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Analysis of a Photovoltaic System Based on a Highly Efficient Single-Phase Transformerless Inverter

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Abstract: The essential requirement for a cleaner environment, along with rising consumption, puts a strain on the distribution system and power plants, reducing electricity availability, quality, and security. Grid-connected photovoltaic systems are one of the solutions for overcoming this. The examination and verification of transformerless topologies and control techniques was a significant goal of this study. The transformerless concept is advantageous for its high efficiency; the transformerless converter has added advantages of reduced price, complexity, weight, and size. This study presents a novel high-efficiency transformerless architecture that does not create common-mode currents and does not inject DC current into the grid. A single-phase transformerless inverter circuit with two step-down converters was constructed in this study. Low-frequency switches determine the polarity of the grid connection. In order to control the gate pulses of switching devices, which each regulate a half-wave of the output current, a PIC 16F877 was employed. Because there were fewer semiconductors and they were simpler to operate, it was possible to achieve a high degree of efficiency and reliability. A prototype model with input 12 V, 2 A was fabricated, test results were obtained with reduced common-mode current and DC current, and high efficiency was obtained with reduced switching losses. Further investigation for the improvement of efficiency with the elimination of ground current and leakage current has been analysed through simulation.

Keywords: transformerless inverter; photovoltaic; high-efficiency inverter; grid-connected system; single-phase inverter



Citation: Aljafari, B.; Loganathan, A.K.; Vairavasundaram, I.; Ramachadran, S.; Nagarajan, A.P. Analysis of a Photovoltaic System Based on a Highly Efficient Single-Phase Transformerless Inverter. *Energies* **2022**, *15*, 6145. <https://doi.org/10.3390/en15176145>

Academic Editor: Marco Pasetti

Received: 3 July 2022

Accepted: 20 August 2022

Published: 24 August 2022

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1. Introduction

For safety reasons, galvanic isolation is employed in most photovoltaic (PV) systems. When the isolation transformer is removed, the inverter may be more efficient, lighter in weight and size, and more affordable. When the transformer is removed, the overall efficiency of the PV system can be boosted by 1–2%. When compared to PV systems with galvanic separation, the most significant gains of transformerless PV systems are less weight, small size, and improved efficiency.

Transformer-less inverters have recently been presented as a way to shrink the size and cost of photovoltaic power systems. The earth-leakage current problem then arises, posing a significant challenge in the system. Both the general public and the power industry acknowledge the importance of renewable energy sources. According to some scholars, environmental concerns have taken precedence above the necessity to conserve scarce natural resources for future generations. The following are some of the advantages of reformation: increased rivalry in the energy-producing business; and individual consumers' opportunity to pick the greatest cost-effective dealer to distribute electricity to them.

According to consumer polls, both urban and rural electricity customers are prepared to pay a higher power cost to promote the growth of renewable energy sources. This

strong public backing has offered an incentive for developing a technically proved low-cost alternative to fossil-fuel-based power. Photovoltaic generation is one of these options, albeit it is currently not a cost-effective technique of generating electrical energy except in a few, generally remote, applications.

Many electrical experts are investigating grid-connected PV systems as a viable substitute energy source. When installed at the point of use, grid-connected PV systems can save money by reducing: (i) transmission power losses; (ii) required transmission line capacity; (iii) the necessity for traditional power generation; (iv) emissions of CO₂ and the cost of gasoline.

The quantity of electricity generated by a solar system linked to a customer does not necessarily match that consumer's energy consumption. As a result, utilizing all the energy generated by such a system requires the use of a huge energy storage capacity in combination with PV generating. Any excess energy from the PV system may be sent directly into the grid network, which would be more budget friendly. The benefit of the PV system that is generating power connected to the utility grid, versus a stand-alone PV generation, is that backup power and massive capacity are shared.

Utility backup capability is required in the grid-shared PV system being examined. Without battery storage, the PV energy is directly converted to utility energy in the Utility Tie Technology method. The benefits of not using batteries to store surplus energy from PV panels in household applications are: (i) lower PV system capital and maintenance costs; (ii) elimination of all battery-related health and safety issues from customers' homes.

The designed inverter can also be used in classic applications, including voltage regulation systems, uninterruptible power supply systems, and motor controllers, even though it is intended for grid-connected PV systems. The primary drawbacks of consuming solar power are its high initial price compared to other energy sources and its low conversion efficiency, which is less than 20% in commercially available PV systems. When the price of the solar panels and inverter system decreases along with their improved efficiency, then utility-connected PV generation becomes a viable alternative power source.

Institutions in India are conducting research into producing more efficient PV panels, which was not included in this paper's mandate. However, the inverter is quite important in the utilization of solar energy. The major goal of this paper was to increase the inverter efficiency. Greater efficiency was expected to be obtained through enhanced inverter output power quality and lower costs.

In India, inverters are used in household systems. A home system's distribution capacity is often less than 5 kW. The infrastructure, on the other hand, uses transformers to connect the inverter output to the grid system. As a result, there is no undesired DC offset current injected into the grid network. However, one of the strategies employed in the proposed circuit is not to use 50 Hz power transformers in the inverter to decrease price, size, and power loss. Whether or not transformers are required depends on how the quantity of the injected DC offset current into the grid system is controlled. The injection of DC current into PV inverters that are directly linked to the grid is limited to 5 mA, or 0.5 percent of the rated output current; whichever is larger.

As a second method of boosting PV inverter efficiency, the use of unipolar switching inverters for utility-connected systems, was proposed. Unipolar switching has the benefit of resulting in fewer power losses. It was also necessary to improve approaches to current controller design to maximize inverter efficiency. This targeted increased efficiency, on the other hand, could only be achieved if the IEEE Standards and the local electrical supply authority's requirements were attained by the output from the inverter system, without raising the cost of the inverter system, and the conventional supply system's safety and reliability were not jeopardized.

This research is difficult due to the vast number of control loops that must be examined to obtain better efficiencies without losing inverter power quality, as well as the limits set by the IEEE Std. 1547, 2003. Table 1 summarizes the tactics, potential difficulties, and potential

solutions to be researched to obtain better inverter efficiency, reduced costs, and enhanced power quality.

Table 1. Summary of Tactics to Maximize Inverter Efficiencies.

Solution No	Tactics for Maximizing Efficiency	Consequences for Power Quality	Types of Keys to Be Examined
1	Transformerless Operation	Offset DC current intrusion into the grid system at unacceptably high levels is a source of worry.	Progress of low-cost methods for removing DC offset current
		Electromagnetic compatibility issues are more likely to occur.	Current and voltage controller design options that decrease EMC concerns
2	Unipolar Switching	Current distortion at zero crossing, as well as high amounts of low and switching frequency harmonics fed into the grid system, could cause issues.	Current harmonics are eliminated using (a) Low frequency harmonics are reduced utilising current steering AC filter designs. (b) designs for feedback loops

The primary goal of this essay was to increase the efficiency of a PV inverter system while maintaining the quality of the power generated and lowering the cost.

The study describes a system that is controlled by a microcontroller that consists of stand-alone PV system with an energy storage system and a complete bridge inverter. It is made up of two sets of Boost-type chopper circuits, a modest number of switching elements and a complete bridge voltage source inverter resulting in a small overall system volume. As a result, the systems' costs are kept to a minimum. Pulse Width Modulation (PWM) signals reduce the number of pulses on the output waveform, increasing conversion efficiency. The suggested inverter's output power is less than 288 W. It is not necessary for the system to connect to a utility grid line using an inductor or a transformer. The theory underpinning the system is that there is no earth-leakage current. Simulated and experimental findings are presented in this research using prototype devices with a power of 37 W.

2. Literature Review

Multilevel converters for single-phase grid-connected solar systems were invented by M. Calais et al. [1]. They investigated the applicability of several multilevel topologies for single-phase grid-connected solar systems. The system power rating, component count, stress, and solar array earth capacitance influence of several transformerless photovoltaic systems with multilayer converters were all investigated.

Inverters for single-phase grid-linked solar systems were created by M. Calais, J. M. A. Myrzik, and V. G. Agelidis [2]. The information included not only commercially available topologies but also efficiency, pricing trends, market share, switching devices and switching frequencies. Finally, the article analysed the difficulties associated with defining acceptable worldwide industry standards for PV inverter technology.

