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Slip Angle Controlled DTC of Open End Winding Induction Motor Drive Using Triple Randomized Decoupled PWM Based Acoustic Noise Mitigation for EV Application

***Abstract**. Low acoustic noise, vibration, and effective DC link utilization are beneficial for Electric Vehicle (EV)s. Direct Torque Control of Induction Motor drives fulfil the demands of the EVs. However, at steady state, flux, torque ripples cause acoustic noise. From the stand point of human health and safety EV noise is required to reduce. This paper proposes a Triple Randomized Decoupled Random Pulsed Width Modulation schemes to suppress acoustic noise for Slip Angle Controlled DTC of an open-end winding induction motor drive for EV application.*

***Streszczenie.** Niski poziom hałasu, wibracji i efektywne wykorzystanie łącza DC są korzystne dla pojazdów elektrycznych (EV). Bezpośrednia kontrola momentu obrotowego napędów silników indukcyjnych spełnia wymagania pojazdów elektrycznych. Jednakże w stanie ustalonym fale strumienia i momentu obrotowego powodują hałas akustyczny. Z punktu widzenia zdrowia i bezpieczeństwa ludzi konieczne jest ograniczenie hałasu pojazdów elektrycznych. W artykule zaproponowano schematy potrójnej losowej, oddzielonej losowej modulacji szerokości impulsu w celu tłumienia hałasu akustycznego dla kodu DTC sterowanego kątem poślizgu napędu silnika indukcyjnego z otwartym uzwojeniem do zastosowań w pojazdach elektrycznych. (**Sterowanie kątem poślizgu DTC silnika indukcyjnego z otwartym uzwojeniem końcowym przy użyciu potrójnego losowego rozdzielonego tłumienia hałasu akustycznego opartego na PWM dla zastosowań EV**)*

Keywords: Acoustic Noise, Direct Torque Control, Electric Vehicle, Open End Winding Induction Motor.
Słowa kluczowe: Hałas akustyczny, bezpośrednia kontrola momentu obrotowego, pojazd elektryczny, silnik indukcyjny z uzwojeniem otwartym.

Introduction

An Electric Vehicle (EV) is a transportation vehicle that runs on electricity. It consists of a motor, gearbox system, and wheels. The electric propulsion system is the key component of an EV [1]. Induction motors (IMs) are commonly used in EVs because to their compact size, robustness, affordability, high velocity, and low maintenance requirements [2]. EVs gain benefits including as higher DC link use, lower acoustic noise, and less vibration. The Direct Torque Control (DTC) technology has proven its ability to meet the stringent needs of modern industries. Recently, there has been an increase in interest in employing DTC for EV applications [3] due to its ability to instantly regulate torque and eliminate the need for online calculations. However, it suffers from torque and flux fluctuations under stable operating conditions and variable frequency operation. The use of a Multi Level Inverter (MLI) can help lessen these fluctuations. The Dual Inverter (DI) topology for Open-End Winding Induction Motors (OEWIMs) [4] has gained popularity. It may find widespread use in EVs [5]. Space Vector Pulse Width Modulation (SVPWM) can avoid difficulties caused by varying switching frequencies. It can also increase the efficiency of the DC bus, which is critical for addressing the needs of EVs. SVPWM-based drives have inherent constraints such as high-frequency harmonics, EMI, acoustic noise, and vibration.

One drawback of SVPWM is that motor drives may vibrate and make noise due to the high-frequency harmonics generated by Voltage Source Inverters (VSIs). This is due to the fact that switching frequencies and human hearing frequencies frequently coincide [6,7]. The harmonics at the sidebands of the multiples of the switching frequency in the load current of the VSI. These harmonics have a high frequency and a narrow bandwidth, which makes the motor vibrate and produce noise in the narrow band that is uncomfortable for the operators. As a result, the introduction of noise pollution in the EV have raised serious concerns that affect productivity, public health, and safety. The switching frequency can be increased to a value higher than 20 kHz in order to reduce this restricted range of noise. However, it will result in higher switching losses [8], lower the conversion efficiency of the VSI, and reduce the distance that the EV can go. The Random Pulse Width Modulation (RPWM) technique is an effective choice for reducing narrow-band noise by dispersing the harmonics of the output voltage and current. This is accomplished by utilizing a constant switching frequency [9]. RPWM technology incorporates random variables into the control unit of the inverter. As per the statistical communication notion [10], when the switching signal undergoes random variation, the power device it controls amplifies the frequency spectrum of the switching harmonics. The RPWM techniques provide cost-effective and efficient solutions to the aforementioned issues [11].

