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Comparative Analysis of Fault-Tolerant on Three Phase and Five Phase VSI fed Induction Motor Drive

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***Abstract** Multi-phase Induction motor drives (MPIMD) with numerous advantages dominates three-phase drives and emerges as a potential contender and viable solution for the high power electric drive applications. When multi-phase AC drives fed from voltage source inverters (VSIs) requires a suitable PWM method of control. This paper investigates the performance of 3- ϕ and 5-ϕ induction motor drive with various PWM techniques. First, a 3- ϕ and 5-ϕ VSI model is compared with different open fault conditions to show the fault tolerant capability of 5- ϕ induction motor drive. Next, PWM switching techniques are designed for 5-ϕ VSI fed induction motor drive for an efficient control. The suitable switching technique is identified by setting the high fundamental voltage with reduced %THD in the output voltages. The proposed scheme uses the full DC bus voltage, and the output response superior with low lower order harmonics than the conventional sinusoidal pulse width modulation (SPWM) methods. The performances of the 5-ϕ VSI fed IM drive tested with various switching techniques, and the results observed in terms of harmonic contents present in the output voltage waveform. MATLAB/Simulink software results included in this paper to show and verify the theoretical concepts.*

***Index Terms**: SPWM, three phase VSI, five-phase VSI, five-phase induction motor, total harmonic distortion*

I. INTRODUCTION

In general, multi-phase systems have many advantages, and they are used in applications such as automotive industry, aeronautics and electric power generation due to a variety of benefits provided by multi-phase drives over 3-ϕ drives. [1]. In the case of even number phases, the poles are coinciding with each other, and it will reduce the motor performance. So, odd number phases are preferred over even number phases [2]-[3]. Also, the output power of a 5-ϕ system is greater than that of the 3-ϕ system. This has attracted the interest in the development of multi phase machines [4], [5].

The broad choice of switching techniques can be used for the VSI to produce the expected output [6]-[9]. The techniques start with sin triangle PWM, harmonic injection method, offset addition, conventional SVPWM, and modified SVPWM. SVPWM technique is more suitable for multiphase VSI, and the no. of vectors increase with the no. of a levels and no. of phases (i.e., 'm' is the no. of level of VSI and 'n' is the no. of phases) [10], [11].

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A 2 level VSI has 32 vectors represented into d_1-q_1 & d_3-q_3 subspaces. All subspaces are a source of lower order harmonics except the d_1-q_1 subspace. The switching techniques proposed in [12] can eliminate the harmonics present in d_3-q_3. In addition, this method can generate a sinusoidal phase voltage waveform. There are few SVPWM techniques proposed in [13]-[16] to minimize the switching losses of a 5-ϕ inverter.

The comparative analysis of 3-ϕ and 5-ϕ VSI fed IM dive is present in terms of its fault tolerant capability. Then the carrier based PWM switching schemes are designed in this paper for the 5-ϕ VSI fed IM drive. The MATLAB/ Simulink is used to construct the system. The performances of the proposed techniques are compared with conventional SVPWM technique.

II. MODELING OF FIVE PHASE INDUCTION MOTOR

A Mathematical model can be represented for an induction motor. The 5-ϕ system variables are transformed into 2-ϕ variables in d-q plane rotating with synchronous speed. The displacement between two phases is 72 degrees, and the number of phases must be the same before and after the transformation. The relationships between 5-ϕ and 2-ϕ variables are as follows.

$$V^s_{dq} = K_S\, V^s_{abcde} \qquad i^s_{dq} = K_S\, i^s_{abcde} \qquad \Psi^s_{dq} = K_S\, \Psi^s_{abcde} \qquad (1)$$

$$V^r_{dq} = K_r\, V^r_{abcde} \qquad i^r_{dq} = K_r\, i^r_{abcde} \qquad \Psi^r_{dq} = K_r\, \Psi^r_{abcde} \qquad (2)$$

