MICROCOMPUTER-BASED HYSTERESIS SPEED CONTROL OF THREE-PHASE INDUCTION MOTOR

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Abstract

In this paper, a microcomputer-based hysteresis speed control of a three-phase induction motor is proposed. Combination of a phase control and an integral cycle control is adopted to provide a switching pattern for controlling MOSFET's converter. Each MOSFET switch is connected in parallel with a single-phase diode bridge which is connected in series with each motor phase. To achieve the desired speed, a hysteresis controller is used to control the switching pattern. Experimental set-up has been implemented to verify the proposed control scheme. Simulation and experimental results are compared to show the effectiveness of the proposed method of control.

Keyword

Speed control, Microcomputer, Hysteresis control, Induction motor

1. Introduction

The rapid growth in microelectronics and power electronics technologies has introduced various advanced control methods for AC motors. Such methods have been successfully implemented in real time and shown to be useful in controlling induction motors with high dynamic performance[1,2]. Speed control is an integration technology of control theory, power electronics, and microcomputer to achieve a precision speed control [3]. Traditionally, AC induction motor, particularly the cage type, has been the workhorse in industry because of its raggedness, reliability, efficiency, and low cost. Although induction machines are simple, their control is complex due to their nonlinear multivariable dynamic behavior. The complexity increases as higher performances are demanded. Many different control techniques of varying degrees of complexity have appeared in the evolution of induction motors. With the advent of microelectronics and microcomputers, field vector control techniques are now being accepted almost universally for control of induction servo motors. Inverter-fed induction motors controlled by field vector control strategy are replacing dc motors in many applications where fast response is required[4,5]. In most reported methods of

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motion control, the disadvantage of high cost is a common feature. The design of microprocessor-controlled power-electronic equipment will in the future continually emphasize the shift from hardware to software design, as more powerful microprocessors become available[6,7]. The present production of microprocessor devices and their quick development, combined with the continuous reduction of their computing times, make now possible a widespread use of fully digitalized controls for the solution of a lot of control problems in electric drives [8]. Ac phase-controlled switching is used for the speed control of three-phase induction motor, but it introduces large high-order harmonics. Alternatively, an integral-cycle method is also available, but it introduces sub-harmonics in the line, and the output voltage is adjustable in steps only. To mitigate these situations, a hysteresis controlled switching technique is proposed. The voltage control is done by a combination of the phase control and the integral-cycle switching. Conventional voltage controllers, including ac regulators, offer a very limited speed control range.

The paper introduces a novel low cost scheme for hysteresis control of voltage fed induction motor (ON/OFF control). The new scheme utilizes only three controlled MOSFETs switches and three capacitors. The triggering circuit of the MOSFETs gates are designed using low rating electronic components. A feed-back on-line closed loop speed control system is described.

2.System description and principle of operation

A schematic diagram of the proposed system is shown in Fig.1. It is composed of a power electronic converter of three switching legs and the controller. Each converter leg consists of one MOSFET transistor, a single-phase diode bridge and an R-C circuit. The stator windings of the motor are connected to the ac source through the three switching legs. The speed controller receives the error signal between the preset speed (reference speed) and the actual measured speed of the motor shaft, then transfers it to the microcomputer through an Analog/Digital (A/D) converter. The controller is intrefaced to the power converter through a three-channel gate drive circuit. Each channel consists, as shown in Fig. 2, of an optocoupler isolator and open buffer gates to deliver the control signales to the MOSFET. The input signals to the gate drive circuit are obtained from the microcomputer output port to give the speed control action according to the input error signal. An assembly program is designed and written for the microcomputer to apply the hysteresis method and the ON/OFF control. The microcomputer controls the switching process according to the following conditions:

If ***error signal*** > ***zero***, the MOSFETs are ***ON***
If ***error signal*** ≤ ***zero***, the MOSFETs are ***OFF*** (1)

