

HYBRID SWITCHING SEQUENCES FOR HARMONIC DISTRIBUTION IN VOLTAGE SOURCE INVERTER

Tamilarasu Viswanathan¹, Anbukumar Kavitha²

¹Research scholar, ²Associate Professor,

Department of Electrical and Electronics Engineering, College of Engineering, Guindy, Anna University,

Tamil Nadu, India

Viswa.tamilsri@gmail.com

Abstract

This paper analyzes the harmonic distribution in the voltage and current of the voltage source inverter (VSI) through adjusting randomize the inactive vectors operating period of the space vector modulation (SVM) for different sequence inside the sector. Initially the range of inactive vector operating period is analyzed for different sequence is studied with respect to harmonics distribution. Degree of randomization inside the sector is analyzed in terms of sequences which is decide means of modulation index as well as selection of inactive vectors. Based on the selection of inactive vectors randomization, five different inactive vector timing is proposed namely null active $T_0 > T_7$, full inactive $T_0 < T_7$, alternate null full, alternate with fixed random T_0 dominant and alternate with fixed random T_7 dominant. These randomized operating times is implemented in the zone wise sequence which results in harmonic spreading in the output voltage. Additionally, the zonal distribution of T_0 & T_7 inactive vector operating timings is make significant effect in the current ripple. The randomization of inactive operating time is analyzed in terms of d-q axis and RMS current ripple expression which is suitable for motor fed drive. Advantage of the proposed scheme is reducing the switching loss than existing schemes with superior harmonics distribution. Effectiveness of the proposed scheme is analyzed through harmonic spreading factor, harmonic distortion in the output voltage and current. Practical implementation of new scheme is through the dead time showing the effectiveness of the study. The simulation and experimental results showing the effectiveness of the mathematical concepts proposed.

Keywords: Voltage source inverter (VSI), Space vector modulation (SVM), Harmonics distribution, Degree of randomization.

1. Introduction

Harmonics distribution is needed to distribute the dominant harmonics which are producing the resonance effect and adding ripple content in the output voltage. Many methods are

proposed to reduce the harmonic effect by means of selection appropriate switching sequence and operating timing. Initially the random based scheme used to vary the carrier frequency which results in high switching loss for high speed drives [1]. For other converter like matrix converter selecting the carrier wave results in adding the sub harmonics which is unwanted also the dead time effect produce unwanted harmonic spikes inside the output voltage [2]. Another method of producing the harmonics for even frequencies, the variable switching frequency is proposed [3]. But it is not preferable for the inverter reduce the lifetime of the switching period.

The modified version of the scheme is fixed frequency with alternate variation in the pulse position of the inverter which makes suitable preference inside the switching period. The same scheme is applied for the multi-level converter varied with for n level of switches increase the voltage gain in the output voltage with unbalance current ripple [4]. Many methods proposed for the inverter system; start with the different random pulse position for the different period. Generation of operating period through pseudo random is producing the alternative carrier inside the alternate carrier [5]. This scheme is not give any detail about distribution of harmonics in terms of d-q axis modelling. The objective of the scheme is only to reduce the voltage gain not focusing on the current ripple. For overcome this modulation based scheme needed to control the d-q modelling to be proposed.

More than decade the placement of the zero vectors in SVM makes the significant effect in the output voltage is proved [6]. Zero vector distribution with the variation inside the variable frequency may lead the uneven distribution leads the value of the losses [7]. Separation of the harmonic content inside the distribution of the centre based is discussed and amount of the ripple is distributed is significantly greater than the existing one. Split the space vector diagram in terms of veronica region makes the effective distribution but the effect of switching sequence in each period is not discussed [8]. Sub harmonics based control of the SVM sequences are

proposed which is not focused on the control of the harmonics distribution [9].

The doubling the carrier frequency is proposed recently make drastic effect in terms of switching loss increase the unwanted ripple content inside the output voltage [10]. Harmonics present in the output voltage spread through the hybrid switching sequences within the sector results in reduction of THD [11]. The average switching frequency of this scheme is same as conventional switching sequences. In addition, the switching sequence reduces the RMS current ripple [12]. Among random sequences, the operating period of the zero vectors results in distribution of the harmonics in the voltage spectra results in lower THD. Moreover, the ripple content reduced in RMS current [13].

