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Grid Tied Photovoltaic System with Switched Capacitor Multilevel Inverter for Power Quality Enhancement

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Abstract

Grid-tied photovoltaic (PV) systems are becoming increasingly important for sustainable energy production. However, conventional inverter designs often face challenges such as high total harmonic distortion (THD), significant switching losses, and increased complexity due to the use of numerous switches. These issues negatively impact power quality, efficiency, and system reliability. To address these problems, advanced multilevel inverters with fewer switches and innovative modulation techniques provide a promising pathway for improving power quality and operational performance. This project introduces a grid-tied PV system utilizing a switched-capacitor multilevel inverter (SCMLI) with a reduced switch count for enhanced power quality. The system incorporates an isolated DC-DC flyback converter to stabilize and boost the DC output voltage for grid connection. A 17-level SCMLI, designed with fewer switches and capacitors, ensures efficient DC-to-AC conversion while minimizing THD in the output waveform. A three-phase H-bridge inverter paired with an LC filter refines the output, producing high-quality AC power that meets grid standards. Advanced pulse-width modulation (PWM) techniques based on DQ theory manage inverter operations and regulate active and reactive power flow. PI controllers are employed to dynamically adjust reference currents, ensuring accurate power tracking and improved grid stability. This configuration enhances power quality, reduces switching losses, and maximizes energy efficiency. By integrating the SCMLI, this grid-tied PV system delivers a cost-effective, energy-efficient, and reliable solution that aligns with modern power quality requirements for renewable energy systems.

1. Introduction

Photovoltaic (PV) systems, which convert sunlight into direct current (DC) electricity, are pivotal in advancing sustainable energy solutions. To integrate PV systems with the electrical grid, it is crucial to efficiently convert DC power to alternating current (AC). Conventional inverter designs, however, often face limitations such as high total harmonic distortion (THD), intricate control mechanisms, and extensive component requirements, which can compromise their effectiveness in grid-tied scenarios. To overcome these challenges, this project introduces an innovative grid-tied PV system that incorporates a switched-capacitor multilevel inverter (SCMLI) with a reduced number of switches, enhancing power quality and system efficiency [1]. The proposed system begins with a PV array that generates DC electricity from solar energy. An isolated DC-DC flyback converter processes this DC power, providing both voltage boosting and electrical isolation from the grid [2]. The output is then fed into a three-phase inverter system, where a three-phase H-bridge inverter transforms the DC into AC. An LC filter further conditions the AC output, eliminating high-frequency noise to ensure compliance with grid quality standards [3]. Advanced pulse-width modulation (PWM) strategies, derived from DQ theory, regulate inverter operations by managing active and reactive power dynamically [4]. Proportional-integral (PI) controllers continuously adjust these power flows to maintain grid stability and optimize energy delivery. This system leverages state-of-the-art inverter technology to maximize energy conversion efficiency and enable seamless integration of solar energy into the grid. By reducing THD, lowering switching losses, and simplifying the system design, the proposed solution provides an economical and adaptable approach to meet the increasing demand for renewable energy integration into modern [5-7].

1.1. Problem Statement

- Traditional inverters produce waveforms with high harmonic distortion, adversely affecting power quality.
- Conventional inverter designs often exhibit lower efficiency, resulting in energy losses during power conversion.
- Many existing systems face challenges in maintaining a high-power factor, which can compromise grid stability [8].

1.2. Objectives

- To develop a grid-tied photovoltaic system utilizing a switched-capacitor multilevel inverter to enhance power quality.
- To minimize harmonic distortion and produce smoother output waveforms that comply with grid standards.
- To improve energy conversion efficiency, reducing losses and ensuring maximum power transfer to the grid [9].

2. Literature Review

In recent years, renewable energy integration into the grid has garnered significant attention, particularly through photovoltaic (PV) systems due to their clean and sustainable energy generation capabilities [10]. Traditional inverter topologies, as highlighted in the existing system, suffer from inherent challenges such as high total harmonic distortion (THD), increased switching losses, and the need for a complex configuration involving a significant number of power components. The existing system utilizes a seventeen-level step-up switched-capacitor-based multilevel inverter, which aims to address some of these challenges by employing fewer power switches and incorporating inductors to reduce charging current stress on capacitors, thereby enhancing overall efficiency and operational stability [11]. However, it still faces limitations such as complexity in control and the need for additional DC sources. On the other hand, the proposed system introduces a novel architecture that combines advanced pulse-width modulation strategies and a reduced-switch switched-capacitor multilevel inverter (SCMLI). This approach offers a cost-effective solution for enhancing power quality, minimizing THD, and reducing component count without compromising system efficiency. By leveraging PI controllers and an isolated DC-DC flyback converter, the proposed system demonstrates improved operational efficiency and better compliance with power quality standards compared to the existing system, positioning it as a promising solution for modern renewable energy applications [12]. The comparison between the existing and proposed systems reveals key advancements and challenges. The existing system features a seventeen-level step-up switched-capacitor-based multilevel inverter (SCMLI) designed to reduce charging current stress on capacitors and enhance efficiency. This system offers advantages such as fewer power switches, voltage boosting capability, and a reduction in current spikes during capacitor charging. However, it encounters challenges with control complexity, efficiency optimization, and system integration [13-15]. In contrast, the proposed system incorporates advanced techniques such as an isolated DC-DC flyback converter and a high-performance SCMLI to overcome these limitations. The integration of PI controllers and sophisticated PWM strategies based on DQ theory enhances active and reactive power control, minimizes THD, and improves energy efficiency. By employing a reduced-switch topology, the proposed system addresses the complexity and component count issues seen in the existing architecture. Overall, the proposed system demonstrates superior power quality enhancement, reduced component count, and better efficiency management compared to the existing system. These advancements position the proposed architecture as a promising solution for modern grid-tied PV applications, emphasizing its ability to meet stringent power quality standards and optimize renewable energy integration.

