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Research paper

Correlation between carrier and space vector based random PWM techniques for induction motor drive

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Abstract

Conventional pulse width modulation (PWM) techniques for voltage source inverter (VSI) generate high amount of harmonics at and around harmonics of switching frequencies. These causes acoustic noise and electron magnetic interference to the nearby electronic systems. In this paper different random PWM techniques were proposed for two-level VSI. The implementations of these PWM techniques were presented based on carrier comparison approach and digital space vector approach. Moreover correlations between these two methods were also presented.

Constant Switching Frequency; Carrier Comparison Approach; Pulse Width Modulation (PWM); Space Vector Approach; Random PWM; Variable Switching Frequency.

1. Introduction

Voltage source inverter shown in Fig. 1is employed with Pulse width modulation techniques for the control of output voltage and frequency [1-6].
The implement of PWM techniques can be carried out through space vector based carrier comparison approach and space vector based digital approach [4]. Authors in [4] explained correlation between carrier comparison approach and digital space vector approach. Different continuous and discontinuous modulating signal based PWM techniques [5-6] are employed to reduce the ripple and improve the quality of output voltage.
All the PWM techniques are concentrated with high amount of harmonics at and around harmonics of switching frequencies. This will results in acoustic noise.

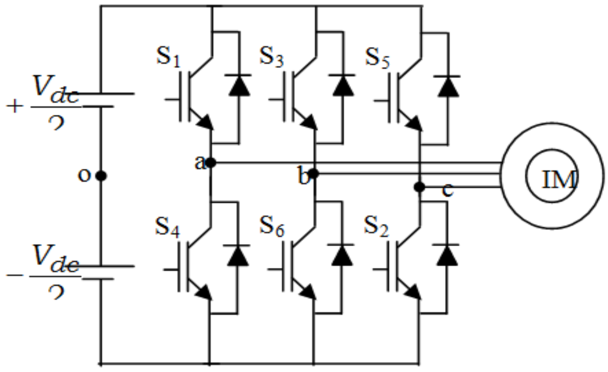
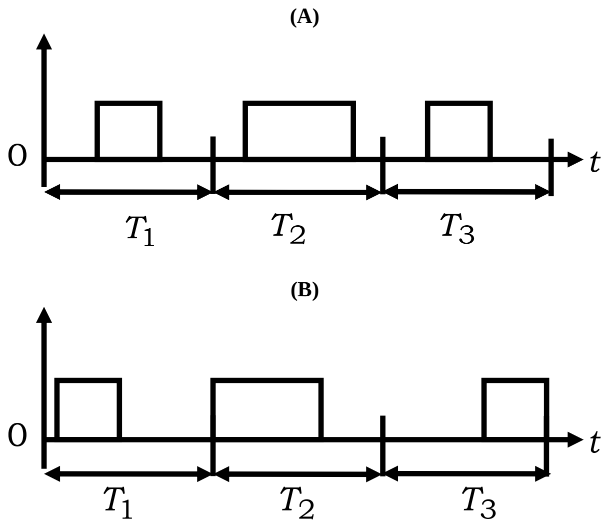


Fig. 1: Circuit Diagram of Two-Level Voltage Source Inverter Fed Induction Motor Drive.

In order to reduce acoustic noise, vibration and electromagnetic interference different random PWM techniques are gaining importance. In these random PWM techniques either pulse position or pulse width or pulse frequency is varied randomly [7-13]. The graphical representations of all such PWM techniques are shown in Fig. 2. In Fig. 2(a) the pulse pattern with conventional PWM is shown in which pulse width is different but the pulse frequency is same in the entire time period. In the pulse position modulation technique pulse frequency remains same but the pulse position is randomly placed as shown in Fig. 2(b). Hence such PWM techniques are called as constant switching frequency random PWM techniques. In Fig. 2 (c) pulse frequency is varied over a wide range of frequencies. Hence such PWM techniques are called as variable switching frequency random PWM techniques.



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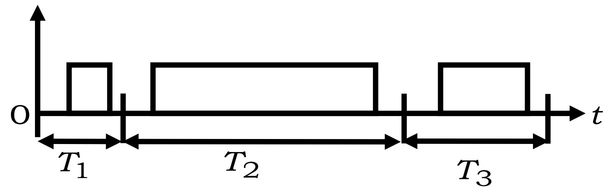

Fig. 2: Pulse Pattern of (A) Conventional PWM Technique (B) Pulse Position Modulation Technique (C) Pulse Frequency Modulation Technique.

Among constant switching frequency [7-8], [13] and variable switching frequency random PWM techniques [15-16], [13], constant switching frequency PWM schemes are gaining importance because of easier filter design. In constant switching frequency PWM techniques pulse position can be modulated in different ways. One such method based on carrier comparison approach is discussed in [11-13]. Alone with the existing method two new different methods were discussed in this paper. The implementation of all these PWM techniques was discussed both in carrier comparison approach and space vector approach. The reduction in magnitude of harmonics at and around harmonics of switching frequencies is small with constant switching frequency random PWM techniques. Hence variable switching frequency random PWM techniques are gaining importance [14-15]. In literature [16] it is discussed that within a band of 1 kHz filter design becomes easier. Hence in this paper two types of variable switching frequency random PWM techniques were also discussed. In these PWM techniques switching frequency is varied in a band of ±200 Hz of base frequency.

