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A RANDOMIZED CARRIER-BASED DISCONTINUOUS PULSE WIDTH MODULATION STRATEGY FOR NEUTRAL POINT CLAMPED THREE-LEVEL INVERTER

AIMAD BOUDOUDA[1,*], ABDERREZAK AIBECHE [1], AHCENE BOUZIDA[2], NASSERDINE BOUDJERDA[3]

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This article introduces a novel approach called randomized carrier-based discontinuous pulse width modulation (RCDPWM) to address the challenge of mitigating both low-order and high-order harmonics concentrated at the switching frequency and its integer multiples in the output voltage and current of a three-level inverter. The proposed strategy reduces switching losses and a wide dispersion of voltage and current harmonics with significantly smaller amplitudes by integrating features from discontinuous and randomized PWM methods. This characteristic proves beneficial for enhancing efficiency and electromagnetic compatibility. The RCDPWM strategy involves three schemes: two simple schemes (one random parameter), randomized pulse position modulation (RPP-DPWM) and randomized carrier frequency modulation (RCF-DPWM), and a dual scheme combining the two previous ones (RPPRCF-DPWM). Power spectral density (PSD) is used to assess the effectiveness of the proposed strategy in quantitatively analyzing the harmonic dispersion degree. The results demonstrate that the proposed RCDPWM strategy significantly expands harmonic clusters around the switching frequency, reducing its intensity. The spectrum analysis revealed that the RPPRCF-DPWM scheme is the most effective in spreading the output voltage and current spectrum compared to simple schemes (RPP-DPWM and RCF-DPWM).

1. INTRODUCTION

The pulse-width modulation (PWM) technique plays a pivotal role in controlling multilevel inverters by facilitating the adjustment of the useful voltage component and mitigating undesirable harmonics [1]. Typically, multilevel inverters operate at a fixed switching frequency, leading to harmonic clusters in both the voltage and current spectrum at multiples of the switching frequency. This phenomenon results in electromagnetic interference (EMI) emissions, substantial switch noise, and audible noise, particularly in variable-speed drives [2].

Efforts to address this issue have seen the application of high switching frequency PWM techniques to minimize harmonic content in the output voltage [3]. However, this approach comes with its own set of challenges. While effective in reducing harmonics, high switching frequencies also increase emissions and switching losses, compromising the overall system efficiency. Striking a balance between harmonic reduction and minimizing adverse effects on efficiency remains crucial in designing multilevel inverter systems [4].

A potential solution involves adopting innovative switching techniques such as zero voltage switching and discontinuous PWM techniques to mitigate switching losses [3]. However, the conventional discontinuous PWM with a fixed switching frequency has challenges. It generates substantial high-order harmonics at the switching frequency and multiples [5,6]. Furthermore, this technique is acknowledged for producing low-order harmonics due to the non-sinusoidal shape of the modulating function. This harmonic distortion is a primary cause of electromagnetic interference (EMI) issues, adversely affecting the system's electromagnetic compatibility (EMC).

In recent years, the random PWM (RPWM) strategy has emerged as an effective and costless solution to the challenges [7–18]. RPWM disperses harmonic components across a smooth, low-amplitude noise spectrum without raising the switching frequency. This approach offers several advantages, notably improving adherence to EMC standards for electromagnetic interference (EMI) and reducing audible noise in variable-speed drives [18]. Existing basic random schemes with a single random parameter are randomized carrier frequency modulation (RCFM) and randomized pulse position modulation (RPPM) [7–10]. However, combining the two schemes (RCFM-RPPM) has also been proposed to maximize the spreading of the voltage spectrum [11–17].

This paper introduces a novel strategy termed randomized carrier discontinuous pulse width modulation (RCDPWM) for the control of a three-level inverter. The proposed strategy seamlessly integrates the efficiency benefits of discontinuous PWM techniques – specifically, reduced switching losses – with the enhanced electromagnetic compatibility (EMC) compliance associated with randomized PWM techniques, leading to minimized electromagnetic interference (EMI) [19–23].

The key focus of this strategy is the randomization of two parameters in discontinuous PWM: the pulse position and the switching frequency. Consequently, three distinct schemes emerge: randomized pulse position (RPP-DPWM) and randomized carrier frequency (RCF-DPWM), each incorporating one randomized parameter, as well as a dual scheme (RPPRCF-DPWM) that combines both previous schemes. The switching signals are generated by comparing a discontinuous DPWM0 modulating function with a triangular carrier characterized by two random parameters (the pulse position and the switching frequency).

The paper is organized as follows: First, it presents the modulating principle of the proposed RCDPWM strategy. Next, it presents the results of the output voltage and current analysis based on the estimated power spectral density using the Welch method. The results demonstrate that the dual RPPRCF-DPWM scheme is the most effective in spreading the output voltage and current spectrum compared to simple schemes (RPP-DPWM and RCF-DPWM). Finally, FFT results confirm the results of the Welch method.

