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Five-level Inverter Fed Five-phase Induction Motor Drive

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ABSTRACT

This paper presents simulation and experimental implementation of five-level, five-phase cascaded H-bridge inverter. The inverter is controlled by sinusoidal pulse width modulation technique and fed five-phase induction motors. The speed of the motor is controlled by varying stator voltage with frequency, so as to maintain v/f ratio constant at the rated value. A fuzzy logic controller is also considered for controlling the speed. Simulation program using the MATLAB/SIMULINK software, for five-phase induction motors controlled by the proposed system is developed. Experimental results of the 1.5 Hp of five-phase induction motor show the effectiveness of the proposed control scheme.

يقدم هذا البحث التصميم والتنفيذ المعملي لعاكس قدرة ذو خمس مستويات في جهد الخرج خماسي الاوجة يغذي محرك حثي خماسي الاوجة. يتم التحكم في هذا العاكس باستخدام تقنية تعديل عرض النبضة الجيبي. تم استخدام التحكم القياسي للتحكم في سرعة المحرك الحثي خماسي الاوجه بحيث تظل نسبة الجهد الي التردد ثابته. تم تطبيق التحكم ذو المسار المغلق باستخدام كل من المتحكم التفاضلي التكاملي التناسبي والمتحكم المنطقي المبهم. تم المقارنة بين أداء المحرك الحثي خماسي الأوجه عندما يتم تغير سرعة المرجع في حالة استخدام كل من المتحكم التفاضلي التكاملي التناسبي والمتحكم المنطقي المبهم. وقد اثبتت النتائج فاعلية نظام التحكم المقترح.

Keywords –Multilevel inverter, Fuzzy Logic Control, Multi-phase Induction Motor

1- INTRODUCTION

In the last few years, interest in multi-phase multi-level inverter technology has increased due to the benefits of using more than three phases in drive applications. Most of the variable-speed electric drives use three phase machines. Nevertheless, since variable-speed AC drives include a power electronic converter, the number of machine phases can be higher than three. Major advantages of using a multiphase machine instead of a standard three-phase one are [1]:

1. Improved reliability and increased fault tolerance;
2. Greater efficiency;
3. Higher torque density and reduced torque pulsations;
4. Lower per phase power handling requirements;
5. Enhanced modularity;
6. Improved noise characteristics.

Some recent applications of multiphase systems include high- torque low-speed brushless machines applied to electric vehicle propulsion, permanent-magnet motor drives for ship propulsion [2], permanent-magnet motors with low torque pulsation [3], and series-connected two-motor drives with a single inverter supply [4].

Multilevel converter technology is based on the synthesis of a voltage waveform from several dc voltage levels. As the number of levels increases, the synthesized output voltage gets more steps and produces a waveform which approaches the reference more accurately. The major advantages of using multilevel inverters are [5]:

1. High voltage capability with voltage limited devices;
2. Low harmonic distortion;
3. Reduced switching losses;
4. Increased efficiency;
5. Good electromagnetic compatibility.

Multilevel converters have been extensively studied in a wide variety of applications. Recent industrial applications of multilevel inverters include induction machine drives [6], active rectifiers, interface of renewable energy sources to the utility grid [7] and static synchronous compensators [8]. Recently, an initial attempt to integrate a multilevel inverter with a multiphase machine was carried out which demonstrated the advantages of combining both technologies [9].

2- CASCADED H-BRIDGE MULTILEVEL INVERTER

A cascade multilevel inverter consists of a series of H–bridge (single-phase full-bridge) inverter units. The general function of this multilevel inverter is to synthesize a desired voltage from several separate DC sources (SDCSs), which may be obtained from solar cells, fuel cells, batteries, ultra-capacitors, and any DC sources. The number of output phase voltage levels in a cascade multilevel inverter is then 2S +1, where S is the number of DC sources.

Each H-bridge unit generates a quasi-square waveform by phase-shifting its positive and negative phase legs switching timings. In this paper, all DC voltages are assumed to be equal. Figure 1 shows the power circuit for five-phase five-level inverter fed five-phase induction motor.

