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Research Paper

# AN IMPROVED FOPID-CONTROLLED HYBRID TRANSFORMER-LESS SINGLE-PHASE GRID-CONNECTED SOLAR PV INVERTER WITH REACTIVE POWER COMPENSATION AND LEAKAGE CURRENT MITIGATION

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**ABSTRACT**

This work presents a FOPID-controlled hybrid transformer-less single-phase grid-connected photovoltaic (PV) inverter designed to mitigate leakage current while enabling reactive power compensation. Conventional transformer-less inverters offer high efficiency and reduced cost but suffer from leakage current issues due to the absence of galvanic isolation, leading to safety concerns and power quality degradation. To address these challenges, a hybrid inverter topology combining DC decoupling, AC decoupling, and mid-point clamping techniques is proposed to suppress common-mode voltage variations effectively. The system employs a Fractional Order Proportional-Integral-Derivative (FOPID) controller to enhance dynamic response, improve tracking accuracy, and ensure robust performance under varying operating conditions such as irradiance fluctuations and load disturbances. The proposed control strategy enables independent regulation of active and reactive power, thereby supporting grid voltage stability and power factor correction. The performance of the system is validated using MATLAB/Simulink simulations under both open-loop and closed-loop conditions. Comparative analysis with conventional model predictive control (MPC) demonstrates significant improvements in leakage current suppression, reduced total harmonic distortion (THD), faster transient response, and enhanced stability. The proposed inverter thus provides an efficient, reliable, and grid-compliant solution for modern distributed PV systems.

**Keywords**: Transformer-less inverter, FOPID controller, Leakage current reduction, Reactive power compensation, Grid-connected PV system, Total Harmonic Distortion (THD), Hybrid inverter topology

## INTRODUCTION

The increasing demand for sustainable energy solutions, coupled with the depletion of fossil fuel resources and rising environmental concerns, has accelerated the global transition toward renewable energy systems. Among the various renewable sources, solar photovoltaic (PV) energy has emerged as a highly promising option due to its abundance, scalability, and declining installation costs. Grid-connected PV systems play a crucial role in modern power systems

by enabling efficient energy utilization and supporting distributed generation. As the penetration of PV systems increases, maintaining power quality and grid stability has become a major concern. Advanced power electronic interfaces are therefore required to ensure reliable and efficient operation [1]. The integration of PV systems into utility grids also demands compliance with stringent grid codes and performance standards [2] [3].

Traditionally, grid-connected PV systems use transformers to provide galvanic isolation between the PV array and the grid, ensuring safety and eliminating leakage current issues. However, these transformer-based systems are bulky, expensive, and less efficient due to additional losses and increased size. To overcome these drawbacks, transformer-less inverter topologies have gained significant attention in recent years. These inverters offer higher efficiency, reduced cost, and compact design, making them suitable for modern applications. Despite these advantages, the absence of galvanic isolation introduces leakage current due to parasitic capacitance between the PV array and ground [4]. This leakage current can lead to electromagnetic interference, reduced efficiency, and safety hazards if not properly controlled [5] [6].

Several Transformer-less inverter topologies such as H5, H6, HERIC, and neutral-point clamped structures have been proposed to mitigate leakage current issues. These topologies aim to stabilize the common-mode voltage and minimize leakage current through improved switching techniques. Although effective to some extent, these approaches often involve increased circuit complexity and higher component count. Moreover, many existing systems are designed primarily for active power injection and operate at unity power factor. Modern grid requirements, however, demand inverters capable of providing reactive power support for voltage regulation and improved grid stability [7]. The lack of reactive power control in conventional designs limits their applicability in smart grid environments [8] [9].

Control strategies play a vital role in determining the performance of grid-connected PV inverters. Conventional controllers such as proportional–integral (PI) and proportional–integral–derivative (PID) are widely used due to their simplicity and ease of implementation. However, these controllers often exhibit limitations under nonlinear conditions, parameter variations, and dynamic disturbances. To address these issues, advanced control techniques such as model predictive control, sliding mode control, and intelligent control methods have been explored. Among these, the Fractional Order PID (FOPID) controller has gained attention due to its enhanced flexibility and superior dynamic response [10]. The use of fractional calculus allows more accurate system modelling and improved disturbance rejection capability [11] [12].

In this context, a hybrid transformer-less single-phase grid-connected PV inverter with a FOPID controller is proposed to address leakage current mitigation and reactive power compensation simultaneously. The proposed topology integrates DC decoupling, AC decoupling, and mid-point clamping techniques to maintain constant common-mode voltage and suppress leakage current effectively. Additionally, the control strategy enables independent regulation of active and reactive power, ensuring compliance with modern grid requirements [13]. The system is validated through MATLAB/Simulink simulations under different operating conditions to evaluate its performance. Comparative results demonstrate improved power quality, reduced total harmonic distortion, faster dynamic response, and enhanced system stability compared to conventional methods [14] [15].

## LITERATURE SURVEY

The rapid growth of solar photovoltaic (PV) systems has led to extensive research on grid-connected inverter technologies, particularly transformer-less configurations due to their high efficiency and compact design. Transformer-less inverters eliminate bulky transformers, thereby reducing cost, size, and power losses. However, the absence of galvanic isolation introduces leakage current caused by parasitic capacitance between the PV array and ground. This leakage current has become a major concern as it affects safety, efficiency, and electromagnetic compatibility of the system. Researchers have extensively studied the origin and behavior of leakage current and identified common-mode voltage (CMV) variation as the primary cause [1]. Various studies have focused on analysing

leakage current mechanisms and proposing mitigation strategies to improve system reliability and compliance with grid standards [2] [3].

To address leakage current issues, several Transformer-less inverter topologies have been proposed in the literature, including H5, H6, HERIC, and neutral-point clamped structures. These topologies aim to maintain constant common-mode voltage to suppress leakage current effectively. For instance, the HERIC topology introduces additional switches in the freewheeling path to minimize CMV fluctuations and improve efficiency. Similarly, the H6 topology enhances leakage current suppression by providing additional current paths and reducing conduction losses [4]. Other advanced configurations employ DC-link capacitor clamping and common-ground structures to further stabilize voltage and reduce leakage current levels [5] [6]. Despite these improvements, many topologies involve increased component count and complex switching strategies, which may affect overall system cost and control complexity [7] [8] [9].

In addition to topology development, modulation techniques and control strategies play a significant role in leakage current reduction and performance enhancement. Pulse-width modulation (PWM) techniques, including unipolar and bipolar switching, have been widely used to control inverter output and reduce harmonics. Advanced modulation strategies focus on maintaining constant common-mode voltage during switching transitions to suppress leakage current effectively. Model Predictive Control (MPC) has also been explored as an effective control technique for transformer-less inverters, offering fast dynamic response and improved current tracking capability. Studies have demonstrated that MPC-based control can significantly reduce leakage current while enhancing system stability and efficiency under varying operating conditions [10]. However, these methods may require high computational effort and precise system modelling [11] [12].