3. Proposed Methodology

The proposed system introduces a grid-tied photovoltaic (PV) setup featuring a switched-capacitor multilevel inverter (SCMLI) with a reduced switch count to improve power quality. An isolated DC-DC flyback converter is integrated to stabilize and elevate the DC voltage, ensuring compatibility with grid requirements. The 17-level SCMLI is designed with a simplified structure, utilizing fewer switches and capacitors, to efficiently convert DC power to AC while significantly reducing total harmonic distortion (THD). Figure 1 Shows Circuit Diagram of Proposed System

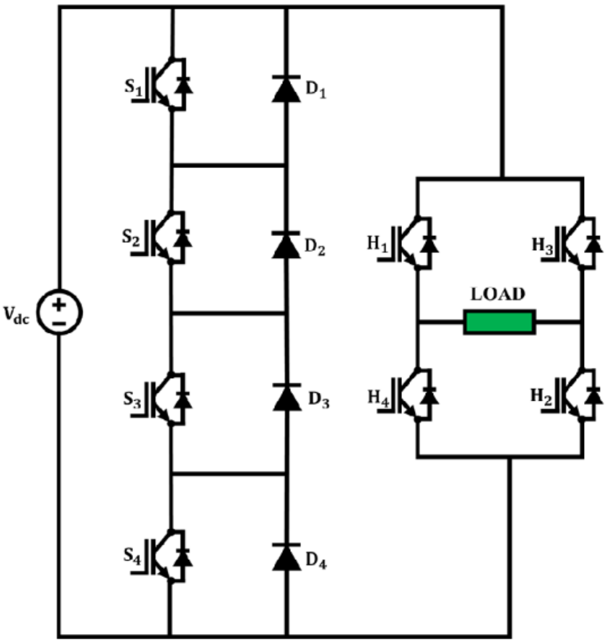
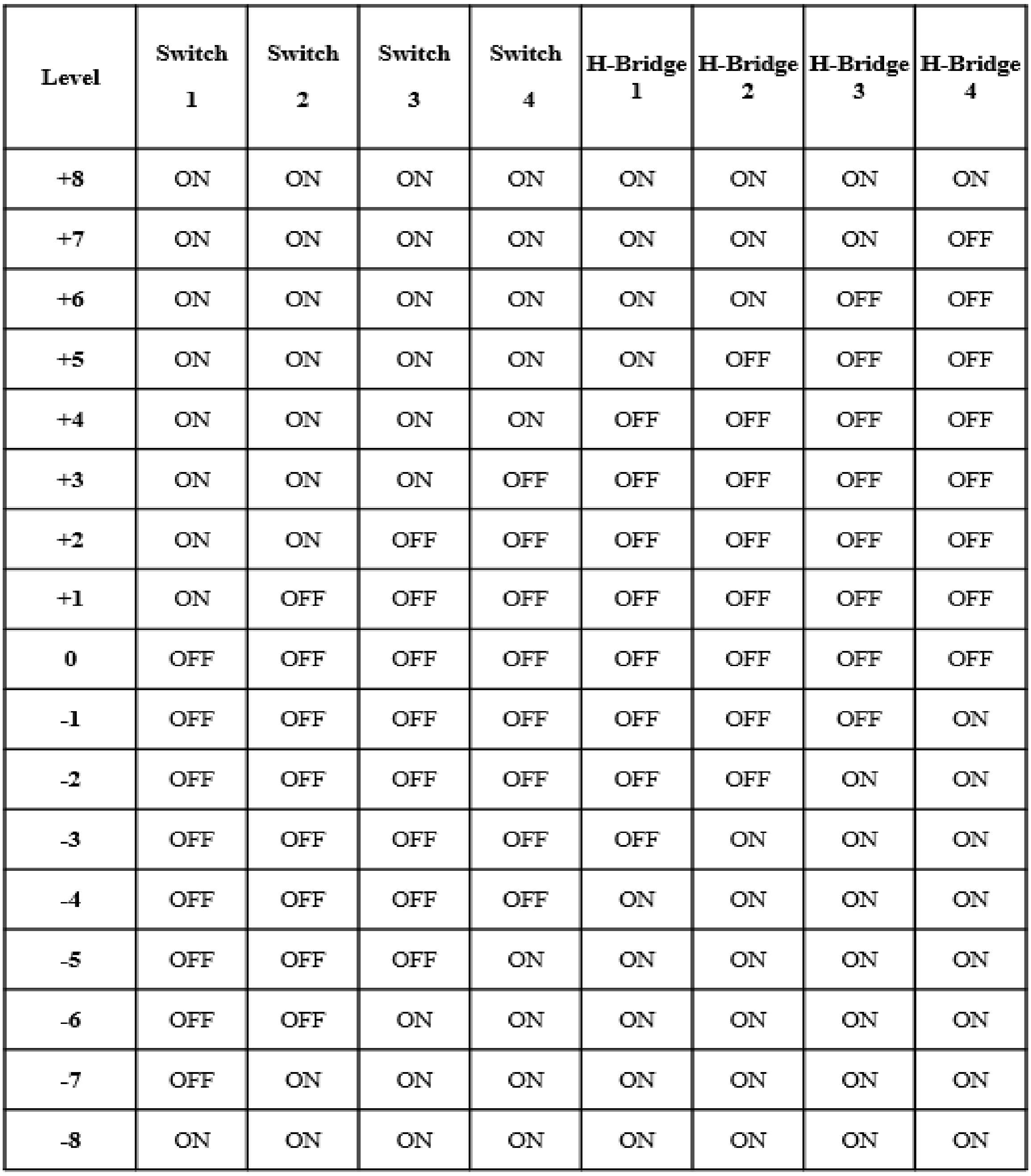