The modulation methods used in multilevel inverter can be classified according to switching frequency, (low switching frequency and high switching frequency), [10]. The popular methods in industrial applications for high switching frequency are the classic carrier-based sinusoidal pulse width modulation (SPWM), selective harmonic elimination (SHEPWM) and space vector PWM (SVPWM) . The popular methods in industrial applications for low switching frequency are the multilevel selective harmonic elimination, and Space vector control [11]. In this paper the classic carrier-based sinusoidal pulse width modulation (SPWM), with triangular carriers is used. Some methods use carrier disposition and others use phase shifting of multiple carrier signals. The phase shifting of multiple carrier signals is considered. In this work, a number of S–cascaded cells in one phase with their carriers, shifted by an angle of 180°/S and using the same control voltage, produce a load voltage with the smallest distortion. For multi-phase inverter, the reference signals are shafted by 360/ (phases number).

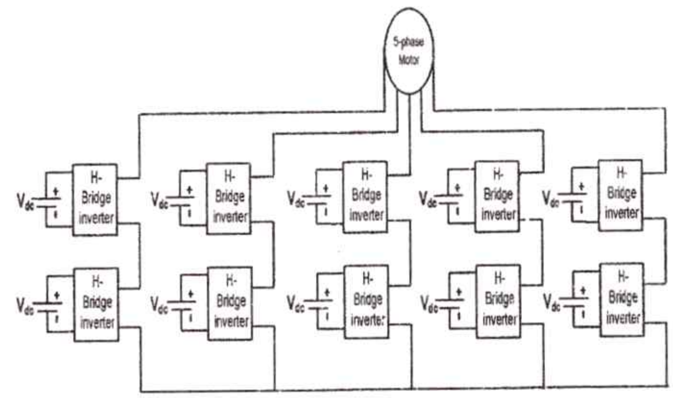


Figure 1 Five-phase five-level inverter fed five-phase induction motor

3- FIVE-PHASE INDUCTION MOTOR MODEL

The winding axes of five stator windings are displaced by 72 degrees. By increasing the number of phases, it is also possible to increase the torque per ampere for the same machine volume. In this analysis the iron saturation is neglected. The line-to-neutral voltages can be transformed to the d-q planes using the following transformation matrix K [12]:

$$K=\frac{2}{5}\begin{bmatrix} \cos\theta & \cos(\theta-\frac{2}{5}\pi) & \cos(\theta-\frac{4}{5}\pi) & \cos(\theta+\frac{4}{5}\pi) & \cos(\theta+\frac{2}{5}\pi) \\ \sin\theta & \sin(\theta-\frac{2}{5}\pi) & \sin(\theta-\frac{4}{5}\pi) & \sin(\theta+\frac{4}{5}\pi) & \sin(\theta+\frac{2}{5}\pi) \\ \cos\theta & \cos(\theta+\frac{4}{5}\pi) & \cos(\theta-\frac{2}{5}\pi) & \cos(\theta+\frac{2}{5}\pi) & \cos(\theta-\frac{4}{5}\pi) \\ \sin\theta & \sin(\theta+\frac{4}{5}\pi) & \sin(\theta-\frac{2}{5}\pi) & \sin(\theta+\frac{2}{5}\pi) & \sin(\theta-\frac{4}{5}\pi) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

The general equations of five-phase induction motor model can be introduced as follows.

The stator Quadrature- axes voltage is given by:

$$v_{qs}=r_s i_{qs}+\frac{d\lambda_{qs}}{dt}+\omega\lambda_{ds} \qquad (1)$$

The stator direct axes voltage is given by:

$$v_{ds}=r_s i_{ds}+\frac{d\lambda_{ds}}{dt}-\omega\lambda_{qs} \qquad (2)$$

For the stationary reference frame ω = 0, substitute into Equations (1) and (2) yields:

$$v_{qs}=r_s i_{qs}+\frac{d\lambda_{qs}}{dt} \qquad (3)$$

$$v_{ds} = r_s i_{ds} + \frac{d\lambda_{ds}}{dt}$$
(4)

The stator quadrature axes flux linkage is given by:

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} = (L_{ls} + L_m) i_{qs} + L_m i_{qr}$$
$$\lambda_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr})$$
(5)

The stator direct axes flux linkage is given by:

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} = (L_{ls} + L_m) i_{ds} + L_m i_{dr}$$
$$\lambda_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr})$$
(6)

