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Acoustic Noise Mitigation in Slip Angle Controlled DTC of Open-End Winding Induction Motor Drive Using Dual Randomized AISPWM for EV Application

Ganesh Challa[1], Dr. M. Damodar Reddy[2]

[1]*Research Scholar, Department of EEE, S. V. University, Tirupati, India; ganesh.challa@gmail.com*

[2]*Professor, Department of EEE, S. V. University, Tirupati, India; mdreddy999@rediffmail.com*

***Correspondence:** *azrataj.eee@gcet.edu.in*

ABSTRACT- Low vibration and acoustical noise as well as effective DC link usage are the demands of industries and Electric Vehicles (EV). Direct Torque Control (DTC) of Induction Motors (IMs) meet the EV and other modern industry requirements. Still, flux as well as torque swings lead to higher acoustical noise. Consequently, EVs as well as working place noise have become major concerns, affecting the health of individuals. Efficiency of dc link use is improved by Space Vector Pulse Width Modulation (SVPWM). Yet, SVPWM is not efficient in lowering acoustical noise. Different RPWM techniques can lower acoustic noise. Still, the lower degree of randomization makes the noise reduction difficult. This work presents a Hybrid Dual Random PWMs (HDRPWMs) based Alternate Inverter Switching (AIS) strategy for Slip-Angle Controlled Direct Torque Control of an Open-End Winding IM Drive (OEWIMD). This technique is aimed to lower the acoustical noise for EVs. The intended PWMs seek to show how well HDRRPWMs distribute the acoustical noise spectra in contrast to conventional techniques.

General Terms: AIS, DTC, EV, and OEWIMD.
Keywords: Acoustical Noise, and RPWM.

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1. INTRODUCTION

An Electrical Vehicle (EV) is a transport vehicle that operates using electricity as its power source. It consists of a motor, gearbox, other equipment. The motor is a crucial component of EVs [1]. Induction Motors (IMs) are typically employed in EVs because of their small size, robustness, affordability, high velocity, and little upkeep requirements [2]. EVs and industry drive applications offer numerous benefits, including enhanced utilisation of the DC link, decreased acoustical limited noise and vibration levels for a more pleasant environment. The Direct Torque Control (DTC) method has demonstrated its capability to fulfil the rigorous requirements of contemporary industries and EVs. In recent years, there has been a growing attraction with utilizing DTC for EV applications [3] because of its ability to quickly control torque and its reduced need for online calculation. However, it experiences torque and flux fluctuations during stable operating conditions and when the switching frequency varies.

The usage of a Multi-Level Inverters (MLIs) can reduce these ripples. The Dual Inverter (DI) topology is favored among many MLIs for Open End Winding Induction Motor Drives (OEWIMDs) [4]. It is commonly employed in EVs [5]. Using Space Vector Pulse Width Modulation (SVPWM) able to effectively address issues associated with variable switching frequency. It improves the efficiency of the DC bus, which is essential for meeting the demands of EVs. SVPWM-fed drives come with inherent limitations such as higher order harmonics, acoustical noise, and vibrations.

One drawback of SVPWM is the potential for vibrations and noise in motor drives due to the higher order harmonics generated by the inverter. This is due to the fact that the frequency at which humans can perceive sound often aligns with the frequency at which switches operate (carrier frequency) [6,7]. The inverter output current is composed of harmonics that are found at the side bands of the multiple of the carrier frequency. These harmonics have a higher frequency and a limited bandwidth, resulting in motor vibrations and the production of narrow-band noise that can be uncomfortable for the operating staff. Thus, the rise of EVs and the issue of workplace noise have become major areas of concern, affecting productivity, employee well-being, and overall protection. In order to address the restricted range of noise, it is possible to increase the switching frequency to a value higher than 20kHz. However, the increased inverter losses [8] will have an adverse effect on the conversion efficacy of the converter and the overall length of the EV travel. The Random PWM (RPWM) method is an effective solution to reduce acoustical noise by evenly distributing harmonics of the inverter output. This is accomplished by utilizing a fixed carrier frequency [9].

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The RPWM technique incorporates stochastic components for the inverter control algorithm. Based on the statistical theory [10], if the gating pulse varies random, the switching device it controls amplifies the harmonic spectra. The RPWM approaches provide optimum as well as efficient strategies in the above-mentioned circumstances [11].

