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An Investigation on the Performance of Random PWM Controlled Converters

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Abstract— This paper provides an insight on various random pulse width modulation techniques and their effect on spreading the harmonic spectrum for various applications like drives, hybrid electric vehicles and renewable energy sources, for two level as well as three level inverter. Acoustic noise reduction, electromagnetic interference conducted and torque ripple are obvious advantages of random pulse width modulation (PWM). PWM converters with multilevel topology can meet with global quality standards for power supplies. The random PWM technique provides additional advantages. Among others, it may be implemented to achieve switching loss equalization in power switches for cascaded H-Bridge multilevel inverters. This paper provides in depth understanding for different random PWM techniques and their applications.

Keywords-Random PWM, Random SVPWM, Multilevel inverter, drives

I. INTRODUCTION

With the increased penetration of automation due to advancements in power semiconducting devices and processors like DSP, FPGA, CPLD etc., power electronic converters have found numerous applications in different fields. This has led to topological advancements in power electronic converters, with multi-level converter being one of them. Effective control of power electronic converters has emerged as a challenge. These converters use modulation techniques such as Selective Harmonic Elimination (SHE) or high switching frequency Pulse Width Modulation (PWM). SHE PWM technique utilizes a low frequency switching and hence can reduce switching losses. By selecting proper angles using advanced artificial intelligence techniques, it is possible to reduce lower order harmonics without affecting the fundamental component. However, this technique will also result to an increased switching frequency. For unbalanced load 3phase 4 leg neutral point clamped inverters the SHE PWM [1] and SHE pulse width amplitude modulation is proposed [2]. Selective harmonic mitigation (SHM) is combined with SHE to provide a better harmonic control [3]. However, SHE is limited to offline calculations and multicarrier techniques are also been worked upon [4]. Various PWM techniques have been implemented for the control of these converters.

PWM techniques are classified as Current Controlled PWM and Voltage Controlled PWM. These PWM techniques are also categorized as either carrier based or carrierless PWM schemes. For carrier based PWM schemes, a typical harmonics spectrum exhibits prominent harmonics around the carrier frequency. This results to the generation of acoustic noise at these frequencies by the machines controlled by such schemes. Also, it is better to have a distribution of harmonic energy over a wide frequency spectrum as compared to the energy being concentrated at few frequencies. This is achieved by carrierless PWM scheme.

Random PWM schemes also achieve spreading of the energy spectrum by randomly switching, random switching frequency and random pulse position [5]. For random PWM schemes research till now has mostly focus on a carrier based implementation. However, space vector (carrierless) based random PWM techniques which results in better DC bus voltage utilization and easier digital implementation is also gaining popularity. With increasing requirements of power electronic converter application at higher power levels (especially grid connected systems), implementation of multi-level converters is also continuously increasing. This paper is focused on investigating the performance for various random PWM schemes based two-level and multi-level inverter systems.

II. DIFFERENT RANDOM PWM (RPWM) TECHNIQUES [6-45]

Various PWM techniques are depicted in Figure 1. Acoustic switching noise gets remarkably reduced by increasing the carrier frequency above 18 kHz, however, that increases the switching losses in the inverter and decreases operating efficiency. An inverter with random PWM has an advantage of spread and continuously dispersed output harmonic spectra [6].