In this paper correlation between carrier comparison approach and space vector approach is presented for both constant and variable switching frequency random PWM techniques. The realization of these PWM techniques is discussed and the results are presented and evaluated using MATLAB/Simulink

2. Conventional pulse width modulation technique

To generate control signals for three phase two level inverter three reference signals as given in (1) are considered. In sinusoidal PWM technique these reference signals are compared with common carrier signal to generate control signals. This sinusoidal PWM technique gives poor DC utilisation and high switching losses. Hence modified sinusoidal PWM technique or space vector PWM technique are gaining importance.

$$V_{a\,ref} = Vm * \cos(\omega t)$$
$$V_{b\,ref} = Vm * \cos(wt - 120)$$
$$V_{c\,ref} = Vm * \cos(wt - 240) \quad (1)$$

These Modified PWM techniques can be implemented based on space vector based carrier comparison approach and space vector based digital approach. In space vector approach three reference signals which are in time domain is converted in to space domain using (1). The space vector plane formed by different switching states of inverter and reference space vector formed from three reference voltages are shown in Fig.2.

$$v_s = \frac{2}{3}\left(V_{ao} + V_{bo} e^{j(\frac{2\Pi}{3})} + V_{co} e^{j(\frac{4\Pi}{3})} \right) \quad (2)$$

Here V0 and V7 are the zero voltage vectors and V1 to V6 are the active voltage vectors. Based on the position of reference voltage vector (V_{ref}) nearest two active voltage vectors and two zero voltage vectors are sampled by satisfying the volt-sec balance condition. The time for which active vectors are applied and zero vectors are applied is given by (3).

$$T_1 = \frac{3V_{ref}}{2V_{dc}} * \frac{\sin(60-\alpha)}{\sin 60°} * T_s$$

$$T_2 = \frac{3V_{ref}}{2V_{dc}} * \frac{\sin\alpha}{\sin 60°} * T_s$$

$$T_z = T_s - T_1 - T_2 \quad (3)$$

The zero voltage vector times is divided into two equal half's as in (4).

$$T_7 = 0.5T_z \text{ and } T_0 = 0.5T_z \quad (4)$$

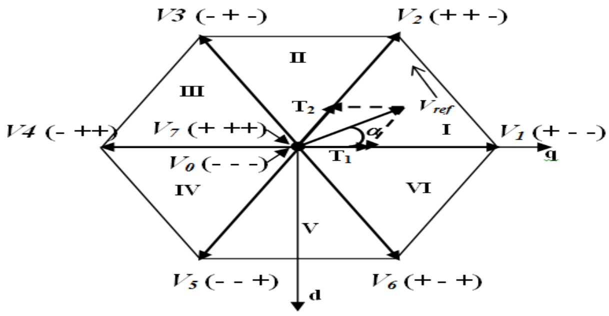

Fig. 2: Two –Level Space Vector Plane.

a) Space vector based carrier comparison approach

In space vector based carrier comparison approach switching times of S1, S3, S5 are calculated in all the sectors in terms of active vector times and zero vector times. For simplicity, if the reference vector lies in first sector the switching times are calculated using Fig.4. In sector-I the vectors utilised to synthesise reference vector are V0, V1V2, V7 (0127).

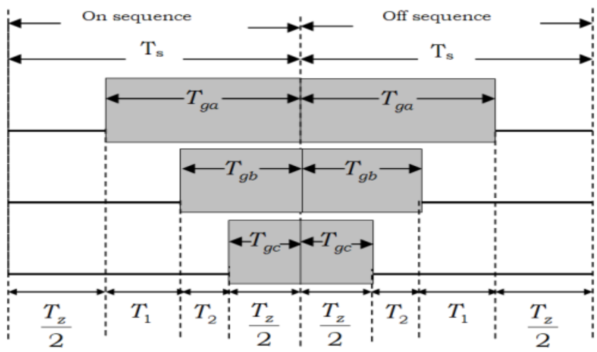

Fig. 4: Switching Times of Switches S1, S3 and S5.

Switching times of switches in sector-I are S1=T1+T2+T0; S3=T2+T0; S5=T0; In similar way using switching sequence or vectors given in table-I switching times of switches (S1,S3,S5) are calculated in all the remaining sectors. These switching times are nothing but the three modulating or new reference signals as shown in Fig. 5. These are compared with high frequency carrier signals to generate control signals for inverter.

Table 1: Switching States in All the Six Sectors

Sector number	OFF-sequence	ON-sequence
1	7-2-1-0	0-1-2-7
2	7-2-3-0	0-3-2-7
3	7-4-3-0	0-3-4-7
4	7-4-5-0	0-5-4-7
5	7-6-5-0	0-5-6-7
6	7-6-1-0	0-1-6-7

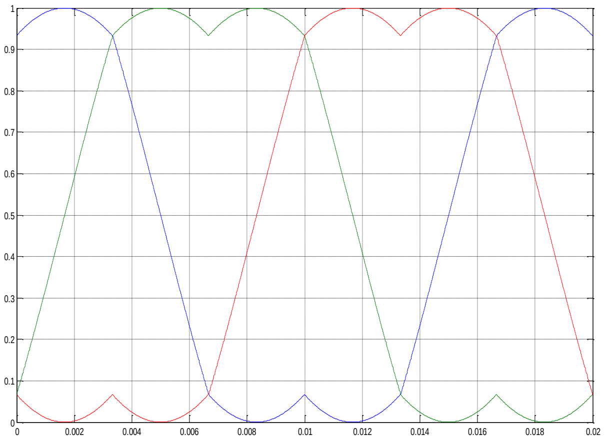

Fig. 5: Switching Times or Modulating Signals for Sequence 0127.

