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Digital pseudo-random modulation: a key to EMI reduction in EVS boost converters

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ABSTRACT

Pseudo-random position pulse modulation (RPPM) technique can be implemented either analogically using pseudo-random binary sequences (PRBS) to generate a pulse-width modulation (PWM) control signal or digitally through an Arduino Uno board. It plays a critical role in mitigating conducted electromagnetic emissions (EMI) in boost converters dedicated to electric vehicle systems (EVS) applications. The digital implementation offers a significant advantage by enabling a substantial widening of the frequency spectrum of the control signal. This expanded spectral range results in a noticeable reduction in emitted electromagnetic interference (EMI), making the digital method the preferred choice. The increased spectral bandwidth effectively mitigates EMI, which is particularly advantageous for EMI-sensitive EVS systems. In conclusion, the digital pseudo-random modulation approach, facilitated by Arduino Uno, proves to be more effective in reducing EMI in EVS boost converters. Its capability to broaden the control signal's frequency spectrum leads to a favorable reduction in emitted EMI, ultimately enhancing electromagnetic compatibility and overall system performance.

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1. INTRODUCTION

In the rapidly evolving domain of electric vehicle systems (EVS), the pursuit of cleaner and more efficient transportation has spurred innovation at an astonishing rate [1]. Boost converters have emerged as pivotal components within this transformative landscape, facilitating the efficient conversion of energy for EV propulsion systems [2], [3]. However, this progress has concurrently revealed a persistent challenge: the mitigation of conducted electromagnetic emissions (EMI). EMI, originating from the switching operations within these converters, poses a significant hurdle to achieving the desired electromagnetic compatibility (EMC) in EVS applications [4].

This paper aims to explore a novel solution for addressing the EMI predicament: the pseudo-random position pulse modulation (RPPM) technique [5]. RPPM offers a versatile approach that can be implemented either analogically using pseudo-random binary sequences (PRBS) or digitally through an Arduino Uno board [6], [7]. Its primary mission is to optimize EMC in boost converters tailored for EVS applications [8].

The proliferation of EVS necessitates not only the evolution of power electronics but also the development of a comprehensive strategy to address EMI concerns [9]. EMI has the potential to disrupt the operation of neighboring electronic systems, introducing potential safety hazards and regulatory complications. Traditional pulse-width modulation (PWM) control signals in boost converters generate EMI due to their deterministic nature, resulting in concentrated spectral emissions [10]. This paper is centered on resolving this issue by exploring the possibilities offered by the digital implementation of the RPPM technique.

The literature surrounding EMI mitigation techniques in power electronics is extensive. Previous research has explored various strategies, including filtering, shielding, and alternative modulation schemes [11]–[13]. Traditional PWM techniques, while effective to some extent, possess limitations in terms of comprehensively controlling EMI emissions, especially within the context of EVS applications. The concept of pseudo-random modulation has been previously applied in different domains, such as spread spectrum communication systems, yet its application in the context of EVS boost converters is a relatively uncharted territory [14].

This paper proposes a pioneering approach to mitigate EMI in EVS boost converters by adopting digital pseudo-random modulation through an Arduino Uno board. In stark contrast to traditional PWM methods, which generate predictable harmonic content, digital RPPM offers a unique advantage by substantially broadening the frequency spectrum of the control signal. This expansion effectively disperses the spectral emissions, resulting in a noticeable reduction in the emitted EMI [15].

The innovative facet of this research lies in the application of digital pseudo-random modulation to EVS boost converters, where it holds the potential to revolutionize EMC. By expanding the control signal's frequency spectrum, our aim is to significantly curtail EMI emissions, rendering EVS systems more EMC-compliant [16], [17]. This innovation is particularly invaluable in the context of EMI-sensitive EVS applications where stringent EMC requirements must be met.