A. Random Carrier Frequency (RCF-PWM) [7]

The method is based on a random selection of the carrier frequency for each carrier period. The only requirement for RCF-PWM is to maintain the volt-second balance during a carrier period, ensuring that the fundamental frequency component is not affected by the randomization.
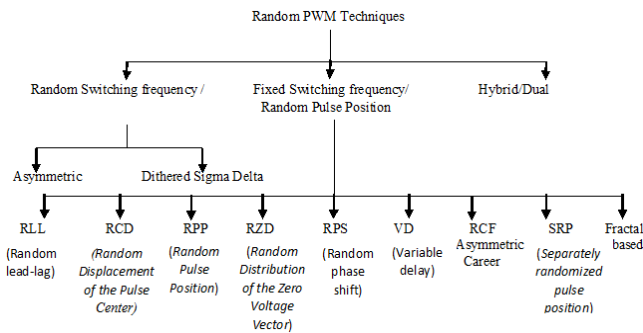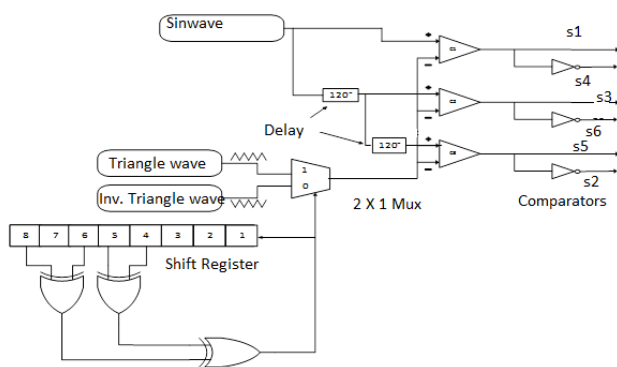
Fig. 1 Random PWM Techniques.

Fig. 2 Random Carrier Frequency PWM

The Random Carrier PWM technique uses two different triangular carriers as depicted in Figure 2. One is of required frequency and the other is 180 degree phase shifted. The selection of the carrier among these carriers is done by a random bit generated. That is, if '1' is the output carrier 1 (basic) is selected as carrier 2 (180° shifted). The selection is done for ever carrier cycle and the selected carrier is compared with the reference sinusoidal waveform. The Pseudo random carrier modulation scheme is most commonly used for the random triangular frequency generation. Here, the random triangular frequency is achieved in the range of 3 kHz. Space vector based random carrier frequency scheme and switching pulse generation is shown in Figure 3
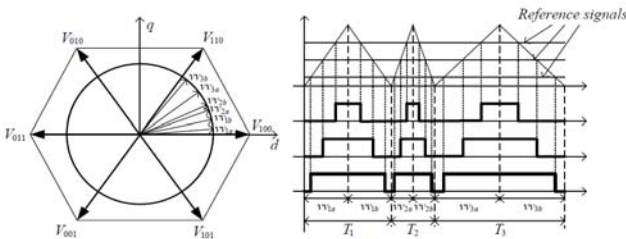

Fig. 3 Random Carrier frequency, SVM generated vector and switching pulse generation

1)   Random Switching Frequency (RSF) [8]

Random switching frequency has a similarity with random pulse duration. Here the switching period is changed in every cycle and pulse period is placed at the beginning of switching cycle, i.e. the problem of randomization is minimized by randomly varying the switching period for a limited interval in the control loop as shown in Figure 4. A reference number or slope of triangular wave is varied in between a min and a max value randomly for all phases. However, it is difficult to select random frequency for real time applications,. In the majority of applications, sampling and PWM periods need to be synchronized. Random sample rate puts limitation on code size. Space vector based scheme requires either switching interval per cycle or sub cycle interval equivalent to 60 degrees are to be randomized. This applies a limitation on the interval for which frequency can be varied.
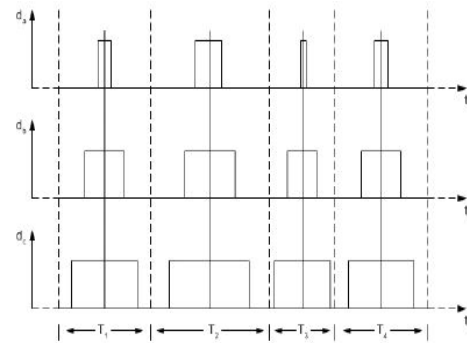

Fig. 4 Random switching frequency (RSF)

2)   Dithered Sigma Delta Modulator (DSDM) based RPWM Switching Scheme [9-23]