[1] University of Boumerdes, Laboratoire Ingénierie des Systèmes et Télécommunications (LIST), 35000, Boumerdés, Algeria (correspondence)
[2] University of Bouira, Faculty of Sciences and Applied Sciences, Department of Electrical Engineering, 10000, Bouira, Algeria
[3] University of Jijel, Faculty of Science and Technology, Laboratory of Renewable Energy (LER), 18000, Jijel, Algeria
Emails: a.boudouda@uinv-boumerdes.dz, aibeche_umbb@univ-boumerdes.dz, a.bouzida@univ-bouira.dz, n_boudjerda@yahoo.fr

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2. RANDOMIZED CARRIER DISCONTINUOUS PWM METHOD

Figure 1 shows the topology of a three-level neutral point clamped NPC inverter.

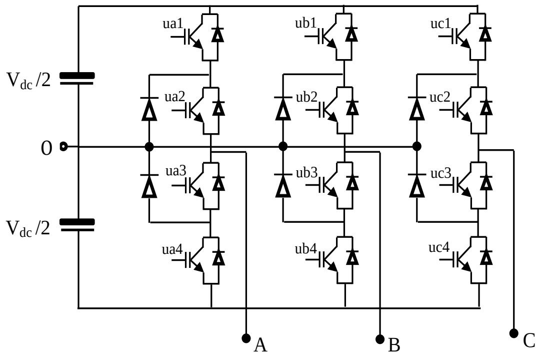

Fig. 1 – Topology of 3-level NPC inverter.

The carrier-based pulse width modulation (CPWM) scheme for a multilevel inverter is generated by comparing the reference phase voltage signal with several symmetrical level-shifted carrier waves [24]. For a 3-level inverter, 2 level-shifted carrier waves are required for comparison with the sinusoidal reference.

2.1. PRINCIPLE OF THE PROPOSED RCDPWM

Based on the proposed strategy, randomized carrier discontinuous pulse width modulation (RCDPWM), the switching signals are obtained by comparing the discontinuous modulating signal with the randomized triangular carriers, as shown in Fig. 2.

For one leg of the 3-level inverter, the required switching signals for upper half-leg ua1 and ua2 are obtained by comparing one discontinuous modulating signal *r* with two randomized triangular carriers, C1 and C2. As shown in Fig. 2, one random carrier, C1, is on the positive side, and the other, C2, is on the negative side. Each carrier signal is responsible for a pair of switches. One switch is controlled directly by a positive carrier, and the second by a negative carrier.

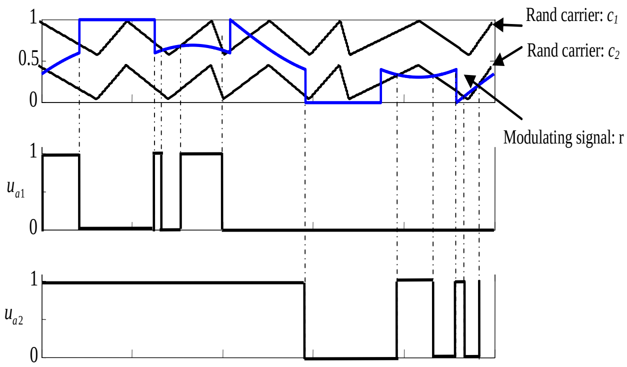

Fig. 2 – Modulating principle of one leg.

For the lower half-leg, the switching signals are complementary for the upper ones as follows:

$$u_{a3} = \overline{u_{a1}} \text{ and } u_{a4} = \overline{u_{a2}}.$$

The output voltage has three states: $V_{dc}/2$, 0, and $-V_{dc}/2$. For the level of $V_{dc}/2$, switches u_{a1} and u_{a2} need to be turned on. For the zero level, switches u_{a2} and u_{a3} are turned on. For the $-V_{dc}/2$, the switches u_{a3} and u_{a4} must be turned on. The switching state of power devices is shown in Table 1, 1 denotes the on state, and 0 denotes the off state.

Table 1

Switching states of the three-level inverter

u_{a1}	u_{a2}	u_{a3}	u_{a4}	Output phase voltage (V_{an})
1	1	0	0	$+V_{dc}/2$
0	1	1	0	0
0	0	1	1	$-V_{dc}/2$

Discontinuous modulating functions have gained special attention for their reduced-switching characteristics [3,5]. The most common carrier-based discontinuous modulating functions are DPWM0, DPWM1, DPWM2, and DPWM3 [5]. Figure 3 presents DPWM0 as a case study in our work.

