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A Tripartite Random Pulse Width Modulator for Efficient Distribution of Harmonic Power in High Power AC Drives

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Abstract

The incessant research effort on variable speed AC drives has resulted several performance enhanced pulse width modulation (PWM) strategies with improved features like the efficient exploitation of DC link voltage, the reduced voltage total harmonic distortion (THD), the ease of filtering, lesser switching losses etc. The radical contemplation reveals that the intricacy prevails in the harmonic spreading savvy, and the remnant task of distributing the harmonic power in the PWM strategies has not been addressed to the fruition, hitherto. The random PWM (RPWM) schemes are successful in reducing the harmonic spread factor (HSF) significantly, whilst to retain the basic metrics, the tenet of introducing randomness to be amalgamated with the high performance deterministic PWM strategies. This research paper suggests an inventive RPWM, a tripartite RPWM (TRPWM), wherein both the random position and random carrier abilities pervade to the pristine space vector PWM (SVPWM) to invigorate the harmonic power spreading feature in the three phase voltage source inverter (VSI) fed induction motor drive system. The reference waves are obtained by the time calculation of states in respective sectors of the space vector diagram. The initial carrier selection amid the four triangular carriers is done using two pseudo random binary sequence (PRBS) generators. As a sequel of this randomized carrier generation, the gating pulses are generated by comparing with reference signals, and finally, the positional randomization is incorporated using a third PRBS. A formulaic investigation on the harmonic spreading ability of the pristine SVPWM, the SVPWM with single randomness, and the suggested TRPWM is performed in MATLAB/Simulink platform. Further the experimental corroboration is done in a proof-of-concept (POC) prototype, with the patronage of a SPARTAN-6 (XC6SLX45) FPGA processor, an IGBT based three phase VSI and a 2.2kW, 14Nm induction motor.

Keywords: *Distribution of harmonic power, harmonic spread factor (HSF), random pulse width modulation, tripartite RPM (TRPWM), voltage source inverter (VSI).*

1. Introduction

The significance and the utilization of voltage source inverters (VSIs) are increasing unrivalled in industrial applications, day by day [1]-[2]. The principle of the pulse width modulation (PWM) strategy, which is used to synthesize the desired output voltage of VSI, influences the output quality [3]-[4]. Sinusoidal PWM (SPWM) and its variants

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prevail as the most imperative PWM strategies for VSI drives. PWM-VSIs are increasingly involved in the power conversion systems of modern industries [5]. As a sequel of the SPWM, a host of PWM switching strategies have been suggested in the last few decades to confront the application demanded waveforms quality[6]-[8]. The resourceful PWM tenets not only pledge high quality output, but also augment the overall system performance [9]-[10]. Most VSI drives utilize the SPWM and its variations owing to their fixed switching frequency, lesser ripple current, and determined harmonic spectrum characteristics [11]. This kind of carrier based, natural sampled PWM methods establish a “per carrier cycle average output voltage” equal to the reference voltage. The establishment of PWM pulse patterns by a modulation scheme is simply an amplitude to pulse width conversion, and hence the resulting harmonic profile is deterministic, in turn these traditional PWM strategies are named as deterministic PWM methods.

In addition to the requirements like the waned distortion, the improved fundamental, the simple filtering etc. the industrial electric drives appended additional constraints on the VSI drives, which are limited values of the acoustic noise and the vibration [12]. The harmonic spectrum of output voltage in any deterministic PWM method has a huge number of harmonic components about the carrier (switching) frequency and its integer multiples. Due to this, the AC drives create an acoustic noise, the radio interference, and the undesirable harmonic heating [13]. To reduce the acoustic noise and the associated vibrations, the discrete harmonic clusters inherited in the deterministic PWM strategies must be distributed over the complete range of frequency spectrum. That is, instead of having few dominant harmonics (at discrete frequencies), having colossal number of harmonics (as a continuous frequency band) with an insignificant magnitude. More preciously, it requires a shift from deterministic PWM schemes to non-deterministic PWM schemes. For instance this non-deterministic feature can be obtained by varying either the pulse position or the switching frequency, randomly and as a result the harmonics components will spread over a band and the discrete harmonic components can be appreciably diminished. This is the indispensable tenet of random pulse width modulation (RPWM) methods, which have attracted the application engineers in the recent years [14]. Though the Figure 1 accommodates the comprehensive family tree of the RPWM [15], still there exist several categories.

