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Research Paper

FRACTIONAL-ORDER PID-BASED CONTROL FOR LEAKAGE CURRENT SUPPRESSION IN SINGLE-PHASE TRANSFORMER-LESS PV INVERTERS

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ABSTRACT:
This paper presents a FOPID-controlled hybrid transformer-less single-phase grid-connected solar PV inverter designed to reduce leakage current and provide reactive power compensation. The proposed topology combines decoupling and mid-point clamping techniques to suppress RMS and peak leakage currents while enabling independent control of active and reactive power. A Fractional Order PID (FOPID) controller is used to improve dynamic performance, power quality, and robustness. The system is validated through MATLAB/Simulink simulations and experimental results under both open-loop and closed-loop conditions. Comparative analysis shows superior performance in terms of leakage current reduction, control accuracy, and grid support capability compared to existing transformer-less inverter topologies.

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I. INTRODUCTION

The rapid depletion of fossil fuel reserves, combined with escalating concerns over environmental pollution and global climate change, has accelerated the worldwide transition toward renewable energy–based power generation systems. Among various renewable energy sources, solar photovoltaic (PV) energy has emerged as one of the most promising alternatives due to its sustainability, modular structure, ease of installation, and decreasing installation costs. In particular, grid-connected PV systems play a critical role in modern power systems by enabling distributed generation, reducing transmission losses, and improving overall system reliability. As the penetration level of PV systems into utility grids increases, the requirements for power quality, safety, efficiency, and grid support capability have become more stringent [1]. Consequently, advanced power electronic converter topologies and intelligent control strategies are essential to ensure compliance with international grid codes and operational stability.

Conventional grid-connected PV systems often incorporate bulky low-frequency transformers to provide galvanic isolation between the PV array and the grid. Although transformer-based systems offer inherent safety and eliminate leakage current issues, they suffer from significant disadvantages such as reduced efficiency, increased weight and volume, high cost, and complexity. To overcome these limitations, transformer-less inverter configurations have gained substantial research attention due to their high power density, lower cost, superior conversion efficiency, and compact design. However, the absence of galvanic isolation introduces a critical challenge—leakage current flowing through parasitic capacitances between the PV array and ground [2-3]. This leakage current not only reduces efficiency but also creates safety concerns, increases electromagnetic interference (EMI), degrades power quality, and may violate electrical safety standards.

Leakage current in transformer-less PV inverters primarily originates from the high-frequency common-mode voltage variations generated by switching operation. The parasitic capacitances between the PV module and earth form a conductive path that allows unwanted current to circulate, leading to excessive RMS and peak leakage currents. If not adequately controlled, this phenomenon can lead to insulation failure, electric shock hazards, and accelerated aging of system components [4]. Furthermore, excessive leakage current increases filtering requirements and may cause nuisance tripping of residual current devices (RCDs), thereby compromising system reliability. As a result, minimizing leakage current has become a primary design objective in transformer-less PV inverter topologies.

Over the past decade, various transformer-less inverter topologies have been proposed, including HERIC, H5, H6, oH5, and neutral point clamped (NPC) structures. While these topologies achieve varying degrees of leakage current reduction, they often involve trade-offs such as increased component count, higher conduction losses, complex modulation strategies, and limited grid support features [5-7]. Moreover, many existing designs primarily focus on reducing leakage current under unity power factor operation and often do not adequately support reactive power injection or absorption required by modern grid codes. Contemporary grid standards demand that inverters not only deliver active power but also provide reactive power support for voltage regulation and power factor correction.

With increasing penetration of PV systems, electrical utilities now require distributed generators to actively contribute to grid stability. This shift transforms PV inverters from passive power conversion devices into *active grid support units*. Features such as dynamic reactive power compensation, low-voltage ride-through (LVRT), frequency support, and harmonic mitigation are becoming mandatory [8-9]. However, incorporation of these ancillary services into transformer-less inverters is technically challenging due to additional control complexities and inherent limitations of inverter structures. Therefore, there is a growing need for innovative inverter topologies that can simultaneously reduce leakage current while enabling advanced grid-support functions.

In addition to topology development, control algorithms play a vital role in determining inverter performance. Conventional proportional–integral–derivative (PID) controllers are widely employed due to their simplicity and ease of implementation. However, PID controllers may fail to deliver optimal performance under nonlinear operating conditions, parameter uncertainties, sudden irradiance fluctuations, and variable grid impedance [10]. Furthermore, classical controllers are often insufficient in achieving fast transient response, low steady-state error, and robust tracking performance under real-world disturbances.

To overcome these limitations, advanced control methodologies such as model predictive control (MPC), sliding mode control (SMC), neural networks, fuzzy logic, and fractional order controllers have been extensively investigated. Among them, Fractional Order PID (FOPID) controllers have attracted increasing interest in power electronics applications [11-12]. Unlike conventional PID controllers that use integer-order derivatives and integrals, the FOPID controller introduces fractional powers, offering greater tuning flexibility and enhanced system modeling accuracy. The concept of fractional calculus allows dynamic behavior to be characterized more precisely, particularly for nonlinear and time-varying systems.

The key advantage of the FOPID controller lies in its additional tuning parameters, which improve system responsiveness and robustness. By incorporating fractional integration and differentiation orders, the controller can better handle transient disturbances, resonance effects, and system

uncertainties [13]. FOPID controllers have demonstrated superior performance in terms of overshoot reduction, settling time minimization, and harmonic suppression in power converter applications. However, despite their potential, FOPID controllers have seen limited application in transformer-less grid-connected PV inverters, particularly for combined leakage current reduction and reactive power compensation.

