Performance Investigation of Inverter fed 7-Phase Induction Motor Drive

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Abstract - *This paper presents the Performance Investigations of 7-Phase Inverter fed Induction Motor Drive. Compared to three-phase drive multi-phase induction motor drive possess several advantages, reduced current per phase, torque ripple frequency is high and amplitude of torque ripple is low, resulting lower operating noise and mechanical vibration. The total power rating of multi-phase motors in the same frame can be increased significantly without overloading a single phase and better fault tolerant capability. The 7th harmonic fed 7-phase drive is proposed in this paper. The performance of the 7 -phase VSI is studied with the varying modulation index. The VSI fed multi-phase drive is analyzed for different load conditions. The simulation results are presented for different modulation indices and compare the performance of the drives are presented.*

***Key Words*: 7th harmonic injection, multi-phase drive, pulse width modulation, switching technique, voltage source inverter.**

1. INTRODUCTION

Multi-phase machine drives are fast increasing in recent years, due to their several inherent benefits such as lower torque pulsation, reduction in harmonic currents, and reduced current per phase without the need to increase the phase voltage, greater reliability, fault tolerant feature and increased power in the same frame as compared to three phase machine. They are mostly used in high power applications, such as ship propulsion, electric aircraft, and electric/hybrid electric vehicles etc. Multi-phase motors require multi-phase voltage source inverter (VSI) for their input supply. An inverter topology uses two switches connected in series as one inverter pole. The number of inverter poles depends on number of phases. For example, a three-phase inverter will have three inverter poles whereas a five-phase inverter will have five inverter poles. The switching pattern of the three phase inverter should be modified according to the number of phases. For three phase inverters, the sinusoidal pulse width modulation (SPWM) method, space vector pulse width modulation (SVPWM), harmonic injection method and offset injection method are extensively discussed in literature [1-22].The SPWM and SVPWM techniques are extended for multi-phase VSI [1-16]. The SPWM schemes are more flexible and easy to implement. However the output waveforms contain more harmonics resulting in reduced fundamental component and efficiency. To achieve the better output voltage, the several space vector pulse width modulation (SVPWM) techniques are discussed, such as conventional SVPWM, space vector disposition SVPWM, discontinuous SVPWM and multi-dimensional SVPWM [4-17]. The complexity involved in the SVPWM technique is more for higher number of phases. The inverter output voltage space vectors changes to 2n states, since there are 2n different switching configurations. Hence the SVPWM has complicated controlling algorithm for sector identification, look up table, angle information and voltage space vector amplitude measurements. Therefore a simple and efficient switching technique is needed for multi-phase voltage source inverter which would overcome the complexity involved with higher number of phases. In this paper to investigate the performance of the 7-phase VSI with the improved PWM techniques namely harmonic injection method, which is commonly used for three phase VSIs can be used for multi-phase VSIs. In the harmonic injection method the linear modulation range is extended by adding the mth harmonic component with respective phase of the reference phase voltages and the fundamental output voltage is increases without moving into the over-modulation region [18-22].

The main contribution of this paper is to detail study of harmonic injection PWM technique for multi-phase voltage source inverter. The performance of the inverter is investigated with these switching technique and the results are presented for 7-phases. Based on the inverter fed simulation results the multi-phase drive is analyzed in terms of current/phase, output power and torque frequency.

2. POWER CIRCUIT OF MULTI-PHASE VSI

The power circuit of 7-phase VSI is shown in Fig.1. The circuit consists of *7* half-bridges, which are mutually displaced by *2π/7* degrees to generate the 7-phase voltage waves. The input dc supply is obtained from a single phase or 3-phase utility power supply through a diode-bridge rectifier. The voltages V_a, V_b, V_c, V_d, V_e, V_f, V_g are the inverter pole voltages connected to load terminals. It is seen that the switching states of each pole should be combined with each other pole to create the required *7*-phase output voltages. The load phase voltages and inverter pole voltages is as given in the following relations (1)