An intensive research effort has been noticed in the field of RPWM applied to AC drives. To exhort the ambit importance a search on the keyword "random pulse width modulation" is performed in the IEEE portal. The Figure 2 shows the surfeit of the keyword in the adored publisher's portal, year wise. The limbs indicate both year and the count of the paper published (year, count). The count of entirety spells the heap of research interest on this breed of PWM method, which is 830 [16]. The pseudorandom carrier produced in [17] is a bizarre one than random switched carrier, wherein the zero ('0') and one ('1') states of the pseudo random binary sequence (PRBS) generator chooses between the a fixed frequency carrier and the inverted form. This strategy is referred as random carrier PWM (RCPWM) in this article.

A kind of hybrid RPWM suggested in [18] mixes the characteristics both the RCPWM and the random pulse position PWM (RPPWM). The corroboration based on TMS320LF2407 DSP has been successful in spreading the acoustic noise in the 1.5kW three-phase induction motor under the 2.5A load condition. P.Muthukumar et al. have devised a co-simulation procedure for implementing the RCPWM using Spartan3E500 FPGA device to effectively scatter the acoustic noise spectra in the three phase inverter drive [19]. The successful implementation of RCPWM for multilevel inverter fed brushless DC motor has been presented [20]. Many authors have attempted to incorporate the randomness in the prevailing variations of space vector PWM (SVPWM) [21]-[22].

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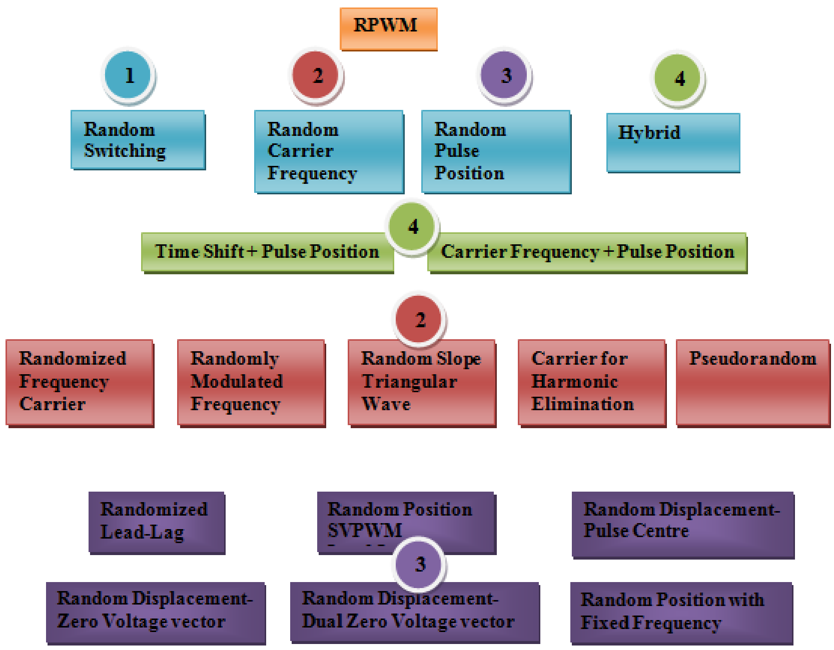