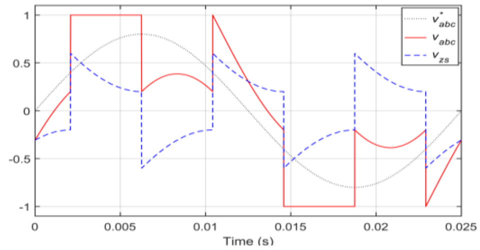

Fig. 3 – Modulating function of DPWM0.

2.2. RANDOMIZATION OF THE TRIANGULAR CARRIER SIGNAL

As depicted in Fig. 4, for each phase of the inverter, the obtained switching signal is characterized by three parameters: switching period *T*, delay report δ, and duty cycle *d*. Theoretically, *T*, δ and *d* can be randomized in a combined or a separate way. In practice, d is obtained from a deterministic reference signal, thereby adjusting the output voltage. Therefore, only *T* and δ are randomized. This can be obtained by a triangular carrier having two random parameters: the period *T* and the fall-time report β. The resulting random discontinuous schemes are as follows:

- Conventional Discontinuous PWM (DPWM): The carrier is deterministic (parameters *T* and β fixed).
- Randomized Pulse Position Discontinuous PWM (RPP-DPWM): The carrier is randomized (fixed period *T* and randomized β).
- Randomized Carrier Frequency Discontinuous PWM (RCF-DPWM): The carrier is randomized (randomized period *T* and fixed β).
- Combined random scheme: Dual Randomized Pulse Position Carrier Frequency Discontinuous PWM (RPPRCF-DPWM): The carrier is randomized (*T* and β are simultaneously randomized).
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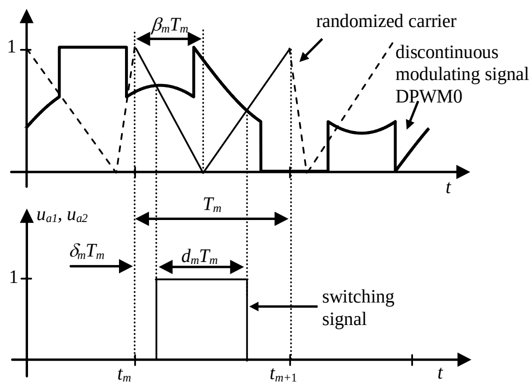

Fig. 4 – Switching signal parameters.

3. ANALYSIS OF THE OUTPUT VOLTAGE USING POWER SPECTRAL DENSITY

Generally, the analysis of random signals can be performed either by Fast Fourier Transform (FFT) or by power spectral density (PSD) [1, 2, 11–14]. The FFT (which is originally discrete) leads to a continuous random spectrum, depending on the considered signal sample. Thus, the (PSD) is more appropriate for such signals [25]; it can be expressed as follows:

$$W(f) = \lim_{T \to \infty} \frac{1}{T} E\{|F[u_T(t)]|^2\}. \qquad (1)$$

$F[u_T(t)]$ – Fourier transform of the signal sample u_T of length T, $E\{.\}$ – mathematical expectation.

A numerical estimation of the PSD based on (1) called the Welch method is used. The estimated PSD is computed by applying Welch's method to experimentally a sample of the considered signals or by simulation (output voltage, current…). The obtained signals are sampled with a sampling time of Ts, and then the power spectral density can be computed offline using MATLAB [26]. This method is very satisfactory; it gives very good results compared to the measurement and analytical ones [1, 2, 11–14]. In this work, the analysis of phase-to-phase voltage v_{ab} is carried out using the (PSD) estimated by the Welch method. The Welch's estimation method is implemented in the Signal Processing Toolbox of MATLAB by the pwelch function [26]:

PSD = pwelch (X, Window, Noverlap, NFFT, Fs),

where X – discrete-time signal vector (sampled data); Window – the window function is applied to segments; Noverlap – the number of overlapped samples; NFFT – the number of discrete FFT samples used to calculate the estimated PSD; Fs – the sampling frequency.

4. SIMULATION RESULTS

This section will verify the proposed randomized carrier discontinuous PWM schemes using the PSD estimation-based-Welch's method. The estimated PSD is computed by applying Welch's method on a sample of the output voltage and current after the simulation of the 3-level inverter. The simulations are performed under the following conditions:

- Input voltage: V_{dc} = 800 V.
- Load: R = 10 Ω, L = 5 mH
- Random triangular carrier: the intervals of randomization of parameters T and β are obtained with R_T = 0.4 and R_β = 2.
- Switching frequency f_s =2 kHz, which gives $T = 1/f_s = 5\ 10^{-4}$ s.
- The uniform probability density function is used for all randomizations.
- Reference signal – discontinuous modulating function DPWM0 of fundamental frequency f = 50 Hz, modulation index M = 0.8.
- Settings of the Welch estimation method used in all simulations:

Sampling frequency:	1 MHz
Window type:	Hamming
Record length:	200 000 samples
Window length:	40 000 samples
Overlap percentage:	20 %.