Delta Sigma modulation is an oversampling method where sampling frequency is much above the frequency mentioned by Nyquist criteria. Here analog input is converted to digital output same as in an Analog to Digital Controller (ADC). As shown in Figure 5(a) the addition of a 1-bit random sequence to the LSB of the input signal, results in suppression of harmonic spikes in   Dithered Sigma Delta Modulation (DSDM). The Dithered Sigma-Delta Modulation (DSDM) scheme has a Sigma Delta Modulator (SDM) and a random dither generator as component can be realized with simple hardware and software algorithms. As shown in Figure 5(b) random dither generation constitutes of random magnitude adjustment where in for every sampling period a random number is generated and subtracted by a bias as well as a sign discriminator which decides the application of dither [9]. There are two types of SDM, depending upon the position of random dither generator and quantizer viz. Space-Dither SDM (SDSDM). Space-Dither SDM (SDSDM) scheme employs quantizer being fed from a random dither generator in SDM while in Time-Dither SDM (TDSDM) the quantizer feeds the output to random dither generator. Harmonics spikes at multiples of switching frequency are reduced by using a sigma delta modulator where switching frequency is varied randomly using a vector quantization technique [10]. DSDM scheme is easy to implement due to less arithmetic operations and limited use of times. Harmonic Spread Factor is also

comparable in the case of DSDM and RSVPWM [11-22]. A 2nd ordered space dithered SDPWM is investigated in [23].
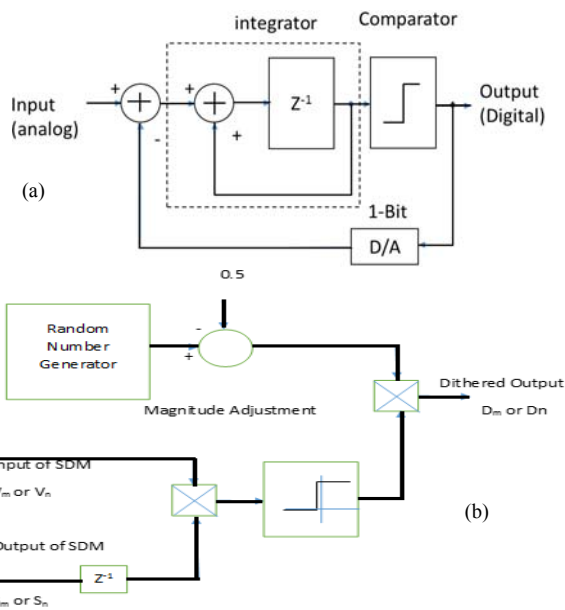

Fig 5. (a) Block diagram of SDM scheme, (b) Random Dither Generator

B. *Fixed Career frequency- Random PWM (FCF-RPWM) [24-38]*

In this method, the switching period is fixed and pulse position is varied randomly. These methods portray a good closed loop response. Figure 6 shows the control block of FCF-RPWM which can be implemented with open loop or closed loop. Control block calculates the reference voltage vector in αβ plane. SVM block will estimate and compare values for pwm. FF_RPWM block will randomize active vectors and zero vectors in the given modulation period. Duty ratios are converted to compare values for generating random PWM output required by VSC block.
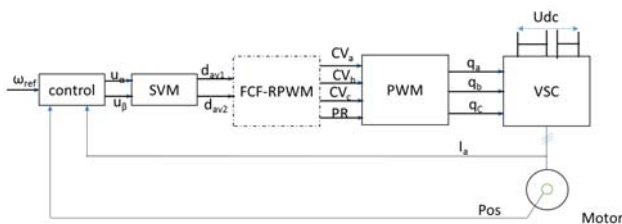

Fig. 6 FCF–RPWM in open & Closed loop

The FCF-RPWM methods, even though easy to synchronize with the control algorithm suffer from problems like current sampling, calculation overhead and spreading effectiveness. The ollowing methods of FCF-RPWM are finding many applications in adjustable speed drives.

