked with the P.V. output. This research confirms the validity of the proposed method by comparing its results with a similar system that is only integrated through filters and with a system with a P.I. control technique. The simulation proves the effectiveness of seamlessly integrating the Photovoltaic (P.V.) source into the A.C. grid.

1. Introduction

The capacity to generate electricity when solar energy is not accessible is one of the main advantages of integrating solar power into the A. C. grid. Hybrid systems can guarantee a stable supply of electricity that satisfies demand by mixing solar power with other sources like wind, hydropower, or gas-fired generators (Díaz et al., 2019; Soomar et al., 2023). It is crucial when solar power production is limited in high demand.

Storage of additional power produced during sunny hours for later usage is another benefit of integrating solar electricity into the A.C. grid. Batteries or other energy storage technology can be used for this. The requirement for additional energy sources can be decreased by using the stored energy to meet demand when solar power production is low. By substituting renewable energy sources for fossil fuels, hybrid solar power systems have the potential to lower greenhouse gas emissions (Awosusi et al., 2022). This can enhance air quality and lessen the effects of climate change. Incorporating hybrid solar power systems into A.C. grids can support the transition to a low-carbon economy, assure a sustainable and stable electricity supply, and reduce greenhouse gas emissions (Hashim and Ho, 2011).

A boost converter increases the D.C. voltage solar panels generate to the level the inverter needs. In solar power systems, boost converters are employed to ensure that the D.C. voltage generated by the solar panels is suitable for the inverter's conversion to A.C. power (Steimer and Manjrekar, 2001). The solar inverter, on the other hand, is a component that transforms the D.C. electricity generated by the boost converter into A.C. power. The inverter creates A.C. electricity, which is timed and fed into the A.C. grid. Using the pulse width modulation (PWM) method, the inverter transforms the D.C. voltage into a high-frequency A.C. voltage (Blaabjerg, 1997). The desired A.C. voltage and frequency for the A.C. grid are then created by filtering the high-frequency A.C. voltage. To reduce losses and guarantee that the most significant amount of power is sent to the A.C. grid, the inverter must be built to operate in such a way that it may get integrated into the A.C. grid smoothly, and an intelligent control design for the inverter is necessary to incorporate a solar power system into an A.C. grid. The proper control design is required to guarantee that the system runs safely and effectively and that the voltage and power factor are within reasonable bounds.

Here, modified sliding mode control (MSMC) describes a mutual control mechanism that works on the combined effect of a traditional power of sliding mode control (SMC) and phase-locked loop (PLL). PLL

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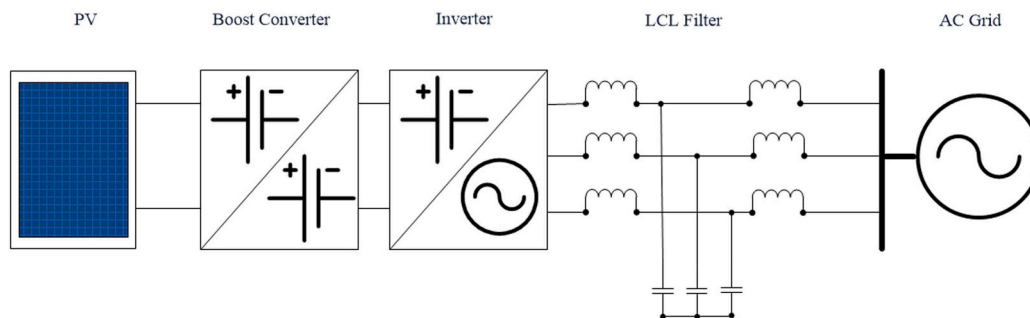
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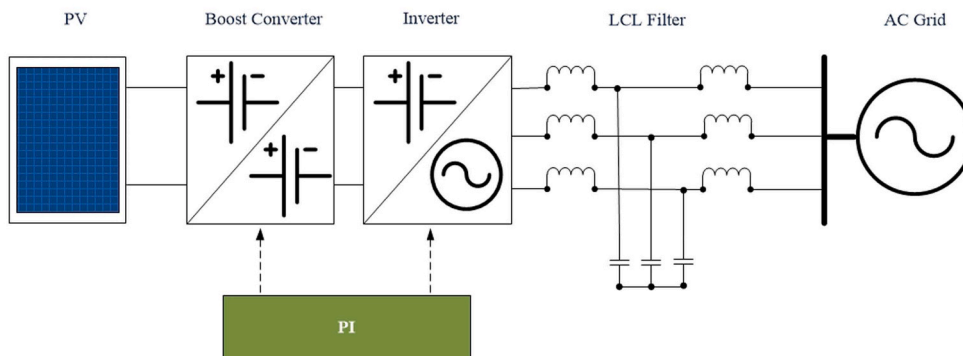
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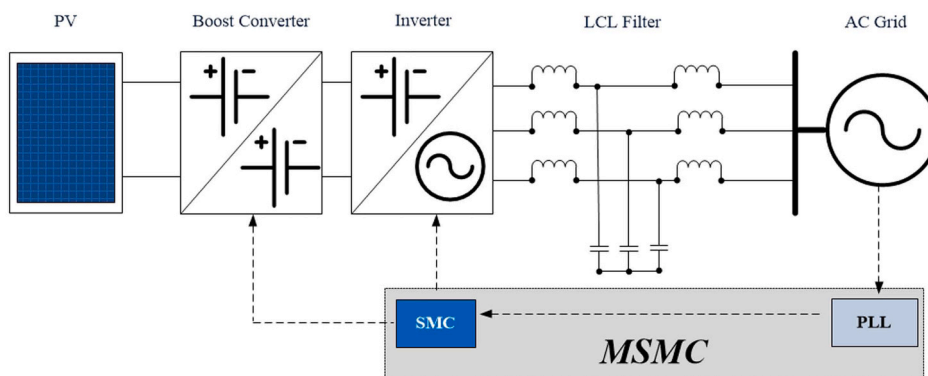
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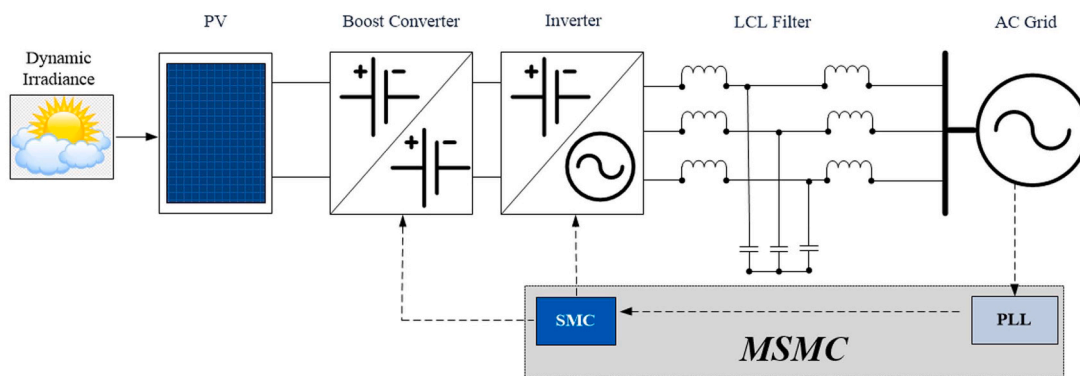
Case 1



Case 2



Case 3



Case 4

Fig. 1. Abstractable representation of the paper.

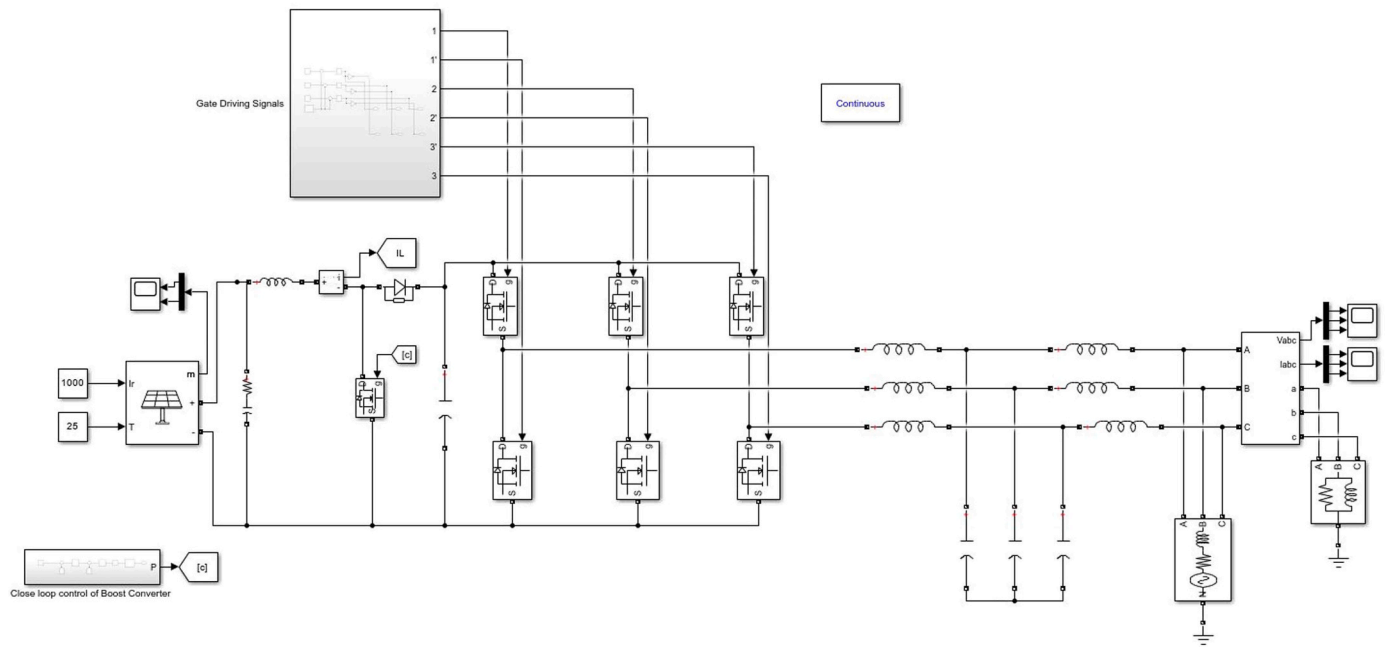


Fig. 2. Simulation model for Case 1.