4.1. SWITCHING SIGNAL WAVEFORMS

Figure 5 depicts the waveforms of the discontinuous modulation function DPWM0, the carrier signal, and the switching signals for upper switches K_{a1}, and for lower switches K_{a2}, respectively, for the four schemes: DPWM, RPP-DPWM, RCF-DPWM, and RPPRCF-DPWM. The figures clearly show that the proposed modulation scheme gives fewer switching losses.

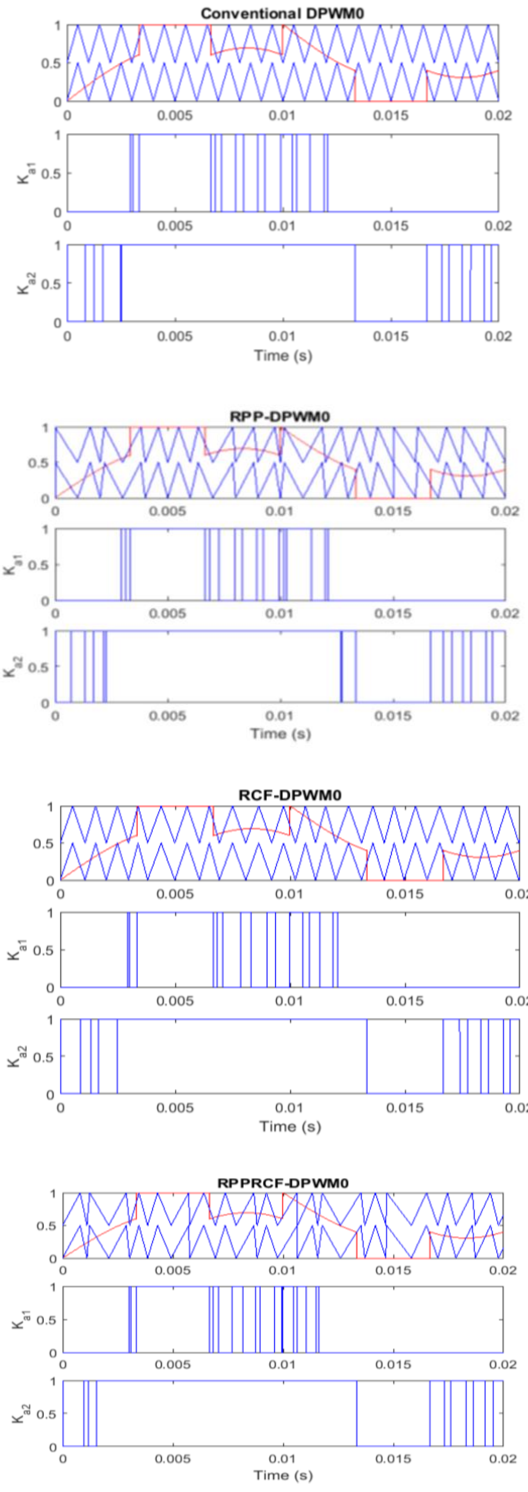

Fig. 5 – Simulated waveforms of triangular carrier and modulating function (upper trace), switching signal for Ka1 (middle trace), switching signal Ka2 (lower trace) (f_s = 2 kHz, M = 0.8, R_T= 0.2, R_β = 1.2): a) – DPWM; b) – RPP-DPWM; c) – RCF-DPWM; d) – RPPRCF-DPWM.

4.2. VOLTAGE AND CURRENT WAVEFORMS

Figure 6a–d illustrates the corresponding waveforms of the phase-to-phase voltage (v_{ab}) and phase current (i_a) for all schemes.