In summary, this paper introduces a pioneering approach to enhance EMC in EVS boost converters. The utilization of digital pseudo-random modulation, facilitated by an Arduino Uno board, promises to revolutionize EMI mitigation in this critical domain [18]. Through the reduction of EMI emissions, this approach contributes to the overall improvement of electromagnetic compatibility in EVS systems, aligning with the evolving landscape of cleaner and more efficient transportation.

2. EXPLORING CONDUCTED DISTURBANCE CHARACTERISTICS IN A BOOST CONVERTER: A STUDY AND MEASUREMENT APPROACH

Boost converters are crucial in electric vehicles (EVs), elevating battery voltage to meet motor controller requirements. In our study, we investigate raising voltage from 24 V to 48 V in a standard 48 V EV using a switching configuration involving a freewheeling diode (HFA25TB60) and a high-frequency MOSFET transistor (IRFP460), as shown in Figure 1. The MOSFET is controlled by a fixed-frequency (F_s) logic signal V_{GS} with duty cycle D.

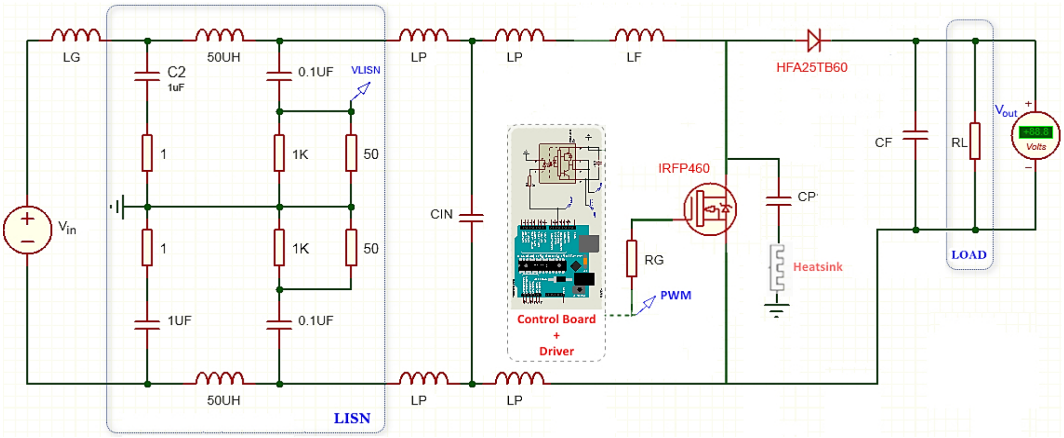


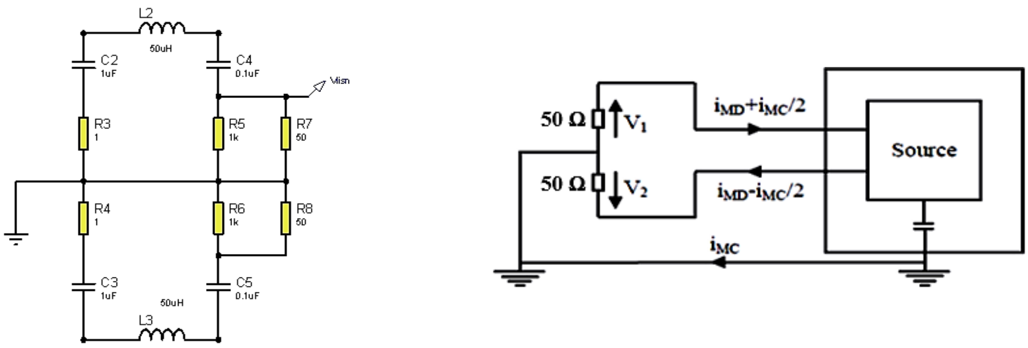
Figure 1. Schematic of the utilized boost converter structure

A PWM signal, generated by a control card, is vital for precise power regulation in diverse electrical applications. When combined with a driver like the TLP250, it is amplified and electrically isolated to effectively control the power device (MOSFET). PWM adjusts pulse duration to manage output, while the driver ensures accurate switching and safeguards the Arduino board from high power circuit voltages. This synergy achieves efficient energy management and shields sensitive components from electrical interference. The specifications for which this Boost converter is designed are outlined in the Table 1.