Another critical aspect in grid-connected PV inverters is the ability to independently control active and reactive power. Active power governs real energy injection into the grid, whereas reactive power controls voltage stability and grid support. Decoupled control architecture ensures that modulation signals governing power flow do not interfere with each other, allowing simultaneous regulation of inverter output current and grid voltage phase angle [14-16]. Without appropriate decoupling, reactive power injection may increase leakage current and harmonic distortion, thereby degrading performance.

II. LITERATURE SURVEY

[1] Int. Energy Agency. (2024). PVPS Trends Report 2024. [Online]. Avail able: https://www.iea-pvps.org

This Paper presents a comprehensive global analysis of photovoltaic deployment, market growth, and policy evolution during 2023–2024. It highlights accelerating capacity additions, declining system costs, and the expansion of rooftop and utility-scale PV installations worldwide. The report also discusses technology trends including bifacial modules, floating PV, and hybrid energy systems. It emphasizes emerging challenges such as grid integration, inverter compliance with evolving grid codes, and recycling of PV modules, while forecasting continued growth driven by decarbonization commitments and renewable energy targets.

[2] M. N. H. Khan, Y. P. Siwakoti, M. J. Scott, L. Li, S. A. Khan, D. D. Lu, R. Barzegarkhoo, F. Sidorski, F. Blaabjerg, and S. U. Hasan, "A com mon grounded type dual-mode five-level transformerless inverter for photovoltaic applications," IEEE Trans. Ind. Electron., vol. 68, no. 10, pp. 9742–9754, Oct. 2021, doi: 10.1109/TIE.2020.3028810.

This paper proposes a novel common-grounded five-level transformer-less inverter designed for photovoltaic applications. The topology offers dual operating modes that enable reduced conduction loss and improved efficiency across different power levels. By maintaining a constant common-mode voltage, the design significantly minimizes leakage current. Simulation and experimental validation confirm enhanced power quality, lower device stress, and improved reliability compared with conventional transformer-less inverters, making it suitable for high-performance grid-connected PV systems.

[3] M. Islam and S. Mekhilef, "An improved transformerless grid connected photovoltaic inverter with reduced leakage current," Energy Convers. Manage., vol. 88, pp. 854–862, Dec. 2014, doi: 10.1016/j.enconman.2014.09.014.

The authors introduce an enhanced transformer-less inverter topology that focuses on leakage current suppression using optimized switching sequences. The design ensures improved waveform quality with reduced harmonic distortion. Analytical modeling and experimental tests demonstrate effectiveness in maintaining low leakage current and high conversion efficiency. The work provides practical insights into ensuring compliance with safety standards while maintaining improved inverter performance in grid-connected PV installations.

[4] H.Xiao,"Overviewoftransformerlessphotovoltaicgrid-connectedinvert ers," IEEE Trans. Power Electron., vol. 36, no. 1, pp. 533–548, Jan. 2021, doi: 10.1109/TPEL.2020.3003721.

This article presents a detailed technical overview of transformer-less PV inverter architectures and modulation techniques. It categorizes inverter topologies based on grounding structure, switching behavior, and leakage current characteristics. Challenges related to safety, common-mode voltage, and

efficiency are critically analyzed. The paper further discusses future trends in topology development and control strategies, serving as a foundational reference for researchers working on high-efficiency PV inverters.

[5] X. Zhao, D. Jiang, J. Chen, Z. Shen, and Q. Li, "Leakage current sup pression with capacitor voltage control of three-level flying capacitor grid-connected inverters," IEEE Trans. Ind. Electron., vol. 69, no. 3, pp. 2191–2201, Mar. 2022.

This work introduces an advanced control strategy for three-level flying capacitor inverters to suppress leakage current in grid-connected systems. The authors propose real-time capacitor voltage balancing to reduce common-mode voltage fluctuations. Simulation and experimental results demonstrate effective RMS leakage current reduction and improved voltage stability, validating the approach as a practical enhancement technique for multilevel transformer-less PV inverters.

[6] S. V. Araujo, P. Zacharias, and R. Mallwitz, "Highly efficient single phase transformerless inverters for grid-connected photovoltaic systems," IEEE Trans. Ind. Electron., vol. 57, no. 9, pp. 3118–3128, Sep. 2010, doi: 10.1109/TIE.2009.2037654.

The authors present early designs of highly efficient single-phase transformer-less PV inverters, including unipolar PWM operation and novel topologies to enhance efficiency and safety. Detailed loss analysis shows improved performance compared to conventional inverters. The paper laid foundational principles for modern transformer-less inverter designs focusing on minimizing common-mode currents and increasing overall system efficiency.

III. PHOTOVOLTAIC TECHNOLOGY

3.1 INTRODUCTION

Photovoltaic's is the field of technology and research related to the devices which directly convert sunlight into electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic effect involves the creation of voltage in a material upon exposure to electromagnetic radiation.

