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Research Article

Design and Optimization of RLC Filters for Harmonic Reduction in Single-Phase Inverters Using MATLAB

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Abstract

Harmonic distortion is a significant issue in modern power systems, particularly for single-phase inverters used in motor drives, uninterruptible power supplies, and renewable energy integration. The non-linear switching of inverters introduces high-order harmonics that can shorten equipment lifespan, increase losses, and degrade power quality. This study focuses on designing and optimizing a passive RLC filter for harmonic mitigation in a MATLAB Simulink-modeled single-phase inverter system. A full-bridge inverter with sinusoidal pulse-width modulation (SPWM) was developed to assess distortion levels using Total Harmonic Distortion (THD). The unfiltered inverter output demonstrated a THD of about 25-30%, making it unsuitable for sensitive loads. With the optimized RLC filter, THD levels dropped below 5%, yielding a near-pure sinusoidal output and complying with IEEE-519 power quality standards. The results also showed that RLC filters enhance stability across various load impedances and improve efficiency to 96%, outperforming standard LC filters. Overall, this study presents a practical and cost-effective solution to enhance power quality in inverter-based renewable energy applications, while also paving the way for future experimental validation and hybrid filter development.

Keywords: *Harmonic Distortion, Single-Phase Inverter, RLC Filter Design, Total Harmonic Distortion (THD), MATLAB Simulink Simulation*

1. Introduction

Harmonic distortion is a significant concern in modern power systems, particularly with the increasing use of power electronic devices such as inverters. A single-phase inverter, which converts direct current (DC) power to alternating current (AC), is commonly used in applications such as renewable energy systems (like solar photovoltaic and wind turbines), uninterruptible power supplies (UPS), and motor drives. However, the switching operations of these inverters create non-sinusoidal waveforms, resulting in the introduction of harmonics into the output.

Harmonic distortion negatively impacts power quality, increases losses, and can lead to premature aging and malfunctions of sensitive electronic equipment. Harmonics—higher frequency components that are integer multiples of the fundamental frequency (50 or 60 Hz)—deviate from the ideal sinusoidal waveform. These harmonics can disrupt the normal operation of electrical devices, causing issues such as overheating, increased losses, and resonance in certain systems.

The switching processes involved in Pulse Width Modulation (PWM), which is commonly used to control the inverter's output, contribute to the generation of harmonics in single-phase inverters. As the demand for reliable and efficient energy systems grows, reducing harmonic distortion becomes increasingly important (Langella et al., 2014).

Passive filters, such as RLC (Resistor–Inductor–Capacitor) filters, have gained popularity for their simplicity, reliability, and cost-effectiveness. An RLC filter is specifically designed to allow the fundamental frequency to pass while attenuating higher-order harmonics, thus enhancing the quality of the inverter's output. The effectiveness of an RLC filter depends on the precise selection of component values, which determine its resonance frequency and damping characteristics.

With the advent of advanced simulation tools like MATLAB Simulink, researchers and engineers can model, simulate, and analyse the performance of inverters and filters before real-world implementation. MATLAB Simulink provides a platform to observe harmonic content, design filters, and optimize system performance in a cost-effective and time-efficient manner.

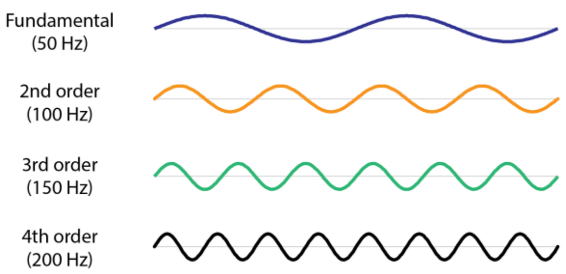

Figure 1. Harmonic orders in power systems

Single-phase inverters are commonly used in low-power applications, such as small motor drives, uninterruptible power supplies (UPS), and home solar photovoltaic (PV) systems. These inverters utilize switching components like metal-oxide-semiconductor field-effect transistors (MOSFETs) or insulated-gate bipolar transistors (IGBTs) to convert direct current (DC) power to alternating current (AC). The main method for controlling the inverter output is through Pulse Width Modulation (PWM), which can introduce harmonics into the system. Although PWM is effective in regulating voltage and current, it generates harmonics at the switching frequency and its multiples (Muhammad, 2004).

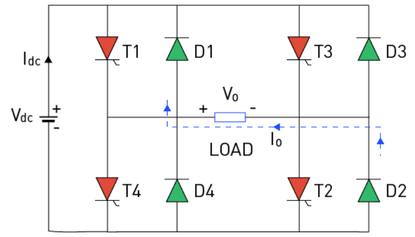

Figure 2. Single-phase full-bridge inverter circuit

Harmonic distortion in single-phase inverters can negatively impact both the inverter and the connected load. High levels of harmonics can increase the operating temperature of the inverter's components, reduce efficiency, and cause electromagnetic interference (EMI). Additionally, harmonic currents can lead to increased losses in the power system, diminishing the overall energy efficiency of the inverter. For sensitive equipment, such as communication and medical devices, harmonic distortion can result in operational malfunctions.

