RANDOM PULSEWIDTH MODULATION TECHNIQUE FOR A 4-LEVEL INVERTER

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ABSTRACT

Random Pulse Width Modulation (RPWM) technique for a 4-level inverter in open-end winding induction motor configuration is proposed in this paper. Reference voltage space vector is randomly sampled and it is realized in average sense by switching its three nearest vectors. Switching frequency is randomly varied within the bounds to get randomly spaced samples. The method requires no sector identification. The reference phasor is converted into a vector lying in the basic 2-level inverter to calculate switching time vectors. The proposed scheme is implemented and experimental results are presented for a dual inverter fed 4-level open-end winding induction motor drive using DSP platform, TMS 320LF2407A.

Keywords : Random Pulse Width Modulation, Space Vector, 4-Level Inverter, Open-End Winding.

1. INTRODUCTION

Due to reduced acoustic noise, mechanical vibration and electromagnetic interference, various Random PWM (RPWM) techniques have been emerged as an alternative to deterministic PWM methods [1]-[11]. In these techniques, the energy concentrated at the harmonics of switching frequency is spread into a continuous frequency spectrum. Conventionally random switching, random switching frequency and random pulse position are widely used for spectral spreading [1]. Most of the RPWM techniques are of carrier based. But there exist a few Random PWM implementations using the principles of space vector [5], [9]-[10]. Digital implementation of Space Vector PWM (SVPWM) techniques is easy. Moreover, better utilization of DC bus is also ensured in
SVPWM [12].

For medium and high power applications, due to reduced stress on power switches, low output voltage distortion and less harmonic distortion, multilevel inverters are widely used [13], [14]. Multilevel inverter topologies - Neutral Point Clamped, Flying Capacitor, Cascaded and Open-end winding induction motor based inverters and their modulation schemes are researched extensively [13]-[17]. Sine triangle PWM (SPWM) and Space Vector PWM are the most commonly used modulation strategies for multilevel inverters.

Principles of random modulation techniques originally researched for 2-level inverters are currently being applied for 3-level inverters also [8]-[11]. The advantages of random techniques are combined with the advantages of multilevel inverters such as less harmonic distortion, less stress on power devices and lower common mode voltage. A RPWM technique with weighted switching decision which combines the advantages of deterministic and non deterministic methods is proposed in [8]. By randomizing the sequence of switching vectors RPWM can be achieved and is proposed in [9]. RPWM technique implemented in [10] uses the concept of distribution ratio used for voltage balancing of linked capacitors. A random switching scheme with a decoupled strategy can be adopted for a dual inverter fed 3-level open-end winding induction motor drive [11].

A space vector based RPWM scheme for a 4-level inverter using the principle of variable switching frequency is presented in this paper. Samples of reference voltage space vector, which are obtained by random sampling, are realized in the average sense by switching nearest vectors with appropriate switching times. In the proposed scheme, by randomizing vectors for a 2-level inverter only, random switching vectors for the multilevel inverter are generated. The proposed space vector based scheme uses algorithm in which no sector identification methods are required. From instantaneous amplitudes of three phase reference voltages switching vectors are automatically generated.

The proposed scheme is implemented for a 2 hp open-end winding induction motor based 4-level inverter using TMS320LF2407 DSP platform and the experimental results are presented. Virtex II PRO XC2VP30 FPGA board is used along with the DSP platform for the generation of switching vectors.

2. 4-LEVEL INVERTER BASED ON OPEN-END WINDING INDUCTION MOTOR CONFIGURATION

Open-end winding induction motor is realized by opening the neutral point of a star connected induction motor. Multilevel inverter structures can be obtained by feeding it with 2-level inverters from both ends [15]-[17]. In open-end winding induction motor configuration, when individual inverters are applied with asymmetric DC link voltages of \((2/3)V_{dc}\) and \((1/3)V_{dc}\), the resultant switching vector combination is equivalent to a 4-level inverter [17]. A 4- level inverter in open-end winding configuration and the space vector combinations of individual 2-level inverters are shown in 1(a) and Fig. 1(b) respectively. The space vector locations of the resultant 4-level inverter are shown in Fig. 2. As each 2-level inverter can assume 8 states independently, there are 64 \((2^8)\) switching combinations for the resultant 4-level inverter. These 64 switching combinations are distributed over 37 locations as shown in Fig. 2.
Fig. 1(a): 4-level inverter in open-end winding induction motor configuration