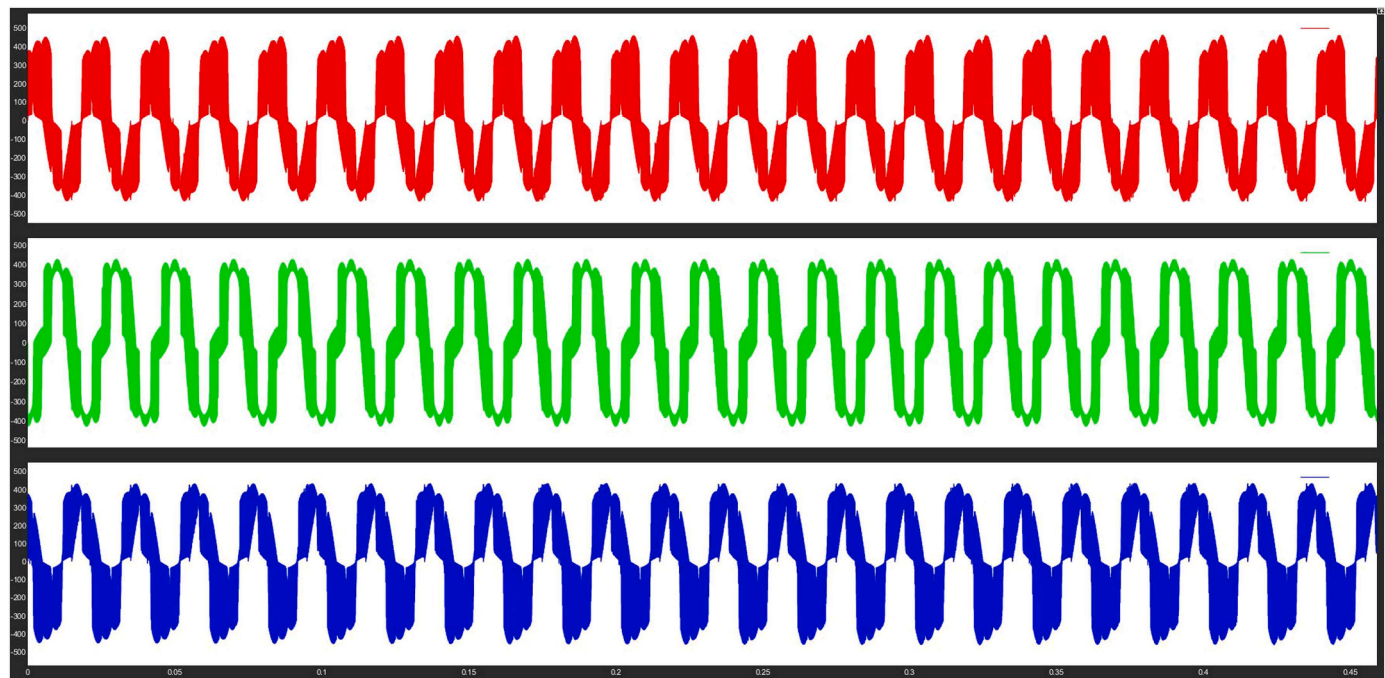


Fig. 3. Three-phase grid line voltage with no control mechanism.

is a control method that matches the grid voltage with the inverter output voltage. The PLL measures the grid voltage as a reference signal to produce a synchronized output voltage. To preserve grid stability and minimize harmonic distortion, the PLL ensures the inverter output voltage synchronizes with the grid voltage. The PLL is constructed by determining the grid voltage's phase angle and frequency and creating a reference signal for the inverter output voltage. Any phase or frequency errors are then determined by comparing the reference signal and the inverter output voltage.

On the other hand, SMC is a control method that manages an inverter's output voltage and current. The SMC tracks the required output

voltage and current by continuously altering the control input to the inverter. When the grid voltage is unpredictable or there are changes in load demand, the SMC is beneficial. Despite grid voltage or load demand variations, the SMC modifies the inverter input to maintain a consistent output voltage and current. The system dynamics and control objectives must be carefully considered before PLL and SMC are implemented in the inverter control design. The PLL and SMC are designed to operate in unison to ensure that the inverter output voltage and current are controlled and synchronized with the grid voltage.

While integrating solar-generated inverter output into the A.C. grid offers many benefits, there are also some drawbacks, such as voltage and



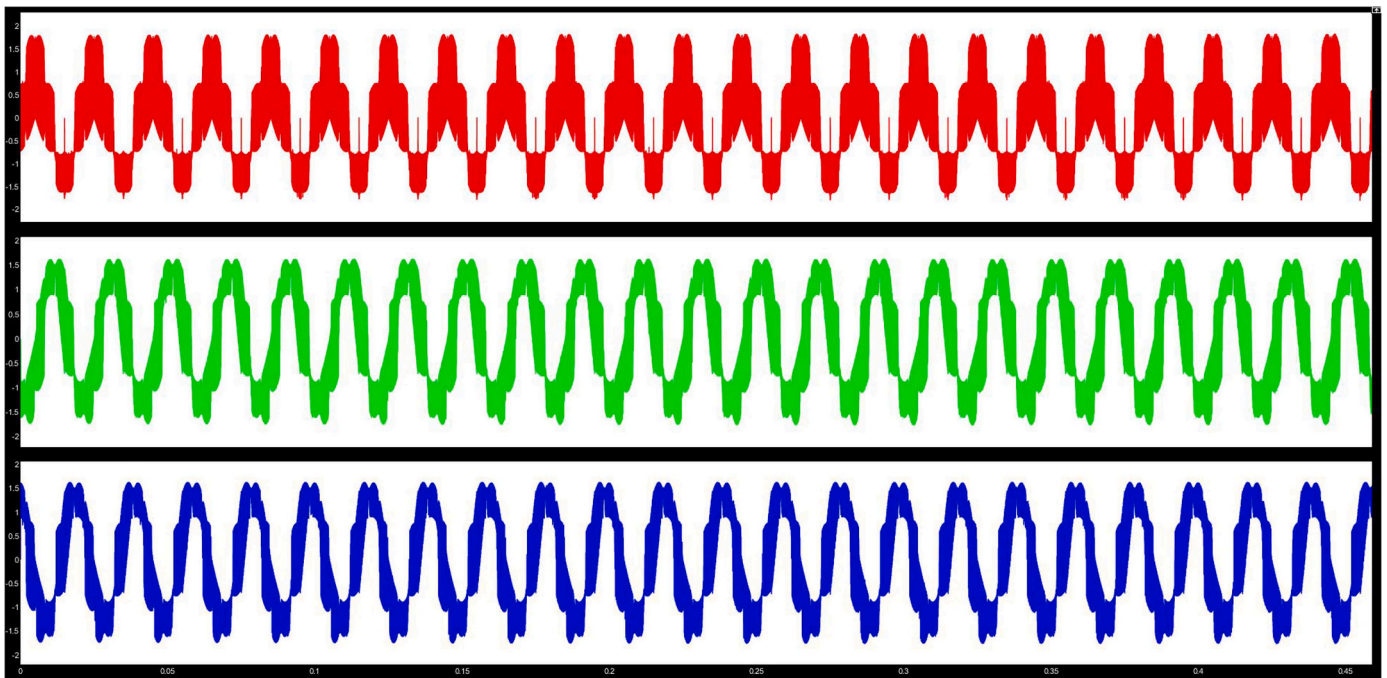


Fig. 4. Three-phase grid line current with no control mechanism.

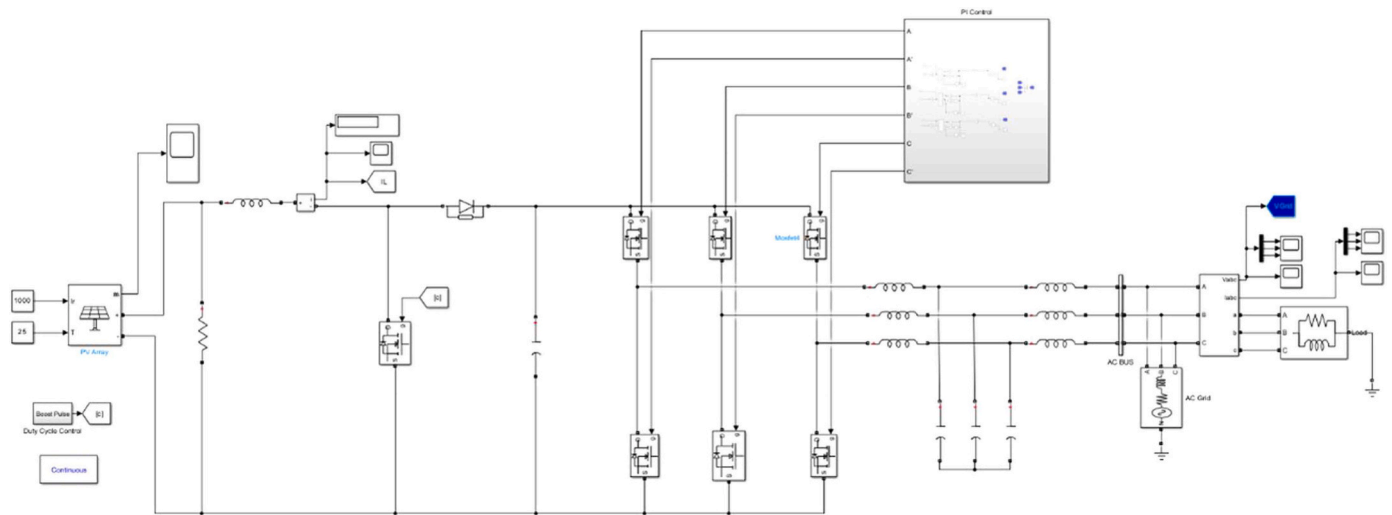


Fig. 5. Simulation model for Case 2.

current waveform distortion (Wang et al., 2010). A.C. grids' voltage and current waveforms are intended to be pure sine waves with a predetermined frequency and amplitude. However, the output of solar inverters is often a modified sine wave or a square wave, which, when integrated into the A.C. grid, can lead to distortion in the voltage and current waveforms. Voltage and current waveform distortion can raise losses in the power system, resulting in decreased efficiency and higher operating costs. The functioning of sensitive equipment in the power system may be impacted by harmonic distortion, voltage flicker, and electromagnetic interference brought on by the distortion of voltage and current waveforms (Liu et al., 2018a) Voltage and current waveform distortion can result in safety issues, including electric shocks and equipment damage, which can put workers and the public at risk.

The output of solar inverters is generally a modified sine wave, which can cause distortion in the voltage and current waveforms when integrated into the A.C. grid. Waveform distortion caused by voltage and

current can increase power system losses, which lowers system efficiency and raises operating expenses. Harmonic distortion, voltage flicker, and electromagnetic interference caused by the distortion of voltage and current waveforms can affect the operation of sensitive equipment in the power system (Liu et al., 2018a). Waveform distortion caused by voltage and current can lead to safety problems, such as electric shocks and equipment damage, endangering both the public and relevant workers. This research introduces a modified sliding mode control that can provide seamless integration of the P.V. output into A.C. grid and thereby preventing the potential harms.

Fig. 1 shows an abstract representation of the concept. To address these issues, it is crucial to design a seamless integration mechanism that can smoothly integrate solar power into the A.C. grid and produce a sine wave output compatible with the A.C. grid. Here, a concept of modified sliding mode control is depicted to seamlessly integrate inverted solar power into the A.C. grid.