Where,

$$K = \sqrt{\frac{2}{5}} \begin{bmatrix} 1 & \cos\left(\frac{2\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{2\pi}{5}\right) \\ 0 & \sin\left(\frac{2\pi}{5}\right) & \sin\left(\frac{4\pi}{5}\right) & \sin\left(\frac{4\pi}{5}\right) & \sin\left(\frac{2\pi}{5}\right) \\ 1 & \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{8\pi}{5}\right) & \cos\left(\frac{8\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) \\ 0 & \sin\left(\frac{4\pi}{5}\right) & \sin\left(\frac{8\pi}{5}\right) & -\sin\left(\frac{8\pi}{5}\right) & -\sin\left(\frac{4\pi}{5}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \qquad (3)$$

'K' is the 5-ϕ induction machine decoupling transformation matrix given in equation 2. The 5-ϕ machine is represented in the d-q-x-y-o arbitrary plane. The d-q components are responsible for power generation, fluxes and torque production in the machine. System losses are accounted by x-y components, and the reason

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for zero components being used is to show unchanged in the system. The 5-ϕ IM is modeled in the MATLAB Simulink, and the characteristics responses are obtained.

Essential machine model equations for stator sides and rotor sides in stationary reference frame are represented as follows:

$$V_{ds} = R_s i_{ds} + p\Psi_{ds} \qquad V_{qs} = R_s i_{qs} + p\Psi_{qs} \qquad (4)$$
$$\Psi_{xs} = L_{ls} i_{xs} \qquad \Psi_{ys} = L_{ls} i_{ys} \qquad (5)$$
$$V_{dr} = R_r i_{dr} + p\Psi_{dr} \qquad V_{qr} = R_r i_{qr} + p\Psi_{qr} \qquad (6)$$
$$\Psi_{xr} = L_{lr} i_{xr} \qquad \Psi_{yr} = L_{lr} i_{yr} \qquad (7)$$

Flux Linkage equations for stator and rotor sides are expressed as follows:

$$\Psi_{xs} = L_{ls} i_{xs} \qquad \Psi_{xr} = L_{lr} i_{xr} \qquad (8)$$
$$\Psi_{ds} = (L_{ls} + L_m) i_{ds} + L_m i_{dr}$$
$$\Psi_{qs} = (L_{ls} + L_m) i_{qs} + L_m i_{qr} \qquad (9)$$
$$\Psi_{dr} = (L_{lr} + L_m) i_{dr} + L_m i_{ds}$$
$$\Psi_{qr} = (L_{lr} + L_m) i_{qr} + L_m i_{qs} \qquad (10)$$
$$\text{Where, } L_s = L_{ls} + L_m \qquad L_r = L_{lr} + L_m \qquad (11)$$
$$\Psi_{ys} = L_{ls} i_{ys} \qquad \Psi_{yr} = L_{lr} i_{yr} \qquad (12)$$

The equation for torque can be denoted as

$$T_e = P L_m (i_{dr} i_{qs} - i_{ds} i_{dr}) \qquad (13)$$
$$w_r = \int \frac{P}{2J} (T_e - T_L) \qquad (14)$$

III. TWO-LEVEL THREE PHASE AND FIVE-PHASE VSI

Multi-phase IM drives used for variable speed applications. The conventional multiphase VSI does not suitable for this application owing to the high amount of harmonics presented in the voltage waveforms. A space vector concept is used with a modified switching sequence to reduce the harmonics and also helps to maximize the fundamental voltage.

Fig.1 shows the circuit diagram for 3-ϕ VSI fed IM drive comprises six power switches, two switches per leg. The pole voltage is equal to V_{dc} when the upper switch is ON and it is zero when it is OFF. Fig.2 shows the circuit diagram for 5-ϕ VSI fed 5-ϕ IM drive comprises ten power switches, two switches per leg. The pole voltage is equal to Vdc when the upper switch is ON and it is zero when it is OFF. To avoid the direct short circuit of same leg switches, they switched opposite to each other.