Fig. 1(b): Space vector locations of two 2-level inverters with asymmetric DC link voltages

The hexagonal structure in Fig. 2 is having an inner sub hexagon with its center as O and its six vertices marked as A to F. With these vertices as center, six other sub hexagons (referred to as middle sub hexagon) can be identified. Centered on the vertices of middle sub hexagons marked as G to S (except O), there are twelve outer sub hexagons.

3. PRINCIPLE OF THE PROPOSED SCHEME

By sampling the reference space vector at random intervals randomization can be achieved. Switching frequency is randomly varied to obtain randomly spaced samples of the reference phasor for every PWM cycle. These random samples of random phasor are realized by SVPWM. The PWM signals resulting from this random sampling are non periodic, leading to spectral spreading. In different cycles of reference signal samples are obtained at different angular positions as shown in Fig. 3. This non periodic time domain PWM signal generated leads to spreading of the frequency spectrum.

Fig. 2: Space vector combinations of 2-level inverters with asymmetric dc link voltages resulting in space vector locations of 4-level inverter
In the proposed method, the reference space vector is sampled at randomly spaced intervals determined by the random frequency generated by the Linear Congruential Generator (LCG) implemented by the DSP. LCG is given by the equation (1).

\[ x_{n+1} = (ax_n + c) \pmod{l} \quad (1) \]

where the coefficients \(a\), \(c\) and \(l\) are multiplier, increment and modulus. \(x_{n+1}\) is the current value of random number generated from the previous value \(x_n\). \(x_0\) is the seed for the LCG [6]. In the proposed scheme, switching frequency is randomly varied in the range 2.5±1KHz by properly selecting the parameters.

The space vector diagram can be viewed as consisting of 3 layers marked as \(L_1\), \(L_2\) and \(L_3\) and are shown in three different shades in Fig. 4 [20]. The layer in which the tip of the reference space phasor lies is given by the equation

\[
L = 1 + \text{int} \left(\frac{\sqrt{3} V_{dc}}{2 n - 1} \right) \quad (2)
\]

In this figure, locus of reference space vector for three different modulation index lying in layers \(L_1\), \(L_2\) and \(L_3\) and randomly sampled vectors \(OT_1\), \(OT_2\) and \(OT_3\) respectively are shown. Depending on the modulation index, the tip of the reference space vector is either in layer \(L_1\), \(L_2\) or \(L_3\) and the 4-level inverter operates in 2-level, 3-level or 4-level.

### 3.1 Two-level operation of the inverter

When the tip of the reference space vector in layer \(L_1\), and \(m < 0.288\) (as for vector \(OT_1\) in Fig. 4), 2-level operation results. Then the reference phasor can be realized by a 2-level inverter only. In the proposed scheme inverter-2 switches SVPWM and inverter-1 is clamped to origin.
3.2 Three-level operation of the inverter

When the tip of the reference space vector is in layer $L_2$ and $m < 0.577$, 3-level operation results and reference phasor is realized by switching both the inverters. In Fig. 5, $OT_2$ shows the randomly sampled reference space vector. The vector is resolved into two components with sub hexagon center nearest to the tip of reference space vector as one of the vectors ($OC$). The second component, $CT_2$, which is completely lying in layer $L_2$ is mapped into $OT_2'$, a vector lying in layer $L_1$. Switching time of the vectors is found out for the mapped reference vector by using algorithm for switching time calculation for a 2-level inverter.