For single-phase grid-connected solar systems, J. M. A. Myrzik et al. investigated string and module integrated inverters [3]. They discussed PV inverters, their efficiency, pricing trends, and market share, as well as innovative inverter topologies and PV system concepts that have recently emerged.

Single-phase grid-connected inverters for solar modules were studied by S. B. Kjaer et al. [4]. They focused on PV inverter technology used to link PV modules to a single-phase grid. Several inverter topologies were explained, compared, and evaluated in terms of their requirements, longevity, price, and component ratings. The optimal topologies for single- or multi-module applications were highlighted in their last section.

A transformerless inverter for residential solar energy systems was created by Amitava Das and Debasish Lahiri [5]. They created a Z-source inverter that eliminated the need

for a transformer. The system's operating concept, control approach, and attributes were discussed and the article compared the new and conventional system configurations. To showcase the new features, analysis, and simulation results were provided.

The earliest PV inverters were based on technology that had been used in electrical drives since the early 1980s as line commutated inverters with several kW of power rating. High efficiency, cheap cost, and robustness were the key advantages; however, with values ranging from 0.6 to 0.7, the power factor constituted a major disadvantage.

These days, inverters with a power range greater than 1.5 kW are force-commutated inverters. Traditional transformerless architecture having switching frequencies larger than 16 kHz of H-Bridge is used to eliminate sound disturbance. Due to the significant switching losses, the line commutated topology has lower efficiency. However, it is indeed a reliable, low-cost, and famous technology.

If the PV voltage level falls below the necessary minimum, a boost converter is added between the PV array and the inverter. In the European scenario, this increases the PV input voltage to a DC-link value of roughly 700 V for three-phase grid connection and 400 V for single-phase. In Figure 1a, a single-phase topology is shown.

The H-bridge forced commutated inverter, see Figure 1b, consists of a boost rectifier that elevates the PV array voltage from 100 V to more than 680 V. When there is a need for positive output voltage the upper switches are used, and bottom switches are used for getting the negative output voltage.

The Highly Efficient and Reliable Inverter Concept (HERIC) makes use of an enhanced version of the H-Bridge, as illustrated in Figure 1c, by connecting two diodes with two more switches in series for the freewheeling period and to boost the inverter's efficiency, two additional switches (T5 and T6) are used, thus depending on the current's signal, the freewheeling current finds a way via T5 or T6 and the appropriate diode rather than returning to the DC-link capacitor.

Figure 1d shows the H5 inverter for a grid-connected PV system. It has a normal H-Bridge architecture with a fifth switch added to the DC side. Maximum conversion efficiencies utilizing this circuit design have been reported to reach up to 98 percent, depending on the input voltage.

In all the above topologies of transformerless PV systems, inverters have been proposed, however their primary flaw is that they require a complicated control structure and several transformation stages, which lowers total conversion efficiency and increases inverter complexity and element computation. In the previous several decades, the PV inverter business has advanced significantly. Many transformerless topologies have been developed throughout the years, but only a handful have been approved as appropriate topologies for grid-connected PV systems by the industry. As a result, inverters are among the most promising topologies in terms of efficiency, price, safety, structure, and complexity on the feasible market.

For solar power generation, Y. Chen et al. [6] presented a single-stage inverter with maximum power point tracking at a reasonable price in conjunction with one-cycle control (OCC). The output current-adjusting capability of OCC is used in this control method. The inverter's output current may be modified based on the voltage of the photovoltaic (PV) array to get the most power out of it. All of this is accomplished with a single power stage and a straightforward control circuit. This strategy is far more efficient and cost-effective than the previously offered ways while still delivering good results.

The investigation, design, and implementation of a maximum power point tracking (MPPT) system for standalone solar power generation were the topics covered by Roger Gules et al. [7]. They constructed a solar streetlamp with a locally developed smart charge controller by L. Nirupa Rathnayake and T. Chandana Peiris [8]. This intelligent charger controller was built with the utmost commonly available less price PIC microcontroller, offering the system design flexibility. The newly designed charge controller gave the maximum amount of electricity from the solar panel; besides it protected the battery from overcharging. Another important aspect was that automatically the streetlamp turned on

and off. The smart charge controller was cost-effective, and it could certainly be adapted to various energy sources, including wind turbines.

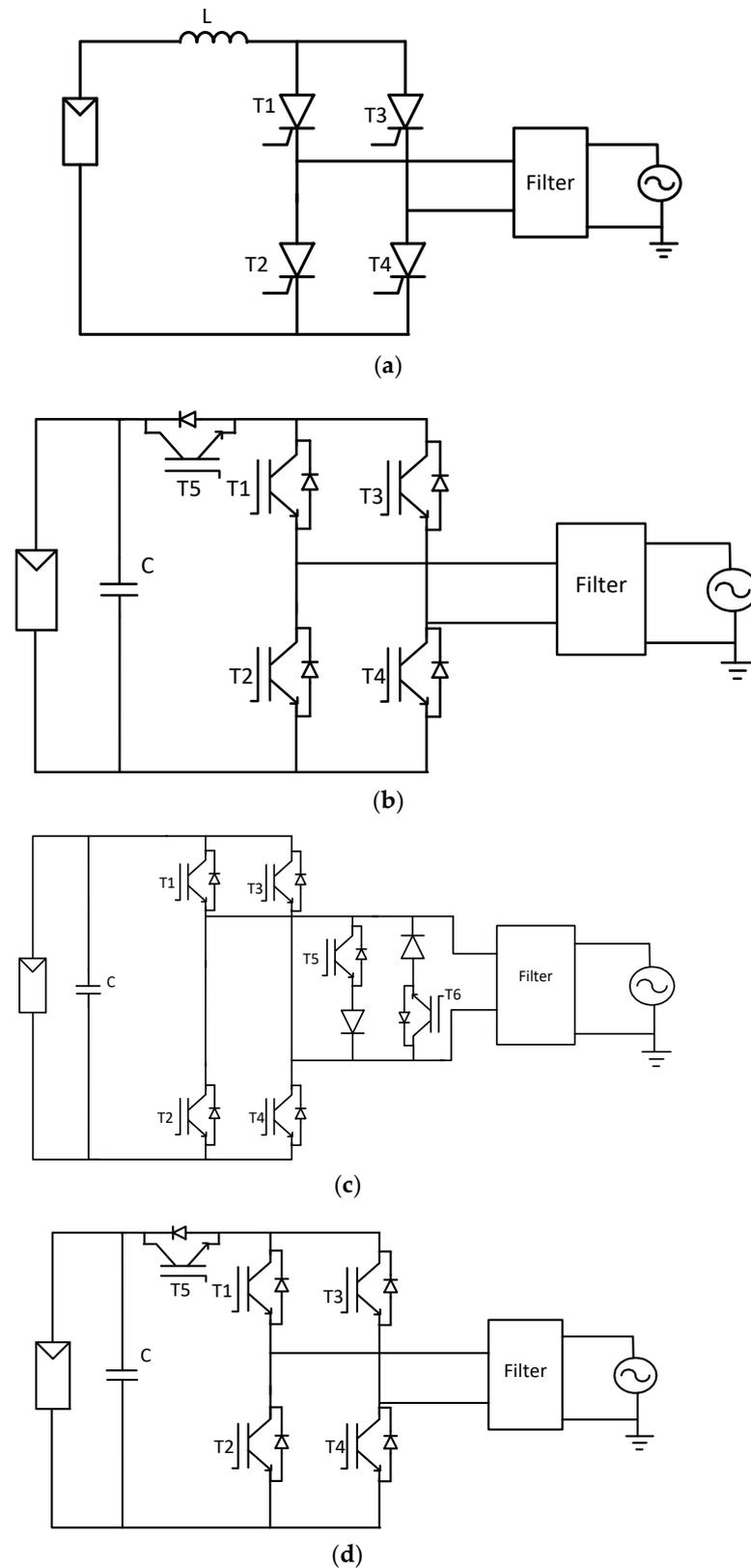


Figure 1. (a) Line commutated inverter; (b) H-bridge forced commutated inverter; (c) Highly Efficient and Reliable Inverter; (d) H5 topology inverter.

R. Akkaya and A. A. Kulaksiz [9] devised and constructed a stand-alone solar power system to power domestic AC-powered equipment, including fluorescent lamps and fans. By maintaining the solar module perpendicular to the sun's rays, the sun-tracker increased the system's efficacy. The charging technique was implemented using a buck-boost DC-DC converter with closed-loop current regulation. The PWM approach employed eliminated chosen harmonics with the fewest number of switches, resulting in an increase in system efficiency by minimizing switching losses and making inverter output filtering easier. The PWM inverter systems and charge controllers were built using PIC16F873 microcontrollers. To validate the system's efficiency, simulation, and experimental data were provided.

