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Farouk Abdel Kader
Suez Canal University, Faculty of Engineering P.O.Box 42523, Port Said, Egypt

Hassan Eldeeb
Suez Canal University, Faculty of Engineering P.O.Box 42523, Port Said, Egypt

Ahmed Kalas
Suez Canal University, Faculty of Engineering P.O.Box 42523, Port Said, Egypt

M. Dessouki
Suez Canal University, Faculty of Engineering P.O.Box 42523, Port Said, Egypt

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Field Oriented Control of Hybrid Stepping Motor

التحكم الاتجاهى فى محرك الخطوة الخليط

Prof. Dr. Farouk M. Abdel Kader **Prof. Dr. Hassan E. Eldeeb**

Dr. Ahmed E. Kalas **Eng. M. El Shahat Dessouki**

Suez Canal University, Faculty of Engineering
P.O.Box 42523, Port Said, Egypt

ملخص البحث

يعتبر التحكم فى الموضع هو المجال الرئيسي لتطبيقات محركات الخطوة، وأنه يتم استخدام نظام التحكم اللامرجعى فى معظم هذه التطبيقات حيث أنها تناسب العديد من التطبيقات، ولكن فى التطبيقات التى تحتاج الى دقة عالية نجد أن هذه المحركات باستخدام هذه الطريقة تبدى آداء سيئ، وكذلك عدم القدرة على الاتباع الدقيق لنبضات دائرة التحكم.

يتجه هذا البحث الى تغيير استراتيجية أساليب التحكم فى هذه المحركات عن طريق استخدام التحكم فى توجيه المجال، آخذين فى الاعتبار مبادئ هذا الأسلوب من محركات التيار المتردد، حيث أن التحكم الاتجاهى فى محركات التيار المتردد أصبح طريقة قياسية لما تبديه هذه الطريقة من أداء عالى.

ولتطبيق هذا الأسلوب تم استنتاج نموذج مناسب للتحكم الاتجاهى وذلك عن طريق إلغاء مركبة الفيض العمودية ومن ثم يمكن تعظيم العزم وكذلك الحصول على سرعات عالية.كما تم تنقية الجهود الداخلة الى المحرك وذلك لتقليل التوافقيات التى تحتويها تلك الجهود نتيجة لطبيعة دائرة التشغيل والتى بدورها تحدث تذبذب فى كلا من منحنى العزم والسرعة للمحرك.

تم محاكاة هذا النموذج باستخدام برنامج Matlab Simulink Toolbox وعمل مقارنة لأداء المحرك فى حالات التحكم المذكورة وقد أظهرت النتائج أداء عالى للمحرك بتطبيق نظام التحكم الاتجاهى.

Abstract

The strategy of controlling the stepping motor is changed in this research using the field oriented control, by taking over control principles from a.c motors. In this purpose two-phase rotor oriented mathematical model of the motor is deduced. Then the new control strategy of the self-commutated motor, based on active current control is proposed the effect of this control strategy with and without filtered voltages have been studied by numerical simulation using matlab simulink toolbox.

Introduction

It is well known that position control is the main field of the stepping motors applications. Stepping motors are receiving wide attention in industrial applications, which require high performance. Stepper motor with open loop position control are very well suited to many fields of application, but they show a poor performance with respect to very precise motion control and high dynamic requirements. So a closed loop control is required to increase the accurate positioning of the stepping motor. It is difficult to control the complicated systems by using the traditional closed loop control theory, such as PID control is weak, because these algorithms are not sensitive enough when confronted by mechanical configuration changed. To improve motor performances, new control strategy is deduced based on field orientation principle of synchronous machines[1-2]

The hybrid stepping motor it consists of an 8-pole laminated stator and a laminated rotor built by two sectors (A and B) separated by a cylindrical axially oriented permanent magnet. The two rotor sections have toothed structure shifted between them by a half-a-tooth pitch. Each stator pole is bifilar wounded, successive poles of each phase are wounded in the opposite sense. The stator winding can be conneeted in a few modes (star,series or parallel connection) so that 4-phase or 2-phase machines are resulted. Choosing star conneetion of the stator windings, an equivalent four-phase synchronous machine with constant air gap and one pole pair is obtained as shown in Fig.1. [3], [4] and [5]