b) Space vector based digital approach

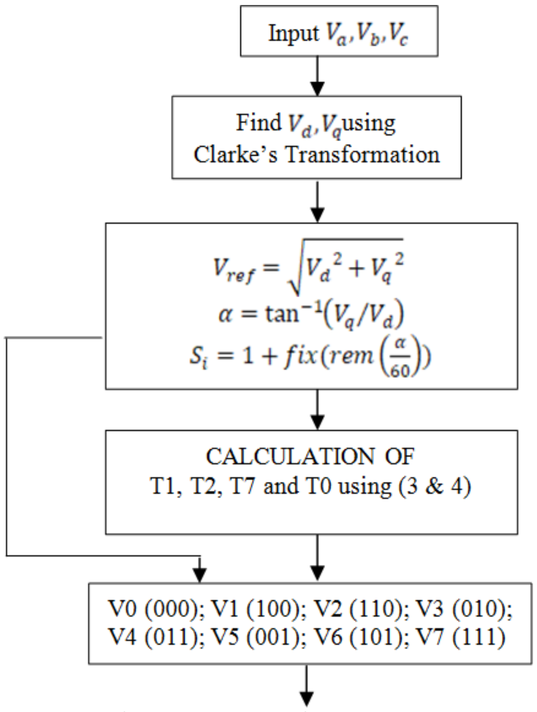

Fig. 6: Flow Chant for Implementation of Digital Space Vector Approach.

In space vector based digital approach pulse pattern of switches (S1, S3, and S5) are directly obtained by using lookup tables. All the switching states and switching sequence are to be stored in the form of lookup tables. The flow chard for the digital approach is given in Fig.6. Using active vector times (T1 and T2), zero voltage vectors times (Tz) and switching sequence for each sector given in table-I switching states or switching vectors are directly derived from the lookup table. The diagram showing correlation between digital and carrier comparison space vector approach is shown in Fig.7. As small time interval (Ts) is considered, the modulating signals shown in Fig.5 will appear as straight lines in Fig. 7. Tga, Tgb and Tgc are the switching times of switches S1, S3 and S5. From the Fig. 7 it is concluded that the pulse pattern obtained from both the methods are same.

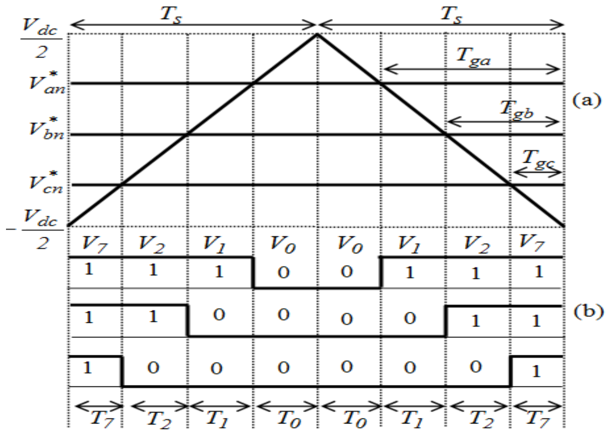

Fig. 7: Correlation between Carrier Comparison Approach and Digital Space Vector Approach.

3. Random pulse width modulation techniques

With the switching fashion employed in conventional SVPWM technique reduce current ripple and improves the DC utilization. But because of constant switching frequency employed to carrier signal, in the harmonic spectra it is observed that much amount of energy is concentrated at the multiples of switching frequencies. To reduce the magnitude of harmonics different random PWM techniques were identified.

Similar to conventional SVPWM techniques random PWM techniques can also be implemented based on carrier comparison approach and digital space vector approaches. In constant switching frequency random PWM techniques based on carrier comparison approach pulse position can be modulated by randomly varying the modulating signal or carrier signal.

a) Random reference PWM (RR-PWM):

In this type of PWM pulse position and pulse width is randomly varied by introducing the random ness in the reference signal. This type of reference signal is also called as random reference signal and it can be generated in similar way as continuous modulating signal.

To generate three phase random modulating signals, the zero time intervals are randomly shared among both the zero voltage vectors. This can be achieved by just modifying (4) as in (5)

$$T_7 = k_0 T_z \text{ and } T_0 = (1 - k_0) T_z \quad (5)$$

Ko is choosen as 0.5 to generate continuous new modulating signals. Now to generate random modulating signals ko is chosen randomly between 0 and 1. The resulting random modulating signal is shown in Fig. 8. It is observed from the modulating signals shown in Fig. 5 and Fig.8 is the continuous modulating signals are smoothly varying signals where random modulating signals contains abrupt variations. When such type of modulating signals is compared with high frequency carrier signal, gives rise to RR-PWM.

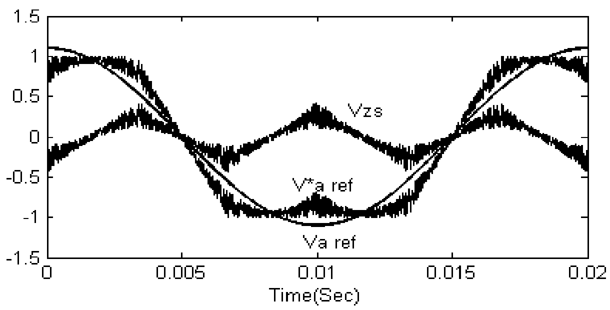

Fig. 8: Random Modulating Signal.