Recent research has shifted toward advanced control techniques and hybrid topologies to achieve better performance and grid support capability. Fractional Order PID (FOPID) controllers have gained attention due to their superior flexibility and robustness compared to conventional PI/PID controllers. These controllers provide improved dynamic response, reduced overshoot, and better disturbance rejection in nonlinear and time-varying systems. Furthermore, modern grid requirements demand that PV inverters support reactive power compensation in addition to active power injection. Studies have shown that combining leakage current suppression techniques with advanced control methods can significantly improve power quality and grid stability. Hybrid inverter topologies integrating decoupling methods and mid-point clamping have demonstrated promising results in reducing leakage current and enhancing overall system performance, making them suitable for next-generation PV applications [13] [14] [15].

## METHODOLOGY

The methodology of the proposed FOPID-controlled hybrid transformer-less grid-connected photovoltaic (PV) inverter is structured into a systematic sequence of design, modelling, control implementation, and performance evaluation stages. The overall process ensures effective leakage current suppression, reactive power compensation, and improved dynamic response. The following steps describe the complete methodology adopted for the proposed system.

The first step involves the modelling of the photovoltaic (PV) source. A PV array is designed based on standard solar cell characteristics, where output power depends on irradiance and temperature conditions. To ensure maximum energy extraction, a DC–DC converter integrated with a Maximum Power Point Tracking (MPPT) algorithm is used. The MPPT continuously adjusts the operating point of the PV system to extract maximum available power under varying environmental conditions. For simplification in simulation studies focused on inverter behaviour, the PV array is often represented as a constant DC voltage source, assuming that MPPT maintains a stable DC-link voltage.

In the second step, the proposed hybrid transformer-less inverter topology is designed. The topology incorporates nine power switches along with two DC-link capacitors, filter inductors, and a filter capacitor. The inverter structure integrates DC decoupling, AC decoupling, and mid-point clamping techniques. DC decoupling switches isolate the

PV source during zero voltage states, thereby minimizing leakage current paths. AC decoupling switches provide a freewheeling path for current during switching transitions, improving efficiency. The mid-point clamping switch stabilizes the neutral point voltage, ensuring constant common-mode voltage. This combined approach significantly reduces both RMS and peak leakage currents while maintaining efficient power conversion.

The third step focuses on the development of operating modes of the inverter. The system operates under both unity power factor and non-unity power factor conditions. During each grid cycle, the inverter undergoes multiple operating modes depending on the polarity of grid voltage and current. These modes define the switching states of different power devices. In non-unity power factor operation, the inverter supports both active and reactive power flow, where current may lead or lag the voltage. Eight distinct operating modes are identified to ensure smooth current transition and proper power flow. These modes are carefully designed to maintain constant common-mode voltage and avoid sudden switching transitions that could increase leakage current.

The fourth step involves the design of the control strategy. Model Predictive Control (MPC) is initially used to generate switching pulses based on predicted future behaviour of the system. The controller evaluates possible switching states and selects the optimal one that minimizes the error between reference and actual current. Grid synchronization is achieved by measuring grid voltage and generating reference current signals. The control system ensures independent regulation of active and reactive power by controlling the amplitude and phase angle of the inverter current. The reference signals are generated in the stationary reference frame using α–β transformation for accurate control performance.

The fifth step introduces the Fractional Order Proportional–Integral–Derivative (FOPID) controller into the closed-loop system. The FOPID controller enhances system performance by providing additional tuning parameters compared to conventional PID controllers. It processes the error between reference current and actual current and generates control signals to regulate inverter output. The fractional orders of integration and differentiation allow better handling of nonlinearities and disturbances. This results in improved transient response, reduced overshoot, faster settling time, and enhanced steady-state accuracy. The FOPID controller is particularly effective under varying irradiance conditions and grid disturbances.

The sixth step deals with the modulation strategy for switching pulse generation. Unipolar Pulse Width Modulation (PWM) is employed for both open-loop and closed-loop operation. In open-loop mode, switching pulses are generated based on predefined patterns to validate inverter functionality. In closed-loop mode, the pulses are generated dynamically based on controller output to regulate current and voltage. The switching signals for each power device are carefully designed to ensure proper decoupling action and mid-point voltage clamping. This helps in maintaining constant common-mode voltage and reducing leakage current significantly.

The final step involves simulation and performance evaluation using MATLAB/Simulink. The complete system, including PV source, inverter topology, control strategy, and grid interface, is modelled and tested under different operating conditions. Performance parameters such as leakage current, total harmonic distortion (THD), output voltage, grid current, and dynamic response are analysed. Comparative analysis is carried out between the existing system using MPC control and the proposed system using MPC combined with FOPID control. The results demonstrate improved waveform quality, reduced leakage current, lower THD, and faster response in the proposed system. This validates the effectiveness of the methodology and confirms the suitability of the proposed inverter for modern grid-connected PV applications.

**PROPOSED SYSTEM**

The proposed system presents a hybrid transformer-less single-phase grid-connected photovoltaic (PV) inverter designed to address key challenges such as leakage current mitigation, reactive power compensation, and improved dynamic performance. The system integrates a PV array as the primary energy source, which is connected to a DC–

DC converter for maximum power point tracking (MPPT). The output of the DC–DC converter feeds the inverter stage through a split DC-link capacitor arrangement. The inverter is directly connected to the utility grid through an L–C filter that smooths the output waveform and reduces harmonic distortion. The overall objective of the proposed system is to deliver high-quality power to the grid while ensuring safety, efficiency, and compliance with modern grid standards.

The core of the proposed system is the hybrid transformer-less inverter topology, which combines DC decoupling, AC decoupling, and mid-point clamping techniques. This topology utilizes multiple power switches arranged in such a way that the common-mode voltage is maintained nearly constant during switching operations. By stabilizing the common-mode voltage, the leakage current flowing through the parasitic capacitance between the PV array and ground is significantly reduced. The DC decoupling switches isolate the PV array from the grid during zero voltage states, while the AC decoupling switches provide a freewheeling path for current, thereby improving efficiency. The mid-point clamping circuit ensures that the voltage across the DC-link capacitors remains balanced, further enhancing system stability and performance.

The proposed inverter operates under both unity and non-unity power factor conditions, enabling it to supply not only active power but also reactive power to the grid. This capability is essential for modern grid requirements, where distributed generation systems are expected to support voltage regulation and power factor correction. The system allows independent control of active and reactive power by adjusting the phase angle and magnitude of the inverter output current. During operation, the inverter can inject or absorb reactive power depending on grid requirements, thereby improving voltage stability and reducing stress on the distribution network. This feature makes the proposed system highly suitable for smart grid and microgrid applications.

To enhance control performance, a Fractional Order Proportional–Integral–Derivative (FOPID) controller is employed in the closed-loop system. Unlike conventional PID controllers, the FOPID controller introduces fractional-order integration and differentiation, providing additional tuning flexibility and improved dynamic response. The controller processes the error between the reference and actual grid current and generates appropriate control signals to regulate inverter operation. This results in faster transient response, reduced overshoot, and improved steady-state accuracy. The FOPID controller also demonstrates better robustness under varying operating conditions such as irradiance changes, load disturbances, and grid fluctuations, making it more effective than traditional controllers.

The proposed system is implemented and validated using MATLAB/Simulink simulation. Both open-loop and closed-loop analyses are performed to evaluate system performance under different operating scenarios, including changes in power demand and reactive power requirements. Simulation results demonstrate significant improvements in leakage current suppression, reduction in total harmonic distortion (THD), and enhanced dynamic response compared to conventional systems. The inverter maintains stable operation under varying conditions while delivering high-quality power to the grid. Overall, the proposed hybrid inverter system with FOPID control offers an efficient, reliable, and advanced solution for grid-connected PV applications, meeting the demands of modern power systems.