Phase to neutral voltages (Va ~ Ve) of 5-ϕ VSI can be expressed in terms of inverter pole voltages as given in equation (15) and (16) [12], [17].

$$V_j = \frac{4}{5} V_j - \frac{1}{5} \sum_{i,i \neq j}^{5} V_j, \text{ if } j < 5 \qquad (15)$$
$$V_j = \frac{4}{5} V_j - \frac{1}{5} \sum_{i,i \neq j}^{4} V_j, \text{ if } j = 5 \qquad (16)$$

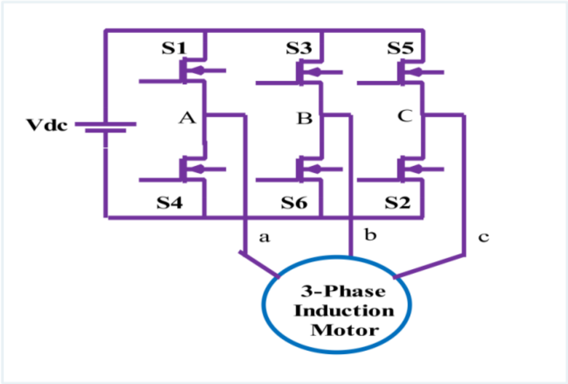

Fig. 1 3-ϕ VSI fed IM drive

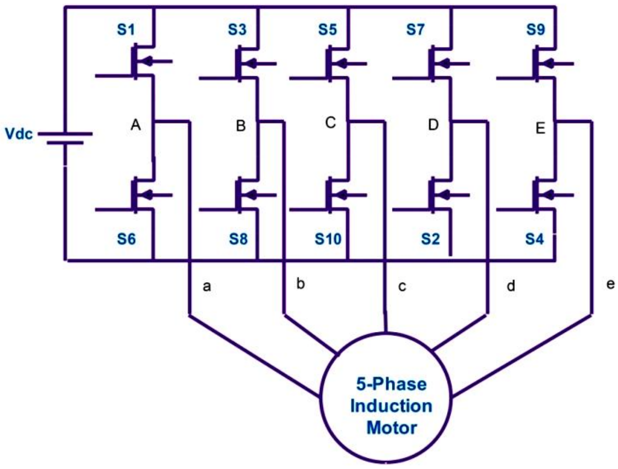

Fig. 1 5-ϕ VSI fed 5-ϕ IM drive

IV. FAULT-TOLERANT COMPARISON OF 3-Φ AND 5-Φ INDUCTION MOTOR

The performance investigations of multi-phase voltage source inverter with different PWM techniques are carried out in this paper. Some of the conventional PWM techniques such as sinusoidal Pulse Width Modulation (SPWM), harmonic Injection PWM and offset addition PWM techniques are discussed for n number of phases. Comparisons between different PWM techniques are presented.

The 5-phase system is compared with the 3-ϕ system in terms of its voltage and power levels as shown in Table 1. From this table, it is inferred that the non-adjacent line voltage for the 5-ϕ system is more than the 3-ϕ system and also the power level is greater in the 5-ϕ system. Hence the 5-ϕ induction motor is an alternative solution for the 3-ϕ induction motor in industrial applications.

Next, it is compared by applying the different fault conditions in both the 3-ϕ and 5-ϕ induction motor system as shown in Table 2. When a fault in any of the phase leads to an increase in the current of other phases and reduced output power of the machine. When the fault in any two phases leads to inoperative conditions of a 3-ϕ induction motor system. Whereas the 5-ϕ system can able to produce the almost 85 % of the rated power output. Hence the 5-ϕ

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system has high fault tolerant capability than the 3-ϕ system. The graphical representation of the fault conditions is shown in Fig.3 and Fig. 4 for 3-ϕ and 5-ϕ induction motors. The reduction in speed and variation in torque can be observed for the single phase open fault condition is applied at time t=1 sec and two phases open fault condition is applied at t= 1.5 sec as shown in figure 3 & 4.

Table 1
Voltage and power Relationship for 3 phase and 5 phase machine

No. of phases	Adjacent Line Voltage Vab (V)	Non -Adjacent Line Voltage Vac (V)	Power (W)
3- phase	1.732 V_{Ph}	-	1.732 V_L I_L cosΦ
5- phase	1.1755 V_{Ph}	1.902 V_{Ph}	2.6288V_L I_L cosΦ

Table 2
Comparison under Normal and Fault Condition at T_L = 5 Nm

No. of phases / Parameters	3-ϕ IM drive			5-ϕ IM drive		
	Normal Condition	Fault Condition		Normal condition	Fault Condition	
		1-phase open	2-phase open		1-phase open	2-phase open
Nr (rpm)	1428	967	0	1460	1427	1368
Is/Phase (Amps)	2.089	1.677 A 6.278 A 5.437 A	0.6342 A 4.095 A 4.19 A	1.08	0.2415 A 1.87 A 1.399 A 1.031 A 2.026 A	0.435 A 2.931 A 1.517 A 2.046 A 2.739 A
Output Power (watts)	747.7	394.8	0	763.6	748.7	690