Several authors have introduced a variety of RPWM algorithms, to mitigate the acoustical noise [12-15]. [16] conducted a comparison of between SVPWM and couple of Discontinuous PWM (DPWM) approaches, such as 30º DPWM and 60º DPWM. This study showed that the first DPWM scheme outperforms the second in terms of reducing noise. [17] examined the effects of DPWM techniques on the acoustical noise generated by motors. [18] conducted a study comparing RPWM with spread spectrum techniques. [19,20] documented the discrete RPWM approaches used to address harmonic dispersion. Currently, there are ongoing efforts to minimize the acoustical noise produced in EV application [21,22]. [23] introduced a novel N-State Random Pulse Position Modulation technique to effectively disperse harmonics. This study introduces Alternate Inverter Switching (AIS) mode for Slip Angle Controlled (SAC) Direct Torque Control of Open-End Winding IM Drive (OEWIMD). In this work, couple of Hybrid Dual Random PWMs (HDRPWM-1,2) are introduced to mitigate acoustical noise for EV application. This study assesses the efficacy of the proposed schemes in spreading the noise spectrum of an EV throughout the audible frequency band and are compared with the traditional RPWM schemes.

2. SLIP ANGLE CONTROLLED DTC OF OEWIMD

The SAC-based DTC is a sophisticated control approach utilized in electric drive systems, particularly in induction motors. This technology combines the advantages of SAC and DTC to achieve precise control over motor torque and flux, resulting in increased performance and efficiency. The SAC scheme adjusts the deviation between synchronous speed and running speed of the motor and is crucial for controlling torque production. It plays a vital role in ensuring professional and precise control over the motor's performance. The slip angle is the angle formed by the stator and rotor flux vectors, and accurate control provides optimal torque generation and operation.

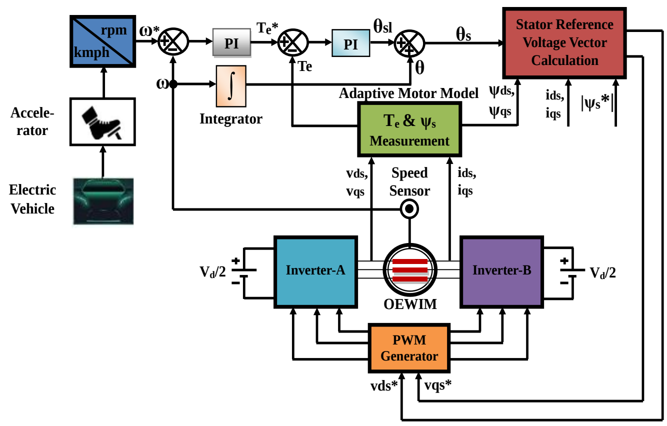

Figure 1. SAC Based DTC fed OEWIMD for Electric Vehicle

The *figure 1* showcasing the SAC of the DTC of an OEWIMD fed EV. The EV's desired speed will be compared to its current speed, and this deviation is regulated by a Proportional Integral (PI) regulator in a precise manner. A regulator is responsible for generating a torque command, and is compared to the motor torque to produce torque error. This error is currently controlled using torque PI controller. The slip angle and rotor angle are added to generate the stator flux angle, which is a synchronous angle. Through the use of adaptive motor model commanded stator voltage phasors can be obtained. The inverse Park's transformation is used to generate 3-Φ commanded sinusoidal stator voltage vectors will be obtain, which are then modified by the PWM techniques.

3. PROPOSED AIS MODE BASED MODULATED SIGNAL GENERATION

The sinusoidal commanded voltage signals are written by,

$$v_{abc} = v_m \sin\left(\omega t - 2(x-1)\frac{\pi}{3}\right) \quad (1)$$

Where x = 1, 2, and 3 respectively for a, b, c phases, vm = peak value of the commanded voltage

The positive and negative zero sequence signals can be written as

$$PCM = \left[(1 - \text{maximum}(v_a, v_b, v_c))\right] \quad (2)$$

$$NCM = \left[(-1 - \text{minimum}(v_a, v_b, v_c))\right] \quad (3)$$

The modulated wave for both the inverters are found using

$$v^*_{abc} = \left[1 + (v_{abc} + v_{zero})\right] * (1/2) \quad (4)$$

$$v_{zero} = k_o * NCM + (1 - k_o) * PCM \quad (5)$$

Here v_{zero} = the zero sequence voltage, k_o = constant depending upon type of PWM scheme