The hybrid switching sequence with randomized period in the zero vectors is analyzed for each sector. Initially the randomized period of the switching sequence is identified for every spatial region. Furthermore, the sequence should be valid for the entire modulating region. To analyze the current ripple, d-q axis RMS ripple is calculated for each sub-cycle and distribution effective is explained in error voltage vector. Randomize operating period of zero vectors reflect in the current ripple for different hybrid switching sequences results in spreading harmonics effect. Individually spatial regions are analyzed (Three zone, five zone and Seven zone) and the randomized operating time sequence proposed. The harmonics distortion is analyzed through individual d- axis and q-axis. Finally in practically the dead time is included for the minimum ripple reduction for the random switching sequence.

The entire scheme is analyzed with existing randomized switching scheme and conventional SVM technique. Switching loss greatly reduced in the proposed scheme than conventional scheme for a rated system. The implementation of the randomized hybrid SVM techniques is verified in 5 kVA inverter the firing pulse generated through cortex-M3 processor. The main contribution of the project is for same average switching frequency the hybrid switching sequence is applied for the different zone with randomized operating time of null vector which is not reported earlier.

1. The selection of randomized operating period of switches with respect to d-q axis which ensures the suitable for the drive based applications.
2. Significant amount of ripple is getting reduced in the output RMS current ripple.

3. Switching loss is comparatively less with respect to the any other conventional SVM or randomized switching scheme.
4. Effect of dead time is included for showing the practical feasibility of scheme.

The organization of the paper as follows. Section 2 explains the concept of the randomized hybrid switching sequence for the VSI. Section 3 describes that the zone wise randomization of the switching sequence in terms of inactive vector randomization. Section 4 details the current ripple analysis of the switching sequence in terms of d-q modelling. Discussion on the harmonics distortion and spreading effect is given in the section 5 and section 6 respectively. The switching loss and dead time effect discussed in the section 7. Verification of the proposed concept with simulation and experimental results presented in section 8. Comparison of the different randomization method with existing explained in section 9. Finally in section 10, the overview and the extension of the scheme for the proposed control method is discussed.

2. Proposed randomized hybrid SVM

Switching position of switches in each leg of VSI represented in terms of active vectors ($V_1 - V_6$) and inactive vectors (V_0, V_7) are shown in space vector diagram in Fig.1 (a). As two active and two inactive vectors form a sector that vector space divided into six sectors ($S=1, 2 \dots 6$). The reference space vector V_{ref} revolves with angular frequency of $\omega_f = 2\pi f_f$ (where f_f is fundamental frequency 50 Hz) decided by active and inactive vectors for any sector. For a one switching period T_s , the reference vector is given in equations;

$$V_{ref} = \frac{1}{T_s} (V_x \cdot T_x + V_y \cdot T_y + V_0 \cdot T_0 + V_7 \cdot T_7) \quad (1)$$

Where, V_x and V_y are active vectors of specific sector. The operating period of active vectors is given by

$$T_x = \sqrt{3} \cdot m \cdot T_s \cdot \sin \left(\frac{S\pi}{3} - \alpha \right) \quad (2)$$

$$T_y = \sqrt{3} \cdot m \cdot T_s \cdot \sin \left(\alpha - \frac{(S-1)\pi}{3} \right) \quad (3)$$

The remaining is equally shared by the inactive vector is

$$T_0 = T_7 = \frac{T_s - T_x - T_y}{2} \quad (4)$$

According to the conventional SVM, the switching sequence employed either (0 1 2 7) in first sub cycle and (7 2 1 0) in second sub cycle of switching period in a sector I ($S=1, x=1$ and $y=2$) as shown in Fig.1 (b). According to [11], the valid three switching sequences (3ss) with sector I for sub cycle

I and II are (0127, 7210), (1012, 2101), (7212, 2127), (0121, 1210), (2721, 1272). Additionally the two switching sequences (2ss) or clamping sequences may include (012, 210) and (721, 127). Combining the switching sequences different operating zones are explained namely three zone, five zone and seven zone PWM in Fig 1 (b)-(d). In three zone 0127(A), 0121(B1), 7212(B2) are used, adding 1012(C1) and 2721(C2) with three zone produce five zone PWM and finally the 2ss switching sequence 012(D1) and 721(D2) produce seven zone PWM are shown in Fig.2.