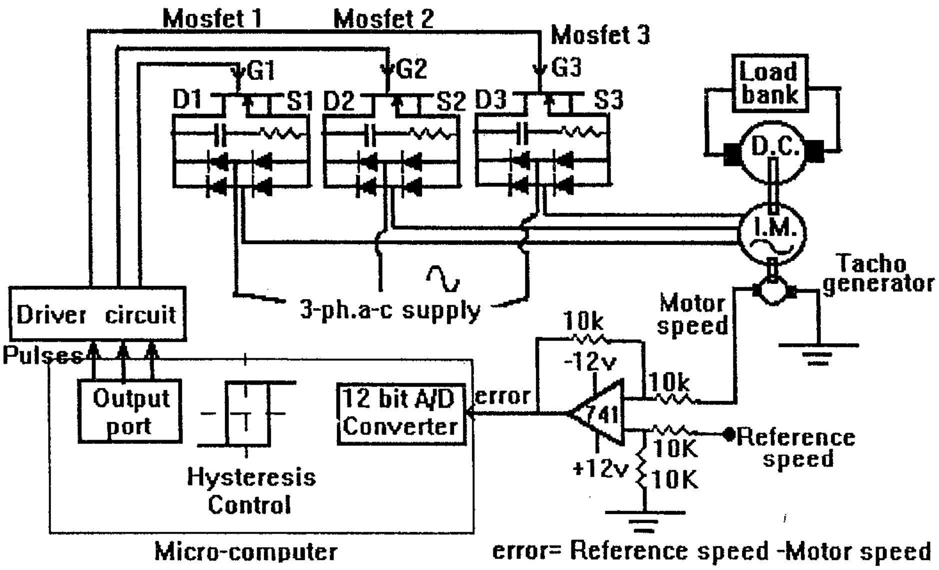


Fig.1 Configuration of the proposed system

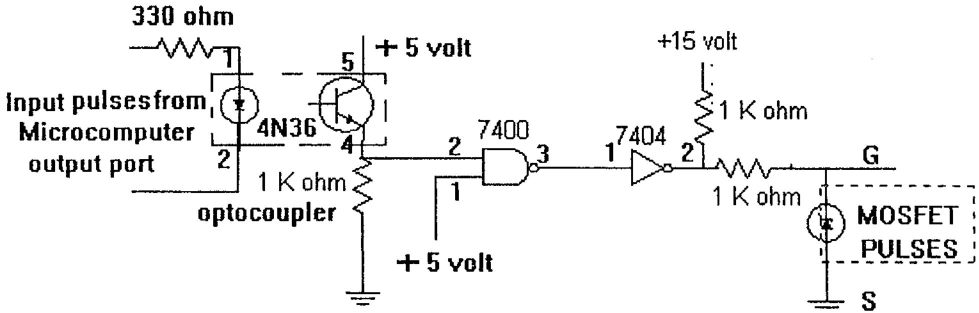


Fig. 2 Driver circuit for one MOSFET

3. Motor mathematical model

Neglecting core losses, saturation effects, and space harmonics, the voltage balance equations for a three-phase motor are [9]

$$
\begin{aligned}
e_{sa} &= \rho\ \psi_{sa} + r_s i_{sa} \\
e_{sb} &= \rho\ \psi_{sb} + r_s i_{sb} \\
e_{sc} &= \rho\ \psi_{sc} + r_s i_{sc} \\
e_{ra} &= \rho\ \psi_{ra} + r_r i_{ra} \\
e_{rb} &= \rho\ \psi_{rb} + r_r i_{rb} \\
e_{rc} &= \rho\ \psi_{rc} + r_r i_{rc} \qquad (2)
\end{aligned}
$$

In matrix notation, the relation between the phase flux linkages and the phase currents may be expressed as:

$$\psi = [L]\, i \qquad (3)$$

where

$$\psi = [\psi_{sa}\ \psi_{sb}\ \psi_{sc}\ \psi_{ra}\ \psi_{rb}\ \psi_{rc}]^T \qquad (4)$$

and

$$i = [i_{sa}\ i_{sb}\ i_{sc}\ i_{ra}\ i_{rb}\ i_{rc}]^T \qquad (5)$$

and $[L] = \begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix}$ (6)

where

$$L_{11} = \begin{bmatrix} L_{ss} & L_{sm} & L_{sm} \\ L_{sm} & L_{ss} & L_{sm} \\ L_{sm} & L_{sm} & L_{ss} \end{bmatrix} \qquad L_{22} = \begin{bmatrix} L_{rr} & L_{rm} & L_{rm} \\ L_{rm} & L_{rr} & L_{rm} \\ L_{rm} & L_{rm} & L_{rr} \end{bmatrix}$$

$$L_{21} = \begin{bmatrix} M_{sr}\cos\Theta & M_{sr}\cos(\Theta - \frac{2\Pi}{3}) & M_{sr}\cos(\Theta + \frac{2\Pi}{3}) \\ M_{sr}\cos(\Theta + \frac{2\Pi}{3}) & M_{sr}\cos\Theta & M_{sr}\cos(\Theta - \frac{2\Pi}{3}) \\ M_{sr}\cos(\Theta - \frac{2\Pi}{3}) & M_{sr}\cos(\Theta + \frac{2\Pi}{3}) & M_{sr}\cos\Theta \end{bmatrix}$$

$$L_{21} = \begin{bmatrix} M_{sr}\cos\Theta & M_{sr}\cos(\Theta - \frac{2\Pi}{3}) & M_{sr}\cos(\Theta + \frac{2\Pi}{3}) \\ M_{sr}\cos(\Theta + \frac{2\Pi}{3}) & M_{sr}\cos\Theta & M_{sr}\cos(\Theta - \frac{2\Pi}{3}) \\ M_{sr}\cos(\Theta - \frac{2\Pi}{3}) & M_{sr}\cos(\Theta + \frac{2\Pi}{3}) & M_{sr}\cos\Theta \end{bmatrix}$$

Instantaneous torque and speed equations are given by

$$T_e = -[(i_{sa}\, i_{ra} + i_{sb}\, i_{rb} + i_{sc}\, i_{rc}) \sin\theta + (i_{sa}\, i_{rb} + i_{sb}\, i_{rc} + i_{sc}\, i_{ra}) \sin(\theta + 2\pi/3) + (i_{sa}\, i_{rc} + i_{sb}\, i_{ra} + i_{sc}\, i_{rb}) \sin(\theta - 2\pi/3)]\, M_{sr} \qquad (7)$$

and the mechanical torque equation of the motor and load is given by

$$J \frac{d^2 \Theta_m}{dt^2} + K \frac{d\Theta_m}{dt} + T_m = T_e \qquad (8)$$

$$\Theta = \frac{P}{2} \Theta_m \qquad (9)$$

In solving the above differential equations, the Runge-Kutta method has been employed.

4. Microcomputer-based controller

A microcomputer-based controller [10] is composed of microprocessor 8088-based programmable digital controller (MCU). Its detailed circuit schematics is shown in Fig.3. It consists of central processing unit (CPU), which includes the 8088 microprocessor, 8087 numerical data processor (co-processor), 16K dual-port RAM, 16K EPROM, 8254 programmable interval timer (PIT), and 8259 programmable interrupt controller (PIC). The other is named input/output (I/O) unit which may include programmable digital I/O controller, programmable duty-cycle controller, A/D, D/A, etc. In the proposed system, the analog error signal between the reference motor speed and actual motor speed is transferred to digital value through A/D channel 1, and store the value in memory location of RAM. The comparator is used to compare the error signal with the zero according to hysteresis control technique, then generates three pulses from output port to be deliver to the gates of MOSFETs through driving circuits. A system controller, which resides on a 16-bit microcomputer, provides task coordination, external interfaces, motion profile control, parameter tuning, and signal recording, and can also be used to monitor the operational status of individual processors.

