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Implementing Pseudo-Random Control in Boost Converter: An Effective Approach for Mitigating Conducted Electromagnetic Emissions

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ABSTRACT

Currently, pulse width modulation (PWM) is a prevalent technique in the field of DC-DC converter control. Its primary objectives encompass maintaining the regulation of the converter's output voltage and improving the load's performance by mitigating the adverse effects caused by harmonic distortions. Unfortunately, the utilization of PWM is associated with significant levels of residual harmonics, characterized by notable amplitudes and frequencies, which have the potential to induce mechanical vibrations, acoustic disturbances, and electromagnetic interference (EMI).To address this challenge, a method known as pseudo-random modulation (PRM) has been developed. In comparison to traditional PWM, PRM offers ease of implementation and high efficacy in EMI mitigation. PRM achieves this by distributing harmonic power across a broader frequency range, thereby reducing the prominence of high-amplitude harmonics at specific frequencies. Within the context of Spread Spectrum Modulation (SSM), this study extensively explores diverse converter topologies and proposes an innovative hardware implementation using the cost-effective Atmega328p microcontroller. Furthermore, the study scrutinizes the consequences of implementing this randomized control strategy to reduce electromagnetic emissions from a Boost converter, a well-recognized source of significant interference in its operational environment. Ultimately, the aim is to evaluate the effectiveness of these applied methodologies in achieving the maximum dispersion of the power spectrum, thereby enhancing overall electromagnetic compatibility.

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1. INTRODUCTION

Over the past decade, semiconductor-based power converters have gained significant popularity in a wide range of applications, including electric vehicles, renewable energy systems, industrial settings, power supply solutions, and telecommunications [1,2]. They play a crucial role in efficiently managing electrical energy in various fields. However, they also bring about significant electromagnetic compatibility (EMC) challenges due to their frequent high-frequency switching and rapid semiconductor transitions. These factors lead to substantial current and voltage gradients ($\frac{di}{dt}, \frac{dv}{dt}$), resulting in significant electromagnetic disturbances [3,4].These disturbances occur in both conducted and radiated modes, spanning a frequency range of 150 kHz to 1 GHz.

In the context of electric vehicles (EVs), ensuring efficient electronic system operation and minimizing electromagnetic interference (EMI) through electromagnetic compatibility (EMC) filters [5-7] is crucial. However, the limited space available in certain EV applications poses size constraints for these filters. To address this challenge, innovative approaches are needed to effectively mitigate conducted electromagnetic disturbances [8-10] within these size limitations. This research aims to introduce a novel technique that utilizes spectral spreading to reduce or eliminate electromagnetic noise levels. This involves distributing harmonic energy across a wide frequency spectrum, as supported by references [11-13]. Pseudo-random modulation is the chosen method, involving the randomization of three key parameters: duty cycle, period, and delay time, known as random pulse width modulation (RPWM), random carrier frequency modulation (RCFM), and random pulse position modulation (RPPM) [14,15].

To enable the practical adoption of these various pseudo-random modulation techniques, this paper introduces a pragmatic solution centered on the Arduino Uno microcontroller platform. This digital implementation approach was conceptualized in response to the constraints and shortcomings inherent in analog methodologies, encompassing diminished reliability, susceptibility to environmental variables, and the impact of aging phenomena.

This article provides an overview of the three commonly used pseudo-random spread-spectrum modulation techniques and explains their implementation using the Atmega328p microcontroller [16,17]. The focus then shifts to the spectral analysis of conducted EMI noise generated by a boost converter designed for EV applications, with the ultimate goal of optimizing compliance with EMC requirements [18].

2. PSEUDO-RANDOM MODULATION FRAMEWORK: FUNDAMENTALS AND APPLICATIONS

Pseudo-random modulation constitutes a fundamental technique within the realms of communication and signal processing. This method employs linear feedback shift registers (LFSRs) to generate a pseudo-random sequence denoted as PRBS (Pseudo-Random Bit Sequence). This approach capitalizes on the inherent characteristics of LFSRs, which are electronic circuits with the unique capability to generate maximal-length pseudo-random bit sequences without repetition. This distinctive feature imparts the generated bit sequence (P) with highly desirable pseudo-random properties, rendering it well-suited for a diverse array of modulation applications. The PRBS sequence is then used to control a 2/1 multiplexer. This multiplexer designed to handle two distinct triangle input signals (c and $\overline{c}$) that are 180° out of phase, and it routed them to the carrier output (R). Following that, the reference signal is compared to the random carrier (R) in order to generate the switch control signal. This comparison procedure adheres to a rigorously defined methodology, as visually elucidated in Figure 1.

