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EXPERIMENTAL STUDY OF A MULTI-STAGE CONVERTER CIRCUIT

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Abstract. *An experimental analysis was carried out on a multi-stage energy conversion system configured in a solar panel–converter–load structure. Multi-stage converters are operated according to fundamental energy transfer principles, enabling the conversion of solar radiation into usable electrical power for consumer applications. The performance of the system was evaluated under different load scenarios, with variations in efficiency and output voltage behavior analyzed. The experimental results indicate that the integration of multiple converter stages leads to enhanced productivity of photovoltaic power systems. These findings emphasize opportunities for the optimization of photovoltaic technology and the advancement of energy conversion designs intended for automotive applications.*

Keywords: multilevel inverter, energy efficiency, IGBT, power converter, photovoltaic system, multi-stage energy conversion

EKSPERYMENTALNE BADANIE UKŁADU PRZEKSZTAŁTNIKA WIELOSTOPNIOWEGO

Streszczenie. *Przeprowadzono analizę eksperymentalną wielostopniowego systemu konwersji energii skonfigurowanego w strukturze panel słoneczny–konwerter–obciążenie. Konwertery wielostopniowe działają zgodnie z podstawowymi zasadami transferu energii, umożliwiając konwersję promieniowania słonecznego na energię elektryczną nadającą się do zastosowań konsumenckich. Wydajność systemu oceniono w różnych scenariuszach obciążenia, analizując zmiany wydajności i zachowania napięcia wyjściowego. Wyniki eksperymentów wskazują, że integracja wielu stopni konwertera prowadzi do zwiększenia wydajności systemów fotowoltaicznych. Wyniki te podkreślają możliwości optymalizacji technologii fotowoltaicznej i rozwoju projektów konwersji energii przeznaczonych do zastosowań motoryzacyjnych.*

Słowa kluczowe: wielopoziomowy falownik, sprawność, IGBT, przekształtnik mocy, system fotowoltaiczny, wielostopniowa konwersja energii

Introduction

Advanced power conversion technologies have seen significant advancements in response to the growing global demand for renewable energy, particularly in photovoltaic (PV) systems. Converters play a crucial role in solar energy conversion by transforming direct current (DC) from solar panels into alternating current (AC) for various applications. However, conventional photovoltaic converters often encounter challenges such as harmonic distortion, complex system designs, and efficiency losses due to multiple conversion stages [1, 14]. Addressing these limitations requires innovative techniques that enhance conversion efficiency, system stability, and reliability.

The reconfigurable solar converter (RSC) offers an integrated approach to multistage conversion, streamlining the design of traditional three-phase solar inverters. By reducing the number of components and optimizing switching mechanisms, this system enhances operational reliability while minimizing power losses and improving overall efficiency. This research explores the development of a seven-level inverter using MATLAB/Simulink modeling, which converts DC voltage from three PV panels into a seven-step AC output. Additionally, a five-level operational mode serves as a backup, ensuring uninterrupted power delivery in case of panel disconnection. Performance analysis indicates improved harmonic characteristics, with total harmonic distortion (THD) values of 4.19% in five-level mode and 1.13% in seven-level mode. The system employs phase-shift modulation with six carrier signals and a fundamental reference signal to achieve precise control [17, 20].

This research focuses on the design and evaluation of a single-phase multilevel inverter that incorporates insulated-gate bipolar transistors (IGBTs) and operates using amplitude-pulse control [5]. The proposed system generates an output voltage waveform that closely resembles a sinusoidal signal, facilitating efficient conversion of solar energy into grid-compatible AC. To assess its effectiveness, experimental tests are conducted to analyze its ability to maintain a stable AC output under varying load conditions [15]. The findings highlight the benefits of multi-stage conversion, demonstrating its potential to enhance PV system performance and contribute to advancements in converter technology for sustainable energy applications.

1. Materials and methods

This study explores the design, development, and experimental evaluation of a multi-stage power converter for PV applications [2]. An RSC is integrated into the system to simplify the conventional three-phase inverter structure. The inverter employs a seven-level topology to convert DC voltage from three photovoltaic panels into a seven-step AC output, modeled and analyzed using MATLAB/Simulink. To ensure continuous operation, the system automatically transitions to a five-level mode when a panel disconnects. Performance assessment through THD analysis indicates reduced high-frequency harmonics, with values measured at 4.19% for five-level operation and 1.13% for seven-level operation [18].