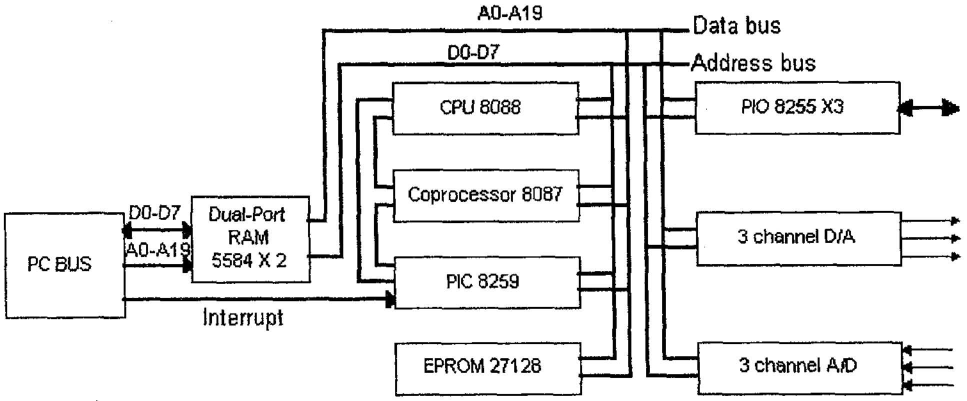


Fig.3 Microcomputer architecture

5. Modelling and simulation Results

The system model provides information about transient changes in the main variables under the influence of the switching device modulation scheme. The control problem can be integrated to find the duration of the ON and OFF states for converter switches so that the given dynamic specifications of the closed-loop system are satisfied. The block scheme of a proposed system is shown in Fig.1. The speed command (reference speed) is compared with the actual speed, the error signal is transferred through A/D circuit to the microcomputer. According to the hysteresis controller algorithm, and a machine language program built in the EPROM interfaced to the CPU of a microcomputer, the output pulses from the microcomputer port are delivered to the gates of MOSFETs ON or OFF depending on the value of the error signal.

5.1 During ON period of MOSFETs

To prove the effectiveness of the proposed method, the digital simulation is implemented. A computer program has been constructed for solving Eqs. 1-9 using the 4th order Runge-Kutta of numerical method with a step of 100 µsec. Electrical power is transferred through MOSFETs to the stator windings of three-phase induction motor.

5.2 During OFF period of MOSFETs

The induced terminal voltage V(t) at the motor terminals can be found [9] as

$$v(t) = \frac{V_c}{w} e^{-R't/2L}\left[\frac{R'}{2L}\sin wt + w\cos wt\right] \qquad (10)$$

where Vc : initial voltage across the effective capacitor,

$$w = \left[\frac{1}{LC} - \frac{R'^2}{4L^2}\right]^{1/2}$$

L; magnetizing inductance

R' : stator resistance minus slope of the magnetization curve in the linear region. Also a series resistance is connected in series with a capacitor C in order to keep R positive and hence V(t) will be decaying.

5.3 Computed results

Closed-loop system dynamic behaviour is examined through digital simulation with a developed FORTRAN77 program on a pentium 233 PC. It provides a simple method of representing non-linear time differential equations on a digital computer, simulating the starting of a light loaded induction motor fed from three converters, each of them consists of one MOSFET, single-phase bridge and R-C branch. With a command speed (reference speed) = 1400 r.p.m., transient and steady state response of motor phase current, terminal phase voltage, speed, supply voltage and current are shown in Figs. 4,6. During starting process, all MOSFETs are in the ON period mode, the motor speed reaches a desired reference speed, then the OFF period of MOSFETs starts, the capacitor voltage is increased, and motor terminal voltage is decreased , then restarting the ON period of the MOSFETs and so on untill motor speed reaches steady state operation mode. By using R-C connected in parallel with MOSFETs, the spikes of motor current and voltage are decreased, and they may be used for MOSFETs protection. Figure 8 shows the transient response of motor speed loaded with light load is stepped-up by 20%. So, the simulation results verify that the proposed controller is accurate and has a fast response. Also, the response time is about 200 m.sec. to reach final speed.

6. Experimental results

To verify the validity of the simulated results given in section 5 as well as the effectiveness of the proposed control strategy, an experimental system is implemented as shown in Fig.1, a squirrel-cage induction motor has been chosen whose data are listed in table 1

Table 1 Data of the induction motor

Nameplate data	Nominal parameters
220 v, 50 Hz	Lss 0.4671 H.
3-phase	Lrr 0.4671 H.
star connected	Lsm 0.23155 H.
4 poles	Lrm 0.23155 H.
0.75 HP	Msr 0.42887 H.
rated speed 1450r.p.m.	R1 19 ohm
rated current 1.2 Amp.	R2 10 ohm
	K 0.0001 kg.m²/s
	J 0.004 kg.m²

The hardware setup consists of a microcomputer based on microprocessor 8088, 12-bits A/D, 12-bits D/A, three MOSFETs with type IRFP740, three phase auto-transformer, three uncontrolled single phase bridge, and three R-C circuits. The microcomputer-based control system designed for the induction system is shown in Fig.1, the control algorithm is implemented on an EPROM interfaced to the CPU of a microcomputer. The proposed control scheme was executed every 0.5 m.sec. The neutral line is connected between the neutral point of the stator windings of the motor and the secondary winding of the transformer. The error signal between command speed and actual motor speed is transferred through 12-bit A/D converter, the generated pulses to MOSFETs are processed from output port depending upon the error signal and hysteresis control. The R-C circuit is connected across drain-source of each MOSFET with R=47.5 ohm and C=0.2 μF. Figure 5 shows the transient response of motor phase current, voltage, speed, supply phase voltage and current for reference speed = 1400 r.p.m. and motor with light load. The steady state response of motor phase voltage and current is shown in Fig.7. which shows a good performance of motor speed. It can be seen that the experimental results are nearly as the simulation results, the capacitor is used for smoothing the variation of motor terminal voltage and current during the case variation between MOSFET ON state and MOSFET OFF state. As motor load is stepped up by 20% , a motor speed performance at input supply voltage = 110 volt. is shown in Fig.9. Also, the performance of motor during transient and steady state conditions is shown in Fig.10, for reference speed = 1000 r.p.m. In which, it can be noted that the proposed controller is an effective tool to achieve the desired motor speed. Also, a study of the performance of the motor during one phase open fault at a reference speed =

