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VECTOR CONTROL OF THREE PHASE INDUCTION MOTOR FED FROM TWO PHASE PULSE WIDTH MODULATION

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ABSTRACT:

The possibility of feeding a three phase induction motor by 60° two phase P.W.M. supply (by means of four-switches inverter) is presented in this paper in order to minimize the cost of the conventional three phase inverter (six-switched inverter). The main goal of this paper is to implement the idea of the control system of a three phase induction motor fed by two phase inverter using field oriented technique. The implemented control algorithm permits the motor to operate under the dynamic and steady state conditions. Finally, simulated results of the motor under control are presented.

يقدم هذا البحث تغذية محرك تاثيرى ثلاثي الأوجه من مغير بوجهين عن طريق أربعة مفاتيح الكترونيـــة وذلــك باستخدام إستراتجية المجال الموجة كتقديم جديد للتحكم وعند استخدام أربعة مفاتيح الكترونية يمكن بــذلك تقليــل التكلفة للمغير وذلك بالمقارنة مع المغير العادي المستخدم فيه ستة مفاتيح الكترونية وعلاوة على ذلك تمتاز دائــرة التحكم بالمغير ببساطتها وذلك نتيجة لحذف مفتاحين من الستة مفاتيح.

يقدم هذا البحث طريقة تصميم المحكم الذي يمكن بواسطته أن يعمل المحرك تحت الحالات الديناميكيـــة وحـــالات الاستقرار المختلفة وتم عرض نتائج التمثيل العددي للمحرك باستخدام التحكم المقترح في حالات التشغيل المختلفة.

Keywords : Vector control, Two phase inverter.

1. INTRODUCTION

Field oriented control enables induction motors to have characteristics similar to that of a separately Excited dc motor. In this method, the torque and the flux components of the current are identified and control is applied to them. The model of three phase induction motor is presented, this model can be implemented in the microprocessor which serves as a state observer of different variables of the motor that may be difficult to measure. Nowadays the vector control of an induction motor is widely employed in industrial applications where high performance torque control is required[1]. To develop the high performance vector control system, the following two points may be considered:

1- The exact information about the rotor flux vector to be available.

2- The actual stator currents have to be adjusted instantaneously and precisely according to their reference values.

The cost of the ac power converter exceeds that of the phase-controlled line commutated reversible converter for supplying dc machine, while the mechanical construction of the dc machine is complicated and expensive, but its control is straight forward due to the decoupled orthogonal field and armature axes. In constrat, ac machines are of simpler design. The aim of the vector control of ac machine is to obtain a control strategy similar to that of the dc machine[2].

The aims of this paper are to:

1- Model the three phase induction motor fed from two phase inverter .

2- Implement the control of the motor fed by two phase pulse width modulation (P.W.M.) source.

The modeling of the motor in field coordinates has been introduced by many authors[3] [4][5], while the main goal of this paper is to present the control of three phase induction motor fed by two phase P.W.M. source using the field-oriented concept.

2. MATHEMATICAL MODEL OF AC-MACHINE

The design of a.c. drive system requires a suitable mathematical model of the machine. The model should be simple and does not need all the details that should be required for design and building of the machine. On the other hand, the model should represent with adequate accuracy its important static and dynamic characteristics[4].

If the stator currents are sinusoidal and form a symmetrical three phase system, the current vector moves on the circular path with constant angular velocity. The geometric combination of the phase currents form the current vector $i_s(t)$, so that

$$\underline{i}_s(t) = i_{s1}(t) + i_{s2}(t)\, e^{j\gamma} + i_{s3}(t)\, e^{j2\gamma} \quad , \; \gamma = 2\Pi/3 \qquad (1)$$

The simplification of Equation (1) results in

$$\underline{I}_s(t) = 3/2\, i_{s1} + j\,(\sqrt{3}/2)\,[\, i_{s2}(t) - i_{s3}(t)]$$

$$= I_{sa}(t) + j\, i_{sb}(t) \qquad (2)$$

with the assumption of the sinusoidal distribution of the windings, the flux linkages may be computed as[6]

$$\underline{\Psi}_S(t) = Ls\, \underline{i}_s(t) + M\, \underline{i}_R(t)\, e^{j\varepsilon(t)}$$

and $\qquad (3)$

$$\underline{\Psi}_R(t) = L_R\, \underline{i}_R(t) + M\, \underline{i}_s(t)\, e^{-j\varepsilon}$$

where Ls, L_R, and M are the stator, rotor, and mutual inductances per phase, respectively and ε is the angle of rotation.

