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Slip angle control based DTC of open-end winding induction motor drive using dual randomized decoupled PWM for acoustic noise mitigation in EV application

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ABSTRACT

Reduced vibration, acoustic noise, and higher DC link utilization are advantageous for industrial drives and/or electric vehicle (EV) drives. Direct torque controlled (DTC) induction motor drives fulfill the stringent demands of the EV and/or industries of the modern era. However, torque and flux ripples occur at steady state conditions, resulting in increased acoustical noise. As a result, EV and/or workplace noise has emerged as a major issue, both in terms of human health and safety. The space vector pulse width modulation (SVPWM) improves DC bus utilization. However, SVPWM is less effective in reducing acoustic noise. Many random PWM (RPWM) approaches, including random zero vector PWM (RZVPWM), random pulse position modulation (RPPM), random carrier frequency modulation (RCFM), and RCFM-RPPM are effective in reducing acoustic noise. However, due to the decreased level of randomization, reducing noise remains problematic. This research proposes a decoupled hybrid dual randomized RPWM (HDRRPWM) schemes for slip angle control based DTC of an open-end winding induction motor drive for acoustic noise mitigation in EV applications. The suggested schemes aim to demonstrate the efficacy of HDRRPWMs in dispersing the acoustic noise spectrum as compared to traditional methods.

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1. INTRODUCTION

Electric vehicle (EV)s are road vehicles with electric propulsion, which consist of motor, transmission system, and wheels. The electric propulsion system is the heart of EV [1]. Induction motor (IM)s is commonly used in EVs due to their compact size, durability, low cost, high speed, and low maintenance [2]. EVs and/or industrial drives benefit from increased DC link utilization, lower acoustic noise, and vibration. The direct torque control (DTC) approach has proven its ability to meet the stringent demands of industries & EVs of the modern era. In recent years DTC has gained attraction for EV applications [3] due to its rapid torque control, and less on-line computation. However, it suffers from torque, flux ripples during steady-state conditions and variable switching frequency operation. These ripples can be mitigated by the use of a multi-level inverter (MLI)s. Among many MLIs, dual inverter (DI) topology for open-end winding induction motor (OEWIM) is preferred [4] and can be used extensively in EVs [5]. Variable switching frequency issues can be avoided by space vector pulse width modulation (SVPWM). SVPWM improves DC bus utilization as demanded by EVs. High-frequency harmonics, electromagnetic interference (EMI), acoustic noise, and vibration are all inherent drawbacks of SVPWM-based drives.

Among the demerits of SVPWM, the high-frequency harmonics of voltage source inverter (VSI)s are responsible for the vibration and noise of motor drives, as the range of human hearing typically coincides with the switching frequency [6], [7]. The load current of the VSI comprises harmonics at the sidebands of the multiples of switching frequency. These harmonics have the nature of high frequency and narrow bandwidth, which results in the motor vibrating thereby producing narrow-band noise making operating personnel feel uncomfortable. Hence, EV and/or workplace noise has emerged as a major issue, both in terms of efficiency, human health, and safety. This narrow band noise can be reduced by increasing the switching frequency to more than 20 kHz. However, it will increase the switching losses [8] reduce the conversion efficiency of the VSI, and deteriorate the distance of run of the EV.

Random pulse width modulation (RPWM) approach is an alternative solution for reducing narrow band noise as it disperses the output voltage and current harmonics, with fixed switching frequency [9]. RPWM technology incorporates random variables into the inverter's control unit. According to the statistical communication principle [10] when the switching signal changes randomly, the power device controlled by it improves the frequency spectrum of the switching harmonics. The RPWM techniques are effective and costless solutions to the above-mentioned issues [11].