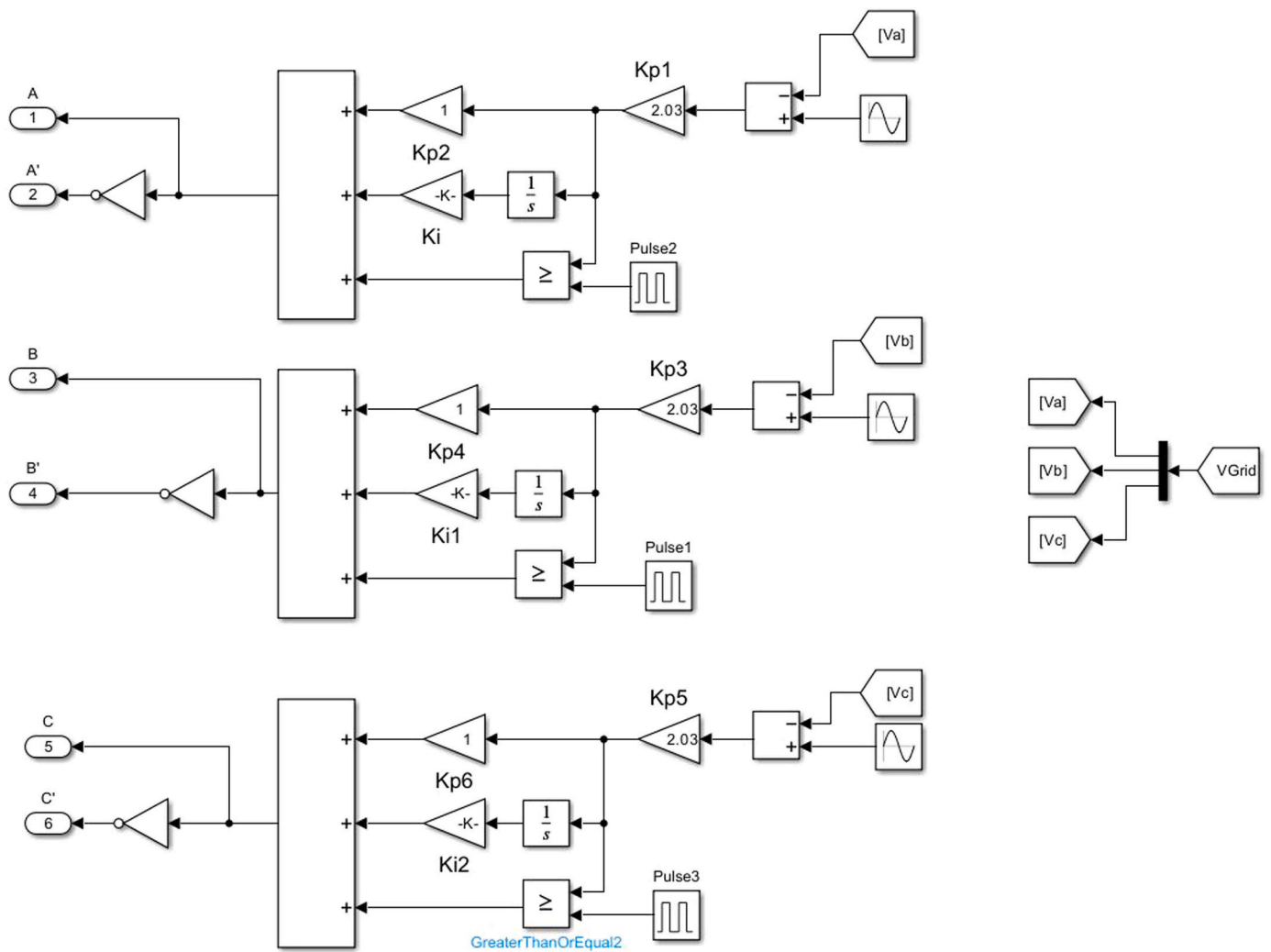


Fig. 6. P.I. control loop for integration of P.V. power into A.C. grid.

2. Literature review

The boost converter is a DC-DC converter used in P.V. systems to increase the voltage of the D.C. power generated by the P.V. panels to a level compatible with the grid or other loads. The duty cycle of the boost converter can be adjusted to control it, and it may include protection features to prevent system damage (Reatti et al., 2019). The efficiency of the boost converter is an essential consideration in designing a P.V. system, and it can be used in conjunction with an MPPT controller to maximize the energy output of the P.V. panels. Inverters are electronic devices that convert D.C. (direct current) power to A.C. (alternating current) power. Inverters are used in photovoltaic (P.V.) systems to convert the D.C. power generated by the P.V. panels into A.C. power that can be fed into the grid or used to power A.C. loads. Inverters can be controlled using various schemes to optimize performance and efficiency (Singh et al., 2019).

The four-leg interleaved boost converter (FLIBC) coupled to photovoltaic panels (P.V.) is the subject of this paper's proposed control approach, which uses a proportional-integral (P.I.) controller optimized with particle swarm optimization (PSO) (Daia Eddine O et al., 2022).

A PLL-based control method for integrating a grid-connected solar P.V. system was proposed in the control mechanism can provide faster integration with the grid to obtain the proper system synchronization (Priya et al., 2018). To integrate a grid-connected solar P.V. system, research in (Reveles-Miranda et al., 2020) developed a hybrid control

mechanism that integrated P.I. and phase-shift control. The grid's power quality was maintained via the control mechanism.

The unique high-performance control approach for a three-phase solar grid-connected inverter is proposed in this paper and is based on fuzzy logic. Using a digital signal processor controller board, the method produces sinusoidal pulse width modulated signals for inverter operation. After construction and testing, an inverter prototype showed stable A.C. output voltage in both transient and steady states with minimal harmonic distortion (Hannan et al., 2015).

Using cascaded multilevel inverters (MLIs) connected to the three-phase grid, this research suggests a more straightforward feedforward distributed maximum power point tracking (MPPT) solution for photovoltaic (P.V.) systems. To solve the problem of partial shading of P.V. modules, the suggested solution employs phase-shift pulse width modulation (PS-PWM) and a modified modulation compensation mechanism. The technique is used in a 15 kW P.V. system and has performed better than earlier attempts described in the literature (Elmelegi et al., 2019).

To achieve stable closed-loop performance, the photovoltaic inverter design in this study employs a Cuk switched mode power supply (SMPS) and a sliding mode control strategy. This control mechanism makes using smaller, more dependable non-electrolytic capacitors possible. By building a prototype inverter, the design has been put to the test (Knight et al., 2006).

For a three-phase grid-tied single-stage photovoltaic system

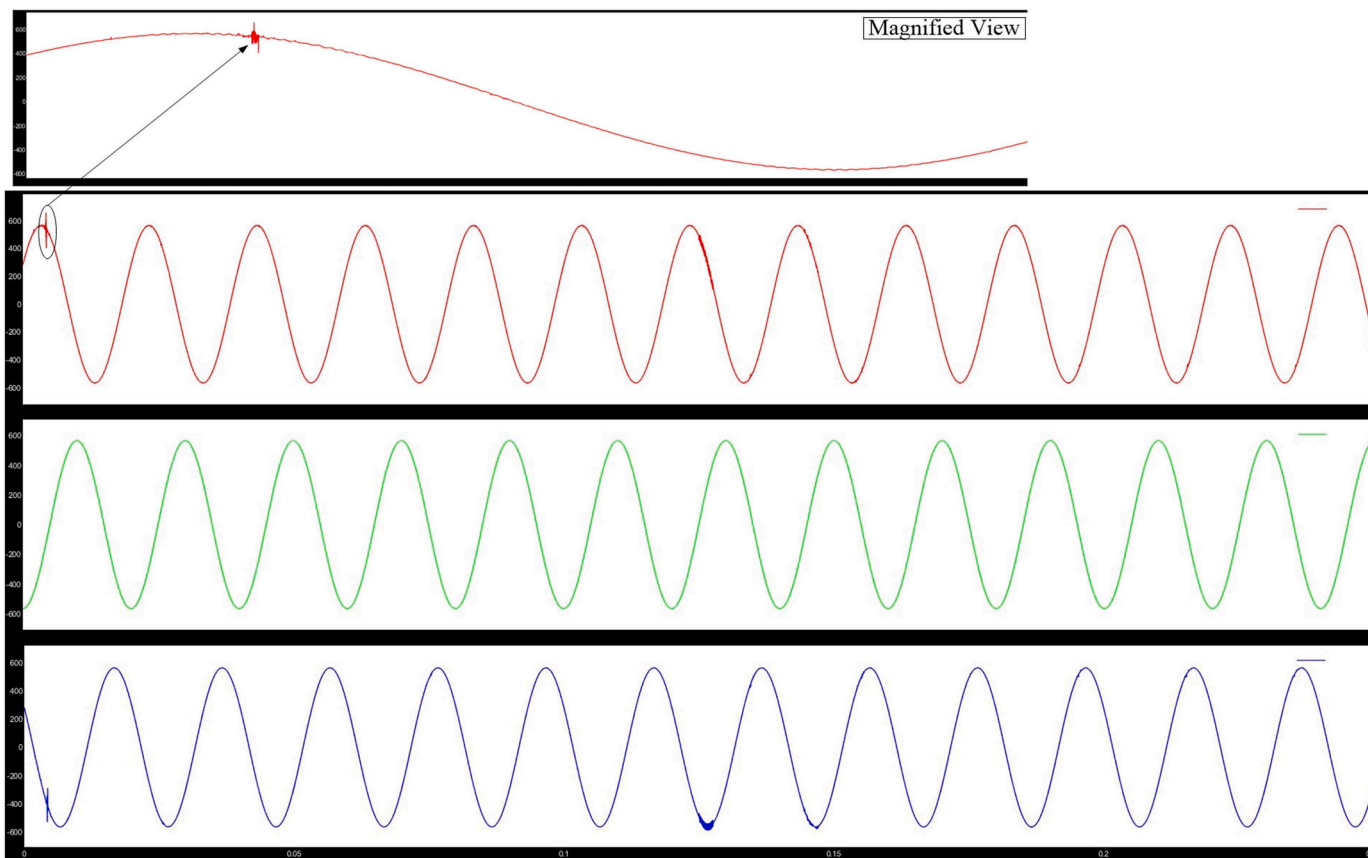


Fig. 7. Magnified view of Three-phase grid line voltage with P.I. control.