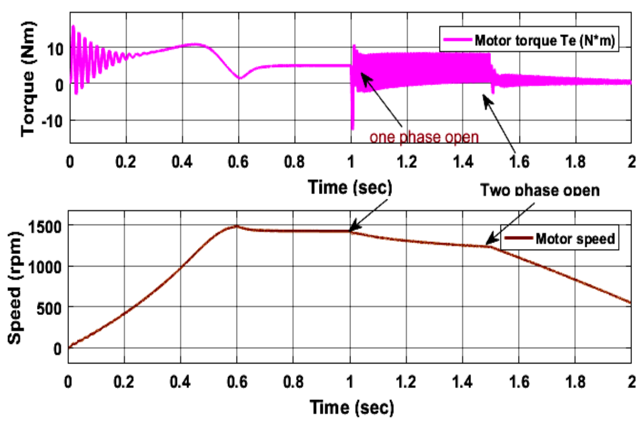

Fig. 3 Speed and torque response under one phase and two phase open condition of 3-ϕ IM drive

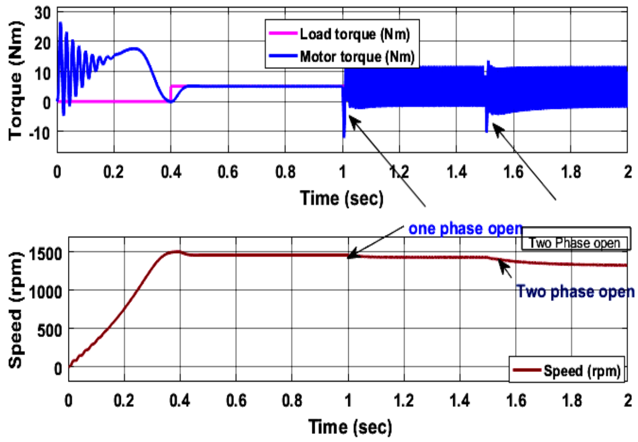

Fig. 4 Speed and torque response under one phase and two phase open condition of 5-ϕ IM drive

V. PWM SWITCHING SCHEMES FOR 5-Φ VSI

A. Sinusoidal Pulse Width Modulation Technique (SPWM)

The analog and digital realization of carrier based SPWM techniques is the most popular method for the voltage source inverters. The high frequency carrier signal is compared with the sinusoidal signal to generate the firing pulses for the VSI switching devices. In 5-ϕ VSI, there are 5 reference signals displaced by 2π/5 are compared with the triangular signal to generate gate pulses for 5- phase VSI as shown in Fig. 5. The amplitude of the reference signal decides the output voltage of the VSI. The reference voltages for the multi-phase VSI are given in equation (17) to (23).

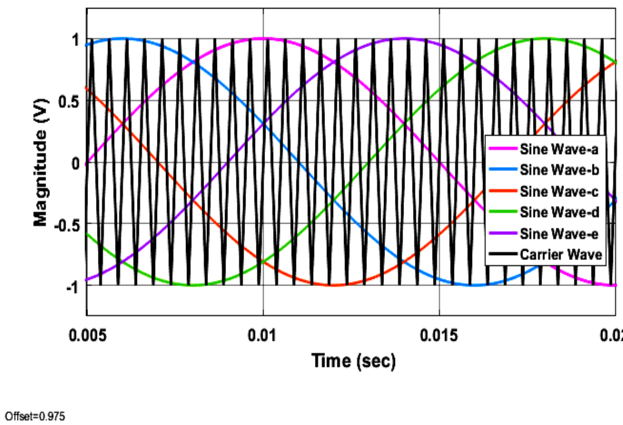

Fig. 5 Sine- triangular PWM switching scheme

$$V_a = v\cos\omega t \quad (17)$$
$$V_b = v\cos(\omega t - \propto) \quad (18)$$
$$V_c = v\cos(\omega t - 2\propto) \quad (19)$$
$$V_d = v\cos(\omega t - 3\propto) \quad (20)$$
$$V_e = v\cos(\omega t - 4\propto) \quad (21)$$
$$V_f = v\cos(\omega t - 5\propto) \quad (22)$$
$$V_n = v\cos(\omega t - n\propto) \quad (23)$$