Figure 1 Circuit Diagram of Proposed System

The presented circuit diagram illustrates a three-phase inverter topology, which is commonly utilized in power electronic applications for converting DC voltage into AC voltage to drive various loads, such as electric motors. The left section of the circuit consists of four semiconductor switches (S_1, S_2, S_3, S_4) and associated freewheeling diodes (D_1, D_2, D_3, D_4), forming a DC-link stage that regulates the input voltage. The right section features an H-bridge inverter configuration (H_1, H_2, H_3, H_4), which facilitates the generation of an AC output by alternating the polarity of the voltage applied to the load. This design is widely implemented in industrial motor drives, renewable energy systems, and power conversion applications due to its high efficiency and controllability. The 17-level cascaded H-bridge (CHB) inverter operates by controlling multiple H-bridge cells, each supplied with an independent DC voltage source. The inverter generates stepped output voltage levels ranging from +8Vdc to -8Vdc by sequentially turning ON and OFF different combinations of power semiconductor switches. Each H-bridge contributes an incremental ±Vdc step, allowing the inverter to synthesize a near-sinusoidal output waveform with significantly reduced Total Harmonic Distortion (THD). During positive voltage generation (+8Vdc to +1Vdc), the first H-bridge (H_1) is switched ON to provide +Vdc, followed by sequential activation of additional H-bridges (H_2, H_3, H_4, etc.), adding their respective voltage contributions to reach the desired output level. Similarly, for negative voltage levels (-8Vdc to -1Vdc), the switching sequence is reversed, where the last H-bridge (H_8) is activated first, and additional bridges are progressively turned ON to step down the voltage. When all switches are OFF, the inverter outputs 0V, ensuring a smooth transition between positive and negative cycles. To efficiently control the switching states, modulation techniques such as Multi-Carrier Pulse Width Modulation (MCPWM) or Selective Harmonic Elimination (SHE-PWM) are employed. These techniques optimize the switching pattern to minimize harmonics and improve power quality. The staircase voltage waveform generated by this switching pattern closely approximates a sinusoidal AC waveform, making the 17-level inverter highly efficient for high-power applications, including renewable energy systems, electric vehicle drives, and industrial motor control. The system incorporates a three-phase H-bridge inverter combined with an LC filter to produce clean AC power that adheres to grid standards. Control is achieved using advanced pulse-width modulation (PWM) strategies grounded in DQ theory, enabling precise management of active and reactive power. Proportional-integral (PI) controllers dynamically adjust reference currents, ensuring accurate power delivery and enhancing grid stability. This approach not only improves power quality and minimizes switching losses but also maximizes energy efficiency. By integrating the SCMLI, the system provides a cost-effective and reliable solution that aligns with current power quality standards in renewable energy applications. Figure 2 shows Puls Pattern of Proposed System