## RESULTS AND DISCUSSION

The performance of the proposed FOPID-controlled hybrid transformer-less grid-connected photovoltaic (PV) inverter is evaluated using MATLAB/Simulink under various operating conditions. The results are analyzed for both the existing system based on Model Predictive Control (MPC) and the proposed system integrating MPC with a Fractional Order PID (FOPID) controller. Key performance parameters such as output voltage and current waveforms, leakage current, common-mode voltage, total harmonic distortion (THD), and dynamic response are considered. The simulation results clearly demonstrate the effectiveness of the proposed system in improving power quality and system stability.

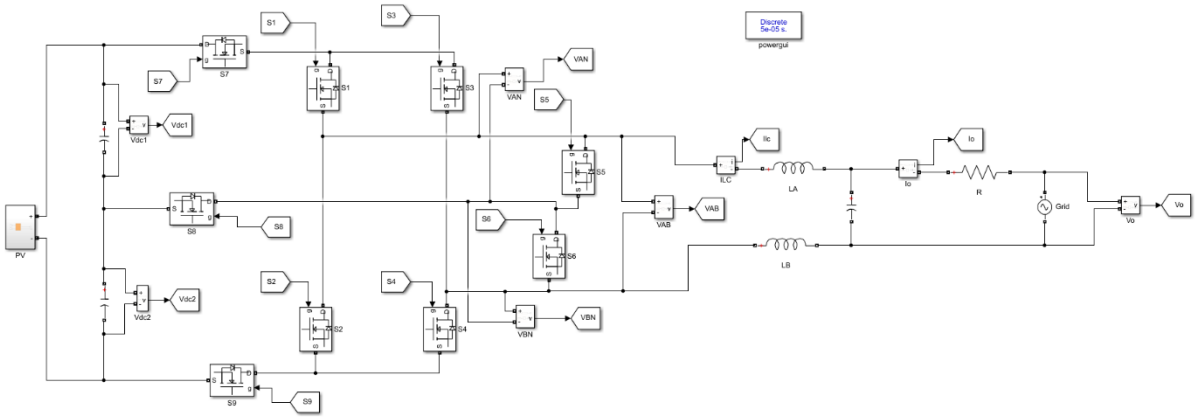



Fig 1. MATLAB/SIMULINK circuit diagram of the proposed system

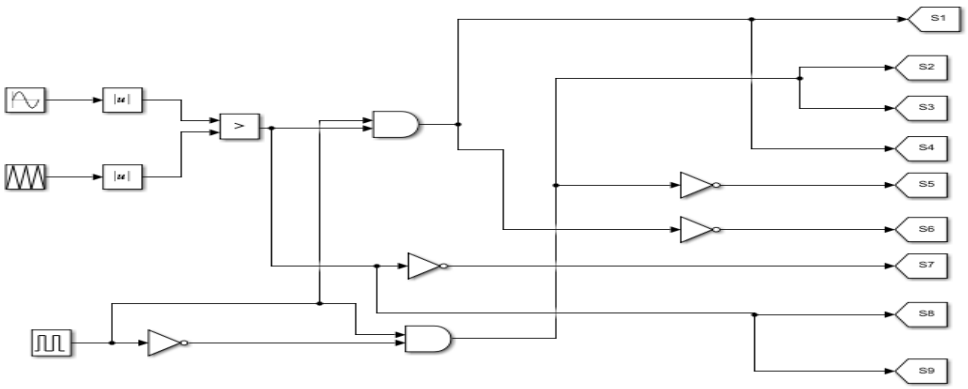
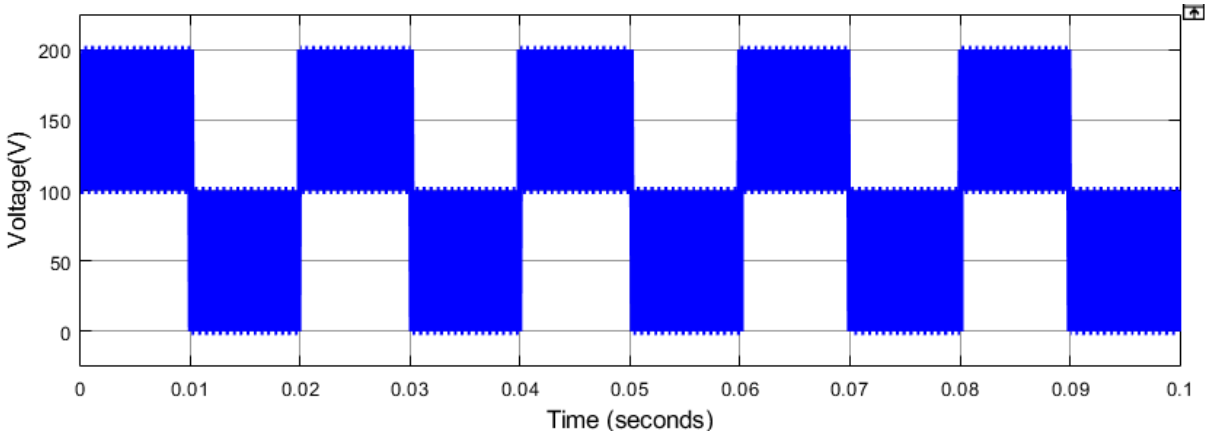
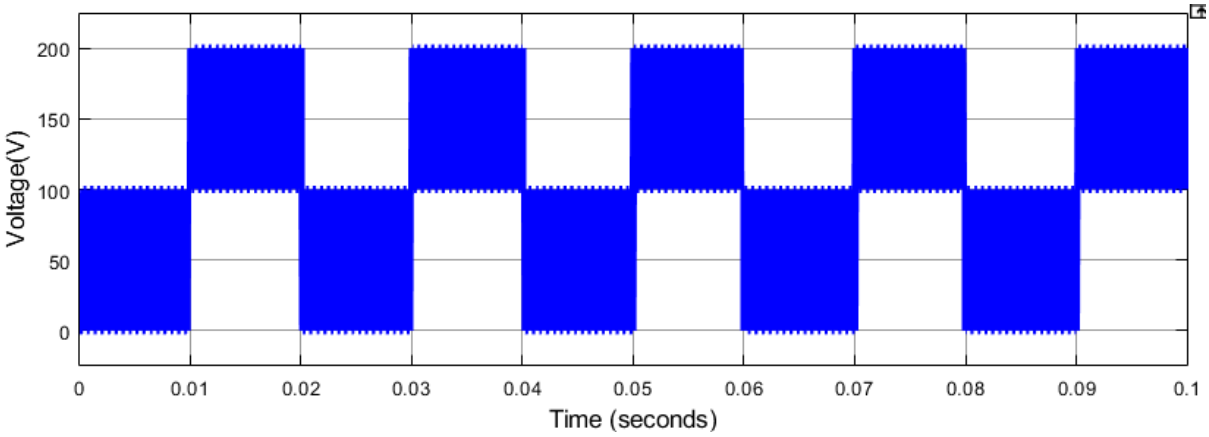



Fig 2. Modulation technique of the proposed topology for open loop.