Where $\propto = \frac{2\pi}{n}$
Modulation index is given by the amplitude of

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reference signal to the amplitude of carrier signal.

$$MI = \frac{V_{ref}}{V_{car}} \quad (24)$$

B. Harmonic Injection Method

The modulating signal in case of harmonic injection method is obtained by adding the *nth* harmonic component with the ref. sine signal with the support of equations (25) to (29). Then the firing pulses for 5-ϕ VSI are obtained by comparing the high frequency carrier signal with the modulating signals.

$$Va(ref + n^{th}har) = Vdc[M\cos\omega t + Mn\cos n\omega t] \quad (25)$$

$$Vb(ref + n^{th}har) = Vdc[M\cos(\omega t - \propto) + Mn\cos n\omega t] \quad (26)$$

$$Vc(ref + n^{th}har) = Vdc[M\cos(\omega t - 2\propto) + Mn\cos n\omega t] \quad (27)$$

$$Vd(ref + n^{th}har) = Vdc[M\cos(\omega t - 3\propto) + Mn\cos n\omega t]. \quad (28)$$

$$Vn(ref + n^{th}har) = Vdc[M\cos(\omega t - n\propto) + Mn\cos n\omega t] \quad (29)$$

Where

M I– Modulation index $0 \le MI \le 1$

C. Offset Addition or Injection PWM Switching Technique

The simplified SVPWM scheme is achieved by using the offset addition concept for the 5-ϕ VSI. It need not required the long procedure to generate the modulating signal. The signal generation is offset addition is dependent only on the amplitude of the reference signal and their time period. The offset calculation to generate the modulating signal is given in equations (30) to (36). When the actual firing signals for the power switches are produced by a time-shifting procedure is applied to the imaginary switching times for each inverter pole.

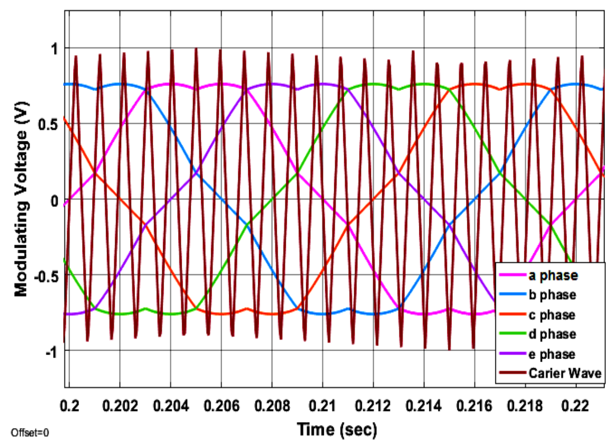


Fig. 6 Offset additions or injection switching scheme

$$T_{offset} = T_{max} - T_{min} \quad (30)$$

$$T_{max} = \max\{Vas, Vbs, Vcs, Vds, Ves\} \quad (31)$$

$$T_{min} = \min\{Vas, Vbs, Vcs, Vds, Ves\} \quad (32)$$

The offset time T_{offset} should satisfy the following constraint.