Level	Switch 1	Switch 2	Switch 3	Switch 4	H-Bridge 1	H-Bridge 2	H-Bridge 3	H-Bridge 4
+8	ON	ON	ON	ON	ON	ON	ON	ON
+7	ON	ON	ON	ON	ON	ON	ON	OFF
+6	ON	ON	ON	ON	ON	ON	OFF	OFF
+5	ON	ON	ON	ON	ON	OFF	OFF	OFF
+4	ON	ON	ON	ON	OFF	OFF	OFF	OFF
+3	ON	ON	ON	OFF	OFF	OFF	OFF	OFF
+2	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF
+1	ON	OFF	OFF	OFF	OFF	OFF	OFF	OFF
0	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
-1	OFF	OFF	OFF	OFF	OFF	OFF	OFF	ON
-2	OFF	OFF	OFF	OFF	OFF	OFF	ON	ON
-3	OFF	OFF	OFF	OFF	OFF	ON	ON	ON
-4	OFF	OFF	OFF	OFF	ON	ON	ON	ON
-5	OFF	OFF	OFF	ON	ON	ON	ON	ON
-6	OFF	OFF	ON	ON	ON	ON	ON	ON
-7	OFF	ON	ON	ON	ON	ON	ON	ON
-8	ON	ON	ON	ON	ON	ON	ON	ON

Figure 2 Puls Pattern of Proposed System

3.1. PV System

A Photovoltaic (PV) system is a sustainable energy solution that converts sunlight into electricity using solar panels. These panels are constructed with the semiconductor materials, such as silicon, which generate electricity through the photovoltaic effect. This process occurs when sunlight excites electrons within the semiconductor, resulting in an electric current. As a clean and renewable method of power generation, PV systems play a significant role in the global shift toward sustainable energy sources. Figure 3 shows Block Diagram of Proposed System

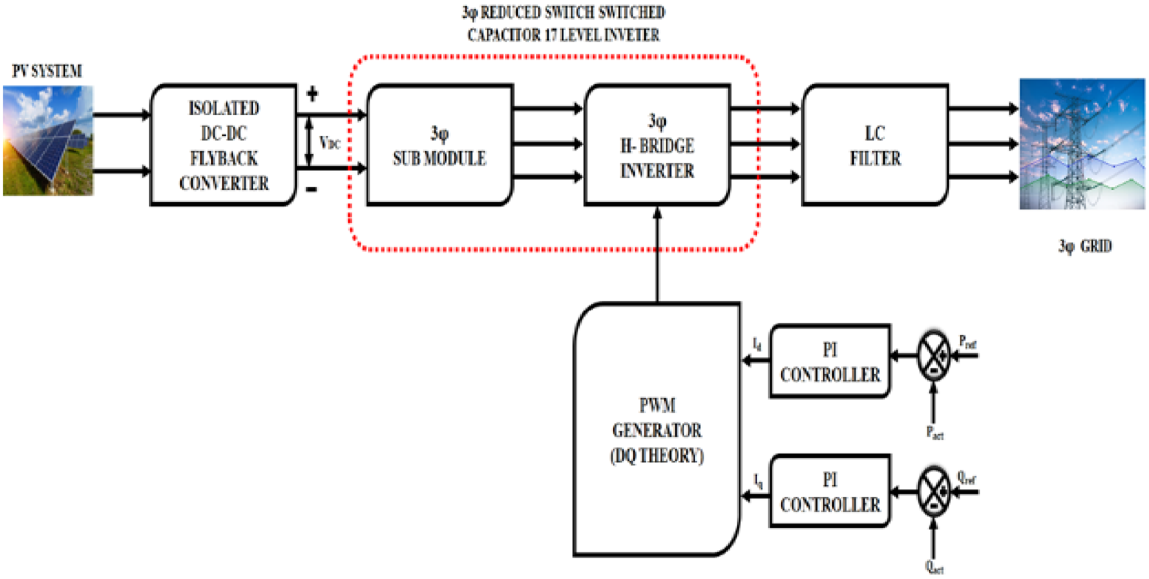


Figure 3 **Block Diagram of Proposed System**

Over the years, PV technology has seen substantial advancements, including improvements in efficiency, reductions in cost, and enhanced integration capabilities, making solar energy a widely adopted renewable resource. A typical PV `system includes essential components such as solar panels, inverters, charge controllers, batteries, and in some cases, a battery management system (BMS) for energy storage. Solar panels, arranged in arrays to meet energy needs, are the primary component, converting sunlight into direct current (DC) electricity. The generated DC power is then converted into alternating current (AC) by an inverter, making it suitable for use in households, industries, and grid integration. Figure 4 shows Equivalent Circuit of PV System