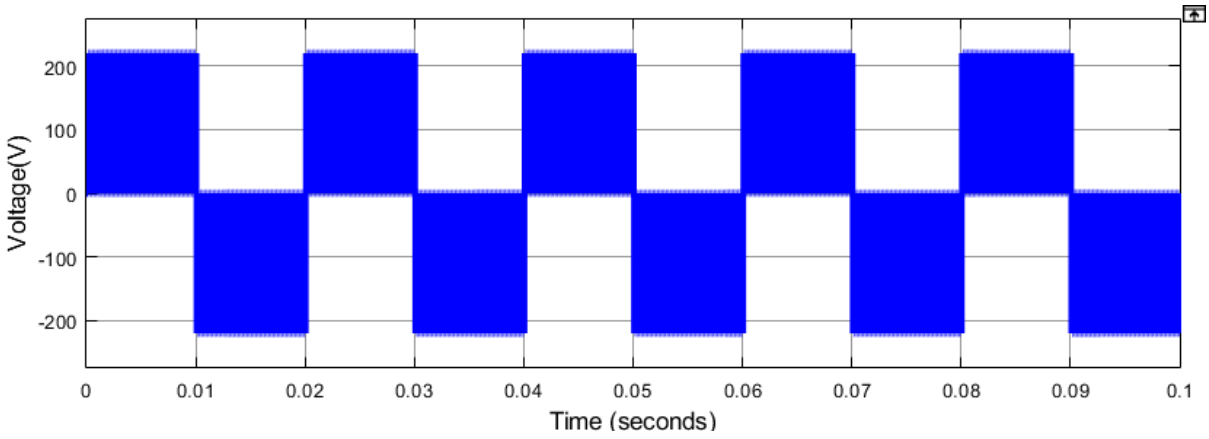
In the open-loop operation, the inverter successfully generates the required AC output from the DC input, validating the functionality of the proposed topology. The voltage waveforms obtained across the inverter terminals exhibit the expected switching characteristics, while the current waveform follows the applied load conditions. However, minor distortions are observed due to the absence of feedback control. The common-mode voltage shows moderate variations during switching transitions, which contribute to leakage current flow. Although the leakage current remains within acceptable limits, it is not optimally minimized in open-loop operation. These results establish the baseline performance of the inverter without advanced control.


Voltage(V)
200
150
100
50
0
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time (seconds)

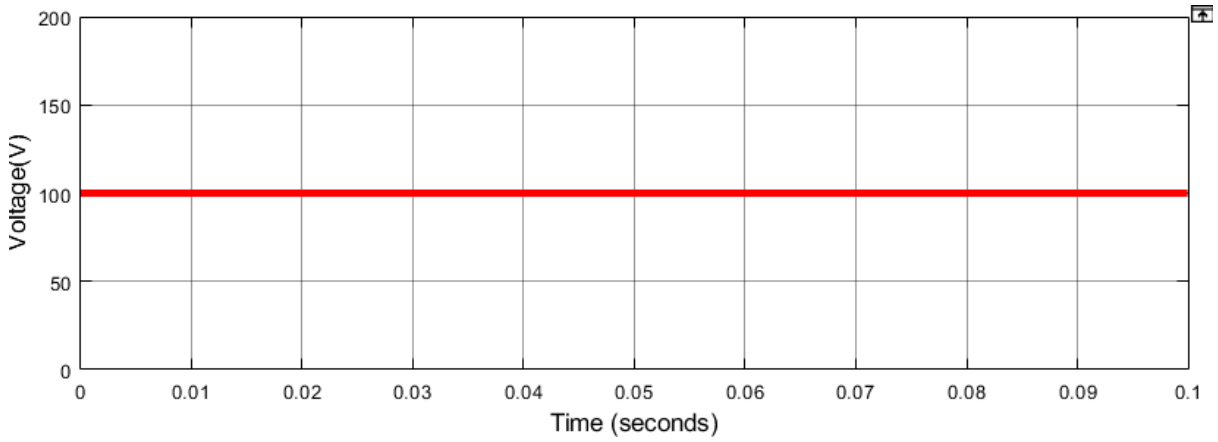
(a)


Voltage(V)
200
150
100
50
0
0
0.01
0.02
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0.09
0.1
Time (seconds)

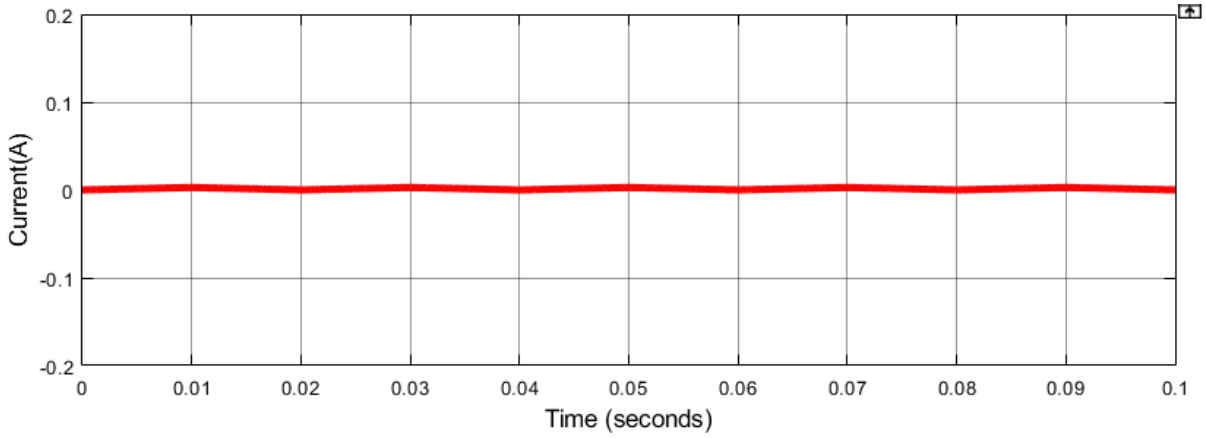
(b)


Voltage(V)
200
100
0
-100
-200
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time (seconds)

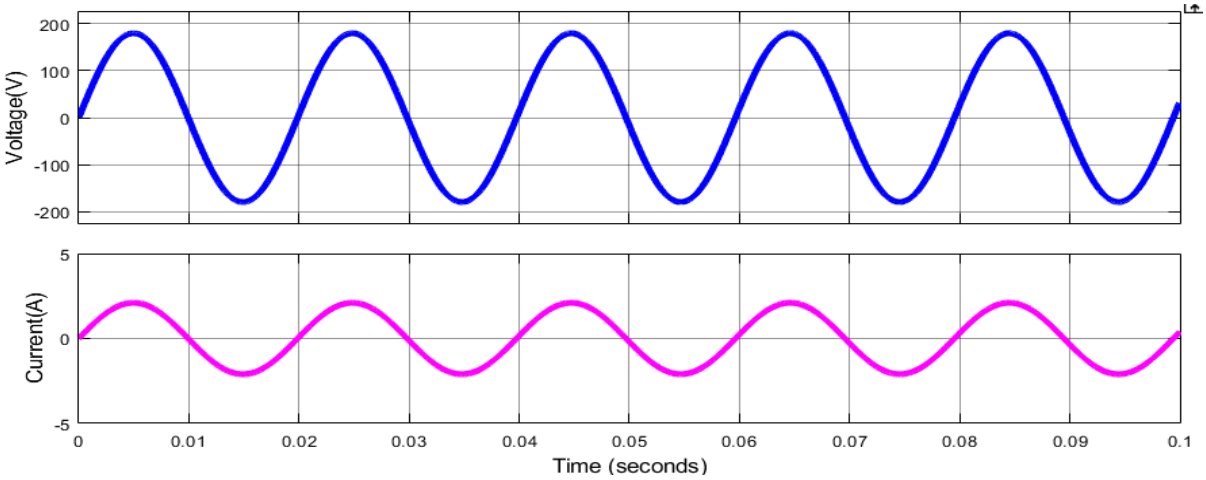
(c)




(d)




(e)




(f)

FIGURE 3. Simulation results for open loop (a) VAN and VBN(b) VAB(c) VtCM (d) ILC(e) VO and IO.