The photovoltaic effect was first noted by a French physicist, Edmund Becquerel, in 1839, who found that certain materials would produce small amounts of electric current when exposed to light. In 1905, Albert Einstein described the nature of light and the photoelectric effect on which photovoltaic technology is based, for which he later won a Nobel prize in physics. The first photovoltaic module was built by Bell Laboratories in 1954. It was billed as a solar battery and was mostly just a curiosity as it was too expensive to gain widespread use. In the 1960s, the space industry began to make the first serious use of the technology to provide power aboard spacecraft. Through the space programs, the technology advanced, its reliability was established, and the cost began to decline. During the energy crisis in the 1970s, photovoltaic technology gained recognition as a source of power for non-space applications.

The solar cell is the elementary building block of the photovoltaic technology. Solar cells are made of semiconductor materials, such as silicon. One of the properties of semiconductors that makes them most useful is that their conductivity may easily be modified by introducing impurities into their crystal lattice. For instance, in the fabrication of a photovoltaic solar cell, silicon, which has four valence electrons, is treated to increase its conductivity. On one side of the cell, the impurities, which are phosphorus atoms with five valence electrons (n-donor), donate weakly bound valence electrons to the silicon material, creating excess negative charge carriers.

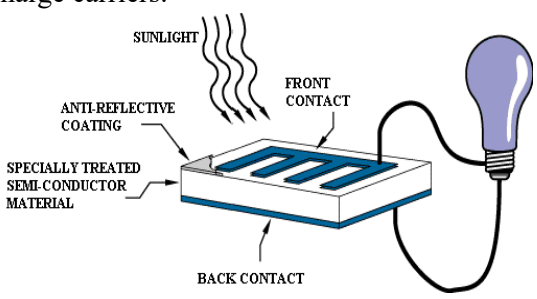


Fig 3.1: Solar cell.

3.1.1 Solar cell

The photovoltaic effect was first reported by Edmund Becquerel in 1839 when he observed that the action of light on a silver coated platinum electrode immersed in electrolyte produced an electric current. Forty years later the first solid state photovoltaic devices were constructed by workers investigating the recently discovered photoconductivity of selenium. In 1876 William Adams and Richard Day found that a photocurrent could be produced in a sample of selenium when contacted by two heated platinum contacts. The photovoltaic action of the selenium differed from its photoconductive action in that a current was produced spontaneously by the action of light.

A number of solar cells electrically connected to each other and mounted in a single support structure or frame is called a 'photovoltaic module'. Modules are designed to supply electricity at a certain voltage, such as a common 12 volt system. The current produced is directly dependent on the intensity of light reaching the module. Several modules can be wired together to form an array. Photovoltaic modules and arrays produce direct-current electricity. They can be connected in both series and parallel electrical arrangements to produce any required voltage and current combination.

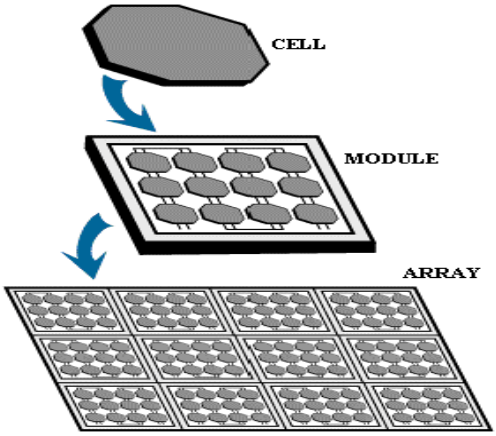


Fig 3.2: cell, module and array

3.1.2 Electrical connection of the cells

The electrical output of a single cell is dependent on the design of the device and the Semi-conductor material(s) chosen, but is usually insufficient for most applications. In order to provide the appropriate quantity of electrical power, a number of cells must be electrically connected. There are two basic connection methods: series connection, in which the top contact of each cell is connected to the back contact of the next cell in the sequence, and parallel connection, in which all the top contacts are connected together, as are all the bottom contacts. In both cases, this results in just two electrical connection points for the group of cells.

- **Series connection:**

Figure shows the series connection of three individual cells as an example and the resultant group of connected cells is commonly referred to as a series string. The current output of the string is equivalent to the current of a single cell, but the voltage output is increased, being an addition of the voltages from all the cells in the string (i.e. in this case, the voltage output is equal to 3Vcell).

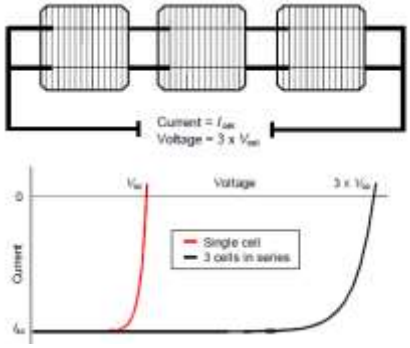


Fig. 3.3 :Series connection of cells, with resulting current–voltage characteristic.

It is important to have well matched cells in the series string, particularly with respect to current. If one cell produces a significantly lower current than the other cells (under the same illumination conditions), then the string will operate at that lower current level and the remaining cells will not be operating at their maximum power points.

- **Parallel connection:**

Figure shows the parallel connection of three individual cells as an example. In this case, the current from the cell group is equivalent to the addition of the current from each cell (in this case, 3 I cell), but the voltage remains equivalent to that of a single cell.

As before, it is important to have the cells well matched in order to gain maximum output, but this time the voltage is the important parameter since all cells must be at the same operating voltage. If the voltage at the maximum power point is substantially different for one of the cells, then this will force all the cells to operate off their maximum power point, with the poorer cell being pushed towards its open-circuit voltage value and the better cells to voltages below the maximum power point voltage. In all cases, the power level will be reduced below the optimum.