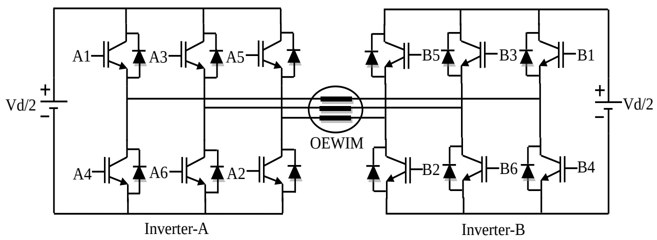

Figure 2. 3-Level Dual Inverter Structure for OEWIMD

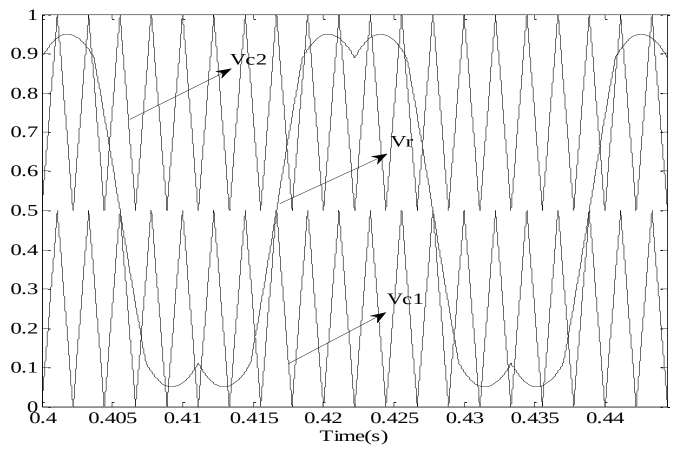

Figure 3. Alternate Inverter Switching Mode for 3-Level DI

Figure 2 displays 3-level Dual Inverter structure. The AIS-based SVPWM technique utilizes a modulating signal (Vr) and two-level shifted carriers (Vc1, Vc2) to operate the Three-Level DI as depicted in *figure 3*. Through a careful analysis of the modulated signal and the two carrier signals, one can derive the gating signals. In the AIS strategy, Vc1 is responsible for generating the inverter-A pulse pattern, while Vc2 generates the inverter-B pulse pattern. In addition, the inverters operate in alternating cycles of 180 degrees. This means that while one inverter is switching, the other inverter is clamping, and vice-versa. The net output voltage of the DI is given to the stator of OEWIMD. Each of the Inverters powered by Vdc/2 via two separate dc supplies. The logic for the switching of the inverter switches is outlined in *table 1*.

Table 1. Switching Logic

Condition	Switch States	
Vra > Vc1	A1 Turned ON	A4 Turned OFF
Vrb > Vc1	A3 Turned ON	A6 Turned OFF
Vrc > Vc1	A5 Turned ON	A2 Turned OFF
Vra > Vc2	B1 Turned ON	B4 Turned OFF
Vrb > Vc2	B3 Turned ON	B6 Turned OFF
Vrc > Vc2	B5 Turned ON	B2 Turned OFF

4. GENERATION OF CARRIER SIGNAL FOR SVPWM, AND RPWM TECHNIQUES

RPWM is a technique used in various fields such as power electronics and signal processing. It involves varying the width of pulses in a pseudo-random manner rather than using a fixed pattern. The key benefits of RPWM are Reduction of EMI and noise, Improved Acoustic Performance, Enhanced Signal Quality, Better Thermal Management, etc. The gating pulse is determined by 3 parameters: the fundamental period T (not displayed), the delay period δ_m, and the duty cycle d_m. Here only T and δm are considered as randomized parameters. The delay period (δ_m) of any typical signal is indicated as [12].

$$\delta_m = \beta_m(1-d_m) \tag{6}$$

The carrier's slope β_m and delay period δ_m are randomized within certain ranges (β_m [0,1] and δ_m [0, (1− d_m)]), while the place of the gating signal is arbitrarily distributed throughout the switching period. This implementation involves a triangular carrier and two random parameters such as T and β_m for different PWM approaches such as SVPWM, Random Pulse Position Modulation (RPPM), Random Carrier Frequency Modulation (RCFM), Random Reference PWM (RRPWM) etc.