Under closed-loop conditions using MPC control, the system demonstrates improved performance compared to open-loop operation. The grid current waveform becomes more sinusoidal and closely tracks the reference signal. The inverter effectively injects active power into the grid, and basic reactive power compensation is achieved. The common-mode voltage variation is reduced compared to open-loop operation, resulting in lower leakage current levels. However, some limitations are still observed in terms of dynamic response and steady-state accuracy. During sudden changes in power demand, such as transition from 330 W to 660 W, the system exhibits slower response and noticeable transient oscillations. Additionally, the THD of the grid current is reduced to approximately 2.07%, which, although acceptable, still leaves scope for further improvement.

The proposed system incorporating the FOPID controller shows significant enhancement in overall performance. The output voltage and current waveforms are smoother with reduced distortion, indicating improved control accuracy. The grid current closely follows the reference signal with minimal steady-state error. The ability of the FOPID controller to handle system nonlinearities and disturbances results in better waveform quality and improved synchronization with the grid. Furthermore, the system demonstrates superior capability in reactive power control, allowing more precise adjustment of power factor and voltage regulation. This makes the inverter more suitable for modern grid requirements.

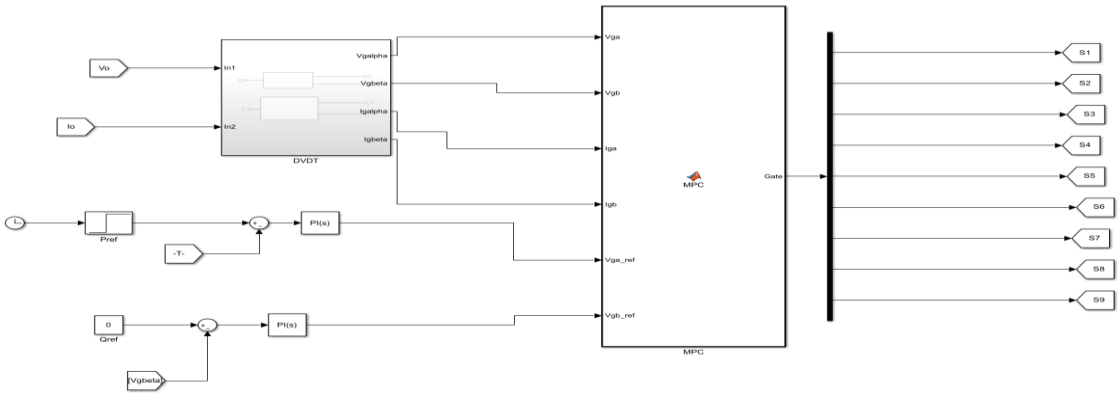



Fig 4. Control scheme for the proposed MPC topology

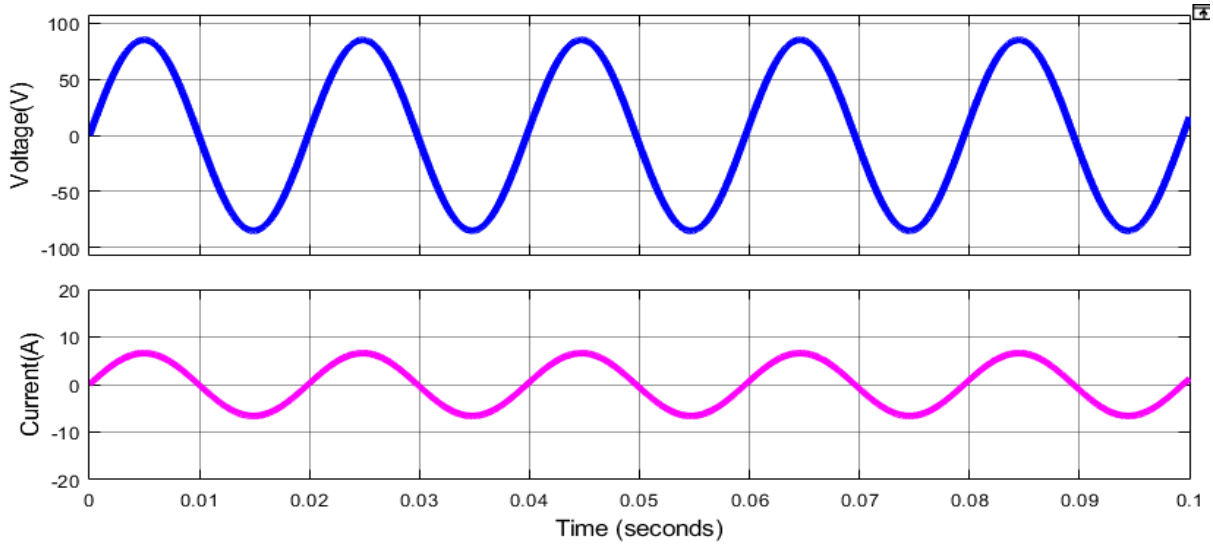



Fig 5. Simulation results of static performance with maximum instantaneous P of 660W.

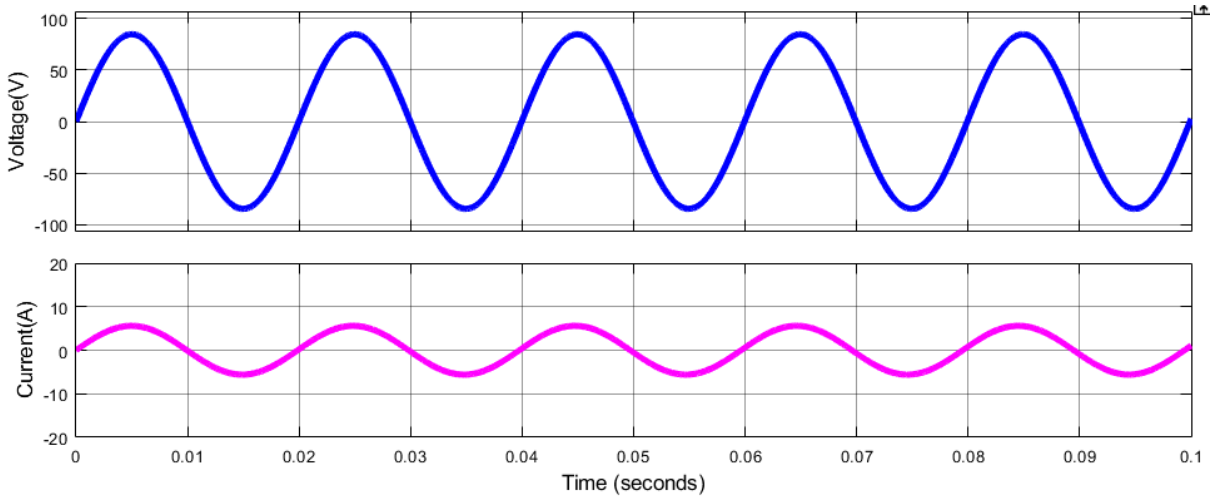



Fig 6. Simulation results of static performance with maximum instantaneous P and Q of (560W+j220VAR).