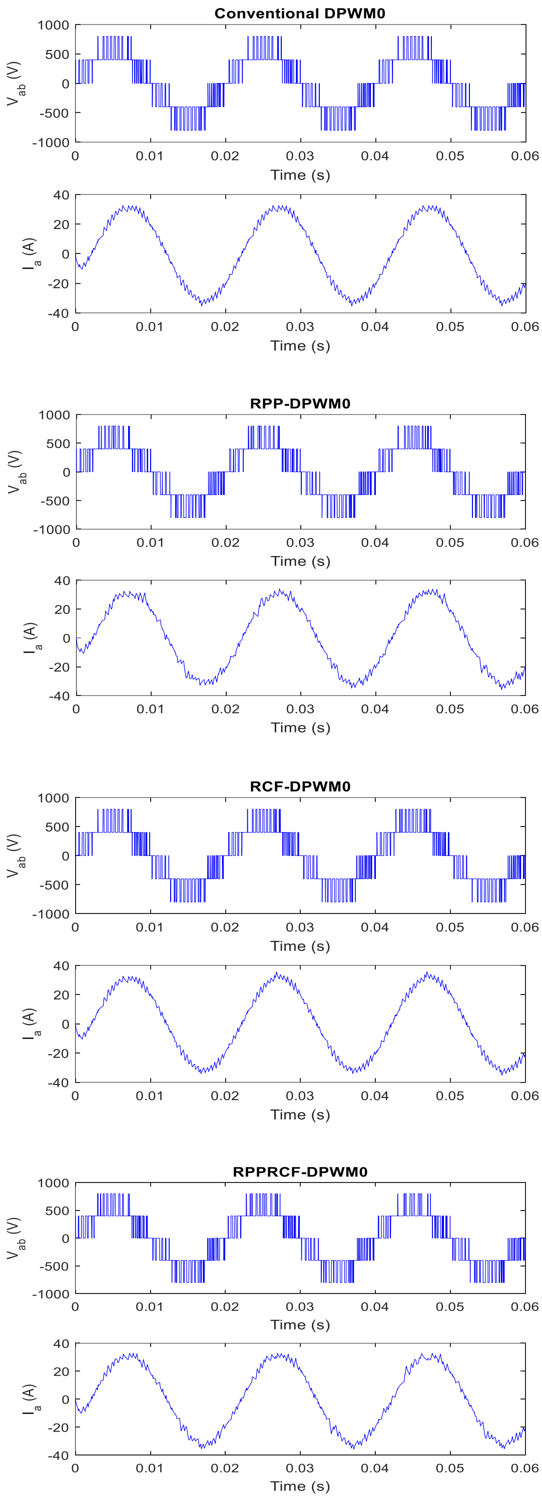

Fig. 6 – Simulated voltage (upper trace) and current (lower trace), f_s = 2 kHz, M = 0.8, voltage: 500 V/div., current: 20 A/div.)

As shown in Fig. 6, even when the random schemes (Figs. 6b–d) are applied to the 3-level inverter, the voltage, and the current waveforms are very similar to those of the conventional scheme (Fig. 6a). Indeed, it is well known that the randomization does not affect the output voltage and current fundamental; the operating performance of the converter is therefore not altered [2].

4.3. PSD ANALYSIS OF THE OUTPUT VOLTAGE

To verify the RCDPWM harmonics dispersion performance, Fig.7 depicts the estimated power spectral density of the voltage (v_{ab}) for different RCDPWM schemes. Notably, the conventional DPWM scheme is utilized as a benchmark for comparison.

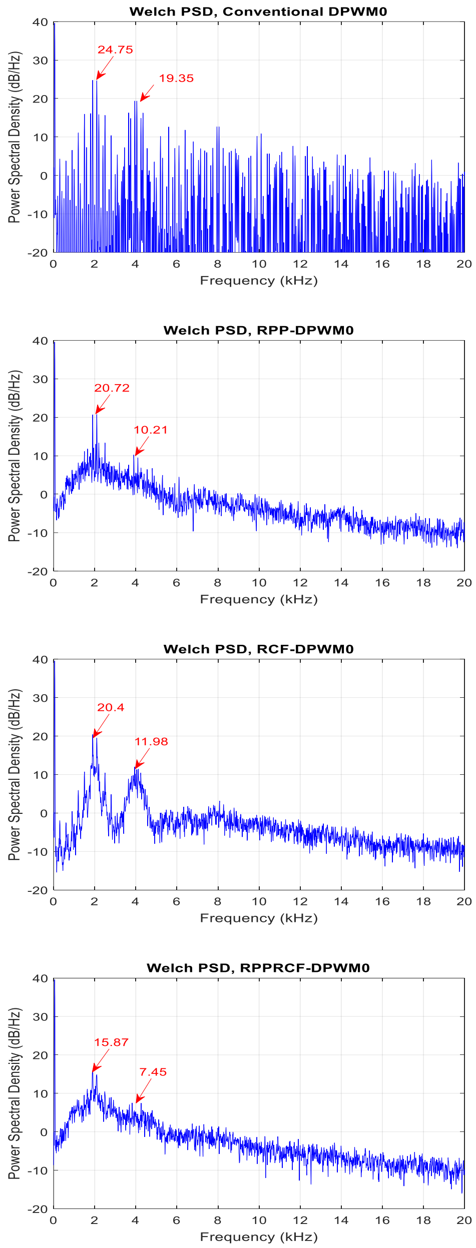

Fig. 7 – Welch PSD of phase-to-phase voltage, f_s = 2 kHz, f = 50 Hz, M = 0.8, X-axis: 2 kHz/div., Y-axis: 10 dB/div.