A new form of utility-interactive inverter for solar systems was created by Y. Nishida et al. [10]. This inverter lacked a transformer to save space, but it did have a unique power processing system. In addition, the DC-DC converter limited the input current, trapping the utility's ripple-power fed back in the inductor. Since then, with this new method, a huge capacitor does not need to be connected to the inverter's input.

A single-phase multilevel-based solar inverter without a transformer was reported by Roberto Gonzalez et al. [11]. This notion not only reduced the conversion step's cost, size, and weight, but it also enhanced the system's overall efficiency. The novel high-efficiency topology described in this study prevented common-mode currents and assures that no topological DC is introduced into the grid for transformerless systems.

A cascaded inverter for transformerless single-phase grid-connected solar systems was created by Martina Calaisa et al. [12].

The IEEE Std. 1547, published in 2003, is the IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems [13]. The technical requirements for, and testing of, the interconnection itself are the emphasis of this standard. It specifies performance, operating, testing, safety concerns, and maintenance standards for the interconnection. Design, production, installation evaluation, as well as general requirements, commissioning, and abnormal condition response, periodic tests power quality, islanding, and test standards and requirements, are all included. The aforementioned requirements are often required for the interconnection of distributed resources (DR), like power inverters and converters, induction machines, and synchronous machines, and they are appropriate for the great majority of installation scenarios. The DR is a 60 Hz source. Thus, this standard was created with that in mind.

S. M. Babu, et al. [14] presented a new three phase transformerless stepup inverter with pulsating DC-link for PV/EV applications with reduced components and capacitor size.

Informed by to a thorough literature search, the goal of this work was to reduce concerns linked to implementation delays, which are all crucial to the research work's success and will need to be investigated.

Reference [10] compared three alternative standards (IEEE 1547, EN 61000-3-2 and IEC 61727), with an emphasis on the formerly mentioned difficulties. Table 2 summarizes the criteria set out by each standard for DC current injected (an essential problem in the case of grid-connected inverters).

Table 2. DC current injection maximum per various standards.

	IEEE 1547	IEEE 929-2000	VDE 0126-1-1	EN 61000-3-2	IEC 61727
DC current injection	<0.5% of rated output current	<0.5% of rated output current	<1 A	<0.22 A corresponds to a 50 W half-wave rectifier	<1% of rated output

Moreover, when a DC current injection surpasses 1 A, the VDE 0126-1-1 standard mandates that disconnection must occur within 0.2 s. A time requirement for disconnection is not mentioned in any of the other standards. There is just one standard that particularly

addresses failure and leakage current levels in transformerless PV systems: the German VDE 0126-1-1 standard. There are three separate currents that must be measured according to the standard.

- Ground Fault Current, which occurs when the insulation on the ground wire fails and current flows through it.
- Fault current, which is equivalent to the sum of the major currents' instantaneous values and is zero in normal conditions.
- Leakage Ground currents are caused by potential changes in capacitive coupled parasitic components.

3. Transformerless Utility Connected PV Systems

The research success was dependent on overcoming the technological obstacles associated with connecting the inverter system to the mains supply without using 50 Hz power transformers. Table 3 compares 30 single-phase inverters with outputs up to 12 kW for grid-connected PV systems, including seven that were transformerless. The price disparity between the two types of inverters is particularly apparent when the weight and price data are adjusted to the inverters' rated power; the transformerless kind was nearly 25 percent less expensive.

Table 3. Comparison of Inverters.

A Total of 30 Inverters for Single Phase Grid Connected PV Systems (1–2 kW) Were Examined, 23 with Transformers and 7 without			
Type of Inverter	Price Rs/W	Weight kg/kW	Max. Efficiency %
With Transformer	81.90	16.1	93.1
Transformerless	61.74	12.3	95.9

Calais examined string inverters, central inverters, module-oriented or module integrated inverters, and inverter topologies in single-phase utility-linked PV systems. Because it offered the most freedom in developing and testing each stage independently, the module integrated inverter was recommended as the most acceptable configuration for the household PV application being examined in this study (Figure 2).

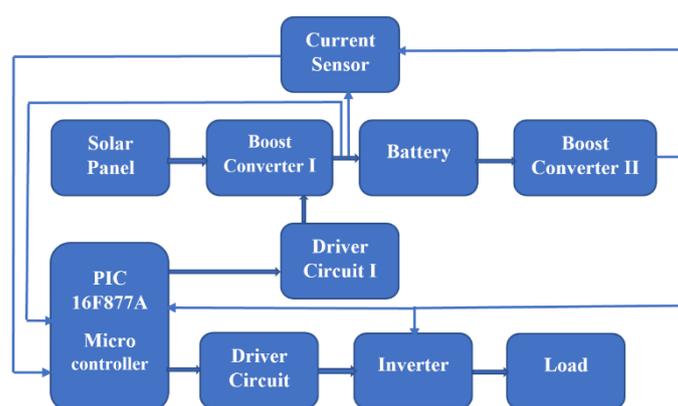


Figure 2. Utility connected PV System Configurations.

A Maximum Power Point Tracking (MPPT) capacity is usually included in a photovoltaic energy conversion system to ensure optimal efficiency. As previously stated, the voltage controller is responsible for maintaining V_c constant in the proposed inverter system. It does so by ensuring that all the electricity generated by the PV panels is fed into the grid. The magnitude of the output current is controlled by the voltage controller, which regulates the power flow. The current controller's task is to generate a sinusoidal output with adjustable amplitude and frequency.

This sort of half-bridge would require double the DC voltage from the boost converter without the usage of a step-up transformer as compared to the full-bridge version. As a result, this approach was deemed inappropriate, and the single-phase full-bridge inverter was adopted.

Using the PWM method, the electronic switches in the single-phase bridge's current loop can be operated in either bipolar or unipolar mode. In bipolar mode, the diagonally opposed switches are switched in pairs for the two legs of the inverter bridge. The two legs of the bridge are not switched simultaneously in the unipolar mode but are controlled individually. The output voltage swing in unipolar mode is half of that in the bipolar mode for the same input DC voltage. When comparing several elements, as given in Table 4, the achieved simplicity becomes clear not only in terms of function but also in terms of structure.

Table 4. Comparison of Existing Transformerless Inverters with Proposed model.

Existing Topology	H5	HERIC	Proposed
Low-frequency switches	2	2	2
High-frequency switches	3	4	2
The total number of switches	5	6	4
Number of inductors	1	1	1
Semiconductor in the current path	3	2	2

Furthermore, all the high-frequency switches in the form of the proposed circuit do not require high-side drivers, which, as previously said, decreases the cost and increases the efficiency greatly.

4. AC Filter Design

The use of sinusoidal PWM and proper voltage control loop design reduces low-frequency harmonics below the values allowed by the standard. These harmonics can be minimized to fulfil EMC requirements by using a Radio Frequency Interference (RFI) filter and excellent circuit layout and design during implementation.

Harmonics can even be seen around the switching frequency of the inverter. These frequencies are in the kHz range. Inverters with electronic switches are increasingly being used in distributed renewable energy generation to switch currents at high frequencies. This can cause waveform distortion and the possibility of harmonic resonance, which can cause shunt capacitors to fail. To minimize such concerns, numerous national and international standards limit the permitted degree of current distortion. The maximum Total Harmonic Current Distortion (THCD) is limited to fewer than 5% per the IEEE standard. As these requirements become stricter and the technology for switching huge currents at high frequencies improves, the necessity to filter switching frequency current harmonics becomes increasingly important.

The ripple current must be attenuated without reducing the inverter system's efficiency, which is a crucial prerequisite of a switching frequency filter made specifically for this document. As a result, current filter designs must be assessed to find appropriate AC filter configurations for this research.

Passive and active power filters have both been utilized to reduce current harmonics and control reactive power. Active power filters provide the advantage of greater output control and a faster reaction time, as well as being smaller in size. The cut-off frequency of the active filter determines the order of harmonics that can be controlled. This approach has the following drawbacks:

- It necessitates a high number of active components.
- It may necessitate sophisticated algorithms to operate several switches.
- In rare cases, they can act as negative resistances, enhancing the supply system's harmonic content.
- A higher price.