The impact of the boost converter on conducted-mode electromagnetic disturbances is noteworthy [19], [20]. The switching cell serves as the disruptive component that fosters current and voltage gradients, thereby contributing to EMI generation within the frequency range [150 KHz, 30 MHz]. To assess these interferences, a line impedance stabilization network (LISN) is commonly employed, as illustrated in Figure 2(a). Acting as a filter between the tested boost converter and the power supply network, the LISN effectively isolates the power supply from the equipment under test, which can generate disturbances in both common-mode and differential-mode [21], as demonstrated in Figure 2(b).

Table 1. Simulation settings

	Parameter	Normalized value	Units
1	Input DC voltage (V_{in})	24	V
2	Output voltage (V_o)	48	V
3	Inductance (L_F)	150	uH
4	Capacitance (C_F)	10	uF
5	Load resistance (R_L)	12	Ω
6	Input capacitance (C_{in})	2.2	mF
7	Parasitic capacitor (C_P)	130	pF
8	Switching frequency (F_s)	100	KHz
9	Duty cycle (D)	0.5	---



(a) (b)

Figure 2. Conducted electromagnetic emissions measurement through the (a) LISN devise for both and (b) common and differential modes

3. METHOD

3.1. Design and deployment of an analog control signal generator for the RPPM technique

Pseudo random binary sequences are generated using linear feedback shift registers (LFSR) in digital systems, as depicted in Figure 3. These registers utilize algebraic computations within Galois fields [22] to create binary sequences, with their length (L) determined by the number of flip-flops (N) and clock period (T_{CLK}), calculated as L= (2^N-1)* T_{CLK}. Although these sequences are deterministic, they exhibit very long repetition periods, making them appear similar to random sequences in practical applications. These sequences are also valuable in controlling control signals for power electronics systems. By employing pseudo-random modulation, engineers can introduce controlled "noise" into control signals, such as pulse-width modulation (PWM) signals, for power electronic devices like inverters and motor drives. This approach can reduce EMI by spreading energy across a broader spectrum, improve system efficiency, and enhance security against external disturbances or unauthorized access, providing benefits in various power electronics applications.

The technique involves utilizing pseudo-random modulation for control, where a multiplexer is guided by a pseudo-random binary sequence to select between two triangular waveform signals in opposing phases, resulting in the creation of a control system carrier signal V_P. This carrier signal is then compared to a reference signal, V_{ref}, leading to the generation of a switch control signal, as depicted in Figure 4. This approach finds versatile applications, notably in the realm of boost converters for electric vehicles (EVs). When applied to EVs, pseudo-random modulation can yield significant benefits, including improved boost converter efficiency, reduced power losses, and extended battery life. Additionally, it serves as a means to address EMI issues frequently encountered in power electronics systems, thereby enhancing the overall reliability and robustness of the EV power infrastructure. The control signal obtained demonstrates pseudo-random pulse position modulation, featuring a stable duty cycle and frequency switching, a technique referred to as random pulse position modulation (RPPM).

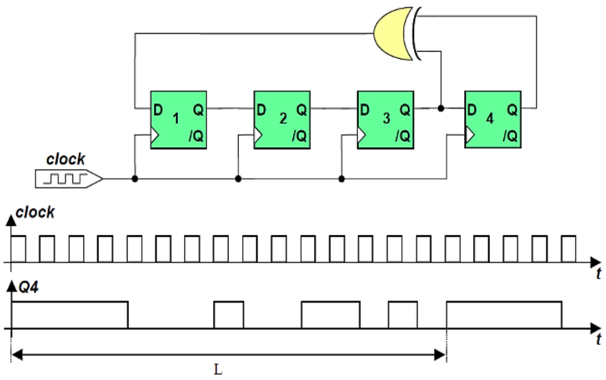


Figure 3. The fundamental concept of pseudo-random binary sequences (PRBS)