From Fig. 7a, when using conventional DPWM, dominant discrete power harmonics will appear around the switching carrier frequency and its integer multiples, which is the inherent limitation of conventional DPWM. The proposed RCDPWM schemes are an effective and costless method to solve this problem. It can be seen from Figs. 7c, d that RCF-DPWM and RPPRCF-DPWM provide a fully dispersed PSD, significantly reducing the harmonics' amplitudes. In contrast, the RPP-DPWM in Fig. 7b fails to fully disperse the PSD, where the spectrum contains a discrete part (harmonics) and a continuous part (noise). The RCF-DPWM is, therefore, more proficient than the RPP-DPWM. Nonetheless, as depicted in Fig. 7d, the RPPRCF-DPWM scheme results in the most dispersed PSD relative to simple schemes (RPP-DPWM and RCF-DPWM). It reduced the PSD amplitudes near the switching carrier frequency (f_s = 2 kHz) by 9 dB and near ($2f_s$ = 4 kHz) by 12 dB, especially at higher frequencies. Notably, these benefits are envisaged, given that the proposed scheme merges the features of RCF-DPWM and RPP-DPWM.

4.4. PSD ANALYSIS OF THE PHASE CURRENT

Figure 8 gives the Welch PSDs of the phase current (i_a) for all random carrier discontinuous schemes: DPWM, RPP-DPWM, RCF-DPWM, and RPPRCF-DPWM.

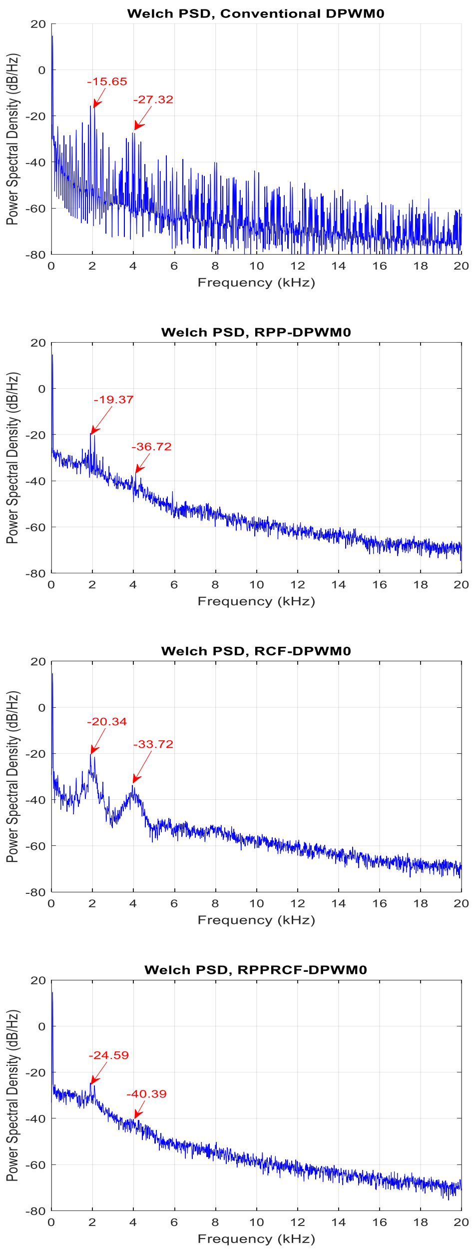

Fig. 8 – Welch PSD of phase current, f_s = 2 kHz, f = 50 Hz, M = 0.8, X-axis: 2 kHz/div., Y-axis: 20 dB/div.

For the conventional DPWM scheme, the PSD is formed by discrete power harmonics (Fig. 8a). Conversely, the PSD is spread out with reduced peaks for random carrier discontinuous schemes (Figs. 8b–d). For the RPP-DPWM scheme, the PSD has a continuous part (noise) and a discrete part (power harmonics) (Fig. 8b). The RCF-DPWM scheme provides more PSD spreading than RPP-DPWM (Fig. 8c). The most spread PSD of the phase current is obtained by the dual scheme RPPRCF-DPWM (Fig. 8d).

4.5. FFT ANALYSIS OF THE VOLTAGE

To reinforce the validity of Welch PSDs results, the spectrum analysis of the output voltage for the conventional DPWM and random DPWM is shown in Fig. 9 using the FFT analysis tool of MATLAB/Simulink. The same signal sample under the same conditions is used for the analysis.