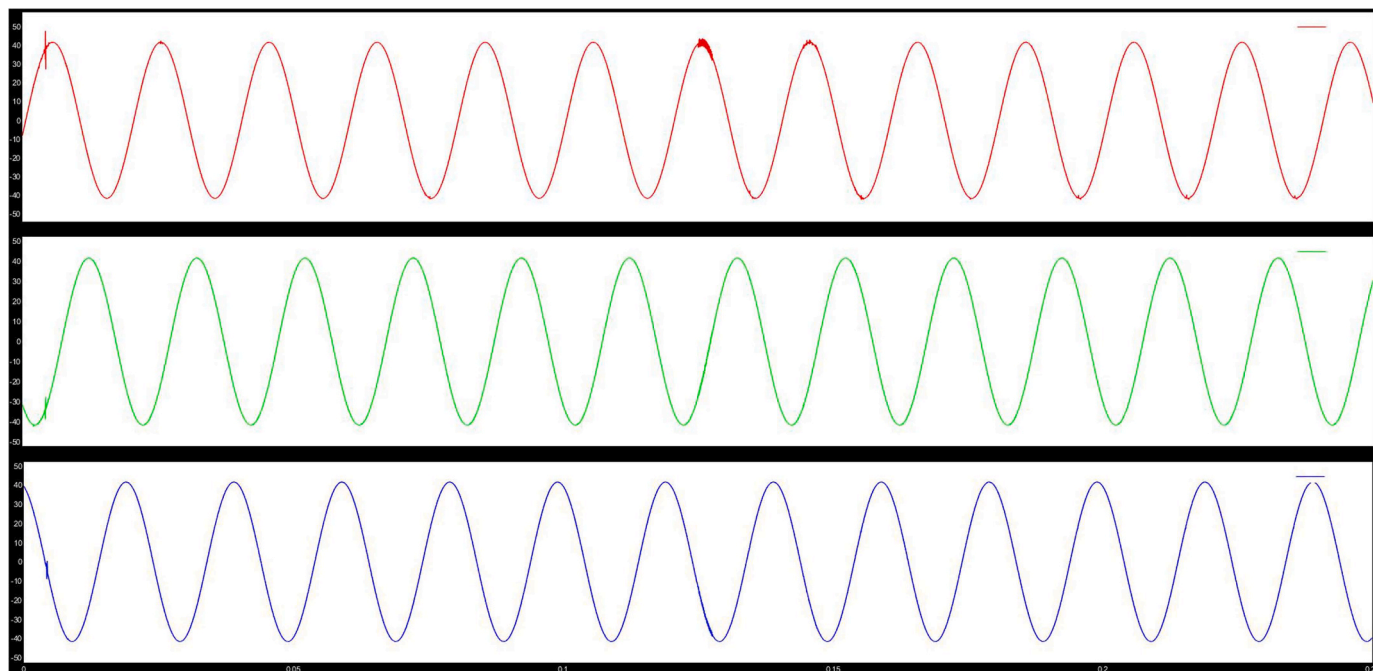


Fig. 8. Three-phase grid line current with P.I. control.

(GTPVS), the research suggests a reliable generalized modified Blake-Zisserman adaptive filter (GMBZAF)-based control strategy to enhance power quality. The GMBZAF-based control scheme may preserve balanced sinusoidal grid currents, reduce current harmonics, and

provide reactive power to the inductive load in fluctuating load and irradiance. The results are presented in MATLAB/Simulink, and the suggested control method is contrasted with the current adaptive filtering-based control schemes, such as LMS and LMF (Karthik et al.,



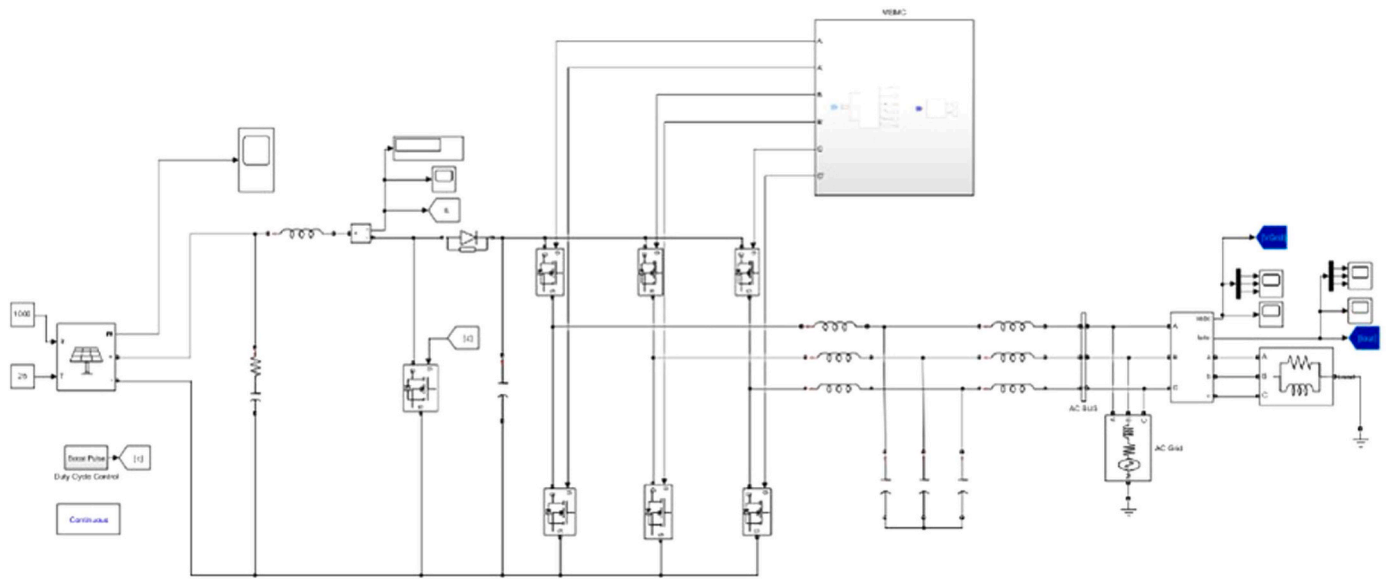


Fig. 9. A simulation model for Case 3.

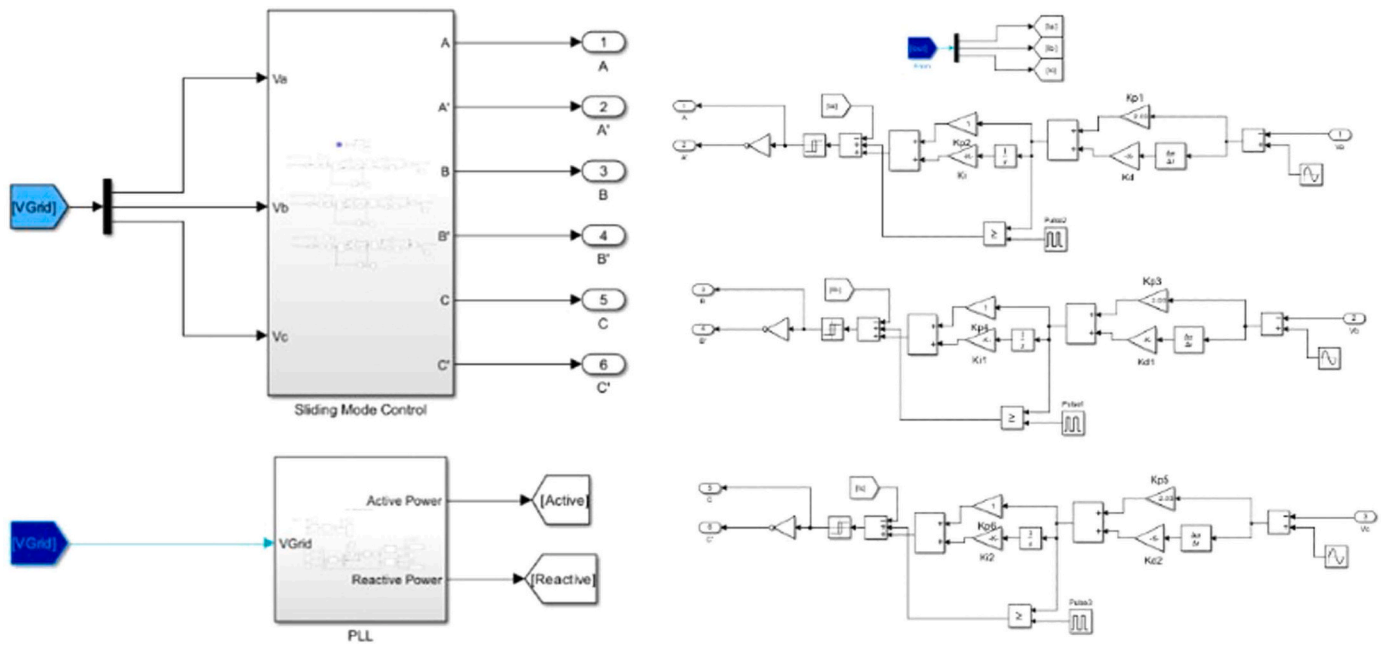


Fig. 10. MSMC control for seamless integration of P.V. power into A.C. grid.

2022).

Multiple types of multi-level inverters (MLIs) and their modulation and control strategies for grid-connected photovoltaic (P.V.) systems are covered in this research. With a better power factor, the MLI's low-harmonic staircase output voltage can be injected into the grid. Future developments are highlighted as various control strategies for single-phase and three-phase grid-connected MLI-based PV systems are compared and explored (Sinha et al., 2018).

An active neutral point clamp (ANPC) inverter topology is presented in this article for the grid integration of solar P.V. systems with fewer switches and flying capacitors. The suggested inverter eliminates the voltage balancing issues that typical ANPC inverters have and provides galvanic isolation by using a high-frequency transformer and a model predictive control technique. The power conversion system is dependable for P.V. power plants, the control method is straightforward, and

the topology has been confirmed through simulation and laboratory testing (Mahfuz-Ur-Rahman et al., 2020).

The maximum power point tracking (MPPT) technique for a photovoltaic (P.V.) system is presented in this research and is based on adaptive sliding mode control. The suggested method uses an adaptive sliding mode controller (ASMC) to drive a boost converter between the P.V. generator and the load. The effectiveness of the proposed technique is shown through simulation results using actual data in MATLAB-SIMULINK, and the robustness and stability of the ASMC controller are examined in changing weather conditions (Kchaou et al., 2017).

The research suggests a modified pq-theory-based control for a solar P.V. array that combines clean energy production and power quality enhancement. Even though the point of standard coupling (PCC) voltages are distorted, the fundamental-frequency positive-sequence components of PCC voltages can be extracted for pq-theory-based control

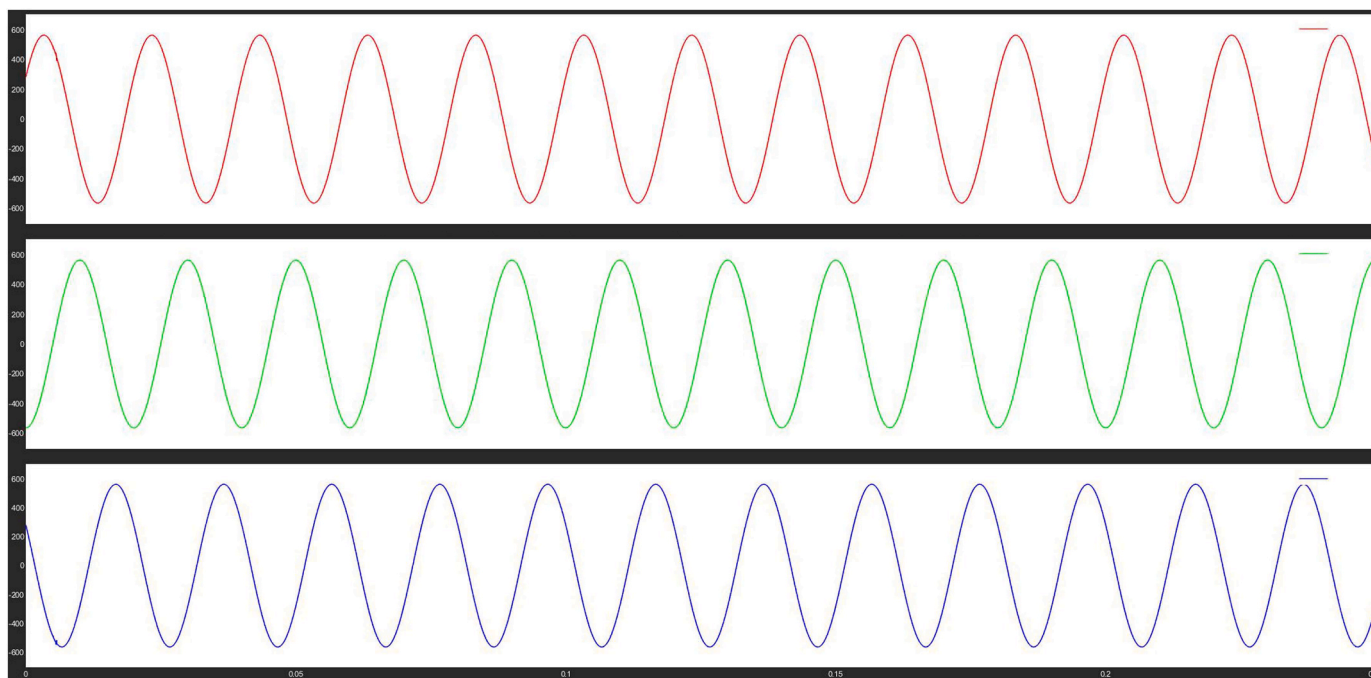


Fig. 11. Three-phase grid line voltage with MSMC.