With these definitions the voltage equations can be written in vectorial form as follows :

$$\underline{U}s(t) = Rs\, \underline{i}_s + d\underline{\Psi}_{s1}/dt = Rs\, \underline{i}_s + Ls\, d\, \underline{i}_s/dt + M\, d\,(\underline{i}_R\, e^{j\varepsilon})/dt \qquad (4)$$

$$\underline{U}_R(t) = R_R\, \underline{i}_R + d\underline{\Psi}_{R1}/dt = R_R\, \underline{i}_R + L_R\, d\, \underline{i}_R/dt + M\, d\, \underline{i}_s\, e^{-j\varepsilon}/dt \qquad (5)$$

where Rs and R_R are the winding resistance per phase *of stator and rotor, respectively. The line to neutral* voltages applied to the terminal of the machine have also been combined to form a complex vector; that is

$$\underline{U}_s(t) = U_{s1}(t) + U_{s2}(t)\, e^{j\gamma} + U_{s3}(t)\, e^{j2\gamma} \qquad (6)$$

The electrical driving torque (m_d) created at the circumference of the motor becomes

$$m_d = = (2/3)\, Lm\, Im\, [\underline{i}_s(t)\, (\, \underline{i}_R\, e^{j\varepsilon})^*] \qquad (7)$$

and the mechanical motion of the stator is described by

$$J\, d\omega/dt = m_d(t) - m_L(t) = (2/3)\, Lm\, Im\, [\underline{i}_s(t)\, (\, \underline{i}_R\, e^{j\varepsilon})^*] - m_L(t) \qquad (8)$$

and,

$$d\varepsilon / dt = \omega \qquad (9)$$

where J is the rotor moment of inertia , mL is the *effective* load torque, and ω is the rotor angular velocity.

3. FIELD-ORIENTED PRINCIPLE

Because of the open loop flux control, it would be difficult to operate the machine with full torque at low speed or even standstill. In order to remove this restriction, it is necessary to return to the dynamic *model equations* of the induction motor.

The expression for the electrical (or drive) torque is

$$m_d(t) = (2/3)\, Lm\, Im\, [\underline{i}_s(t)\, (\, \underline{i}_R\, e^{j\varepsilon})^*] \qquad (10)$$

where ρ is the angle between stator axis and the magnetizing current vector.

This equation was obtained by describing the *interaction* between the rotor currents and the flux wave resulting from the stator currents. Since the rotor currents cannot be measured in cage rotors, it is appropriate to replace ($\underline{i}_R\, e^{j\varepsilon}$) with an equivalent quantity that could be measured with stator - based sensing equipment. A good choice, is the magnetizing current vector ($\underline{i}_{mR}(t)$) representing rotor flux, defined in stator coordinates,

$$\underline{i}_{mR}(t) = \underline{i}_s(t) + (1+\sigma_R)\, \underline{i}_R\, e^{j\varepsilon} = i_{mR}(t)\, e^{j\rho} \qquad (11)$$

Eliminating the rotor current from equation (10) results in,

$$m_d(t) = (2/3)\, (Lm/(1+\sigma_R)\, Im\, [\, \underline{i}_s\, (\underline{i}_{mR} - \underline{i}_s)^*]$$

which can be simplified to

$$m_d(t) = (2/3)\, (Lm/(1+\sigma_R)\, \underline{i}_{mR}\, Im\, [\, \underline{i}_s\, e^{-j\rho}]$$

With $Lm\, i_{mR} = \Phi_R$, and

$$\underline{i}_s\, e^{-j\rho}\, \underline{i}_s\, e^{j\delta} = i_{sd} + j\, i_{sq} \qquad (12)$$

where i_{sd} is the current in the direction of the magnetizing current and i_{sq} is perpendicular to it, represents the stator current vector as seen from a moving frame of reference which is defined by the magnetizing current vector i_{mR}. The angular relationship of the current vectors are depicted in Figure (1); the stator current vector in field coordinates is shown to consist of two orthogonal components.