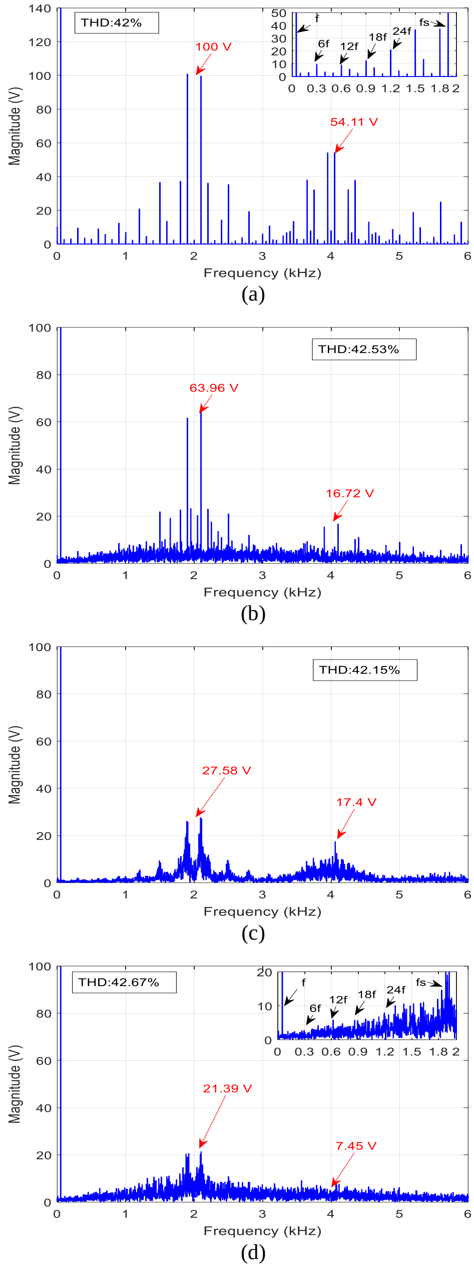

Fig. 9 – Spectrum analysis of voltage using FFT: a) – DPWM; b) – RPP-DPWM; c) – RCF-DPWM; d) – RPPRCF-DPWM.

To corroborate the accuracy of the estimated PSD results, Fig 9 depicts the spectra obtained via FFT analysis of identical signal samples under the same simulation conditions. Notably, the results of Fig. 9 perfectly align with the PSDs depicted in Fig. 7 for all schemes.

DPWM: the voltage harmonics near the switching frequency f_s have significant amplitudes, resulting in a discrete spectrum. We see that DPWM intrinsically adds even-order low-frequency harmonics into the output voltage; this can be seen in the graph marked by 6f, 12f, 18f, 24f. These are caused by the zero sequence signals in the modulating function.

- RPPRCF-DPWM has a more widely spread spectrum, especially for harmonics at high frequencies. The amplitude value of the switching harmonics is six times lower than the amplitude value for DPWM at a fixed switching frequency. We notice that the even-order low-frequency harmonics have disappeared.

5. CONCLUSIONS

This paper uses randomized carrier discontinuous pulse width modulation (RCDPWM) to control a three-phase, three-level inverter. RCDPWM shares the advantages of discontinuous PWM in terms of efficiency and randomized carrier PWM in terms of a perfect spread spectrum. Based on simulation results, the proposed strategy has a voltage and current spectrum that is widely distributed with substantially reduced PSD amplitudes, which is advantageous in terms of electromagnetic compatibility. The analysis revealed that the dual scheme (RPPRCF-DPWM) permits a reduction of 36 percent of the PSD peaks near the carrier switching frequency relative to the simple schemes (RPP-DPWM and RCF-DPWM) and conventional DPWM. Also, the proposed scheme mitigates all the low-frequency harmonics in the output voltage.