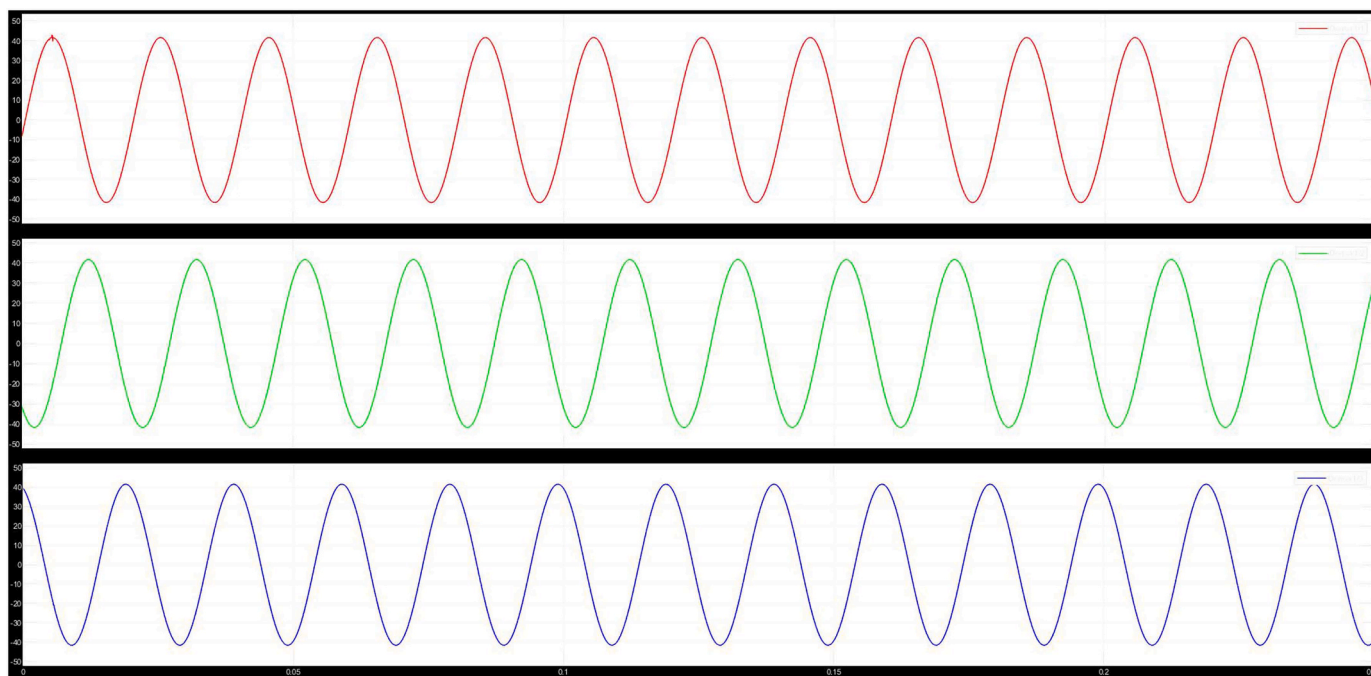


Fig. 12. Three-phase grid line current with MSMC.

using the generalized cascaded delay signal cancellation technique.

To estimate the inductor current and output voltage, a switched observer is used in the paper to offer a current sensor-free control method for a boost dc/dc converter. For the average model of the converter, which consists of a voltage loop and a current loop, a proportional-integral controller in the outer circle and a second-order sliding mode controller based on a super-twisting algorithm in the inner loop are used as the control structures. The simulation results demonstrate that the suggested strategy is successful (Devassy and Singh, 2017).

This research suggests a two-mode control technique for grid-

connected AC/DC hybrid microgrids operating under weak grid conditions using bidirectional power converters. The method relies on short-circuit ratio identification, voltage source control, current source control, and system inertia to achieve steady operation. Results from simulations show the effectiveness (Liu et al., 2018b).

The control method for large-scale photovoltaic power plants that employ DC-collective boosting and delivery techniques is suggested in this research. The proposed approach is based on the input parallel output series (IPOS) topology and uses an optimized decoupling dual synchronous reference coordinate system phase-locked loop (DDSRF-PLL) for positive and negative sequence dual current loop control in

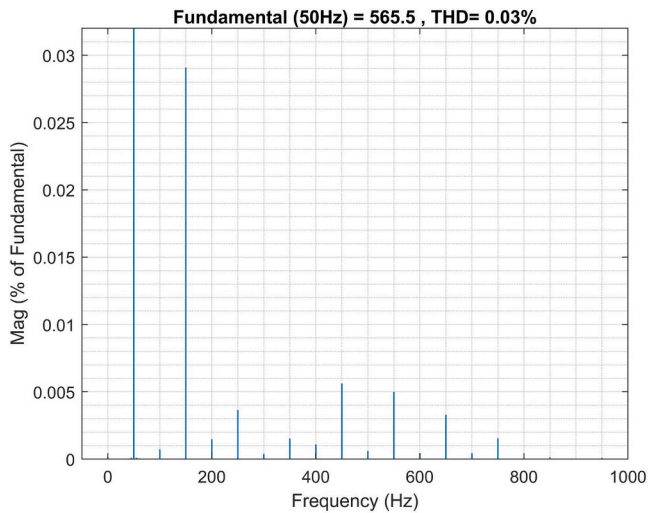


Fig. 13. THD response of the output voltage of A.C. grid.

conjunction with a DC-boost converter dynamic output voltage compensation control. The suggested approach successfully reduces the impact of the D.C. bus's over-voltage and negative-sequence components on the grid-connected current, and a soft start control approach is recommended to reduce the system's overcurrent. The simulation results demonstrate that the proposed strategy is successful (Wang et al., 2021).

The resilient nonlinear controller for voltage source converters (VSCs) connected to weak A.C. grids is proposed in this study. The feedback linearization method creates the control inputs for the grid-connected converter's active power and output voltage. The suggested controller is demonstrated to be resilient to unexpected active power orders and can ride through faults when the A.C. grid is highly unreliable. Eigenvalue analysis of the linearized closed-loop model and time-domain simulations are used to assess the proposed controller's robustness (Fan et al., 2019).

This article gives a general overview of microgrids, which are

regarded as the basic building block of an intelligent grid. It explains the procedures and controls used in microgrid operation, such as load sharing, isolation during faults, and voltage matching. The article briefly describes the four primary control approaches used in microgrids and the many technical difficulties that arise during microgrid operation in grid-connected and freestanding modes. The essay also explores alternative strategies for microgrid integration and innovative grid features, research intervals, and future scope (Khazaee et al., 2021).

This study proposes a Novel Adaptive Filter (NAF), an enhanced version of the traditional Adaptive Vectorial Filter (AVF), to control the best grid-integrated solar P.V. generating systems. The NAF can handle phase imbalance and phase shift problems. The suggested method attempts to supply excess power to the grid while supplying solar P.V. power generated to meet the active power requirements of loads. The NAF-based control also offers harmonics filtering, power factor correction, and other power quality problem mitigation. The proposed method is experimentally verified under various grid disturbances and solar insolation variations (Sarathkumar et al., 2023).

This study compares the traditional finite-set model-based predictive current control (FS-MPC), and a novel fixed switching frequency approach for grid-connected neutral-point clamped voltage source converters. According to simulation data, both plans are effective at integrating renewable energy, with the FS-MPC offering a marginally better D.C. bus balance and the new program enhancing current quality and spectrum characteristics. The comparison also considers control criteria regulations and merit statistics (Kumar et al., 2019).

The research suggests a modified fuzzy logic controller (FLC) method for grid-connected photovoltaic (P.V.) systems' maximum power point tracking (MPPT). It has been demonstrated that the suggested FLC can track full power under typical and unusual solar radiation circumstances. The interface between the P.V. panels and the load is a boost converter, and the output voltage is converted to A.C. voltage by an inverter based on a proportional-integral (P.I.) controller. The efficiency of the suggested control is demonstrated by the simulation results produced by MATLAB/Simulink (Rivera et al., 2021; Shaikh et al., 2022; Guanghai et al., 2024).

This study suggests a dual-loop control structure for single-phase shunt active power filters (SAPF) that uses feedforward control to



Fig. 14. Dynamic irradiance for Case 4.

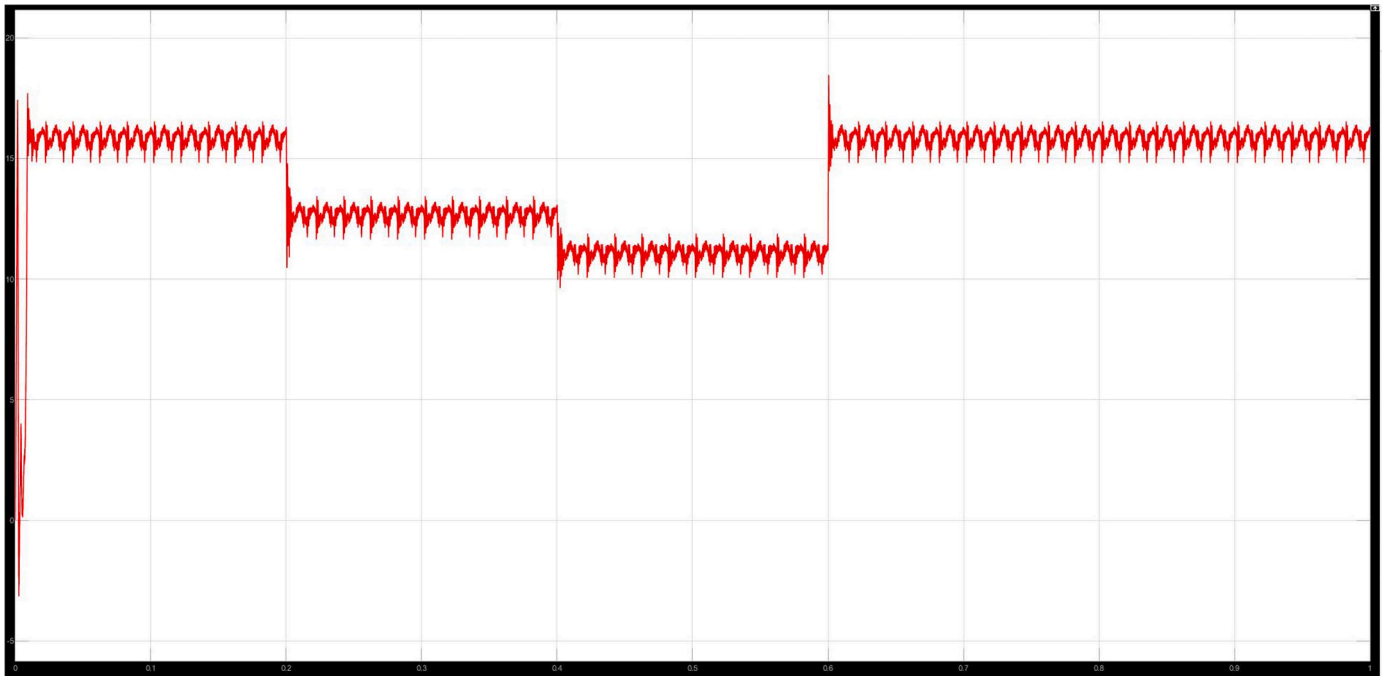


Fig. 15. Current response of dynamic irradiance.