1) *Random Lead-Lag Modulation (RLL)[24-25]*

With regular sampling, output cycle frequency is equally divided into equal switching intervals. At constant frequency the pulse position in all 3 phases, is either originating at the beginning of the switching interval (leading-edge modulation) or at its trailing edge (lagging-edge modulation) [24] as shown in Figure 7. Trailing edge modulated pulse width is used in lead mode, whereas leading-edge modulated pulse width is used in lag mode. Average switching frequency is decided to provide the optimum solution for switching losses as well as quality of output current. The random number generator decides leading and lagging edge modulation. Advantage of the scheme is a requirement of single bit random generator for randomization [25]. Sampling of current produces problems and use of anti-aliasing filter becomes necessary.
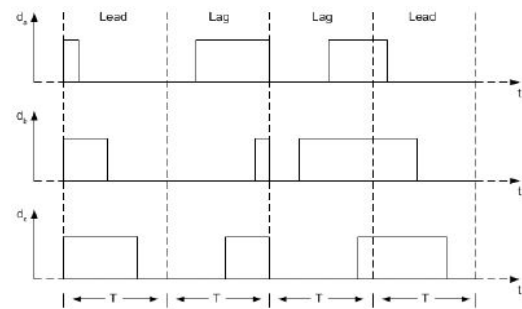

Fig. 7 Random lead-lag modulation (RLL)

2) *Random Displacement of the Pulse Centre (RCD) [26]*

In this method the pulses are mutually center-aligned at constant frequency as in space vector modulation (SVM), but the common pulse center is displaced by a small amount randomly (Trand1,) from the middle of the period [26]. At high (Modulation Index) MI values, displacement becomes very small. Variation of RCD PWM is available as the Dual Zero RCD, where for MI>0.8 (1 1 1) is regarded as zero vector and for MI<0.8 (000) is considered as zero vector. This helps to overcome issues with High MI values and provides randomization effect in a whole range of MI. Figure 8 shows PWM technique applied to two phase PWM.
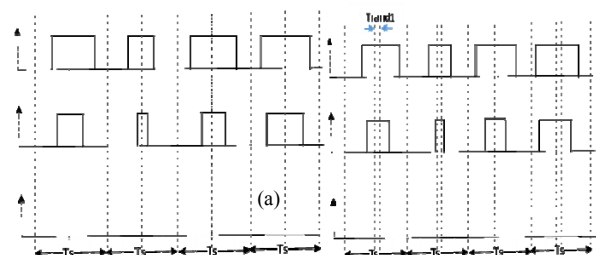

Fig. 8 (a) Centre Allign SVPWM (b) RCDPWM

3) *Random Pulse Position PWM (RPP) [25-28]*

The central idea is that the average output voltage over an interval is not dependent on pulse position. Methodology implements randomization of pulse position of one phase, pulse position of remaining phase is randomized as per previous

phase in sequence. RPP PWM can be implemented by time intervals of zero states controlled randomly within a switching cycle. RLL is considered as a case of RPP. Here pulses can be placed anywhere randomly within switching interval [28]. RPP strategy cannot generate desired ideal noise spectra, though the harmonic clusters of power spectra for fixed switching intervals are less dominant and distributed in a better manner as compared to the deterministic vector PWM technique [25].