Several researchers proposed various RPWM algorithms, such as Random Pulse Position Modulation (RPPM), Random Lead-Lag PWM (RLLPWM), Random Carrier Frequency Modulation (RCFM), Random Carrier PWM (RCPWM), Random Centre Displacement PWM (RCDPWM), and Random Zero Vector Distribution PWM (RZDPWM) [12,13,14,15]. Overall, RCFM performs better than RPPM in terms of PWM harmonic dispersion. However, the combined RCFM-RPPM technique provides the broadest range of frequencies. [12]. [16] compared the electrical and acoustic noise spectra of SVPWM to two Bus Clamping PWM (BCPWM) techniques, 30° BCPWM and 60° BCPWM. The study found that the former BCPWM scheme outperformed the later in terms of noise reduction. [17] investigated how modern BCPWM techniques affected the acoustic noise produced by motors. [18] investigated the Direct-Sequence Slow-Frequency Hopping method and RPWM for grid-connected Voltage Source Converters (VSCs) employing spread spectrum techniques. [19,20] described the discrete RPWM methods used to address harmonic dispersion. Previously, studies focused on the distribution of harmonics in VSIs and the increase of the noise spectrum in motor drives. Efforts are currently being made to minimize the acoustic noise produced by the motors used in EVs [21,22]. [23] demonstrated the usage of a N-State RPPM-based SVPWM approach for harmonic dispersion. This article presents Decoupled switching mode-based Triple Randomized PWM approaches for the Slip Angle Controlled (SAC) DTC of an Open-End Winding Induction Motor (OEWIM) drive for acoustic noise mitigation in EV applications.

Slip Angle Controlled DTC of OEWIM Drive

Figure 1 shows a block schematic of the DTC of an OEWIM-fed EV using Slip Angle Control (SAC). The EV's commanded speed is compared to its running speed, and the error is processed through a speed regulator (PI regulator), which provides the electromagnetic torque command and compares it to the motor torque. The torque error is now controlled by the torque controller (PI controller), whose output slip angle, when added to the rotor angle (which is the integral of rotor speed), yields a synchronous angle (stator flux angle). Reference stator voltage vectors can be constructed using reference flux, d-axis, and q-axis stator flux connections (derived from the adaptive motor model), as well as stator currents. The 2-Φ to 3-Φ translation produces three-phase sinusoidal reference stator voltages, which can be modulated by SVPWM and/or RPWM. The proposed generalized modulating signal generation is discussed below.

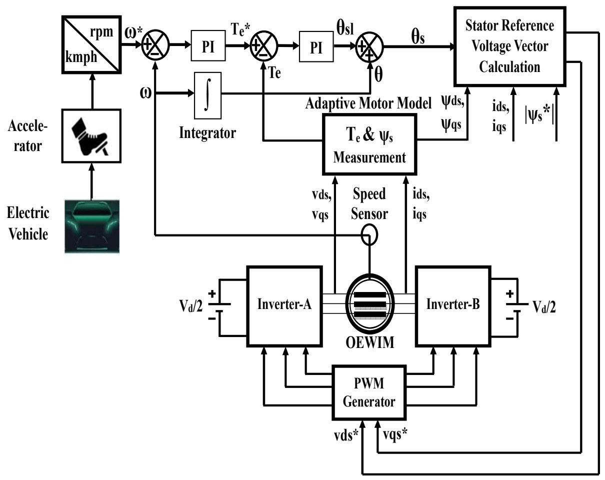


Fig.1. Direct Torque Control of OEWIM-fed EV using Slip Angle Control.

Proposed Modulating Signal Generation for Decoupled Switching Mode

The 3-Φ sinusoidal reference voltages can be expressed as,

(1) $$v_x = v_m sin\left(\omega t - 2(y-1)\frac{\pi}{3}\right)$$

Here x = a, b, and c, y = 1, 2, and 3, v_m = amplitude of the reference sinusoidal voltage

The positive and negative zero sequence signals are given by

(2) $$PCM = \left[(1 - max(va, vb, vc))\right]$$

(3) $$NCM = \left[(-1 - min(va, vb, vc))\right]$$

The modulating signals for inverter-A and B can be generated by

(4) $$v_{Ax}^{*} = \left[1 + (v_x + v_z)\right] * 0.5$$

(5) $$v_{Bx}^{*} = \left(1 - v_{Ax}^{*}\right)$$

(6) $$v_z = k_o * NCM + (1 - k_o) * PCM$$

where vz = the zero-sequence signal, ko = constant = 0.5 for SVPWM.