RR-PWM can be implemented in digital space vector approach by using the same switching sequence as in table-I (as in conventional

SVPWM), but the zero voltage vector times applied to the zero voltage vectors using (5).

b) Random carrier PWM (RC-PWM):

In this type of PWM technique instead of using one carrier signal, two carrier signals (positive triangular signal and negative triangular signal) are used for the generation of control signals. Though PWM techniques use both carrier signals, but at any instant only one carrier signal used for the generation of control signal. The selection among the two carrier signals is carried out randomly. The illustration of carrier selection scheme is shown in Fig. 9. From Fig. 9 it is observed that both positive and negative carrier signals are fed as inputs to carrier selector, along with these random generator output is also given as input. At any instant random generator generates 0 or 1. If random generator generates 1, then carrier selector selects positive carrier signal and if random generator generates 0, then carrier selector selects negative carrier signal. Hence the output of carrier selector is blend of positive and negative carrier signal. This resulting random carrier signal is compared with continuous modulating signal shown in Fig. 5. The PWM technique with continuous modulating signal and random carrier signal is called as RC-PWM technique.

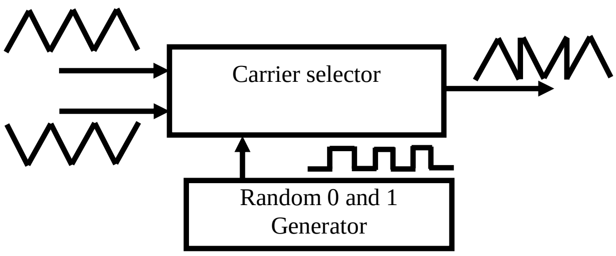

Fig. 9: Illustration of Random Carrier Selection Scheme.

Table 2: Switching States in All the Six Sectors for RC-PWM

	Sequence-1		Sequence-2	
Sector Number	OFF- Sequence	ON- Sequence	OFF- Sequence	ON- Sequence
1	7-2-1-0	0-1-2-7	0-1-2-7	7-2-1-0
2	7-2-3-0	0-3-2-7	0-3-2-7	7-2-3-0
3	7-4-3-0	0-3-4-7	0-3-4-7	7-4-3-0
4	7-4-5-0	0-5-4-7	0-5-4-7	7-4-5-0
5	7-6-5-0	0-5-6-7	0-5-6-7	7-6-5-0
6	7-6-1-0	0-1-6-7	0-1-6-7	7-6-1-0

This RC-PWM can be implemented in digital space vector by just randomly selecting any one of the switching sequence given in Table-II for a given sector. As only triangular signal is changed, hence only sequence is changed active vector times and zero vector times are not affected.

c) Variable switching frequency random PWM (VSF-RPWM) technique

In these types of random PWM techniques carrier signal frequency is varied over a wide band of frequencies (fs±500 Hz). The block diagram illustrating variable switching frequency random PWM (VSF-RPWM1) is shown in Fig. 10. In the Fig. 10 random frequency generator block randomly generates a frequency of ±500 of base switching frequency (5000 Hz). Based in this frequency, carrier signal generator block generates variable switching frequency carrier signal. In this VSF-RPWM1 the output, variable switching frequency carrier signal is compared with continuous modulating signal to generate control signals.

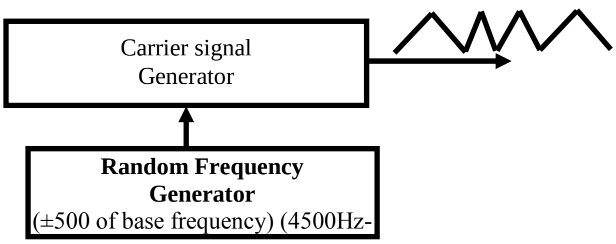

Fig. 10: Block Diagram Illustrating Variable Switching Frequency Carrier Signal Generation Scheme.

The VSF-RPWM can be implemented in digital space vector approach by just randomly changing the times Ts ($Ts = \frac{1}{f_s}$).

d) Random carrier selection and random variable switching frequency PWM (RCVSF-PWM) technique:

In this type of PWM technique instead of using one random variable switching frequency carrier signal, two sets (positive and negative carrier signals) of random variable switching frequency carrier signals are used. The selection among positive and negative variable switching frequency carrier signals is done randomly. The block diagram illustrating the RCVSF-PWM is shown in Fig. 11. In the Fig.11 carrier signal generator generates both the carrier signals (positive and negative carrier signals) with randomly variable switching frequency. These two signals are fed as inputs the carrier selector. Based on random generator, carrier selector randomly selects positive and negative carrier signal. The output carrier selector will be blend of positive and negative variable switching frequency carrier signals. The blended carrier signal (positive and negative carrier signals) is compared with continuous modulating signal to generate control signals.