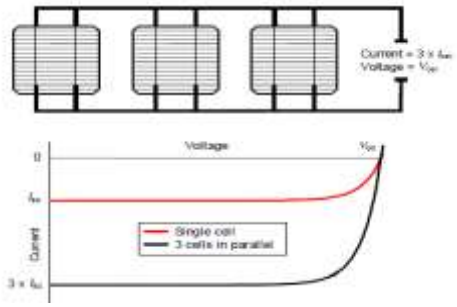


Fig.3.4 :Parallel connection of cells, with resulting current–voltage characteristic.

System design

There are two main system configurations – stand-alone and grid-connected. As its name implies, the stand-alone PV system operates independently of any other power supply and it usually supplies electricity to a dedicated load or loads. It may include a storage facility (e.g. battery bank) to allow electricity to be provided during the night or at times of poor sunlight levels. Stand-alone systems are also often referred to as autonomous systems since their operation is independent of other power sources. By contrast, the grid-connected PV system operates in parallel with the conventional electricity distribution system. It can be used to feed electricity into the grid distribution system or to power loads which can also be fed from the grid.

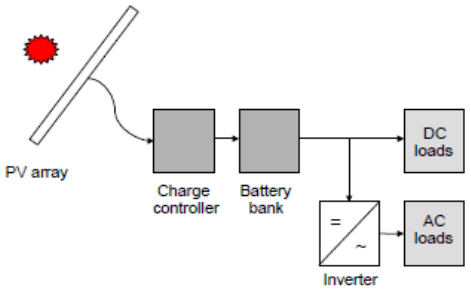


Fig. 3.5 :Schematic diagram of a stand-alone photovoltaic system.

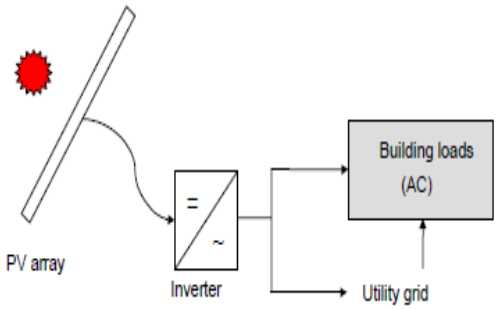


Fig. 3.6 :Schematic diagram of grid-connected photovoltaic system.

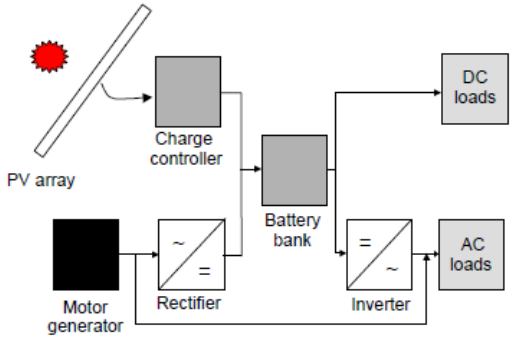


Fig. 3.7 :Schematic diagram of hybrid system incorporating a photovoltaic array and a motor generator (e.g. diesel or wind)

IV. INVERTER

The main objective of static power converters is to produce an ac output waveform from a dc power supply. These are the types of waveforms required in adjustable speed drives (ASDs), uninterruptible power supplies (UPS), static VAR compensators, active filters, flexible ac transmission systems (FACTS), and voltage compensators, which are only a few applications. For sinusoidal ac outputs, the magnitude, frequency, and phase should be controllable. According to the type of ac output waveform, these topologies can be considered as voltage source inverters (VSIs),

where the independently controlled ac output is a voltage waveform.

Static power converters, specifically inverters, are constructed from power switches and the ac output waveforms are therefore made up of discrete values. This leads to the generation of waveforms that feature fast transitions rather than smooth ones. For instance, the ac output voltage produced by the VSI of a standard ASD is a three-level

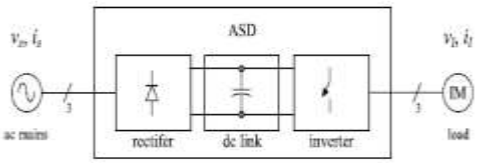
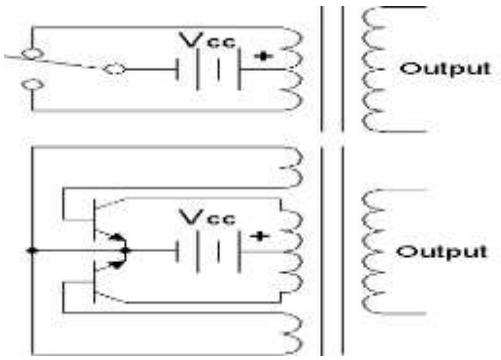


Fig 4.1 Inverter connection

Basic designs:

In one simple inverter circuit, DC power is connected to a transformer through the centre tap of the primary winding. A switch is rapidly switched back and forth to allow current to flow back to the DC source following two alternate paths through one end of the primary winding and then the other. The alternation of the direction of current in the primary winding of the transformer produces alternating current (AC) in the secondary circuit.