Apart from power losses, the filter in the household PV inverter system under consideration must be simple in design and affordable in cost. Because of its complexity and expense, active filtering was ruled out as a viable solution. Instead, passive filtering would be employed for this work.

A filter is any circuit that removes some components of a signal or power source while allowing the other parts to function normally. The filter in a power supply must eliminate or greatly minimize ac fluctuations while still providing the necessary dc to the load circuits.

To smooth the pulsations and give the load circuit a much “cleaner” dc power source, when the load current is high, the RC filter reduces the ripple voltage but introduces excessive resistive losses. We may replace the resistor with an inductor to minimize the ripple even further without adding a lot of dc resistance.

$$L_c = 1 / (2 \times \pi \times f_c) \cdot 2 \cdot C_c \quad (1)$$

The DC currents in transformerless commercial inverters are around three times larger than those seen in their counterparts with transformers due to grid requirements for Total Harmonic Distortion (THD), output-current control, DC component limits and islanding-detection techniques. To avoid exceeding these limits, extra attention is paid to the control and measurement of transformerless systems to minimize losses.

5. Proposed Single-Phase Inverter System

The single-stage sans transformer contributes to a highly efficient single-phase inverter design at minimal cost in this study. Prior single-stage systems had the restriction of possessing the PV array voltage over a certain threshold to supply the grid directly. To overcome these concerns, a novel architecture was established, with the basic notion of retaining a single-stage circuit when the input voltage is sufficient and simply using the step-up operation while the voltage drops beneath a particular level. The gains of this hybrid technique compared to the usual two stage system include lower losses due to the step-up stage being active for a short period of time and improved efficiency due to the stage being built for a low power level. The disadvantages are the enormous quantity of semiconductors used and the complicated process.

A single-stage single-phase circuit with excellent efficiency is suggested. Integrating two parallel step-down converters in series with their outputs linked to the opposite polarities of the load is the primary goal. A single switch regulates the output voltage at a high frequency for one half-wave, while a second switch commutated at a low frequency connects the load properly. The direct manipulation of the current makes this circuit a voltage-source-inverter method. The positive and negative half-waves are produced, respectively, by the two step-down and step-up converters T1-L1-D1-T3 and T2-L2-D2-T4. The PV array is represented by V_{in} as the input source, while the utility grid is represented by V_{out} as the output source. When paired with the impedance of the low-voltage grid, just a minute quantity of filtering action, indicated by the inductors L1 and L2, is required to meet common grid needs (Figure 3).

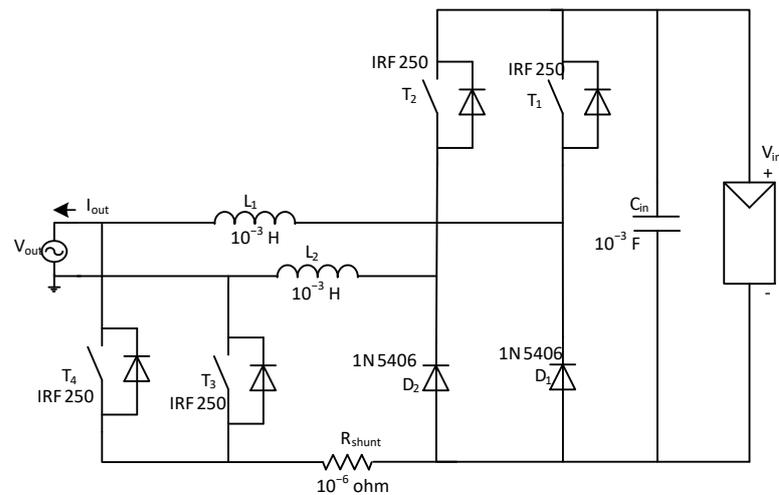


Figure 3. Proposed inverter circuit.

The employment of various inductors increases the presence of dc components in the output current, which increases the possibility of asymmetry between each stopped wave. Despite having a significant influence on the overall cost but not on efficiency, using separate inductors increases the likelihood of asymmetry between each half-wave, leading to the existence of dc components in the output current. As a result, the construction of such inductors may be done with great accuracy. The recommended circuit offers a high level of dependability because the risk of a leg short circuit only arises at zero crossing rather than at each commutation of the high-frequency switches. It is also less costly as the output-current measurement may be completed using a straightforward resistive shunt and does not require galvanic separation. Because there are no high-frequency oscillations as the PV array's negative output is connected directly to the neutral and phase output during the positive and negative half-waves, leakage currents are avoided. Reactive processing is also not possible as the dc-link capacitance and current freewheeling are independent. The suggested circuit's high-frequency switches (T1 and T2) necessitate galvanic-isolated driver circuits; hence a different architecture is recommended. Low-frequency switches lead to cost savings and enhanced dependability in this case. Although the diodes D3 and D4 have little impact in normal operation, they were added to clamp the voltage between the switches T3 and T4 during input voltage level transients (Table 5). The most notable change is that during the negative half-wave, the PV array's positive terminal is linked to the phase output.

Table 5. Full-Bridge Single-Phase VSI Switch States.

State	State #	V0	Components	Conducting
T ₁ and T ₃ are on and T ₂ and T ₄ are off	1	V _i	T ₁ and T ₃ D ₁₊ and D ₂₋	if i _a > 0 if i _a < 0
T ₂ and T ₄ are on and T ₁ and T ₃ are off	2	-V _i	D ₁₋ and D ₂₊ T ₂ and T ₄	if i _a > 0 if i _a < 0
T ₁ and T ₄ are on and T ₂ and T ₃ are off	3	0	T ₁ and D ₂₊ D ₁₊ and T ₄	if i _a > 0 if i _a < 0
T ₂ and T ₃ are on and T ₁ and T ₄ are off	4	0	D ₁₋ and T ₃ T ₂ and D ₂₋	if i _a > 0 if i _a < 0
T ₁ , T ₂ , T ₃ and T ₄ are all off	5	-V _i V _i	D ₁₋ and D ₂₊ D ₁₊ and D ₂₋	if i _a > 0 if i _a < 0

This design works similarly to a Voltage Source Inverter (VSI); the main difference is that inductors are used in the output to provide waveform filtering. An extra capacitor is

frequently placed in the same direction as the load to subordinate the inductor size. An LC filter could be used to filter the entire solution. A limiting resistor can be used to alleviate the problem of capacitor charging current and then switching it with a relay, or at the zero-crossing instant, synchronizing the grid connection.

6. Results and Discussion

The simulation result is a filtered output, which shows that the inverter's output voltage is 78% of the input rate due to the filter parameters presented in the model (Figure 4) and current waveform presented in Figure 5. Table 6 lists the simulation parameters.

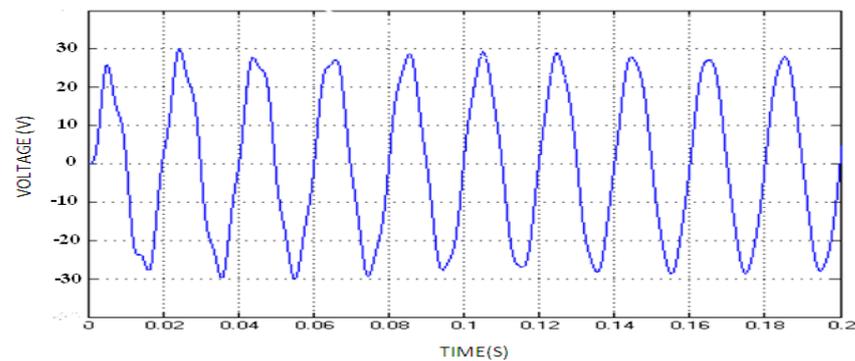


Figure 4. Output Voltage Waveform of the Inverter.

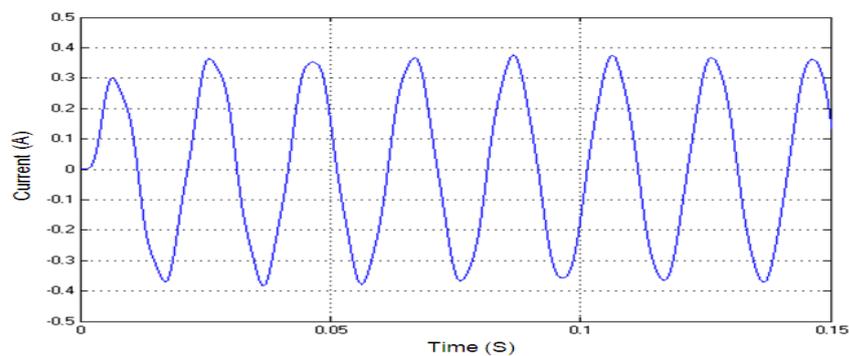


Figure 5. Output Current Waveform of the Inverter.