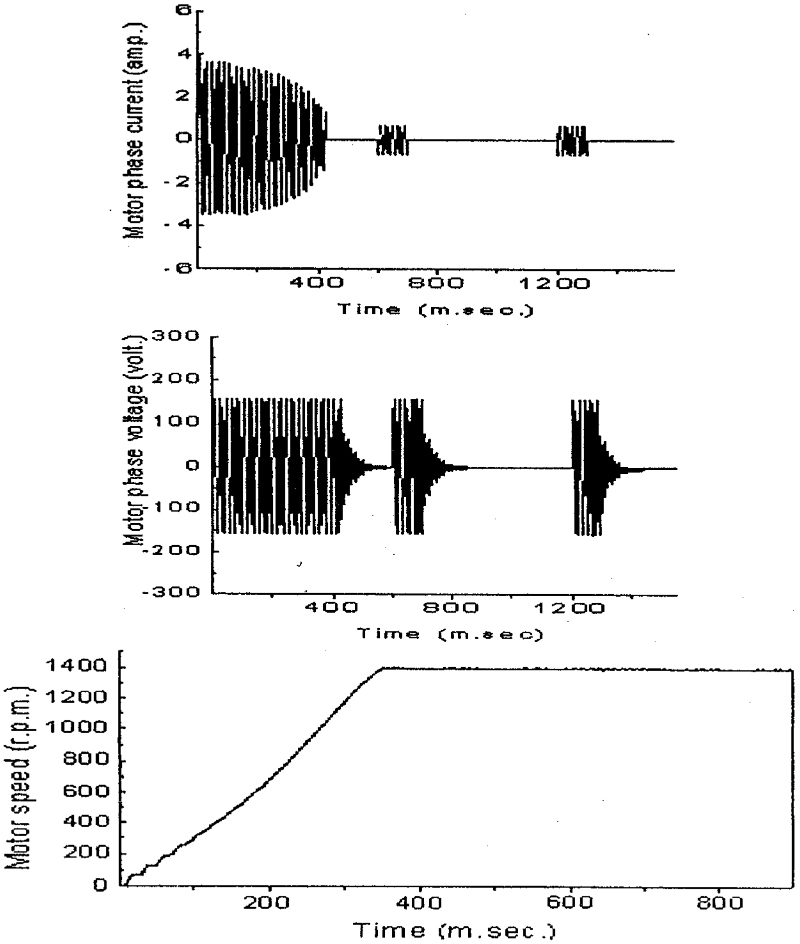
1400 r.p.m. is shown in Fig.11., motor speed is almost constant, this means that the proposed controller is fast response to achieve the desired speed. As, the reference speed is changed up or down from a certain value to another one then returned back to its initial value, the motor speed follows the reference speed as shown in Fig. 12. Finally, a motor speed is achieved smoothly as the required command speed with a simplified and low cost control arrangement. It can be seen that the motor phase voltage and current are nearly decreasing smoothly during OFF period of MOSFETs, and the motor speed is nearly constant if all supply ac phases voltage are connected to the motor or a fault is occurred of one of them but the other two supply ac phases delivers an ac power to the motor. Also, It can be control the motor speed from a zero value to a nominal motor speed value.

7. Conclusion

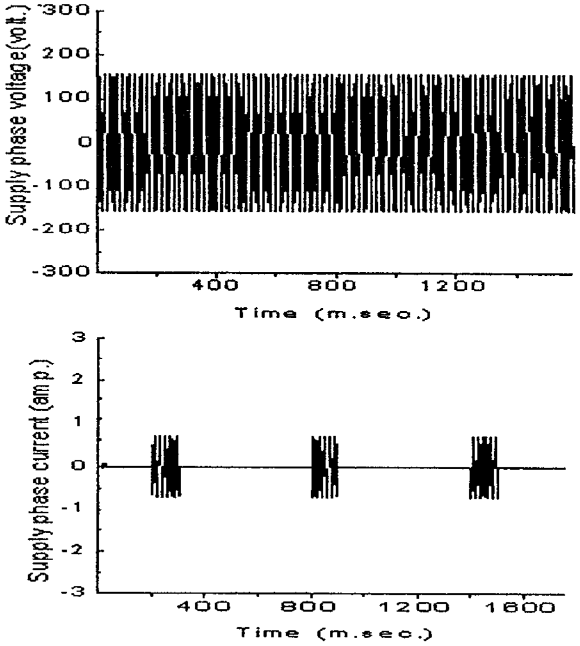
The paper proposes a simple and an effective speed control method for the three-phase induction motor. The proposed system uses only three MOSFETs, each of them is connected in series with each stator phase winding of the induction motor. A microcomputer is used as a controller to turn on or off the MOSFETs according to the hysteresis control technique. Three R-C branches are used, each of them is connected in parallel with the drain-source of a MOSFET. This is useful for two purposes, first for protection against dv/dt across the MOSFET and second to reject voltage spikes and smooth the motor current. An experiment set-up has been implemented to verify the proposed control scheme. Simulation and experimental results are compared and found to be in good agreement. These results show the effectiveness of the proposed control scheme and the feasibility of control algorithm by using a microcomputer. The proposed scheme uses minimum switching elements and has the advantages of robustness, effectiveness and offers many features which are attractive for speed control of induction motor drive applications. The proposed controller is suitable of a fan load and other loads with the same fan load characteristics.