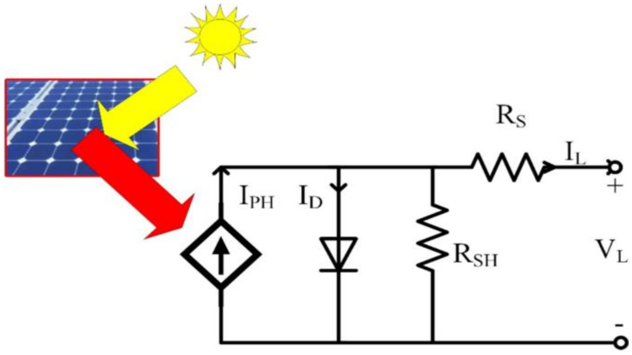


Figure 4 **Equivalent Circuit of PV System**

For off-grid PV systems, energy storage solutions, usually in the form of batteries, enable electricity supply during periods without sunlight, such as at night or on overcast days. Charge controllers protect batteries from overcharging or excessive discharging, ensuring longevity and efficient energy usage. Advanced systems often employ a battery management system (BMS) to monitor and regulate battery performance, balance cell voltages, and ensure safe operation. One of the key benefits of PV systems is their scalability. This system can be used for various applications, from small residential installations to large utility-scale projects. Grid-tied PV systems allow users to connect to the local power grid, reducing energy costs through net metering, where excess energy generated during peak sunlight hours can be sold back to the grid. Conversely, off-grid systems operate by the power grid and rely on battery storage. Hybrid systems, which combine grid-tied functionality with battery storage, provide greater flexibility by enabling energy storage for later use while maintaining grid access for additional power needs.

3.2. Isolated DC-DC Flyback Converter

An isolated DC-DC flyback converter is a power circuit designed to adjust DC voltage levels while providing electrical separation between the input and output. The converter has two side in primary side the input voltage applied and in secondary side the output voltage is delivered. The operation starts by the input DC voltage is applied to the primary winding of a transformer. A switching device, such as a MOSFET or transistor, alternates rapidly between on and off states, generating a high-frequency AC signal. This signal induces a corresponding voltage in the transformer's secondary winding. On the secondary side, a diode and filter capacitor rectify and smooth the signal, producing a steady DC output. The transformer plays a critical role in isolating the input from the output, which is essential for safety in various sensitive applications. Feedback control ensures the switching mechanism maintains a consistent output voltage, enhancing the converter's efficiency and reliability. Figure 5 shows Isolated DC-DC Flyback Converter

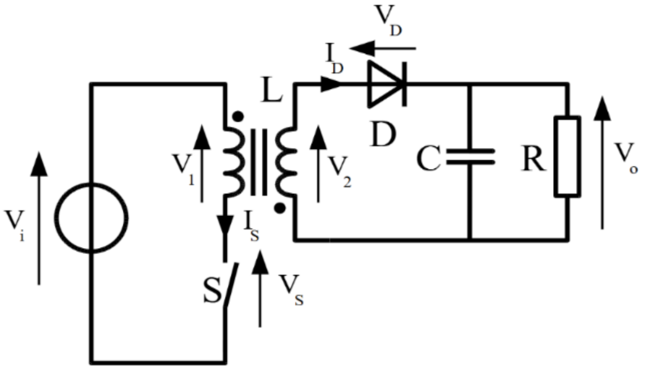


Figure 5 Isolated DC-DC Flyback Converter

- During the on-state, energy from the input source to the transformer's magnetic core, while the output capacitor supplies energy to the load.
- During the off-state, the stored energy in the transformer is delivered to the output load through the secondary circuit, assisted by the output capacitor.

3.3. PWM Generator

A PWM (Pulse Width Modulation) generator operates by producing a sequence of on-off pulses with varying widths to regulate the average power delivered to a load. This process typically starts with a stable clock signal, which establishes the PWM output's frequency. A comparator or microcontroller compares this clock signal with a reference voltage to set the desired duty cycle. When the reference voltage surpasses the clock signal's input, the output pulse is activated and remains high for a duration corresponding to the duty cycle. This duration can be adjusted, enabling precise control of the pulse width. For instance, a 25% duty cycle means the signal stays high for one-fourth of the period and low for the remaining three-fourths, resulting in a lower average output. In contrast, a 75% duty cycle keeps the signal high for three-fourths of the time, producing a higher average output. Figure 6 shows PWM Generator

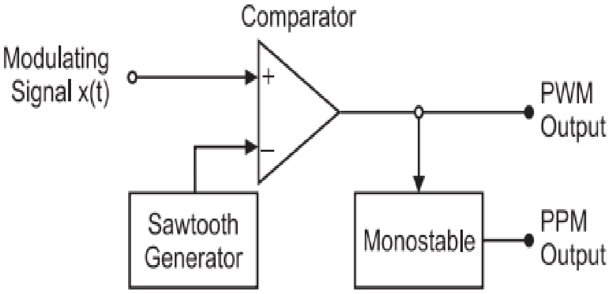


Figure 6 PWM Generator

The main advantage of PWM lies in its efficiency. Since switching devices like MOSFETs operate either fully on or off, they generate minimal heat, reducing power loss. This efficiency makes PWM suitable for applications such as motor speed control, where varying the motor's speed is achieved by adjusting the effective voltage, or LED dimming, where brightness can be finely controlled. Additionally, PWM integrates seamlessly into digital systems, enabling the use of advanced control algorithms and feedback mechanisms to improve performance and responsiveness. In certain applications, PWM techniques utilize DQ theory for precise control. This approach involves converting three-phase AC signals into a rotating reference frame for simplified analysis. DQ theory, or Park Transformation, converts three-phase currents and voltages into two components: the direct (D) and quadrature (Q) axes. These components represent active and reactive power, respectively, allowing for independent and efficient control of power flow in the system.