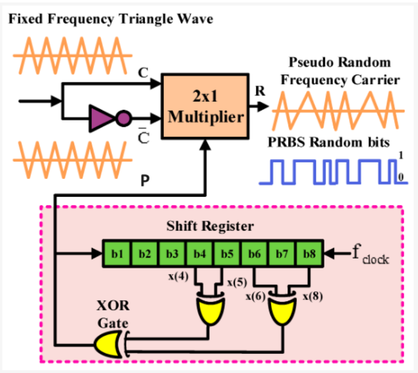

Figure 1. Conventional pseudorandom binary sequence RPWM.

Certainly, the PWM signal finds widespread application in a diverse array of contexts, including power converters, motor control systems, and LED lighting, owing to its demonstrated effectiveness and versatility. In figure 2, we illustrate a conventional PWM control configuration, characterized by three key parameters: modulation period, duty cycle, and delay time. In the context of pseudo-random modulation, these parameters undergo randomization to yield variations in the duty cycle $\mathbf{d_k}$, switching time $\mathbf{T_k}$, and pulse position $\boldsymbol{\varepsilon_k}$. Consequently, this deliberate randomization process consistently disperses the harmonic spectra in the output, thereby effecting a reduction in undesired frequency peaks, as expounded upon in reference [19].

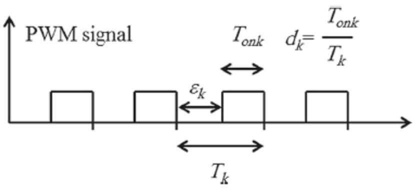

Figure 2. Pulsed control signal.

A multitude of modulation types can be achieved through this method:
- The RPWM introduces the capability to adjust the duty cycle, facilitating a more uniform distribution of harmonic frequencies.
- The RCFM involves modifying the switching period, providing increased flexibility in distributing harmonics across frequencies.
- The RPPM allows for the manipulation of pulse position within the cycle, thereby influencing the distribution of harmonic spectra.

The following table summarizes the different PWM configurations that are available.

Table 1. Configurations of pseudo-random modulation.

Configuration	T_k	d_k	δ_k
DPWM	Constant	Constant	Constant
RPWM	Constant	Random	Constant
RPPM	Constant	Constant	Random
RCFM	Random	Constant	Constant

3. METHOD PROPOSED

3.1. Implementing Pseudo-Random Modulation with Arduino Uno: Real-world Applications and Benefits

Random modulation has evolved into a formidable methodology within the domain of power electronics system management. Its application has notably extended to address the mitigation of acoustic noise emanating from electrical machines, with its initial inception focused on reducing noise in power electronic components. The fundamental objective of this approach centers on the attainment of a balanced frequency distribution across the spectrum. This method's core objective is to attain a balanced frequency distribution across the spectrum. It achieves noise reduction, lowers noise amplitude, and enhances electromagnetic compatibility (EMC), as supported by existing research [20,21].

Extensive research has been conducted on the digital application of the pseudo-random modulation technique. Within this field, there is significant utilization of programmable circuits known as FPGAs (Field-Programmable Gate Arrays). These FPGAs commonly incorporate a PWM modulator and a pseudo-random sequence generator, which are essential components in this context. Their limited use is a result of their high cost.

To address the issue at hand, a recommended solution is proposed, centered on the Arduino Uno platform. This method, known for its dependability and user-friendly characteristics, employs an innovative and cost-effective approach. The practical implementation involves utilizing an interrupt function, leveraging Timer1 within the Atmega328p microcontroller integrated into the Arduino board. The primary aim is to generate a pseudo-random Pulse Width Modulation (PWM) signal. Notably, two operational modes are available for this purpose: the "Fast PWM mode" and the "Phase-corrected PWM mode." The former offers a higher PWM frequency but comes with a lower resolution compared to the latter.