Various researchers presented different RPWM techniques such as random pulse position modulation (RPPM), random lead-lag PWM (RLLPWM), and random carrier frequency modulation (RCFM). Random carrier PWM (RCPWM), random center displacement PWM (RCDPWM), and random zero vector distribution PWM (RZDPWM) [12]-[16]. In general, RCFM is better than RPPM in terms of PWM harmonic dispersion. Nonetheless, the combined RCFM-RPPM technique provides the largest spread spectrum [12]. Binojkumar *et al.* [17] compared electrical and acoustic noise spectra for SVPWM and two bus clamping PWM (BCPWM) such as 30° BCPWM and 60° BCPWM methods, and showed that the former BCPWM scheme is better than the latter. [18] investigated the effect of advanced BCPWM methods on motor acoustic noise. [19] made the comparative spread spectrum analysis between the direct-sequence slow-frequency hopping scheme and RPWM for grid-connected voltage source converter (VSC). Wang *et al.* [20], and Bhattacharya *et al.* [21] reported the discrete RPWM techniques for harmonic dispersion. In past years, researchers have focused their attention on the dispersion of harmonics of VSI, the spread of the noise spectrum of motor drives, etc. In recent years, they are currently working on the mitigation of acoustic noise produced by the motors employed in EVs [22]-[25]. Most recently an N-State RPPM based SVPWM [26] is reported for harmonic dispersion. In this paper, two hybrid dual randomized RPWM (HDRRPWM-1,2) are proposed for the decoupled PWM-based DTC of OEWIM in EV applications. These schemes compare the performance of conventional single randomized RPWM (SRRPWM) and dual randomized RPWM (DRRPWM) techniques in spreading the noise spectra of EV motor over the audio frequency range.

2. PROPOSED SLIP ANGLE CONTROL BASED DTC OF OEWIM FED EV

The block diagram of the DTC of OEWIM fed EV using slip angle control (SAC) is shown in Figure 1. The commanded speed of the EV is compared with the running speed, and then this error is processed through speed regulator (PI regulator) which generates the electromagnetic torque command and is then compared with the motor torque. The torque error now is controlled by the torque controller (PI controller) and whose output slip angle is added to the rotor angle (which is the integral of rotor speed) produces a synchronous angle (stator flux angle).

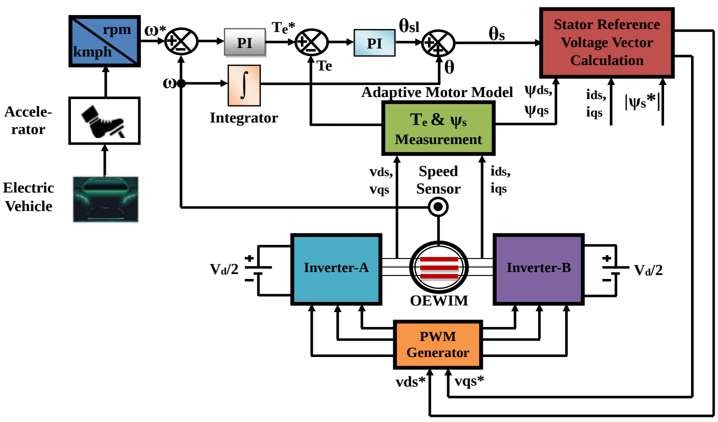

Figure 1. Direct torque control of OEWIM fed EV using slip angle control

From the knowledge of reference flux, d-axis, and q-axis stator flux linkages (which are calculated from the adaptive motor model) and stator currents, reference stator voltage vectors can be generated. By using the 2-Φ to 3-Φ transformation, the three-phase sinusoidal reference stator voltages are obtained and can be modulated using SVPWM and/or RPWM. The proposed generalized modulating signal generation is explained as follows.

3. PROPOSED GENERALIZED DECOUPLED MODULATING SIGNAL GENERATION

The 3-phase sinusoidal reference voltages can be expressed as (1).

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

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) and (3).

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

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

The modulating signals for inverter-A and B can be generated by (4)-(6).

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

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

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

where v_z = the zero-sequence signal, k_o = constant = 0.5 for SVPWM.