Figure 1. Growing Family of RPWM

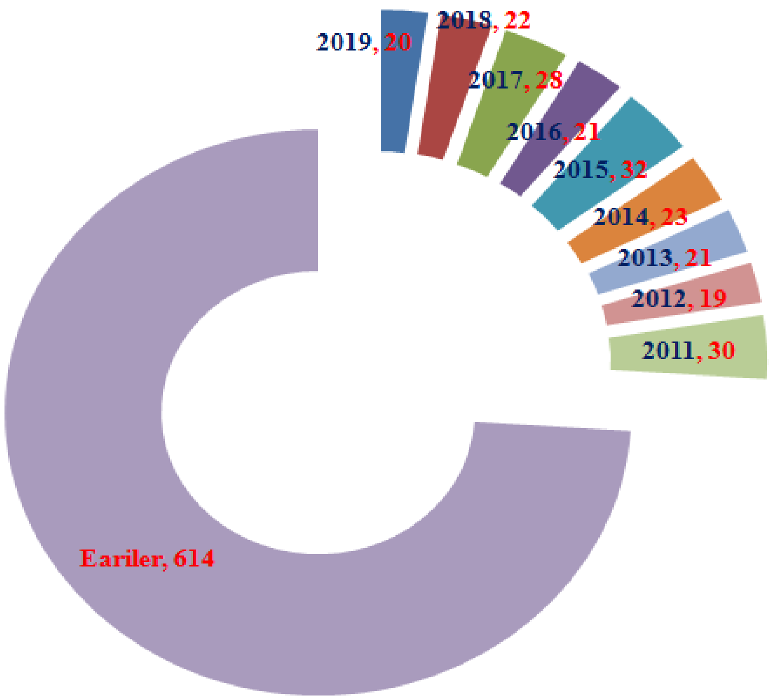

Figure 2. Surfeit of RPWM Articles - Year Wise Data (IEEE)

The onus of any RPWM lies in two fold; the first one is the introduction of high randomness to enable the distribution of the harmonic power; the second one is retaining the primary performance indices like the fundamental magnitude of output voltage (voltage gain), total harmonic distortion (THD) etc. in the acceptable limit. This paper has carefully viewed the lapses this field, and inventively amalgamates the SVPWM with the RCPWM and RPPPWM to have a praiseworthy harmonic spreading effect in the high

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performance three phase PWM scheme suggested. The suggested RPWM is named as a tripartite RPWM (TRPWM). In a formulaic study involving both theoretical investigation and experimentation, the basic SVPWM, random carrier cuddled SVPWM, random pulse position cuddled SVPWM and finally the proposed TRPWM are compared for output voltage fundamental component (V_1), harmonic spread factor (HSF), THD and the harmonic spectrum. All the four PWM strategies subsumed are coded using the very high speed integrated circuit hardware description language (VHDL) in a structured optimum architecture. The ModelSim 6.3 is employed for the functional simulation, and the register transfer level (RTL) authentication and the accomplishment are done in the Xilinx ISE 13.2 synthesize tool. Finally, the modulators are configured to the SPARTAN-6 XC6SLX45 field programmable gate array (FPGA) device. The generated pulses are fed to the IGBT based VSI to drive the 2.2kW, 14Nm induction motor. The proposed TRPWM is successful in spreading the harmonic power than other three cases subsumed without sacrificing the primary indices.

2. Tripartite Random PWM

The Figure 3 shows the scheme for the proposed TRPWM, which involves three stages as suggested by the name to synthesize the required gate pulses. The architecture consists of a triangular carrier generator, a space vector reference wave generator, PRBS generators, multiplexers, comparators, and apposite logic gates.