$$0 <= T_{min} + T_{offset},\ T_{max} = +T_{offset} <= T_s \quad (33)$$

Therefore, the range of T_{offset} can be computed as follows

$$T_{minoffset} = -T_{min} \quad (34)$$

$$T_{maxoffset} = T_s - T_{max} \quad (35)$$

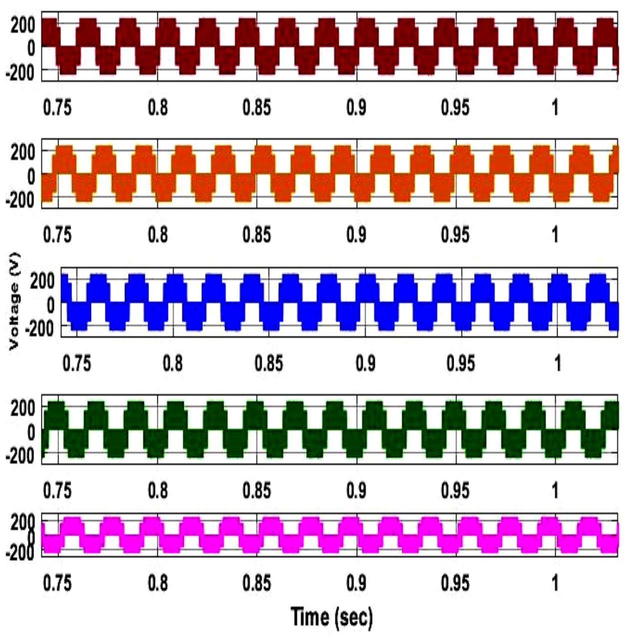
$$T_{offset} = 0.5(T_{maxoffset} + T_{minoffset}) \quad (36)$$

Where, n= number of phases.

VI. SIMULATION RESULTS

A MATLAB software simulation is used to determine the effect of different switching techniques and to compare the results of various switching techniques such as sin triangle, harmonic injection and offset addition. The simulation parameters used for the system are: Vdc=400V, the fundamental output frequency of VSI is 50Hz, switching frequency fs = 5 kHz and the dead time of switches present in the same leg has not been considered.

Table 3 lists the simulation parameters of the system, and the performance characteristics are shown in Fig. 7. The phase and line voltage of 5-ϕ VSI is shown in Fig.7 (a) & (b). The 5-phase induction motor electromagnetic torque is tracking the reference torque command of 3 Nm, 2 Nm and 4.4 Nm at the instants 0.4 sec, 0.8 and 1.3 sec respectively as shown in Fig. 7 (c). The stator and rotor current variations regarding the load changes have been recorded and shown in Fig. 7 (d).



(a)

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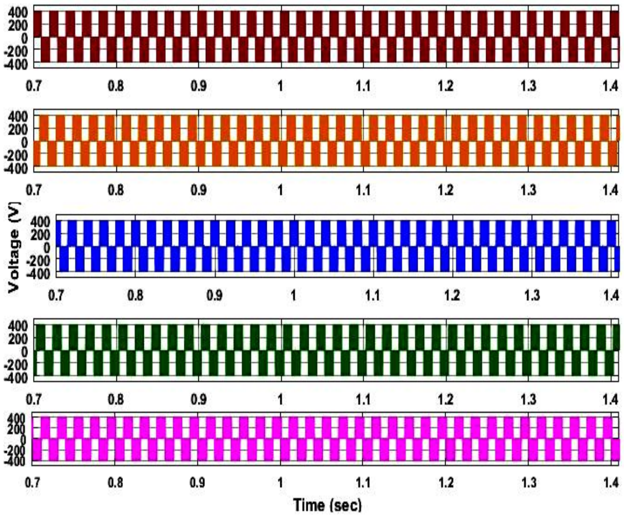
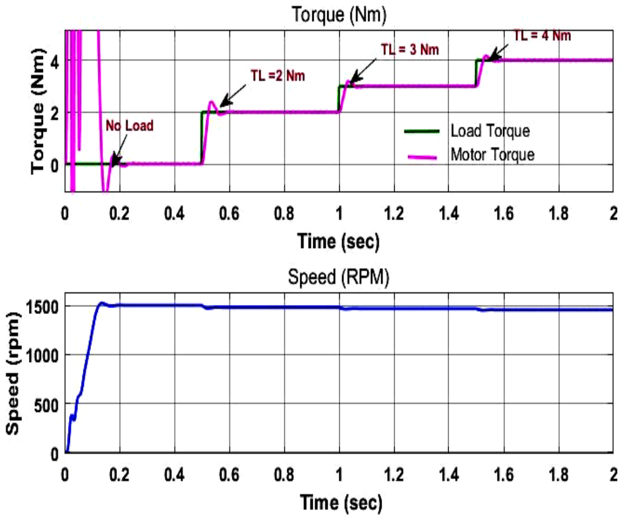
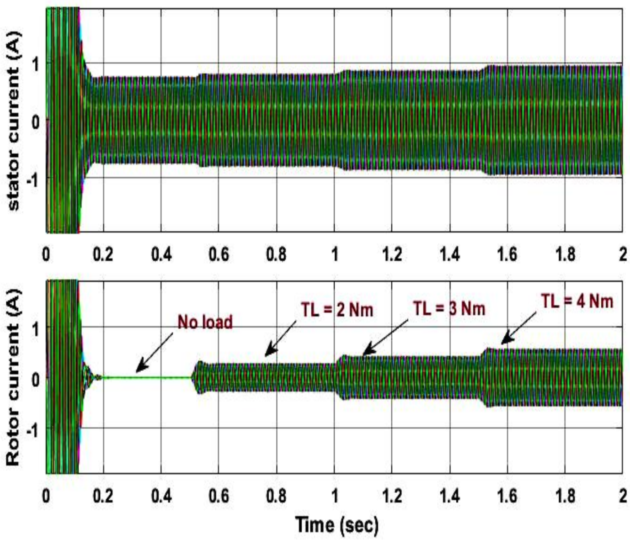


