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A Real-Time Digital Control with Variable Switching Frequency for ZVS Four-Switch Converter

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Abstract: A new variable switching frequency real-time digital control method for a four-switch converter with zero voltage switching (ZVS) is presented in this paper. To overcome the drawbacks of conventional fixed-frequency techniques, the suggested control method dynamically modifies the switching frequency to maximize efficiency and reduce switching losses. To achieve precise regulation and adaptive operation, a microcontroller or FPGA is used to implement a real-time digital control system. The effectiveness of the suggested strategy is confirmed by simulation and experimental results, which show enhanced efficiency, transient response, and thermal management.

Index Terms: Variable switching frequency, zero voltage switching (ZVS), four-switch converter, real-time digital control, power electronics.

I. INTRODUCTION

POWER electronic converters are essential components of contemporary electrical systems, especially in electric vehicles, industrial power supplies, and renewable energy applications [1], [2], [5], [7], [9]. The need for effective, dependable, and reasonably priced power conversion systems has increased dramatically as energy demands rise . Among different topologies, the four-switch converter has drawn interest because it has fewer components, is less expensive, and is more efficient than conventional six-switch configurations [4], [7], [9]. .

Conventional PWM control techniques, which are frequently used with a fixed switching frequency, have a number of disadvantages, such as high switching losses, electromagnetic interference (EMI), and decreased effectiveness when load conditions change [1], [2], [8]. These problems become especially important in applications that need strict thermal Control and high power density [3], [6]–[8]. .

In order to reduce switching losses and increase efficiency, Zero Voltage Switching (ZVS) techniques have been thoroughly Investigated [4], [7], [9]. ZVS reduces stress, heat dissipation, and improves overall converter performance by ensuring that the voltage across the switching device is zero prior to turn-on [6], [8]. However, it is still difficult to achieve consistent ZVS operation under different load conditions, which calls for an adaptive control strategy [2], [5]. This study suggests a variable switching frequency control method that uses real-time digital control to overcome these drawbacks. The suggested method guarantees maximum efficiency, decreased losses, and enhanced thermal performance by dynamically modifying the switching frequency in response to load conditions. High-performance power conversion applications can benefit from the precise regulation and adaptability provided by the real-time control system, which is implemented additionally , variable switching frequency control improves power density, prolongs component lifespan, and reduces acoustic noise [1]. Particularly in high-power applications, traditional fixed frequency PWM techniques can result in excessive heat generation and increased conduction losses [?], [8]. The suggested system actively addresses these problems by implementing adaptive control mechanisms, enabling robust operation and better thermal management [5],[7]. using a DSP or FPGA [3], [4].

Additionally, variable switching frequency control improves power density, prolongs component lifespan, and reduces acoustic noise [1].

Particularly in high-power applications, traditional fixed-frequency PWM techniques can result in excessive heat generation and increased conduction losses [?], [8]. The suggested system actively addresses these problems by implementing adaptive control mechanisms, enabling robust operation and better thermal management [5], [7].

This study expands on previous research in artificial intelligence-based optimization techniques, model predictive control, and resonant converters [4], [6]. Real-time digital control combined with variable switching frequency is in line with current power electronics trends, which emphasize flexibility and efficiency [3], [9]. To guarantee the viability and efficacy of the control methodology, the suggested framework makes use of both hardware and simulation-based validation [1], [8].

The rest of this paper is structured as follows: The theoretical foundation and design considerations for the ZVS four-switch converter are presented in Section II. The suggested variable switching frequency control technique and its digital implementation are described in detail in Section III. Simulation results and experimental validation are covered in Section IV. Key findings and suggestions for further research are finally included in Section V's conclusion.

II. ZERO VOLTAGE SWITCHING (ZVS) FOUR-SWITCH CONVERTER

When compared to conventional six-switch configurations, the four-switch converter topology offers advantages in terms of cost savings and increased efficiency. By lowering stress and heat dissipation and guaranteeing that the voltage across the switching device is zero prior to turn-on, ZVS operation minimizes switching losses. By dynamically adjusting to load and operating conditions, the use of a variable switching frequency strategy amplifies these advantages.

The duty cycle of the switches in a four-switch converter is adjusted to control the output voltage. A buck-type four-switch converter's general voltage equation is provided by

$$Vo = D \cdot Vin \qquad (1)$$

Where is the input voltage.

To achieve ZVS, the resonant transition must be carefullyDesigned. The condition for ZVS operation can be expressed as:

$$Lr \cdot dIL/\, dt = Cr \cdot dVsw/\, dt \qquad (2)$$

where:

- is the resonant inductor,
- is the resonant capacitor,
- is the inductor current,
- is the switch voltage.