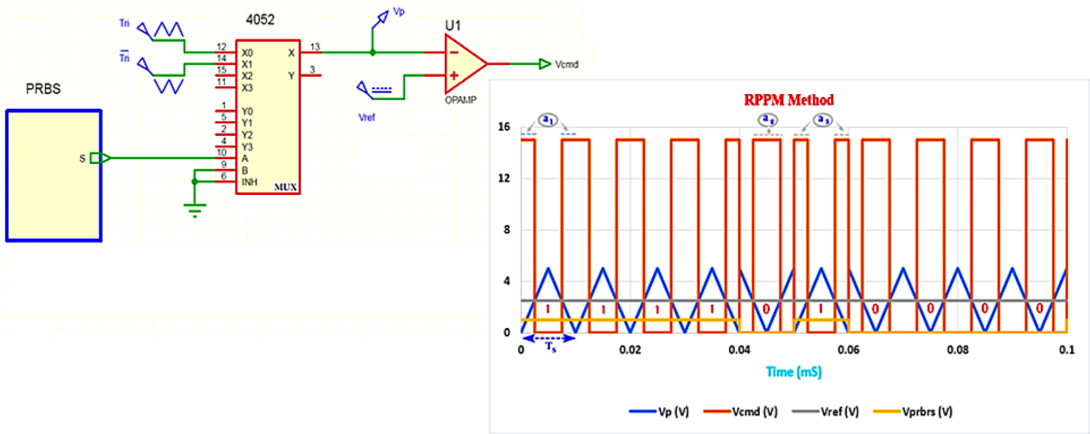


Figure 4. Design of the control signal generator in RPPM: structural insights

3.2. Development and application of a digital control signal generator for RPPM technology

It is commonly recognized that the digital implementation of pseudo-random modulation techniques requires programmable circuits such as digital signal processors (DSPs) and programmable gate arrays (FPGAs), which are commonly used but often expensive, or microcontrollers. In this study, we deliberately chose to use an Arduino Uno board, which integrates the renowned ATmega328p microcontroller, primarily due to its affordable cost. The implementations we have developed rely on an interrupt routine exploiting the integrated Timer 1 of the microcontroller. In Figure 5, we present an exposition of a traditional PWM control configuration, characterized by its three primary parameters: the modulation period, duty cycle, and delay time [23].

In this context, we focused on the technique of RPPM. This technique will be derived from a combination of random pulse width modulation (RPWM) and the NE555 integrated circuit operating in monostable mode. The fluctuations in duty cycle (D_k) will generate a variable falling edge within the fixed switching period, which will subsequently control the NE555 monostable to produce a constant pulse width in each period while introducing significant variations in the pulse position (see Figure 6). Timer 1, as illustrated in Figure 7, holds the responsibility of managing two output pins, specifically, pins 9 and 10.

Indeed, the clock signal, clk_{Tn}, is routed to the control logic, originating either from external (T_1) or internal clock, in conjunction with the prescaler. The control logic increments or decrements the timer counter $TCNT_1$, which is then compared to the values in registers OCR1A and OCR1B. When equality is reached, a signal is generated and directed to the block called "Waveform Generation". It is precisely this block that shapes the PWM signal by setting the output registers OC1A or OC1B to logic states 0 or 1.

In the continuation of our study, we opted for the "fast PWM 14" mode due to its ability to provide PWM signals at a higher output frequency compared to the "phase correct PWM" mode. Please note that our main objective is to control the Boost converter using a PWM signal with a frequency of F_s and a uniformly variable duty cycle ranging from 0% to 50%. This configuration requires the following steps:

- Declare the output pin for the PWM signal using the pinMode function.

- Configure registers TCCR1A and TCCR1B to use 14-bit fast PWM mode with the desired frequency and appropriate prescaler.
- Define the value of register ICR1 to generate the desired PWM frequency.
- Adjust the value of register OCR1B to set the PWM duty cycle, using the random[min,max] function to ensure variability within the 0% to 50% range.