The proposed four-stage power inverter is structured using ten power switches, divided into five sections per polarity, to generate stepped AC voltage waveforms [3, 8]. Phase-shift modulation is implemented, utilizing six carrier signals and a fundamental reference signal to regulate switching behavior efficiently. The functional block diagram of the four-stage power inverter is presented in Fig. 1, showing the PV array, the microcontroller unit (MCU) with gate drivers, the four inverter stages based on IGBTs, and the AC-side protection and load [4, 7].

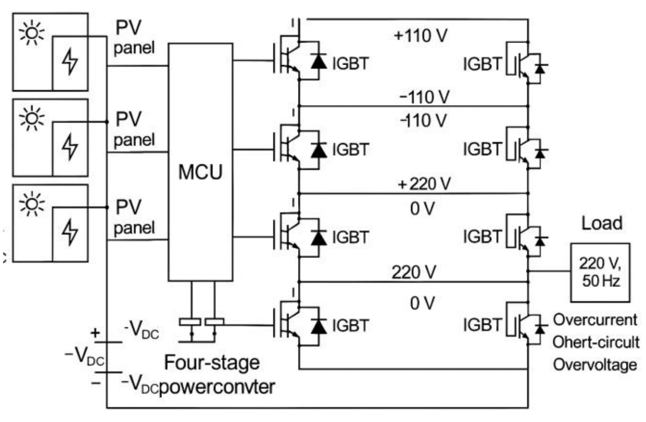

Fig. 1. Functional block diagram of the four-stage power inverter

The system consists of four principal subsystems: (i) an MCU with optocoupler-isolated gate drivers, (ii) power switches configured in four stages to synthesize stepped AC waveforms, (iii) additional DC voltage sources forming the input bus, and (iv) AC-side protection with overcurrent, short-circuit, and overvoltage control. The Texas Instruments C2000 MCU governs the real-time switching of IGBTs using a phase-shift modulation strategy. A bridge-based pulse summation method generates stepped sinusoidal voltages, while a 0.5 ms dead-time ensures safe switching operation.

Fig. 2 presents the experimental measurement system designed for output voltage acquisition during converter operation.

The converter system incorporates an integrated protection mechanism to safeguard against overcurrent, short-circuit, and overvoltage conditions. The protection circuit features B2 as a current sensor, DA1 as a Schmitt trigger comparator, an integrating circuit, and D15 functioning as a logic OR gate [6, 9]. When the comparator detects a high-level signal surpassing the predefined threshold, it initiates the capacitor charging process. If the capacitive charge exceeds safe limits, the system triggers a protective shutdown by sending a signal from the Schmitt trigger to disable the microcontroller, thereby deactivating the converter.

Additionally, a secondary protection circuit monitors output voltage levels [16]. When voltage surpasses safe limits, it transmits a logic "1" signal to the microcontroller, initiating an emergency shutdown sequence to prevent system damage.

Fig. 2. Experimental measurement system for output voltage acquisition

2. Experiment and results

The converter system was tested under various load conditions, including resistive (R), inductive (L), and capacitive (C) loads. Figures 3-6 illustrate oscilloscope waveforms recorded during tests with inductive-active loads, demonstrating how inductors limit instantaneous changes in waveform transitions.

A four-stage single-phase inverter was used to evaluate different load types, including resistive, inductive-active, capacitive-active, and inductive-capacitive-active configurations. The testing procedure involved executing specific operating conditions to assess converter performance across these load variations:

1. Input Voltage: The converter received a 220 V DC supply from a photovoltaic panel simulator during testing.
2. Switching Frequency: IGBT transistors were configured to operate at a 5 kHz switching frequency, ensuring stable conversion efficiency.
3. Control System: The Texas Instruments C2000 microcontroller was programmed to regulate switching sequences using a phase-shift modulation strategy.
4. Loads:

- Experiment 1: Load with an inductance of 10 mH and a resistance of 400 Ω.
- Experiment 2: Load with an inductance of 10 mH and a resistance of 200 Ω.
- Experiment 3: Load with an inductance of 100 mH and a resistance of 400 Ω.