4) Random Distribution of the Zero Voltage Vector (RZD) [24]

Phase voltages are not altered by the duration of zero voltage vector in a three-phase, three-wire system. This point is employed in the random distribution of the zero voltage vectors at constant frequency. Random distribution of zero vectors limits maximum pulse change and becomes difficult at high MI values. Control strategy and required vector distribution are shown in Figure 9.
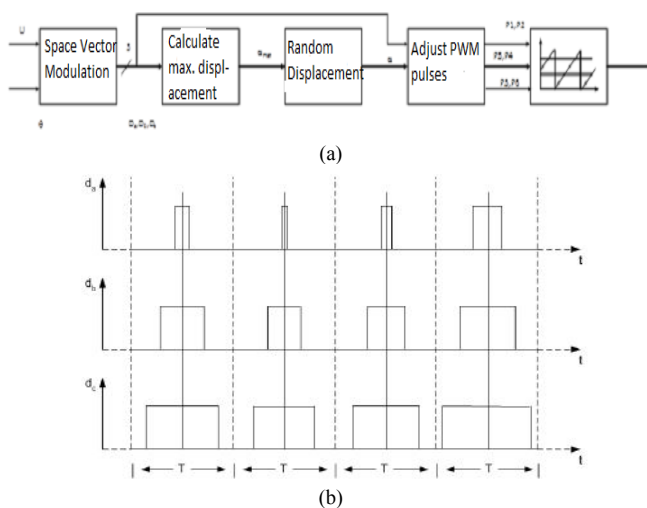

(a)

(b)

Fig. 9 (a). Random zero-vector distribution (b) Random zero-vector distribution

5) Random Phase shift PWM (RPS)

Here random phase shift time is applied randomly at constant frequency. Figure 10 shows RPS technique output waveform, where t_{RP} is the Random Phase Shift time in the positive half-cycle, and t_{RN} is the Random Phase Shift time for the negative half-cycle. At each half cycle both t_{RP} and t_{RN} are altered randomly. In this method, the phase shift is varied randomly, keeping the switching frequency constant. For the RPS scheme, there is a random variation of phase shift keeping switching frequency constant. It has the advantage of reducing acoustic noise emissions generated by the PWM inverter. The phase shift of the fundamental component for each half-cycle controls, discrete harmonic components of the inverter output voltage.

6) Variable delay random PWM (VD-RPWM) [30]

In this method a random delay is introduced at the trailing edge of next PWM output cycle. Figure 11 shows the process for the calculation of switching time and random delay. Random delay is a product of sample period and the

normalized random number. Obviously maximum delay will be produced with random number equal to 1. Here switching period is varied randomly in between min switching period to double the value of sampling period that implements variable delay random PWM [30].
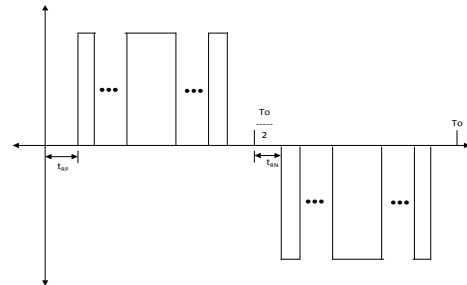

Fig. 10 Timing waveform of RPS scheme
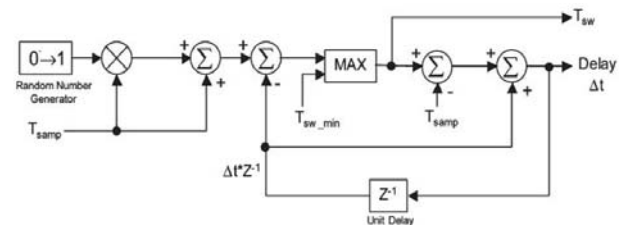
Fig. 11 Block diagram for computation of delays and switching period

7) Asymmetric Carrier Random PWM (AC-RPWM) [31-32]

This scheme can be considered as a kind of RCF-PWM in which the new voltage vector is updated with a constant frequency. A different frequency is used to generate the voltage vector in the rising time period and falling time period. The scheme works well for both low and high MI values. The method selects a random time length for falling edge as well as rising edge for every modulation period, varying randomly time length of the active vector region as shown in Figure 12.