The electromechanical version of the switching device includes two stationary contacts and a spring supported moving contact. The spring holds the movable contact against one of the stationary contacts and an electromagnet pulls the movable contact to the opposite stationary contact. The current in the electromagnet is interrupted by the action of the switch so that the switch continually switches rapidly back and forth. This type of electromechanical inverter switch, called a vibrator or buzzer, was once used in vacuum tube automobile radios. A similar mechanism has been used in door bells, buzzers and tattoo.As they became available with adequate power ratings, transistors and various other types of semiconductor switches have been incorporated into inverter circuit designs.



Output waveforms:

The switch in the simple inverter described above, when not coupled to an output transformer, produces a square voltage waveform due to its simple off and on nature as opposed to the sinusoidal waveform that is the usual waveform of an AC power supply. Using Fourier analysis, periodic waveforms are represented as the sum of an infinite series of sine waves. The sine wave that has the same frequency as the original waveform is called the fundamental component. The other sine waves, called *harmonics*, that are included in the series have frequencies that are integral multiples of the fundamental frequency.

The quality of the inverter output waveform can be expressed by using the Fourier analysis data to calculate the total harmonic distortion (THD). The total harmonic distortion is the square root of the sum of the squares of the harmonic voltages divided by the fundamental voltage:

$$\mathrm{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2}}{V_1}$$

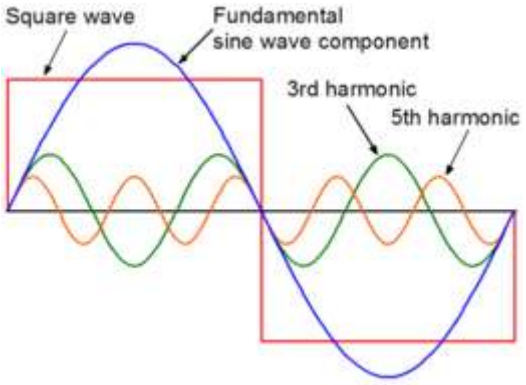


Fig 4.2 Total Harmonic Distortion

4.1Types of inverters

Generally inverters are of Two Types:

4.1.1 VOLTAGE SOURCE INVERTER

4.1.2 CURRENT SOURCE INVERTER

4.2 Single-phase voltage source inverters:

Single-phase voltage source inverters (VSIs) can be found as half-bridge and full-bridge topologies. Although the power range they cover is the low one, they are widely used in power supplies, single-phase UPSs, and currently to form elaborate high-power static power topologies, such as for instance, the multicell configurations that are reviewed The main features of both approaches are reviewed and presented in the following.

4.3 Types of VSI:

4.3.1 Half-Bridge VSI:

The power topology of a half-bridge VSI, where two large capacitors are required to provide a neutral point N, such that each capacitor maintains a constant voltage=2. Because the current harmonics injected by the operation of the inverter are low-order harmonics, a set of large capacitors (C. and Cÿ) is required. It is clear that both switches S. and Sÿ cannot be on simultaneously because short circuit across the dc link voltage source vi would be produced. There are two defined (states 1 and 2) and one undefined (state 3) switch state as shown in Table 14.1. In order to avoid the short circuit across the dc bus and the undefined ac output voltage condition, the modulating technique should always ensure that at any instant either the top or the bottom switch of the inverter leg is on.

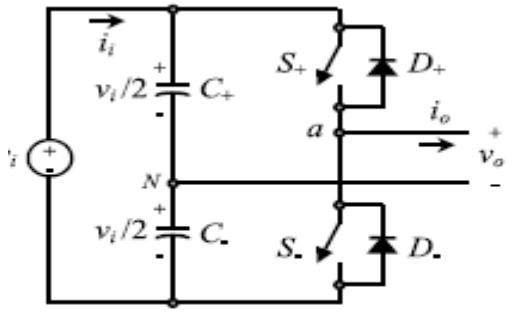


FIGURE 14.2 Single-phase half-bridge VSI.

Fig 4.3 Single Phase Half bride VSI

4.3.2 Full-Bridge VSI:

The power topology of a full-bridge VSI. This inverter is similar to the half-bridge inverter; however, a second leg provides the neutral point to the load. As expected, both switches S1. and S1ÿ (or S2. and S2ÿ) cannot be on simultaneously because a short circuit across the dc link voltage source vi would be produced. There are four defined and one undefined

The undefined condition should be avoided so as to be always capable of defining the ac output voltage. In order to avoid the short circuit across the dc bus and the undefined ac output voltage condition, the modulating technique should ensure that either the top or the bottom switch of each leg is on at any instant. It can be observed that the ac output voltage can take values up to the dc link value vi , which is twice that obtained with half-bridge VSI topologies. Several modulating techniques have been developed that are applicable to full-bridge VSIs. Among them are the PWM (bipolar and unipolar) techniques.

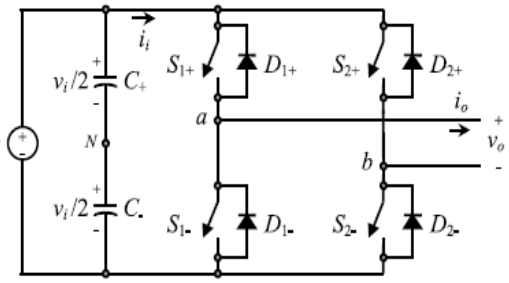


Fig 4.6 Full Bridge VSI

4.4 Current Source Inverters:

The main objective of these static power converters is tom produce ac output current waveforms from a dc current power supply. For sinusoidal ac outputs, its magnitude, frequency, and phase should be controllable. Due to the fact that the ac line currents ioa, iob, and ioc (Fig. 14.23) feature high di=dt, a capacitive filter should be connected at the ac terminals in inductive load applications (such as ASDs).