(b)



(c)



(d)

Fig. 7 Performance characteristics of 5-ϕ VSI fed IM Drive (a) Phase Voltage (b) Line Voltage (c) Speed & torque response (e) stator & rotor current

Table 3
Parameters of 5-ϕ VSI fed IM Drive

Parameters	Values
DC Bus voltage	400 V
Switching frequency	5 KHz
Motor RMS Input Voltage (V)	220
No. of Phases	5
Number of Poles (p)	4
Resistance (stator)	10.1 Ω
Inductance (stator)	0.833 Henry
Resistance (rotor)	9.854 Ω
Inductance (rotor)	0.782 Henry
Mutual Inductance	0.782 Henry
Inertia	0.0088

Table 4
Fundamental voltage for different PWM Techniques

Modulation Index	Fundamental Voltage Peak (pu)		
	Sinusoidal PWM	Harmonic Injection	Offset addition PWM
0.2	0.0964	0.0967	0.0975
0.4	0.1951	0.2011	0.2022
0.6	0.2976	0.2976	0.3013
0.8	0.3982	0.3982	0.4263
1	0.501	0.4993	0.501

Three different PWM switching schemes are designed for 5-ϕ VSI fed IM drive. The output phase fundamental voltage and total harmonic distortions are considered as the factors to identify the best switching scheme for 5-ϕ VSI. Also, these two factors are obtained for different values of the modulation index. The fundamental voltage peak is high for the offset addition PWM switching scheme when compared to other PWM technique as noted from the Table 4. The %THD in the phase voltage of 5-ϕ VSI fed IM drive is observed for different modulation index is as shown in the Table 5.

The comparative results of different PWM switching techniques are presented, the offset addition switching produces less % THD than the conventional PWM techniques. Therefore it is inferred that the 5-ϕ VSI with offset addition PWM switching scheme gives the optimum results for the output voltage fundamental peak and lower % voltage THD.

Table 5
Voltage THD for different PWM Techniques

Modulation Index	Voltage THD (%)		
	Sinusoidal PWM	Harmonic Injection	Offset addition PWM
0.2	266.92	264.61	260.41
0.4	172.18	170.20	169.78
0.6	127.77	126.13	125.52
0.8	98.34	98.67	97.20
1	75.15	75.44	75.10

VII. CONCLUSION

The comparative analysis is made between 3- ϕ and 5- ϕ VSI fed IM drive in terms of different fault conditions. The fault-tolerant capability of 5- ϕ VSI is superior to the 3-ϕ drive. A 5- ϕ VSI with various PWM techniques are presented to improve the power quality of input voltage applied to 5-ϕ IM drive. Use of offset addition PWM technique improves the utilization of DC bus voltage when compared to other SPWM techniques. This control technique also improves the fundamental output voltage by than the sinusoidal pulse width modulation techniques. This investigation is performed in the MATLAB Simulink for 5-ϕ VSI fed IM drive. The results of the fundamental voltage and % THD in the output voltage for different modulation technique are obtained. This comparison result shows that offset addition switching technique gives the maximum fundamental voltage and lesser %THD in output voltage than other methods.