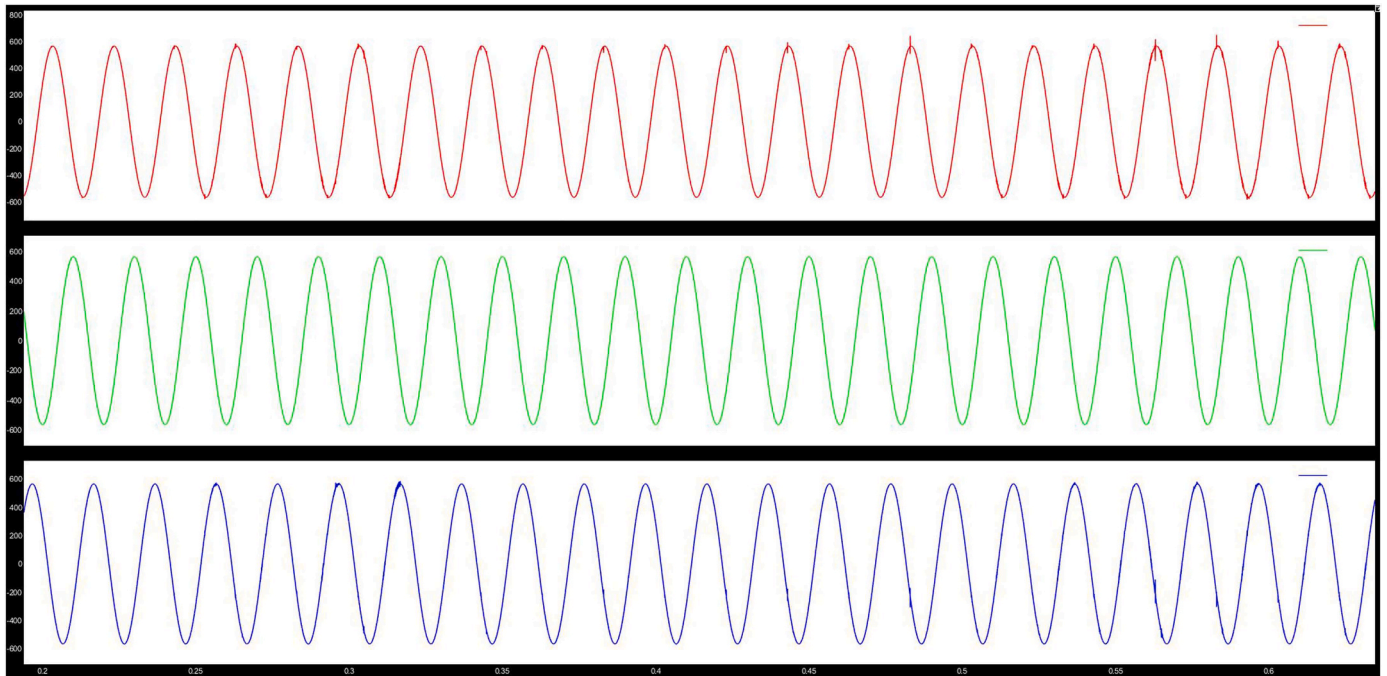


Fig. 16. Output voltage response on dynamic irradiance.

reduce grid voltage disturbance and a plus-in repetitive controller as the outer loop controller. To produce a quick transient response and to make the design of the external loop controller more straightforward, the inner loop P.I. controller alters the frequency response of the LCL filter. The performance of feedforward control, the stability and robustness of the dual-loop control system, and experimental results that demonstrate good steady-state performances, quick transient response, sound grid voltage attenuation, and robustness to variations in LCL filter parameters are all thoroughly analyzed in this paper (Brahim et al., 2022; Zhang et al., 2021).

3. Methodology

Photovoltaics (P.V.) use solar arrays to convert sunlight into electricity. When exposed to sunlight, these solar panels produce direct current (D.C.) electricity. Solar panels generate direct electricity, but most power grids and electrical systems use alternating current (A.C.). To be effective, solar power must be integrated into the A.C. grid, the leading electrical distribution network that supplies energy to homes, businesses, and industries. A boost converter is an electronic device that raises the voltage of direct current electricity. A boost converter is used

to integrate solar power into the A.C. grid to increase the low voltage generated by the solar panels to a higher level suitable for conversion and integration into the grid. An inverter is a device that converts direct current (D.C.) electricity into alternating current (A.C.). Because solar panels generate D.C. power and the A.C. grid operates on A.C. power, the D.C. power from the boost converter must be converted into A.C. power before it can be fed into the grid by an inverter. Because it is dependent on the availability of sunlight, solar power is classified as an intermittent energy source. Cloudy or nighttime conditions will result in lower or no power generation from solar panels. When solar power is available, it must be integrated into the A.C. grid efficiently and smoothly. Similarly, if solar power generation fluctuates or ceases due to weather changes, the transition from solar to other sources (e.g., fossil fuels or other renewable sources) should occur smoothly and without causing grid disruptions. Various technologies and control mechanisms can be used to achieve this seamless integration. For example, energy storage systems such as batteries can store excess solar energy when production is high and return it to the grid when production is low. Furthermore, advanced control algorithms and forecasting techniques can be used to predict solar power generation patterns and assist grid operators in more effectively managing power flow.

3.1. Mathematical modeling

Sliding mode control for the boost converter is developed for constant power load. It can be fed through a boost converter, and the amount of the cloud's current amount—the mathematical modeling in Eq. (1) to (b) is discussed in (Martinez-Treviño et al., 2019)

$$i_L = \frac{P}{V_{C1}}, \quad V_{C1} \geq v_g \tag{1}$$

Where $P > 0$ is the power absorbed by the, v_g is the input voltage and V_{C1} is the output capacitor voltage. The corresponding state equations can be expressed in a compact form in (2) and (3):

$$\frac{di_{L1}}{dt} = -\frac{V_{C1}}{L_1}(1 - u_1) + \frac{v_g}{L_1} \tag{2}$$

$$\frac{dv_{C1}}{dt} = \frac{i_{L1}}{C_1}(1 - u_1) + \frac{P}{C_1 v_{C1}} \tag{3}$$

The converter behaviour in each topological state is now analysed by obtaining the corresponding state vector trajectories in the $i_{L1} - v_{C1}$ phase plane. Analysis of the trajectories for $u_1 = 1$. The differential equations in (2) for $u_1 = 1$ lead to

$$i_{L1} = i_{L1}(0) + \frac{v_g}{L_1} t \tag{4}$$

$$\frac{dv_{C1}}{dt} = \frac{P}{C_1 v_{C1}} \tag{5}$$

Solving for t in (5) results in

$$t = \frac{(i_{L1} - i_{L1}(0)) L_1}{v_g} \tag{6}$$

Introducing the change of variable, $v^2 C_1 = z$, so that $z = 2v_{C1} \dot{v}_{C1}$ this non-linear equation becomes

$$z = -\frac{2P}{C_1}$$

Solving (5), and introducing (4) yield

$$z(t) = z(0) - \frac{2PL_1}{C_1 v_g} (i_{L1} - i_{L1}(0)) \tag{7}$$

Where $z(0) = i_{L1}(0)$ are the initial conditions of $z(t)$ and $i_{L1}(t)$, respectively, hence of voltage $V_{C1}(0)$,

$$V^2 C_1 = V^2 C_1(0) - \frac{2PL_1}{C_1 V_g} (i_{L1} - i_{L1}(0)) \tag{8}$$

From (7) the phase-plane trajectory during the ON state is given in Eq. (10),

$$i_{L1}(t) - i_{L1}(0) = \frac{C_1 V_g}{2PL_1} (V^2 C_1(0) - V^2 C_1) \tag{9}$$

Hence, (8) represents a parabolic curve which is illustrated in that intersects axes i_{L1} and V_{C1} at the points P_a and P_b respectively given by (10) and (11),

$$P_a = \left(\frac{i_{L1}(0)2PL_1 + C_1 v_g^2 c_1(0)}{2PL_1}, 0 \right) \tag{10}$$

$$P_b = \left(\sqrt{\frac{v^2 c_1(0)C_1 v_g + 2PL_1 i_{L1}(0)}{C_1 V_g}}, 0 \right) \tag{11}$$

Analysis of the trajectories for $u_1 = 0$. The state equation in (2) for $u_1 = 0$. Lead to the (12) and (13),

$$\frac{d^2 v_{C1}}{dt^2} - \frac{P}{C_1} \frac{1}{v^2 c_1} \frac{dv_{C1}}{dt} + \frac{v_{C1}}{C_1 L_1} = \frac{V_g}{C_1 L_1} \tag{12}$$

$$i_{L1} = -\frac{1}{L_1} \int_0^t V_{C1}(\lambda) d\lambda + \frac{v_g}{L_1} t + i_{L1}(T_{off}) \tag{13}$$

3.2. Equilibrium Points locus (EPL) switching surface and control law

The EPL is obtained assuming that the derivatives of the trajectories in the phase plane during on and OFF are opposite with equal absolute value

$$T_{ON} = \frac{dv_{C1}}{di_{L1}}, \quad T_{OFF} = -\frac{dv_{C1}}{di_{L1}} \tag{13a}$$

EPL will be determined by (14),

$$i_{L1} = \frac{P}{V_g} \tag{14}$$

It can be summarized that the boost converter feeding a CPL exhibits an unstable behavior in both on and OFF intervals; therefore, any SMC method intending to regulate the converter must combine erratic trajectories to generate a stable one for the regulated converter dynamics.