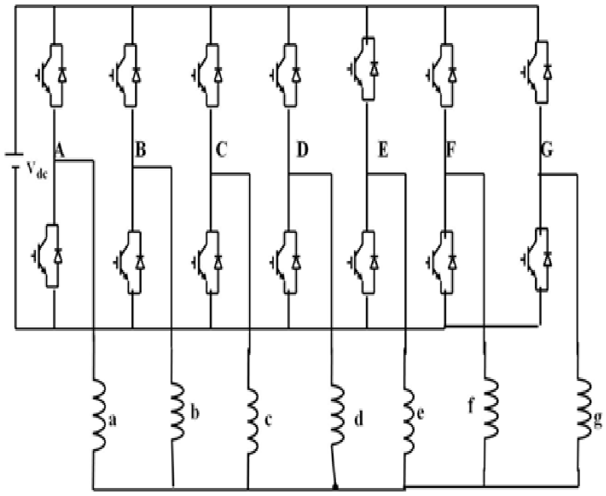


Fig - 1: Power circuit of 7-phase VSI

$$\begin{aligned}
V_{aN} &= \frac{n-1}{n}V_a - \frac{1}{n}(V_b + V_c + V_d + V_e + V_f + V_g) \\
V_{bN} &= \frac{n-1}{n}V_b - \frac{1}{n}(V_a + V_c + V_d + V_e + V_f + V_g) \\
V_{cN} &= \frac{n-1}{n}V_c - \frac{1}{n}(V_a + V_b + V_d + V_e + V_f + V_g) \\
V_{dN} &= \frac{n-1}{n}V_d - \frac{1}{n}(V_a + V_b + V_c + V_e + V_f + V_g) \\
V_{eN} &= \frac{n-1}{n}V_e - \frac{1}{n}(V_a + V_b + V_c + V_d + V_f + V_g) \\
V_{fN} &= \frac{n-1}{n}V_f - \frac{1}{n}(V_a + V_b + V_c + V_d + V_f + V_g) \\
V_{gN} &= \frac{n-1}{n}V_g - \frac{1}{n}(V_a + V_b + V_c + V_d + V_e + V_f)
\end{aligned} \quad (1)$$

The 7th harmonic injection method with simulation results of 7th harmonic injection fed drives are discussed detail in the following sections.

3. SINUSOIDAL PWM WITH 7th HARMONIC INJECTION

To eliminate the 3rd harmonic component in the output of the three phase voltage source inverter, the 3rd harmonic is injected to the sinusoidal reference voltages [1]. This would increase the maximum fundamental output voltage without moving into the over-modulation region. By analogy, the linear modulation range can be extended by injecting the 7th harmonic component for 7-phase VSI.

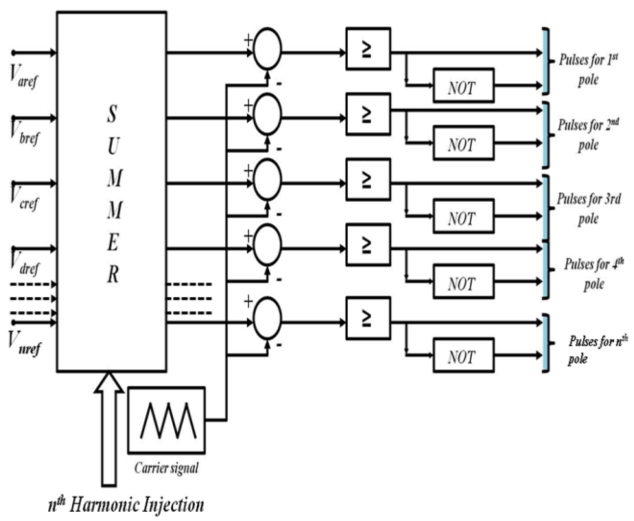


Fig - 2: Block diagram of sinusoidal PWM with n^{th} harmonic injection

The *7th*-harmonic injection reduces the peak of the *7*-leg reference voltages and hence the modulation index can be moved beyond the value of 1 without entering into over-modulation region. The block diagram of sinusoidal PWM with *7th* harmonic injection of a *7*-phase VSI is shown in Fig.2. In the *7*-phase VSI (V_{aref}, V_{bref}, V_{cref}, V_{dref}, V_{eref}, V_{fref}, V_{gref}) are reference phase voltages displaced by $\alpha=(2\pi/7)$ degrees. The reference sinusoidal signals are added with *7th* harmonic component to obtain a non sinusoidal modulating signal. The carrier based modulating signal is compared with the relational operator. The intersections between the modulating signals and the carrier signals give the opening and closing time of inverter switches. The best possible *7th*-harmonic injection for the *7*-phase VSIs is achieved using (2).