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REFERENCES

1. A. Boudouda, *Dual randomized discontinuous pulse width modulation for three-phase inverter*, International Journal of Electronics, **111**, *9* (2023).
2. A. Boudouda, Boudjerda N., Aibeche A., *dSPACE-based dual randomized pulse width modulation for acoustic noise mitigation in an induction motor*, Journal of the Brazilian Society of Mechanical Sciences and Engineering, **44**, *493*, pp. 1–16 (2022).
3. P.K. Chaturvedi, I.S. Jain, P. Agarwal. *Reduced switching loss pulse width modulation technique for three-level diode clamped inverter*, IET Power Electron., **4**, *4*, pp. 393–399 (2011).
4. Y. Shrivastava, S.Y. Hui, *Analysis of random PWM switching methods for three-level power inverters*, IEEE Transactions on Power Electronics, **14**, *6*, 1156–1163 (1999).
5. A.M. Hava, R.J. Kerkman, T.A. Lipo, *A high-performance generalized discontinuous PWM algorithm*, IEEE Transactions on Industry Applications, **34**, *5*, pp. 1059–1071(1998).
6. O. Ojo, *The generalized discontinuous PWM scheme for three-phase voltage source inverters*, IEEE Transactions on Industrial Electronics, **51**, *6*, pp. 1280–1289 (2004).
7. M. Paramasivan, M.M. Paulraj, S. Balasubramanian, *Assorted carrier-variable frequency-random PWM scheme for voltage source inverter*, IET Power Electronics, **10**, *14* (2017).
8. P. Lezynski, *Random modulation in inverters with respect to electromagnetic compatibility and power quality*, IEEE Journal of Emerging and Selected Topics in Power Electronics, **6**, *2*, pp. 782–790 (2018).
9. Z. Zhang, L. Wei, P. Yi, Y. Cui, P.S. Murthy, A.M. Bazzi, *Conducted emissions suppression of active front end (AFE) drive based on random switching frequency PWM*, IEEE Transactions on Industry Applications, **56** *6*, pp. 6598–6607 (2020).
10. C.H. Moon, C.J. Chen, S.W. Lee, *A random modulation spread-spectrum digital PWM for a low system clock digital buck converter*, IEEE., **9** (2021).
11. N. Boudjerda, A. Boudouda, M. Melit, B. Nekhoul, K. El Khamlichi Drissi, K. Kerroum, *Spread spectrum in three-phase inverter by an optimised dual randomised PWM technique*. International Journal of Electronics, **101**, *3*, pp. 308–324 (2014).
12. A. Boudouda, N. Boudjerda, A. Aibeche, A. Bouzida, *Dual randomized pulse width modulation technique for buck converter fed by photovoltaic source*. Rev. Roum. Sci. Techn. – Électrotechn. et Énerg, **63**, *3*, pp. 289–294 (2018).
13. A. Boudouda, N. Boudjerda, K. El Khamlichi Drissi, K. Kerroum, *Combined random space vector modulation for a variable speed drive using induction motor*, Electrical Engineering, **98**, *1*, pp. 1–15 (2016).
14. A. Boudouda, A. Bouzida, F. Nafa. *Spectral analysis of switch voltage for dual randomized PWM DC-DC converters operating in DCM*, International Journal of Electronics Letters, **10**, *1*, 101–114 (2022)
15. K.S. Kim, Y.G. Jung, Y.C. Lim, *A new hybrid random PWM scheme*. IEEE Transactions on Power Electronics, **24**, *1*, pp. 92–200 (2009)
16. F. Bu, T. Pu, W. Huang, L. Zhu, *Performance and evaluation of five-phase dual random SVPWM strategy with optimized probability density function*, IEEE Transactions on Industrial Electronics, **66**, *5*, pp. 3323–3332 (2019).
17. Y. Huang, Y. Xu, W. Zhang, J. Zou, *Hybrid RPWM technique based on modified SVPWM to reduce the PWM acoustic noise*. IEEE Transactions on Power Electronics, **34**, *6*, pp. 5667–5674 (2019).
18. Y. Li, H. Wu, Q. Si, Y. Liu, *Vibration noise suppression approach based on random switching frequency control for permanent magnet motor*, Transactions of the Canadian Society for Mechanical Engineering, **45**, *3*, pp. 444–460 (2021).
19. A.M. Trzynadlowski, R.L. Kirlin, S.F. Legowski, *Space vector PWM technique with minimum switching losses and a variable pulse rate [for VSI]*. IEEE Transactions on Industrial Electronics, **44**, *2*, pp. 173–181 (1997).
20. H. Khan, E.H. Miliani, K.E.K. Drissi, *Discontinuous random space vector modulation for electric drives: a digital approach*. IEEE Transactions on Power Electronics, **27**, *12*, pp. 4944–4951 (2012).
21. S. Bhattacharya, D. Mascarella, G. Joos, G. Moschopoulos, *Reduced switching random PWM technique for two-level inverters*, IEEE Energy Conversion Congress and Exposition (ECCE), 2015.
22. Z. Zhang, L. Wei, P. Yi, P.S. Murthy, Y. Cui, *Optimized digital implementation of carrier-based randomized discontinuous PWM technique for active front end (AFE) drives*, IEEE Energy Conversion Congress and Exposition (ECCE), 2019.
23. Aimad Boudouda, *Power spectral density of dual randomized discontinuous pulse width modulation*, Rev. Roum. Sci. Techn.– Électrotechn. et Énerg., **68**, *2*, pp. 132–138 (2023).
24. T.S. Kiran, K. N. Pavithran, *Novel approach for harmonic reduction with random PWM technique for multilevel inverters*, International Conference on Power, Instrumentation, Control and Computing (PICC), 2015.
25. P. Welch, *The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms*, IEEE Transactions on Audio and Electroacoustics, **15**, *2*, pp. 70–73 (1967).
26. Matlab. *Signal Processing Toolbox User's Guide*, The MathWorks. Inc., Natick, MA, 2004.