In the Fast PWM mode with the TCNT1 timer configuration, the timer starts at 0 (BOTTOM) and counts up to ICR1 (TOP), where it resets to 0 (overflow). Simultaneously, it continuously compares its value to OCR1x (where "x" denotes A or B). When a match occurs, the waveform generation block generates a PWM signal on pin OC1x. The PWM signal's frequency can be calculated using a specific formula:

$$\boldsymbol{F_{out}} = \frac{\boldsymbol{F_{clk}}}{\mathbf{N} * (\mathbf{1} + \mathbf{ICR1})} \quad (1)$$

Where F_{clk} represents the Arduino Uno's 16 MHz clock frequency and N is the value of the prescaler (Fig. 3).

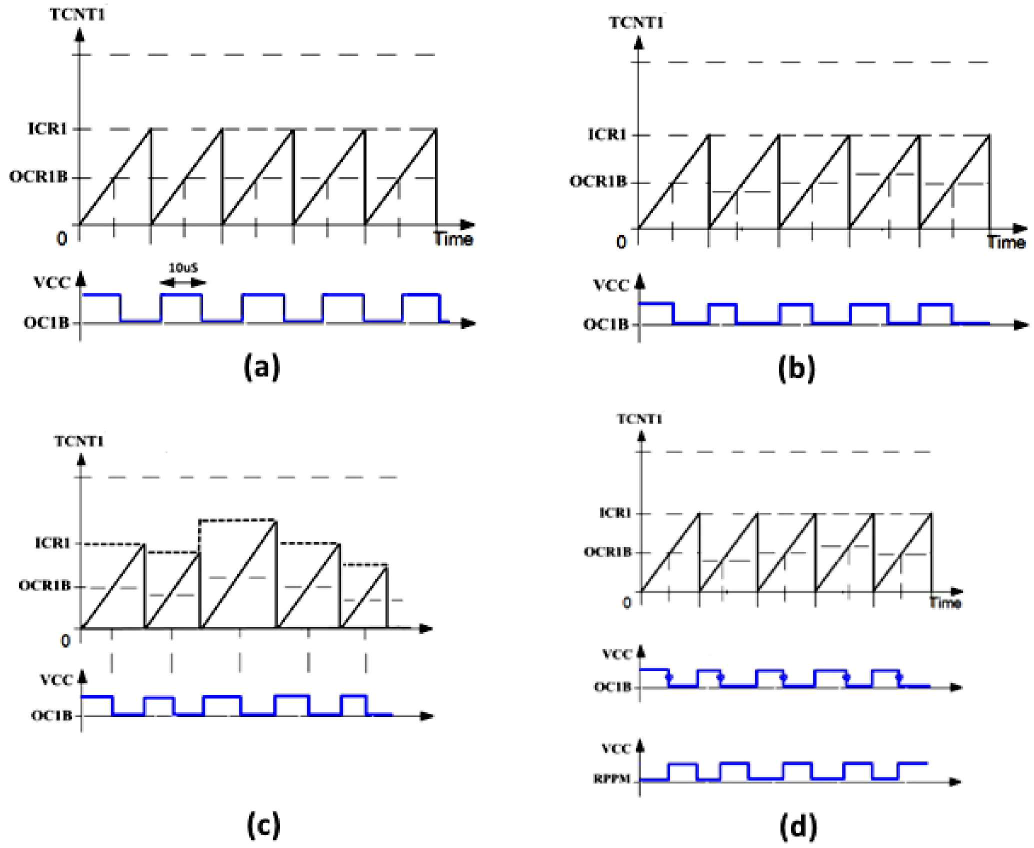

Figure 3. Time Diagrams for Different Modulation Techniques: (a) DPWM, (b) RPWM, (c) RCFM, and (d) RPPM.