Examples of switching devices used in these inverters to convert direct current (DC) to alternating current (AC) include metal-oxide-semiconductor field-effect transistors (MOSFETs) and insulated-gate bipolar transistors (IGBTs). The primary source of harmonics in single-phase inverters is the Pulse Width Modulation (PWM) technique, which is often employed to regulate the inverter's output. Although PWM helps with voltage and current regulation, it also generates harmonics at the switching frequency and its multiples (William et al., 2007).

Passive filters, such as RLC filters, offer simpler and more cost-effective ways to reduce harmonics. They function by attenuating specific harmonic frequencies, creating a low-impedance path for these undesirable harmonics to ground. By carefully selecting the component values for R, L, and C, passive filters can effectively minimize harmonics in an inverter's output (Moura et al., 2002). These filters are preferred for applications that require reliability and minimal maintenance; however, their performance can be influenced by variations in system impedance and load.

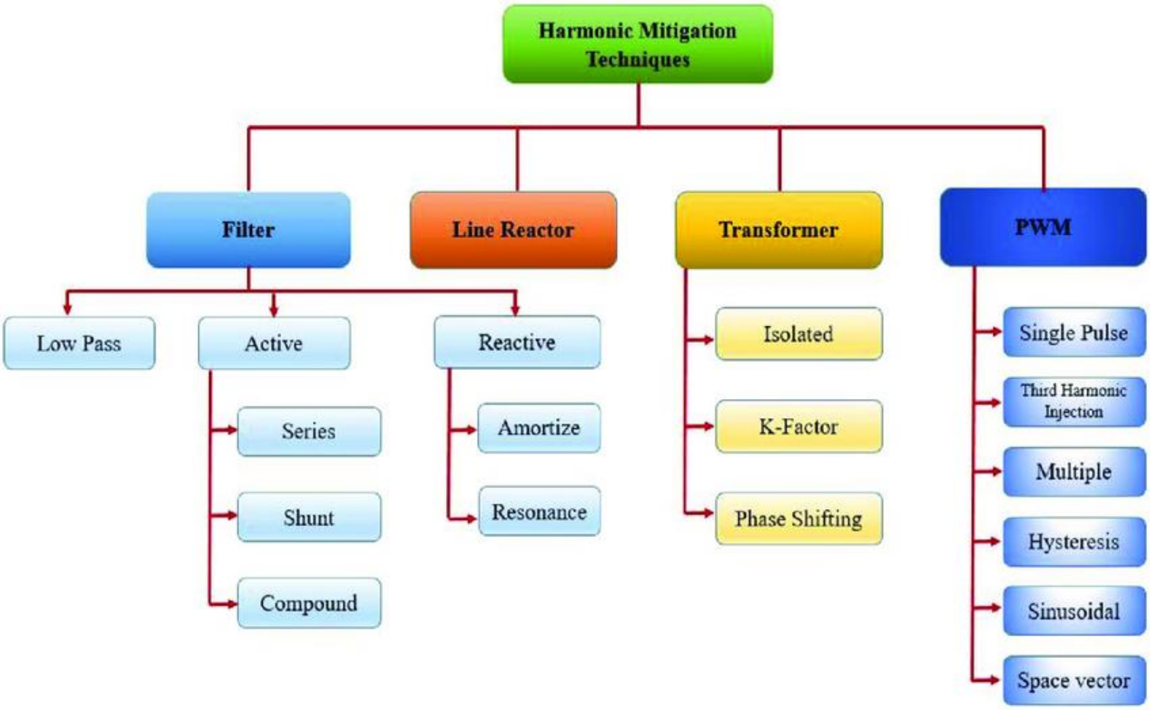

Figure 3. Harmonic mitigating techniques

RLC filters are among the most commonly used passive filters for reducing harmonics in power electronic systems. These filters consist of a resistor (R), an inductor (L), and a capacitor (C) connected in various configurations, such as series or parallel, to attenuate specific harmonic frequencies while allowing the fundamental frequency to pass through. The design of RLC filters focuses on tuning the resonance frequency to cancel out specific harmonic orders, such as the 3rd, 5th, or 7th harmonics (Vaidya et al., 2025).

One of the main advantages of RLC filters is their simplicity and reliability. Once designed and implemented, they do not require complex control systems, and their operation is passive, meaning they do not consume additional power for harmonic mitigation. The performance of an RLC filter largely depends on the accuracy of component selection, particularly the values of inductance and capacitance. Incorrect values can result in poor harmonic attenuation, increased losses, or even resonance issues in the system.