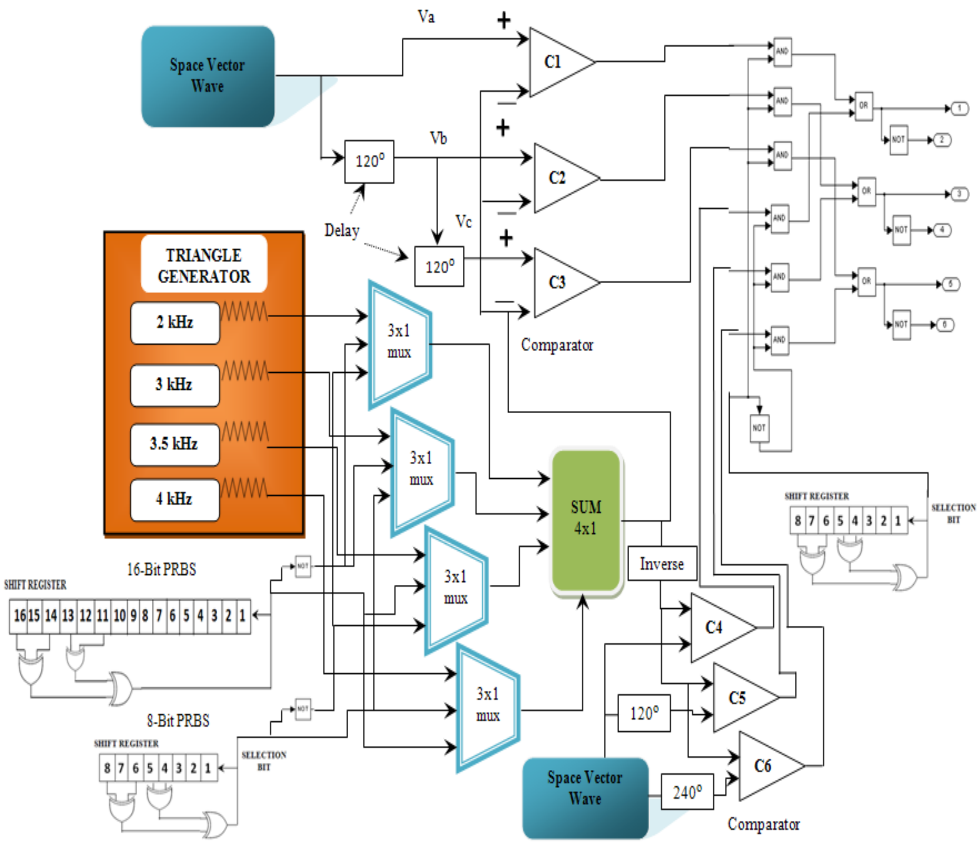

Figure 3. The scheme of TRPWM

As mentioned earlier, the TRPWM incorporates both the randomness of RCPWM and RPPWM in the SVPWM. The randomness in the carrier is done in the pre-pulse

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generation (before comparators) stage and the positional randomness is induced in the post pulse generation stage. In the carrier randomness, there are four carriers used. The selection amid them are done using two select bits obtained from the PRBS generators (one is 16-bit and other is 8-bit). It is worth to note that in the basic RCPWM, commonly two carriers are being used, while in this architecture four carriers are employed to have better cycle wise randomness in the carrier. The random carrier obtained is compared in the comparators C1, C2 and C3 with the space vector references, abreast. The typical comparison of this case is hinted in Figure 4 for the ready reference. This results three different trains of pulses.

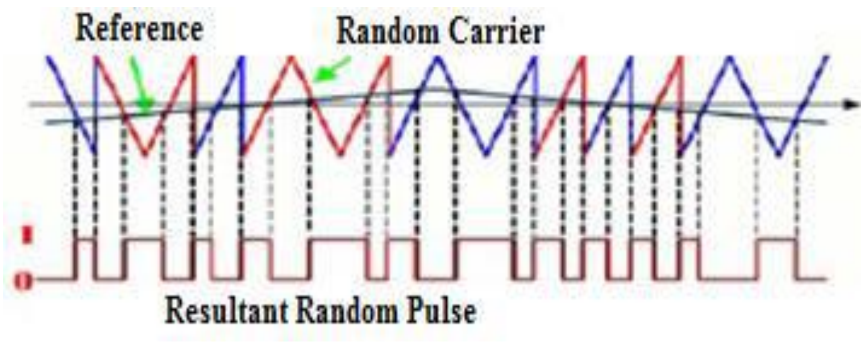

Figure 4. Generation of Gate Pulse in RCPWM

Similar to the pulses obtained in the above discussion another set of pulses obtained by the comparison of the inverted form of the random carrier with those three space vector references in comparators C4, C5 and C6. Three space vector references are same signals with 120^0 phase differences. Hence there are two sets of RCPWM pulses; each set has three pulses and total six pulses. The random positioned pulses are obtained as a sum-of-product (SOP) function involving two terms; first one is by the PRBS bit and the pulse belongs to first set (product term), and the second term is the product term of inverted PRBS bit and the second set pulse. This is done for every phase separately. The resulting three pulses and their inverted forms six pulses for the three phase VSI. The PRBSs are linear feedback shift registers (LFSRs) based on the feedback logic created through the linear XOR, wherein the output sequence is determined by three values, viz. initial states (values) of the shift register, shift register tapings and the feedback structure.

3. Simulation Study

The comprehensive simulation is performed in MATLAB R2010a. The complete drives system with the devised PWM strategies is schematized in the MATLAB's Simulink window. The key specifications of the induction motor are listed in Table 1. The carrier frequencies for RCPWM are 2kHz, 3kHz, 3.5kHz and 4kHz. For RCPWM and RPPWM the carrier with 3 kHz and its inverter signal are used. In case of SVPWM, an analog space vector reference with a triangular carrier of frequency 3 kHz is used. The input voltage for the front end rectifier is calculated as follows.

$$V_{dc} = \frac{3\sqrt{V_m}}{\pi} \quad (1)$$

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Considering the DC link voltage, V_{dc} as 415V, the supply peak (V_m) obtained as 250.9V. The rated torque is obtained from the motor parameters listed in the Table 1 using the basic equations.