5. Measurement Equipment:

- Oscilloscope: Used to capture the output voltage waveforms.
- Power Analyzer: Used to measure input and output power for efficiency calculations.

The testing system evaluated the converter's performance under various load conditions, particularly its ability to operate efficiently with inductive loads while maintaining waveform stability.

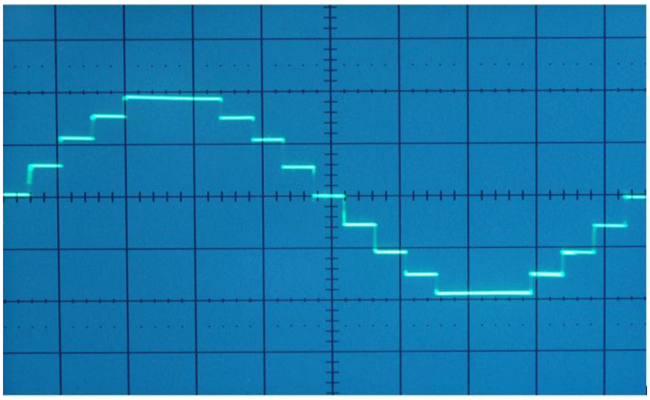

Fig. 3. Stepped sinusoidal waveform

It is shown in Fig. 3 that the stepped sinusoidal output voltage was observed under standard load conditions. The step transitions correspond to IGBT transistor switching, enabling a gradual approximation of a sinusoidal waveform. The distinct step formations in the waveform confirm the precise execution of the modulation algorithm.

The stepped sinusoidal waveform serves as a benchmark for evaluating converter performance, particularly in minimizing harmonic distortion to meet the requirements of sensitive electrical equipment. This step-based structure highlights the DC-to-AC inversion process, producing high-quality AC power suitable for a variety of applications [19].

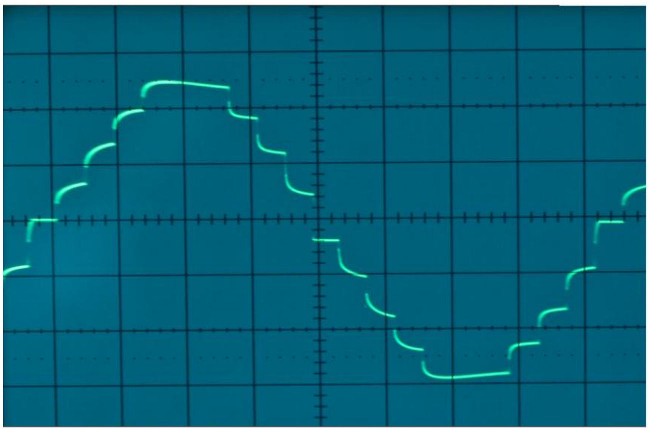

Fig. 4. Effect of reduced resistance

As presented in Fig. 4, the effect of reduced resistance on system performance was observed while inductance remained constant. As resistance decreases, the corresponding increase in current draw leads to waveform rounding. This deviation from an ideal stepped sinusoidal waveform introduces minor harmonic components due to the impact of increased current.

To enhance waveform stability and efficiency under variable load conditions, improvements in the switching algorithm are necessary [10–12]. These modifications can help sustain optimal power conversion performance while minimizing harmonic distortions.

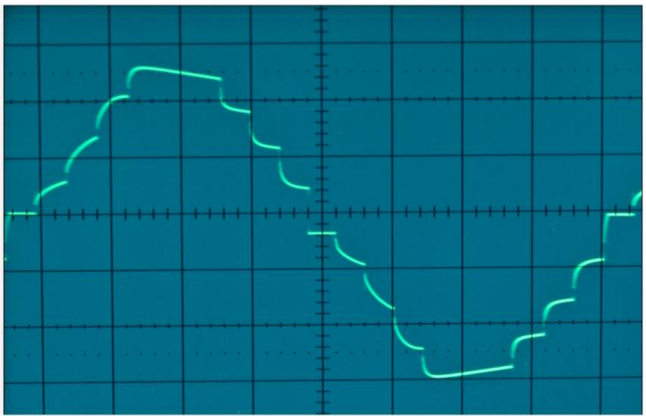

Fig. 5. Effect of increased inductance

Waveform variations resulting from increased inductance are presented in Fig. 5. The oscillogram reveals extended transition times and slight peak voltage overshoots. Due to its opposition to sudden current changes, inductance causes delays in steady-state voltage stabilization.