Fig.2 depicts the schematic diagram of the three-level DI structure. The effective output voltage (3-level) of the two 2-level inverters is applied to the OEWIM's stator terminals. Inverters A and B receive half of the DC link voltage from two isolated DC sources.

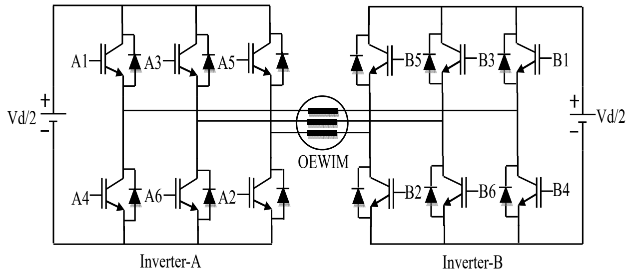


Fig.2. Three-Level DI Topology

The decoupled switching-based SVPWM approach requires two out-of-phase modulating signals (Vr1, Vr2) and a single carrier signal (Vc) for the Three-Level DI depicted in fig.3. The switching spectrum is derived by comparing two modulated signals to a carrier. The comparison of Vr1 and Vc generates gating signals for inverter A, whereas the comparison of Vr2 and Vc generates gating signals for inverter B. Table 1 shows the switching conditions for the operation of DI.

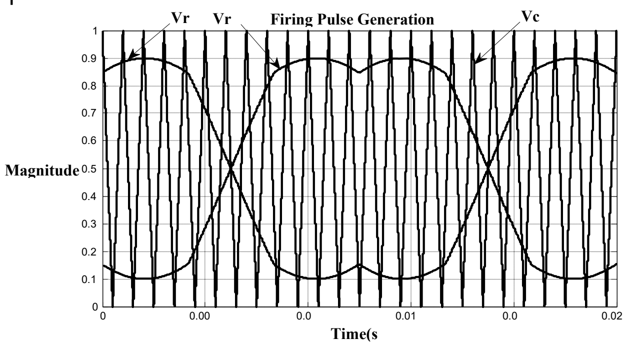


Fig.3. Decoupled PWM Mode

Table 1. Switching Logic for Decoupled Switching Mode

Condition	State of Inverter's Switches	
$V_{ra1} > V_c$	A1 ON	A4 OFF
$V_{ra1} > V_c$	A3 ON	A6 OFF
$V_{ra1} > V_c$	A5 ON	A2 OFF
$V_{ra2} > V_c$	B1 ON	B4 OFF
$V_{ra2} > V_c$	B3 ON	B6 OFF
$V_{ra2} > V_c$	B5 ON	B2 OFF

Random Carrier Generation for Proposed RPWM Schemes

The switching pulse is specified by three parameters: carrier switching period (T), delay time (δ_m), and duty cycle (d_m). Randomized parameters include simply T and δm. The delay time (δ_m) of an arbitrary signal [12] is.

(7) $$\delta_m = \beta_m (1 - d_m)$$

Randomizing the carrier's slope β_m[0,1] which yields δm [0,(1−dm)], and the switching pulse's location varies randomly between the beginning and conclusion of the switching period. The implementation includes a triangular carrier and two randomized variables: switching period T and slope β_m.

Proposed Triple Randomized PWM Scheme-1 (RC-RZDPWM-RPPM)

This method randomized the carrier selection, reference signal and the pulse position. It is a combination of RCPWM, RZDPWM and RPPM. In this scheme, the

RCPWM is accomplished by using inverted and non-inverted carriers which are selected randomly by generating 0's and 1's. If '0' is generated inverted carrier and/or if '1' is generated non-inverted carrier can be selected. For generating 0's and 1's, Pseudo Random Binary Sequence (PRBS) generator can be employed. The RZDPWM is implemented by randomize the modulating signal is upon substituting k_o = a random value between 0 and 1 into equation (6). The following equations illustrate how to implement RPPM.

(8) $$R_\beta = \left[\frac{\beta_{max} - \beta_{min}}{\bar{\beta}} \right]$$

(9) $$\beta \in [\beta min, \beta max]$$

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 $\bar{\beta}$ = average of the delay time = 0.5.