3.4. LC Filter

An LC filter is a key component in electrical and electronic systems, designed to eliminate unwanted frequencies from a signal while allowing desired frequencies to pass through. This type of filter consists of an inductor (L) and a capacitor (C), which use the distinct properties of these components to create a circuit that effectively attenuates certain frequency ranges. LC filters are widely used in applications such as power supplies, audio systems, radio frequency (RF) circuits, and communication networks. The operation of an LC filter relies on the impedance characteristics of the inductor and capacitor. As frequency increases, the inductor’s impedance rises, while the capacitor’s impedance decreases. By combining these components, the filter can be designed to block certain frequencies and let others through. Depending on whether the filter is configured in series or parallel, its frequency response and filtering behaviour will vary. In a series LC filter, the inductor and capacitor are connected in series, blocking high frequencies while passing low frequencies. In contrast, a parallel LC filter allows high frequencies to pass while blocking low frequencies. One of the main benefits of LC filters is their ability to offer precise frequency filtering with minimal signal degradation. This is due to the high-quality factors (Q factors) of the inductors and capacitors, which help maintain a narrow bandwidth around the cutoff frequency. LC filters are particularly valuable in areas where signal integrity is critical, such as in audio processing, where they help reduce noise and unwanted frequencies, or in radio communication, where they ensure that only the desired signals are transmitted or received. Additionally, in power electronics, LC filters are essential for reducing electromagnetic interference (EMI) and maintaining the stable operation of power supplies and converters. By filtering out high-frequency noise, they help to smooth voltage and current waveforms, reducing the risk of instability or inefficiency in electronic circuits. This is especially important in switching power supplies, where high-frequency switching introduces noise and harmonics into the system.

3.5. PI Controller

An LC filter is an essential component in electrical and electronic systems, designed to remove unwanted frequencies from a signal and ensure that only the desired frequencies pass through. Comprising an inductor (L) and a capacitor (C), this type of filter uses the unique properties of these two passive components to effectively attenuate specific frequencies. LC filters has various applications in various fields, including power supplies, audio equipment, radio frequencies, and communication systems. The operation of an LC filter is based on the impedance characteristics of inductors and capacitors. An inductor’s impedance increases as frequency rises, while a capacitor’s impedance decreases with frequency. By appropriately combining these components, the filter can block certain frequencies and allow others to pass. The configuration of the LC filter, whether series or parallel, dictates its frequency response and filtering behaviour. In a series LC filter, the inductor and capacitor are connected in series, which blocks high frequencies and lets low frequencies through. On the other hand, in a parallel LC filter, the components are connected in parallel, blocking low frequencies while allowing high frequencies to pass. Figure 8 shows PI Controller

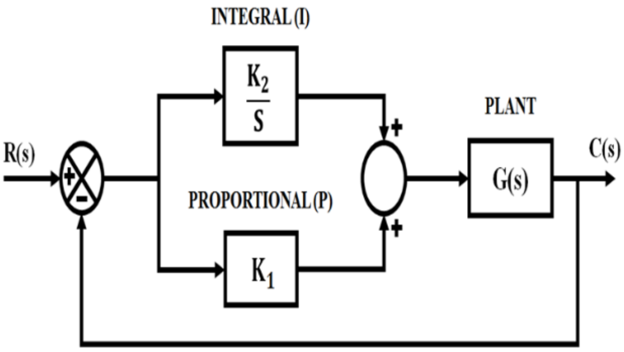


Figure 8 **PI Controller**

One of the main advantages of LC filters is their ability to provide precise frequency discrimination with minimal signal loss. This is due to the high-quality factors (Q factors) of the inductors and capacitors, which help achieve a narrow bandwidth around the cutoff frequency. LC filters are particularly useful in scenarios where signal clarity is vital, such as in audio processing to eliminate noise or in radio communications to isolate the desired signal frequencies. In power electronics, LC filters also reduce electromagnetic interference (EMI) and enhance the stability of power supplies and converters. They smooth out voltage and current waveforms by filtering high-frequency noise, which can otherwise cause instability or inefficiency in circuits. This is especially important in switching power supplies, where high-frequency switching generates harmonics and noise.

F. 3-Phase Sub Module and H-Bridge Inverter

The 3-phase sub module and H-bridge inverter are key elements in the system, responsible for converting the stepped-up DC voltage into AC power that is compatible with the grid. After the DC voltage is processed by the isolated DC-DC flyback converter, it enters the 3-phase sub module, which allocates the power across the three phases. This sub module serves as an intermediary stage, ensuring the power is evenly distributed and preparing it for efficient conversion into AC. The output from the sub module is then directed to the 3-phase H-bridge inverter, which converts the DC power into AC power.