$$T = \frac{P}{\omega} = \frac{2200}{157.07} = 14Nm \quad (2)$$

For a fan type load, the torque coefficient is computed as detailed beneath.

$$T = K\omega^2 \quad (3)$$

$$14 = \mathrm{K} \times 157.072 \quad (4)$$

$$K = 0.0005675 \quad (5)$$

Table 1. Specifications of Induction Motor

Parameter	Value
Rated power	2200W
Line voltage	380V (rms)
Stator resistance	3Ω
Rotor resistance	3Ω
Magnetizing inductance	220mH
Stator inductance	9mH
Rotor inductance	9mH
Pole pair	2
Frequency	50Hz

The simulation is performed for the entire range of modulation index and a wide range of load torque values. The representative results are provided for rated load for the TRPWM from Figure 5 to Figure 7. The Figure 5 shows the line voltages of the inductor motor with the TRPWM and the corresponding voltage harmonic spectrum for R phase voltage. Similarly the line currents and the harmonic spectrum for the R phase are pictured in Figure 6. Figure 7 demonstrates the common mode voltage (CMV) and the torque response for the TRPWM.

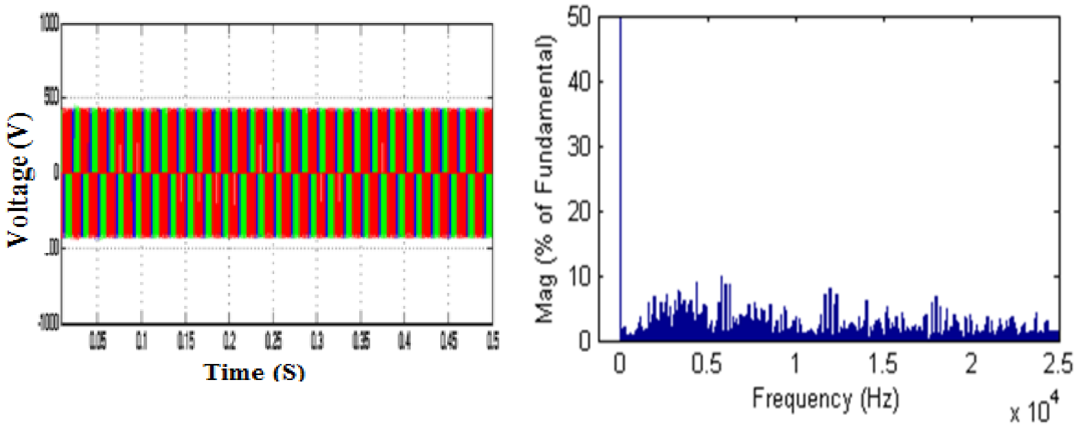

Figure 5. Line Voltage and Harmonics Spectrum for R-Phase - TRPWM

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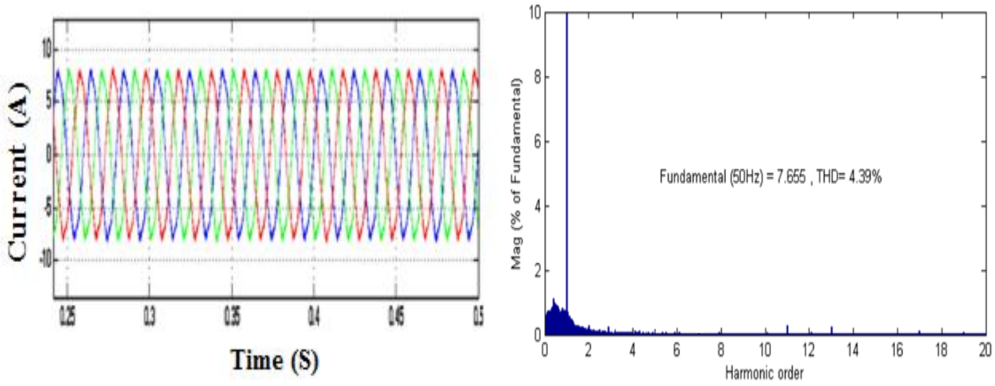