Subsequently, the NE555 circuit in monostable mode is employed to generate a fixed-duration pulse $\frac{T_s}{2}$ in response to a falling edge of the generated RPWM signal (see Figure 8).

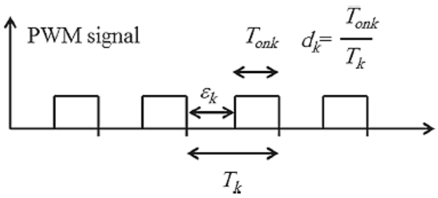


Figure 5. Pulsed control signal

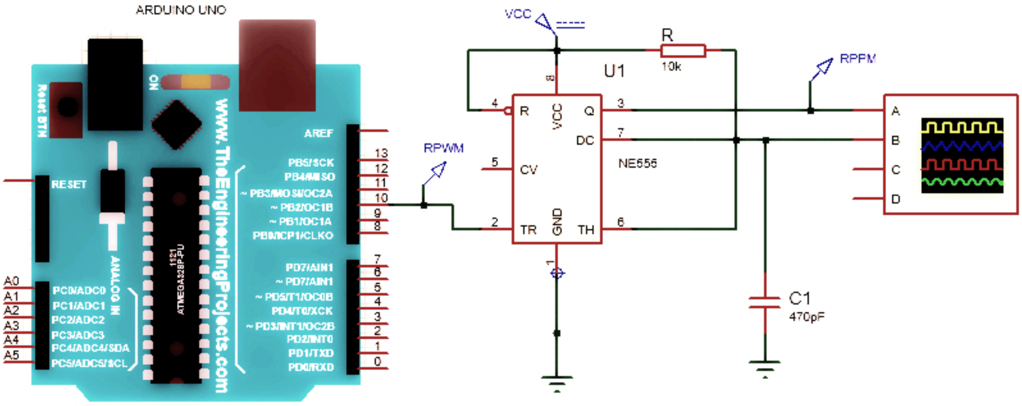


Figure 6. Framework for implementing the RPPM technique

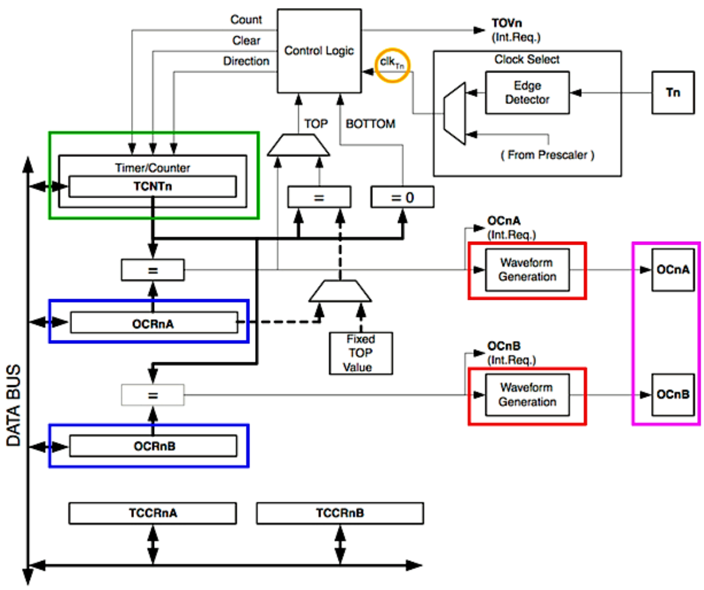


Figure 7. The internal timer block structure within the ATmega328P microcontroller