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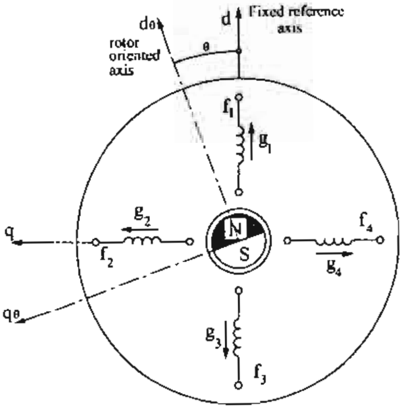

Fig. 1 equivalent constant air gap

Two phase rotor oriented mathematical model

The implementation method of field orientation control is based on the space-phasor theory in this purpose the definition of the space phasor according to the phase number of stepping motor has to be given. The space phasor $\bar{g}$ corresponding to four phase system of magnitudes g_1, g_2, g_3 and g_4 where $\bar{g}$ can be stator current i_s, voltage V_s or flux ψ_s is given by [6]:

$$\bar{g} = \frac{2}{k}\sum g = \frac{1}{2}(g_1 + jg_2 - g_3 - jg_4) = g_d + jg_q \qquad (1)$$

Where:

g_d and g_q	are the components in the complex plane.
k	is the number of phases

The homopolar components g_{0+} and g_{0-} needed for the transformation of 4-phase system into 2-phase system are calculated with the expressions

$$g_{0+} = \frac{1}{4}(g_1 + g_2 + g_3 + g_4) \qquad (2)$$

$$g_{0-} = \frac{1}{4}(g_1 - g_2 + g_3 - g_4) \qquad (3)$$

The two systems can be linked to each other in a matrix form by using the definition of the space-phasor matrix $[\bar{g}]$ as follow:

$$[\bar{g}] = \begin{bmatrix} \bar{g} \\ \bar{g}^{*} \\ g_{0+} \\ g_{0-} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & j & -1 & -j \\ 1 & -j & -1 & j \\ 1/2 & 1/2 & 1/2 & 1/2 \\ 1/2 & -1/2 & 1/2 & -1/2 \end{bmatrix}\begin{bmatrix} g_1 \\ g_2 \\ g_3 \\ g_4 \end{bmatrix} = \begin{bmatrix} 1 & j & 0 & 0 \\ 1 & -j & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} g_d \\ g_q \\ g_{0+} \\ g_{0-} \end{bmatrix} \qquad (4)$$

Which can be written as:

$$[\bar{g}] = [\bar{a}_4][g]_4 = [\bar{J}_4][g]_2 \qquad (5)$$

Hence the formulae of system transformations from 4-phase system into 2-phase and vice verse are

Where $[g]_2 = [A_4][g]_4$ and $[g]_4 = [A_4]^{-1}[g]_2$ (6)

$[A_4] = [J_4]^{-1}[a_4]$ and $[A_4]^{-1} = [a_4]^{-1}[J_4]$ (7)

a rotational operator $[D_4(\theta)]$ is used to change the fixed stator d-q system into rotational dθ-qθ system as follows:

$$[g]_{2\theta} = [D_4(\theta)][g]_2 \tag{8}$$

where
$$[D_4(\theta)] = \begin{bmatrix} \cos\theta & \sin\theta & 0 & 0 \\ -\sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}$$

The mathematical model of the stepping motor in dθ-qθ system of axes is given by expressions:

$$[V_s]_{2\theta} = R_s[i_s]_{2\theta} + Z_r\omega_m[Q][\psi_s]_{2\theta} + \frac{d}{dt}[\psi_s]_{2\theta} \tag{10}$$

$$[\psi_s]_{2\theta} = [\psi_{ss}]_{2\theta} + [\psi_{mr}]_{2\theta} \tag{11}$$

$$[\psi_{ss}]_{2\theta} = [L_s]_{2\theta}[i_s]_{2\theta} \tag{12}$$

where ω_m is the rotor angular speed, Z_r is the no. of rotor teeth, $[L_s]_{2\theta}$ is the matrix of inductivities, $[\psi_{ss}]_{2\theta}$ is the armature reaction flux and $[\psi_{mr}]_{2\theta}$ is the PM flux in the air gap.

The matrix $[Q]$ is deduced from $[Q] = [D_4(\theta)]\, {}^{d}\!/_{d\theta}\, [D_4(\theta)]^{-1}$ (13)

while the electomagnetic torque becomes:

$$T_e = 2Z_r(\psi_{sd\theta} i_{sq\theta} - \psi_{sq\theta} i_{sd\theta}) \tag{14}$$

where indexes sdθ and sqθ refer to rotor oriented system of axes dθ-qθ.