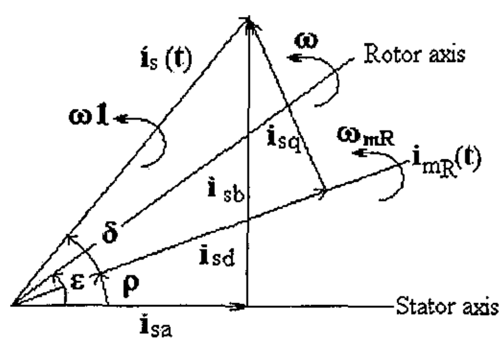

Fig 1. Angular relationship of current vectors.

That is

$$i_{sd} = \mathrm{Re}\,([\,\underline{i}_s\, e^{-j\rho}\,) = \underline{i}_s \cos(\delta)$$
$$i_{sq} = \mathrm{Im}\,([\,\underline{i}_s\, e^{-j\rho}\,) = \underline{i}_s \sin(\delta) \quad (13)$$

where δ is the angle between the magnetizing current vector and the stator current vector . In the steady state condition, i_{sd} and i_{sq} are constant apart from the converter induced ripple, i.e. the stator current vector $\underline{i}_s$ and the magnetizing current vector $\underline{i}_{mR}$ rotate in synchronism.

Then the torque equation becomes

$$m_d = K\, i_{mR}\, isq\ ,\quad K = (2/3)\,(Lm\,/\,(1+\sigma_R) \quad (14)$$

which gives the reason, why the transformation of the stator current vector into field coordinates, also called field orientation, is the key of rapid control of AC machine. This principle has been proposed by F.Blaschke [2], and Leonhard[3,4].

Equation (14) reminds us of the expression for the electrical torque of a dc machine (m_d = K Ia Φe), where i_{mR} corresponds to the main flux Φe, and i_{sq} to the armature current Ia. The magnetizing current i_{mR} will be controlled by the direct current i_{sd} of the stator current vector, which may be compared to the field voltage of the dc machine because there is also considerable magnetic lag between i_{sd} and i_{mR}.

In order to obtain the complete model of the AC machine in field coordinates, i_{mR} is now inserted into the rotor voltage, Equation (5) becomes,

$$R_R\, \underline{i}_R + Lm\, d\,[(1+\sigma_R)\, \underline{i}_R + \underline{i}_s\, e^{-j\varepsilon}\,]\,/\,dt = 0\ , \text{and}$$
$$\underline{i}_{mR}\, e^{-j\varepsilon} = [(1+\sigma_R)\, \underline{i}_R + \underline{i}_s\, e^{-j\varepsilon}\,]$$

which results in

$$T_R\, d\underline{im}_R\,/\,dt + j\, w_{mR}\, T_R\, \underline{i}_{mR} + (\,1 - jw\, T_R)\, \underline{i}_{mR} = \underline{i}_s\, e^{-j\rho} \quad (15)$$

where dε / dt = ω

The real part of equation (15) is,

$$T_R\, d_{imR}\,/\,dt + i_{mR} = i_{sd} \quad (16)$$

and the imaginary part is,

$$d\rho\,/\,dt = w_{mR} = w + i_{sq}\,/\,(\,T_R\, i_{mR}\,) = w + w_2 \quad (17)$$

Equations (14), (16), and (17), together with Equations (8) and (9) represent the mathematical model of a three phase induction motor in field coordinates which is known as current fed model.

