PULSE WIDTH MODULATION FOR HIGH PERFORMANCE HYBRID STEPPER MOTOR

Prof. Dr. Qais S. AL- Sabbagh **M.Sc. Student Ali Sabah Mahdi**

College of Engineering/ University of
Baghdad, Iraq- Baghdad

الخلاصة

هذا البحث يقوم بتنفيذ طريقة السيطرة الأتجاهية العالية الأداء لسيطرة على تيار وسرعة محرك الخطوة الهجين (HSM) لتحسين الأداء الديناميكي لهذا المحرك. هذه الفائدة الأساسية من محركات الخطوة على غرار الأنواع الأخرى من المحركات. طريقة السيطرة ذات الحلقة المفتوحة تبين أداء ديناميكي سيء. أن محركات الخطوة كثيرة الأستعمال في الحركات الدقيقة التي تتطلب ديناميكية عالية. على أية حال، طريقة السيطرة ذات الحلقة المفتوحة غير كافية، لذا طريقة السيطرة ذات الحلقة المغلقة تكون مطلوبة. طريقة السيطرة الأتجاهية سوف تحسن الأداء الديناميكي للمحركات الخطوة. تم تصميم وتنفيذ نموذج محرك الخطوة الهجين HSM بأستخدام برنامج MATLAB/ SIMULINK. أن نموذج HSM مستند على الدوائر المكافئة اللاخطية الذي تمثل عمل المحرك. تم مقارنة نتائج المحاكاة للمحرك الهجيين (HSM) مع نتائج الدائرة العملية (RDK) وتم الحصول على أتفاق قريب في النتائج.

ABSTRACT

This paper presents a high performance vector control approach of the current and speed for Hybrid Stepper Motor (HSM) to improve the dynamic performance of the motor. This is the basic advantage of stepper motors over other types of motors. The open loop controller shows a poor dynamic performance. The stepper motors are widely used in precise motions which is required a high dynamic. However, an open loop control is insufficient, so a closed loop control is required. The field oriented control will improve the dynamic performance of the stepper motor which becomes as

a high- dynamic ac- servo. A design and implementation model of HSM using in MATLAB/ Simulink is given. The model is based on nonlinear equivalent circuits representing the operation of the motor. The simulation results of the HSM are compared with practical results of reference design kit (RDK) stepper motor, and a close agreement is noticed.

INTRODUCTION

The HSM is used in many applications [1], such as robotics system, printers and consumer electrics. The HSM is a double salient machine which incorporates a permanent magnet in the robots as described in [2]. Stepper motors are a class of electromechanical device used to produce discrete or non-continuous motion. Stepper motor fall within a broader class of devices known as incremental motion devices, which include incremental actuators and other digital control devices used in motion control. Stepper motor is a synchronous motor with the magnetic field controlled by using electronic switches to rotate the rotor [3]. The theory of stepper motor is similar to a permanent magnet synchronous motor. The motor rotation not only has a direct relation to the number of the input pulses, but its speed is related to the frequency of the pulses [1]. However, precise position, velocity, or acceleration control is required and when very small steps of control are necessary, electrical stepper motors have many advantages.

In the open loop control, the HSM can produce only 50% of its nominal torque. A large torque reserve is required to overcome any load variation. In this classical control scheme there is no feedback of load position to the controller. The motor must response to each excitation change. If the excitation changes are made too quickly the stepper motor can lose steps and, therefore, it is unable to move the rotor to the new demanded position. So a permanent error can be introduced between load position and position expected by the controller. All these limitations can be overcome with a closed loop controller. In this case, the motor requires a rotor position sensor for providing the proper commutation sequence.

In the classical control scheme the stepper motor is driven by a discrete sequence of current pulses. Regular stepping introduces large overshoot, resonance and **torque** ripple problem which have plagued the stepper motor for a long time. In order to reduce these problems, a micro-step excitations are applied to inject various ratio currents into phase coils. So the position resolution will be improved [4]. The HSM is a two phase synchronous machine and can be driven as the permanent magnet synchronous motor (PMSM). A better performance of the HSM can be obtained by driving it with field oriented control (FOC), rather than stepping [5]. In this paper, we present experimental results of the field oriented control for a new speed and position estimation strategy of HSM drive. Finally, a simulation of the nonlinear model of the HSM is done. The simulation and experimental results show the validity of the proposed vector control approach.

- MATHMATICAL MODEL OF HSM

The motor considered in this paper is a two phases HSM with the following assumptions:

- Non-salient pole structure (uniform air gap).
- Sinusoidal winding distribution, i.e. (sinusoidal flux distribution).
- Negligible magnetic saturation and iron losses.
- Constant self inductances.

With these assumptions, the equivalent model of the HSM with two- phases winding on the stator and no windings on the rotor is shown in Fig.1.