Vector control strategy

The orientation of the d-axis is chosen on the flux axis while q-axis is π/2 ahead in the rotation direction. The phasor diagram shown in figure 2 corresponds to the classically controlled stepping motor.

In this figure Ψ_M represents the permanent magnet flux phasor, Ψ_{ss} the reaction flux phasor and i_s denotes the stator current phasor. As is observed, when the mechanical load is increased, the direct axis flux is affected by the longitudinal reaction flux of the stator current $\Psi_{ssd\theta}$. This influence consists in the saturation effect or in demagnetization of permanent magnet and consequently it tends to diminish the electromagnetic torque.

In order to eliminate these negative effects and to optimize the motor operation from the point of view of the electromagnetic torque, the perpendicularity of the stator current phasor i_s upon the ecitation flux axis dθ is imposed [2] and [5]. This occurs when longitudinal reaction flux of the stator current Ψssdθ is nulled out (Ψssdθ = 0 i.e isdθ = 0) and therefore a new phasor diagram of the motor is obtained as is indicated in figure 3. Hence for optimal control the components of the phase currents, respectively of fluxes become:

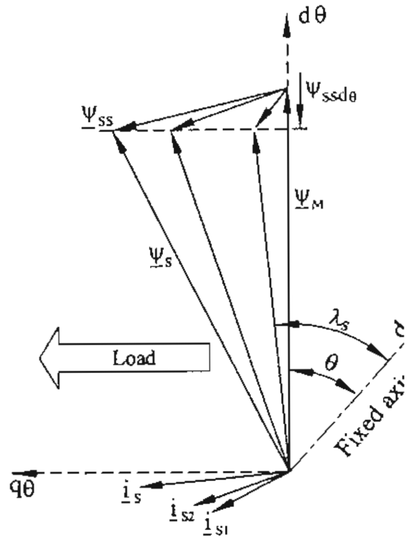

Fig. 2 phasor diagram of uncontrolled motor

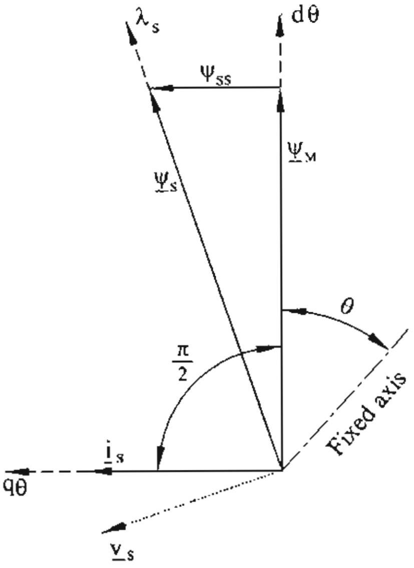

Fig. 3 phasor diagram of vector controlled motor

$$
\begin{aligned}
&isd\theta = 0\\
&isq\theta = is = iA \qquad (15)\\
&\Psi sd\theta = \Psi_M = \text{const.}\\
&\Psi ssd\theta = L\ is = L\ iA
\end{aligned}
$$

Hence the expression of torque equation (14) will be simplified to:

$$T_e = 2\, Z_r\, \Psi_{sd\theta}\, i_{sq\theta} = 2\, Z_r\, \Psi_M\, i_s \qquad (16)$$

The configuration of field-oriented control for the 4-phase hybrid stepping motor system based on self commutation principle is shown in figure 4. The rotor oriented magnitudes are deduced using rotational operator expressions (8) and (9) as follows:

$$[\, i_s\,]_{2\theta} = [\, D(\theta)\,]\, [i_s\,]_2 \qquad (17)$$

which the active component $i_{sq\theta}$ of the phasor i_s is deduced:

$$i_{sq\theta} = i_{sq} \cos\theta - i_{sd} \sin\theta \qquad (18)$$

self commutation of the motor is achieved by maintaining the active component of the current (i_A) and cancelling the reactive one, thus the space phasor of the stator current i_s will be perpendicular to the excitation flux phasor. Hence the reference currents in rotor oriented system will be:

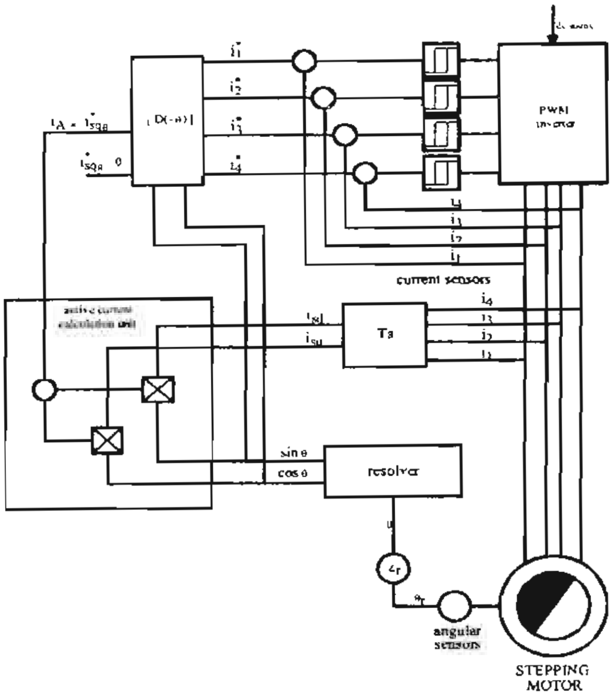

Fig. 4 vector control block diagram of stepping motor

$$i^{*}_{sq\theta} = i_{sq\theta} \qquad \text{and} \qquad i^{*}_{sd\theta} = 0 \tag{19}$$

where the asterisc " * " marks reference magnitudes.
Reference currents in stator fixed orthogonal system of axes are obtained as follows:

$$[i_s]_2 = [D(-\theta)][i_s]_{2\theta} = [0 \quad i^{*}_{sq\theta} \quad 0 \quad 0] \tag{20}$$

where

$$[D(-\theta)] = [D_s(\theta)]^{-1} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{21}$$

and consequently the reference currents can be obtained by using the following equation:

$$[\, i_s \,]^{*}_{4} = [\, A_4 \,]^{-1} [\, i_s \,]^{*}_{2} \tag{22}$$

$$[\, i_s \,]^{*}_{4} = i^{*}_{sq\theta}\, [-\sin\theta, \cos\theta, \sin\theta, -\cos\theta]^{t} \tag{23}$$

these reference currents are compared with the actual currents and the produced current error are processed by current controller and the produced signals are used to gate the inverter switches to force the motor current to follow as closely as possible the reference currents.

these reference currents are compared with the actual currents and the produced current error are processed by current controller and the produced signals are used to gate the inverter switches to force the motor current to follow as closely as possible the reference currents.

Simulation results

The control system is tested by numerical simulation by using matlab simulink toolbox, taking into account the deduced field oriented model of the motor.

Fig. 5 shows the simulated and reference current for phase-1 of the hybrid stepping motor it is noted that the stepping motor draws a sinusoidal current, and the simulated current follows the reference one.

Fig. 6 shows the wave forms of the phase current and voltage. As is expected, phase current oscillations occur as effect of PWM inverter, which switches each phase to d.c. source at a frequency that depends mainly on the hysteresis width of the current comparators, on the motor phase time constant and also on the feeding voltage magnitude. Fig. 7, 8 and 9 illustrate the dynamic behaviour of the motor.

As shown from Fig. 8 and Fig.9 respectively, the motor torque and motor speed contain oscillations due to the expected phase current oscillations result from the effect of PWM inverter. To reduce the effect of harmonics content, the voltages input to the motor are filtered by using a lowpass filter is used to eliminate high frequencies content in the motor voltages.

A comparitive study of dynamic characterestics of hybrid stepping motor under open loop control, vector control without filter and vector control with filter is perfoemed. As illustrated in fig. 10-12 the oscillations content in the hybrid stepping motor torque and speed are reduced after filtering the motor input voltages also in steady state higher speed is achieved duc to the effect of the optimal control of the torque.