Fig. 12 AC-RPWM, 1st modulation time has symmetrical carrier and in 2nd modulation time it has asymmetric carrier

8) Separately randomized pulse position (SRP) [33]

Pulses are placed randomly in switching interval as shown in Figure 13. As there is full possibility to place pulse

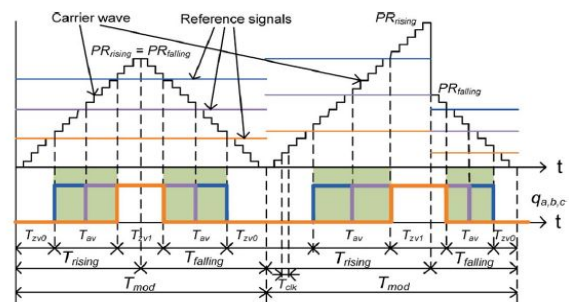anywhere, a control for full range of MI is possible, as far as switching sequence is maintained. Calculation of duty ratio is done using space vector modulation, with each pulse located randomly. As pulse can be positioned randomly, harmonic spectrum is more flattened as compared to conventional methods. So, SVM based duty ratio calculation is followed by random positioning of pulse to realize SRP-PWM [33]
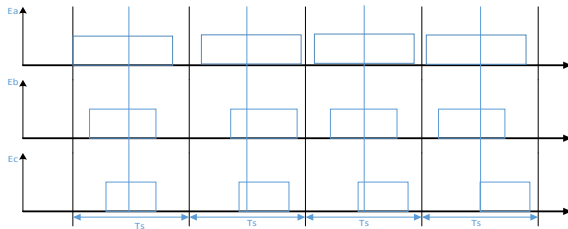

Fig. 13 SRP-PWM

9) Fractal Based Space Vector PWM [34-38]

Fractals are known as never ending patters made by repeating simple patterns by recursion and feedbacks. SVM representation of multi-level inverters have inherent fractal structure. Fractal approach can reduce the complexity in computation for sector identification and switching vector determination in SVPWM. The position of the reference vector in a given sector can be found by fractal methods. The basic pattern in the fractal base unit is a triangle comprised by three adjacent inverter voltage space vectors as shown in Figure 14 for 2-level, 3-level and 5-level inverter. In multilevel inverter, for higher level, each sector is divided into triangles and smaller sub triangles. Triangularization helps to implement this technique for any level of MLI [34]. For multi-level inverter, the number of sectors increases as the number of level increases. It is very complex to identify the location of reference vectors in the sector. 2-level inverter has 6 sectors, 3-level inverter has 24 sectors. If we take 60° coordinate system, fractal calculations can be avoided for 5-level inverter having 96 sectors [35-38]. The sector identification algorithm used in this method with reverse mapping technique does not require memory crunchy lookup tables. The inverter switching states for a sector are generated along with sector identification. This provides optimum switching of the vectors [35].
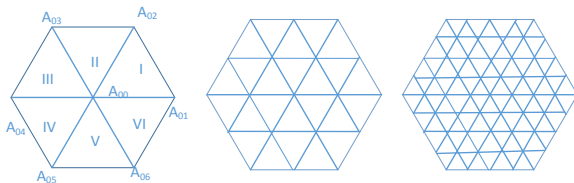

Fig. 14 2-level, 3-level and 5-level SVPWM

C. Hybrid Random PWM or Dual Random PWM [39-43]

With a view to gain advantage of better performance for the different Modulation Index (MI) values including over modulation region or to reduce the complexity of computation, the hybrid or dual random PWM methods are proposed. Here

an attempt is made to maximize the advantages of various PWM schemes. A hybrid random PWM using dithered pulse position and zero vector position are suggested, simulated with complex calculations [39]. Hybrid scheme is also given by [40] using random pulse position and random career frequency PWM [5]. Lead lag random bit and random triangular carrier are used in [41-42]. Time for zero voltage is randomized to get better result with Direct Torque Control (DTC) for drives [43].