When randomization is apply in the inactive operating period, the value is not same for all sequence and zone. The center of the switching pulses is varied randomly within the switching period [7]. For the switching sequences A1, A2, D1, D2, the center distribution varied with respect to the two sub cycle T_s and for remaining sequence B1, B2, C1, C2 the distribution varied with one sub cycle $T_s/2$. The degree of randomization of each sequence is varied with modulation index M

For sequence 0127 A1;

$$T_0 - T_x + T_7 - T_y = T_s - 2T_x - 2T_y \quad (5)$$

$$= T_s - 2\sqrt{3}.m.T_s.\sin\left(\frac{S.\pi}{3} - \alpha\right) - 2\sqrt{3}.m.T_s.\sin\left(\alpha - \frac{(S-1)\pi}{3}\right)$$

$$= T_s \left\{ 1 - 2\sqrt{3}.m.\sin\left(\frac{S.\pi}{3} - \alpha\right) - 2\sqrt{3}.m.\sin\left(\alpha - \frac{(S-1)\pi}{3}\right) \right\}$$

$$\left\{ 1 - 2\sqrt{3}.m.\sin\left(\frac{S.\pi}{3} - \alpha\right) - 2\sqrt{3}.m.\sin\left(\alpha - \frac{(S-1)\pi}{3}\right) \right\} = 0$$

$$m = \frac{1}{2\sqrt{3}.\sin\left(\frac{S.\pi}{3} - \alpha\right) - 2\sqrt{3}.\sin\left(\alpha - \frac{(S-1)\pi}{3}\right)}$$

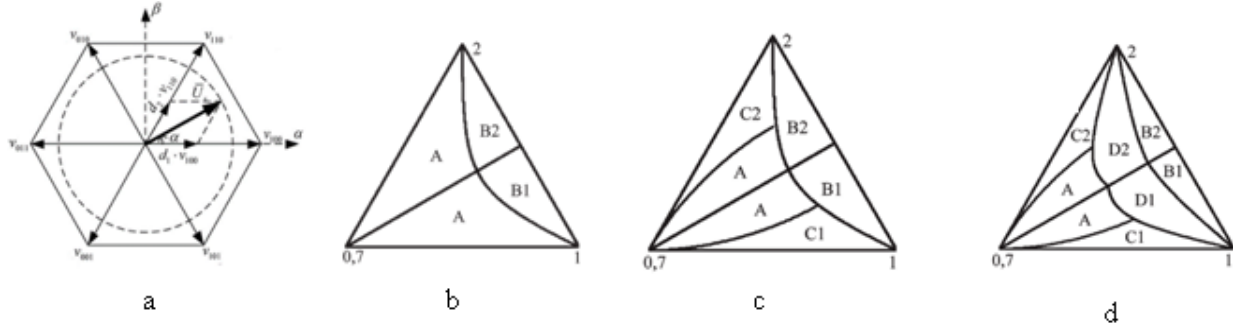


Fig. 1(a) Space vector diagram of VSI switches (b) Three zone (c) Five zone, and (d) Seven zone

For 1012 B1 and 0121 C1 and D1 012

$$T_0 - T_x = T_s - 2T_x - T_y \quad (6)$$

$$m = \frac{1}{2\sqrt{3}.\sin\left(\frac{S.\pi}{3} - \alpha\right) - \sqrt{3}.\sin\left(\alpha - \frac{(S-1)\pi}{3}\right)}$$

For 7212 B2, For 1210 C2 and 721 (D2)

$$T_0 - T_x = T_s - 2T_x - T_y \quad (7)$$

$$m = \frac{1}{\sqrt{3}.\sin\left(\frac{S.\pi}{3} - \alpha\right) - 2\sqrt{3}.\sin\left(\alpha - \frac{(S-1)\pi}{3}\right)}$$

The limitation of the sequence is only valid within the linear modulation range. On the other hand, for spreading the harmonics is through random centered distribution PWM proposed in [1], randomly adjusting the operating period of zero vectors within a fixed switching period. Within linear modulation range ($m < 0.8$), the zero vector (000) operating period is randomly adjusted, otherwise the zero vector (111) operating period is randomly varied. There is no variation in operating period of other active vectors V_x and V_y . The adjustment in the zero vector operating time is (3), the operating period of T_0 and T_7 are not always equal. Generalized function of the operating period is given by

$$T_{0rand} = T_s - T_x - T_y - T_{7rand},$$

$$\text{Or } T_{7rand} = T_s - T_x - T_y - T_{0rand}. \quad (8)$$

The change in modulation index will reflect in the modulation index and generalized equation to derive with respect to the V_{ref} . Combining the two concepts for three phase inverter which is not reported earlier and handful idea to improve the harmonic profile as well as reduce the current ripple with improved voltage gain.