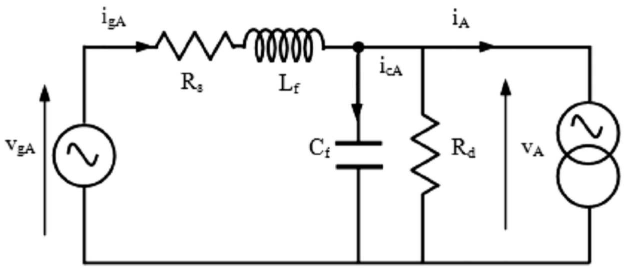

Figure 4. Single-phase RLC input filter with a damping resistor

The optimization of RLC filter designs to enhance their harmonic reduction performance has been a primary focus of study in recent years. This involves researching new topologies, improving component materials, and developing simulation models to predict and assess filter performance before installation. Researchers can now test filter designs and evaluate their effectiveness in harmonic reduction using MATLAB Simulink, a valuable tool for building and simulating RLC filters (Chatterjee et al., 2020).

Power electronics are used to process and control the flow of electrical energy by supplying voltage and current in a manner optimally suited to the user's load. Compared to linear electronics, an electrical device in power electronics should achieve higher efficiency. Linear electronics rely on semiconductor devices that operate in their active region and use a transformer solely for electrical isolation. Power electronic systems typically utilize a closed-loop operation for better performance.

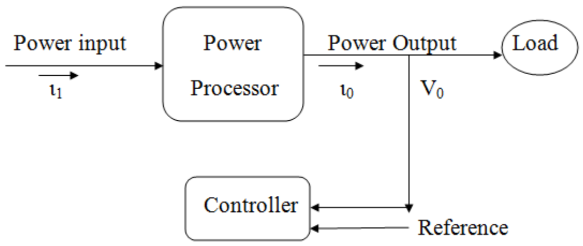

Figure 5. Power electronic system

In managing the energy consumed by the load, the power electronics system utilizes switching methods to minimize the appearance of the active region in the semiconductor device. Although it is impossible to remove all power dissipated by the semiconductor, switching mode has greatly reduced the power consumed in semiconductor devices. As a result, the switching frequency and the power used in semiconductors are proportional. The branch of electrical engineering known as "power electronics" deals with using semiconductor devices to transform available power into the amount needed by a load. The load may or may not require isolation from the power supply, and it may be single-phase or three-phase, AC or DC. The power source may be a commercial power supply, an electric battery, a solar panel, an electric generator, or a DC or AC source (single-phase or three-phase with a line frequency of 50 or 60 Hz). The power supplied by the source is transformed into the form that the load needs by a power converter (Mohan et al., 2003).

Because of their modular operation, converters can be installed closer to the user. For low-power applications, a single-phase converter is usually used, embedded with a low- or high-frequency transformer. It is possible to remove the transformer from the inverter in order to reduce the losses, size, and cost of those systems, namely transformer-less PV systems. Transformer-less inverters are developed to provide high power density and efficiency. A family of flying-capacitor transformer-less inverters has been proposed for single-phase photovoltaic systems to modulate the inverter so as to minimize the switching loss, output current ripple, and the filter requirements by using a unipolar sinusoidal pulse-width modulation technique. Several methods have been employed to reduce the ground leakage current via the PV array's parasitic capacitance. When the transformer is not used, the common-mode behaviour generated by the inverter topology has a significant impact on the ground leakage current through the PV array's parasitic capacitance. For grid-tied PV systems, a single-phase transformer-less photovoltaic (PV) inverter was developed using the idea of a charge pump circuit to stop leakage. Transformers and battery storage are not necessary for the effective conversion of PV power into AC power. Also, middle linkages can be omitted to make the system light and low cost (Langella et al., 2014).

A voltage-sourced inverter converts power from a DC voltage source, and its output effectively serves as an AC source. The fundamental circuit involved in this conversion is known as a full-bridge inverter, also called an H-bridge inverter, and is shown in Figure 6. In accordance with Kirchhoff's Voltage Law (KVL), the voltage source cannot be shorted; thus, switches 1,1 and 2,1 cannot both be closed at the same time, and the same is true for switches 1,2 and 2,2. If switches 1,1 and 2,2 are both closed, then the output, V_{out}, will be the positive DC voltage. If switches 2,1 and 1,2 are both closed, then the output will be the negative value of the DC voltage. In any other scenario, the output will be zero.

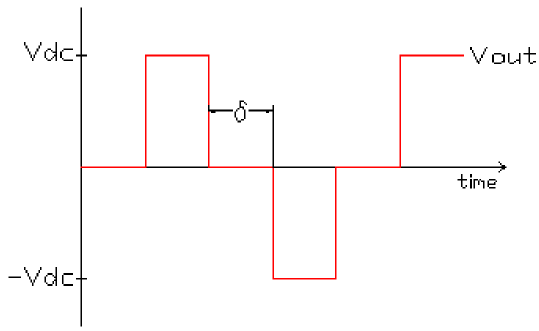

Figure 6. Full-bridge voltage-sourced inverter output voltage

The H-bridge topology is capable of producing an alternating value across its output terminals, which can be vaguely similar to the desired sinusoidal waveform. Different control strategies are applied to the switches to produce the desired output. The most basic inverters produce an output voltage at one of two values: the positive or negative value of the DC input. Three-level inverters are quite common as well; their output can be zero volts in addition to the positive and negative values of the DC input. There are more complex topologies whose output can have more than three values, and they fall into the category of multilevel inverters (Erickson & Maksimovic, 2007).