D. Random SVPWM [44-45]

SPWM converters have sideband harmonics and carrier acting as source of electromagnetic noise and pollution by common mode and differential mode noise. The Random PWM inverter has low weight, volume, filtering and has better EMI/EMC. Lower switching losses are useful to improve battery efficiency and reduced switching losses. SVM is digitally better implementable and has a higher output. Fixed frequency SVM also has high harmonics in switching frequency this can be spread by using random Space Vector PWM (RSVPWM).   Three types of random SVPWM are suggested, random zero vector distribution PWM (RZDPWM), random pulse position PWM (RPPPWM) and random switching frequency PWM (RSFPWM) [44]. Mathematically random SVPWM is similar to traditional SVPWM and so existing methods for capacitor voltage balancing can be modified to reduce switching harmonics [45].

III.   RANDOM PWM CONTROLLED TWO -LEVEL INVERTERS [46-59]

Output current of two-level inverters has a square wave with limited power range. It is rich with harmonics. The two-level 3-phase Voltage Source Inverter (VSC) is considered as a mature technology and has become an industrial standard. The alternative topology to the VSC is the Current Source Converter (CSC), well suited for medium-voltage industrial applications with voltage waveforms having high quality required.   Various authors have also implemented random PWM techniques for multilevel inverter, keeping methodologies adopted for 2-Level [46-58]. C. Guoqiang, W. Zhihong, Z. Yuan, and Z. Junwei realized Random Space Vector Pulse Width Modulation methods Based on Infineon Tricore TC1767/TC1797 like RSFPWM, RPPPWM, RZDPWM and Hybrid Random PWM is involving various combinations of three listed herewith [59]. The AC-RPWM technique is found appropriate for applications like heating, ventilation and air conditioning (HVAC) [31].

IV.   RANDOM PWM CONTROLLED THREE-LEVEL INVERTERS [60-74]

Multilevel inverters provide nearly sinusoidal output and achieve higher power output. This allows the use of renewable energy sources such as PV, wind, fuel cells to be easily interfaced with MLI for medium voltage, high power drives, distributed energy sources and Hybrid Electric Vehicles. Topology itself helps in reducing harmonics. Multilevel inverters are replacing conventional two-level inverters due to reduced dv/dt stresses, common mode voltages, and lower harmonic distortion. 3-level RPWM in comparing to 2-level RPWM schemes has the advantages of low switching frequency, low continuous noise and low undesirable low-order

harmonics, making it suitable for high voltage inverter application such as motor drives, active filters and power conditioning [60-62]. Different conventional topologies like Neutral Point clamped (NPC), cascaded H-bridge (CHB), and flying capacitor (FC) along with PWM strategies reported, are reviewed in [63]. Novel topologies are report for MLI in form of Crossover Switches Cell (CSC) for renewable energy sources and Pinned Mid-points Multilevel Inverter for high voltage applications [64-65]. In [60-61] the authors compared Random PWM technique for 2-level and 3-level. Their observations include that the fundamental component is found to be smaller in the 3-level RPWM scheme than in the 2-level RPWM scheme. Both 2-level and 3-level have a similar discrete spectral characteristic, however the 3-level has smaller continuous noise as compared to the 2-level. This advantage of the better power spectrum comes at the cost of a relatively higher switching frequency for specified sampling frequency [66]. T. Ramanathan et al. [67] utilized pseudo random carrier modulation technique for CHB MLI. Jacob and Baiju [65-66] applied Space Vector quantized DSDM technique for 3-level inverter to reduce harmonic noise to CHB MLI supplying power to induction motor drive. In [54] the authors implemented space vector based random PWM for 3-level inverter for any topology. In [50] the authors pointed out that the fixed frequency scheme has limitation in the form of the dependency of randomization on the duration of active vectors. In [70] the authors used combined DSDM based random PWM Scheme. Artificial intelligence tools like Fuzzy Logic, Genetic algorithm, etc., are also utilized to randomize the PWM output. In [71], the authors used clonal selection algorithm, a technique based on GA applied for 3-level PWM inverter for optimization. In [72], the authors implemented random frequency based Space vector PWM method and introduced wavelet transformation for better harmonic response. In [74], randomized-SVM application is also extended to Hybrid Electrical Vehicle (HEV).