4.1 Proposed HDRPWM1 (RRPWM-RPPM)

In this case, commanded signal and gating signal position both were randomized. This is a hybrid operation of RRPWM and RPPM. Here, the modulated wave is generated by assigning a value of ko, which is a random number between 0 & 1, in *equation (5)*. The subsequent equations outline the execution of RPPM are

$$R_\beta = \left[\frac{\beta_{max} - \beta_{min}}{\bar{\beta}}\right] \tag{7}$$

$$\beta \in [\beta_{min}, \beta_{max}] \tag{8}$$

where $\beta_{min} = \bar{\beta}\left(1 - \frac{R_\beta}{2}\right)$ and $\beta_{max} = \bar{\beta}\left(1 + \frac{R_\beta}{2}\right)$

where $\bar{\beta}$ = avg. value of the delay period = (1/2).

The ball park values for β_m range from 0 to 1, resulting in a maximum value of R_β equal to 2. Typically, R_β falls within the limit of 0 to 2, which in turn hinders the range of βm. In this work, a value of 1.2 was assigned to R_β, which led to a variation of β_m ranging from 0.2 to 0.8. This PWM technique produces a triangular signal with the operating frequency of 3kHz. However, the gating signal location changed in random depending upon the β_m. The variable β_m follows a uniform distribution law as follows

$$\beta_m = \beta_{min} + (\beta_{max} - \beta_{min}) * R \tag{9}$$

4.2 Proposed HDRPWM2 (RRPWM-RCFM)

Here, both the commanded signal and switching frequency are varied in random. This method involves the blend of RRPWM & RCFM. In this case, the modulated wave is generated by assigning a value of ko, that is a random value between 0 and 1, in *equation (5)*. The subsequent equations define the execution of RCFM.

$$R_T = \left[\frac{T_{max} - T_{min}}{\bar{T}}\right] \tag{10}$$

$$T \in [T_{min}, T_{max}] \tag{11}$$

where $T_{min} = \bar{T}\left(1 - \frac{R_T}{2}\right)$ and, here is the avg. value of fundamental period T.

The ball park values for R_T range from 0 to 2. Nevertheless, a value of 0.2 is chosen for R_T since the perception of lower order harmonic noise becomes more apparent as T_{max} increases. This PWM technique utilizes a triangle carrier frequency ranging from 2.727kHz to 3.333kHz for an operating frequency of 3kHz. Moreover, the gating signal location is precisely generated at the center of triangle waveform. The expression for T can be written using the uniform law as follows:

$$T = T_{min} + (T_{max} - T_{min}) * R \tag{12}$$

where 'R' is a random value ranging from 0 to 1, which can generate based on the Mersenne Twister (MT) technique.

5. ACOUSTICAL NOISE ANALYSIS

Acoustical noise is the result of the interaction between different frequency components. Frequency weighting curves are widely utilized to replicate the sensitivity of the human ear to toned frequencies.

The IEC 61672-2013 standard explains that A-weighting is commonly used and considered the most frequently utilised set of curves compared to other weighting curves. Within the audible band of frequencies between 0.1 to 20 kHz, the human ear

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exposes a heightened sensitivity to specific frequencies [21]. The Human ears show a specialized ability to perceive different frequencies, particularly in the range of 500Hz to 6kHz. In addition, the A-weighted curve indicates spikes in the 1-5 kHz range, which are the frequencies that the human ear is most sensitive to. Therefore, studying noise using A-weighting curves allows for a precise evaluation of acoustical noise. It is an expert noise evaluation curve and is eliminates sounds that cannot be heard by humans. The analysis of acoustical noise provides an evaluation of the collective result of noise at various frequencies over the total noise level [21]. An Unweighted noise values are typically expressed in decibel (dB)s, whereas A-weighting noise evaluations are expressed as dBAs or dB(A)s.

The formula pertaining to noise weighted function can be provided as

$$R_A(f) = \left[\frac{12200^2 f^4}{\left(f^2+20.6^2\right)\left(f^2+12200^2\right)\sqrt{\left(f^2+107.7^2\right)\left(f^2+737.9^2\right)}} \right] \quad (13)$$

Here f = frequencies of noise spectra

The A-weighted noise is expressed as

$$dBA(f) = dB + 20 * \log\left(R_A(f)\right) \quad (14)$$

here dB be the un-weighted noise derived using the Power Spectral Density (PSD) of the motor current or voltage.