Thus, nearly sinusoidal load voltages are generated that justifies the use of these topologies in medium-voltage industrial

applications, where high-quality voltage waveforms are required.

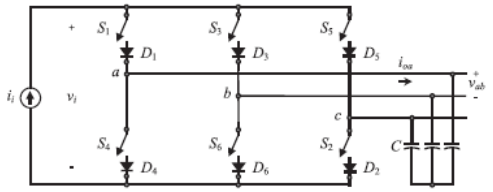


Fig.4.7 Current source Inverter

V. SIMULATION RESULTS

A) EXISTING RESULTS

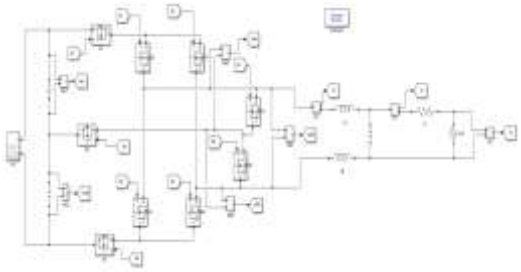


Fig 7.1 MATLAB/SIMULINK circuit diagram of the system

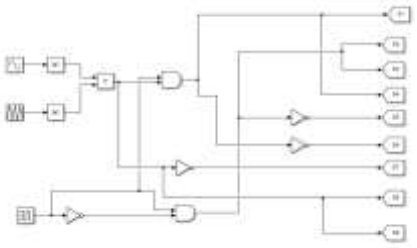
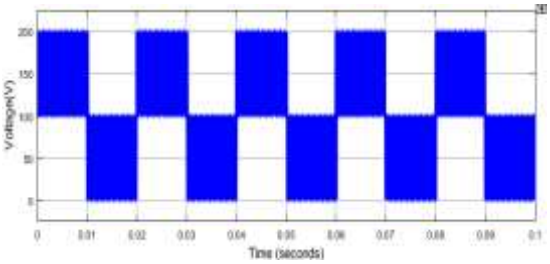
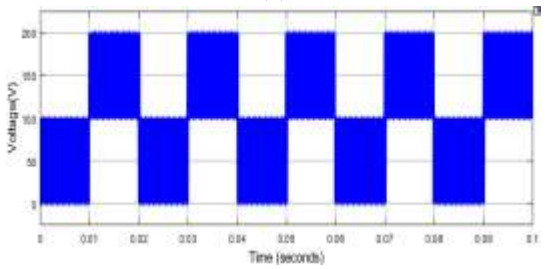


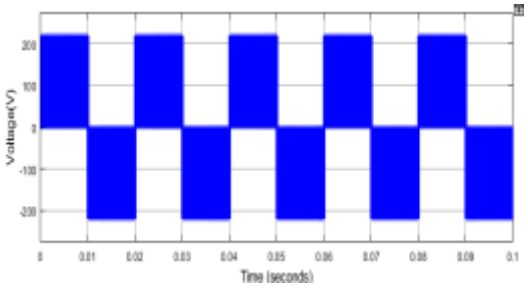
Fig 7.2. Modulation technique of the for open loop.



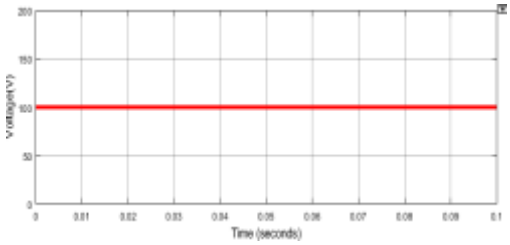
(a)



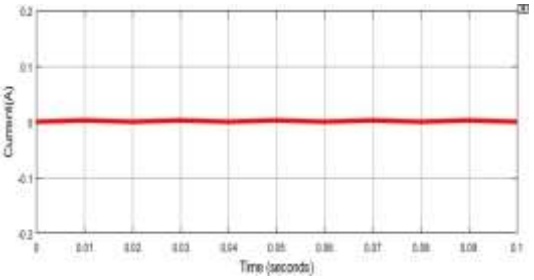
(b)



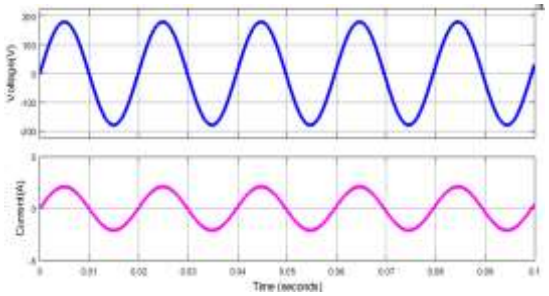
(c)



(d)



(e)



(f)

FIGURE 7.3. Simulation results for open loop (a) VAN and VBN(b) VAB(c) VtCM (d) ILC(e) VO and IO.