Symbols

a,b,c: first, second,and third phases of three-phase system
D1,G1,S1: drain, gate and source of MOSFET 1
D2,G2,S2: drain, gate and source of MOSFET 2
D3,G3,S3: drain, gate and source of MOSFET 3
K: inertia constant, seconds.
i: instantaneous current
J: inertia of motor and connected load
L_{ss}, L_{rr}: self-inductances of three-phase stator and rotor circuits, respectively.
L_{sm}: mutual inductance between stator phases
L_{rm}: mutual inductance between rotor phases
M_{sr}: mutual inductance between three-phase stator and rotor circuits
ρ: differential operator, d/dt
P: number of poles
s, r: suffixed denoting stator and rotor, respectively
r: resistance
s: instantaneous flux linkage
Θ: electrical angle denoting instantaneous rotor position, radians
Θm: mechanical angle denoting instantaneous rotor position, radians
T_e: electrically developed torque
T: superscript denoting transpose of matrix
T_m: external load torque



(a) Transient response



(b) Steady state response

Fig.4 Simulation results of 3-phase induction motor at Reference speed = 1400 r.p.m.

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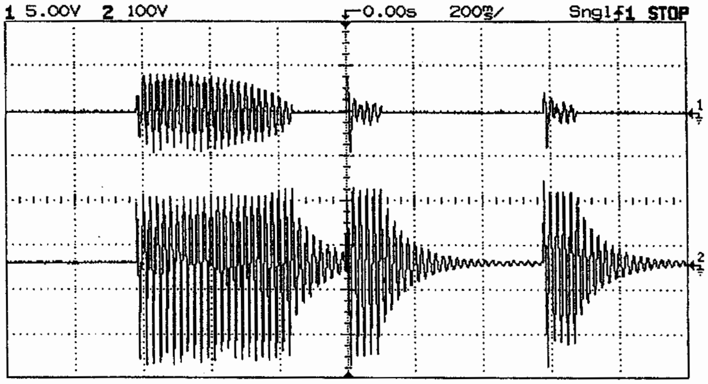
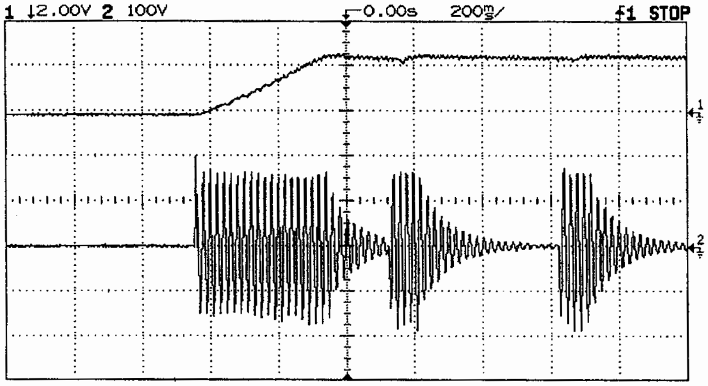
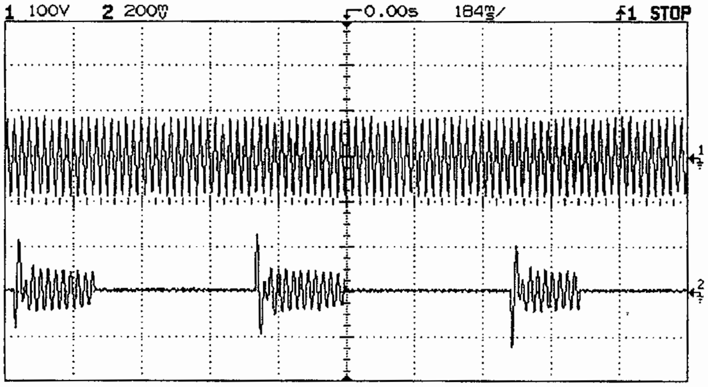


Ch.1 Motor phase current
Ch.2 Motor phase voltage



(a) Transient response

Ch.1 Motor speed
Ch.2 Motor phase voltage



(b) Steady state response

Ch.1 Supply phase voltage
Ch.2 Supply phase current

Fig.5 Experimental results of 3-phase induction motor at Reference speed = 1400 r.p.m