In power electronics applications, high switching frequencies can result in harmonic components in the output waveform. A harmonic of a wave is a component frequency that is an integer multiple of the fundamental frequency. An inverter of multilevel characteristic lowers the harmonic content, which permits the reduction of the harmonic filter required because of fast switching.

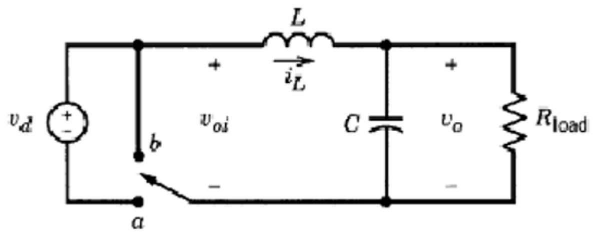

Figure 7. Switching

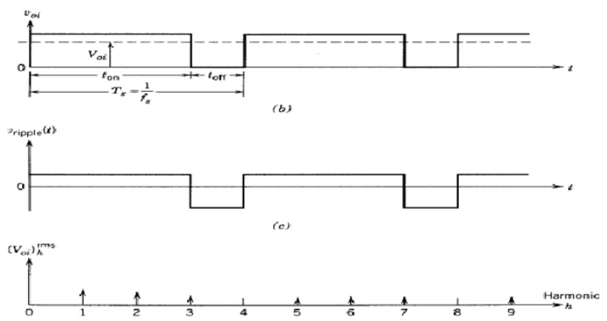

Figure 8. Harmonics generated during switching

A DC voltage V_{oi} is the desired output, while V_d (DC voltage) is the voltage source that is greater than V_{oi}. Switching is used to obtain an average value of the output waveform equal to V_{oi}. The resulting waveform is depicted in Figures 7 and 8. The dashed V_{oi} is known as the fundamental component, and the remainder is known as its harmonics (Mohan et al., 2003). The sum of the fundamental and the harmonics results in the actual waveform. One of the main roles of a grid-tied inverter is supplying power to the grid. The inverter must generate a high-quality output waveform to improve the performance of the overall system and to meet the interconnection requirements of the grid. Interconnection requirements often pertain to voltage magnitude, voltage notching, frequency, power factor, and distortion. The latter can be the most difficult requirement to meet and is of utmost importance to this paper. In some cases, this standard is defined in terms of the total harmonic distortion (THD) present in the waveform, which quantifies distortion based upon the presence of different Fourier components in the waveform.

2. Materials and Methods

The design of a single-phase inverter with an RLC filter involves creating a system that efficiently converts DC to AC while minimizing harmonic distortion. This section focuses on the design considerations for the inverter and the integration of an RLC filter for harmonic reduction.

2.1 Inverter Design

The design of the single-phase inverter begins with selecting an appropriate topology, typically a full-bridge inverter for its ability to provide higher output voltage and better control over the output waveform. The key components of the inverter include:

i. **Switching devices (IGBTs/MOSFETs):** These components are the main switches responsible for alternating the current flow and generating the AC waveform. In this design, a full-bridge configuration is utilized, consisting of four switches.

ii. **Pulse Width Modulation (PWM) control:** PWM is employed to control the switching devices by varying the width of the pulses. This modulation helps create a waveform that closely resembles a sinusoidal AC signal. The PWM frequency is set much higher than the fundamental AC frequency (50/60 Hz) to enhance the quality of the waveform.

2.2 RLC Filter Design

To reduce harmonic distortion in the inverter's output, a passive RLC filter is designed and connected at the output of the inverter. This RLC filter consists of a resistor (R), an inductor (L), and a capacitor (C) that work together to attenuate high-frequency harmonics while allowing the fundamental frequency to pass through. The operation of the RLC filter is based on its resonance properties:

i. *Inductor (L):* provides high impedance to high-frequency harmonics, effectively blocking them.

ii. *Capacitor (C):* offers a low-impedance path for high-frequency components, shunting them to ground.

iii. *Resistor (R):* used to dampen oscillations and prevent resonance issues.

iv. The cutoff frequency of the RLC filter is calculated to ensure attenuation of harmonics above the fundamental frequency (50/60 Hz). The filter is tuned to suppress higher-order harmonics, such as the 3rd, 5th, and 7th harmonics, where L is the inductance in henries (H) and C is the capacitance in farads (F).

2.3 Inverter Output Waveform Analysis

The switching nature of pulse-width modulation (PWM) usually results in a high harmonic content in the unfiltered inverter output. To determine the Total Harmonic Distortion (THD), the output waveform is analysed using the Fast Fourier Transform (FFT).

THD is defined as the ratio of the power of the fundamental frequency to the sum of the powers of all harmonic components. A high THD value indicates significant harmonic distortion in the inverter's output (Yazdani & Iravani, 2010).