The two field-oriented input currents i_{sd} and i_{sq} are produced by transforming the stator currents on the basis of the flux angle (ρ). This is achieved by first converting to an orthogonal two phase ac system (i_{sa}, and i_{sb}); that is

$$\underline{i}_s(t) = i_{s1}(t) + i_{s2}(t)\, e^{j\gamma} + i_{s3}(t)\, e^{j2\gamma} = i_{sa} + i_{sb} \quad (18)$$

with a condition of $i_{s1}(t) + i_{s2}(t) + i_{s3}(t) = 0$. This results in

$$i_{sa}(t) = (3/2)\, i_{s1}(t) \quad (19)$$

$$i_{sb} = (\sqrt{3}\,/2)\,[i_{s2}(t) + i_{s3}(t)\,] \quad (20)$$

the ac current are then , by transformation into field coordinates, converted to dc components

$$\underline{i}_s(t)\, e^{-j\rho} = (\,i_{sa} + j\, i_{sb}\,)\,(\,\cos(\rho) - j\sin(\rho) = i_{sd} + j\, i_{sq}$$

Hence, we have

$$i_{sd}(t) = i_{sa}\cos(\rho) + i_{sb}\sin(\rho) \quad (21)$$

$$i_{sq}(t) = -\, i_{sa}\sin(\rho) + i_{sb}\cos(\rho) \quad (22)$$

4. TWO PHASE INVERTER

The power inverter investigated here have four-switches supplying two phases to a three phase induction motor. Obviously the third phase of the motor is connected to the center tap of the dc voltage source as shown in figure (2)[7].

In this strategy, if we considered a three phase machine supplied by a three phase voltages U_A, U_B, & Uc, and if an additional voltage of UR (which is equal in magnitude and opposite in phase to Uc) is available in all phases, then two phase system is achieved which does not affect the current flow in the system as long as the star point remains floating. There is only one difference between the balanced system U_A, U_B, & Uc and the new system U_1, U_2 , which is that the fundamental voltages of the inverter U_1, and U_2 is greater than that of the fundamental voltages U_A, U_B, & Uc by the factor of √3 and the phase shift between U_1 and U_2 is 60° in order to obtain the same torque as in the normal case of three phase source (see figure 3).

If the load of 60° system U_1 and U_2 is a balanced phase machine, only positive sequence torque will be produced, while it is worthwhile noting that the voltages responsible for the machine stator excitation per phase are not changed and remain as in case of U_A, U_B, & Uc [7].

Consequently, the magnetic circuit of the machine,also operates under exactly the same conditions as with the balanced three phase system, although the voltages U_1 and U_2 have been increased by a factor of √3. It is noted that the machine magnetic field produced by 60° U_1 and U_2 system is a rotating field and of constant magnitude along the magnetic circuit of the rotor.

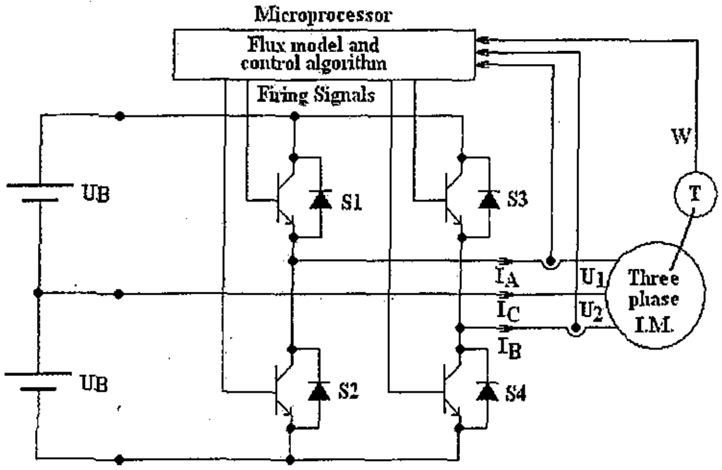

Fig 2. Four switches inverter.

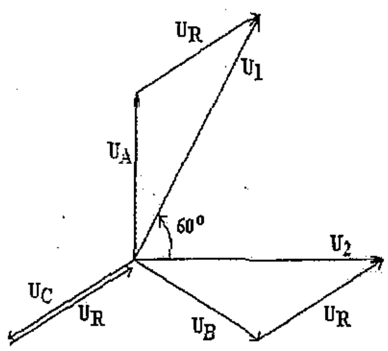

Fig 3. Phasor diagram for the generation of two-phase system.