The Harmonic Spreading Factor (HSF) plays a crucial role in acoustic noise measurement by quantifying the degree to which harmonic's spectrum spreads. This quantity widely used in practical applications in different industries that utilize PWM, such as control engineering, power electronic converters, and the communication sector. This analysis evaluates the PWM scheme's ability to efficiently distribute harmonics by examining the harmonics dispersion over harmonic spectra. Generally, lower value of HSF associated with better distribution as well as greater level of spreading of harmonic's energy [14]. The equation for HSF [24] is derived using statistical deviation.

$$HSF = \left[\frac{1}{N} \sum_{i>1}^{N} \left(H_i - H_o\right)^2 \right]^{\frac{1}{2}} \quad (15)$$

Here, H_i = magnitude of the i^{th} component,

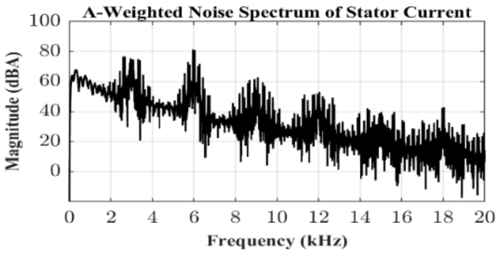
H_o = Mean value of magnitude of the 'N' harmonics

$$= \frac{1}{N} \sum_{i>1}^{N} \left(H_i\right)$$

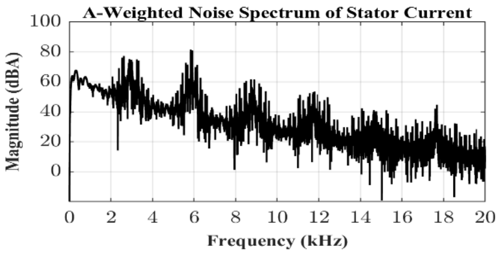
6. RESULTS AND DISCUSSION

This work implements AIS-based SVPWM and various RPWM techniques for SAC of DTC fed OEWIMD for EV application. The study included the presentation and comparison of A-weighting acoustic noise spectra for different works previously reported in relation to the proposed work. In addition, the HSF was computed as well for fair comparison. The simulation results are obtained when the EV's motor steady state speed is maintained at 1200 rpm.

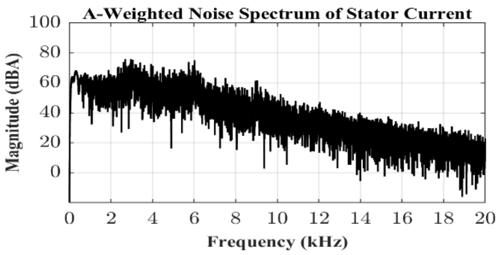
Figure 4 displays the spectrum of A-weighting acoustical noise spectrum with SVPWM and different Random PWM techniques. The variation of HSF for various modulation schemes presented in *table-2*.