4. Results

The simulation of our proposed system was implemented using Matlab Simulink. The Three-Phase Switched Capacitor Multilevel Inverter (TPSC-MI) operates by combining capacitors with a multilevel inverter topology, enhancing both the efficiency and power quality of three-phase systems. Its primary role is to produce high-quality output waveforms with minimal harmonic distortion by selectively switching capacitors into and out of the circuit at specific intervals. The TPSC-MI typically features several voltage levels, created by a series of capacitors and semiconductor switches like IGBTs or MOSFETs, forming a stepped approximation of the intended sinusoidal waveform. The process begins when the inverter starts converting DC voltage from a source into a three-phase AC output. The multilevel design enables the generation of multiple voltage levels, significantly reducing harmonic distortion compared to conventional two-level inverters. The switched capacitors play a crucial role in maintaining voltage stability at each level by providing reactive power compensation, which improves the power factor and reduces the reliance on external reactive power sources. As the load conditions fluctuate, the inverter dynamically adjusts the capacitor switching to maintain appropriate voltage levels across the phases. Additionally, advanced control algorithms are integrated into the multilevel inverter to regulate the switching of capacitors, ensuring that the output waveform remains balanced and smooth. This results in efficient power conversion, enhanced voltage stability, and reduced harmonic distortion, making the TPSC-MI ideal for high-power industrial and renewable energy applications. Figure 8 shows Proposed Grid Tied Switched Capacitor Multilevel Inverter

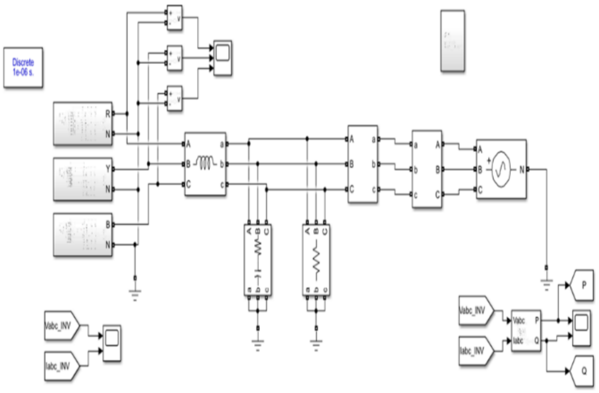


Figure 8 **Proposed Grid Tied Switched Capacitor Multilevel Inverter**

4.1. Input DC Voltage Waveform

Figure 8 illustrates the "Input DC Voltage Waveform," which represents a constant direct current (DC) voltage maintained over a one-second period. The voltage is displayed on the vertical axis, ranging from 100 to 200 volts, while time is shown on the horizontal axis, spanning from 0 to 1 second. The waveform appears as a flat, horizontal line at the 200-volt level, indicating a steady and unchanging voltage throughout the entire time span. This suggests that the input voltage does not vary during the observed duration. The grid lines on the graph assist in reading and interpreting the voltage levels clearly. Overall, the graph effectively portrays the stability of the DC voltage input.

4.2. Three Phase Inverter Output Voltage Waveform

Figure 9 depicts the "Three Phase Inverter Output Voltage Waveform," showing the voltage output from a three-phase inverter over a time period of 0.1 seconds. The voltage is represented on the vertical axis, ranging from -400 to 400 volts, with time displayed on the horizontal axis.

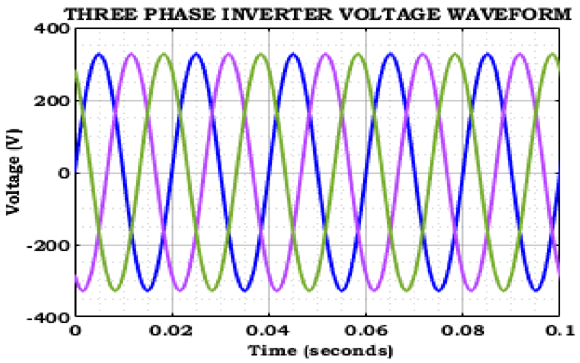


Figure 9 Three Phase Inverter Output Voltage Waveform

4.3. Three Phase Inverter Output Current Waveform

Figure 10 presents the "Three Phase Inverter Output Current Waveform," illustrating the current produced by a three-phase inverter over a 0.3-second period. The current is plotted on the vertical axis, ranging from -40 to 40 amperes, while the horizontal axis represents time.