Fig. 4: Space vector diagram of a 4-level inverter with three switching vectors marked as $OT_1$, $OT_2$ and $OT_3$ and three layers marked as $L_1$, $L_2$ and $L_3$

Determination of the center of sub hexagon nearest to the tip of reference space vector is done from instantaneous amplitudes of reference space vector. The instantaneous polarity of the 3-phase reference signal directly give center of the nearest sub hexagon if a positive polarity is denoted by ‘1’ and negative polarity by ‘0’ [19], [21].

3.3 Four-level operation of the inverter

4-level operation of the inverter results when the tip of the reference space vector is in layer $L_3$ and $m < 0.866$. In Fig. 6, vector $OT_3$ represents a reference space vector lying in layer $L_3$. The vector is resolved into component vectors $OL$ and $IT_3$. $OL$ is the center of the sub hexagon nearest to the tip of the reference space vector. When the reference space vector lies between $\omega t=120^\circ$ and $\omega t=180^\circ$ as shown in Fig. 6, from the polarity of 3-phase reference signal, vector 110 is obtained. By adding the vector 110 to itself, its preceding (100) and succeeding vectors (010), the possible nearest sub hexagon centers 210 (=110+100), 220 (=110+110) and 120 (=110+010) are generated. Of these sub hexagon centers, the one which is having minimum distance to the tip of the reference space vector is chosen as the nearest sub hexagon center. In the figure, vector $OT_3$ is realized by adding $IT_3$ to vector $OI$ (220). The actual switching vectors are generated after calculating the switching timings of mapped reference vector $OT_3'$. 
3.4 Mapping of reference phasor and switching time calculation

Let \((\alpha, \beta)\) coordinates of the sub hexagon center nearest to the tip of reference vector is denoted by \(V_\alpha\) and \(V_\beta\). The \((\alpha, \beta)\) coordinates of the mapped reference vector is the distance of \(V_\alpha\) and \(V_\beta\) from the \((\alpha, \beta)\) coordinates of the tip of reference phasor.

A simple algorithm based on instantaneous amplitudes of 3-phase reference signal is reference used to determine the switching time of 2-level inverter [18]. The instantaneous values of 3-phase phase reference voltages \(v_{as}, v_{bs}\) and \(v_{cs}\) are calculated from the mapped reference phasor.

The switching times \(T_{xs}\) is given by

\[
T_{xs} = \left( T_s / V_{dc} \right) v_{xs} \quad \text{where} \quad x \in \{a, b, c\} \tag{3}
\]

Fig. 7 shows instantaneous 3-phase mapped reference voltages, corresponding switching signals and the effective switching time. The effective time \(T_{eff}\) is the time for which the load is connected to the source. It is given by

\[
T_{eff} = T_{\text{max}} - T_{\text{min}} \tag{4}
\]

where \(T_{\text{max}}\) and \(T_{\text{min}}\) are maximum and minimum of \(T_{xs}\).

By adding an offset to the imaginary switching time, actual gating signal for the 2-level inverter can be generated. In SVPWM, centralized pulses are obtained by placing the effective vector at the center of the sampling period by adding an offset given by

\[
T_{\text{offset}} = T_s / 2 - T_{\text{max}} \tag{5}
\]
3.4 Generation of switching vectors for 4-level inverter

The switching vector for 4-level inverter is obtained by adding the randomized switching vector for 2-level inverter with the center of the sub hexagon nearest to the tip of reference space vector. Thus, from the random signals generated for the 2-level inverter, random signals for the 4-level inverter are obtained.

4 EXPERIMENTAL RESULTS

The proposed RPWM scheme is implemented for a 2 hp induction motor drive for different modulation index. By using the DSP platform TMS 320LF2407A, the algorithm is implemented and the control signals are generated. The actual switching signals of the individual 2-level inverters are generated by Xilinx Virtex II PRO XC2VP30 FPGA board. Experimental results for different modulation index for a switching frequency of 2.5±1 KHz. is presented.