Table 6. Simulation Parameters and Input Values.

Simulation Parameters	Values
Output filter Inductance	6 mH
Output filter Capacitance	100 μ F
Output frequency	50 Hz
DC voltage	12 V

The output voltage and current waveform harmonic spectrum with a filter circuit is shown in Figures 6 and 7, which were obtained from FFT analysis in MATLAB software. From the simulation results, the THD (Total Harmonic Distortion) in voltage and the current waveform is less than 0.7%. When compared to the preceding section's THD of voltage and current waveforms, it is an advantage that the output waveforms have lower THD than that of the inverter without the filter circuit, which reduces the problems due to the harmonics.

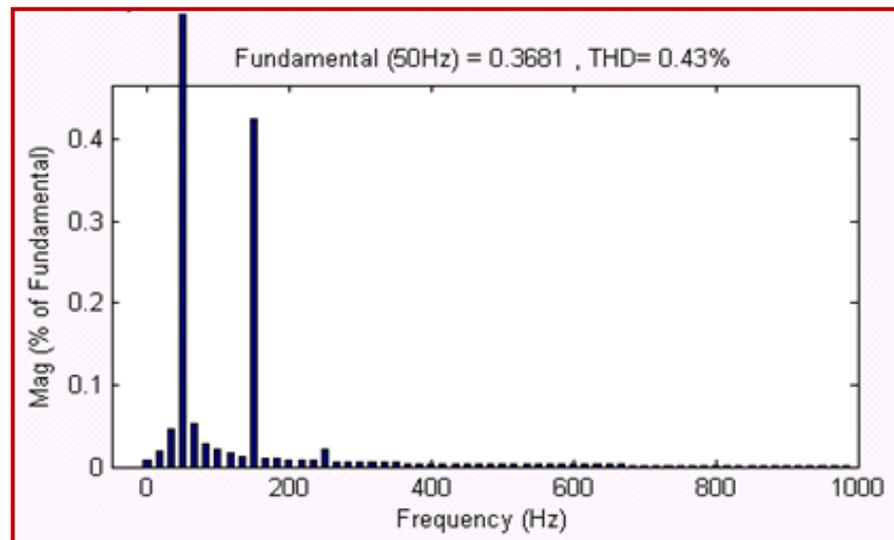


Figure 6. Harmonic Spectrum of Output Current with Filter Circuit.

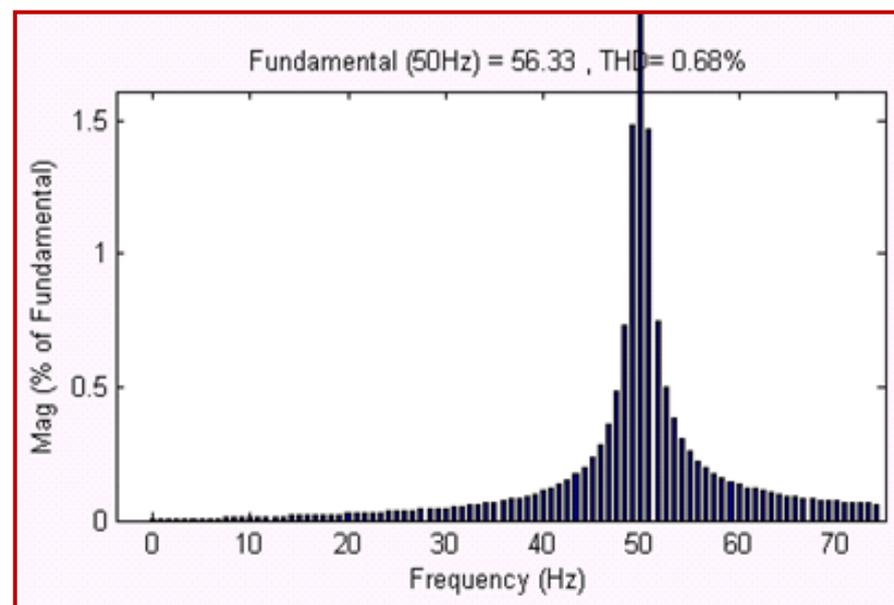


Figure 7. Harmonic Spectrum of Output Voltage with Filter Circuit.

Moreover, the simulation results were verified for the high-power rating. The simulated inverter voltage across the output terminals, the current flowing through the output terminals and the measured current THD are presented in Figures 8–10, respectively. The AC output voltage is obtained for the given DC input of 360 V. The current THD was very low at only 0.22%.

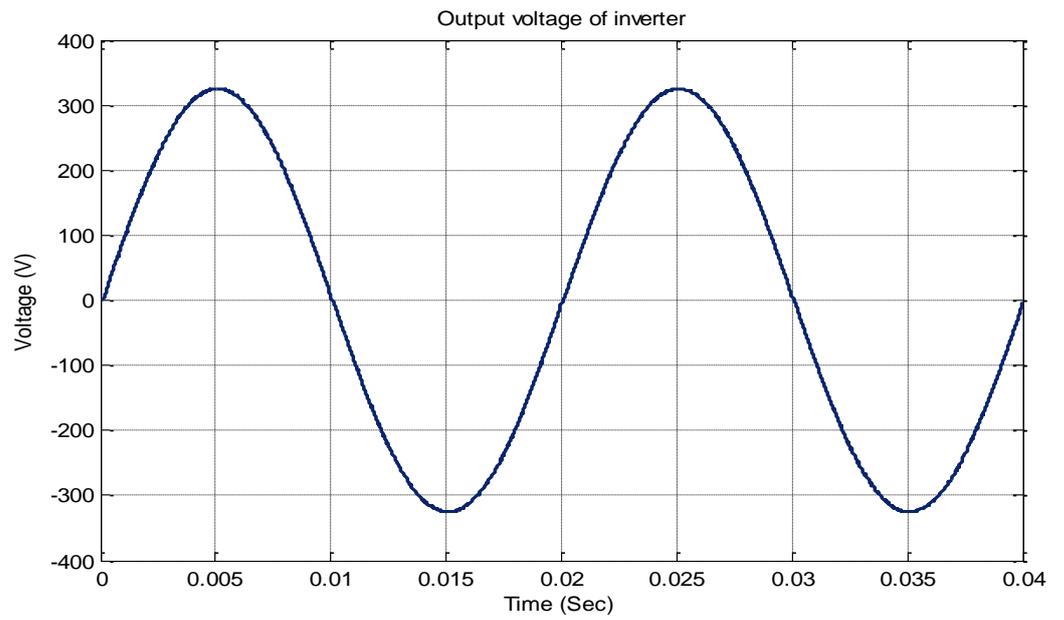


Figure 8. Output Voltage of Proposed Inverter.

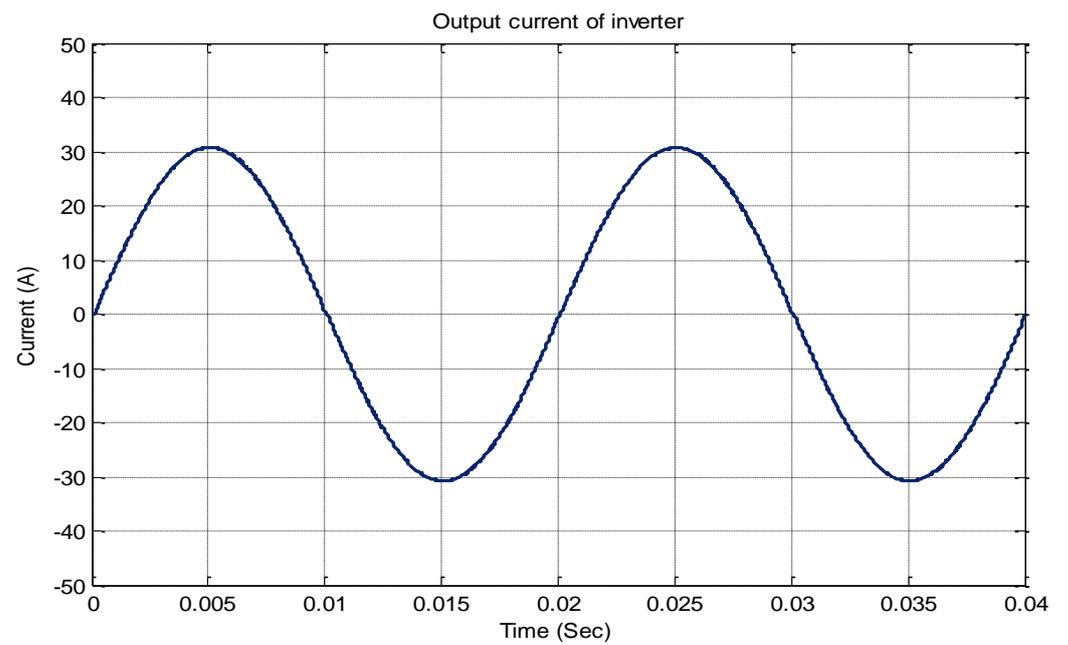


Figure 9. Output Current of Proposed Inverter.