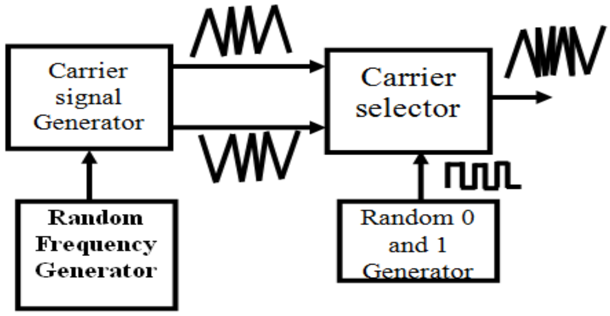

Fig. 11: Block Diagram Illustrating Random Carrier Selection and Random Variable Switching Frequency PWM Technique.

This RCVSF-PWM can be implemented in digital space vector approach by just randomly changing the times Ts ($Ts = \frac{1}{f_s}$) and by randomly selecting the sequence as in table-II.

4. Results and discussion

To validate the performance of proposed constant and variable switching frequency random PWM techniques simulation studies are carried in MATLAB/Simulink environment. The simulation results of pulse pattern with both carrier comparison approach and space vector approach for all the random PWM techniques are show in Fig. 12 to Fig. 17. The obtained pulses are used for the control of 4 Hp, 400 V, 50 Hz, 1430 rpm induction motor drive. For the comparison of pulse pattern the simulation studies are carried at a switching frequency of 1kHz. V/f control is employed for the control of inverter fed induction motor. The control signals are generated at a switching frequency of 5 kHz. The simulation results of line voltage and three phase line currents of voltage source inverter fed induction motor drive at modulation index M=0.81 with CPWM, RRPWM, RCPWM, RRRCPWM, VSF-RPWM and RCVSF-PWM are shown in Fig. 12(b) to Fig. 17(b).

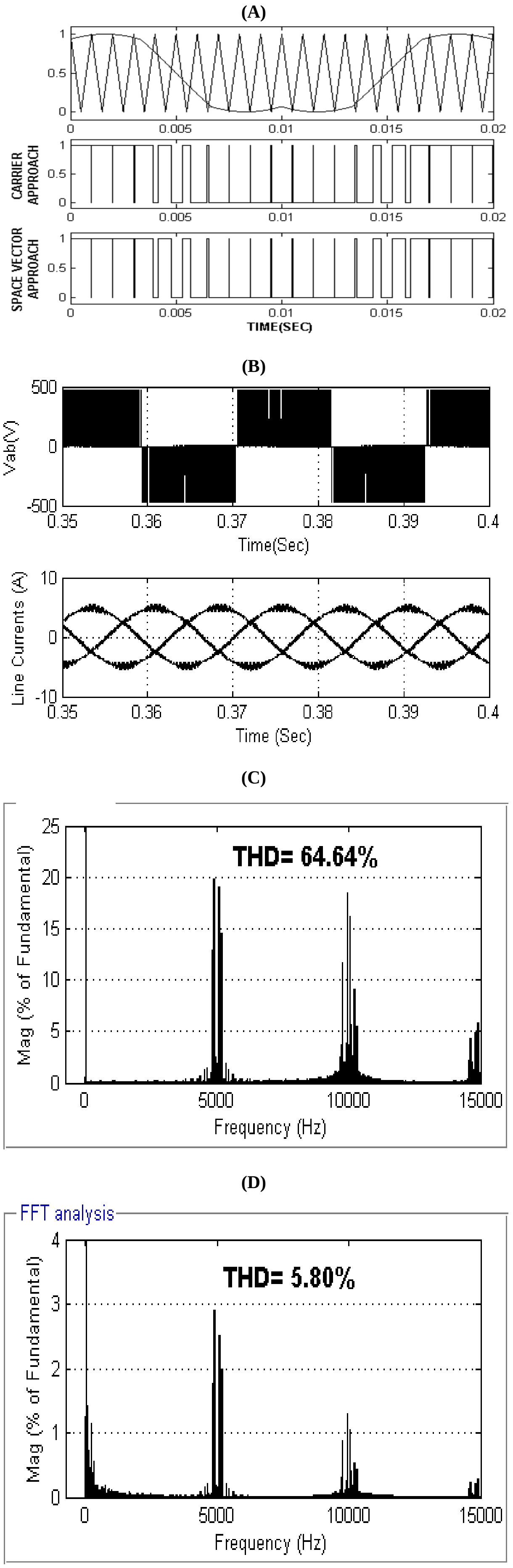

Fig. 12: Simulation Results of SVPWM Based Inverter Fed Induction Motor Drive (A) Line Voltage and Three Phase Line Current (B) Harmonic Spectrum Of Line Voltage (C) Harmonic Spectrum of Line Current.