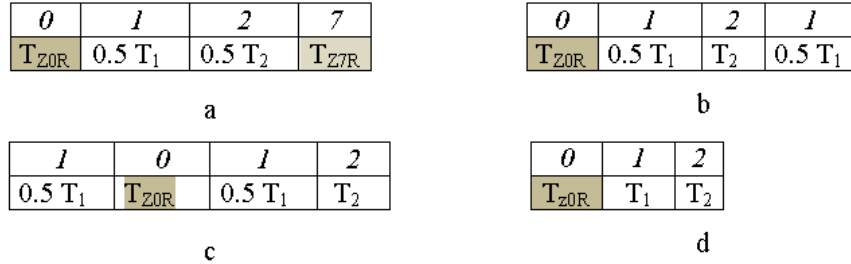


Fig. 2. Different null inactive vector based switching sequence inside the sector I with their operating Period a) A1 sequence b) B1 sequence c) C1 Sequence d) D1 Sequence

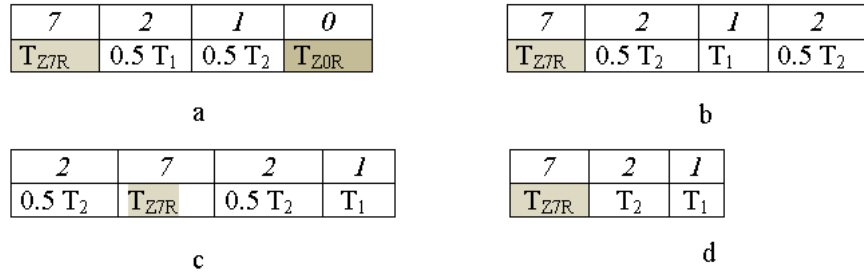


Fig. 3. Different full inactive vector based switching sequence inside the sector I with their operating Period a) A2 sequence b) B2 sequence c) C2 Sequence d) D2 Sequence

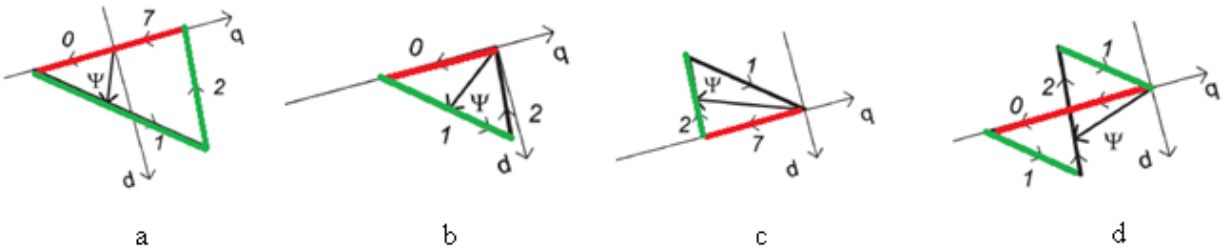


Fig. 4. Variation in d-q axis for sequence (a) 0127 b) 012 c) 721 d) 0121

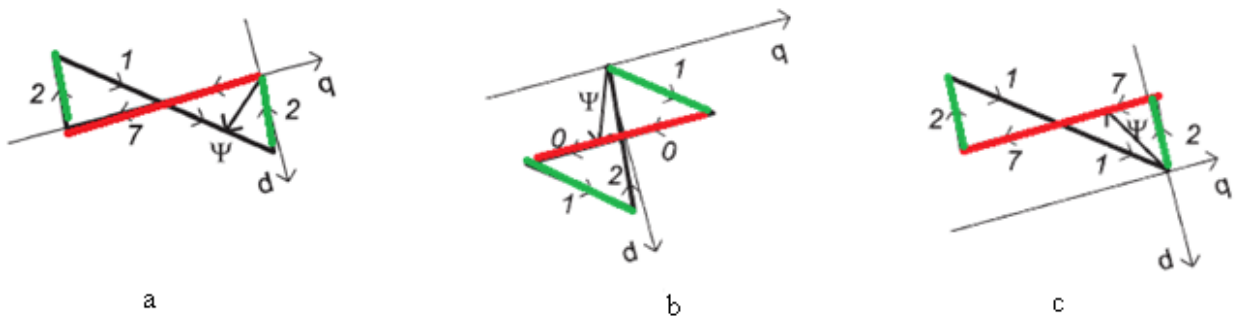


Fig. 5. Variation in d-q axis for sequence (a) 7212 b) 1012 c) 2721

3. Randomized zonal PWM

Based on the randomization of the inactive vector operating timing are five different cases proposed for analyzing for the different zone with in a sector are given as a) Equal Randomization (ER) b) Randomizing $T_7 > T_0 / T_0 > T_7$ same for adjacent sub cycle (AR) c) Sequence wise (SR) d) Zone wise randomization (ZR). Initially the random number calculation through pseudo random numbers, but the disadvantages are overcome through TRUE random

number generation. The operating period randomization is shown in Fig. 3 for each switching sequence with individual case.