Our strategy for implementing pseudo-random modulation is directed at creating a versatile set of control signals tailored to meet the needs of our specific application. The primary objective is to create an RPWM signal for the Boost converter, with a duty cycle ranging from 45% to 55% and a switching frequency of 100 kHz (Fig. 3.b). Furthermore, we explore the feasibility of generating an RCFM signal with a variable switching frequency ranging from 90 to 110 kHz. This signal maintains an average frequency of 100 kHz and a constant duty cycle of 50% (Fig. 3.c). Lastly, we employ the NE555 circuit and the RPWM signal as input to create an RPPM signal, allowing for adjustable pulse positions from 0 to 5 seconds (Fig. 3.d). In all of these pseudo-random methods, achieving the desired signal parameters involves the utilization of the "random" function. This function generates a pseudo-random integer within a predefined range, which can be fine-tuned as needed to attain the desired degree of variation.

In our approach to deterministic pulse-width modulation (DPWM), we maintain a control signal with a stable 100 kHz frequency and an unchanging duty cycle of 0.5, as demonstrated in Figure 4.To create the Randomized Pulse-Width Modulation (RPWM) signal, we introduce randomness by utilizing the "random" function to adjust the duty cycle parameter ($\mathbf{d_k}$) through the OCR1B register. We ensure an average $\mathbf{d_k}$ value of 0.5 by selecting a $\mathbf{d_k}$ range between 0.45 and 0.55. When executing the program in the Arduino IDE, the RPWM signal is generated by timer1 and transmitted to the output pin 10 (OC1B) of the Uno module (as shown in Figure 5).Similarly, the RCFM signal is generated by introducing random variations to the period parameter ($\mathbf{T_k}$) around an average value. This is achieved by adjusting the value of the ICR1 register using the "random" function. Throughout the process, we maintain a consistent duty cycle ($\mathbf{d_k}$) of 0.5. In our specific configuration, we have chosen a $\mathbf{T_k}$ interval ranging from 8.34 to 12.5 seconds, as depicted in Figure 6. In contrast, the RPPM signal is obtained by building upon the RPWM method. This approach involves utilizing the random fluctuations of the falling edge to control a monostable circuit based on the NE555. The outcome of this process is the generation of a 5-second output pulse, as illustrated in Figure 7.

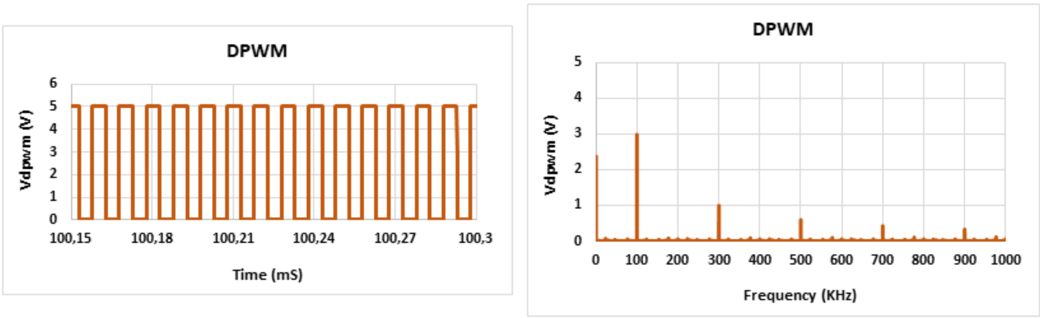

Figure 4. DPWM control signal: spectral analysis and signal characteristics.

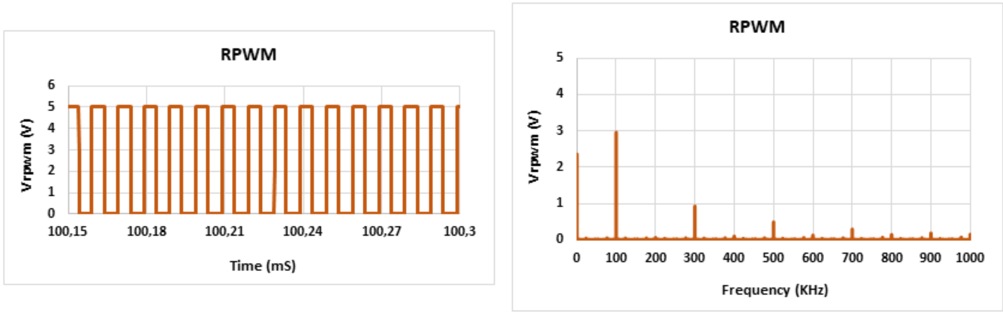

Figure 5. RPWM control signal: spectral analysis and signal characteristics.