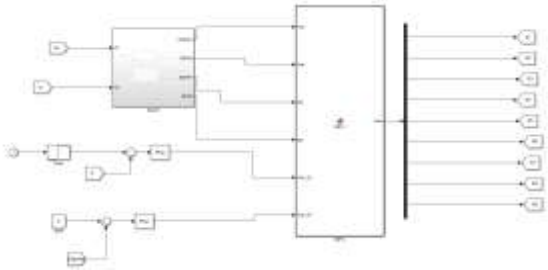


FIGURE 7.4 Control scheme for the proposed MPC topology

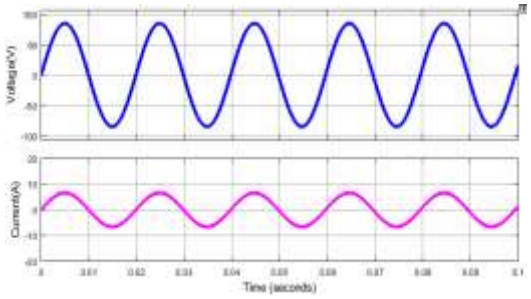


FIGURE 7.5. Simulation results of static performance with maximum instantaneous P of 660W.

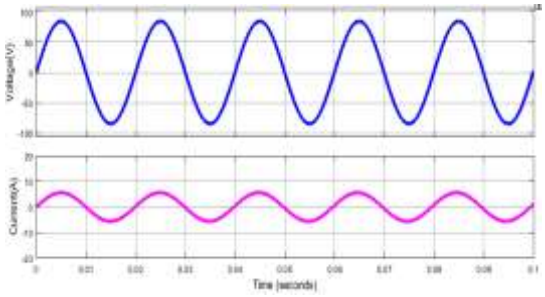


FIGURE 7.6. Simulation results of static performance with maximum instantaneous P and Q of (560W+j220VAR).

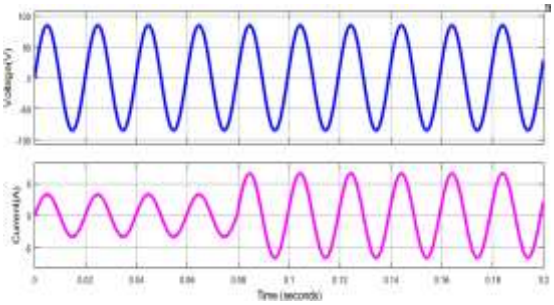


FIGURE 7.7. Simulation results of dynamic performance with maximum instantaneous P changing from 330W to 660W.

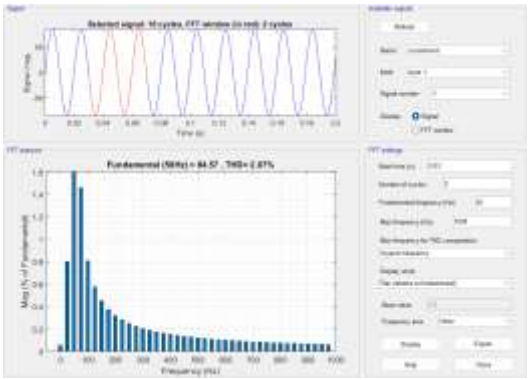


FIGURE 7.8 THD% of Grid current

B) EXTENSION RESULTS

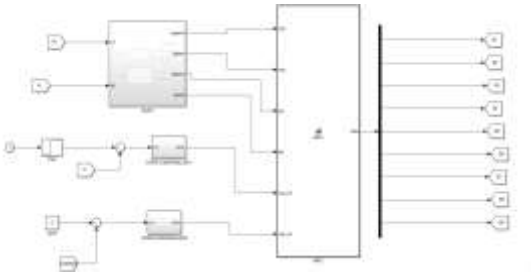


FIGURE 7.9 Control scheme for the proposed MPC topology with FOPID controller

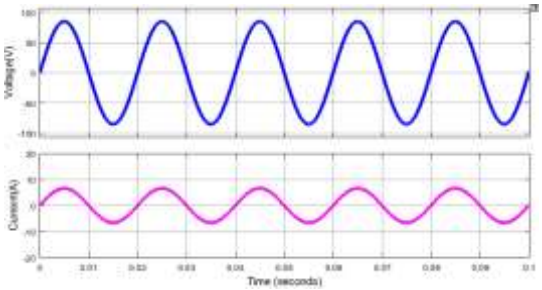


FIGURE 7.10. Simulation results of static performance with maximum instantaneous P of 660W.

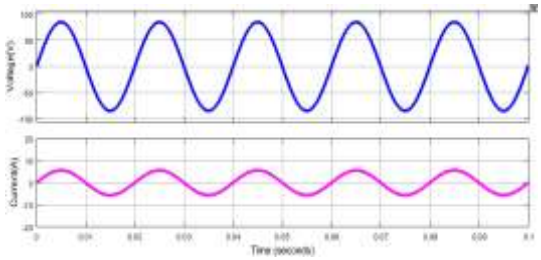


FIGURE 7.11. Simulation results of static performance with maximum instantaneous P and Q of (560W+j220VAR).

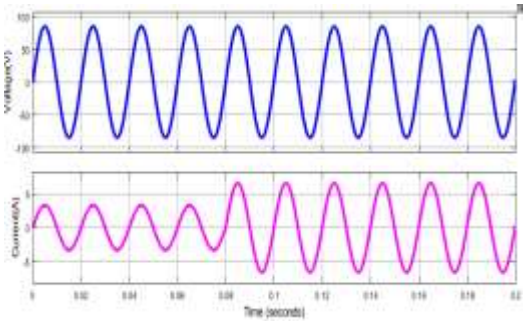


FIGURE 7.12. Simulation results of dynamic performance with maximum instantaneous P changing from 330W to 660W.