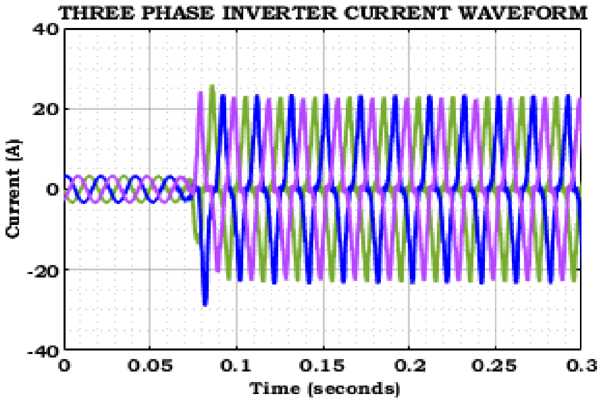


Figure 10 Three Phase Inverter Output Current Waveform

4.4. THD Waveform of the Three Phase Multilevel Inverter

Figure 11 shows the total harmonic distortion (THD) waveform for a three-phase multilevel inverter, providing a frequency spectrum of the signal. The x-axis represents the frequency range from 0 to 1000 Hz, while the y-axis shows the magnitude of these frequencies as a percentage.

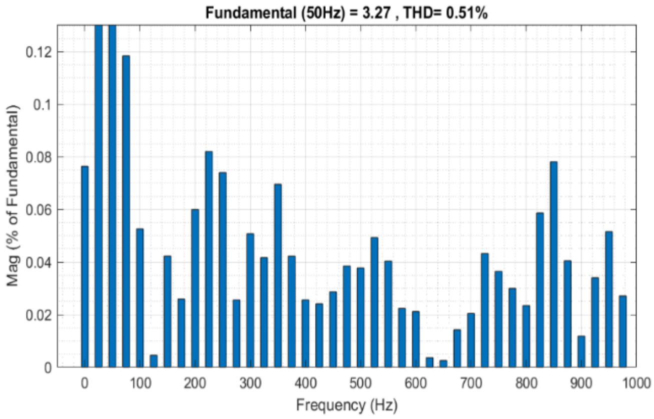


Figure 11 THD Waveform of the Three Phase Multilevel Inverter

4.5. Real Power Waveform

Figure 12 illustrates the real power waveform over a one-second interval. Initially, there is a sharp increase in power, reaching approximately 10,000 watts right after the start of the interval. After this peak, the power stabilizes around 10,000 watts, with slight fluctuations. The waveform indicates steady power generation or consumption over the observed period, with values remaining close to the 10,000-watt mark.

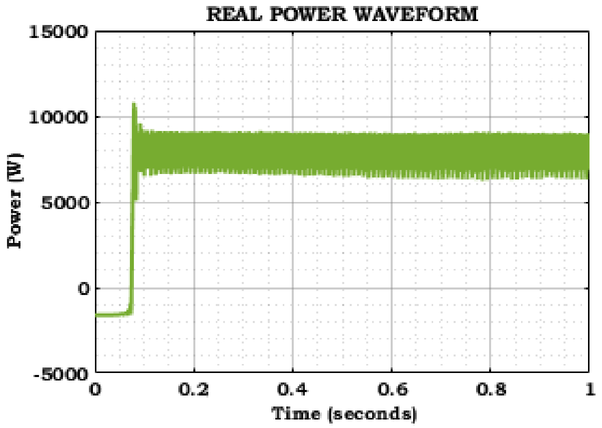


Figure 12 Real Power Waveform

4.6. Reactive Power Waveform

Figure 13 presents the reactive power waveform over a one-second interval. The waveform shows a noticeable surge in reactive power at the beginning, peaking at nearly 5,000 watts. After this initial surge, the reactive power stabilizes close to zero, with minor fluctuations for the rest of the interval. This behaviour suggests that, following the transient event, the reactive power remains relatively stable, indicating a balance in the reactive components of the system.

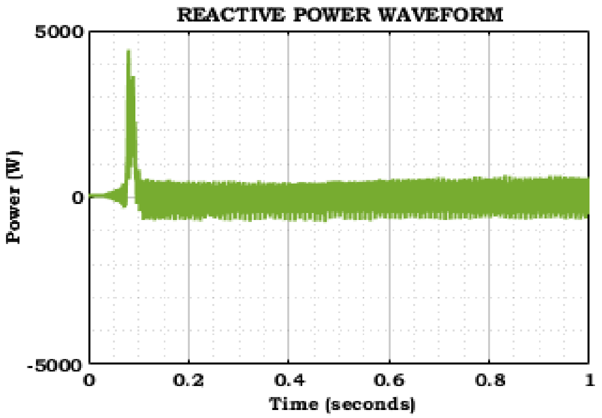


Figure 13 Reactive Power Waveform

Conclusion

The proposed grid-tied photovoltaic system featuring a switched-capacitor multilevel inverter (SCMLI) effectively addresses key challenges associated with conventional inverter designs, such as high total harmonic distortion, switching losses, and system complexity. By integrating an isolated DC-DC flyback converter, a 17-level SCMLI with fewer switches, and advanced DQ-based PWM control strategies, the system significantly enhances power quality, energy efficiency, and grid stability. The use of PI controllers ensures accurate active and reactive power management, making the system highly reliable for modern grid-connected renewable energy applications. Overall, this innovative approach offers a cost-effective, efficient, and sustainable solution that supports the growing demand for clean energy integration into the power grid.

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