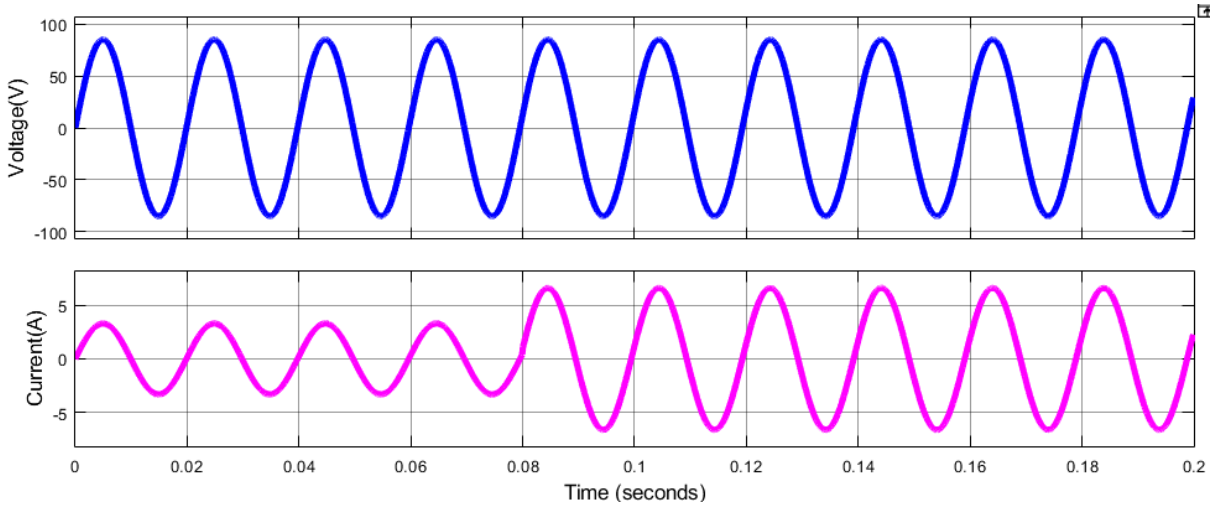



Fig 7. Simulation results of dynamic performance with maximum instantaneous P changing from 330W to 660W.

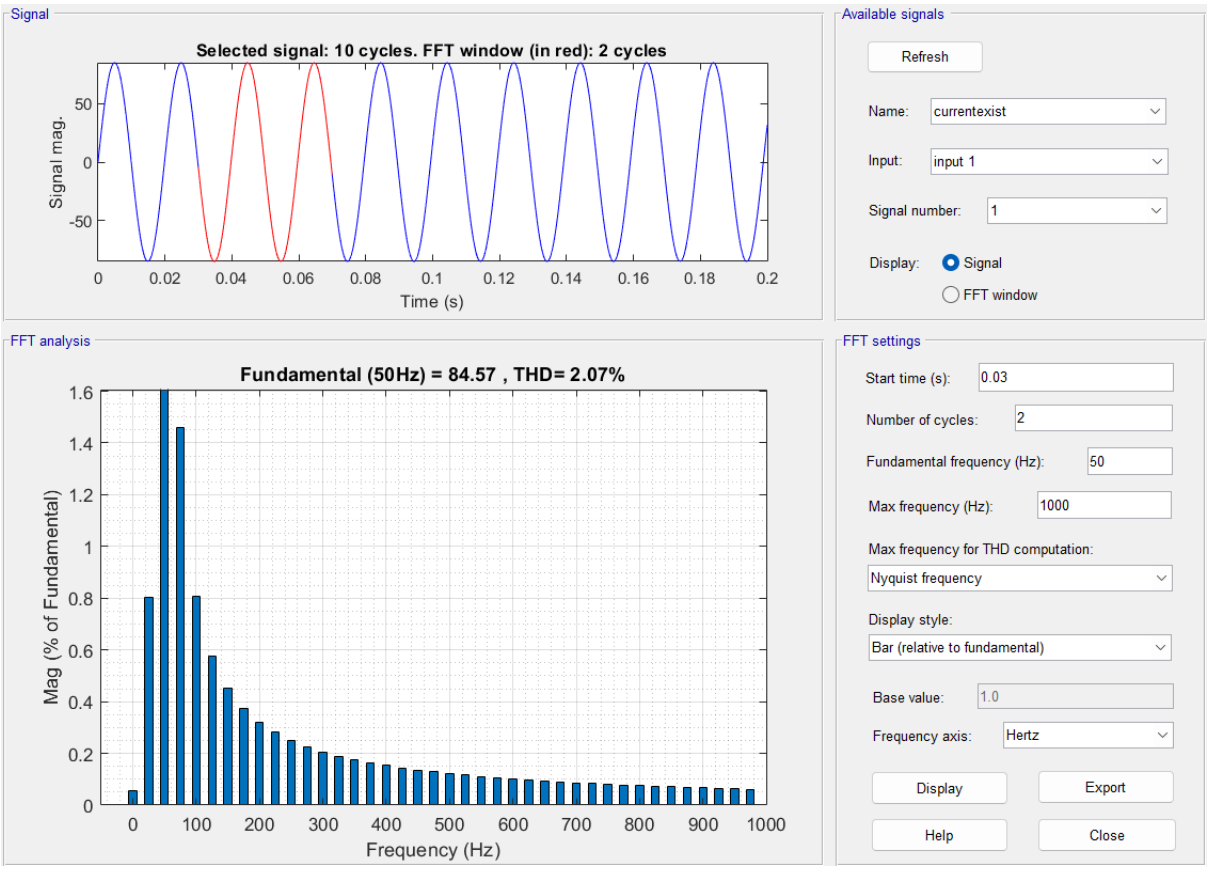



Fig 8. THD% of Grid current

A major improvement is observed in leakage current suppression and common-mode voltage stabilization. The combined effect of DC decoupling, AC decoupling, and mid-point clamping techniques significantly reduces common-mode voltage fluctuations. As a result, both peak and RMS leakage currents are minimized compared to the existing system. This enhances system safety and ensures compliance with grid standards. Additionally, the total harmonic distortion (THD) of the grid current is reduced from 2.07% in the MPC-based system to approximately 0.34% in the proposed system. This substantial reduction highlights the effectiveness of the FOPID controller in improving power quality and minimizing harmonic content.