After applying the RLC filter, the inverter's output is expected to exhibit reduced harmonic content. The filter effectively attenuates the high-frequency harmonics generated by the inverter's switching. The filtered output is then analysed again using FFT, allowing a comparison of the THD before and after filtering. Ideally, the RLC filter should significantly decrease the harmonic distortion, resulting in a THD value within acceptable limits (typically less than 5% for power systems).

2.4 Inverter Switching Methodology

The inverter shown in Figure 9 is grid-connected, voltage-sourced, and current-controlled.

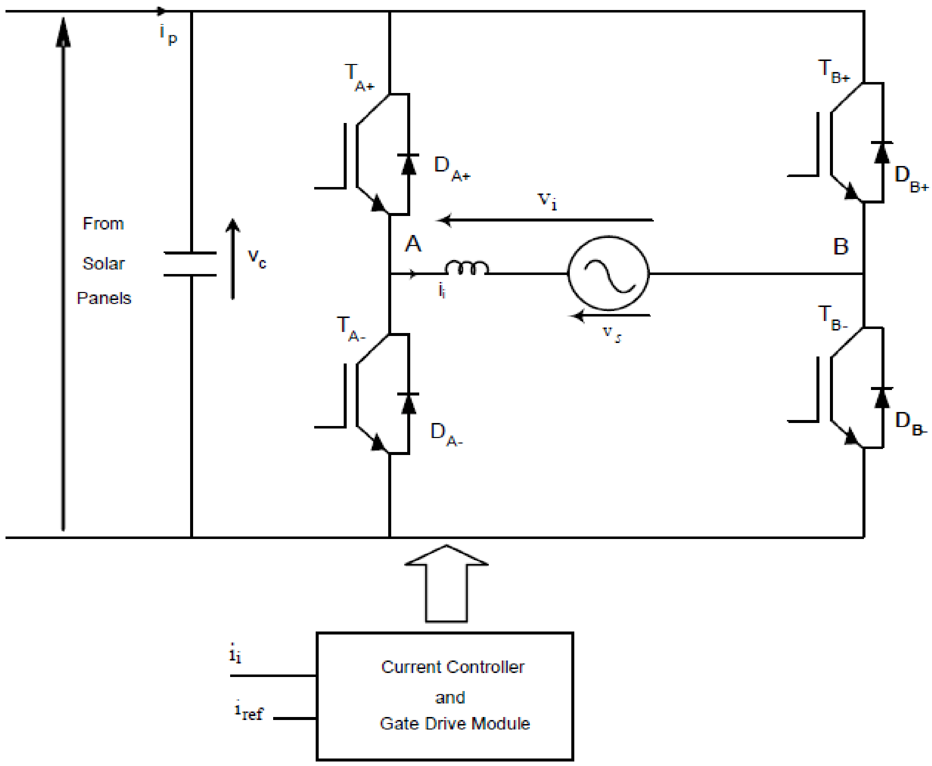

Figure 9. Bridge inverter

2.5 MATLAB Simulink Simulation

The entire inverter and RLC filter system is modelled and simulated in MATLAB Simulink to verify the design's performance. The simulation involves:

i. Creating a PWM-controlled inverter model with four switches in a full-bridge configuration.

ii. Designing the RLC filter and integrating it with the inverter's output.

iii. Running a simulation to analyse the output waveform, perform harmonic analysis using FFT, and compute the THD before and after applying the filter. Through simulation, the effectiveness of the RLC filter in reducing harmonics can be validated, and the design parameters (L, C, and R values) can be optimized for better performance.

2.6 Inverter Efficiency

i. Inverter efficiency is determined by the percentage measurement of energy conversion; that is, the closer the DC-to-AC conversion is to 96% for the longest amount of time, the more refined the inverter efficiency.

ii. When calculating efficiency, it is important to include peak and off-peak percentages in addition to how often the inverter is operating at rated capacity performance.

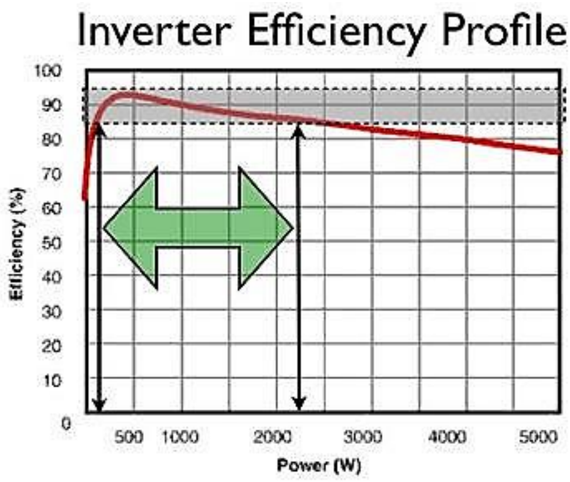

Figure 10. Inverter efficiency profile

Studies show that even a small percentage increase in inverter efficiency means the power supply increase can be quite significant if factored throughout the life span of the inverter.