Figure 6. Line Current and Harmonics Spectrum for R-Phase - TRPWM

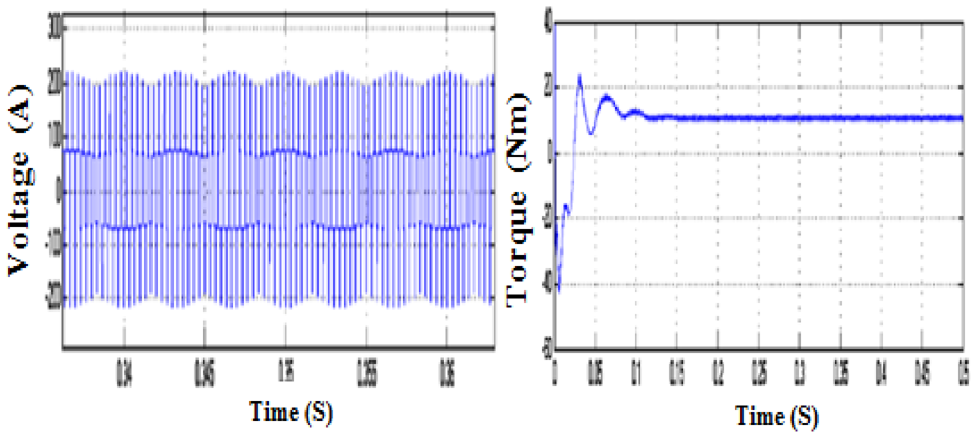

Figure 7. CMV and Torque Response-TRPWM

The CMV is the voltage measured between the load neutral (star point) and the supply ground, which is caused / influenced by the PWM strategies and must be reduced. The CMV plays an objectionable role in the shaft voltage [23]. Thus, one important solution for reducing the shaft voltage and leakage current is the remission of CMV. Practically the voltage between the ground and the mid-point (center) of the DC link 'o' is neglected and hence the CMV of the drive is measured between the neutral and the DC link mid-point.

$$CMV = \frac{v_{ao} + v_{bo} + v_{co}}{3} \tag{6}$$

Where, v_{ao}, v_{bo}, and v_{co} are the voltages between respective phase windings and the DC link mid-point. The accepted metric for quantifying the harmonic distribution savvy of the particular PWM technique is HSF [21]. The HSF directly indicates the spread spectra effect of RPWM and conventional PWM schemes. Its value must be as low as possible to have lesser acoustic noises and mechanical vibration. In fact to have the flat spectra of white noise (ideal case), the HSF value must be zero. The expression for HSF is given below.

$$HSF = \sqrt{\frac{1}{N}\sum_{j\rangle 1}^{N} (H_j - H_0)^2} \tag{7}$$

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Where, 'N' represents number of harmonics taken for the computation; H_j is the amplitude value of the j[th] component of harmonics; and H_0 is the average value calculated for all harmonics components. 'N' is taken as 500 in this study, which is the default restraint in the MATLAB software tool. The relation for obtaining the H_0 is given in (8).

$$H_0 = \frac{1}{N} \sum_{j \rangle 1}^{N} H_j \quad (8)$$

The torque ripple, ΔT_r in the electrical motors is expressed as the percentage (%) of the variation amid the maximum value of torque (T_{max}) and the minimum value of torque (T_{min}) compared to the average value of the torque (T_{ave}).

$$\Delta T_r = \frac{(T_{max} - T_{min})}{T_{ave}} x100\% \quad (9)$$

Table 2 shows the detailed comparison of the different PWM schemes along with the proposed TRPWM. The HSF is computed by copying the harmonics magnitudes of output voltage rendered by the 'Powergui' block of Simulink. Transferring the data from the 'Powergui' to Microsoft Excel is done through Crimson editor. The second column of the table is earmarked for the fundamental component of output voltage, V_1 in volts. The modulation index, which is the control variable for the output voltage in PWM strategies, is different for SPWM and SVPWM both in the way of definition as well as in the concept. Hence to have prevalent platform for the formulaic comparison, a specific value of V_1, 285V (rms) is taken rather than a specific modulation index. The suggested TRPWM outperforms in almost all metrics over its counterparts. Its HSF is 52.8% lesser than the worst performer SPWM, while 24% lesser than its nearest competitor, the RPWM resulted from the amalgamation of SVPWM and RPPWM. Similar performance enhancement is noticed in CMV and torque ripple also. There exists a marginal improvement in the voltage and THD values. The harmonic spectra of the output voltages of RCPWM and RCPWM cuddled SVPWM are pictured in Figure 8.