The electromagnetic torque is given by:

$$T_e = \frac{5}{2}\frac{p}{2}\left[\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\right]$$
(7)

$$T_e - T_L = J\frac{d\omega}{dt} + B\omega$$
(8)

4- SPEED CONTROL OF FIVE-PHASE INDUCTION MOTOR

Speed control of induction motor can be classified to two methods. The first method is called scalar control, while the second method is called vector control. The first approach involves only magnitude of the control variables with no concern for the coupling effects between these variables. Conversely, vector control involves adjusting the magnitude and phase alignment of the vector qualities of the motor [13, 14]. The Scalar control such as the constant Volts/Hertz method is considered in this work. This method is relatively simple to implement with induction motor. But it gives a sluggish response because of the inherent coupling effect due to torque and flux being function of current and frequency.

5- FUZZY LOGIC CONTROLLER (FLC)

In the last few years, fuzzy logic has met a growing interest in many motor control applications due to its non-linearity handling features and independence of the plant modeling. The fuzzy logic controller (FLC) operates in a knowledge-based way, and its knowledge relies on a set of linguistic if-then rules, like a human operator. The present work develops a simulation of a closed-loop speed control, where the manipulated variable is the volts/Hz relation and, therefore, the slip value. For such applications, a proposed FLC is a suitable way to provide the necessary frequency variation command signal [15]. The frequency command also generates the voltage command through a volts/Hz function generator, with the low frequency stator drop compensation. For simulation purposes, all values are normalized to per unit (pu).

Figure 2 shows block diagram of the scalar control of induction motor, with fuzzy knowledge based controller (FKBC). The FLC includes four major blocks: one computes the error into two input variables, a fuzzification block, an inference mechanism, and the last step is defuzzification.

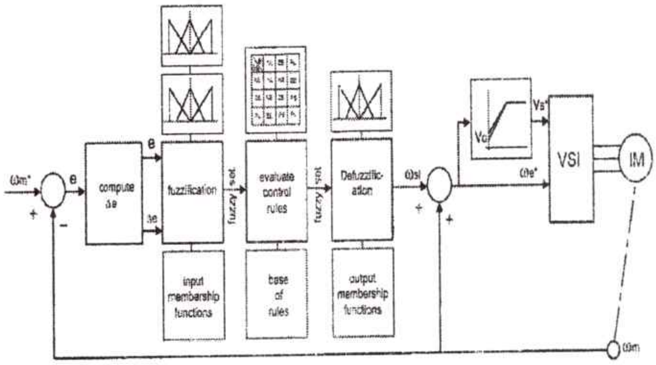


Figure 2 Block diagram of the scalar control of IM with the FLC architectur

Table (1) Linguistic Rule Table

Δe / E	NB	NS	Z	PS	PB
NB	NB	NB	NM	NS	Z
NS	NB	NM	NS	Z	PS
Z	NM	NS	Z	PS	PM
PS	NS	Z	PS	PM	PB
PB	Z	PS	PM	PB	PB

Table (1) indicates the proposed membership functions for output variable and the control rules. The inference strategy used in this system is the Mamdani algorithm, and the center-of-area/gravity method is used as the defuzzification strategy.

According to Ref. [15] the equation giving a PI-like FKBC is

$$\Delta\omega_{sl} = k_p \Delta e + k_i e$$

The fuzzy if-then statements are symbolically expressed with the form If e is (…) and Δe is (…) then w_{sl} is (…)