In the decoupled switching-based SVPWM technique two out-of-phase modulating signals such as (Vr1, Vr2) and a single carrier signal (Vc) are needed for the three-level DI shown in Figure 2. By comparing two-modulated signals with a carrier the switching spectrum can be obtained. Comparison of Vr1 and Vc generates gating signals for inverter-A, whereas comparison of Vr2 and Vc generates for inverter-B. Figure 3 shows the schematic diagram of the 3-level DI topology. The effective output voltage (3-level) of the 2-level inverters is applied across stator terminals of the OEWIM. Inverters A and B are fed by half of the DC link voltage using two isolated DC sources. The switching conditions for the operation of DI are depicted in Table 1.

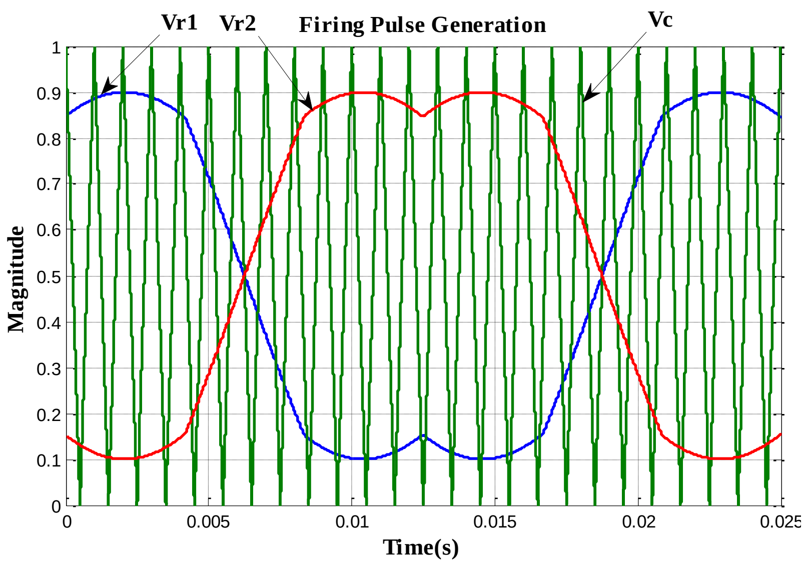

Figure 2. Decoupled PWM mode

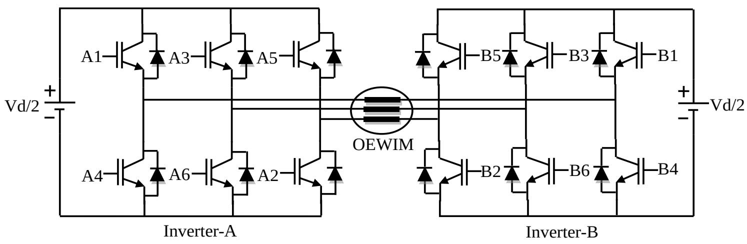

Figure 3. Three-level DI topology

Table 1. Switching logic

Condition	State of Inverter's Switches	
Vra1 > Vc	A1 ON	A4 OFF
Vrb1 > Vc	A3 ON	A6 OFF
Vrc1 > Vc	A5 ON	A2 OFF
Vra2 > Vc	B1 ON	B4 OFF
Vrb2 > Vc	B3 ON	B6 OFF
Vrc2 > Vc	B5 ON	B2 OFF

4. RANDOM CARRIER GENERATION FOR PROPOSED RPWM SCHEMES

The switching pulse is defined by three parameters such as the switching period of the carrier T, delay time δ_m, and the duty cycle d_m. Among them, randomized parameters are T and δ_m only. For any arbitrary signal, the delay time δ_m of the signal is expressed as (7) [12].

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

Randomization of the slope β_m [0, 1] of the carrier gives the random δ_m [0, $(1 - d_m)$], and the resulting location of the switching pulse changes randomly between the starting and ending edge of the switching period. It is implemented with the triangular carrier along with two randomized variables: the switching period T and the slope β_m.