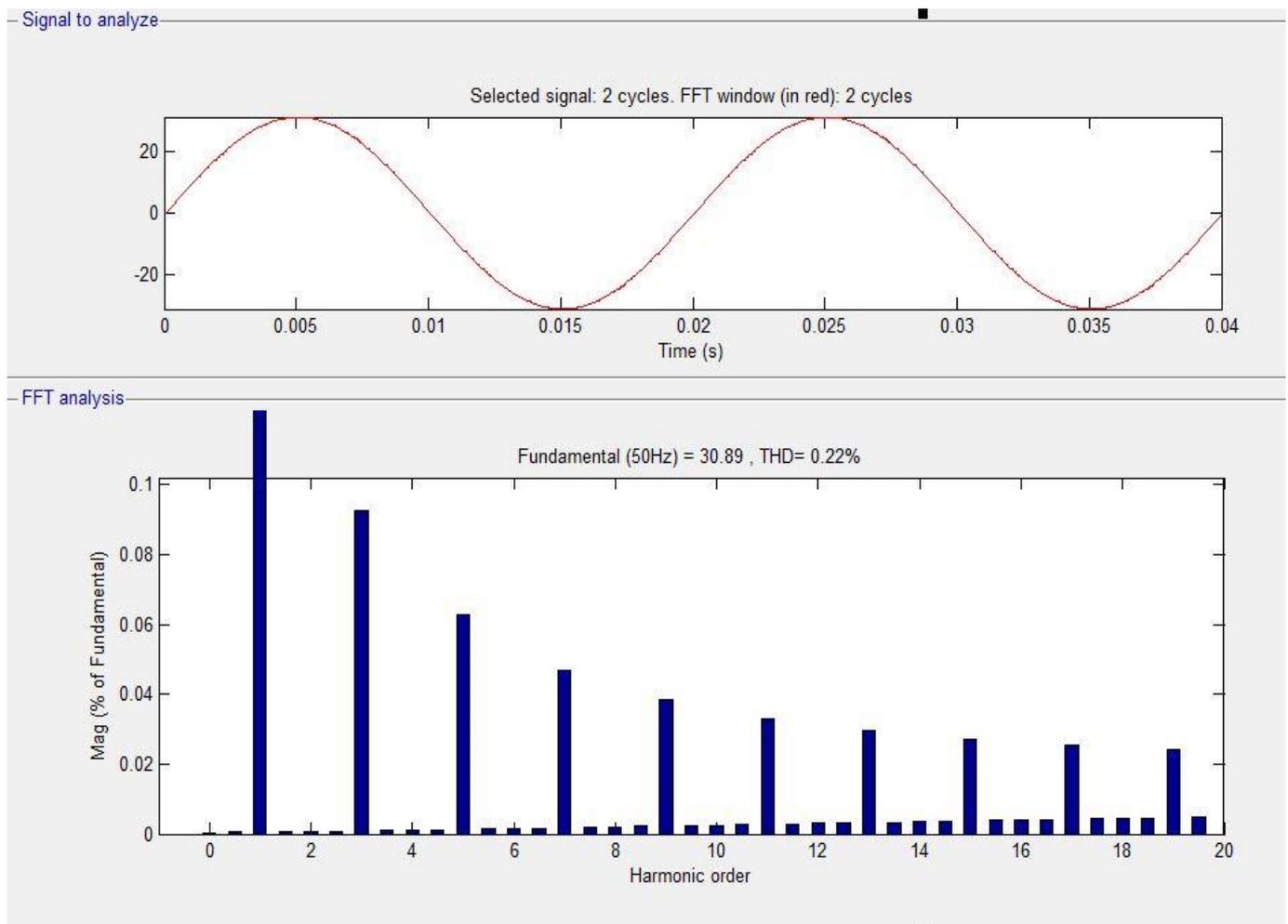


Figure 10. Output Current THD.

7. Experimental Result

An experimental setup was created to verify the simulation results. Tables 7 and 8 depict the experimental setup recorded results for 2 continuous days during summer.

Table 7. Recorded Experimental Values (Day 1).

Day 1	Short Circuit Current (A)	Open Circuit Voltage (V)	Solar Radiation (W/m ²)	Output from Inverter (V)
10.00 am	1.64	17.2	670	28.12
11.00 am	1.59	19.3	761	30.76
12.00 pm	1.71	18.8	782	32.27
01.00 am	1.80	19.0	931	34.20
02.00 pm	1.76	18.6	921	32.80
03.00 pm	1.64	17.4	872	28.56
04.00 pm	1.55	16.6	714	25.78
04.30 pm	1.60	15.6	508	25.07

Table 8. Recorded Experimental Values (Day 2).

Day 2	Short Circuit Current (A)	Open Circuit Voltage (V)	Solar Radiation (W/m ²)	Output from Inverter (V)
10.00 am	1.60	19.2	665	30.72
11.00 am	1.89	17.3	716	32.70
12.00 pm	2.04	16.8	809	34.27
01.00 am	1.90	17.0	801	32.30
02.00 pm	1.77	17.2	720	30.44
03.00 pm	1.58	17.4	590	27.49
04.00 pm	1.16	17.6	418	32.42
04.30 pm	0.84	17.6	312	23.78

The system design leads us to the hardware design of the control unit. The hardware design is the most important part of the work because it is the one that is to be tested in real mode. The hardware design starts by selecting the components for the individual modules and integrating them into a single system. The hardware should be designed such that it meets the requirements of the proposed control strategy (Figure 11). Before beginning the actual hardware design, a generic system design was essential to ensure the control requirements were met. It should be noted that sometimes it may not be possible to implement all the features of the proposed strategy. At such times, some compromises may be made such that the performances are achieved. In this work, it was attempted to implement all the essential features of the proposed control strategy.

**Figure 11.** Experimental setup of proposed Inverter.

In designing the control unit, as said above, difficulty may arise because some of the components may not be available, components may be expensive, and sometimes it may be difficult to implement things in practice. In this work, the control unit was designed considering some of the practical difficulties. However, it was decided at least to implement the basic features of the system through the control unit to be designed.

The proposed control strategy in this paper was to maximize the system efficiency and minimize the cost. However, the design of the actual control unit could not be designed to achieve full-fledged performance. In this work, the defined strategies were simplified and implemented in the hardware unit. The control unit's major goal was to implement all the voltage control modes of operation for the boost converter first. The control of current or the impedance matching between the source and the load were not done in this work, as it was a complex design process.

As shown by the above data (Figures 12 and 13), the output waveform from the experimental findings had a frequency of 50 Hz, which is identical to that of the grid. The output voltage of a single-phase inverter is 27 V, according to both simulation and

experimental investigations, which were found to agree. The leakage current was also reduced, and overall harmonic aberrations in the output waveforms were less than 1%. Figure 14 presents the output of voltage and leakage current.