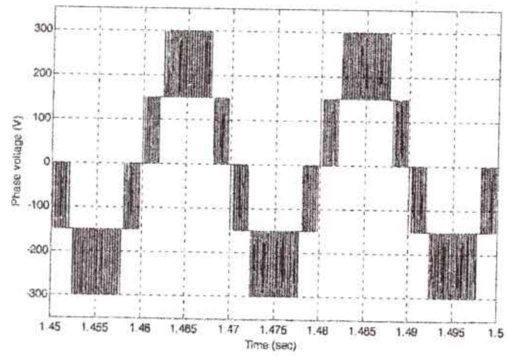
The output control is, then

$$\omega_e^* = \omega_m + \omega_{sl}$$

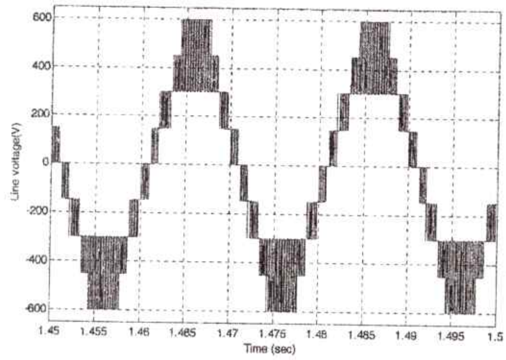
6- SIMULATION RESULTS

A simulation program of five-level inverter fed five-phase induction motor is developed using MATLAB/ SIMULINK software package. The motor is started at no load and it loaded by 1.75 N.m at t = 15sec. The five-phase motor parameters are L_m = 0.85 H, L_{ls} = L_{lr} = 0.0214 H, r_s =14 ohm, r_r = 4.6 ohm, P = 2- pole, J = 0.007 Kg.m2, and B = 0.005

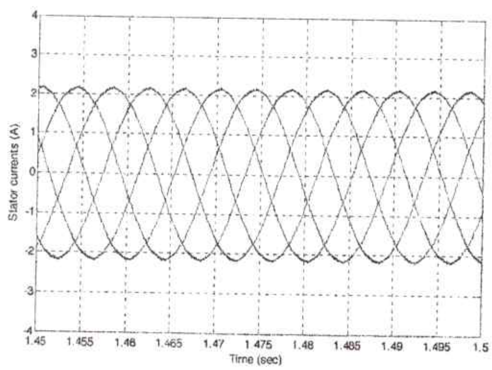
N.m.s/rad. The five-phase motor performances are shown in figure 3. Figure 3-a,b and c show phase voltage, line voltage and steady-state motor current. Figure 3-d show the motor speed response, Figure 3-e show the torque response, Figure 3-f show the locus space phasor and figure 3-j show the five-phase motor currents at starting and steady state.



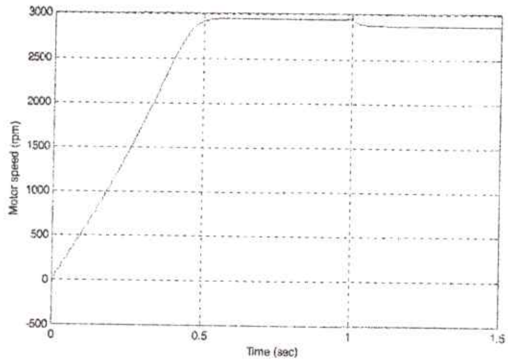
a-Phase voltage



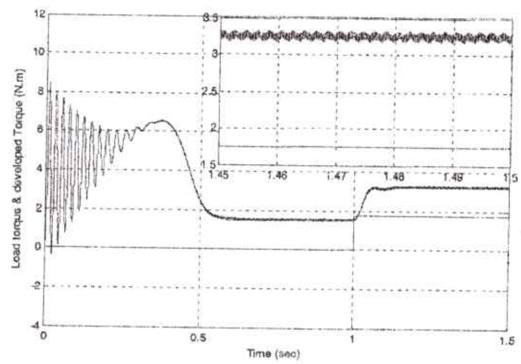
b -line voltage



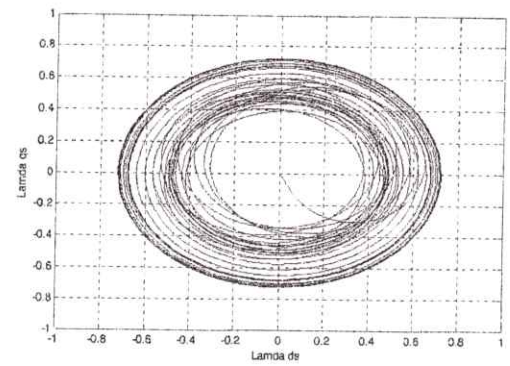
c-Five-phase motor current at steady state