$$\begin{aligned}
v_{a(ref+7^{th}har)} &= V_{dc}[M\cos wt + M_7\cos 7wt] \\
v_{b(ref+7^{th}har)} &= V_{dc}[M\cos(wt-\alpha) + M_7\cos 7wt] \\
v_{c(ref+7^{th}har)} &= V_{dc}[M\cos(wt-2\alpha) + M_7\cos 7wt] \\
v_{d(ref+7^{th}har)} &= V_{dc}[M\cos(wt-3\alpha) + M_7\cos 7wt] \\
v_{e(ref+7^{th}har)} &= V_{dc}[M\cos(wt-4\alpha) + M_7\cos 7wt] \\
v_{f(ref+7^{th}har)} &= V_{dc}[M\cos(wt-5\alpha) + M_7\cos 7wt] \\
v_{g(ref+7^{th}har)} &= V_{dc}[M\cos(wt-6\alpha) + M_7\cos 7wt]
\end{aligned} \quad (2)$$

where *M* – Modulation index $0 \le M \le 1$

M_7 – Modulation index of the *7th* harmonic component. The *7th* harmonic component has no effect on the value of the reference waveform expression when $wt = [2k+1]\pi/2n$, since $\cos\ [n[2k+1]\pi/2n] = 0$ for all k. where *k=0 to n* Hence M_7 can be chosen to make the peak magnitude of the reference waveform defined in (2) occur where the n^{th} harmonic component is zero, that is $wt = \pi/2n$. This would, in turn, assure the maximum possible value for the fundamental component. The reference voltages $v_{a(ref+7^{th}har)}$ reaches maximum when

$$\frac{dv_{a(ref+7t^{h}har)}}{dwt} = -MV_{dc}\sin wt - 7M_7V_{dc}\sin 7wt = 0 \quad (3)$$

where $wt = \pi/2n$

From (3)

$$M_7 = -M\frac{\sin(\pi/2n)}{n} \quad (4)$$

Under these conditions, the maximum possible non sinusoidal modulating signal is given by (5)

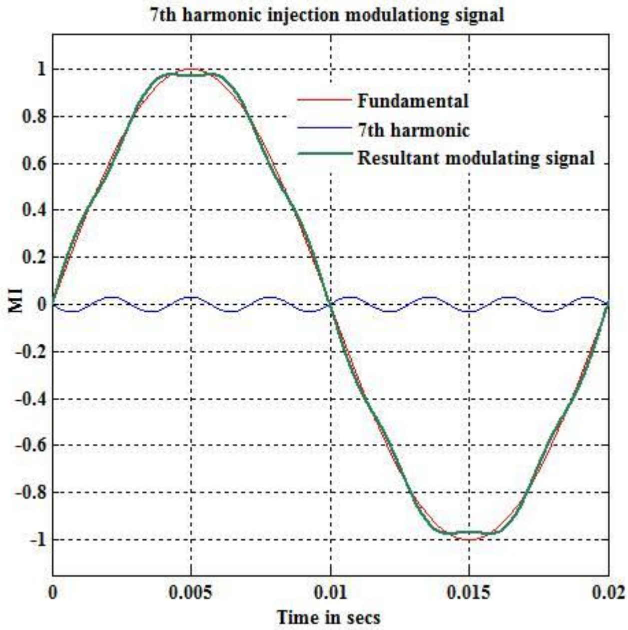
$$\left|v_{a(ref+7^{th}har)}\right| = \left|MV_{dc}\cos wt - M\frac{\sin(\pi/2n)}{n}V_{dc}\cos nwt\right| = V_{dc} \quad (5)$$

From equation (5) M is

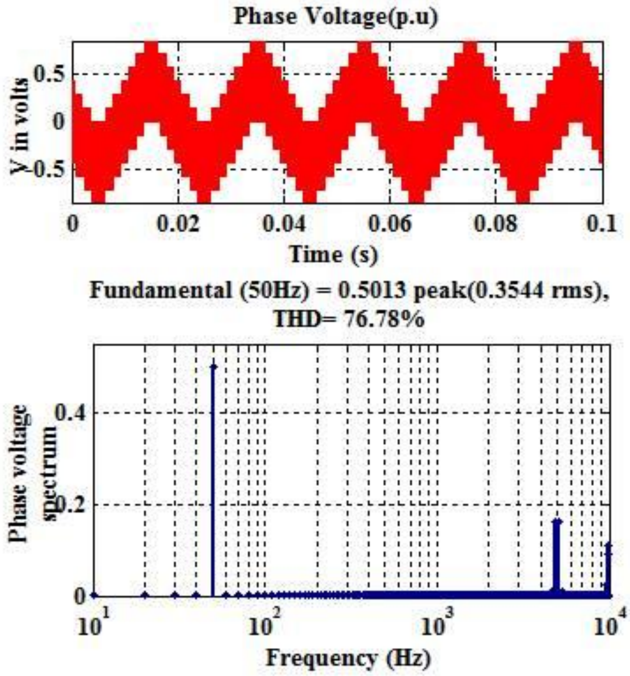
$$M = \frac{1}{\cos(\pi/2n)} \quad (6)$$