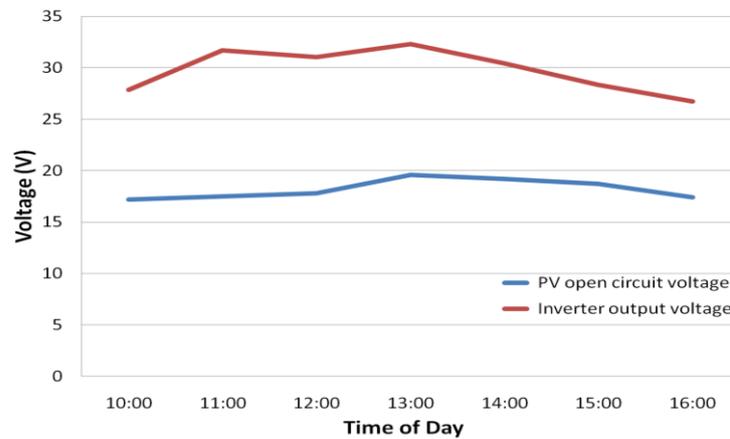


Figure 12. PV panel DC and inverter AC voltage output curves.

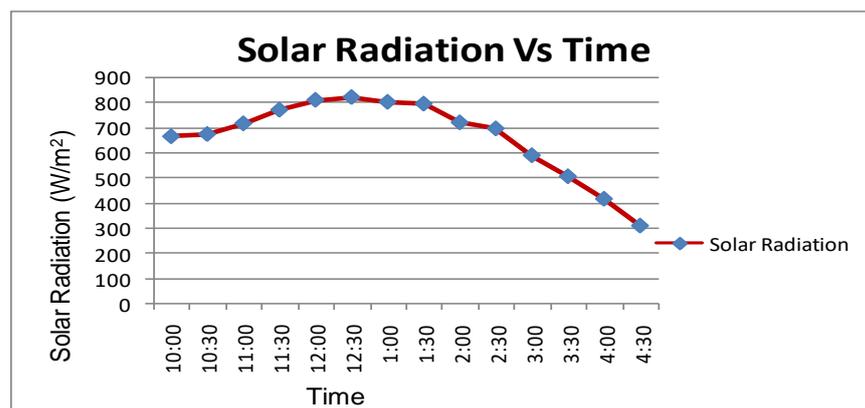


Figure 13. Solar Radiation Vs. Time Curve.

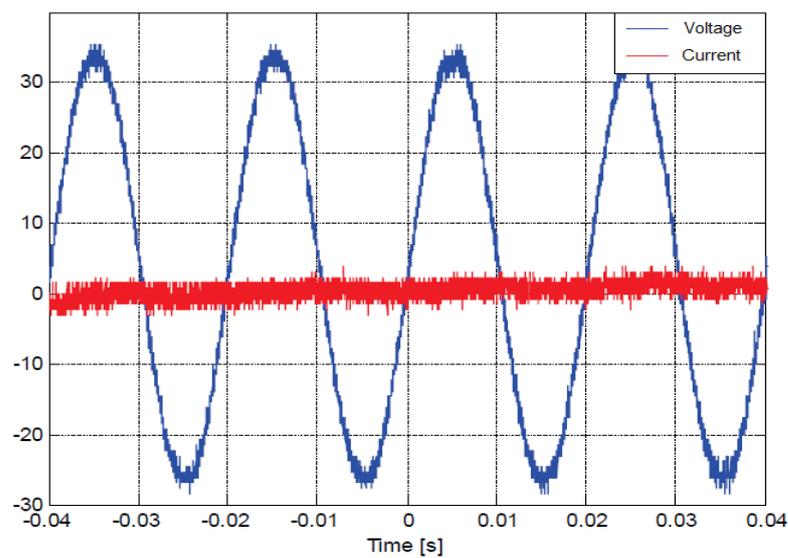


Figure 14. Output of Voltage and Leakage Current.

In this work, the inverter has four switches and two diodes. Considering the requirements, a driver circuit Printed Circuit Board (PCB) for six switches was designed. To drive to high side switches, two IR2112 drivers were used in the design, and for isolation purposes, MCT2E opt isolators were used for the switches. Figure 15 shows the PCB, which consists of six MCT2E opt isolators on the top of the board and two IR2112 drivers with bootstrap circuit on the bottom right of the board. A PC74HC08P AND gate was used to get unipolar PWM signals from the PIC-16F877A, and was placed on the bottom left of the PCB.

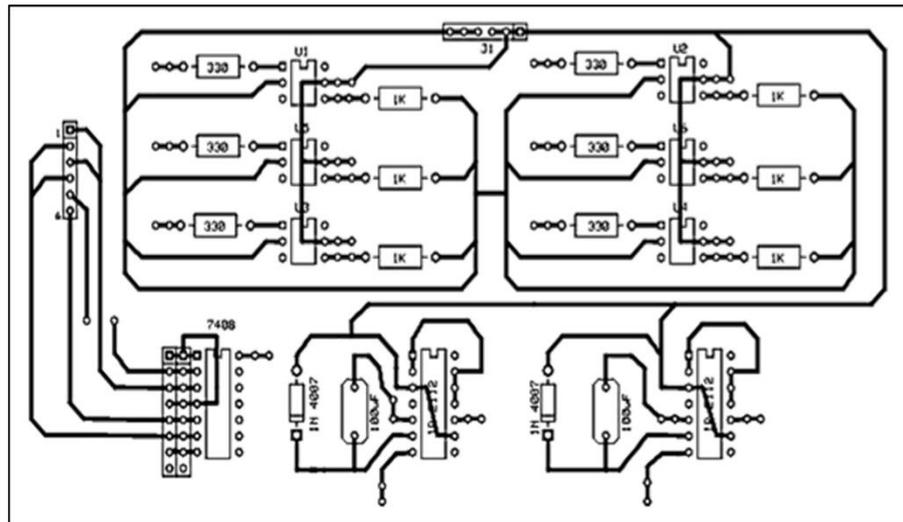


Figure 15. PCB Layout of Driver Circuit.

Figure 16 shows the single layer driver circuit PCB layout; it was designed in Express PCB software, which is very simple to use, even for complicated circuits. By default, this software can generate two-layer PCB layouts. But for this circuit it was sufficient to design a single layer PCB layout, which can be implemented in a short time.

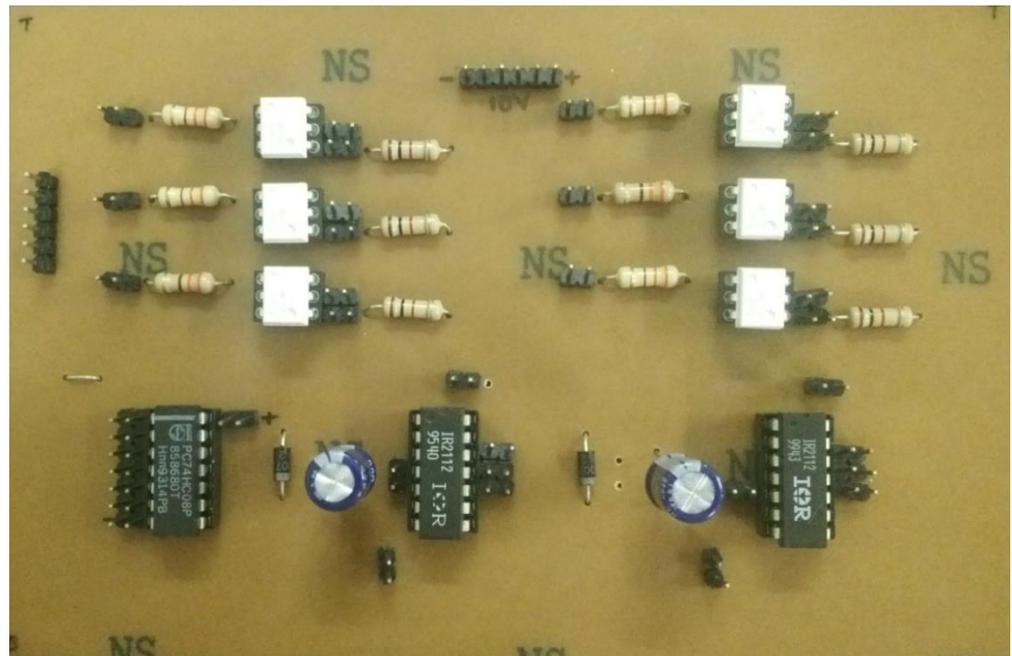


Figure 16. PCB Implementation of Driver Circuit.

The transformerless inverter was connected to a load of 100 W in steps of 10 W, as observed in Figure 17. It is seen that there was no flickering observed in lamp loads. Because of the Cool-MOS used in the transformerless inverter, it was observed that the MOSFET's does not heat up, until 100 W loads. The common mode voltage of the transformerless inverter was constant, which will reduce the leakage currents in the solar PV system.