The monitoring results highlight the negative impact of inductive loads on waveform quality within this converter system [13]. The increased stress on switching components underscores the need for advanced control strategies to minimize waveform distortions and enhance system reliability.

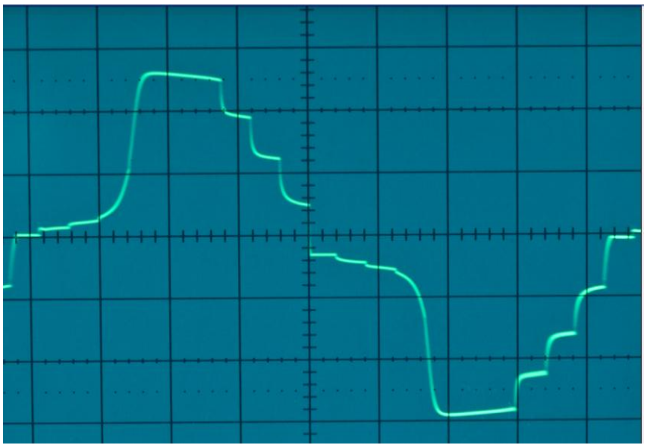

Fig. 6. Combined effect of inductance and resistance

The output waveform under combined inductance–resistance load is shown in Fig. 6. The waveform exhibits significant distortions, characterized by elongated transition phases and diminished step shape definition. These distortions arise as the converter processes both reactive inductance and resistive damping effects simultaneously, making it difficult to maintain an ideal sinusoidal approximation.

These results emphasize the need for adaptive control algorithms that can dynamically adjust to changing load conditions and compensate for complex power patterns. The power loss calculation was conducted with the converter operating at an output power of 2.5 kW. Under normal load conditions, the converter maintained a stepped voltage waveform, with minimal distortion. Measured power losses remained insignificant during testing.

The converter efficiency η is determined using the following formula:

$$\eta = \frac{P_{out} - P_{loss}}{P_{out}} = \frac{2500 - 45.33}{2500} \approx 98\%$$

where $P_{out} = 2.5\ kW$ and $P_{loss} = 45.33\ W$. The calculated efficiency is 98%.

The thermal characteristics of the converter were analyzed by measuring power consumption across both active and passive components. Table 1 provides a summary of active power losses for each examined component type.

The efficiency of the converter was determined using the standard relation between input and output power. Overall, the multi-stage single-phase converter demonstrated the ability to generate a stable stepped sinusoidal output, delivering 220 V at 50 Hz. The design prioritizes high efficiency, compact dimensions, and minimal harmonic distortion, making it well-suited for photovoltaic energy conversion systems.

Table 1. Active power dissipation of circuit elements

No.	Component	Active Power Dissipation (W)	Quantity	Total Power (W)
1	PIC16F877A Microcontroller	0.5	1	0.5
2	Optocouplers AOT101AC	0.1	10	1.0
3	SPROIL 5-15 Converter	0.1	3	0.3
4	Transistors K815Г KT861	0.05	30	1.5
5	Diode Bridges	0.02	4	0.08
6	IGBT-G4PC30F Transistors	20	2	40
7	Fixed Resistors	0.01	75	0.75
8	Fast Diodes 40EPF12	0.02	10	0.2

3. Conclusions

Experimental investigations confirm that the four-stage single-phase converter demonstrates high operational efficiency and reliability across various load configurations. The stepped sinusoidal output voltage enables improved power delivery, closely approximating an ideal waveform. A programmable microcontroller ensures precise sequence control, optimizing waveform quality and fault protection against short circuits and overvoltage conditions.

Efficient energy conversion and thermal stability were achieved, reaching 98% efficiency. By minimizing harmonic distortion, the converter eliminates the need for bulky filters, contributing to size and weight reduction. The converter was shown to support various electrical loads, including resistive, inductive, and capacitive elements, reinforcing its real-world applicability.

Future research should be directed towards the development of advanced control algorithms to improve dynamic response to sudden load variations. Additionally, further material innovations could enhance thermal reliability and long-term durability.

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