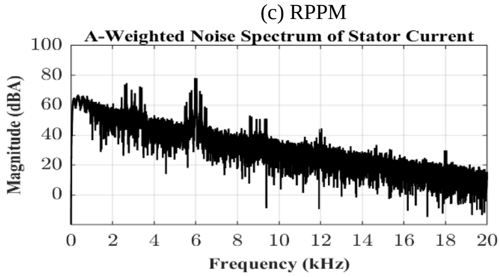
(a) SVPWM



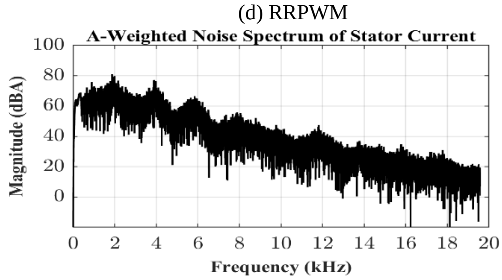
(b) RCPWM



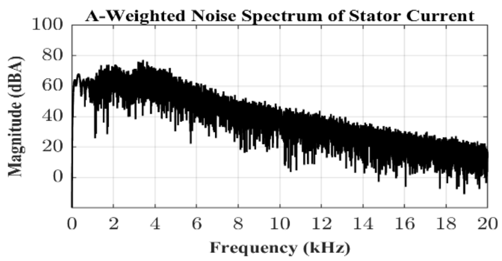
(c) RPPM



(d) RRPWM



(e) PRBS-RCFM



(f) RCFM

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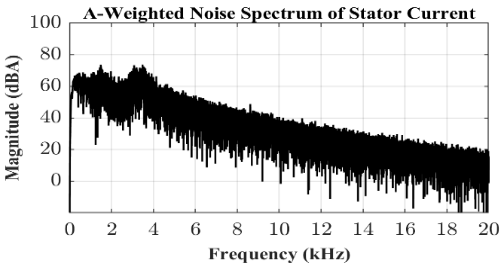
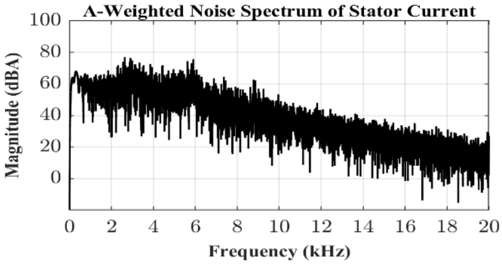
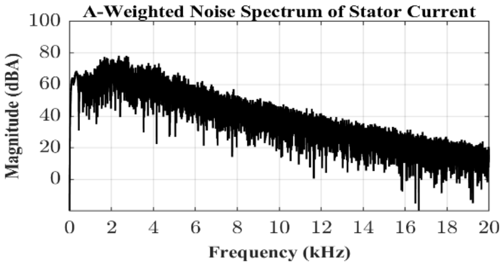


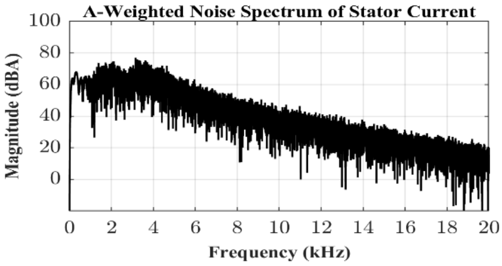
(g) RC-RPPM



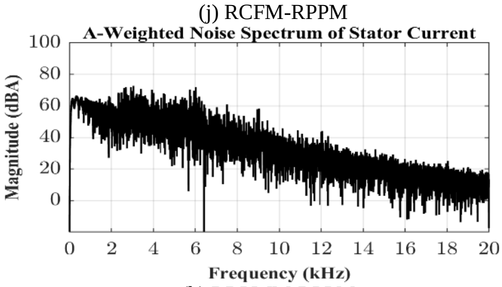
(h) RC-RRPWM



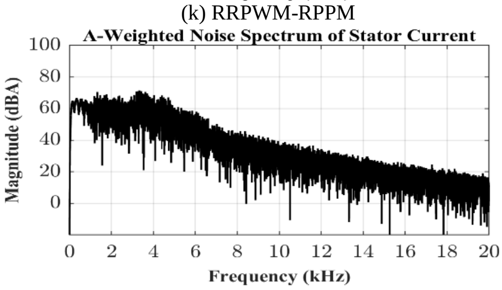
(i) RC-RPPM



(j) RCFM-RPPM



(k) RRPWM-RPPM



(l) RRPWM-RCFM

Figure 4. A-Weighting Acoustical Noise Spectra for Several PWM Schemes

Table 2. Variation of HSF for different Modulation Techniques

S. No.	Modulation Technique	Randomness	HSF
1	SVPWM [16]	Single	3.74
2	RCPWM [16]	Single	3.57
3	RPPM [13]	Single	2.95
4	RRPWM [16]	Single	2.89
5	PRBS-RCFM [15]	Single	2.87
6	RCFM [12]	Single	2.72
7	RC-RRPWM [16]	Conv. Dual	2.65
8	RC-RPPM [13]	Conv. Dual	2.64
9	RCFM-RPPM [12]	Conv. Dual	2.28
10	RC-RCFM [16]	Conv. Dual	2.12
11	**RRPWM-RPPM**	**Proposed Dual**	1.97
12	**RRPWM-RCFM**	**Proposed Dual**	1.81

In certain single random PWM schemes like RCPWM, RPPM, RCFM, and RRPWM, the amount of randomness is quite restricted, resulting in a higher HSF in contrast to other similar methods. In traditional dual random PWM methods like RC-RRPWM, RC-RPPM, RCFM-RPPM, and RC-RCFM, the amount of randomness moderately amplified. This leads to a reduction in HSF. In the proposed dual random PWM methods, viz. RRPWM-RPPM and RRPWM-RCFM, the amount of randomness has been further raised causing HSF to reduce in a greater extent as against to conventional RPWM techniques. Yet, the RRPWM-RCFM scheme provides excellent harmonic dispersion capacity due to favorable qualities of RRPWM & RCFM methods, as evidenced by HSF. Although the RPWM methods are effective in reducing acoustical noise, it faces challenges in terms of design and implementation, efficiency, filtering, stability, and computational burden.