4. SIMULATION RESULTS

The 7-phase inverter is simulated with the above said switching scheme and the results are observed. The input DC is set to 1 volt, switching frequency of the VSI is chosen as 5 kHz and the fundamental frequency is set to 50 Hz. The 7-phase induction motor parameters are shown in Appendix. The 7 -phase VSI is simulated with the pulses obtained by harmonic injection technique. Figs. 3 and 4 show the results for five-phase VSI. Fig. 3(a) shows the fundamental, 7th harmonic component waveform and the resultant modulating signal for a modulation index of 1. It is seen that the peak value of the modulating signal is less than 1. It will reach ±1, when the modulation index $M = 1/\cos(\pi/2n)$, according to expression (4). Also this would increase the maximum fundamental output voltage without moving into the over-modulation region. The output phase voltage and its spectrum are shown in Fig.3(b). It is seen that the output fundamental rms value is 0.3544 p.u. (0.5013 p.u. peak) and THD is 76.78%.The simulation is repeated for the maximum modulation index of 1.0257 and the results are shown in Fig.4 (a) and Fig.4(b). It is observed that the output fundamental rms value is 0.3601p.u. (0.5092 p.u. peak) and THD is 75.05%. It is seen that the maximum fundamental output voltage is increased by 2.57% for the maximum modulation index. Table 1 shows the comparison of fundamental voltage and THD for 7-phase VSI. It is seen increasing modulation index fundamental voltage is increasing THD is decreasing. The harmonic injection fed 5-phase drive is shown in Fig.5 in that case DC voltage is set to 730 Volts. The corresponding transient response of the drive is shown in Fig.6. From the simulation results when increasing phase numbers reduced current/phase, increased power in the same frame and increasing torque frequency are observed.



(a)



(b)

Fig - 3: 7th harmonic injection with MI-1 (a) Reference signal, 5th harmonic component and modulation signal (b) Phase voltage and its spectrum

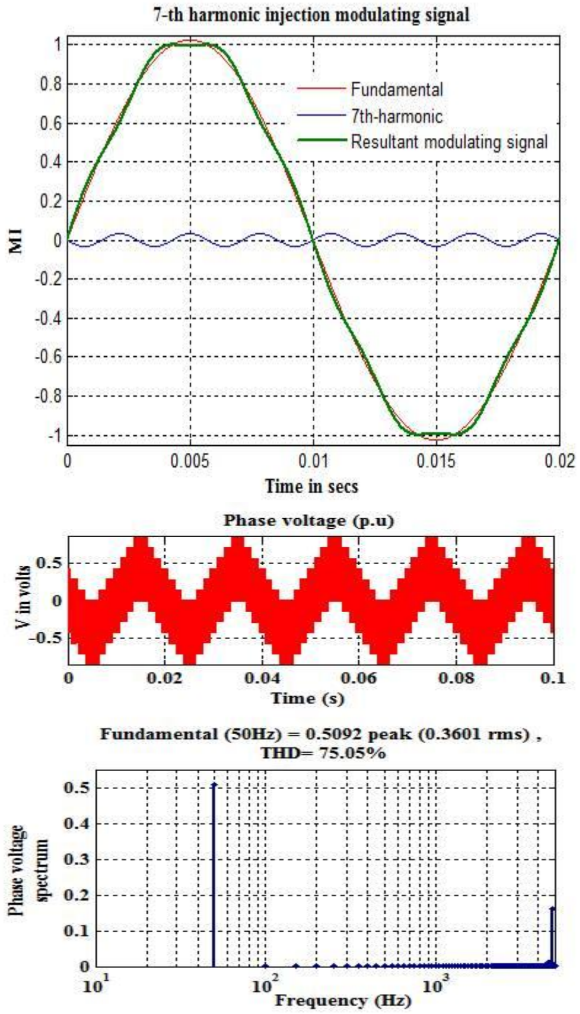


Fig - 4: 7th harmonic injection with MI-1.0257 (a) Reference signal, 7th harmonic component and modulation signal (b) Phase voltage and its spectrum