Table 2. Performance Comparison amid RPWM Strategies

PWM Strategy	**V_1 (V)**	**V_{THD} (%)**	**I_{THD} (%)**	**HSF**	**ΔT_r (%)**	**CMV Peak value**	**CMV Average (V)**
SPWM	285.7	82.76	4.00	7.71	6.76	245.5	29.04
RCPWM	285.7	77.93	3.15	4.21	5.12	221.7	5.878
RPPWM	286.0	76.09	3.17	4.35	4.53	221.9	4.397
SVPWM	286.1	58.02	3.01	5.57	6.01	220.3	4.731
SVPWM+RCPWM	286.4	61.65	3.85	4.10	4.97	211.6	4.236
SVPWM+RPPWM	285.9	61.78	3.74	3.78	5.10	218.1	2.232
TRPWM	**286.0**	**58.32**	**3.39**	**2.87**	**3.19**	**213.5**	**2.236**

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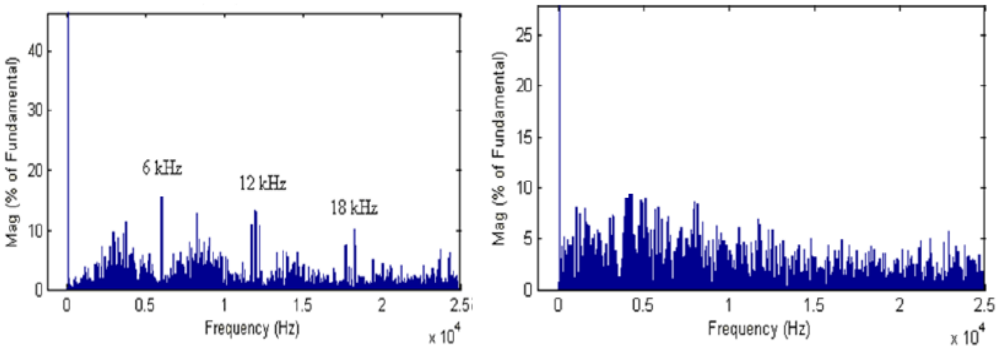

Figure 8. Output Voltage Harmonic Spectra-RCPWM & SVPWM+RCPWM

4. Experimental Investigations

The architectures of TRPWM tenet and other six PWM strategies' tenets are coded using the VHDL language and implemented in the SPARTAN-6 FPGA (XC6SLX45) processor. As mentioned earlier the module wise functionalities of the architectures are simulated scrupulously using the ModelSim software. The proof-of-concept experimental prototype is photographed in Figure 9. The representative RTL view of the architecture resulted for the TRPWM is given in Figure 10 as a screen shot, while the Figure 11 presents the comprehensive timing analysis. Figure 12 diagrams line voltages and currents waveforms obtained from the laboratory testing. Figure 13 and Figure 14 give the output voltage harmonic spectrum for RPPWM and TRPWM at the V_1 value of 285V.