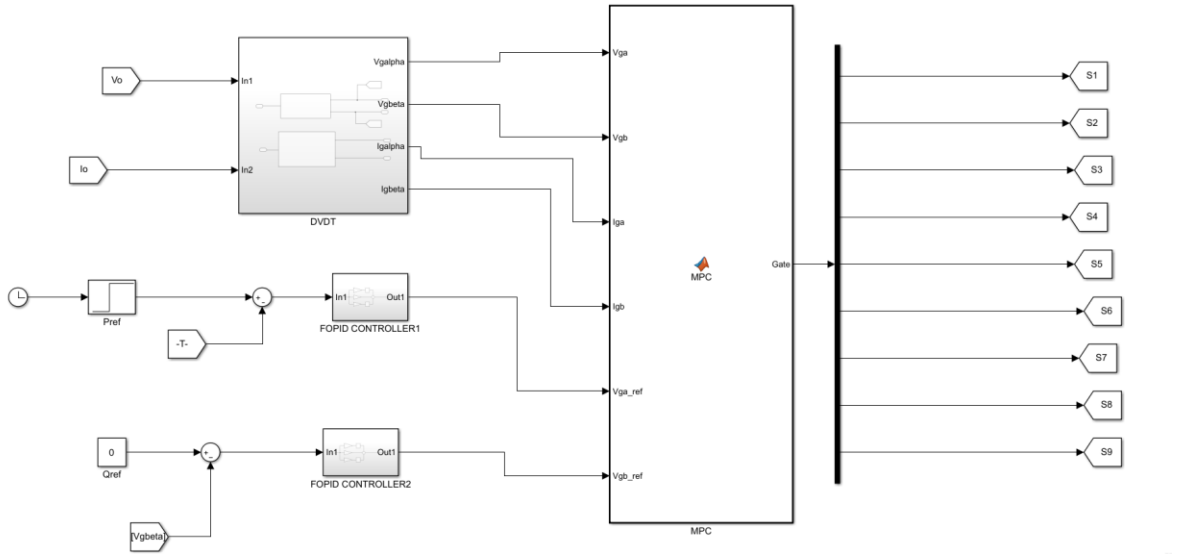



Fig 9. Control scheme for the proposed MPC topology with FOPID controller

The dynamic performance of the proposed system is also considerably improved. During sudden changes in power demand, the inverter exhibits faster transient response with minimal overshoot and reduced settling time. The transition from lower to higher power levels is smooth, and transient oscillations are significantly minimized. This improved dynamic behaviour is attributed to the additional tuning flexibility provided by the fractional-order controller. The system maintains stable operation even under varying irradiance conditions and load disturbances, demonstrating its robustness and adaptability.

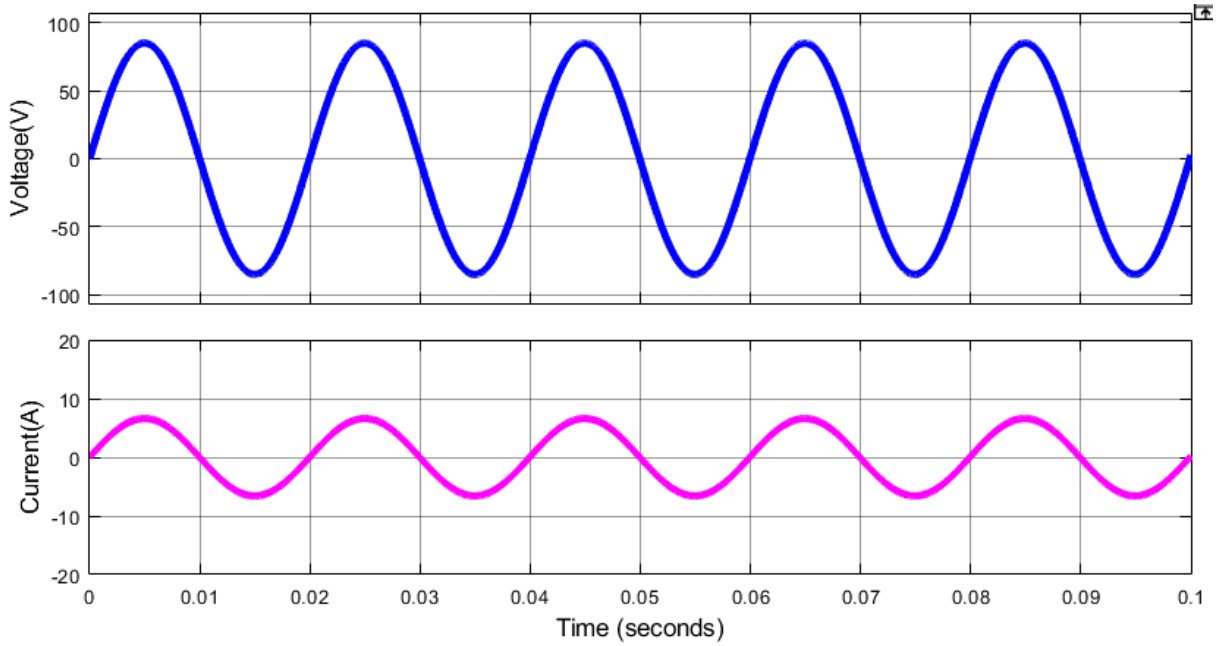



Fig 10. Simulation results of static performance with maximum instantaneous P of 660W.

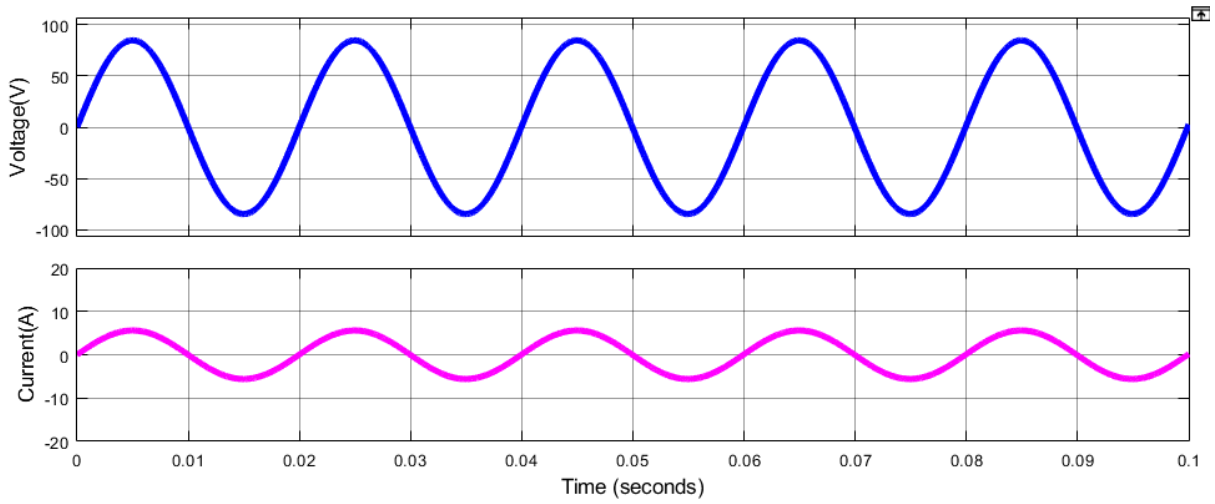



Fig 11. Simulation results of static performance with maximum instantaneous P and Q of (560W+j220VAR).