7. CONCLUSION

This article implements the SVPWM and several RPWM techniques to mitigate acoustical noise in SAC of DTC fed OEWIMD for EV applications. Two hybrids dual random PWM schemes, namely RRPWM-RPPM and RRPWM-RCFM, are introduced and compared to previously documented studies. The suggested approaches have been demonstrated to be efficient at dispersing the spread spectrum, as evidenced by HSF. Hence, suggested PWMs were shown exceptional efficacy in reducing acoustical noise, with a reduction of about 18% compared to the traditional optimum dual random PWM method. Furthermore, RRPWM-RCFM shows superior noise reduction capabilities in comparison to RRPWM-RPPM. Moreover, the progress in Wide Band Gap devices (which have the ability to switch frequencies at a rapid rate), the use of Uniform Sampling PWM techniques, and advanced MLIs are the current options for reducing noise in IM drives used in EV applications.

APPENDIX

The specifications of the motor and inverter for simulation study is given as: V_d = 540V, V_L = 400 V, Power = 4 kW, poles = 4, N_{rated} = 1470 rpm, f =50 Hz and T_{rated} =30 N-m, R_s = 1.57 Ohms, R_r = 1.21 Ohms, L_m = 0.165 Henry, L_s = 0.17 Henry, Lr = 0.17 Henry and J = 0.089 Kg m^2.

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REFERENCES

[1] C. C. Chan, "The state of the art of electric and hybrid vehicles," in Proc. of the IEEE, 2002, 90(2), pp. 247-275, doi: 10.1109/5.989873.

[2] S. Pradhan, A. K. Sahoo, and R. K. Jena, "Comparison of DTC and SVM - DTC of Induction motor drive for Electric Vehicle application,", Int. Conf. on Intelligent Controller and Computing for Smart Power (ICICCSP), Jul. 2022, pp. 01-06, doi: 10.1109/ICICCSP53532.2022.9862317.

[3] J. Faiz, M. B. B. Sharifian, A. Keyhani, and A. B. Proca, "Sensorless direct torque control of induction motors used in electric vehicle," in IEEE Trans.on Energy Conv., 2003, 18(1), pp. 1-10, doi: 10.1109/TEC.2002.805220.

[4] H. Stemmler and P. Guggenbach, "Configurations of high-power voltage source inverter drives," Fifth European Conf. on Power Elec. and Appli., Brighton, UK, Sep. 1993. pp. 7-14,

[5] Junha Kim, Jinhwan Jung, and Kwanghee Nam, "Dual-inverter control strategy for high-speed operation of EV induction motors," in IEEE Trans. on Ind. Elect., 2004, 51(2), pp. 312-320, doi: 10.1109/TIE.2004.825232.

[6] Y. Huang, Y. Xu, W. Zhang and J. Zou, "Hybrid RPWM Technique Based on Modified SVPWM to Reduce the PWM Acoustic Noise," in IEEE Trans. on Power Elec., 2019, 34(6), pp. 5667-5674, doi: 10.1109/TPEL.2018.2869980.

[7] Y. Lv, S. Cheng, Z. Ji, X. Li, D. Wang, Y. Wei, X. Wang, and W. Liu, "Spatial-Harmonic Modeling and Analysis of High-Frequency Electromagnetic Vibrations of Multiphase Surface Permanent-Magnet Motors," in IEEE Trans. on Ind. Elec., 2023, 70(12), pp. 11865-11875, doi: 10.1109/TIE.2023.3239905.

[8] J. Y. Chai, Y. H. Ho, Y. C. Chang, and C. M. Liaw, "On Acoustic-Noise-Reduction Control Using Random Switching Technique for Switch-Mode Rectifiers in PMSM Drive," in IEEE Trans. on Ind. Elec., 2008, 55(3), pp. 1295-1309, doi: 10.1109/TIE.2007.909759.

[9] M. M. Bech, J. K. Pedersen, and F. Blaabjerg, "Field-oriented control of an induction motor using random pulse width modulation," APEC 2000. Fifteenth Annual IEEE Applied Power Electronics Conf. and Exposition (Cat. No.00CH37058), New Orleans, LA, USA, 2000, vol.2, pp. 924-931, doi: 10.1109/APEC.2000.822615.

[10] A. M. Stankovic, G. E. Verghese, and D. J. Perreault, "Analysis and synthesis of randomized modulation schemes for power converters," in IEEE Trans. on Power Electronics, 1995, 10(6), pp. 680-693, doi: 10.1109/63.471288.

[11] X. Zhu et al., "A Passive Variable Switching Frequency SPWM Concept and Analysis for DCAC Converter," in IEEE Trans. on Power Electronics, 2022, 37(5), pp. 5524-5534, doi: 10.1109/TPEL.2021.3123190.