4. Effect of Voltage error from time (ripple analysis)

The effect of the new randomized sequence in the current ripple is measure in terms of flux ripple notation. It can derive through the time integral of the error space vector which is the difference of

instantaneous space vector applied to the switches and the reference space vector. The error voltage vectors for the active vector.

$$\begin{aligned} V_{xerror} &= V_x - V_{ref} \\ V_{yerror} &= V_y - V_{ref} \\ V_{zerror} &= -V_{ref} \end{aligned} \quad (9)$$

To show the effectiveness of the proposed sequences, the RMS current ripple is analyzed for every sub cycle as a result the line current distortion is getting reduced, when compared with existing sequences.

For a case, $V_{ref} = 0.8, \alpha = 35^\circ$ the condition is applied for the all sequences with five different cases shown in Fig. 4. The randomizations of the operating period are decided from the quasi random numbers with different five cases. Normally, the stator flux ripple determines in synchronously reference frame d axis (90° shift with V_{ref}) and q axis (in aligned with V_{ref}). For each vector, the error quantities Q_x, Q_y, Q_z and D showed in Fig 4 and 5. The suggestions given in the literature [12] are taken into consideration, the expression for the stator flux ripple for each switching sequence and cases are shown in Appendix. 1.

Applied the switching sequence for the different zone, the experimental results are proposed in section V.

5. Harmonic Distortion

The harmonic distortion in the output voltage represented as Total Harmonic distortion including the entire three different zones is shown in Table 2 (06340682) and for the different frequency.

6. Harmonic spreading factor

Another advantage of the method is harmonic spreading in the output line voltage is presented for the different proposed PWM. The Harmonic spreading effect measure in terms of Harmonic spreading factor is given as;

$$\begin{aligned} HSF &= \sqrt{\frac{1}{N} \sum_{j>1}^N (H_j - H_0)^2} \\ H_0 &= \frac{1}{N} \sum_{j>1}^N H_j \end{aligned} \quad (10)$$

Applying the mathematical equation for the harmonics spreading effect is shown in Table 3.

7. Simulation and experimental verification

A 10 kVA two-level VSI driving 1 HP three phase induction motor is used for verifying the new randomized zonal scheme. Firing pulses for switches are generated from ARM cortex-M3 CPU which has capable of generating true random numbers (TRNG). For all five methods, the randomization is applied for the three different zones for different modulation indices. The pole voltage V_{a0} and I_a line current of the inverter for $m=0.5$ is shown simulation results in Fig. 6 and Fig. 7 for SR PWM in the Three, Five and seven zone. Fig. 8 and 9 shows the simulation results pole voltage V_{a0} and I_a line current of the inverter for $m=0.5$ for ZR PWM. Fig.9 shows the pole voltage for the three zone, five zone and seven zone PWM, when applying the ZR PWM. Comparison of the ripple content in the line current for three zones, five zones and seven zones is shown in Fig.10, when applying the zone wise PWM techniques.

Table 1. Proposed switching scheme with inactive vector randomization

Schemes	A1 0127	A2 7210	B1 0121	B2 7212	C1 1012	C2 2721	D1 012	D2 721
ERPWM	Either T_{0ZR} or T_{7ZR}	NA	T_{0ZR} Only	T_{7ZR} Only	T_{0ZR} Only	T_{7ZR} Only	T_{0ZR} Only	T_{7ZR} Only
ARPWM	T_{0ZR} and T_{7ZR} in adjacent cycles	NA	T_{0ZR} Small/ High	T_{7ZR} Small/ High	T_{0ZR} Small/ High	T_{7ZR} Small/ High	T_{0ZR} Small/ High	T_{7ZR} Small/ High
SRPWM Include M value	T_{0ZR} M=0.5	NA	T_{0ZR} small	T_{7ZR} High	T_{0ZR} High	T_{7ZR} High	T_{0ZR} High	T_{7ZR} Small
ZRPWM Including alpha value	Upto 15-45 Equal	NA	Upto 45 T_{0ZR} Small	Upto 60 T_{0ZR} High	Upto 0-30	50	Upto 0-30	30 -60