2.7 Calculating THD

The controller calculates the THD in the output voltage waveform, v_{ac}. The output can be described in terms of v_{dc}, as it simply reverses the polarity of v_{dc}. The output voltage can be written simply as a function of the phase angle of the grid voltage, θ_V, and the input capacitor voltage, V_i. For the present system, the input voltage is 220 V and the output voltage is 210 V. The conversion efficiency is therefore given by:

$$\eta = (V_{out} / V_{in}) \times 100\% \qquad (1)$$

Substituting the measured values gives η = (210 / 220) × 100% = 0.9545 × 100% = 95.45%.

2.8 Switching Circuit Design

Sinusoidal Pulse Width Modulation (SPWM) is typically utilized in conventional inverter architecture to obtain AC output. In this study, however, a combination of SPWM and a square wave is used for inverter switching, since this technique decreases losses by reducing the switching frequency. The sine wave of the suggested design is sampled from the electrical grid using a buck power converter to step down the 210 V grid voltage to 5 V DC in order to comply precisely with grid synchronization. Consequently, the grid-tied inverter (GTI) output frequency matches the grid frequency. Next, a comparator is used to create the SPWM by comparing a high-frequency triangular wave (10 Hz) with the sampled sine wave.

The inverter requires four sets of signals, as only four MOSFETs are used in the inverter circuit; under this condition, two sets are SPWM. The four sets of signals can be grouped into two pairs (Ganguly et al., 2023). The first group consists of MOSFETs Q1 and Q4, while the second group consists of MOSFETs Q2 and Q3. When Q4 is switched on, SPWM appears at Q1, and at that time Q2 and Q3 are off. Again, when Q2 is turned on, SPWM appears at Q3, and at that time Q1 and Q4 remain off. For the Q1–Q4 pair, a positive voltage emerges across the load; for the Q2–Q3 pair, a negative voltage emerges across the load. The switches in each branch are operated alternately so that they are not in the same mode (ON/OFF) simultaneously. In practice they are both OFF for a short period of time, called the blanking time, to avoid short-circuiting.

These bridge legs are switched such that the output voltage is shifted from one to another, and hence a change in polarity occurs in the voltage waveform. If the shift angle is zero, the output voltage is also zero, and it is maximal when the shift angle is π.

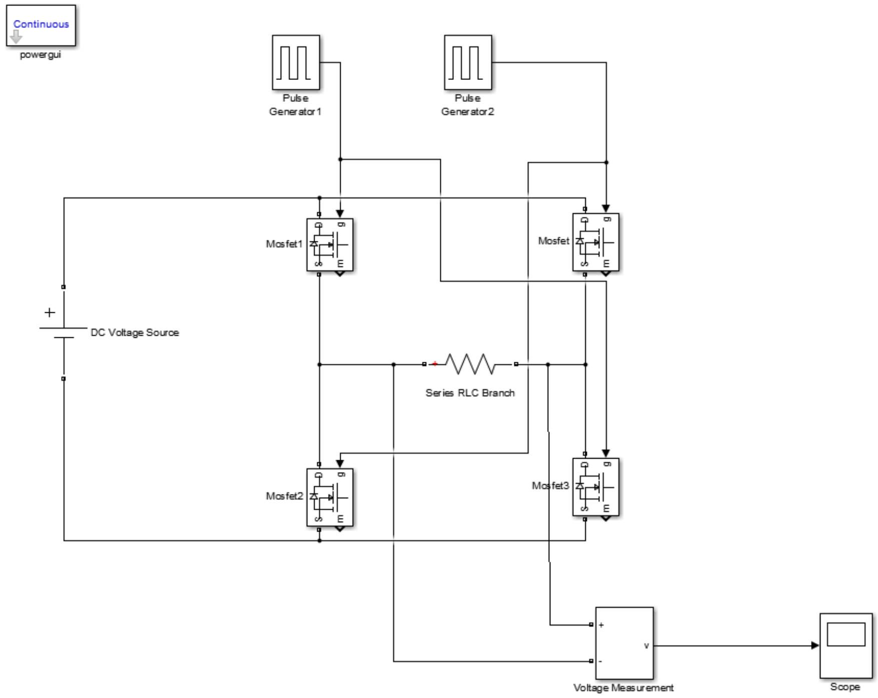

Figure 11. Switching circuit in the Simulink model (subsystem)

3. Results and Discussion

MATLAB Simulink simulation of a single-phase inverter is used to model its control strategy, output waveform analysis, and switching operations. Through the use of an RLC filter, the simulation assists in confirming the design's efficacy and functionality in lowering harmonic distortion.