A. Applications of Random PWM [75-100]

Random PWM finds extensive application in LV and MV Motor drives to reduce acoustic noise, electromagnetic interference, and harmonics at multiple of switching frequency, also it helps to flatten the power density spectrum [75-80]. Motor drives on board are increasing for electric, hybrid and fuel cell based vehicles. To decrease current ripple, switching loss and auto adjust to load characteristics along with other advantages very crucial for the consumer that is acoustic noise and electromagnetic noise make the random PWM better choice for application in automobiles [81-87]. Shunt Active Power filter is used to improve power quality issues like current harmonics and power factor for power system with nonlinear load. With random PWM, APF response can be improved without adding any cost [88-93]. Present scenario for inverter used with renewable energy sources: PWM techniques are used with MOSFET/IGBT while for high power SCR/GTO is required which can be controlled with suitable firing and commutation control. Another way by which we can use MOSFET/IGBT for medium or high power application is to go for Multilevel Inverter (MLI) [94-97]. Grid connected PWM converters used to control power for various applications

including renewable energy sources are reported [99]. Use of SVPWM is reported in 3-Level NPC inverter [100].

V. ANALYSIS OF RESEARCH WORK CARRIED OUT WITH RANDOM PWM AND RANDOM SVPWM

Literature reveals the extensive usage of random PWM techniques in various applications. In order to further validate the research interest year by year refer to Figure 15. Figure 16 indicates that the research for random PWM is dominated by the field of drives, motor control and low power applications.
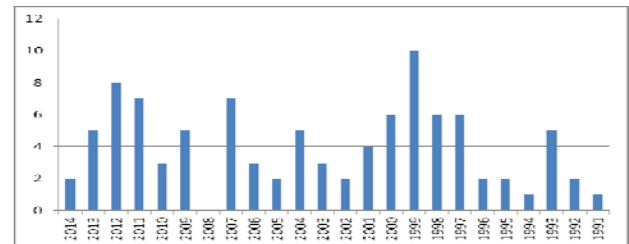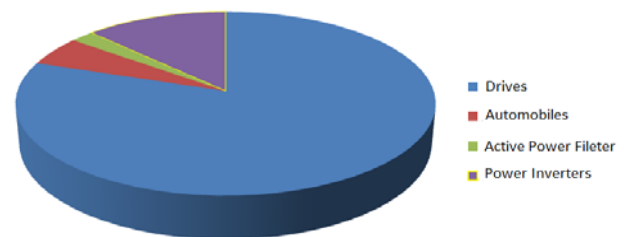

Fig 15. Papers published year wise for random PWM

Fig. 16 Papers reporting random PWM

VIII. CONCLUSION

This paper presents a critical review of random PWM techniques and their applications. The random PWM technique is found to reduce harmonics in particular at a multiple of switching frequency. The technique has proved its advantages in drives especially through reduction of acoustic noise, mechanical vibration, torque ripple and current harmonics. The advantage of RPWM technique in reducing EMI conducted to the source is discussed. Drives, HEVs, active power filters have proved to provide better performance with the random PWM technique. Harmonic power remains unchanged with the randomizing technique, but can reduce the peaks at multiple of switching frequency and can reduce harmonic content in the current waveform. The effect of randomizing for inverters connected with renewable sources using bundled multilevel technique with the advantage of lower switching frequency, spreaded noise and low lower harmonics needs to be worked on, as renewable energy sources are preferred to address issues of pollution, energy security cost, etc. Hence there is a research gap for the issue of harmonic mitigation in grid connected systems by application of Random SVPWM technique for multilevel inverters.

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