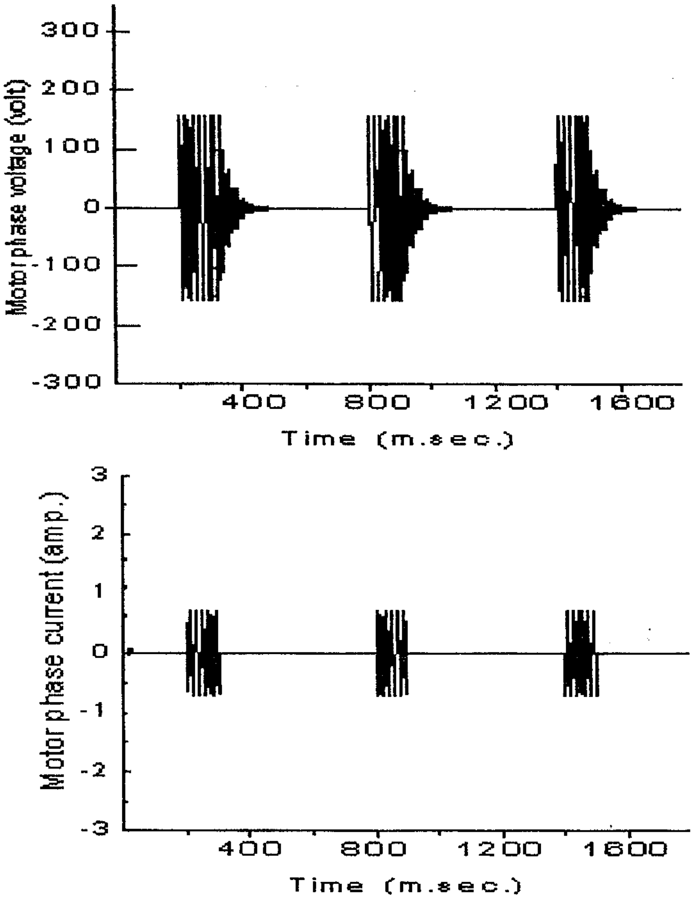


Fig.6 Steady state of Motor phase voltage and current at reference speed = 1400 r.p.m. (Simulation results)

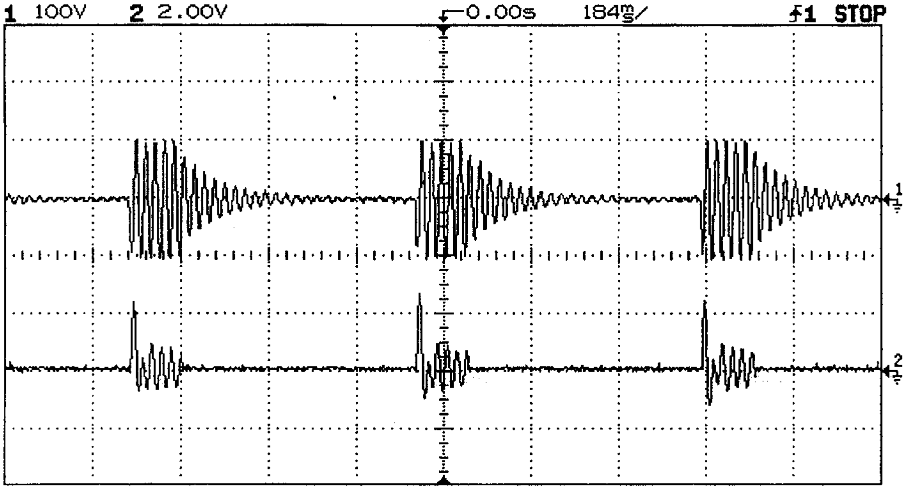


Fig.7 Steady state of Motor phase voltage (Ch.1) and current (Ch.2) at reference speed= 1400r.p.m. (Experimental results)

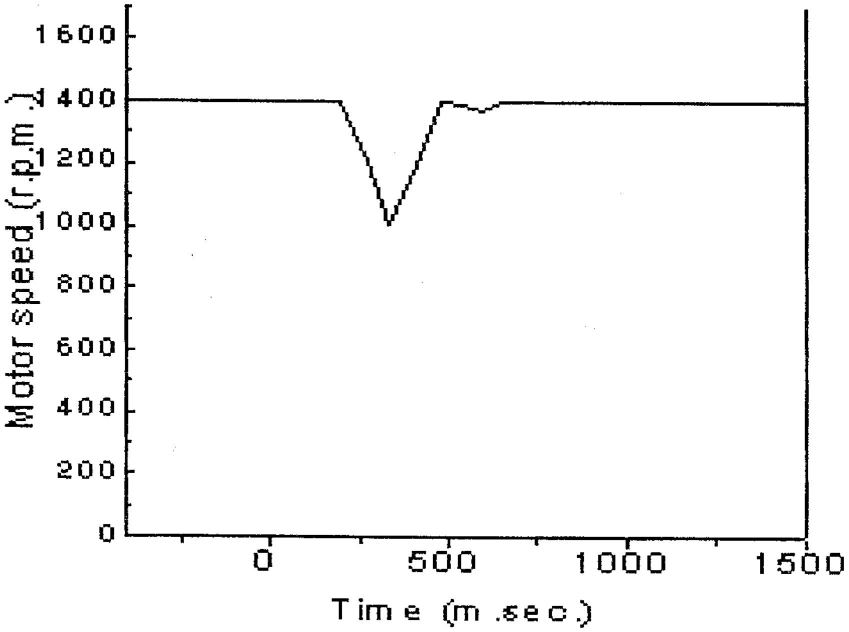


Fig.8 Motor speed during step change in load torque by 20% (Simulation results)