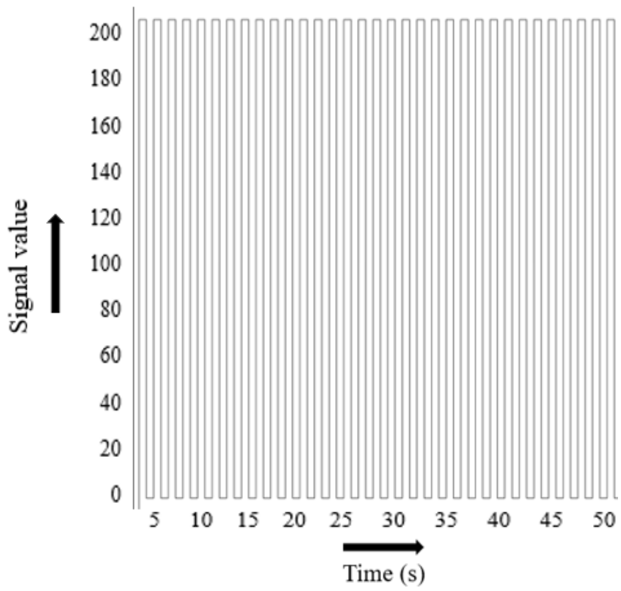

Figure 12. SPWM signal for switching

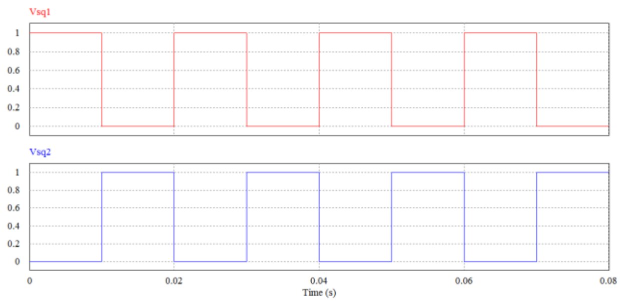

Figure 13. Square-wave gate pulse with 180° phase difference

3.1 Filter Performance

The performance of an RLC filter in reducing harmonics depends on several factors:

i. *Filter tuning:* the filter must be accurately tuned to the desired cutoff frequency to effectively attenuate specific harmonic frequencies while allowing the fundamental frequency (50/60 Hz) to pass with minimal distortion.

ii. *Component selection:* the values of the resistor, inductor, and capacitor have a significant impact on the effectiveness of the filter. Proper sizing of these components is crucial for achieving the desired level of harmonic reduction (Sardar et al., 2023).

iii. *Damping:* adequate damping is essential to prevent oscillations in the system, particularly near the filter's resonance frequency. The resistor in the RLC filter plays a key role in damping unwanted oscillations, thereby ensuring stability (Kumar & Alexander, 2018).

While the RLC filter proved effective in reducing harmonics, certain limitations should also be considered. The results of this simulation nevertheless have important implications for real-world applications of single-phase inverters:

i. **Power quality improvement:** the integration of an RLC filter greatly enhances the power quality of the inverter's output by reducing harmonic distortion. This makes the system suitable for powering sensitive electronic devices and reducing losses in transmission.

ii. **Compliance with standards:** the THD reduction achieved by the RLC filter helps ensure compliance with power quality standards, such as IEEE 519, which sets limits on harmonic content in electrical systems (Ali Khan et al., 2020).

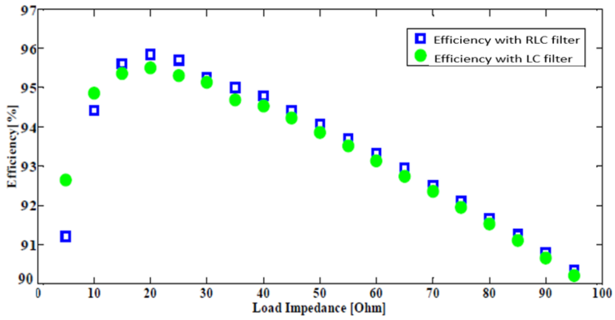

Figure 14. Efficiency versus load impedance

3.2 FFT Analysis

Figure 15 presents the FFT analysis of the output voltage. The fast Fourier transform confirms that the inverter output contains harmonics of the stated magnitude, but that the output retains only the fundamental harmonic, which lies at 50 Hz, while the remaining harmonics are negligible. After filtering, the output has a low THD of about 5%, because the proposed circuit is entirely transformer-less. The corresponding output voltage waveform of the inverter is shown in Figure 16.