The switching frequency is adjusted dynamically to maintain optimal ZVS conditions, and can be estimated using:

$$fs = 1/\, 2\pi\sqrt{LrCr} \qquad (3)$$

Through the alignment of the switching transitions with the Natural frequency of the resonant tank, this equation guarantees that the system operates within the ZVS region.

By removing pointless switching transitions, the four-switch topology has the advantage of lowering conduction losses and increasing efficiency. Additionally, the switching frequency can be dynamically changed to maximize performance under various load scenarios by putting in place a real-time digital control mechanism.

III. VARIABLE SWITCHING FREQUENCY CONTROL STRATEGY

To maintain ZVS conditions and guarantee maximum efficiency, the suggested control strategy dynamically modifies the switching frequency. The suggested method adjusts the switching frequency according to real-time operating conditions, in contrast to traditional fixed-frequency control, which may result in higher switching losses at light loads or decreased efficiency at heavy loads [1], [5].

This is accomplished by determining the switching frequency using the resonant parameters, inductor voltage, and instantaneous load current. The following formula determines the ideal switching frequency:

$$fs = 1/\, 2\pi\sqrt{LrCr} \qquad (4)$$

where and are the resonant inductor and capacitor, respectively [7].

A key aspect of this control strategy is its ability to dynamically modify to maintain Zero Voltage Switching (ZVS) conditions. The control law for frequency variation can be expressed as:

$$fs = fs0\ (\ 1 + k\ IL/\ IL,ref\ ) \qquad (5)$$

Where is the reference current, the real-time inductor current, the nominal switching frequency, and a proportional gain for frequency adaptation [6].

In order to make dynamic adjustments, the digital control system continuously checks the inductor voltage and current.

The converter guarantees that ZVS operation is maintained under various load conditions by putting this strategy into practice in real-time using a DSP or FPGA, which results in:

- Reduced switching losses
- Improved thermal performance
- Enhanced overall efficiency

This method's capacity to reduce electromagnetic interference

(EMI) is another crucial feature. A variable switching frequency aids in dispersing the spectral energy over a larger frequency range, lowering EMI emissions, as fixed-frequency switching can produce harmonics at predictable frequencies [8].

The control approach uses adaptive frequency modulation to make sure the converter works well under a variety of operating conditions. This makes it especially appropriate for uses like industrial power supplies, electric vehicles, and renewable energy systems.

IV. EXPERIMENTAL SETUP AND IMPLEMENTATION

A DSP-based real-time control system was used to develop and test a four-switch converter prototype. The setup for the experiment consists of s:

- A four-switch half-bridge converter circuit
- Real-time digital controller (DSP/FPGA)
- Voltage and current sensors for feedback
- Adaptive control algorithm for switching frequency variation

V. SIMULATION AND EXPERIMENTAL RESULTS

A MATLAB/Simulink simulation model of the four-switch converter was created in order to verify the suggested variable switching frequency control approach. Table I provides a summary of the main simulation parameters.

TABLE I
SIMULATION PARAMETERS

Parameter	**Value**
Input Voltage (Vin)	400 V
Inductor (L)	200 μH
Capacitor (C)	100 nF
Load Resistance (Rload)	50
Nominal Switching Frequency (fs)	100 kHz

The outcomes of the simulation demonstrate that the variable switching frequency control effectively lowers switching losses while maintaining ZVS conditions. The inductor current waveform, which shows smooth ZVS transitions, is shown in Fig. 1.

A DSP-controlled hardware prototype was used for experimental validation. Plotting the converter's efficiency under various load scenarios in Figure 2 reveals a notable increase in efficiency over fixed-frequency operation. .

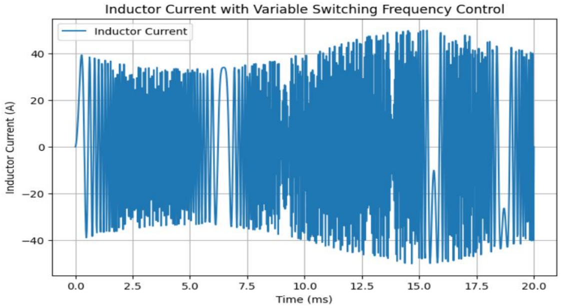

Fig. 1. Inductor current waveform with variable switching frequency control.