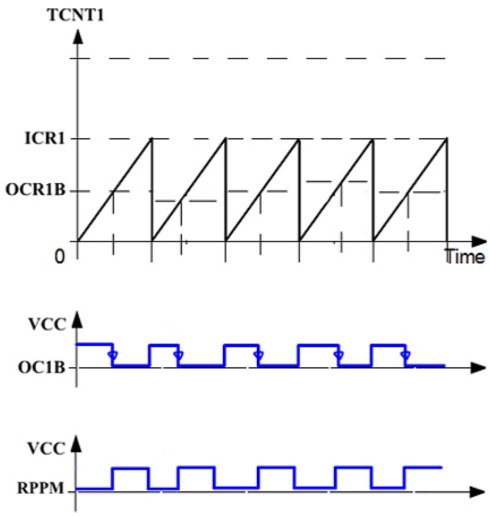
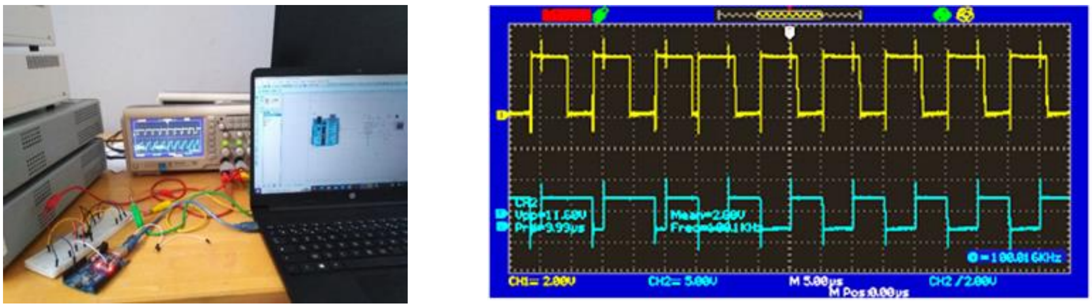


Figure 8. Time diagram for RPPM modulation technique

4. RESULTS AND DISCUSSION

In this section, we present the digital implementation of the random position pulse modulation (RPPM) technique using the ATmega328P microcontroller. We chose this approach for its reliability and cost-efficiency. Figure 9(a) demonstrates the practical application of pseudo-random signals generated by Timer 1 on the ATmega328P microcontroller, wherein we introduce randomness by adjusting the delay time within the PWM control signal, thereby creating a pseudo-random control structure.

Furthermore, we utilized the Siglent SDS1202X-E digital oscilloscope to visualize the PWM control signals generated by the Arduino Uno board. Figure 9(b) depicts a PWM signal characterized by randomized pulse positions. Notably, we employed an RPWM signal (highlighted in blue) to regulate the NE555 circuit, resulting in the desired RPPM control signal. Now, let's analyze the RPPM signal and its frequency characteristics. We conducted a simulation in the frequency domain using fast fourier transform (FFT). This analysis facilitated the extraction of the signal's spectrum, which we then compared to the spectrum generated through the conventional deterministic pulse width modulation (DPWM) method, as depicted in Figure 10.



(a) (b)

Figure 9. Implementing the RPPM technique (a) hardware setup with the Arduino Uno module and (b) control signal output

The analysis reveals a significant difference in spectral characteristics between pseudo-random modulation and conventional DPWM methods. Pseudo-random modulation spreads the spectrum more evenly, reducing harmonic peaks, while DPWM exhibits prominent odd-numbered harmonics [24], [25]. This suggests the potential advantages of using pseudo-random modulation to minimize harmonics in practical applications.

In this research phase, our focus lies in demonstrating the value of the digital RPPM control technique. We achieve this by quantifying conducted-mode electromagnetic disturbances [26], [27] in the studied boost converter, considering various approaches mentioned earlier. Measurement of voltage across the LISN terminals provides insights into these disturbances, with our primary analysis revolving around spectral data extraction. This analytical approach adheres to the framework illustrated in Figure 1.