The main challenge of RPWM techniques is generating random numbers. a pseudo random number (PRN) generator using the Mersenne Twister (MT) approach is used in this work. This algorithm generates high-quality, faster and uniformly distributed real PRNs in the closed interval of [0,1] with a long period of length (2^{19937}-1). The randomness levels R_T and R_β define the lower (T_{min}, β_{min}) and upper (T_{max}, β_{max}) boundaries of the random variables T and β_m.

4.1. Proposed HDRRPWM-1 (RZDPWM-RPPM)

In this method, both reference signal and pulse position were randomized. It is the combination of RZDPWM and RPPM. In this RPWM, the modulating signal is obtained by putting k_o = random number between 0 and 1 in (6). The (8) and (9) describe the implementation of RPPM:

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

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

where $\beta min = \overline{\beta}\left(1 - \frac{R_\beta}{2}\right)$ and $\beta max = \overline{\beta}\left(1 + \frac{R_\beta}{2}\right)$ and $\overline{\beta}$ = average of the delay time = 0.5.

The range of β_m is [0,1] which gives max. value of R_β = 2. In general, R_β has a range of [0,2] which decreases the range of β_m. Therefore, R_β was taken as 1.2 in this study, which makes β_m varies in the range of [0.2,0.8]. This RPWM scheme gives a carrier with a constant frequency of 3 kHz. However, the pulse position is varied randomly based on the value of β_m. The variation of parameter β_m based on uniform law, the expression for β_m can be written as (10).

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

4.2. Proposed HDRRPWM-2 (RZDPWM-RCFM)

In this scheme, both reference signal and carrier frequency were randomized. It is a combination of RRPWM and RCFM. In this RPWM, the modulating signal is obtained by putting k_o = random number between 0 and 1 in (6). The (11) and (12) describe the implementation of RCFM.

$$R_T = \left[\frac{T_{max} - T_{min}}{\overline{T}}\right] \tag{11}$$

$$T \in [Tmin, Tmax] \tag{12}$$

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

The range of values of R_T is [0,2], however, R_T is chosen as 0.2, since higher the T_{max}, low-frequency harmonic noise becomes significant. This RPWM scheme generates a triangular carrier with a variable frequency between 2.727 kHz and 3.333 kHz for a nominal frequency of 3 kHz. In this RPWM, the pulse position is at the middle of the triangular carrier. The variation of parameter T based on uniform law the expression for T can be written as (13):

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

where 'R' is a random number in the range of [0,1] and is obtained by using the MT algorithm.

5. ACOUSTIC NOISE ANALYSIS

Acoustic noise is the effect caused by multiple frequency components interacting together. The human ear's sensitivity to tonal frequencies is typically modeled using frequency weighting curves. Among various weighting curves, A-weighting is the most widely used family of curves described in the IEC 61672-2013 standard. The human ear is more sensitive to specific frequencies within the audio frequency range of 0.1-20 kHz [21]. However, human ears are frequency selective, having higher sensitivity between 500Hz and 6kHz, also the A-weighting curve having peaks at 1-5 kHz, indicating the frequencies most likely perceived by the human ear. Therefore A-weighting noise analysis accurately assesses the acoustic noise. A weighted noise assessment excludes noises that human ears cannot hear.

The A-weighted acoustic noise analysis gives the cumulative effect of the noise at each frequency on overall noise [21]. Non-weighted noise measurements are described in decibels (dB), while A-weighted noise measurements are described in dBA or dB(A). The expression for the weighting function is given by (14):

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

where f = frequency components in the noise spectrum. The A-weighting noise is given by (15):

$$dBA(f) = dB + 20 * log\big(R_A(f)\big) \tag{15}$$

where dB is the non-weighted noise obtained from power spectral density (PSD) using a periodogram of stator current.