Table 2. Distortion for different applied PWM

Proposed Schemes	Three zone		Five Zone		Seven zone	
	M=0.5	M=0.9	M=0.5	M=0.9	M=0.5	M=0.9
For $f_s = 3\text{kHz}$						
ER	4.92	4.44	3.87	4.12	3.72	3.56
AR	3.98	3.88	3.01	3.12	3.08	2.96
SR	4.19	3.21	3.61	3.76	2.19	2.11
ZR	4.00	3.42	3.10	2.67	2.83	1.81

Table 3. Harmonic Spreading for different PWM

Proposed Schemes	Three zone		Five Zone		Seven zone	
	M=0.5	M=0.9	M=0.5	M=0.9	M=0.5	M=0.9
For $f_s = 3\text{kHz}$						
ER	19.4	20.7	18.5	19.2	18.1	18.7
AR	17.3	17.4	15.8	17.2	14.8	15.5
SR	17.8	16.8	17.3	17.8	14.2	14.7
ZR	18.9	19.1	17.0	16.3	15.7	13.1

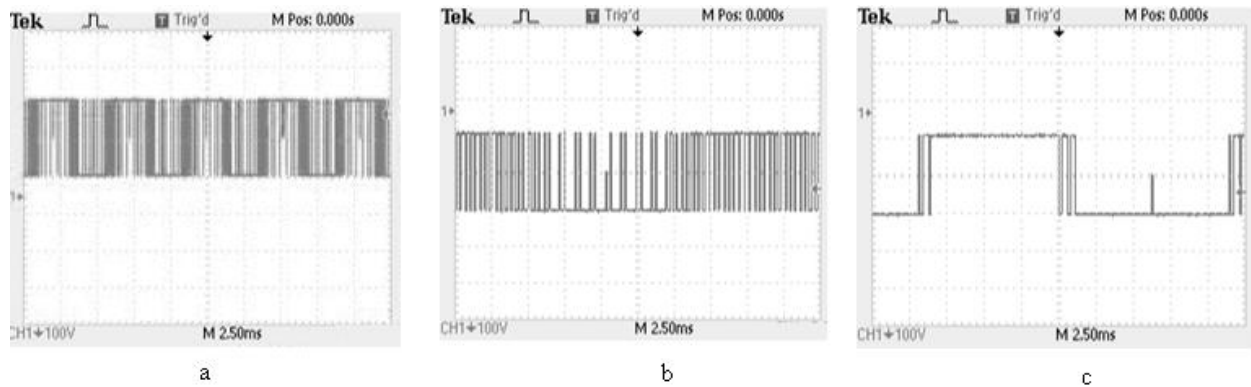


Fig. 9. Applying ZR scheme inside the VSI pole voltage V_{ao} (a) Three zone b) Five zone c) Seven Zone

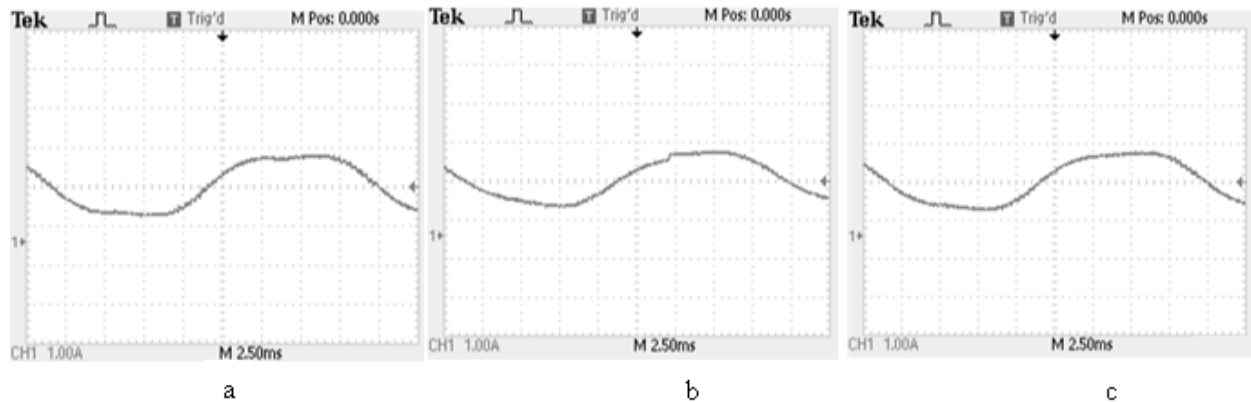


Fig. 10. Applying ZR scheme inside the VSI pole the line current i_a (a) Three zone b) Five zone c) Seven zone