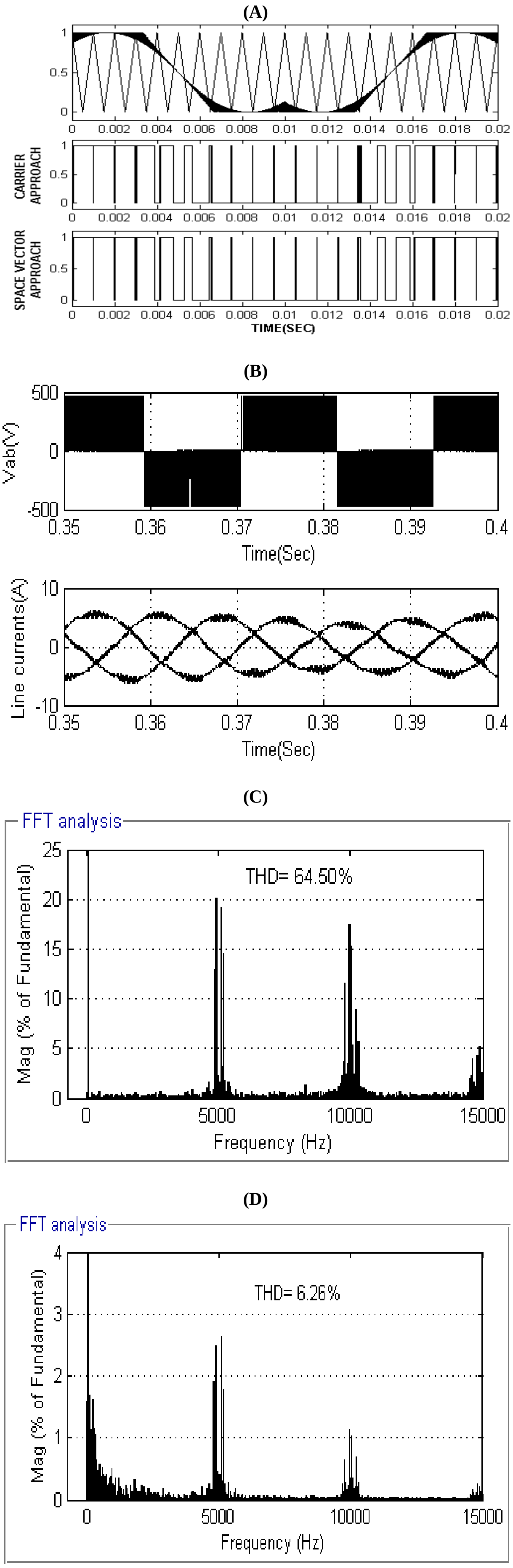

Fig. 13: Simulation Results of RRPWM Based Inverter Fed Induction Motor Drive (A) Line Voltage and Three Phase Line Current (B) Harmonic Spectrum of Line Voltage (C) Harmonic Spectrum of Line Current.

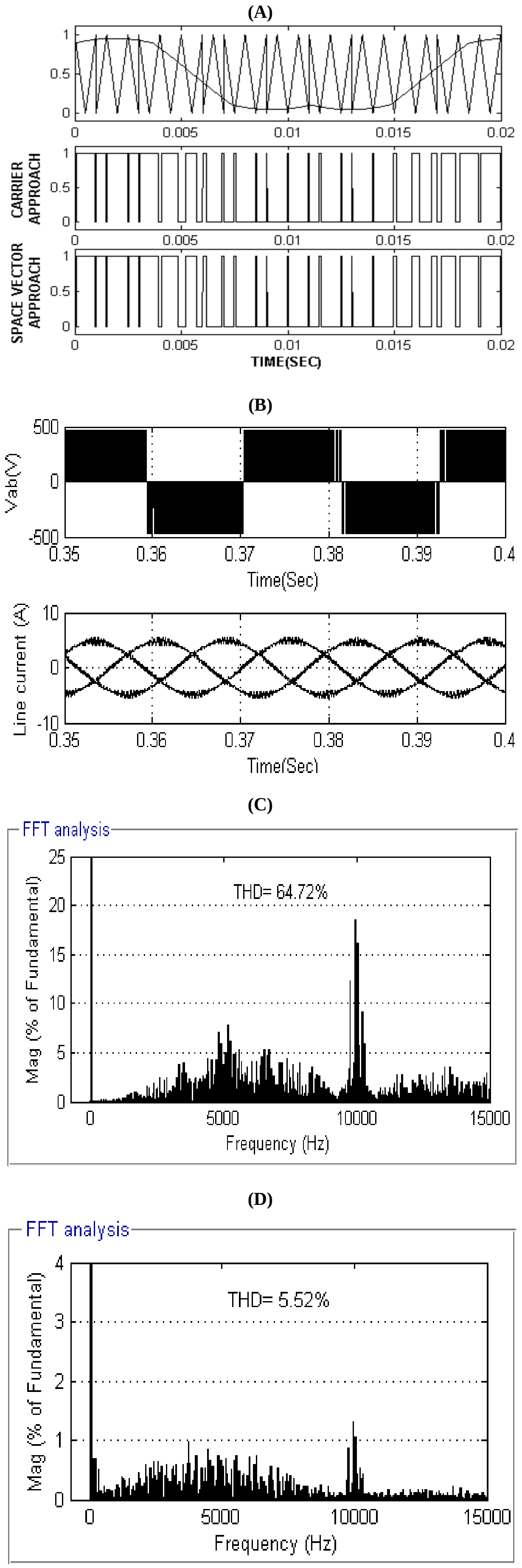

Fig. 14: Simulation Results of RCPWM Based Inverter Fed Induction Motor Drive (A) Line Voltage and Three Phase Line Current (B) Harmonic Spectrum of Line Voltage (C) Harmonic Spectrum of Line Current.