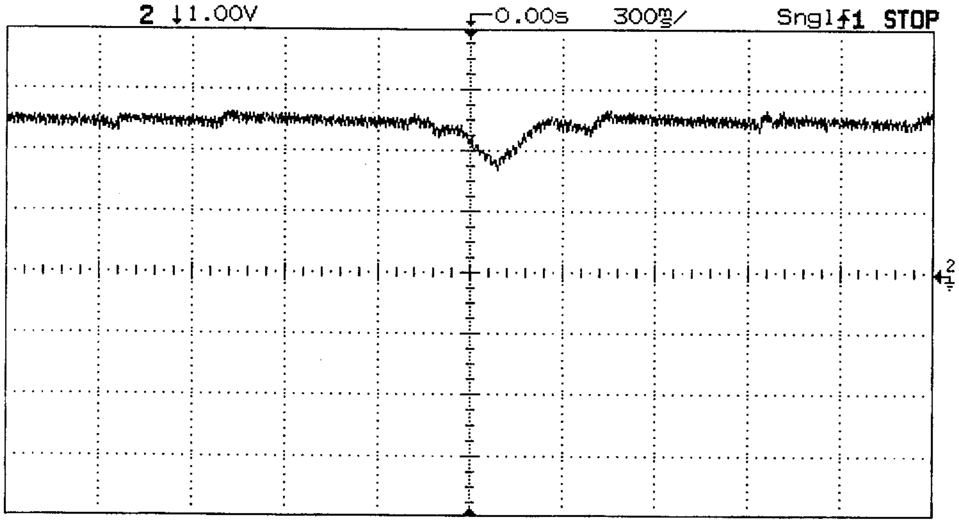
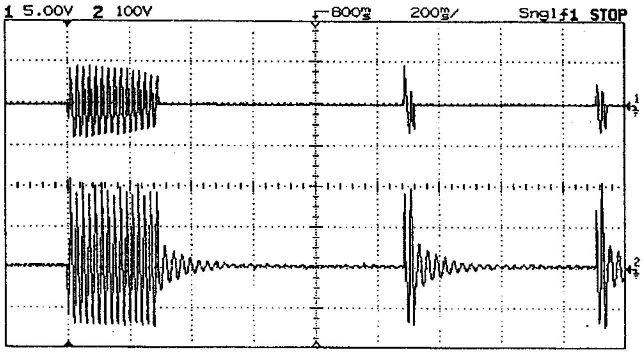
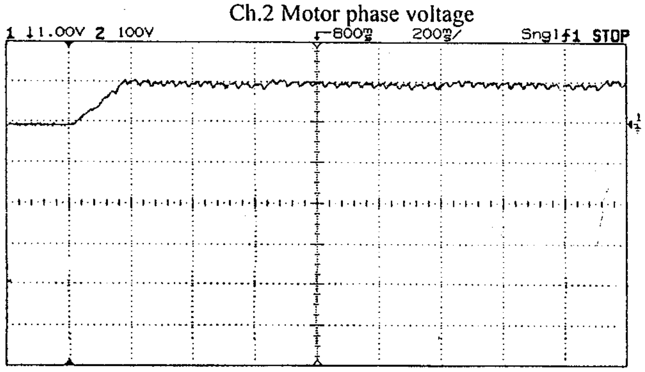


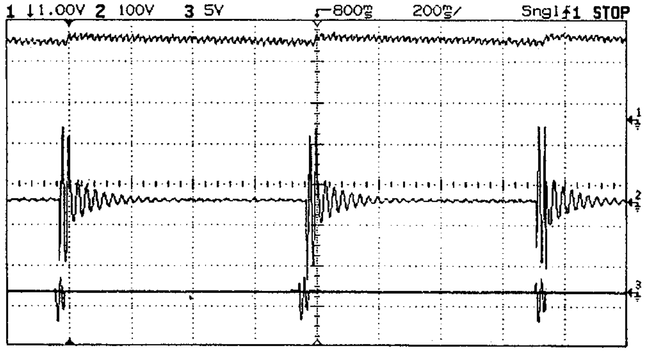
Fig.9 Motor speed during step change in load torque by 20% (Experimental results)



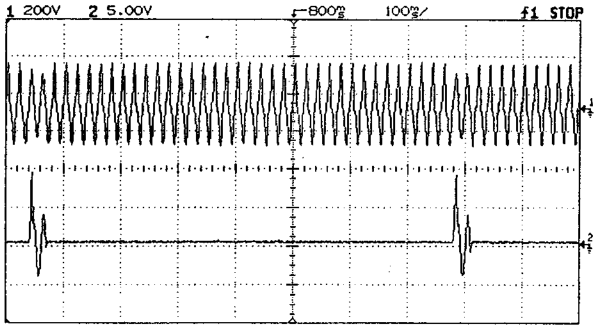
Ch.1 Motor phase current
Ch.2 Motor phase voltage



Motor speed

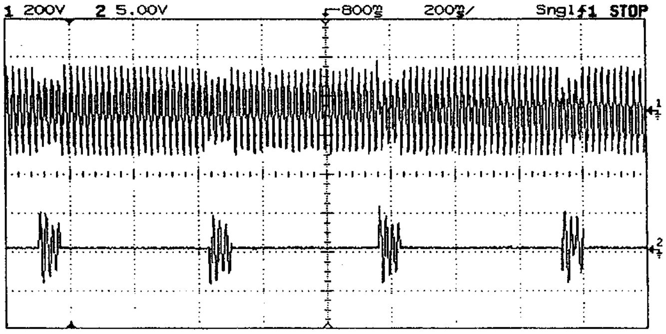


Ch.1 Motor speed Ch.2 Motor phase voltage Ch.3 Motor phase current

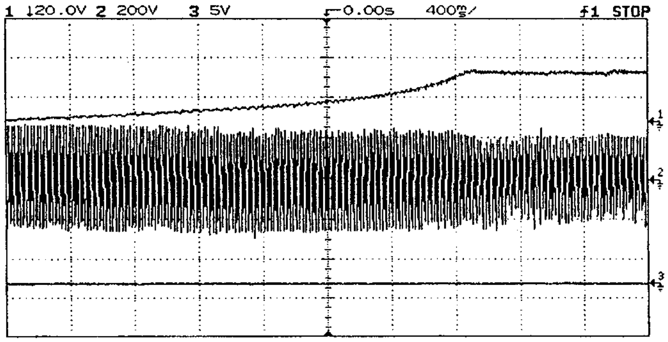


Ch.1 Supply phase voltage Ch.2 Supply phase current

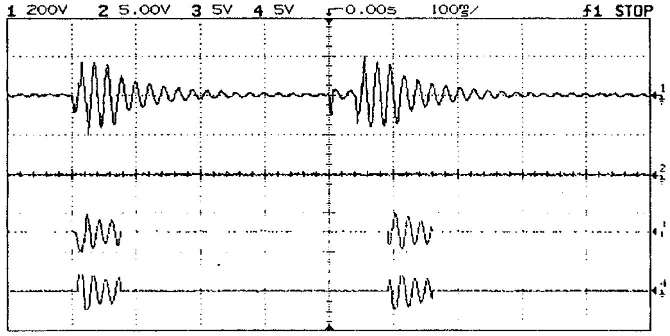
Fig.10 Motor performance at reference speed = 1000 r.p.m. and supply phase voltage =110 volt. (Experimental results)