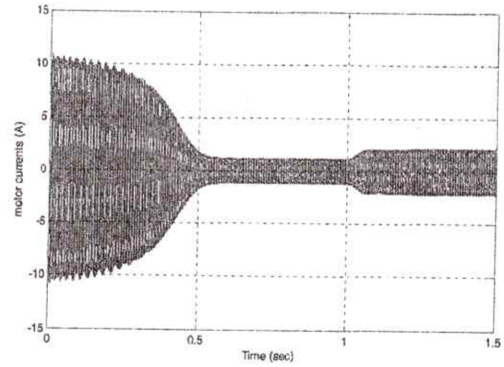
d-Motor speed response



e-Torque response



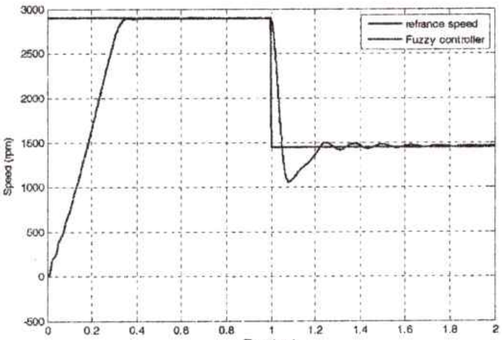
f- Locus stator flux space phasor



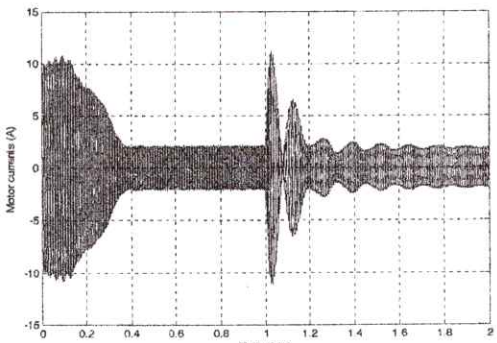
j-Five-phase motor currents

Figure 3 performance of Five-phase induction motor fed from 5-level inverter

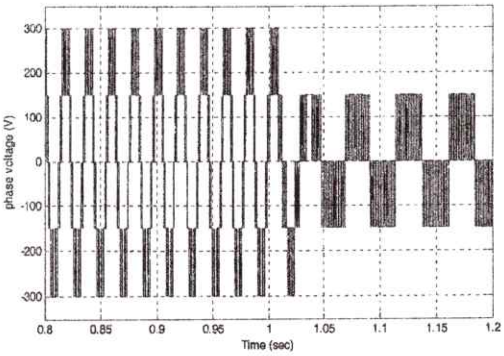
The simulation results of motor speed, current and phase voltage of the five-phase induction motor, when the speed reference decreases from 2900 rpm to 1450 rpm are shown in figure 4 for FLC controller. Figure 4-a shows the speed response when the speed reference decreases from 2900 rpm to 1450 rpm. Figure 4-b show the motor current response, and figure 4-c show the phase voltage before and after change the speed reference. We note that, when the frequency changes from 50 HZ at 2900 rpm to 25 Hz at 1450 rpm, the voltage decreases from 220 V to 110 V. This mean that the flux is maintain constant (V/f = constant).



a-speed response



b-Motor currents response



c-Phase voltage before and after change the refreance speed

Figure 4 Performance of FLC due to speed change for five-phase induction motor

The simulation results show also that the dynamic response of the five-phase system when using the proposed fuzzy logic controller is better when compared to a classical PI controller. As shown in figure 5, the proposed FLC reacts rapidly when there is a change in the speed command

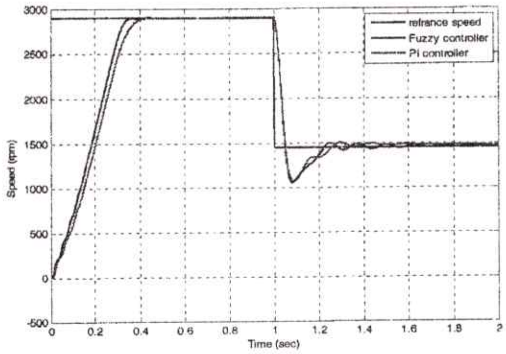


Figure 5 Comparison between fuzzy controller and classical PI controller due to speed change

7- EXPERIMENTAL RESULTS

An experimental set up for test investigation is shown in figure 6. The five-phase induction motor under test is coupled to electro dynamic break, which acts as a load. The phase current is sensed by current transducers (LA-NP25). The phase and line voltage are sensed by voltage transducers (LV-NP25). The motor is supplied by a five-level Inverter. The separated dc-sources are provided from single-phase diode bridge rectifier. This system is fully controlled by a digital signal processor controller board (dSPACE DS1104) that is installed on a personnel computer. The board is supplied with a software development system.