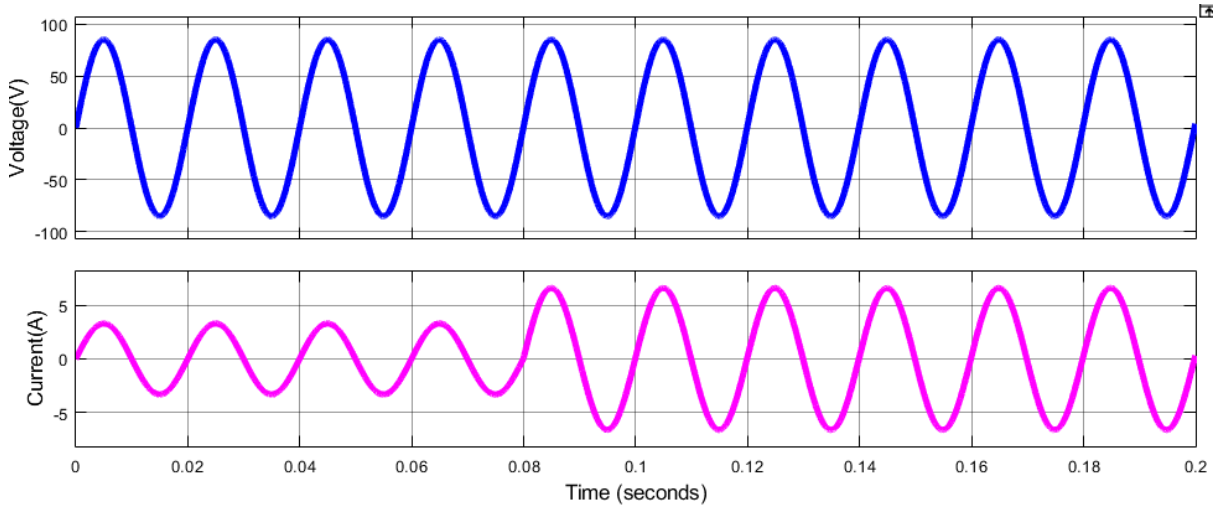



Fig 12. Simulation results of dynamic performance with maximum instantaneous P changing from 330W to 660W.

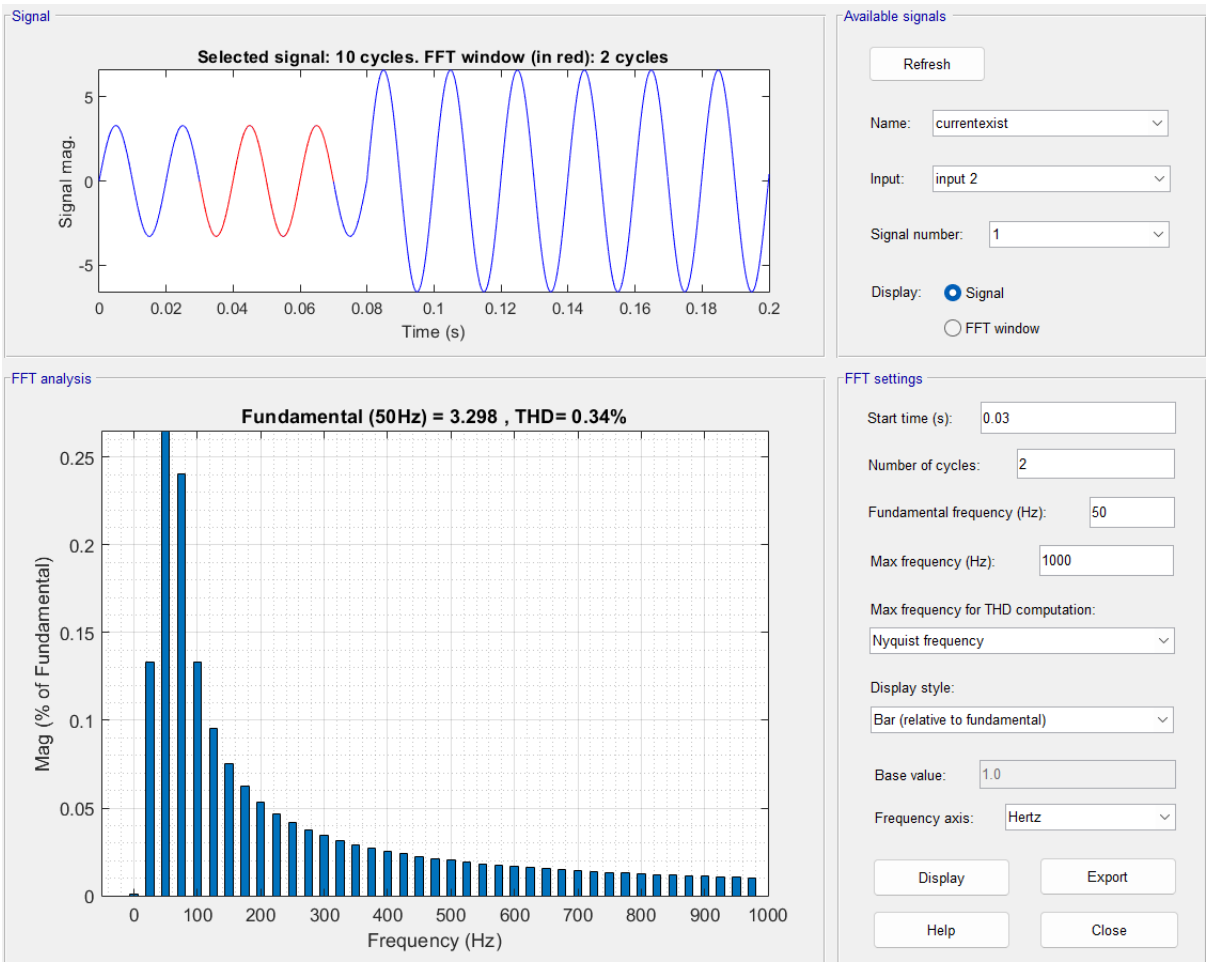



Fig 1.3 THD% of Grid current

Overall, the simulation results confirm that the proposed FOPID-controlled hybrid inverter outperforms the conventional MPC-based system in all major performance aspects. It achieves superior leakage current suppression, enhanced reactive power control, lower THD, improved waveform quality, and faster dynamic response. The system also demonstrates higher stability and better tracking performance under changing operating conditions. These improvements make the proposed inverter a highly efficient, reliable, and grid-compliant solution for modern photovoltaic applications, particularly in smart grids and distributed energy systems.

## CONCLUSION

The proposed FOPID-controlled hybrid transformer-less single-phase grid-connected photovoltaic (PV) inverter successfully addresses key challenges associated with conventional PV inverter systems, particularly leakage current mitigation, reactive power compensation, and dynamic performance improvement. By integrating DC decoupling, AC decoupling, and mid-point clamping techniques, the inverter effectively stabilizes the common-mode voltage, resulting in significant reduction of both RMS and peak leakage currents. The incorporation of the Fractional Order PID (FOPID) controller enhances the overall control performance by providing faster transient response, reduced overshoot, improved steady-state accuracy, and better disturbance rejection compared to traditional control methods. Simulation results demonstrate that the proposed system achieves superior power quality with a substantial reduction in total harmonic distortion (THD) and improved waveform smoothness. Additionally, the inverter is capable of independently controlling active and reactive power, enabling compliance with modern grid requirements and

contributing to voltage regulation and grid stability. The system maintains robust and stable operation under varying load and environmental conditions, validating its effectiveness and reliability. Overall, the proposed approach offers a high-efficiency, compact, and cost-effective solution for next-generation grid-connected PV systems, making it highly suitable for applications in smart grids, distributed generation, and renewable energy integration.

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