One of the key factors for acoustic noise measurement is the harmonic spreading factor (HSF), which indicates the spreading of the harmonic spectrum. This factor has practical applications in a wide range of fields that use PWM, including control systems, power electronics, and telecommunications. It evaluates the RPWM scheme's capability to efficiently disperse harmonic energy by examining the dispersion of a waveform's harmonics in the frequency domain. In general, lower HSF values suggest better dispersion and a more equal distribution of harmonic energy [15]. Based on statistical deviation the equation for HSF [27] is (16):

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

where H_i = amplitude of the i^{th} harmonic, and H_o = Average value of the amplitude of the harmonics = $\frac{1}{N}\sum_{i>1}^{N}(H_i)$.

6. RESULTS AND DISCUSSION

The Simulink model for SAC based DTC of OEWIM fed EV using decoupled PWM is shown in Figure 4. The operation of above model is explained in the section 2. The simulation study is carried out for the EV motor's speed reference is set at 1200 rpm. The A-weighted acoustic noise spectra were presented and compared for various works reported earlier with the proposed work. Also, HSF was calculated for the same.

In this study, the inverter dead time and sampling time are assumed to be zero and 1μs respectively. Figures 5(a)-(l) show the A-weighted acoustic noise (dBA) spectrum of SVPWM and various RPWM techniques. The HSF for various PWM schemes is tabulated in Table 2. The comprehensive analysis of the spread spectrum capability of different PWM schemes is illustrated as under.

The high-frequency harmonics of SVPWM-based VSIs are responsible for the vibration and noise of motor drives as the frequency range of human hearing typically coincides with the switching frequency [8]. So, its power spectrum has peaks at multiples of switching frequencies. Therefore, the motor produces high-pitch acoustic noise as indicated by the large value of HSF. In RPWM techniques switching signal changes randomly, and the power device controlled by it improves the frequency spectrum of the switching harmonics. In RCPWM, similar pulse patterns are generated like SVPWM even though random carriers are selected, hence it has the same HSF as that of SVPWM. In RPPM, the switching frequency is constant and pulse position was randomized only, i.e. its degree of randomness is very much limited and therefore offers high HSF compared to its counterparts. In the case of RZDPWM, the zero vector was distributed randomly over a fundamental sub-cycle. Its power spectrum focuses on multiples of switching frequency because zero-vector duration at high modulation is short and has little random distribution range [12]. Thus, its HSF is close to RPPM. On the other hand, the RCFM and/or PRBS-RCFM generate carriers with random frequency having a high degree of randomness, enabling it to spread the spectrum more effectively than its counterpart.

In conventional dual randomized RPWM schemes such as RC-RZDPWM, RC-RPPM, RCFM-RPPM and RC-RCFM, the degree of randomness is increased moderately and is high compared to single randomized RPWM schemes causes less HSF. In proposed RPWM schemes such as RZDPWM-RPPM and RZDPWM-RCFM, the randomness range increased further compared to both single-randomized RPWM and conventional dual randomized RPWM schemes. Nevertheless, the RZDPWM-RCFM scheme offers superior spread spectrum capability owing to the good attributes of both RZDPWM and RCFM techniques as indicated by the value of HSF.

The proposed and other RPWM techniques are good at reducing EMI in power converters compared to SVPWM. However, there may be a significant EMI conflict that can be seen in power line communication (PLC) systems, where both power converters and communication systems exist. The design considerations used for the simulation study are: i) Specifications of inverter and induction motor: V_d=540 V, V=400 V, P=4 kW, p=4, N_{rated}=1470 rpm, f=50 Hz, and T_{rated}=30 N-m; and ii) Parameters of the induction motor: R_s=1.57 Ohms, R_r=1.21 Ohms, L_m=0.165 Henry, L_s=0.17 Henry, L_r=0.17 Henry, and J=0.089 Kg-m^2.