In reference to the application of the two phase 60° system to the three phase I.M. model mentioned later, the 60° two phase U_1 and U_2 system must be transformed to an orthogonal two phase ac system U_{sa} and U_{sb} (differ from that of three phase source case) as follows,

$$U_{sa} = \sqrt{3}\, U_1 - \sqrt{3}/2\ U_2$$

And (23)

$$U_{sb} = 3/2\, U_2$$

5. CONTROLLER DESIGN STRATEGY

The machine model in the field orientation is reduced essentially to two flow paths, one for the flux governed by Equation (16) with i_{sd} as a control input, and the other for the torque governed byEquations (17) and (8) with control input i_{sq} together with imR, the rotor flux. The flux path in this model is similar to the field circuit, and the torque path is similar to the armature current circuit of a separately excited dc motor. As it is normally done in a dc motor, the flux level in the machine can be maintained at its maximum value, depending on the ac voltage available and the operating flux density of the motor, up to the base speed, above which it may be weakened.

Taking the mentioned points into account, and employing the strategy for designing the controllers implemented above, the controllers of the field and torque loops of the motor are shown in Figure (4) This method of control permits the motor to operate in dynamic and steady state conditions with excellent response.

6. RESULTS

The results introduced in this paper are obtained from the motor whose parameters are given in table (1). A sample result under field oriented control of a three phase induction motor fed by two phase inverter is illustrated in Figure (5), in which the motor starting up to 0.7 P.U. speed, and then the motor is stopped, in this latter case (speed=0) it is noted that some current exists, this current is corresponding to the field current i_{mR}. This case is important because when this motor is started again its response is better.

Table 1. *Motor parameters.*

Power = 1.5 KW, Phase = 3 V =380 V, F = 50 Hz
No. of poles = 4
Rs = 0.6 Ω , Ts = 0.104833 Sec , T_R = 0.15725 Sec.
K = 0.0394238 , J = 0.18 Kg.m2 , σ = 0.0595009 H