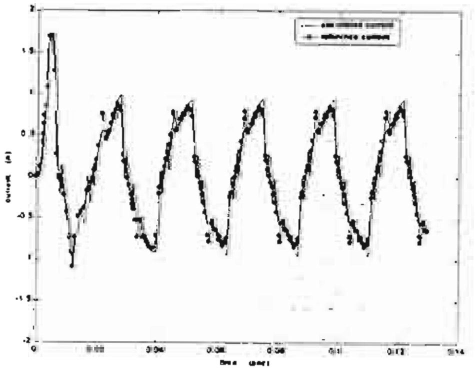

Fig. 5 Simulated and reference current for phase 1

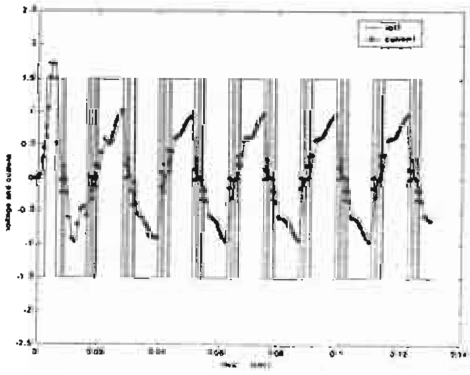

Fig 6 The simulated voltage and current for PMHSM

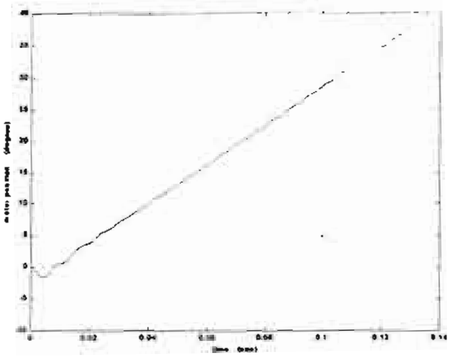

Fig. 7 The position of hybrid stepping motor

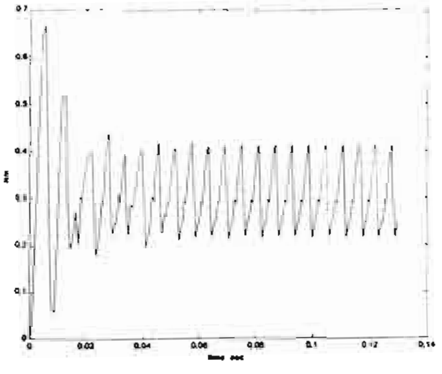

Fig. 8 The torque of hybrid stepping motor

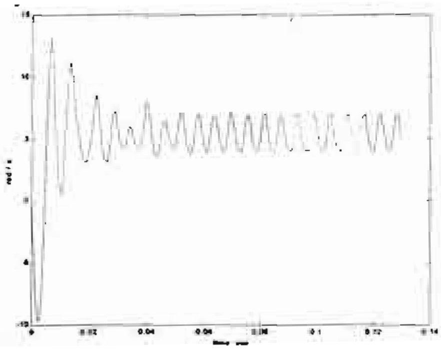

Fig. 9 The speed of hybrid stepping motor

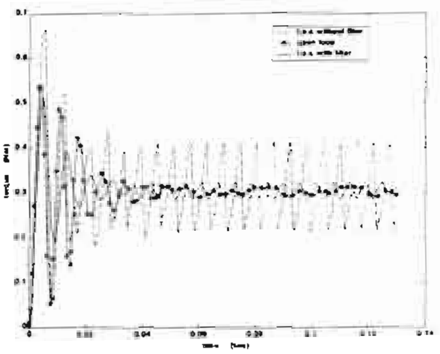

Fig. 10 HSM torque under different control schemess

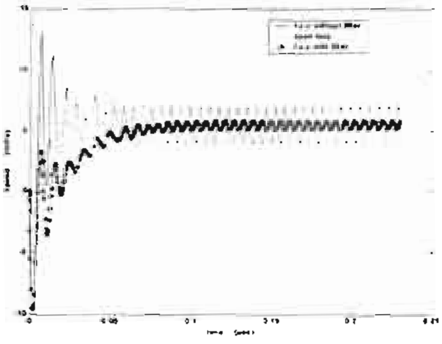

Fig. 11 HSM speed under different control

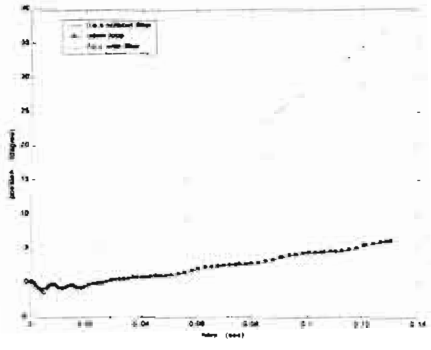

Fig. 12 HSM position under different control

Concolusion

Field oriented control for hybried stepping motor ensures maximum electromagnetic torque for any operational state of the motor because it avoids rotor demagnetizing by the reaction flux, based on establishing the perpendicularity of the current phasor onto the rotor direct axis. therefore the two phase components of the current are calculated for optimal control and then they converted into real four phase reference currents.

Field oriented control with filtered input voltages gives the best dynamic behavior in comparison with both open loop control and field oriented control without filtred input volteges. The oscillations produced in motor speed and motor torque are reduced in case of field oriented control with filtered input voltages.

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