Figure 17. Resistive (Lamp) Load Connected to the Transformerless Inverter.

The corresponding output power and efficiency of the transformerless inverter was calculated and is plotted in Figure 18. The efficiency of the proposed inverter is better than the existing inverter topology [15]. The efficiency of the inverter increases with an increase in the load value (Figure 18). This inverter can be used up to 500 W, and efficiency can be improved further.

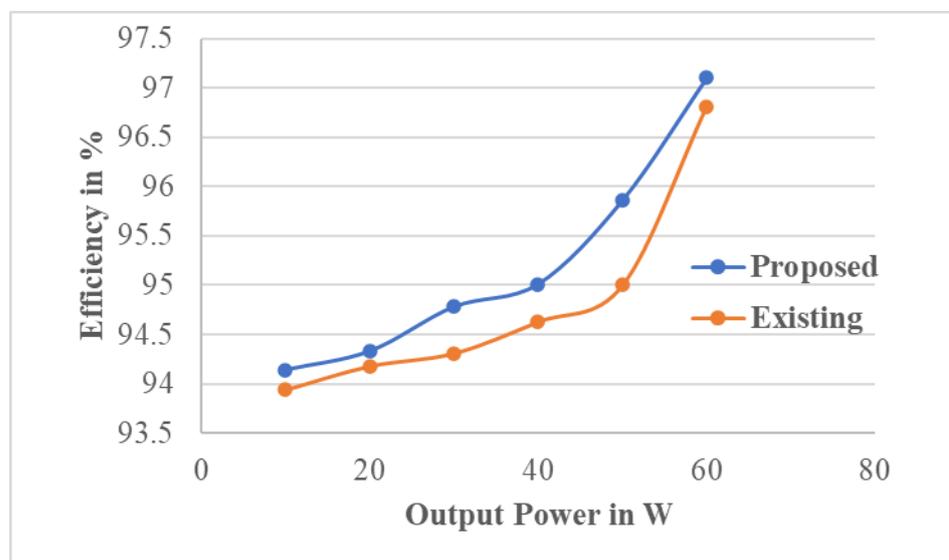


Figure 18. Efficiency Comparison of Transformerless Inverter.

8. Conclusions

Technical concerns for the systematic design of a transformerless inverter for free-standing PV systems were addressed in this study. The research work's major goal was to offer a design approach that would result in high inverter conversion efficiency, higher output power quality, and lower capital costs.

The system's performance was evaluated in simulations using Simulink in stand-alone mode, demonstrating that the suggested scheme might be a good option for a home solar power generating system. The experimental findings were in agreement

with the computational outcomes. With overall voltage and current THD of less than 0.68 percent and 0.43 percent, respectively, the controller board can deliver an inverter output frequency of nearly 50 Hz. Leakage current is eliminated through low-frequency switching, and ground current is eliminated through proper PV panel grounding. The inverter switches are controlled by Sinusoidal Pulse Width Modulation (SPWM). The inverter control circuit hardware is simplified due to the development of a control circuit employing a PIC microcontroller. The frequency modulation ratio and duty cycle of a microcontroller unit may be readily altered by programming without requiring any further hardware adjustments. However, it should be noted that this work did not consider in great detail the hardware control unit and so the hardware design could be improved further.

There are various study challenges for future work, as the simulations in the provided work contained perfect components, and the efficiency of the topology was not measured. However, by accounting for switching and conduction losses for switching parts, and losses for passive components, the efficiency may be calculated in simulations. In transformerless PV inverters, DC-current injection is a hot topic. As a result, potential routes for further reducing low frequency harmonic current production by unipolar switching inverters must be investigated.

Author Contributions: Conceptualization, I.V.; Formal analysis, S.R.; Funding acquisition, B.A.; Investigation, A.K.L.; Methodology, A.K.L.; Project administration, I.V.; Resources, B.A.; Validation, S.R.; Writing—original draft, A.P.N.; Writing—review & editing, A.P.N. All authors have read and agreed to the published version of the manuscript.

Funding: The authors are thankful to the Deanship of Scientific Research at Najran University for funding this work under the Research Groups Funding program grant code (NU/RG/SERC/11/6).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Chowdhury, A.S.K.; Razzak, M.A. Single phase grid-connected photovoltaic inverter for residential application with maximum power point tracking. In Proceedings of the 2013 International Conference on Informatics, Electronics and Vision (ICIEV), Dhaka, Bangladesh, 17–18 May 2013; pp. 1–6.
2. Jana, J.; Saha, H.; Bhattacharya, K.D. A review of inverter topologies for single-phase grid-connected photovoltaic systems. *Renew. Sustain. Energy Rev.* **2017**, *72*, 1256–1270. [[CrossRef](#)]
3. Wen, X.Y.; Lin, P.J.; Chen, Z.C.; Wu, L.J.; Cheng, S.Y. A grid-connected single-phase photovoltaic micro inverter. *IOP Conf. Ser. Earth Environ. Sci.* **2017**, *93*, 012079. [[CrossRef](#)]
4. Khan, M.N.H.; Forouzesh, M.; Siwakoti, Y.P.; Li, L.; Kerekes, T.; Blaabjerg, F. Transformerless Inverter Topologies for Single-Phase Photovoltaic Systems: A Comparative Review. *IEEE J. Emerg. Sel. Top. Power Electron.* **2020**, *8*, 805–835. [[CrossRef](#)]
5. Tsai, M.T.; Chu, C.L.; Mi, C.M.; Lin, J.Y.; Hsueh, Y.C. Designing a Single-Stage Inverter for Photovoltaic System Application. *Math. Probl. Eng.* **2013**, *2013*, 912487. [[CrossRef](#)]
6. Chen, Y.; Smedley, K.M. A cost-effective single-stage inverter with maximum power point tracking. *IEEE Trans. Power Electron.* **2004**, *19*, 1289–1294. [[CrossRef](#)]
7. Gules, R.; Pacheco, J.D.P.; Hey, H.L.; Imhoff, J. A Maximum Power Point Tracking System with Parallel Connection for PV Stand-Alone Applications. *IEEE Trans. Ind. Electron.* **2008**, *55*, 2674–2683. [[CrossRef](#)]
8. Thimbiripolage, P.; Nirupa, R. Development of a Microcontroller Based Solar Smart Charge Controller for Solar Street Lamps. In Proceedings of the World Renewable Energy Congress 2009—Asia the 3rd International Conference on Sustainable Energy and Environment (SEE 2009), Bangkok, Thailand, 18–23 May 2009.
9. Akkaya, R.; Kulaksiz, A.A. A microcontroller-based stand-alone photovoltaic power system for residential appliances. *Appl. Energy* **2004**, *78*, 419–431. [[CrossRef](#)]
10. Nishida, Y.; Nakamura, S.; Aikawa, N.; Sumiyoshi, S.; Yamashita, H.; Omori, H. A novel type of utility-interactive inverter for photovoltaic system. In Proceedings of the IECON'03. 29th Annual Conference of the IEEE Industrial Electronics Society (IEEE Cat. No. 03CH37468), Roanoke, VA, USA; 2003; Volume 3, pp. 2338–2343.
11. Gonzalez, R.; Gubia, E.; Lopez, J.; Marroyo, L. Transformerless Single-Phase Multilevel-Based Photovoltaic Inverter. *IEEE Trans. Ind. Electron.* **2008**, *55*, 2694–2702. [[CrossRef](#)]
12. Calais, M.; Agelidis, V.G.; Dymond, M.S. A cascaded inverter for transformerless single-phase grid-connected photovoltaic systems. *Renew. Energy* **2001**, *22*, 255–262. [[CrossRef](#)]
13. *IEEE Standards 1547*; IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems. IEEE: Piscataway, NJ, USA, 2003.

14. Babu, S.M.; Narasimharaju, B.L.; Rathore, A.K. A New Pulsating DC-link Three-Phase Transformerless Inverter for Renewable Applications. In Proceedings of the 2020 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Jaipur, India, 16 December 2020; pp. 1–4.
15. Ashok Kumar, L.; Indragandhi, V.; Sujith Kumar, N. Design and implementation of single-phase inverter without transformer for PV applications. *IET Renew. Power Gener.* **2018**, *12*, 547–554.