The range of βm is [0,1], giving a maximum value of R_β = 2. R_β has a range of [0,2], which limits the range of β_m. In this investigation, R_β was set at 1.2, resulting in a range of βm between 0.2 and 0.8. This RPWM system produces a carrier at a constant frequency of 3kHz. The pulse position varies randomly depending on the value of β_m.

The variation of parameter βm based on uniform law can be expressed as:

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

Proposed Triple Randomized PWM Scheme-2 (RC-RZDPWM-RCFM)

This method randomized the carrier selection, reference signal and the pulse position. It is a combination of RCPWM, RZDPWM and RCFM. The method of implementing RCPWM and RZDPWM was explained in the above section. The following equations illustrate how to implement RCFM.

(11) $$R_T = \left[\frac{T_{max} - T_{min}}{\bar{T}} \right]$$

(12) $$T \in [T_{min}, T_{max}]$$

Where $Tmin = \bar{T}\left(1 - \frac{R_T}{2}\right)$ and $Tmax = \bar{T}\left(1 + \frac{R_T}{2}\right)$, here $\bar{T}$ is the average of switching period T.

The range of R_T values is [0,2], however R_T is set at 0.2 because as Tmax increases, low-frequency harmonic noise becomes more prominent. This RPWM scheme produces a triangular carrier with a variable frequency of 2.727kHz to 3.333kHz for a nominal frequency of 3kHz. In this RPWM, the pulse is located in the centre of the triangular carrier. Based on the uniform law, the fluctuation of parameter T can be expressed as follows:

(13) $$T = T_{min} + (T_{max} - T_{min}) * R$$

where 'R' is a random number between 0 and 1 produced using the Mersenne Twister (MT) technique.

Acoustic Noise Analysis

Acoustic noise is the result of numerous frequency components interacting together. The A-weighted acoustic noise analysis computes the cumulative influence of noise at each frequency on total noise [20]. Non-weighted noise measurements are described in decibels (dB), whereas A-weighted noise measurements are described in dBA or dB(A).

The weighting function is expressed as follows:

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

f = frequency components in the noise spectrum

The A-weighting noise is given by

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

where dB is the non-weighted noise obtained from Power Spectral Density (PSD) using a stator current periodogram.

One of the most important parameters in acoustic noise assessment is the Harmonic Spreading Factor (HSF), which determines how far the harmonic spectrum propagated. It assesses the RPWM scheme's capacity to efficiently distribute harmonic energy by measuring the dispersion of a waveform's harmonics in frequency domain. In general, lower HSF values indicate better dispersion and a more even distribution of harmonic energy [15]. Using statistical deviation, the equation for HSF [24] is

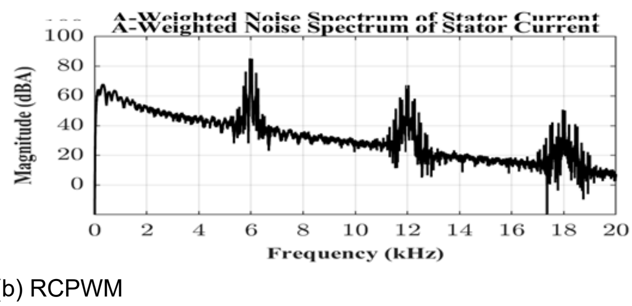
(16) $$HSF = \left[\frac{1}{N} \sum_{i>1}^{N} \left(H_i - H_o\right)^2 \right]^{\frac{1}{2}}$$

Here H_i = amplitude of the i^{th} harmonic, H_o = Avg. value of the amplitude of the harmonics = $\frac{1}{N} \sum_{i>1}^{N} \left(H_i\right)$

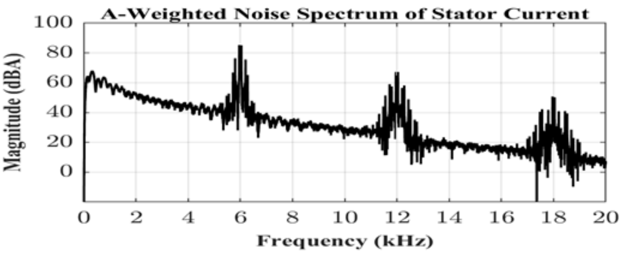
Results and Discussion

These findings are obtained with the EV motor's steady state speed set to 1200 rpm. Fig.4 depicts the A-weighted acoustic noise (dBA) spectrum for SVPWM and other RPWM approaches. Table 2 presents a comparison of HSF for several PWM methods. In conventional dual randomized RPWM schemes such as RC-RZDPWM, RC-RPPM, RCFM-RPPM, and RC-RCFM, the degree of randomization is poor and significantly increased as compared to single randomized RPWM schemes, resulting in reduced HSF. The proposed RPWM schemes, such as RZDPWM-RPPM and RZDPWM-RCFM, have a wider randomization range than both single-randomized RPWM and traditional dual randomized RPWM schemes. Nonetheless, the RZDPWM-RCFM scheme has a higher spread spectrum capability because to the positive characteristics of both RZDPWM and RCFM approaches, as evidenced by the HSF.