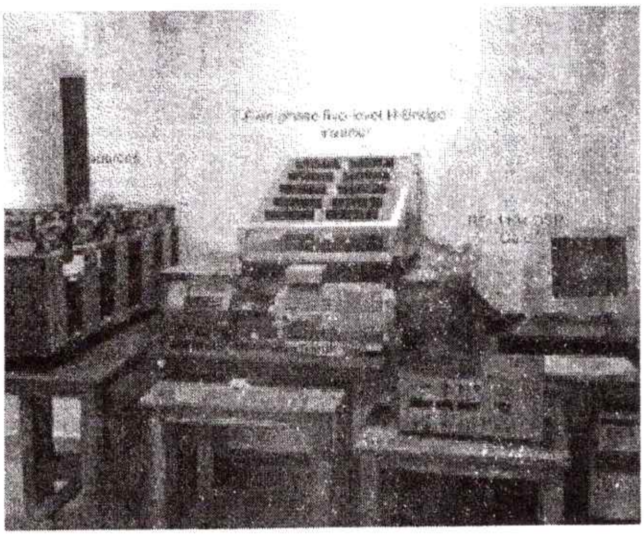
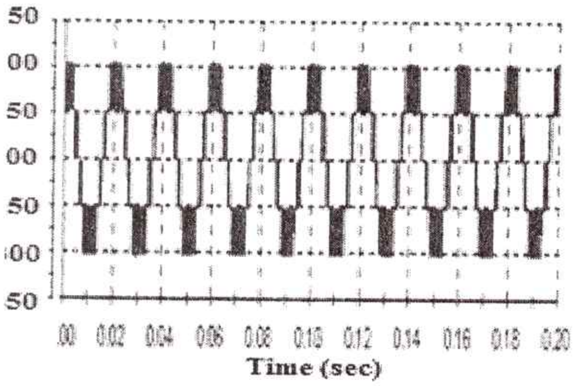


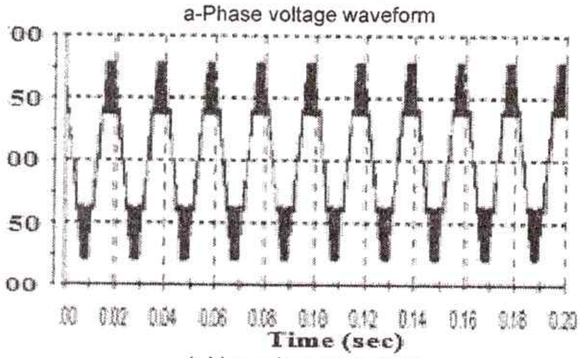
Figure 6 Experimental setup

7.1 Open loop results

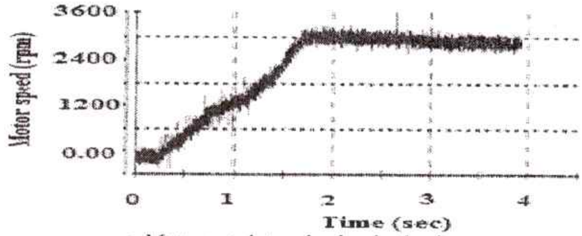
For five-phase system phase voltage and line voltage are shown in figure 7-a and figure 7-b respectively. The motor is started without load at rated voltage and rated frequency (V_{ph}=220 V, F=50 Hz) the steady-state speed is equal to 2960 rpm and the motor current is equal to 1 A. At t=2.8 sec the motor is loaded by 1.75 N.m load, the speed is decreased to 2880 rpm and the motor current is increased to 1.5 A as shown in figure 7-c and figure 7-d respectively