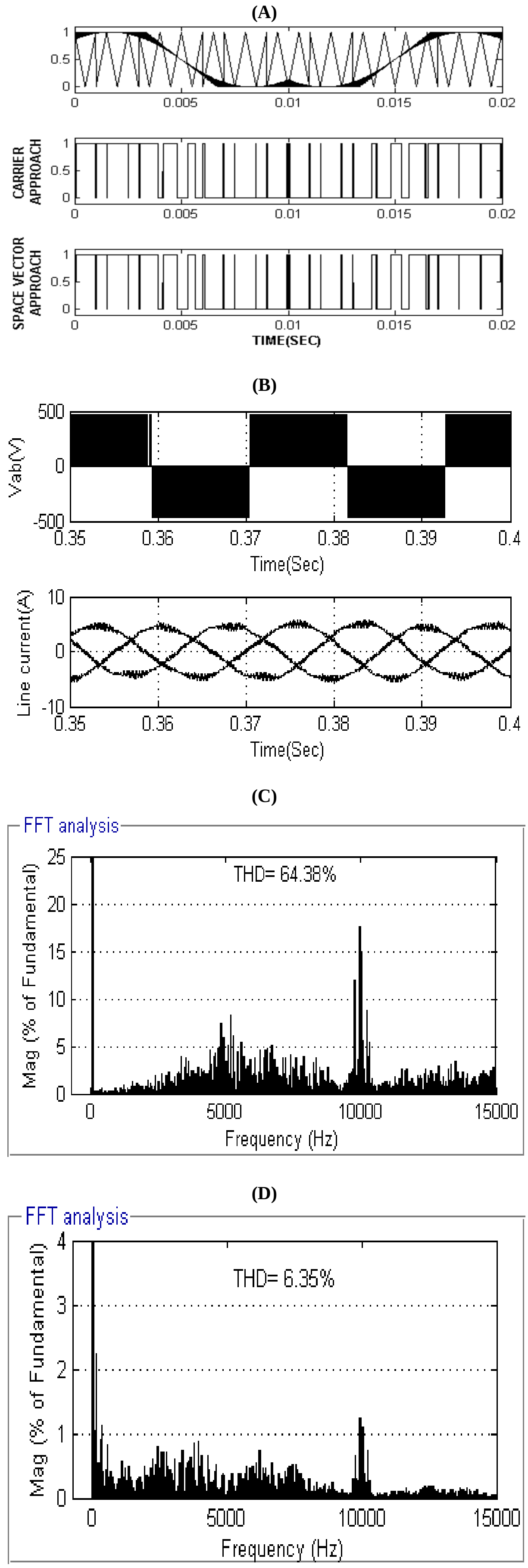

Fig. 15: Simulation Results of RRRCPWM Based Inverter Fed Induction Motor Drive (A) Line Voltage and Three Phase Line Current (B) Harmonic Spectrum of Line Voltage (C) Harmonic Spectrum of Line Current.

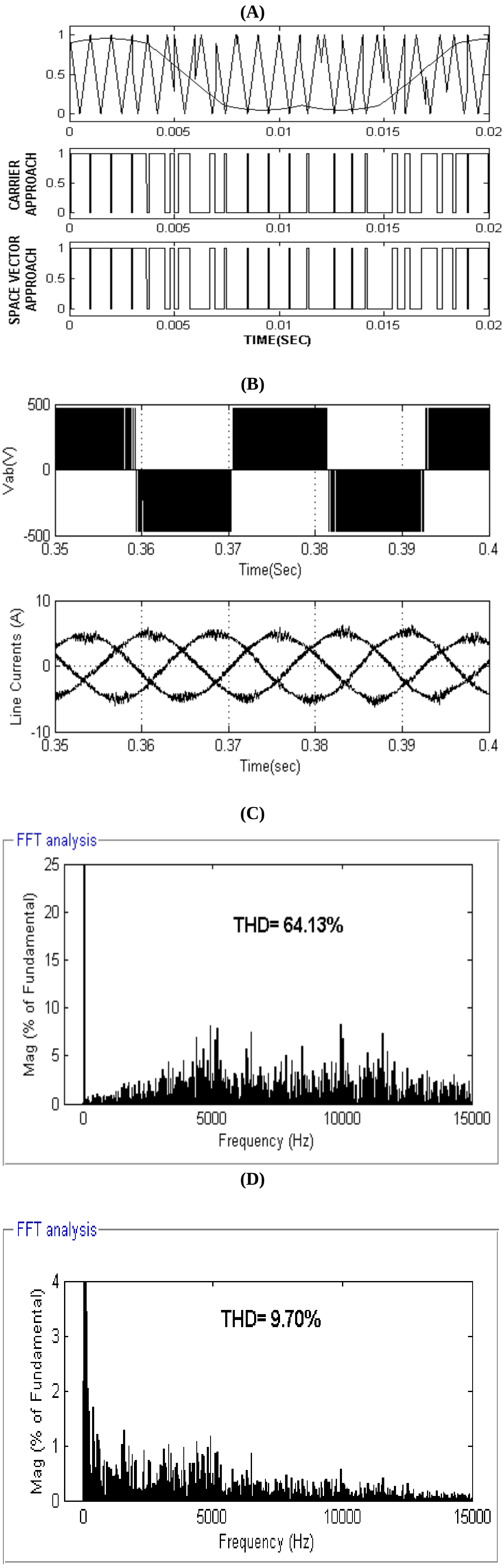

Fig. 16: Simulation Results of VSF-RPWM Based Inverter Fed Induction Motor Drive (A) Line Voltage and Three Phase Line Current (B) Harmonic Spectrum of Line Voltage (C) Harmonic Spectrum of Line Current.