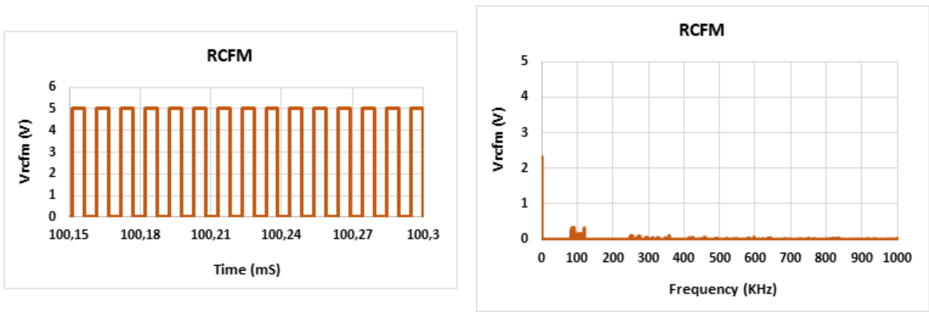

Figure 6. RCFM control signal: spectral analysis and signal characteristics.

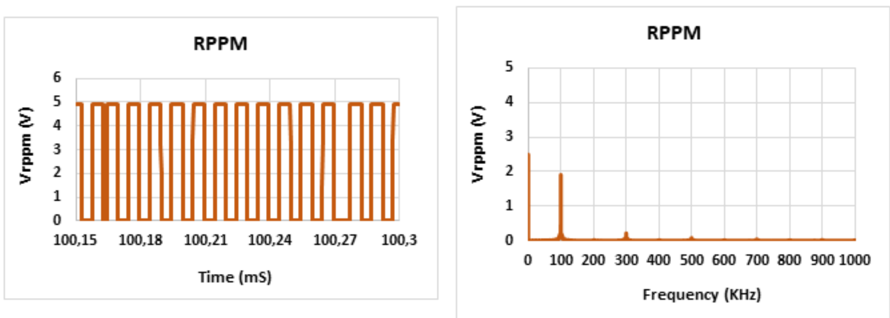

Figure 7. RPPM control signal: spectral analysis and signal characteristics.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1. Practical Pseudo-Random Command creation using the Arduino Uno

In this section, the digital implementation of the pseudo-random modulation technique was demonstrated using the ATMEGA328P microcontroller. The choice of this implementation was driven by its capacity to offer a highly reliable and cost-effective solution. Figure 8 provides a practical illustration of these PWM signals by utilizing the ATmega328P microcontroller's Timer 1. In the real-world scenario, pseudo-random control structures are generated by introducing random attributes into the PWM control signal, such as the duty cycle, period, and delay time. Figure 9 showcases the diverse configurations of the pseudo-random modulation strategy for reference.

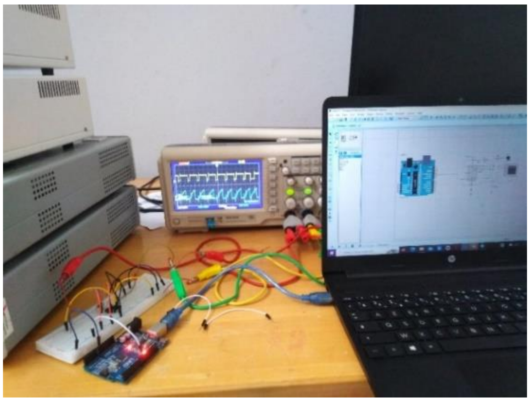

Figure 8. The real implementation of the pseudo-random modulation based on the Arduino Uno module.