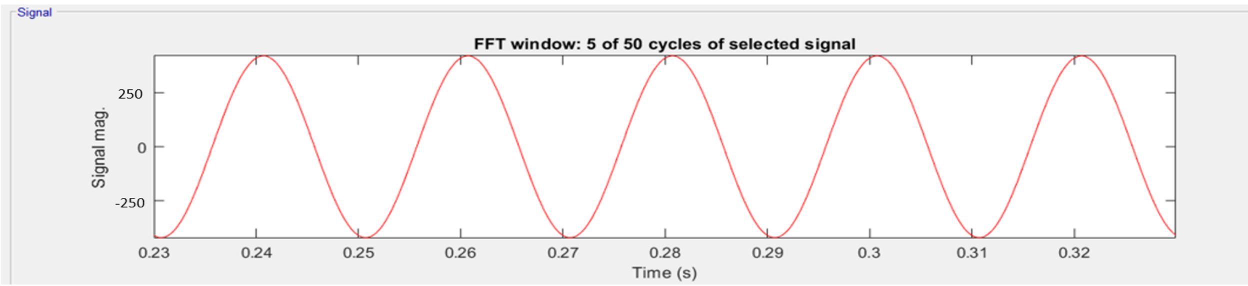

Figure 15. Output voltage THD of the proposed inverter

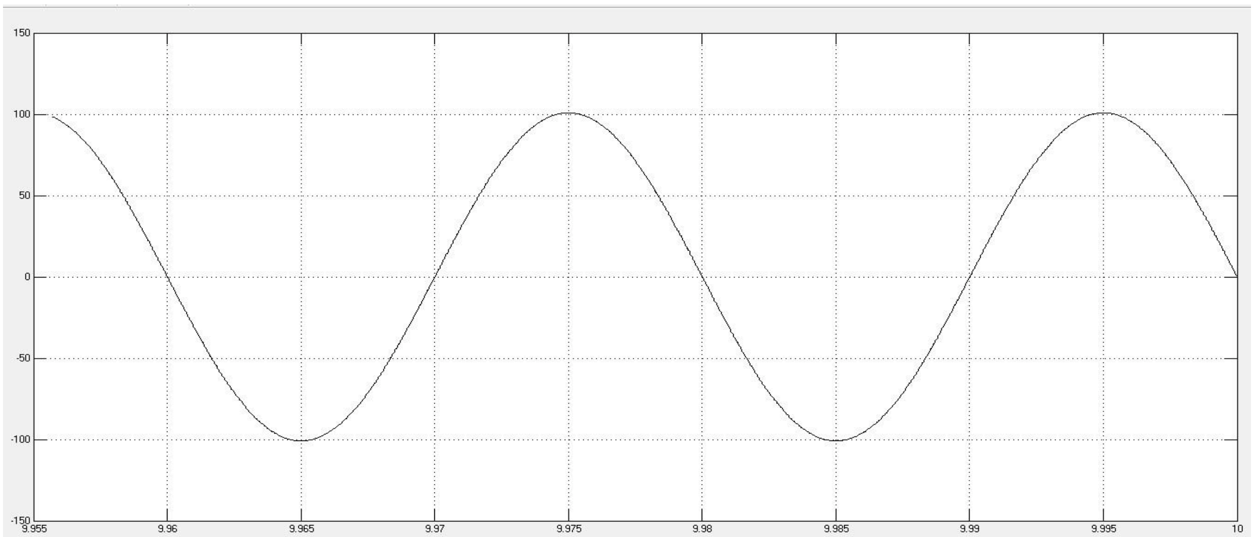

Figure 16. Output voltage of the inverter

3.3 Comparison of Results

Table 1 compares the efficiency and harmonic-reduction performance obtained in this study with the results reported in the recent literature.

Table 1. Comparison of filter efficiency and harmonic-reduction performance with previously reported results

Aspect	Present study (RLC and LC filter efficiency)	Zhou et al. (2021)	Singh & Kumar (2020)	Thakur & Sharma (2019)
Efficiency trend (LC filter)	Peaks at 95% around 30 Ω	Efficiency decreases at higher impedance	LC filter performs worse than RLC; lower efficiency overall	Peaks at a specific load, declines at higher impedance
Efficiency trend (RLC filter)	Peaks at 96% around 30 Ω	Not evaluated	RLC filter efficiency better than LC filter across loads	Not evaluated
LC filter performance	Slightly lower efficiency than RLC filter; peaks at 95%	LC filter efficiency declines with increasing impedance	Performs worse than RLC, especially at higher impedance	Efficiency declines after peaking at a certain load
RLC filter performance	Consistently higher efficiency; peaks at 96% at 30 Ω; better stability at high impedance	Not evaluated	RLC filter provides superior performance in harmonic reduction and efficiency	Not evaluated
Overall conclusion	RLC filter provides better efficiency (up to 96%) and stability	LC filter is less efficient; performance decreases at high impedance	RLC filter outperforms LC filter in both efficiency and harmonic reduction	LC filter peaks in efficiency but struggles at higher impedance

4. Conclusion

This study confirms that RLC filters are highly effective in reducing harmonic distortion in single-phase inverters. Simulation results in MATLAB Simulink showed a reduction of THD from 25–30% to below 5%, achieving compliance with IEEE 519 standards. Compared with LC filters, the RLC design delivered higher efficiency (up to 96%) and greater stability under varying loads. These findings highlight RLC filters as a cost-effective and practical solution for improving power quality in inverter-based renewable energy systems, with future work focusing on experimental validation and hybrid filter development.

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Author Contributions

Research concept and research design – Md. Moien Uddin and Md. Saddam Hossain; materials and data collection – Md. Saddam Hossain; data analysis and interpretation – Md. Moien Uddin, Hasibur Rahman and Md. Zahid Hasan Jamy; literature search and writing of the article – Hasibur Rahman and Afia Ibnat Ruxy; critical review and article editing – Hasibur Rahman and Md. Zahid Hasan Jamy; final approval – all authors.

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