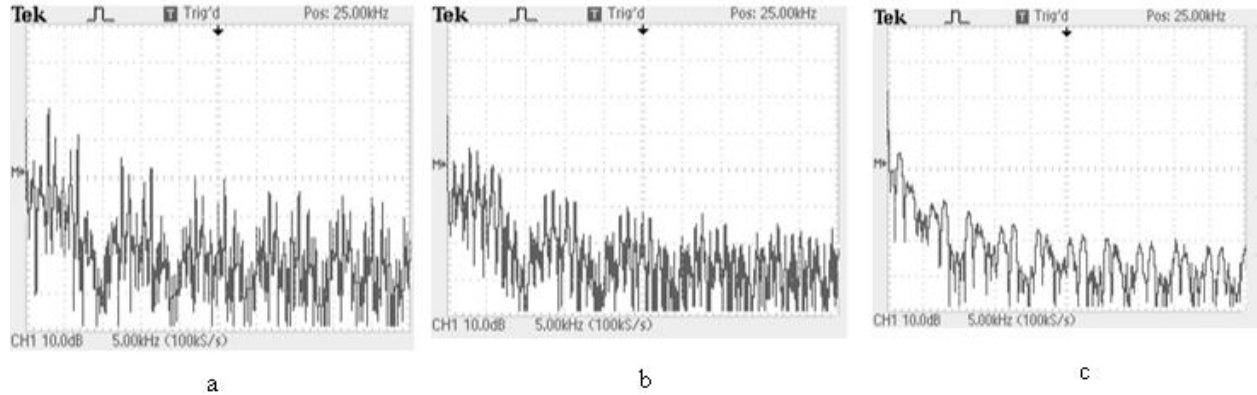


Fig. 11. FFT analysis o-spectra of V_{ao} applying ZR scheme (a) Three zone b) Five zone c) Seven Zone

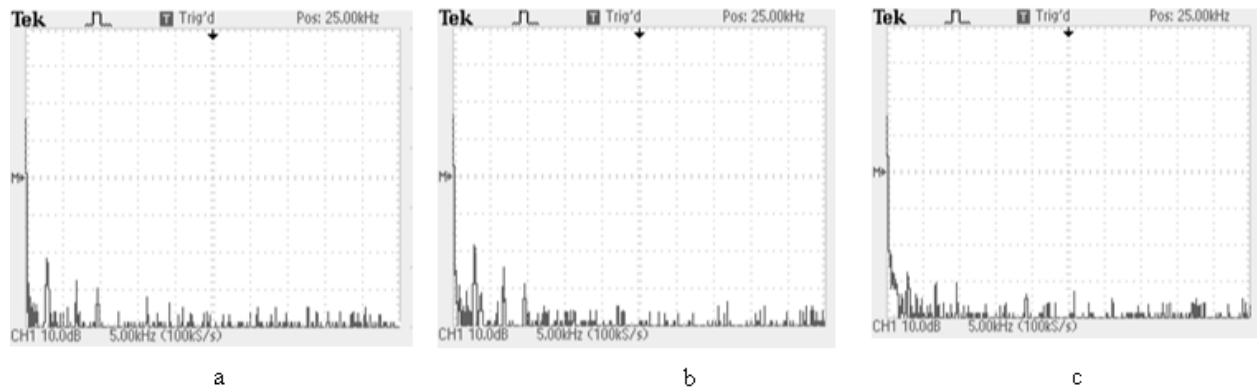


Fig. 12. FFT analysis – spectra of i_{a0} applying ZR scheme (a) Three zone b) Five zone c) Seven Zone

8. Discussion

FFT analysis of the proposed scheme represented in Fig 11-12 for different zone voltage and current respectively. For the three zones PWM, the ZR scheme shows the spreading effect due to the even spreading of the switching inside the V_7 region. For higher modulation index, the SR scheme exhibits the better spreading effect due to the Extension of the sequence 0127 in the higher modulation region. Similarly, the sequence 127, 0127 has dominant in the five zone PWM which excellent spreading of the switching sequences inside the lower modulation index and ZR PWM in the higher modulation region for the better spreading property. Finally the Seven zone PWM, within the lower modulation index the value SR exhibits the better spreading effect sharing of alternate T7 and ZR exhibits good spreading effect inside the higher modulation index because of the switching sequence 0127.