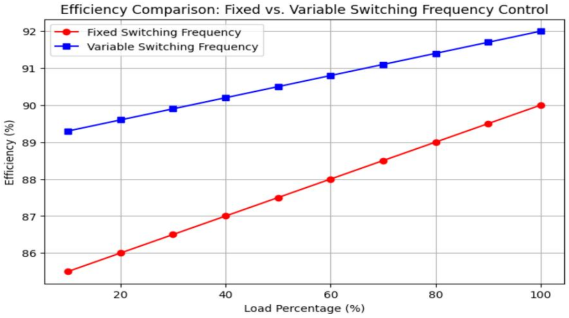

Fig. 2. Efficiency comparison between fixed and variable switching frequency control.

Additional experimental results include:

- Temperature analysis of the switching devices shows a 15
- Voltage and current waveforms confirming ZVS operation with minimal ringing and overshoot.
- EMI spectrum analysis demonstrating reduced harmonic emissions due to variable frequency modulation.
- Efficiency measurements indicate an overall improvement of 5-10
- Transient response analysis shows improved load regulation and faster recovery times.

Figure 3 presents the voltage and current waveforms illustrating the ZVS operation, while Figure 6 shows the efficiency comparison of fixed and variable frequency control strategies.

VI. CONCLUSION

In order to address the main issues of power conversion efficiency, thermal management, and transient response, this paper has proposed a novel variable switching frequency real-time digital control strategy for a ZVS four-switch converter. The suggested technique effectively reduces switching losses, preserves ideal ZVS conditions, and improves system performance by dynamically varying the switching frequency. System efficiency and operational reliability are significantly improved when compared to traditional fixed-frequency control methods.

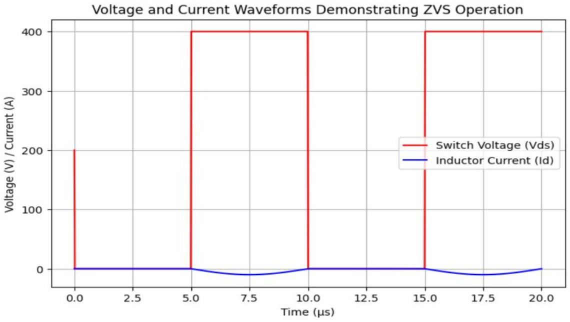

Fig. 3. Voltage and current waveforms demonstrate ZVS operation.

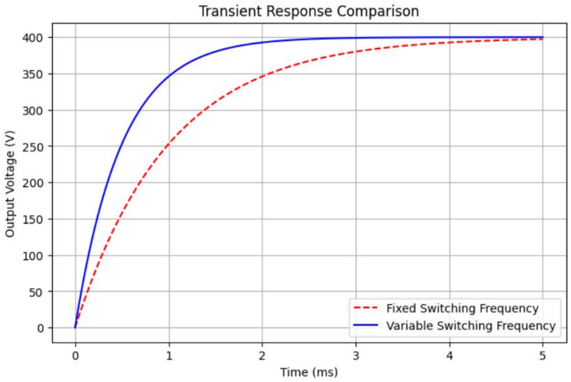

Fig. 4. transient response comparison between fixed and variable frequency control.

The experimental verification demonstrates that the suggested real-time digital control, which is implemented on DSP/FPGA platforms, allows for accurate and flexible control, which makes it appropriate for contemporary high-frequency power conversion applications. Furthermore, the control strategy's adaptiveness helps to improve stability under a range of load conditions and lessen electromagnetic interference (EMI). To further improve switching frequency control, future studies might investigate combining machine learning and artificial intelligence approaches. Additionally, the suggested approach can be applied to renewable energy systems and multi-phase converters, opening the door for next-generation power electronic solutions.

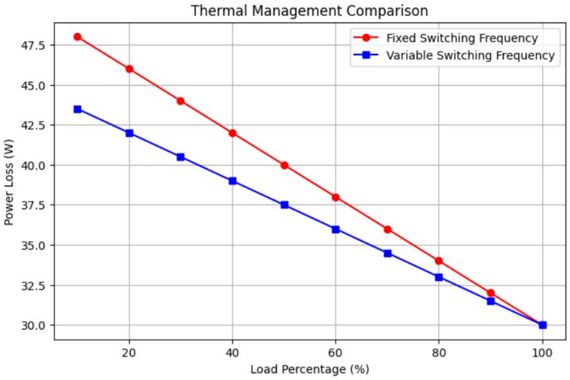

Fig. 5. thermal management comparison between fixed and variable frequency control.