Figure 9. Experimental Arrangement

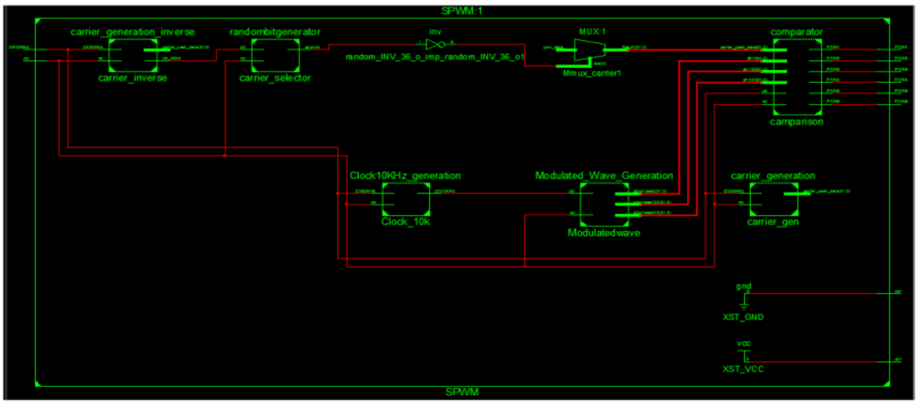

Figure 10. RTL Schematic of Architecture for TRPWM

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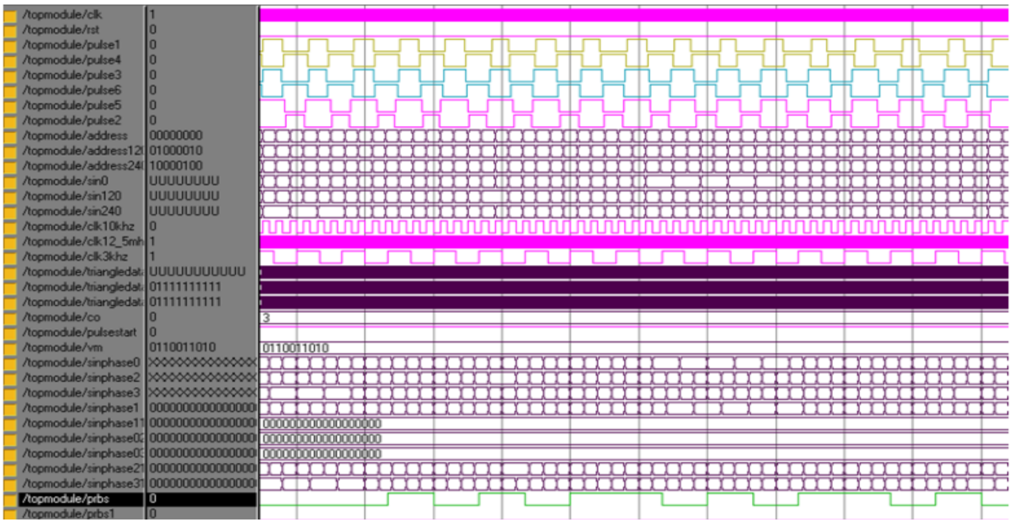

Figure 11. Complete Timing Analysis

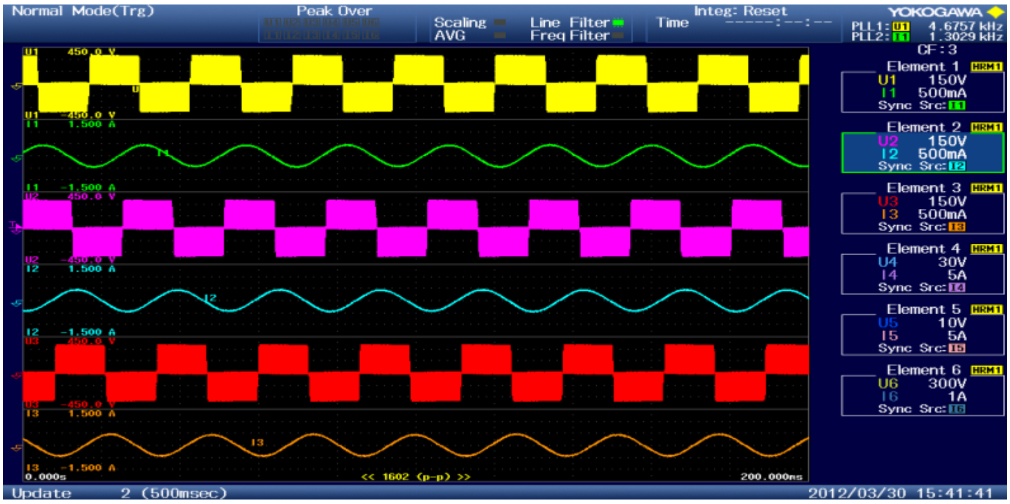

Figure 12. Line Voltages and Line Currents at Rated Load

Figure 13. Harmonic Spectrum of RPPWM-Experimental

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Figure 14. Harmonic Spectrum of TRPWM-Experimental

5. Conclusion

The earlier research effort has sufficiently addressed various issues on PWM-VSI drive of the induction motor. While there exists few issues in such drives, namely, acoustic noise, mechanical vibration, CMV, torque ripple etc. These issues are considered as main interest in this paper. The direct influence of PWM techniques on these issues is obvious. This paper has proposed a kind of RPWM named TRPWM, which is perfect juxtaposition the high performance three phase SVPWM and the randomness like random carrier and random pulse position. This dual randomness is triumphed in improving the metrics like HSF, CMV and torque ripple while the inherent ability of the SVPWM helps in retaining the minimal THD and the boosted voltage gain. For the complete working range, the TRPWM offers lesser HSF and THD. The field programmable gate array (FPGA) based experimentation for the 2.2 kW, 14 Nm induction motor corroborates the simulation denouement and proves that the suggest strategy is prudent. The proposed RPWM can be useful in medium and high power drives to confront issues related to acoustic noises, CMV etc.

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