The plot of gate timing signal $r_{ga}$ for the proposed scheme for different modulation index is shown in Fig. 8 to 10. Fig.8 shows DAC output of $r_{ga}$ for modulation index of 0.2, which is the condition of 2-level operation. Fig. 9 and Fig. 10 show plot of $r_{ga}$ for modulation index of 0.5 and 0.8 where inverter is operating in 3-level and 4-level respectively. Randomly varying switching frequency produces abrupt variations in $r_{ga}$. For all ranges of speed, $r_{ga}$ shows random variations which indicate the effectiveness of the proposed technique. The phase voltage and current of the proposed scheme for a modulation index, of 0.8 is shown in Fig. 11.

The pole voltage of A-phase for a modulation index of 0.8 is shown in Fig. 12. The upper trace shows the pole voltage, $V_{AO}$, of Inverter-I and the middle trace shows the pole voltage, $V_{A'O'}$, of Inverter-II (in Fig. 1(a)). The lower trace shows the effective pole voltage of the 4-level inverter which is the difference between the pole voltages of the individual inverters.

![Fig. 8: Plot of gate timing signal $r_{ga}$ of proposed scheme for modulation index of 0.2. X-axis: 20ms/div; Y-axis: 500mV/div (experimental result - DAC output)](image1)

![Fig. 9: Plot of gate timing signal $r_{ga}$ of proposed scheme for modulation index of 0.5. X-axis: 10ms/div; Y-axis: 500mV/div (experimental result - DAC output)](image2)

![Fig. 10: Plot of gate timing signal $r_{ga}$ of proposed scheme for modulation index of 0.8. X-axis: 4ms/div; Y-axis: 500mV/div (experimental result - DAC output)](image3)
The spectrum of the phase voltage, for the proposed scheme and that of SVPWM (for a fixed switching frequency of 2.5 KHz) for a modulation index of 0.5 is shown in Fig. 13(a) and 13(b). It is observed that for the proposed RPWM scheme, the spreading of spectrum is achieved and no harmonic components of the switching frequency are present. But for the SVPWM, energy is concentrated at amplitudes for all harmonic components.

Fig. 11: Trace of phase voltage and phase current for modulation index of 0.8. (4-level operation)
Upper trace: A-phase voltage;
Scale: X-axis: 5ms/div; Y-axis: 50V/div
Lower trace: A-phase current;
Scale: X-axis: 10ms/div;
Y-axis: 2A/div

Fig. 12: Trace of pole voltage for modulation index of 0.8. (4-level operation)
Upper trace: A-phase pole voltage of inverter-I;
Middle trace: A-phase pole voltage of inverter-II;
Lower trace: Pole voltage of equivalent 4-level

Fig. 13 (a) Spectrum of phase voltage for modulation index of 0.5 for the proposed scheme
Scale: X-axis: 5KHz/div;
Y-axis: 20dB/div

Fig. 13 (b) Spectrum of phase voltage for modulation index of 0.5 for SVPWM with constant switching frequency
Scale: X-axis: 5KHz/div;
Y-axis: 20dB/div

Fig. 14(a) and 14(b) show the spectrum of the phase voltage of the proposed method and that of SVPWM for a modulation index of 0.8. The proposed method is proved to have better spectral spreading characteristics.

Fig. 14 (a) Spectrum of phase voltage for modulation index of 0.8 for the proposed scheme
Scale: X-axis: 5KHz/div;
Y-axis: 20dB/div

Fig. 14 (b) Spectrum of phase voltage for modulation index of 0.8 for SVPWM with constant switching frequency
Scale: X-axis: 5KHz/div;
Y-axis: 20dB/div
5 CONCLUSION

In this paper a space vector based random PWM scheme for a 4-level inverter is presented. The sampling of reference space vector is made at random intervals to achieve randomization. Random switching frequency in the range of 2.5±1KHz. is used in the experimental verification of the proposed scheme. Mapping technique used in this scheme can be used for extending the proposed scheme to any n-level inverter. The experimental results show the effectiveness of this scheme in spreading the energy of output into continuous spectrum for all modulation indexes. The scheme is verified for a 4-level open-end winding induction motor based drive with asymmetric DC link voltage and can be, implemented for any inverter topology.

REFERENCES