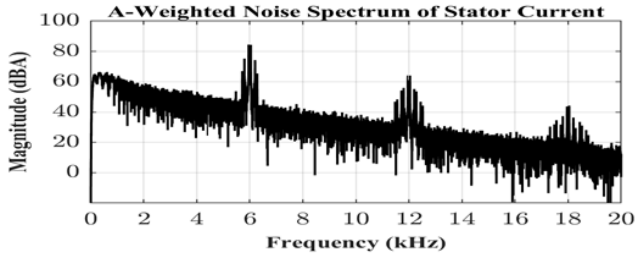
(a) SVPWM



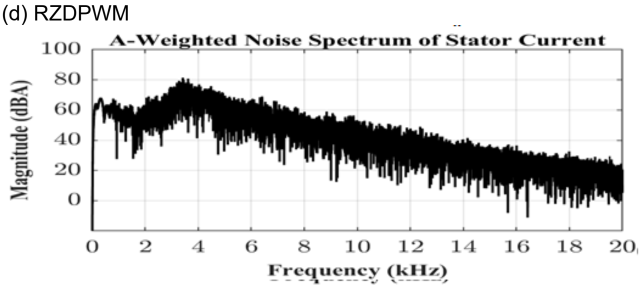
(b) RCPWM



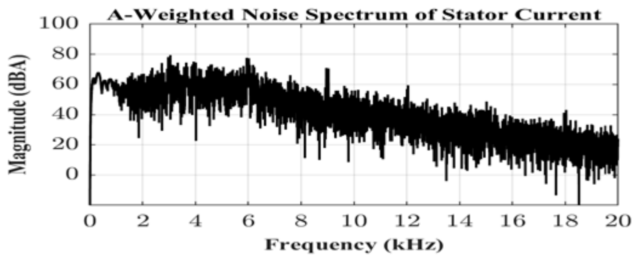
(c) RPPM



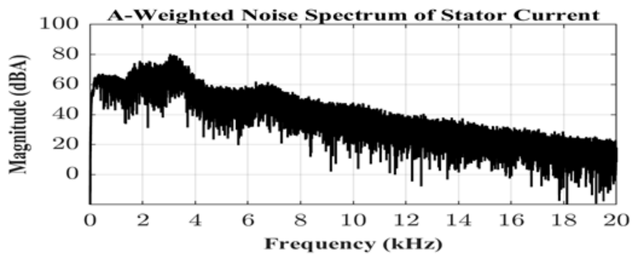
(d) RZDPWM



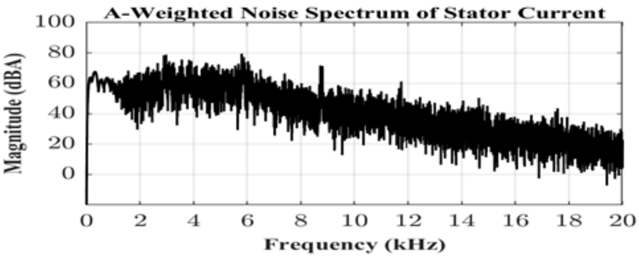
(e) RCFM



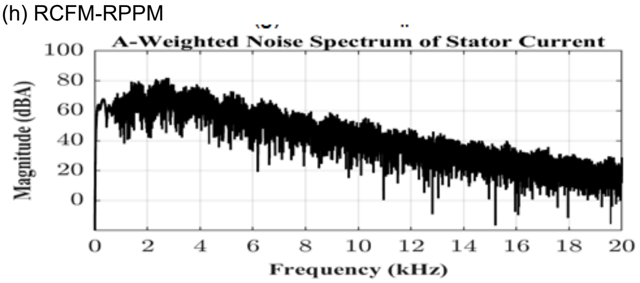
(f) RC-RZDPWM



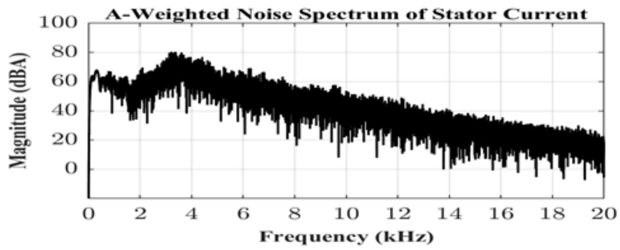
g) RC-RPPM



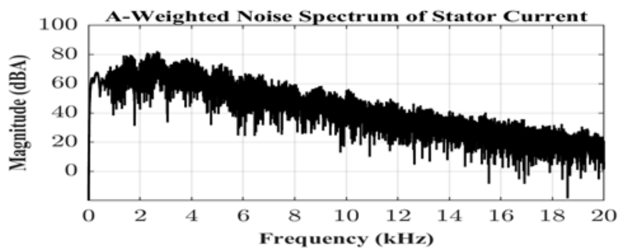
(h) RCFM-RPPM



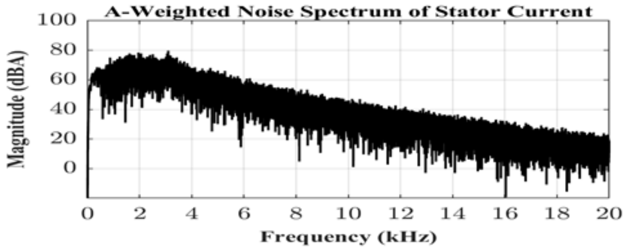
(i) RC-RCFM



(j) RC-RCFM-RPPM



(k) RC-RZDPWM-RPPM



(l) RC-RZDPWM-RCFM

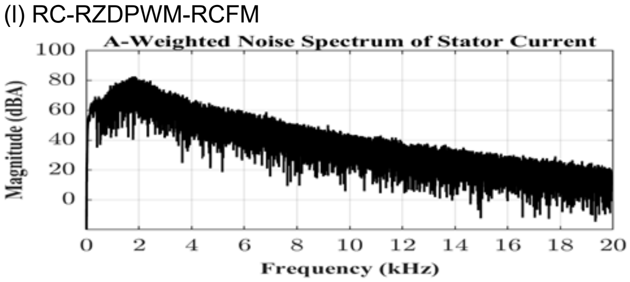


Fig. 4. A-Weighted Acoustic Noise (dBA) Spectrum (Contd…)

Table 2. Comparison of HSF for Various PWM Schemes

S. No.	PWM Scheme	Randomization	HSF
1	SVPWM [15]	Single	6.20
2	RCPWM [15]	Single	6.20
3	RPPM [13]	Single	5.18
4	RZDPWM [15]	Single	5.02
5	RCFM [12]	Single	4.51
6	RC-RZDPWM [15]	Dual	4.40
7	RC-RPPM [13]	Dual	4.30
8	RCFM-RPPM [12]	Dual	4.28
9	RC-RCFM [15]	Dual	4.21
10	RC-RCFM-RPPM [15]	Triple	4.18
11	**RC-RZDPWM-RPPM**	**Proposed Triple**	**3.51**
12	**RC-RZDPWM-RCFM**	**Proposed Triple**	**3.47**

The design considerations used for the simulation study are as follows: i) Specifications of Inverter and Induction Motor: Vd = 540V, V = 400 V, P = 4 kW, p = 4, Nrated = 1470 rpm, f =50 Hz and Trated =30 N-m, Rs = 1.57 Ohms, Rr = 1.21 Ohms, Lm = 0.165 Henry, Ls = 0.17 Henry, Lr = 0.17 Henry and J = 0.089 Kg - m^2.

Conclusion

In this article, the SAC-based DTC of OEWIM using decoupled PWM mode is implemented for acoustic noise analysis in EV applications using SVPWM and various RPWM schemes. Two triple randomized RPWM schemes such as RC-RZDPWM-RPPM and RC-RZDPWM-RCFM are proposed and compared with works reported earlier. The proposed methods are proven to be effective in spreading the harmonic spectra as indicated by the values of HSF. Therefore, the proposed methods are exhibiting superior performance as far as mitigation of acoustic noise is concerned. Also, RC-RZDPWM-RCFM reduces the noise effectively as compared to RC-RZDPWM-RPPM.

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