Reference

1. Boys, J.T., "Theoretical spectra for narrow-band random PWM waveforms," *Electric Power*

Applications, IEEE Proceedings B, vol.140, no.6, pp.393-400, Nov 1993.

2. Chen Qi; Xiyu Chen; Ying Qiu, "Carrier-Based Randomized Pulse Position Modulation of an Indirect Matrix Converter for Attenuating the Harmonic Peaks," *Power Electronics, IEEE Transactions on*, vol.28, no.7, pp.3539-3548, July 2013.
3. Mathe, L.; Lungeanu, F.; Sera, D.; Rasmussen, P.O.; Pedersen, J.K., "Spread Spectrum Modulation by Using Asymmetric-Carrier Random PWM," *Industrial Electronics, IEEE Transactions on*, vol.59, no.10, pp.3710-3718, Oct. 2012.
4. Bech, M.M.; Blaabjerg, F.; Pedersen, J.K., "Random modulation techniques with fixed switching frequency for three-phase power converters," *Power Electronics, IEEE Transactions on*, vol.15, no.4, pp.753-761, Jul 2000.
5. Young-cheol Lim; Seog-Oh Wi; Jong-Nam Kim; Young-Gook Jung, "A Pseudorandom Carrier Modulation Scheme," *Power Electronics, IEEE*

- Transactions on , vol.25, no.4, pp.797-805, April 2010.
6. Holmes, D.G., "The significance of zero space vector placement for carrier-based PWM schemes," *Industry Applications, IEEE Transactions on* , vol.32, no.5, pp.1122-1129, Sep/Oct 1996.
 7. Seung-Yeol Oh; Young-Gook Jung; Seung-Hak Yang; Young-cheol Lim, "Harmonic-Spectrum Spreading Effects of Two-Phase Random Centered Distribution PWM (DZRCD) Scheme With Dual Zero Vectors," *Industrial Electronics, IEEE Transactions on*, vol.56, no.8, pp.3013-3020, Aug. 2009
 8. Jacob, B.; Baiju, M.R., "Spread spectrum modulation scheme for two-level inverter using vector quantised space vector-based pulse density modulation," *Electric Power Applications, IET*, vol.5, no.7, pp.589-596, August 2011.
 9. Stumpf, P.; Jardan, R.K.; Nagy, I., "Subharmonics Generated by Space Vector Modulation in Ultrahigh Speed Drives," *Industrial Electronics, IEEE Transactions on* , vol.59, no.2, pp.1029-1037, Feb. 2012.
 10. Ki-Seon Kim; Young-Gook Jung; Young-cheol Lim, "A New Hybrid Random PWM Scheme," *Power Electronics, IEEE Transactions on*, vol.24, no.1, pp.192-200, Jan. 2009.
 11. Hari, V.S.S.; Narayanan, G., "Space-vector-based hybrid pulse width modulation technique to reduce line current distortion in induction motor drives," *Power Electronics, IET*, vol.5, no.8, pp.1463,1471, September 2012.
 12. Narayanan, G.; Ranganathan, V.T.; Di Zhao; Krishnamurthy, H.K.; Ayyanar, R., "Space Vector Based Hybrid PWM Techniques for Reduced Current Ripple," *Industrial Electronics, IEEE Transactions on*, vol.55, no.4, pp.1614-1627, April 2008.
 13. Young-cheol Lim; Young-Gook Jung; Seung-Yeol Oh; Jeong-Geun Kim, "A Two-Phase Separately Randomized Pulse Position PWM (SRP-PWM) Scheme With Low Switching Noise Characteristics Over the Entire Modulation Index," *Power Electronics, IEEE Transactions on* , vol.27, no.1, pp.362,369, Jan. 2012.
 14. K. S. Kim, Y. G. Jung, and Y. C. Lim, "Shaping the spectra of the acoustic noise emitted by three-phase inverter drivers based on the new hybrid random PWM Technique," in *Conf. Rec. IEEE PESC 2006*, pp. 545–550, PS 1–89 (CD-ROM version).
 15. Dong-Hee Lee; Jin-Woo Ahn, "A Simple and Direct Dead-Time Effect Compensation Scheme in PWM-VSI," *Industry Applications, IEEE Transactions on* , vol.50, no.5, pp.3017,3025, Sept.-Oct. 2014.