4. Modified sliding mode control

The LCL-filtered is a typical third-order system to guarantee global stability and damping effect, and we choose the sum of three error dynamics as the sliding surface function as shown in (15).

$$S = \alpha_1 (i_1^* - i_1) + \alpha_2 (v_{c1}^* - v_{c1}) + \alpha_3 (i_2^* - i_2) \tag{15}$$

Through the analysis mentioned above, the switching function can be realized by pulse width modulation (PWM). Thus, the symbolic process is eliminated, and the reaching law is rewritten in (16)

$$S = -kS \tag{16}$$

Based on (15) and (16), a control law is deduced in (17)

$$u_i = -r_1 x_{e1} - x_{e2} + L_1 i_1 + v_c + r_1 i_1 + L_1 \frac{\alpha_2}{\alpha_1} \left(\frac{1}{C} x_{e1} - \frac{1}{C} x_{e3} \right) + L_1 \frac{\alpha_3}{\alpha_1} \left(\frac{1}{L_2} x_{e2} - \frac{r_2}{L_2} x_{e3} \right) + k \frac{L_1}{\alpha_1} S \tag{17}$$

Through (17), we find that the control law is complex, resulting in the difficulty to design controller parameters. Separating the sliding surface function, the control law can be rewritten in (18)

$$u_i = L_1 \dot{i}_i + v_c + r_1 \dot{i}_i + \left(-r_1^+ L_1 \frac{\alpha_2}{\alpha_1} \frac{1}{C} + kL_1 \right) x_{e1} + \left(-1 + L_1 \frac{\alpha_3}{\alpha_1} \frac{1}{L_2} + k \frac{L_1}{\alpha_1} \alpha_2 \right) x_{e2} \tag{18}$$

As shown in (17), the gain of each state feedback variable is determined by three or four sliding-mode parameters (sliding surface function parameters and the gain of the reaching Jaw). Based on (18), by simplifying the control Jaw and reintegrating the sliding-mode parameters, three new uncoupled controller parameters can be obtained as written in (19), (20) and (21).

$$r_{d1} = \left(-r_1 + L_1 \frac{\alpha_2}{\alpha_1} \frac{1}{C} + kL_1 \right). \tag{19}$$

$$r_{d2} = \left(-1 + L_1 \frac{\alpha_3}{\alpha_1} \frac{1}{L_2} + k \frac{L_1}{\alpha_1} \alpha_2 \right). \tag{20}$$

$$r_{d3} = \left(-L_1 \frac{\alpha_2}{\alpha_1} \frac{1}{C} - L_1 \frac{\alpha_3}{\alpha_1} \frac{r_3}{L_2} + k \frac{L_1}{\alpha_1} \alpha_3 \right). \tag{21}$$

Note that, using the determined new three controller parameters to solve the original sliding surface function parameters and the gain of the reaching Jaw, we can obtain an infinite number of solutions. Thus, the sliding surface function parameters and the gain of the reaching Jaw must exist. As long as the sliding surface passes through the origin, the system would converge to the source, where the Lyapunov stability of PWM-SMC is not affected. Therefore, a new control law can be derived in (22).

$$u_i = L_1 \dot{d}_e + r_{d1} x_{e1} + r_{d2} x_{e2} + r_{d3} x_{e3} \tag{22}$$

However, the LCL filter parameters and parasitic resistances have tolerances in a practical system. L_1 , C , r_1 , and r_2 represent the actual parameters of the system, while L_1' , L_2' , C' , r_1' , and r_2' represent the estimated parameters, respectively. There is a deviation between the actual parameter and the estimated one, and the LCL filter parameters used in the PWM-SMC controller are the estimated parameter. According to (Liu et al., 2018b), this deviation would cause the steady-state error of the system, where the multiple resonant terms can effectively eliminate it. Therefore, a proportional deep (P.R.) term is used instead of the gain of $rd3$ in our case. The transfer function is shown by (23)

$$G_c(s) = k_p + \frac{2k_r \omega_i s}{s^2 + 2\omega_i s + \omega_o^2} \tag{23}$$

where k_p and k_r are the proportional and resonant gains, ω_i and ω_o are the cut off frequency and the fundamental frequency, respectively. Due to the adoption of digital control, it is necessary to consider the delay issue after obtaining the control law.

5. Results and discussion

Simulation is performed in MATLAB Simulink 2022b. In the proposed system, P.V. power capacity of 200 V, 13.5 kW is integrated with secondary distribution of A.C. grid. The secondary distribution system, rated at 400 V (RMS), 50 Hz is interconnected with a two level three-phase inverter, rated at 10 kVA.

A DC-DC Boost converter is connected with the P.V. source to eliminate any unwanted variation in the supply system. The DC-DC Boost converter increases the 200 V input to a 600 V output which serves as an input to the three-phase inverter. P.I. control system is designed to provide feedback to the DC-DC Boost converter. The inverter is provided a closed loop control by a MSMC scheme. LCL filter is used to smoothen the waveform of the inverter. The whole interconnected system feeds a load of 20 kW active load and 4kVAR reactive load. The result section is bifurcated into three sections which describes the effectiveness of the Modified Sliding Model Control in the integration of P.V. energy into the

A.C. grid.

5.1. Case 1: Integration without any control mechanism

In this case, the system is simulated without any control mechanism. In this case, LCL filter is the only smoothing element in the proposed interconnected system. Fig. 2 contains the simulation model for Case 1.

The load draws a line current of 30 A (RMS) rated at line-line voltage of 400 V (RMS). Fig. 3 and Fig. 4 depict the waveforms of voltage and current of A.C. grid when the inverter output is integrated with no controller. It is apparent from the results the LCL filter is unable to perform the overall smooth integration of P.V. inverted output with the A.C. grid. It can be observed from Fig. 3 and Fig. 4 that the voltage and current are not purely sinusoidal, but they carry massive irregularities from an actual sinusoidal wave.

5.2. Case 2: integration with P.I. control

This case classifies the P.I. control mechanism in the control loop system of a three-phase inverter in addition to the LCL filter as the smoothing element in the proposed interconnected system. Fig. 5 contains the simulation model for Case 2. Fig. 6 describes the P.I. control loop of the system.

Three phase load obtains 30 A (RMS) line current drawn at a 400 V line voltage. The line voltage and current of the three-phase A.C. grid is displayed in Fig. 7 and Fig. 8. It is demonstrated through these waveforms that the P.I. control can overcome the massive deviation from a standard sinusoidal waveform. The resultant waveforms of voltage and current depict that the outcomes are very near to the natural sine wave. But the P.I. control cannot overcome the problem of spikes and noise on multiple occasions, as highlighted the Fig. 7 and Fig. 8.

5.3. Case 3: seamless integration with MSMC

This case classifies the MSMC mechanism in the control loop system of a three-phase inverter along with an LCL filter to provide the seamless interconnection of the inverter output with the A.C. grid system. Fig. 9 shows the simulation model for Case 3, and Fig. 10 shows the MSMC for the seamless integration of P.V. power into the A.C. grid.

Three-phase load of 20 kW+4kVAR draws a 30 A (RMS) line current at 400 V (RMS) line voltage. The line voltage and current of the three-phase A.C. grid are shown in Fig. 11 and Fig. 12. The MSMC control mechanism can counter the drawbacks of the P.I. control technique. Fig. 3 and Fig. 4 demonstrate the uncontrolled integration which is comprised of multiple irregularities as compared to a pure sinusoidal waveform of grid voltage and current. The output response becomes better with the implementation of a P.I. control mechanism as depicted in the Figs. 7 and 8. Nevertheless, the output response still lacks the purity in the sinusoidal output. The addition of sliding mode control is implemented by introducing a hysteresis limits to the existing P.I. control. This additional limit to P.I. control restrict the output deviation, thereby providing a seamless integration into the A.C. grid. Therefore, it can be concluded that the proposed MSMC can provide smooth sinusoidal A.C. waveform, thereby providing the seamless integration of P.V. inverted output with the A.C. grid. Fast fourier transform (FFT) analysis as shown in Fig. 13 demonstrates that the total harmonic distortion (THD) of the output voltage is 3 % which is in accordance with the standard of IEEE 519.

5.4. Case 4: performance of MSMC under dynamic irradiance

Floating clouds may cause varying irradiance at the input of the P.V. generation. In this case, this is incorporated to observe the performance of MSMC under dynamic solar irradiance. Fig. 14 contains the varying solar irradiance. Initially, it is reduced by 20 % (i.e., from 1000 W/m² to 800 W/m²) at 0.2 sec which is then further reduced by 30 % (i.e., from

1000 to 700 W/m²) at 0.4 sec. The irradiance is then restored to the initial condition i.e., 1000 W/m² 0.6 sec. As a result, the output current of P.V. panel varies as depicted in Fig. 15. Three-phase AC voltage of the grid is represented in Fig. 16 which demonstrates the effectiveness of MSMC under dynamic irradiance. At 20 % variation in irradiance, MSMC provides smooth A.C. output voltage. At 30 % variation in irradiance, the proposed control action of MSMC is able to provide smooth A.C. grid voltage with an overshoot of 6 %.

This study compares multiple cases to assess the effectiveness of MSMC in the integration of P.V. system. Case 1 studies uncontrolled integration. Meanwhile, Case 2 examines the P.I. control mode to integrate the P.V. output to the A.C. grid. Finally, Case 3 comprises of the MSMC to perform the seamless and smooth integration of solar generation into A.C. grid. The results in Fig. 3 and Fig. 4 demonstrate the output of the Grid voltage and current for uncontrolled mode. This shows that the uncontrolled integration could be disastrous for the A.C. grid as the voltage and current of grid becomes intensively distorted. Fig. 7 and Fig. 8 describe the implementation of P.I. control which contains spikes and distortion in the A.C. grid that is eliminated by MSMC as displayed in Fig. 11 and Fig. 12. Finally, Case 4 presents the dynamic irradiance occurring due to floating clouds. Fig. 16 displays the output voltage of the A.C. grid which demonstrates the seamless integration of P.V. output volage into A.C. grid.

6. Conclusion

Integration of energy produced from solar power can lead to disastrous distortion in voltage and current profile of the AC grid also it may lead to degrading the efficiency of the system. To achieve the seamless integration of solar power into AC grid, this research introduces the combination of sliding mode control and phase-locked loop, here named as modified sliding mode control technique. The first case contains the adverse effect of uncontrolled integration of solar power. Then, the second case tests the existing PI control mode to feed the PV power into AC grid. PI control does remove multiple irregularities, but the voltage and current profile still contains spikes and distortion in the AC grid that may affect the overall power quality of the AC grid. These shortcomings are overcome by the proposed technique in which sliding mode control is integrated with phase locked loop to ensure the removal of any irregularity. Finally, the proposed control mechanism is also tested for the condition of floating clouds, thereby resulting in varying solar irradiance and the results demonstrate that MSMC can effectively withstand the dynamic solar irradiance, thereby performing seamless integration of PV power into the AC grid for dynamic irradiance as well.

Ethical approval and consent to participate

The study does not involve any ethical problem and data collection was completed in accordance with the ethical regulations.

Consent for publication

All the authors have agreed to publish this manuscript.