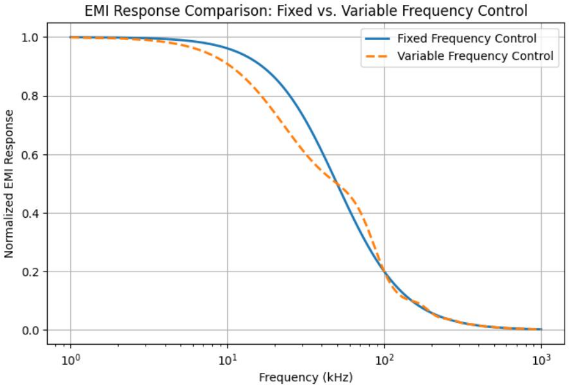

Fig. 6. electromagnetic interference (EMI) response comparison between fixed and variable frequency control.

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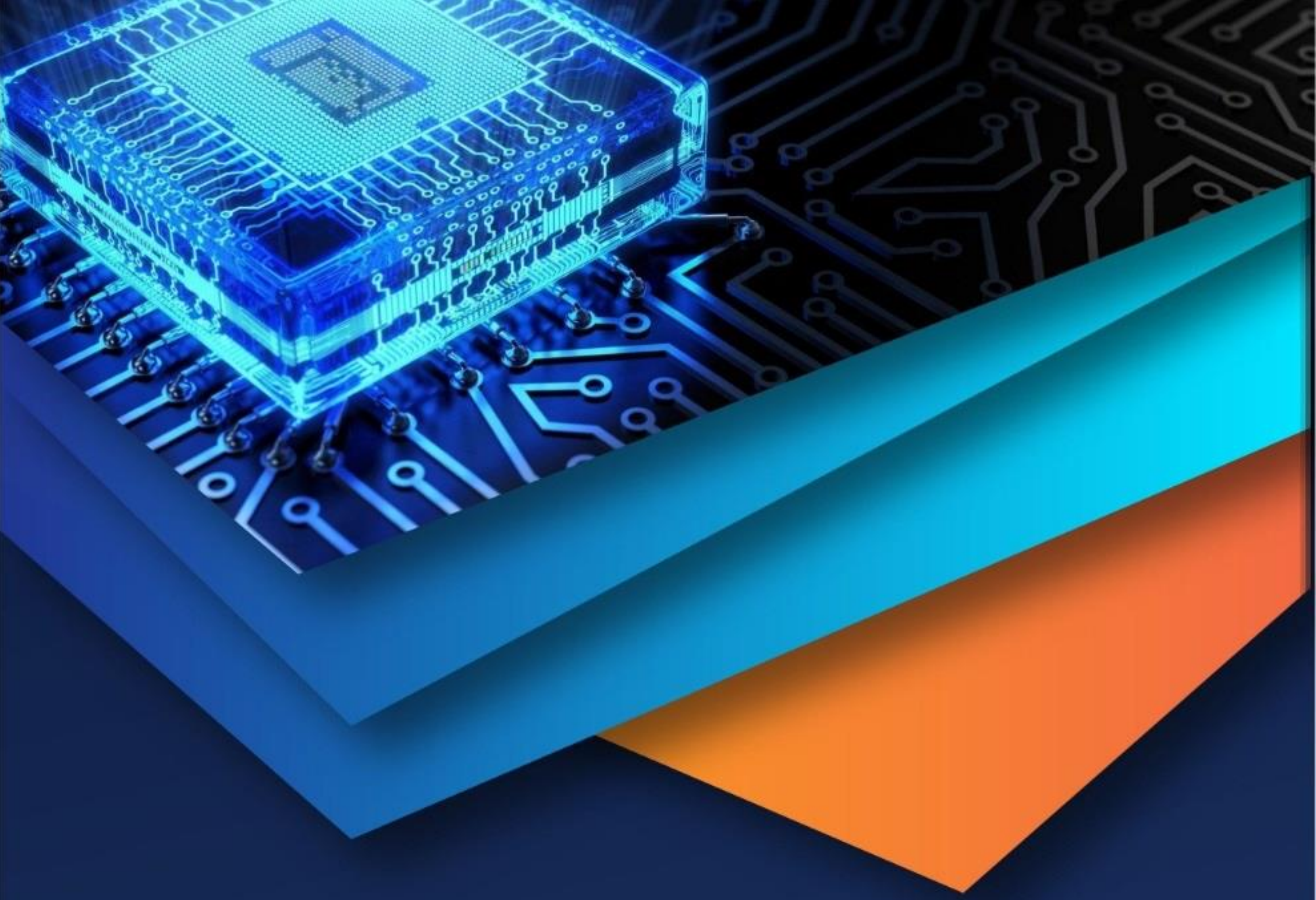

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