REFERENCES

1. Subodh Kanta Barika, Kiran Kumar Jaladi "Five-Phase IM DTC-SVM sche. with PI Control. & ANN control." Publi. by Elsevier Ltd in Procedia Tech. 25 (2016) 816 – 823.
2. K. B. Yadav, Alok Kumar Mohanty, Prabhat Kumar, "Recent Research Trend on Multi-phase Induction Machines" Proc. of Int. Conf. on Control, Communi. and Power Engg., CCPE, Elsevier- 2014. pp. 580 -586.
3. K.S. kumar, Das. A, Ramchand. R, Patel.C & K. G.kumar, "A 5-level inv. scheme for a 4-pole IM drive by feeding the identical voltage-profile windgs from both sides," IEEE Tra. Indu. Electr., vol. 57, no. 8, pp. 2776–2784, Aug. 2010.
4. A. S. A Khalik, S. Ahmed, A. A. E, & A. Massoud, "Effect of stator wdg connection of 5-ϕ IM on Torque Ripples Under Open Line Condition", IEEE Tran.. Mechatronic, vol. 20, no. 2, pp. 580–593, April. 2015.
5. Levi, E, Bojoi, R, Profumo, F, Toliyat, HA and Williamson, S (2007) Multiphase induction motor drives - a technology status review IET electric power applications, 1 (4). pp. 489-516.
6. E.Levi " Multi ϕ IM drive – a technolo. tatus review" IET Elec.. Pow. App. Vol. 1, No.4, pp.489-516, July 2007.
7. E. Levi, "Multiphase Electric Machines for Variable-Speed Applications," in IEEE Transactions on Industrial Electronics, vol. 55, no. 5, pp. 1893-1909, May 2008. doi: 10.1109/TIE.2008.918488
8. MK K Sahu, AK K Panda, BP Panigrahi "DTC for 3-Level NPC Inverter-Fed IM Drive" ETASR – Engg., Tech. & Applied Science Res. Vol. 2, No. 2, 2012, 201-208.
9. B. Jyothi and Dr.M.Venu Gopala Rao"Comparison of Five Leg Inv. and Five Phase Full Bridge Inv. for Five Ph. Supply", Int. Conf. on ISEG 19-20 Sept. 2014.
10. A. Iqbal, S. Moinuddin and M. R. Khan, "Space Vector Model of A Five-Phase Voltage Source Inverter," 2006 IEEE International Conference on Industrial Technology, Mumbai, 2006, pp. 488-493.
11. S. Moinoddin and A. Iqbal, "Space vector model of a five-phase current source inverter," 2016 Biennial International Conference on Power and Energy Systems: Towards Sustainable Energy (PESTSE), Bangalore, 2016, pp. 1-6.
12. Wan Noraishah Wan Abdul Munim, Mohd Firdaus Ismail, Ahmad Farid Abidin, and Harizan Che Mat Haris, "Multi-phase Inverter Space Vector Modulation", IEEE 7th International power engineering and optimization conference ,3-4 june 2013, pp.149-154.
13. Mahmoud Gaballah, Mohammed El-Bardini, "Low cost digital signal generation for driving space vector PWM inverter", Ain Shams Engineering Journal, Volume 4, Issue 4, 2013, Pages 763-774, ISSN 2090-4479.
14. Nanda Kumar, S., Vijayan, S. & Nanda Kumar, E." Asymmetric SVM Technique for Minimizing Switching Loss of Inverter" Arabian Journal for Science and Engineering (2014) 39: 3123.
15. Devisree Sasi , Jisha Kuruvilla P , Anish Gopinath, "Generalized SVPWM Algorithm for Two Legged Three Phase Multilevel Inverter", International Journal of Power Electronics and Drive System (IJPEDS) Vol.3, No.3, September 2013, pp. 279-286 ISSN: 2088-8694.
16. P. Sala-Perez, S. Galceran-Arellano, D. Montesinos-Miracle. "A sensorless stable V/f control method for a five-phase PMSM" , 2013 15th European Conference on Power Electronics and Applications (EPE), 2013.
17. Raja D and Ravi G, "Comparative Analysis of Five Phase Multilevel Inverter Topologies for Five Phase Induction Motor Drive" Journal of Advanced Research in Dynamical & Control Systems, Vol. 10, 09-Special Issue, 2018, pp.1961-1968.

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