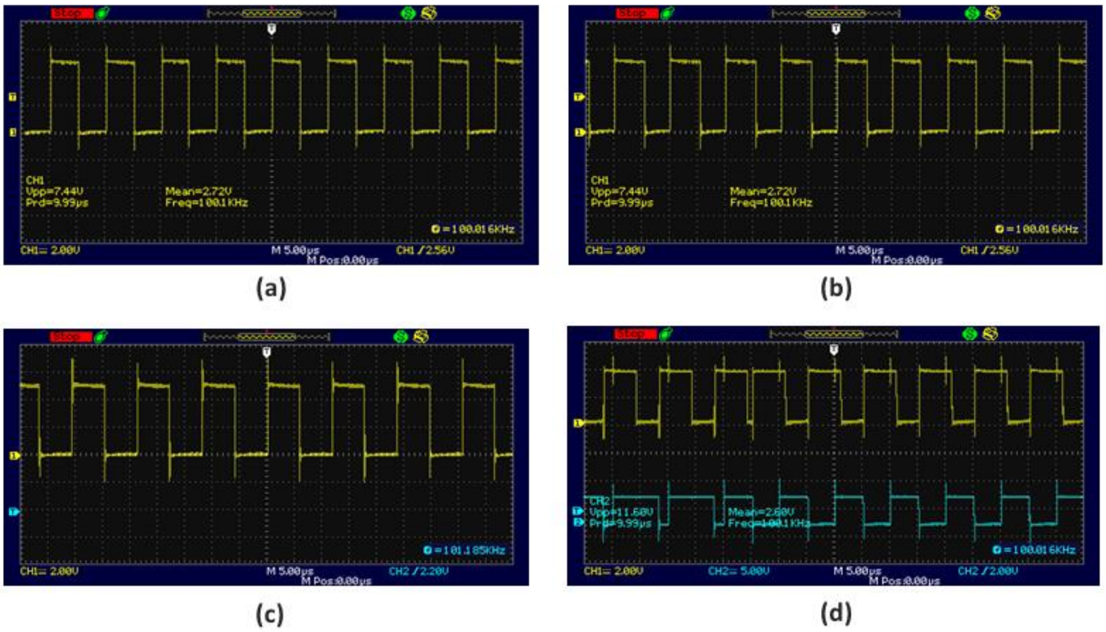

Figure 9. The actual implementation of the different approaches (a) DPWM technique, (b) RPWM technique, (c) RCFM technique, and (d) RPPM technique.

On the basis of the Siglent SDS1202X-E digital oscilloscope, the various PWM command signals (deterministic or random) generated by the Arduino Uno card could be seen. Figure 9.a illustrates a conventional PWM signal, whereas figures 9.b, 9.c, and 9.d show respectively random PWM signals with randomized duty cycle, carrier time, and pulse position. Figure 9.d shows that we have used an RPWM signal (seen in blue) to regulate the NE555 circuit in order to obtain the appropriate RPPM control signal.

4.2. Comparative Analysis of HSF: Exploring Harmonic Spread Factors in Modulation Techniques

The harmonic spreading factor (HSF) is an index used to evaluate the spectral spreading effect of a random pulse-width modulation (PWM) scheme [22,23]. This factor has practical applications in a variety of fields where pulse-width modulation (PWM) is used, such as power electronics, telecommunications, and control systems. It measures the random PWM scheme's ability to efficiently distribute harmonic energy by analyzing the dispersion of a waveform's harmonics in the frequency domain. The mathematical formula for HSF is as follows: HSF=$\sqrt{\frac{1}{N}\sum_{j=0}^{j=N}(H_j - H_0)^2}$ with H_0=$\sum_{k=1}^{k=N} H_k$ is the average value of all harmonics.

Engineers and researchers can use the HSF to compare different random PWM schemes and evaluate their efficiency in terms of harmonic energy distribution. In general, a lower HSF indicates better dispersion and a more uniform distribution of harmonic energy. This enables informed decisions to be made when designing or optimizing a PWM system.