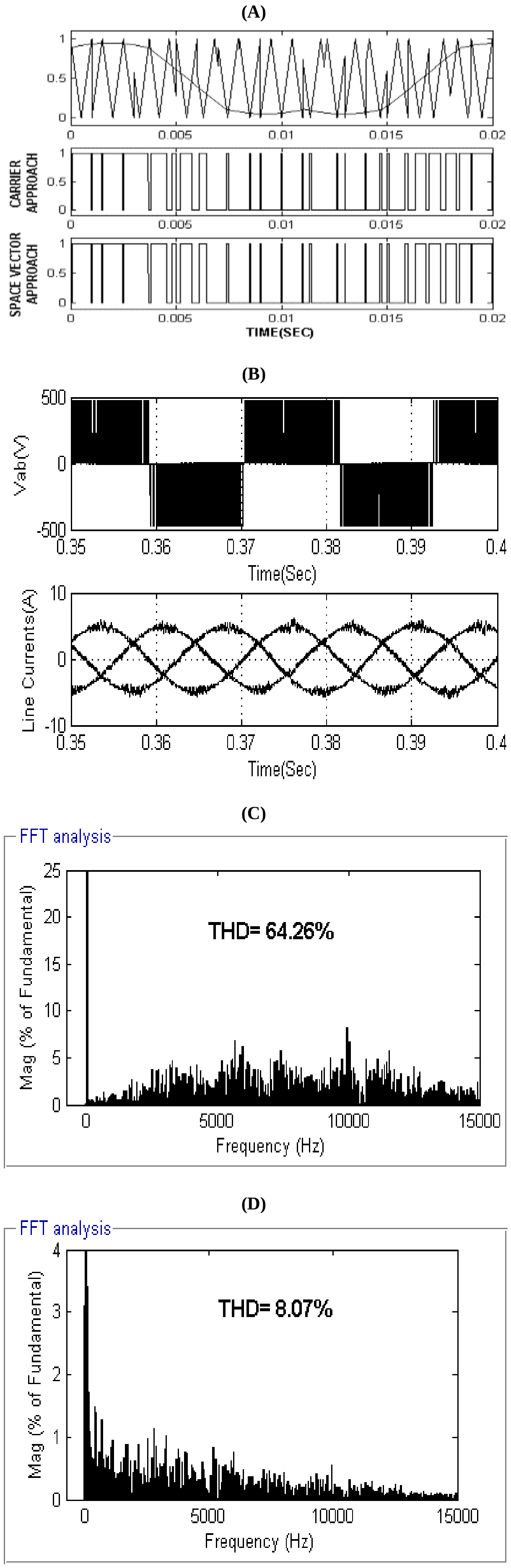

Fig. 17: Simulation Results of RCVSF-PWM Based Inverter Fed Induction Motor Drive (A) Line Voltage and Three Phase Line Current (B) Harmonic Spectrum of Line Voltage (C) Harmonic Spectrum of Line Current.

For the pulse pattern shown in Fig. 12(a) to Fig. 17(a) it is observed that carrier comparison approach and space vector based digital approach gives identical results. As the induction motor drive is employed with two-level voltage source inverter it is observed that the line voltage plot has three different levels of V_{dc}, 0 and $-V_{dc}$. The three phase line currents are shown under no load conditions. Along with line voltage and line currents, their harmonic spectrums are also shown in Fig. 12 (c, d) to Fig. 13 (c, d).

In general, with random PWM techniques total harmonic distortion may increase or decrease when compared with conventional PWM techniques [7-13]. This is because THD depends on pulse position and pulse width. It is observed from the harmonics spectrums shown in Fig. 12 to Fig. 17 that with CPWM technique magnitude of harmonics at multiples of switching frequencies (5 kHz, 10 kHz, 15 kHz…) is high. With the introduction of random ness in modulating signals (RRPWM technique) it is observed that there is only very small reduction in magnitude of harmonics (5 kHz, 10 kHz, 15 kHz…). With the introduction in of random ness in selecting carrier signals (RCPWM and RRRCPWM) it is observed from Fig. 14 and Fig.15, that there is reduction in harmonic magnitude at odd multiples of switching frequencies (i.e at 5 kHz, 15 kHz…….) but still considerable amount of harmonic magnitudes can be observed at even multiples of switching frequencies (i.e 10 kHz, 20 kHz…….). But with VSF-RPWM and RCVSF-PWM the harmonic magnitudes at multiples of switching frequencies (5 kHz, 10 kHz, 15 kHz …) are reduced. The reduction is much better with RCVSF-PWM technique. As the magnitude of harmonics at multiples of switching frequencies (5 kHz, 10 kHz, 15 kHz …) are reduced but remaining harmonic magnitudes may increase or decrease. This can be observed from the harmonic spectrums. Because of increase in harmonics the total harmonic distortion of line voltage and line currents are high with VSF-RPWM and RCVSF-PWM techniques when compared with CPWM technique.

5. Conclusion

In this paper different types of random PWM techniques were presented in both carrier comparison approach and digital space vector approach. Both the approach has given identical pulse pattern. It is observed that when compared with carrier comparison approach space vector based digital approach is simple to implement for random PWM techniques.

When compared with SVPWM technique random PWM techniques reduce the magnitude of harmonics at and around harmonics of switching frequency. Among random PWM techniques variable switching frequency PWM techniques have superior performance.

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