TABLE-1: FUNDAMENTAL VOLTAGE (PU) AND THD FOR 7-PHASE VSI

MI	7-phase VSI	
	Fundamental voltage(Volts)	THD(%)
0.2	0.0964	269.04
0.4	0.2805	173.56
0.6	0.2978	128.89
0.85	0.3981	99.31
1	0.5013	76.78
1.0257	0.5092	75.05

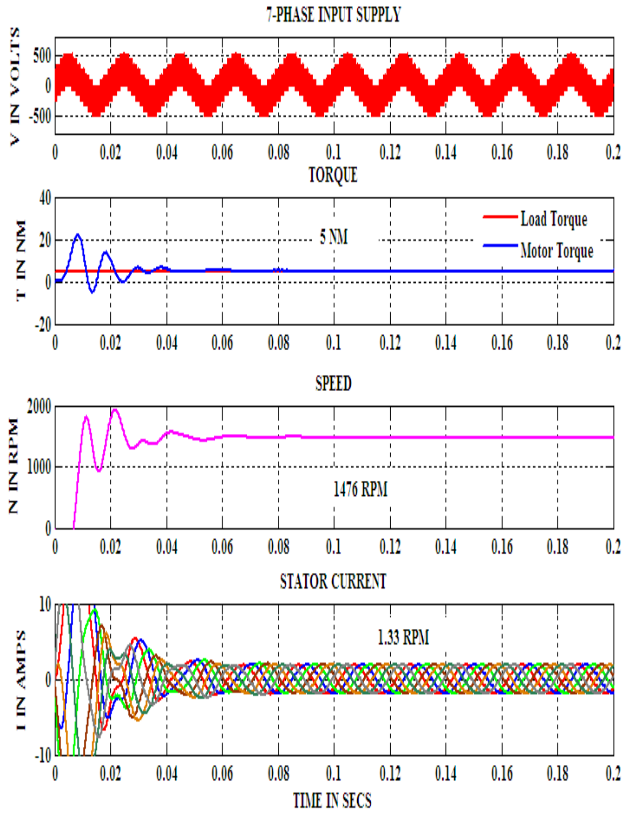


Fig - 5: Simulation results for 7-phase machine with 5 Nm load condition

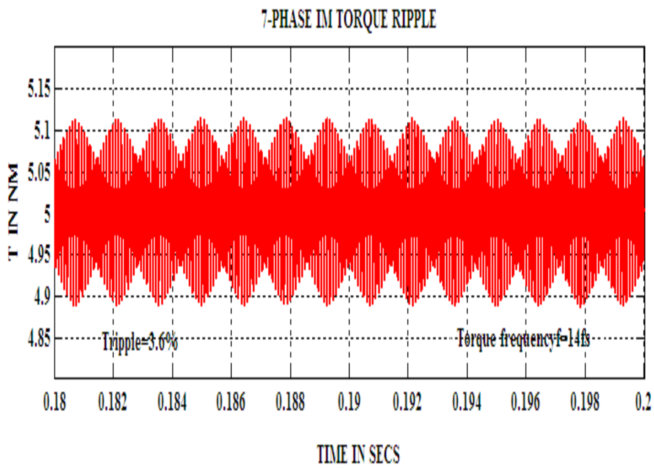


Fig - 6: Transient response of 7-phase induction motor drive

5. CONCLUSIONS

The simulation model of the 7-phase VSI fed induction motor drive is developed im matlab/simulink environment The simulation results are obtained for 7 -phase VSIs. It is found that the linear modulation range is extended without moving into the over-modulation region. The inverter fed 7-phase drive is discussed. From the simulation results when increasing phase numbers reduced current/phase, increased power in the same frame and increasing torque frequency are observed. Further the harmonic injection method eliminates the need for complex control algorithm and its simple calculation makes it easy to implement in digital platform and admirable selection for high power applications.

APPENDIX
PARAMETERS OF THE 7-PHASE INDUCTION MOTOR

PARAMETERS	VALUES
Power	1 hp
Voltage	220 V
Phase	7-phase
Frequency	50 Hz
No. of poles	4
Stator resistance (Rs)	10 ohm
Rotor resistance (Rr)	6.3 ohm
Stator inductance (Ls)	0.04 mH
Rotor inductance (Lr)	0.04 mH
Mutual inductance (Lm)	1.47 mH
Inertia (J)	0.03 kg.m^2
Friction (F)	0.0015N.m.s

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BIOGRAPHIES

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