We then used the harmonic factor (HSF) to compare the various PWM techniques that had already been predicted. The following graph depicts the outcomes:

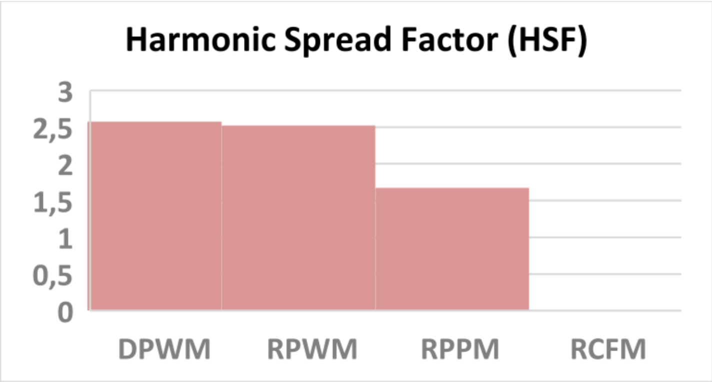

Figure 10. Analyzing the Harmonic Spread Factors for Modulation Techniques.

It appears clear that the RCFM technique achieves harmonic energy distribution over a wider range of frequencies. The RCFM has a relatively low HSF in comparison to other techniques, indicating a good harmonic dispersion.

4.3. Measuring Conducted Electromagnetic Interference in a Boost Converter: Analysis and Solutions

Nowadays, power converters are essential in the field of electric vehicles (EVs).Indeed, the purpose of the boost converter in electric vehicles is to raise the voltage of the primary battery, enabling it to supply power to the propulsion system and high-voltage accessories. Furthermore, it facilitates the recharging of the auxiliary battery and optimizes the efficiency of kinetic energy recuperation during braking.

In our application system, we have a step-up chopper under consideration. It is placed between the load R_{load} and the supply bus, which is represented by a DC voltage source V_{dc} (see Figure 11). To build this converter, we used two main components: a 15ETH06 freewheeling diode and an IRFP460 MOSFET transistor. This chopper was specifically designed to operate at a very high frequency and with medium power.

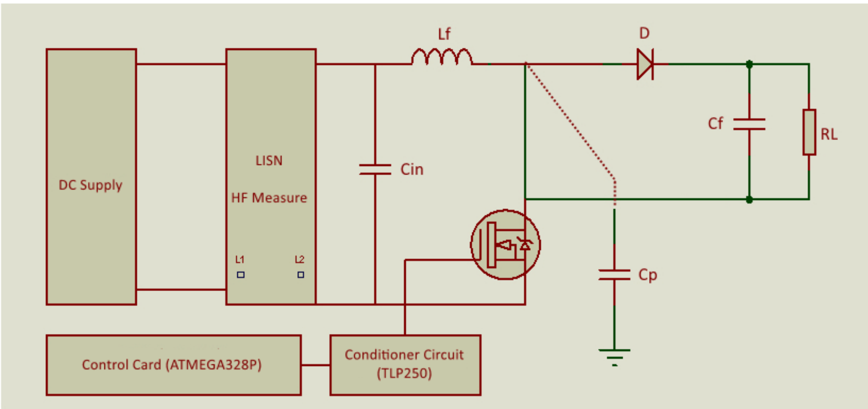

Figure 11. The Conducted Emissions Testing Framework for Boost Converter.

The boost converter is a significant contributor to conducted-mode electromagnetic disturbances. To assess these interferences, a Line Impedance Stabilization Network (LISN) is typically employed (refer to Figure 12.a). The LISN serves as a filter between the tested boost converter and the power supply network. The primary purpose of this system is to effectively isolate the power supply from the equipment being tested, which can produce disturbances in both common-mode and differential-mode [24]. In relation to the disturbances produced by the tested equipment, it maintains a fixed terminating impedance of 50 ohms (Z_{lisn}= 50) (Figure 12.b).

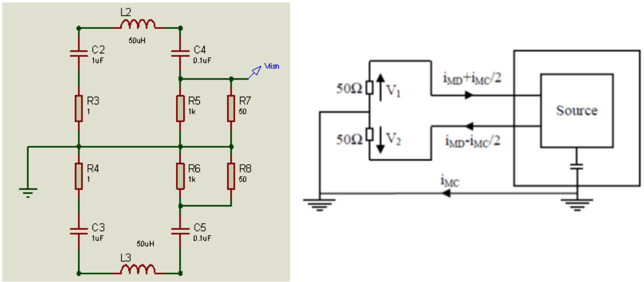

Figure 12. Conducted electromagnetic emissions measurement through the (a) LISN devise for both (b) common and differential modes.