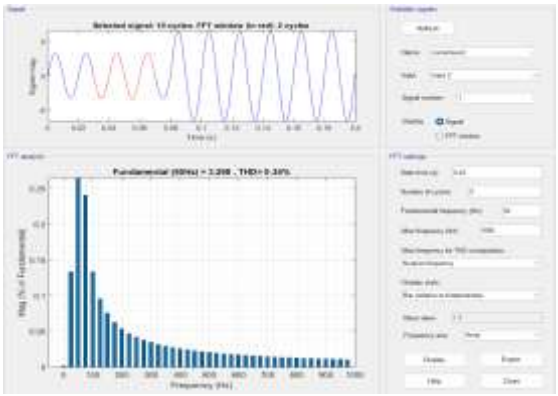


FIGURE 7.13 THD% of Grid current

ADVANTAGES

The proposed FOPID-controlled hybrid transformer-less inverter offers several significant advantages over conventional grid-connected photovoltaic inverters in terms of safety, performance, and grid integration capability.

1. Significant Leakage Current Reduction:

The combined decoupling and mid-point clamping technique effectively suppresses both RMS and peak leakage currents by stabilizing the common-mode voltage. This ensures compliance with international safety standards and improves system reliability.

2. Reactive Power Support Capability:

Unlike traditional transformer-less inverters that operate only at unity power factor, the proposed inverter allows controlled reactive power injection, enabling voltage regulation and grid stabilization.

3. Superior Dynamic Performance Using FOPID Control:

The fractional order PID controller provides faster transient response, lower overshoot, and improved tracking capability compared with conventional PI or PID controllers, particularly under nonlinear and time-varying conditions.

4. High Efficiency and Power Density:

The elimination of bulky isolation transformers leads to a compact structure with reduced losses and improved conversion efficiency.

5. Improved Power Quality:

Low Total Harmonic Distortion (THD) is achieved at the grid side due to the enhanced current control mechanism and optimized switching strategy.

6. Robust Operation Under Grid Disturbances:

The system maintains stable operation under voltage sags, irradiance fluctuations, and load changes.

APPLICATIONS

The proposed inverter can be effectively deployed in several grid-connected and distributed generation scenarios.

1. Rooftop Solar Power Systems

Suitable for residential and commercial rooftop PV installations requiring reactive power compliance with grid standards.

2. Utility-Scale Solar Farms

Can support voltage stabilization and power quality improvement in large-scale PV plants.

3. Smart Grids and Microgrids

Acts as an intelligent power interface in microgrids by providing both power flow control and ancillary services.

4. Weak Grids and Rural Electrification

Supports voltage control in rural or remote locations where grid impedance is high and instability is common.

5. Net-metering Systems

Enhances grid interaction for bidirectional power exchange.

6. Industrial PV Plants

Improves power factor and reduces penalties in industrial energy systems.

7. EV Charging Infrastructure

Can be integrated with solar-powered charging stations to provide grid support.

8. Hybrid Renewable Systems

Supports integration with wind-solar-battery combinations.

9. Power Quality Enhancement Installations

Can operate as a reactive power compensator similar to STATCOM functionality.

10. Building-Integrated Photovoltaics (BIPV)

Offers compact installation with efficiency and grid compliance.

VI. CONCLUSION

This project presented a FOPID-controlled hybrid transformer-less single-phase grid-

connected photovoltaic inverter with reduced leakage current and reactive power compensation capability. The proposed inverter topology effectively suppresses common-mode voltage using decoupling and mid-point clamping strategies, resulting in significantly reduced leakage currents compared with traditional transformer-less structures. A Fractional Order PID controller was implemented to improve dynamic performance, enhance robustness, and lower steady-state error. The control architecture enabled independent regulation of active and reactive power while maintaining grid synchronization. The proposed system was validated through MATLAB/Simulink simulations and experimental results under various operating conditions. Comparative analysis confirmed that the proposed inverter outperforms existing transformer-less topologies in leakage current suppression, current distortion reduction, and grid support performance. The inverter demonstrated stable operation under both unity and non-unity power factor conditions and complied with safety requirements. Overall, the proposed system provides an efficient, reliable, and grid-compliant solution for next-generation PV installations.

FUTURE SCOPE

Future research can extend the proposed work in several promising directions to further enhance the practicality and intelligence of transformer-less photovoltaic inverter systems. The proposed topology and FOPID controller can be extended to three-phase grid-connected and multilevel inverter configurations for high-power and utility-scale applications. Integration with energy storage systems such as batteries or supercapacitors may enable improved power management, smoothing of PV output fluctuations, and islanded-mode operation in microgrids. Advanced control methods, including adaptive FOPID, artificial intelligence–based optimization, reinforcement learning, and neural network controllers, can be explored to achieve self-tuning capability under changing grid conditions. Hardware-in-the-loop (HIL) testing and long-term field validation will strengthen system credibility and commercial feasibility. In addition, grid-support functions such as fault ride-through capability, grid-forming operation, frequency regulation, and voltage support can be incorporated to meet evolving grid codes. Future designs may also focus on EMI mitigation, thermal optimization, and reliability modeling to improve system lifespan. Moreover, cyber-security-aware control frameworks and IoT-based monitoring solutions can be integrated for real-time diagnostics and predictive maintenance. Finally, future work may extend toward standard compliance testing and techno-economic analysis to accelerate market readiness and large-scale deployment.

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