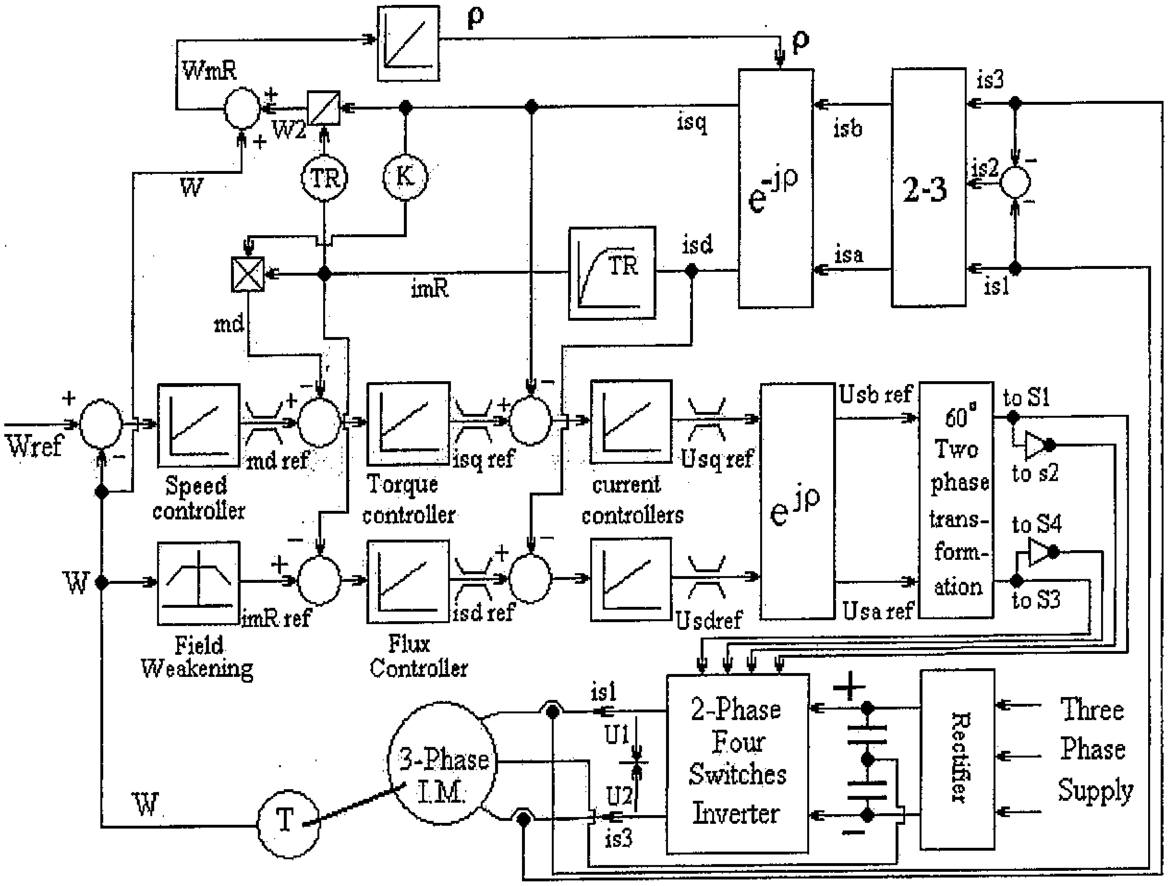

Fig 4. Block diagram of the controlled three phase induction motor fed by two phase P.W.M. source.

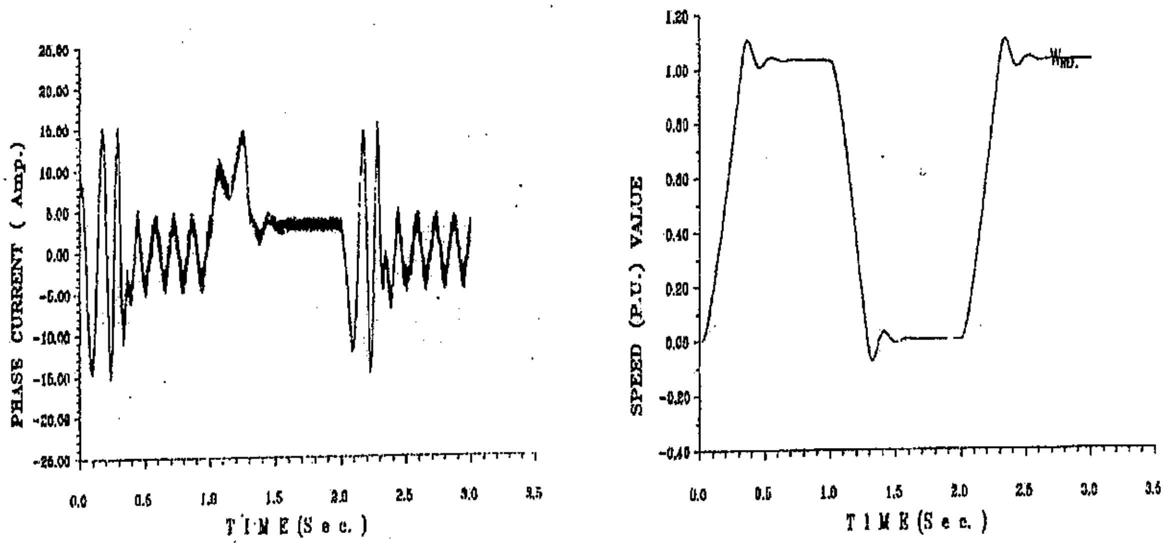

Fig 5. Starting up the controlled motor, then stopping and started again

7. CONCLUSIONS

Control of a three phase induction motor fed by two phase inverter using field oriented strategy is presented as a new idea in controlling this topology. Four switches inverter minimizes the conventional inverter cost and also simplifies its control circuit, because one leg of the six switches inverter is omitted.

The field oriented gives an excellent performance by manipulating the current components responsible for the torque and flux produced in the motor, hence the motor can be controlled in the same efficient manner of a separately excited dc motor.

A method of controller design in exact manner is introduced. Finally simulated results are introduced demonstrate and represent the effective control of the motor in multi mode to operation.

8. REFERENCES

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