[12] A. Boudouda, N. Boudjerda, and A. Aibeche, “dSPACE-based dual randomized pulse width modulation for acoustic noise mitigation in induction motor.” Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2022, 44(10), doi: 10.1007/s40430-022-03814-2.

[13] J. Xu, Z. Nie and J. Zhu, "Characterization and Selection of Probability Statistical Parameters in Random Slope PWM Based on Uniform Distribution," in IEEE Trans. on Power Elec., 2021, 36(1), pp. 1184-1192, doi: 10.1109/TPEL.2020.3004725.

[14] P. Madasamy, R. Verma, C. Bharatiraja, J. Barnabas Paul Glady, T. Srihari, J. L. Munda, L. Mihet-Popa, “Hybrid Multicarrier Random Space Vector PWM for the Mitigation of Acoustic Noise,” Electronics, 2021, 10(12), pp. 1-19, doi: 10.3390/electronics10121483.

[15] S. Nithya Lavanya, T. Bramhananda Reddy, and M. Vijaya Kumar, “Constant and variable switching frequency random PWM strategies for open-end winding induction motor drive”. J. Power Electron., 2020, 20, pp. 1488–1495, doi: 10.1007/s43236-020-00137-0.

[16] A. C. Binoj Kumar, B. Saritha, and G. Narayanan, "Experimental Comparison of Conventional and Bus-Clamping PWM Methods Based on Electrical and Acoustic Noise Spectra of Induction Motor Drives," in IEEE Trans. on Ind. Appl., 2016, 52(5), pp. 4061-4073, doi: 10.1109/TIA.2016.2584578.

[17] A. C. Binoj Kumar, J. S. S. Prasad, and G. Narayanan, “Experimental Investigation on the Effect of Advanced Bus-Clamping Pulse Width Modulation on Motor Acoustic Noise.” IEEE Trans. on Ind. Elec., 2013, 60(2), pp. 433-439, doi: 10.1109/tie.2012.2190371.

[18] R. Alavanthan and A. Kavitha, “Digital implementation of DS-SFH hybrid spread-spectrum modulation technique in three-phase voltage-source converter” Elec. Engg., 2021, 104(3), pp. 1413-1423, doi: 10.1007/s00202-021-01388-1.

[19] Y. Wang, J. Liu, B. Lu and M. Wang, "A Novel Discrete Hybrid Dual Random SVPWM Scheme for Reducing PMSM Harmonic Intensity," in IEEE/ASME Trans. on Mechatronics, 2023, 28(3), pp. 1425-1435, doi: 10.1109/TMECH.2022.3220519.

[20] S. Bhattacharya, D. Mascarella, G. Joos and G. Moschopoulos, "A discrete random PWM technique for acoustic noise reduction in electric traction drives," IEEE Energy Conv. Cong. and Expo. (ECCE), Montreal, QC, Canada, 2015, pp. 6811-6817, doi: 10.1109/ECCE.2015.7310613.

[21] A. R. González, J. R. H. Larrubia, F. M. P. Hidalgo, M. J. M. Gutiérrez, “Discontinuous PWM Strategy with Frequency Modulation for Vibration Reduction in Asynchronous Machines” Machines, 2023, 11(7), pp. 1-22, doi: 10.3390/machines11070705.

[22] R. K. Thakur, R. M. Pindoriya, R. Kumar, and B. S. Rajpurohit, “Effectiveness Analysis of Control Strategies in Acoustic Noise and Vibration Reduction of PMSM-Driven Coupled System for EV and HEV Applications.” Transportation Electrification, 2022, pp. 105-138, doi: 10.1002/9781119812357.ch5.

[23] P. Zhang, S. Wang, and Y. Li, "Three-Phase Two-Level VSIs With Significant PWM Harmonics Dispersion and Improved Performance Using Generalized N-State Random Pulse Position SVPWM With Constant Sampling Frequency," in IEEE Transactions on Power Electronics, 2024, 39(1), pp. 1394-1409, doi: 10.1109/TPEL.2023.3328213.

[24] K. -S. Kim, Y. -G. Jung and Y. -C. Lim, "Shaping the spectra of the acoustic noise emitted by three-phase inverter drives based on the new Hybrid Random PWM technique," 37th IEEE Power Elec. Spec. Conf., Jeju, Korea (South), 2006, pp. 1-6, doi: 10.1109/pesc.2006.1711823.