CRediT authorship contribution statement

Shoaib Shaikh: Writing – original draft, Methodology, Investigation, Conceptualization. **Arsalan Muhammad Soomar:** Writing – review & editing, Resources, Methodology, Conceptualization. **Fuad A. Awwad:** Writing – review & editing, Validation, Resources, Project administration, Formal analysis, Data curation. **Muhammad Kamran:** Writing – review & editing, Software, Methodology. **Kifayat Ullah:** Writing – review & editing, Software, Methodology, Conceptualization. **Emad A. A. Ismail:** Writing – review & editing, Validation, Resources, Project administration, Funding acquisition, Data curation. **Piotr Musznicki:** Writing – review & editing, Supervision, Methodology,

Conceptualization. **Syed Hadi Hussain Shah:** Writing – review & editing, Validation, Methodology, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

- Awosusi, A.A., et al., 2022. How do renewable energy, economic growth and natural resources rent affect environmental sustainability in a globalized economy? Evidence From Colombia based on the gradual shift causality approach (Jan.). *Front Energy Res* vol. 9. <https://doi.org/10.3389/fenrg.2021.739721>.
- Blaabjerg, F., 1997. Single current sensor technique in the DC link of three-phase PWM-VS inverters: a review and a novel solution. *IEEE Trans. Ind. Appl.* vol. 33 (5), 1241–1253. <https://doi.org/10.1109/28.633802>.
- Brahim, A., Soufi, Y., Ounnas, D., Guiza, D., 2022. Fuzzy logic control of a photovoltaic system connected to grid. *Proc. - 2022 5th Int. Conf. Power Electron. their Appl., ICPEA 2022*. <https://doi.org/10.1109/ICPEA51060.2022.9791172>.
- Daia Eddine O, M.C., Ali, C., Abdelhalim, K., 2022. Four leg Interleaved DC/DC boost Converter based PV system using PSO Algorithm based PI controller. *2022 19th IEEE Int. Multi-Conf. Syst., Signals Devices, SSD 2022* 1415–1421. <https://doi.org/10.1109/SSD54932.2022.9955647>.
- Devassy, S., Singh, B., 2017. Modified pq-Theory-Based Control of Solar-PV-Integrated UPQC-S (Sep.). *IEEE Trans. Ind. Appl.* vol. 53 (5), 5031–5040. <https://doi.org/10.1109/TIA.2017.2714138>.
- Díaz, A., Marrero, G.A., Puch, L.A., Rodríguez, J., 2019. Economic growth, energy intensity and the energy mix (Jun.). *Energy Econ.* vol. 81, 1056–1077. <https://doi.org/10.1016/j.eneco.2019.05.022>.
- Elmelegi, A., Aly, M., Ahmed, E.M., Alharbi, A.G., 2019. A simplified phase-shift PWM-based feedforward distributed MPPT method for grid-connected cascaded PV inverters (Jul.). *Sol. Energy* vol. 187, 1–12. <https://doi.org/10.1016/J.SOLENER.2019.05.021>.
- Fan, Y., Li, G., Gao, W., 2019. Integration Control Strategy of IPOS DC Step-up Type Photovoltaic Power Plant Via MMC-HVDC. (Oct.) *APAC 2019 - 8th IEEE International Conference on Advanced Power System Automation and Protection* pp. 1068–1073, 10.1109/APAP47170.2019.9224806.
- Guanghua, L., et al., 2024. Improved maximum power point tracking algorithms by using numerical analysis techniques for photovoltaic systems. *Results Eng.* vol. 21 <https://doi.org/10.1016/j.rineng.2023.101740>.
- Hannan, M.A., Ghani, Z.A., Mohamed, A., Uddin, M.N., 2015. Real-time testing of a fuzzy-logic-controller-based grid-connected photovoltaic inverter system (Nov.). *IEEE Trans. Ind. Appl.* vol. 51 (6), 4775–4784. <https://doi.org/10.1109/TIA.2015.2455025>.
- Hashim, H., Ho, W.S., 2011. Renewable energy policies and initiatives for a sustainable energy future in Malaysia (Dec.). *Renew. Sustain. Energy Rev.* vol. 15 (9), 4780–4787. <https://doi.org/10.1016/J.RSER.2011.07.073>.
- Karthik, M., Naik, N., Venkata Ramana, Panda, A.K., 2022. A robust generalized modified blake-zisserman adaptive filter-based control scheme for grid-tied PV system to improve power quality. *10th IEEE Int. Conf. Power Electron. Drives Energy Syst. PEDES 2022*. <https://doi.org/10.1109/PEDES56012.2022.10080390>.
- Kchaou, A., Ayadi, A., Naamane, A., M'Sirdi, N., Koubaa, Y., 2017. An adaptive sliding mode control based maximum power point tracking method for a PV stand-alone system (Jun.). *2017 6th Int. Conf. Syst. Control, ICSC 2017* 69–74. <https://doi.org/10.1109/ICOSC.2017.7958702>.
- Khazaei, J., Tu, Z., Asrari, A., Liu, W., 2021. Feedback linearization control of converters with LCL filter for weak AC grid integration (Jul.). *IEEE Trans. Power Syst.* vol. 36 (4), 3740–3750. <https://doi.org/10.1109/TPWRS.2021.3049324>.
- Knight, J., Shiravar, S., Holderbaum, W., 2006. An improved reliability cuk based solar inverter with sliding mode control (Jul.). *IEEE Trans. Power Electron* vol. 21 (4), 1107–1115. <https://doi.org/10.1109/TPEL.2006.876786>.
- Kumar, N., Singh, B., Panigrahi, B.K., 2019. Integration of solar PV generation with distribution grid: using novel adaptive filter based control technique (Feb.). *4th IEEE Int. Conf. Univers. Village 2018, UV 2018*. <https://doi.org/10.1109/UV.2018.8642120>.
- Liu, B., Ren, R., Jones, E.A., Wang, F., Costinett, D., Zhang, Z., 2018a. A modulation compensation scheme to reduce input current distortion in GaN-based high switching frequency three-phase three-level vienna-type rectifiers (Jan.). *IEEE Trans. Power Electron* vol. 33 (1), 283–298. <https://doi.org/10.1109/TPEL.2017.2672756>.

- Liu, L., Zhao, Y., Yin, Y., You, J., 2018b. Current sensor-less control for boost DC-DC converter based on switched observer (Dec.). Proc.: IECON 2018 - 44th Annu. Conf. IEEE Ind. Electron. Soc. 1122–1127. <https://doi.org/10.1109/IECON.2018.8591651>.
- Mahfuz-Ur-Rahman, A.M., Islam, M.R., Muttaqi, K.M., Sutanto, D., 2020. Model predictive control for a new magnetic linked multilevel inverter to integrate solar photovoltaic systems with the power grids (Nov.). IEEE Trans. Ind. Appl. vol. 56 (6), 7145–7155. <https://doi.org/10.1109/TIA.2020.3024352>.
- Martinez-Treviño, B.A., El Aroudi, A., Vidal-Idiarte, E., Cid-Pastor, A., Martinez-Salamero, L., 2019. Sliding-mode control of a boost converter under constant power loading conditions (Mar.). IET Power Electron. vol. 12 (3), 521–529. <https://doi.org/10.1049/iet-pel.2018.5098>.
- Priya, M.A.J., Ashok Kumar, B., Senthilrani, S., 2018. Phase Locked Loop for controlling inverter interfaced with grid connected solar PV system (Sep.). 2018 Natl. Power Eng. Conf., NPEC 2018. <https://doi.org/10.1109/NPEC.2018.8476728>.
- Reatti, A., Corti, F., Tesi, A., Torlai, A., Kazimierczuk, M.K., 2019. Effect of parasitic components on dynamic performance of power stages of DC-DC PWM buck and boost converters in CCM. Proc. - IEEE Int. Symp. . Circuits Syst. vol. 2019-May <https://doi.org/10.1109/ISCAS.2019.8702520>.
- Reveles-Miranda, M., Flota-Banuelos, M., Chan-Puc, F., Ramirez-Rivera, V., Pacheco-Catalan, D., 2020. A Hybrid control technique for harmonic elimination, power factor correction, and night operation of a grid-connected pv inverter (Mar.). IEEE J. Photo vol. 10 (2), 664–675. <https://doi.org/10.1109/JPHOTOV.2019.2961600>.
- Rivera, M., Riveros, J., Wheeler, P., 2021. Predictive current control strategies for grid connected NPC converters. 2021 IEEE Congr. Estud. De. Electron. Y. Electr., INGELECTRA 2021. <https://doi.org/10.1109/INGELECTRA54297.2021.9748074>.
- Sarathkumar, D., Raj, R.A., Kumar, V.Sampath, 2023. An extensive critique on microgrid control techniques. 2023 IEEE Int. Stud. Conf. Electr., Electron. Comput. Sci., SCEECS 2023. <https://doi.org/10.1109/SCEECS57921.2023.10063019>.
- Shaikh, S., Kumar, D., Hakeem, A., Soomar, A.M., 2022. Protection system design of induction motor for industries (Aug.). Model. Simul. Eng. vol. 2022, 1–13. <https://doi.org/10.1155/2022/7423018>.
- Singh, S., Perera, C., Kish, G.J., Salmon, J., 2019. Low harmonic loss PWM for a dual inverter drive using a floating capacitor inverter (Sep.). 2019 IEEE Energy Convers. Congr. Expo., ECCE 2019 5981–5988. <https://doi.org/10.1109/ECCE.2019.8912545>.
- Sinha, A., Chandra Jana, K., Kumar Das, M., 2018. An inclusive review on different multi-level inverter topologies, their modulation and control strategies for a grid connected photo-voltaic system (Aug.). Sol. Energy vol. 170, 633–657. <https://doi.org/10.1016/J.SOLENER.2018.06.001>.
- Soomar, A.M., Guanghua, L., Shaikh, S., Shah, S.H.H., Musznicki, P., 2023. Scrutiny of power grids by penetrating PV energy in wind farms: a case study of the wind corridor of Jhampir, Pakistan (Jun.). Front Energy Res vol. 11. <https://doi.org/10.3389/fenrg.2023.1164892>.
- Steimer, P.K., Manjrekar, M.D., 2001. Practical medium voltage converter topologies for high power applications. Conf. Rec. - IAS Annu. Meet. (IEEE Ind. Appl. Soc.) vol. 3, 1723–1730. <https://doi.org/10.1109/IAS.2001.955765>.
- Wang, J., Chang, X., Gao, L., Lei, D., Zhang, D., Ding, Y., 2021. A dual-mode grid-connected control strategy for a bidirectional power converter (Apr.). 2021 4th Int. Conf. Energy, Electr. Power Eng., CEEPE 2021 266–272. <https://doi.org/10.1109/CEEPE51765.2021.9475655>.
- Wang, X., Ruan, X., Liu, S., Tse, C.K., 2010. Full feedforward of grid voltage for grid-connected inverter with LCL filter to suppress current distortion due to grid voltage harmonics. IEEE Trans. Power Electron vol. 25 (12), 3119–3127. <https://doi.org/10.1109/TPEL.2010.2077312>.
- Zhang, Y., Dai, Z., Fang, Y., 2021. Voltage Feed Forward Shunt Active Power Filter Based on Double Loop Control. Proc. - 2021 Int. Conf. Power Syst. Technol.: Carbon Neutrality N. Type Power Syst., POWERCON 2021 1251–1256. 10.1109/POWERCON53785.2021.9697468.