The Isis Proteus software was used to simulate the model depicted in Figure 11, employing the parameters outlined in Table 2. The primary objective of this simulation was to analyze the spectral composition of the voltage V_{lisn}, which signifies electromagnetic disruptions in both differential and common mode [25]. The central aim of the investigation was to diminish the frequency range of this voltage (power spectral density) within the 150 kHz to 30 MHz interval.

Table 2. Simulation parameters

Parameter	Value
V_{in} input DC voltage	24V
C_{in} capacitor	2.2mF, 40nH, 25mΩ
L inductance	150uH, 0.5Ω
C capacitor	10uF
R_{load}	12Ω
C_p parasitic capacitor	130pF, 520nH, 0.3mΩ

In this discussion, we will now explore the significance of the techniques under consideration (DPWM, RPWM, RCFM, and RPPM) and how effectively they can mitigate the conducted electromagnetic disturbances produced by the static converter. The simulation results, which provide valuable insights, will be presented below.

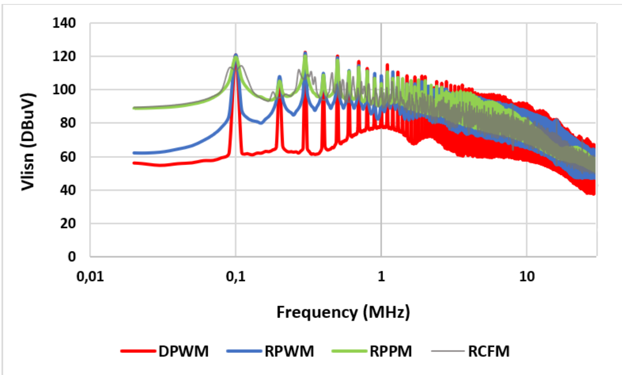

Figure 13. Analyzing the Spectral Content of V_{lisn} in Different Predictive Methods for Conducted Emissions.

As illustrated in Figure 13, the voltage measured across the equivalent resistor V_{lisn} exhibits rapid amplitude variations. The presence of discrete power harmonics, which cover a wide frequency range and exceed the electromagnetic compatibility (EMC) regulatory limits for the DPWM approach, is revealed by spectral analysis of the conducted disturbances. As a result, it is critical to implement disturbance mitigation devices for this type of converter in order to ensure the proper operation of surrounding systems. The use of pseudo-random modulation proves to be a practical and effective approach in this context. Following a thorough examination of the results obtained with the various techniques, it is clear that the RCFM approach provides a more balanced distribution of the power spectrum across a wider frequency range than other methods. Its main feature is its ability to effectively eliminate harmonic peaks, which translates into a

significant advantage in terms of electromagnetic compatibility, with a gain of approximately 18 dBuV over the DPWM approach.

5. CONCLUSION

To summarize, static DC-DC converters pose risks to both their control circuits and the environment due to electromagnetic compatibility limitations. This study proposes an efficient technique implemented digitally using the Arduino Uno, providing a reliable and cost-effective solution. The technique is primarily based on pseudo-random modulation control (RPWM, RCFM, and RPPM). The study explores the utilization of the ATmega328P microcontroller's timers to generate a PWM signal. By incorporating a random component into the PWM control signal (duty cycle, period, and delay time), various pseudorandom control topologies are achieved. The effectiveness of the pseudo-random technique lies in its ability to distribute the power spectrum of disturbances across a broad frequency range, resulting in a reduction of the amplitudes or peaks of harmonics that are generated through deterministic PWM control. The study evaluates the spectral content of electromagnetic emissions from the Boost converter and finds that the RCFM method demonstrates remarkable efficiency in spreading the spectrum, resulting in a significant reduction in power spectral density of disturbances within the frequency range of 150 kHz to 30 MHz. This leads to a notable improvement in electromagnetic compatibility (EMC).

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