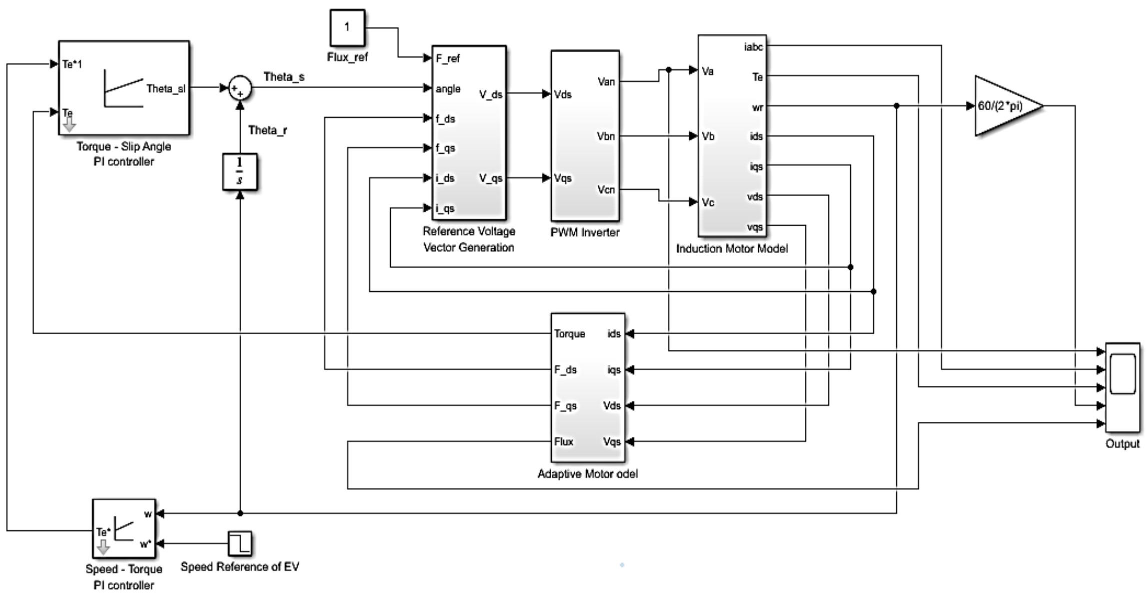

Figure 4. Simulink model for SAC based DTC of OEWIM fed EV using decoupled PWM

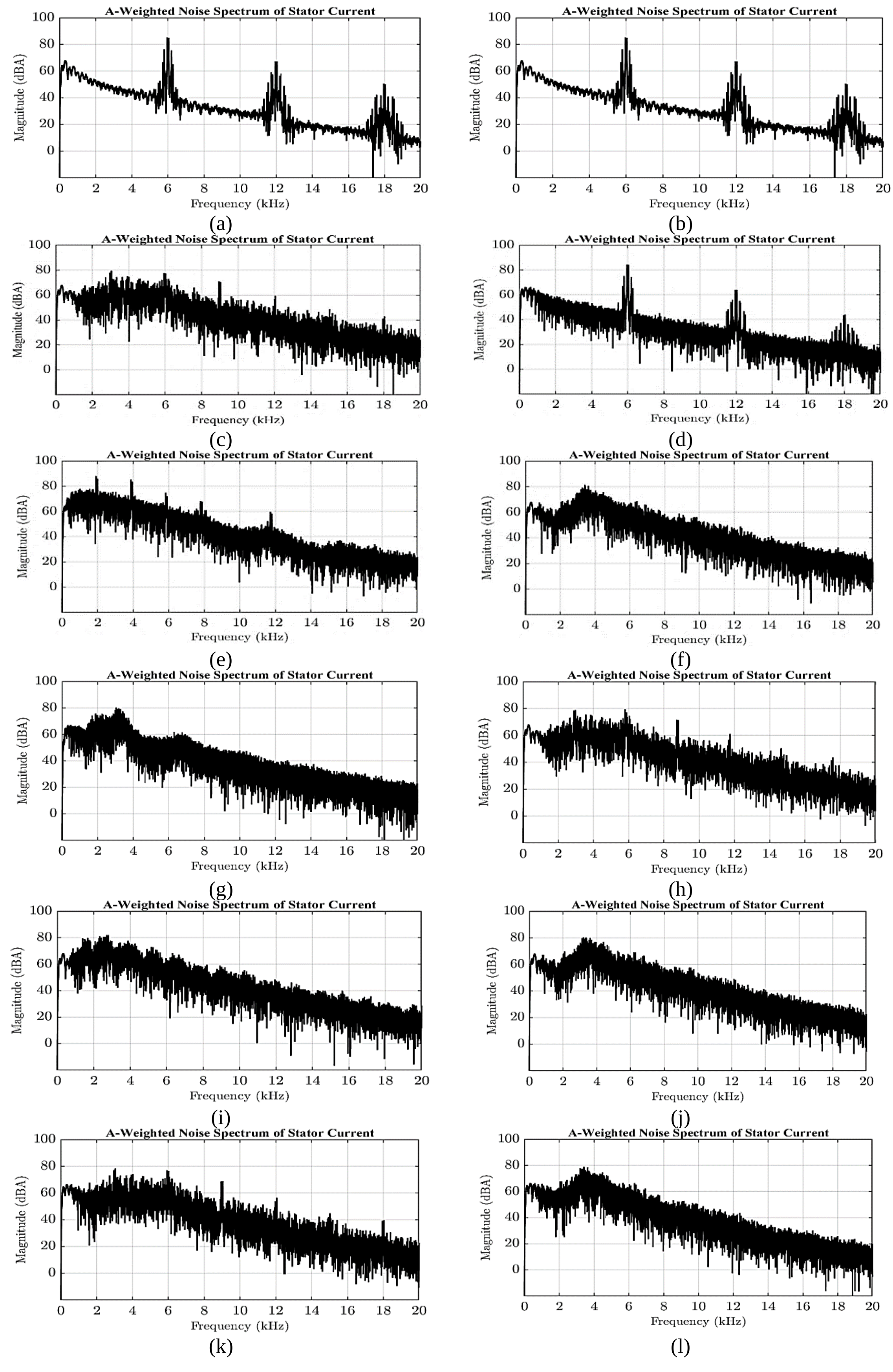

Figure 5. A-weighted acoustic noise (dBA) Spectrum for (a) SVPWM, (b) RCPWM, (c) RPPM, (d) RZDPWM, (e) PRBS-RCFM, (f) RCFM, (g) RC-RPPM, (h) RC-RZDPWM, (i) RC-RPPM, (j) RCFM-RPPM, (k) RZDPWM-RPPM, and (l) RZDPWM-RCFM

Table 2. Comparison of HSF for various PWM schemes

S. No.	PWM Scheme	Randomization	HSF
1.	SVPWM [16]	Single	6.20
2.	RCPWM [16]	Single	6.20
3.	RPPM [13]	Single	5.18
4.	RZDPWM [16]	Single	5.02
5.	PRBS-RCFM [15]	Single	4.54
6.	RCFM [12]	Single	4.51
7.	RC-RZDPWM [16]	Dual	4.54
8.	RC-RPPM [13]	Dual	4.28
9.	RCFM-RPPM [12]	Dual	4.21
10.	RC-RCFM [16]	Dual	4.18
11.	RZDPWM-RPPM	Proposed dual	3.99
12.	RZDPWM-RCFM	Proposed dual	3.73

7. 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 hybrids dual randomized RPWM schemes such as RZDPWM-RPPM and 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, RZDPWM-RCFM reduces the noise effectively as compared to RZDPWM-RPPM. Furthermore, the advancements in Wide Band Gap devices (high switching frequency capability), uniform sampling PWM (UPWM) schemes, and MLI topologies are the contemporary solutions in mitigating noise for VSI-fed motor drives.

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