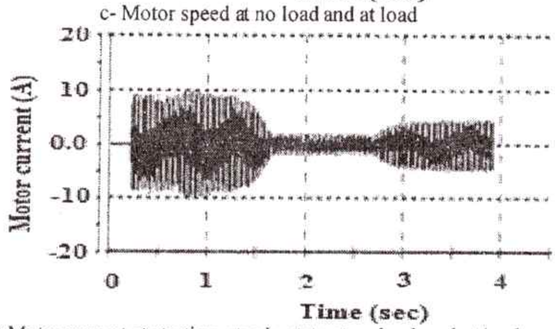
a-Phase voltage waveform



b-Line voltage waveform



c- Motor speed at no load and at load

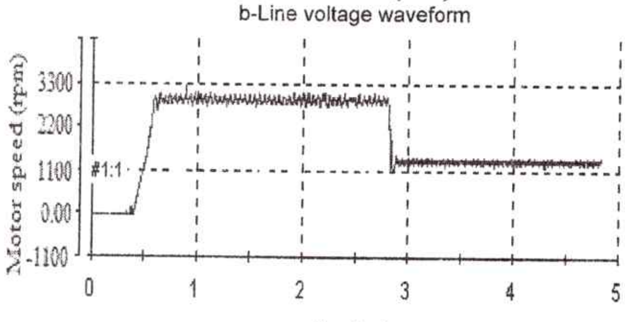


d-Motor current at starting, steady state at no load, and at load

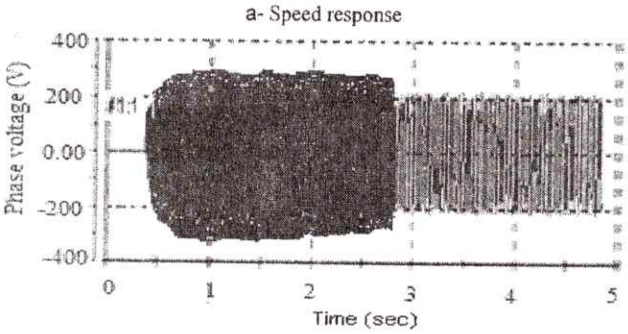
Figure 7 Experimental results for open loop five-phase induction motor fed from five-level inverter controlled by SPWM method

7.2 Closed loop control

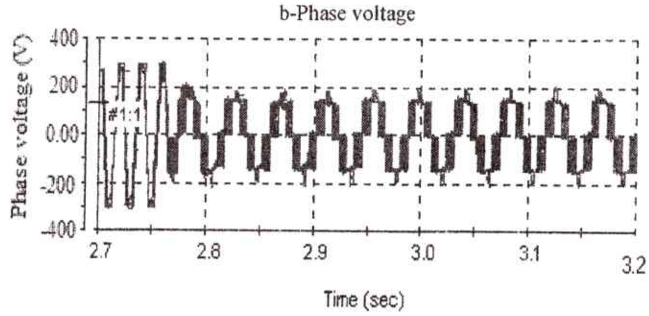
The experimental results of the motor speed, and phase voltage of the five-phase induction motor, when the speed reference decreases from 2900 rpm to 1450 rpm are shown in figure 8 for FLC controller. Figure 8-a shows the speed response when the speed reference decreases from 2900 rpm to 1450 rpm. Figure 8-b show the phase voltage and figure 8-c obtained the phase voltage before and after change the reference speed. We note that the frequency changes from 50 HZ at 2900 rpm to 25 Hz at 1450 rpm and the voltage is decreased from 220 V to 110 V. This mean that the flux is maintained constant (V/f = constant).



a- Speed response



b-Phase voltage



c- Phase voltage before and afer change the refreance speed

Figure 8 Experimental results for closed loop five-phase induction motor fed from five-level inverter (controlled by SPWM method) with FLC

8- CONCLUSIONS

In this paper, simulation and experimental implementation of five-phase inverter fed five-phase induction motor is carried out. The simulation results of FLC for speed control of five-phase induction motor is presented. Using FLC it is not necessary to change the control parameters (as the speed reference) however with the classical PI controller this does not happens. With results obtained from simulation, it is clear that for the same operation condition, the induction motor speed control using FLC had better performance than the PI controller. An experimental set-up of 5-level five-phase cascaded H-bridge inverter, controlled by DSP card was designed, built and tested. Experimental results confirm that, reduction in harmonic contents may be achieved by the proposed drive system.

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