Ch.1 Supply phase voltage Ch.2 Supply phase current in other connected phase

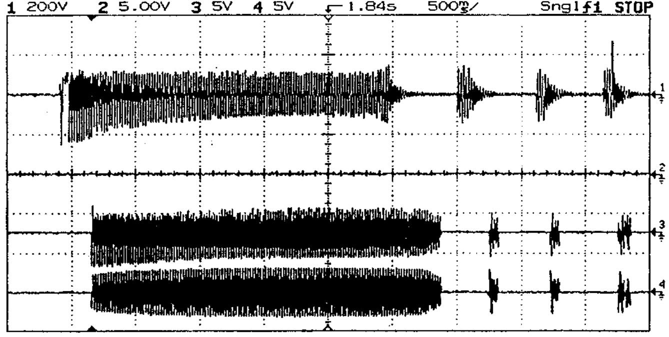


Ch.1 Motor speed Ch.2 supply phase voltage Ch.3 Supply phase voltage in fault phase



(a) Steady state response

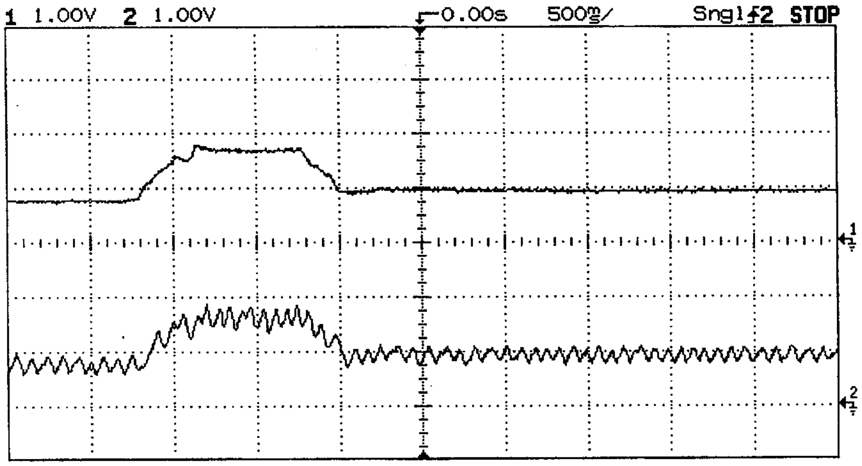
Ch.1 Motor phase voltage Ch.2, Ch.3 and Ch.4 Motor phases currents



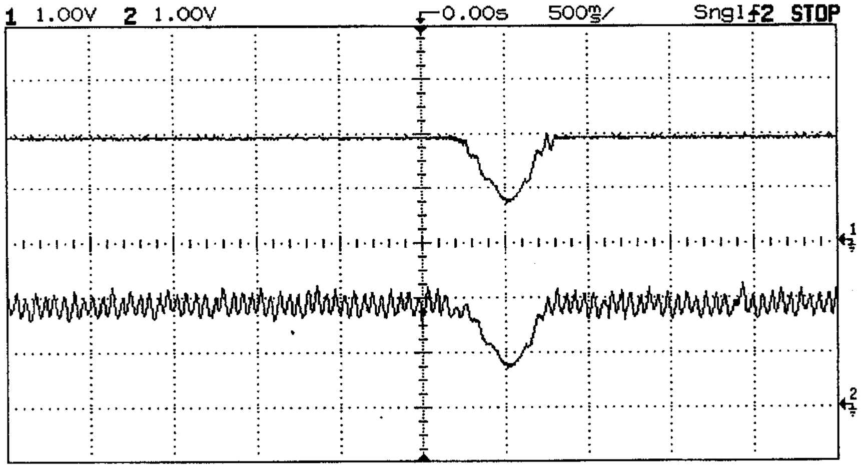
(b) Transient response

Ch.1 Motor phase voltage Ch.2, Ch.3 and Ch.4 Motor phases currents

Fig. 11 Experimental results at reference speed = 1400 r.p.m. and a supply phase fault is occurred



Ch.1 Reference (command) speed
Ch.2 Motor speed



Ch.1 Reference (command) speed
Ch.2 Motor speed
Fig.12 Transient response of motor speed (Experimental result)

التحكم المحكم فى سرعة محرك حثى ثلاثى الأوجه بإستخدام الميكروكمبيوتر

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قسم الهندسة الكهربية – كلية الهندسة بشبين الكوم – جامعة المنوفية

الملخص

يتناول هذا البحث نظام مقترح للتحكم فى سرعة محرك حثى ثلاثى الأوجه بإستخدام الميكروكمبيوتر وبإستخدام طريقة تحكم تجمع بين التحكم الوجهى والتكاملى من أجل ضبط تغذية الترانزستورات من النوع MOSFETs حيث يتصل كل ترانزستورعلى التوازى مع قنطرة مكونة من أربعة دايود متصلة على التوالى مع أحد أوجه المحرك. من أجل ضبط سرعة المحرك طبقا للسرعة المحددة (المطلوبة) يتم تغذية الثلاث ترانزستورات وفقا لطريقة Hysteresis control .

تم تسجيل النتائج المعملية للنظام المقترح (سرعة المحرك، تيار المحرك، الجهدالكهربى لأوجه المحرك .....إلخ) عند حالات تشغيل مختلفة للمحرك. تم تصميم برامج للتحليل النظرى للنظام المقترح ثم تم مقارنة نتائاج التحليل النظرى مع النتائج المعملية التى حصلنا عليها ووجد تطابق إلى حد كبير بين النتائج العملية والنظرية. وعليه فإن النظام المقترح يمتاز بالفاعلية والدقة .