As illustrated in Figure 11, it's clear that RPPM, with its ability to introduce controlled randomness in pulse positions, plays a vital role in distributing harmonic energy across a wide frequency spectrum. Upon scrutinizing the results of different techniques, it's clear that RPPM demonstrates a balanced power spectrum distribution over a wider frequency range compared to other methods. Its standout feature is its effective elimination of harmonic peaks, providing a substantial advantage in electromagnetic compatibility, with an approximately 20 dBuV improvement over DPWM. This dispersion of energy serves as an effective strategy for mitigating the risks of conducted EMI, particularly in EMI-sensitive applications. In practice, the reduction in EMI translates into improved signal quality and enhanced electromagnetic compatibility, making RPPM an invaluable modulation technique.

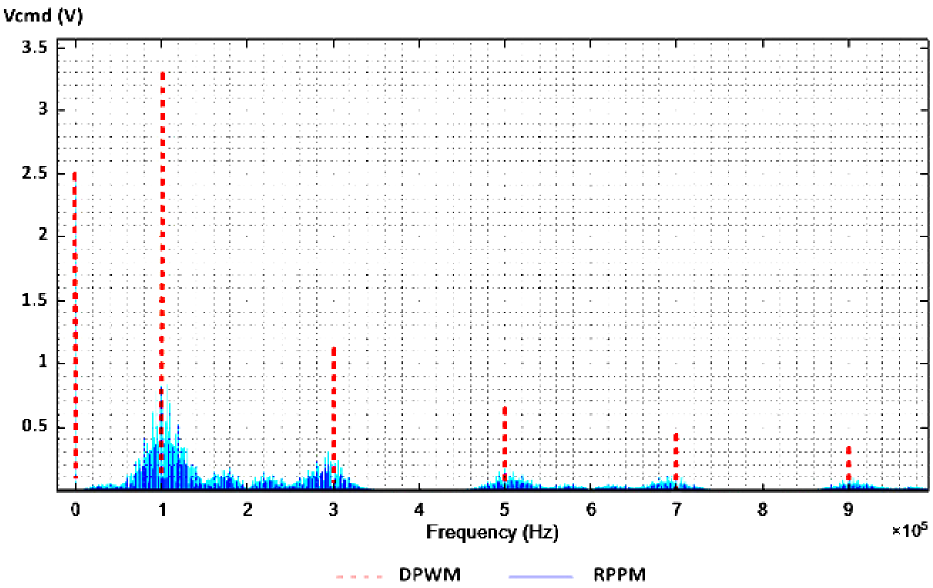


Figure 10. Spectral analysis of control signals in DPWM and RPPM methods

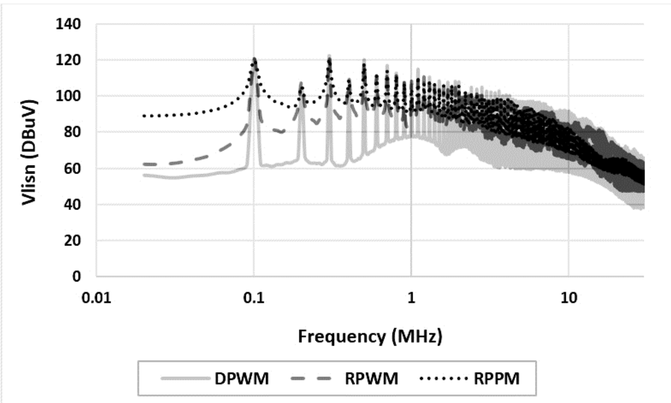


Figure 11. Comparative spectral analysis of V_{lisn} in different predictive methods for conducted emissions

5. CONCLUSION

In summary, digital RPPM stands as a notable advancement in mitigating EMI within electric vehicle systems (EVS) boost converters. Its core advantage lies in the broadening of the control signal's frequency spectrum, breaking away from the predictable patterns of traditional PWM techniques. This randomness effectively scatters EMI perturbations across a wider range of frequencies, reducing their concentration and enhancing overall EMC in EVS applications. This technique's adaptability, allowing for both analog and digital implementations, adds to its appeal, enabling engineers to tailor solutions to specific EVS setups. In the quest for cleaner and more efficient transportation, digital RPPM plays a pivotal role by significantly improving EMC, ensuring the safe and reliable operation of EVS systems.

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