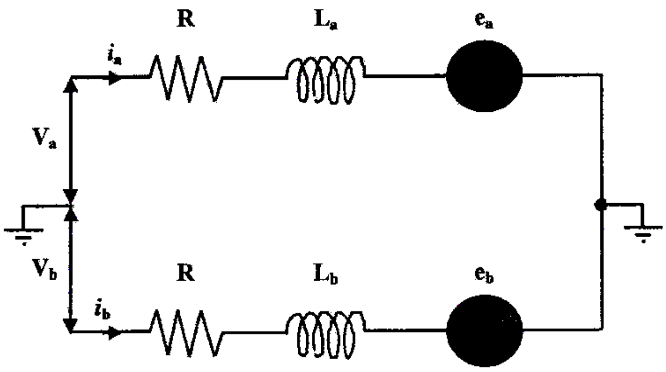

Fig.1. The equivalent circuit of a two phase HSM.

The HSM can be described by a set of voltage differential equations [6].

$$v_a = \mathbf{R}\, i_a + \mathbf{L}\ \mathbf{d}\, i_a \mathbf{/dt} - \mathbf{Km\ w}_m\ \mathbf{sin(Nr}\ \theta_m\mathbf{)} \qquad \mathbf{(1)}$$

$v_b = R\, i_b + L\, d i_b /dt + Km\, w_m \, \sin(Nr\theta_m + 90)$ (2)

Where,

i_a and i_b = Current in phase (a) and phase (b) (A).

v_a and v_b = Voltage in phase (a) and phase (b) (V).

R = Resistance in each phase (ohm).

L = Self inductance in each phase (h).

Nr = Number of stator pole.

Km = Motor torque constant.

w_m = Mechanical angular speed of the rotor (Rad/Sec).

θ_m = Mechanical angle of the rotor (Rad).

The electromagnetic torque in the air gap is given by the following equation:

$Km\,(-i_a \sin(Nr\,\theta_m) + i_b \sin(Nr\,\theta_m + 90)) - TL = J dw_m / dt + B w_m$ (3)

Where,

TL = Load torque (Nm).

J = Moment of inertia ($kg.m^2$)

B = Viscous friction coefficient (Nms/R).

Finally, the equation for angular velocity of the rotor completes the HSM model:

$w_m = d\theta_m / dt$ (4)

The relationship between electrical and mechanical angle (position) of the rotor is given by:

$\theta_e = Nr\,\theta_m$ (5)

The mathematical model of HSM in (a-b) reference frame called (stator reference frame) is not suitable for speed control process, because the model has time varying quantities (voltage, current, and mutual inductances) that can lead **to make solution** of motor equation is very complicated. It is possible to eliminate time varying quantities by using the Park transformation while allows conversion of the stationary reference frame fixed on the stator (i.e. (a-b) components) into reference frame fixed on the rotor (i.e. (d-q) components), where (d) stand for direct axis and (q) for quadrature axis. The (d-q) reference frame can obtained by rotates (a-b) reference frame by an electrical rotor position (Nr θm) as shown in Fig.2.

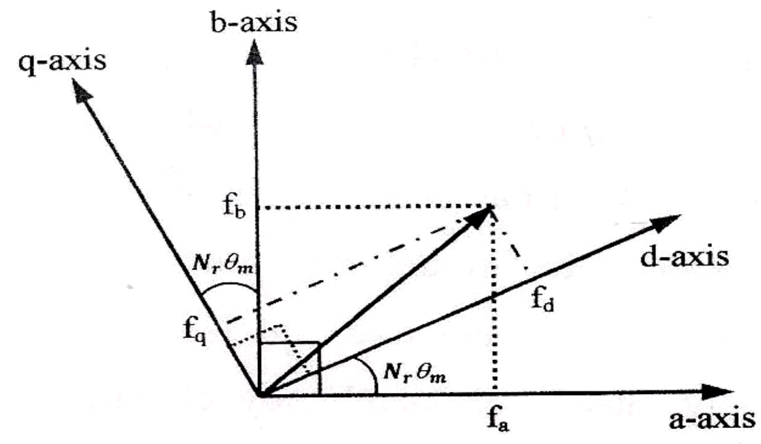

Fig. 2: Transformation of (a-b) to (d-q) reference frame.

The equation of Park transformation can be expressed as [7].

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = K_s^e \begin{bmatrix} f_a \\ f_b \end{bmatrix} \tag{6}$$

Where, (k_s^e) is the Park transformation matrix which is given by:

$$K_s^e = \begin{bmatrix} \cos(\mathrm{Nr}\theta_{\mathrm{m}}) & \sin(N_r\theta_m) \\ -\sin(N_r\theta_m) & \cos(N_r\theta_m) \end{bmatrix} \tag{7}$$

Now, multiply equation (1) through (4) by Park transformation and rearrange these equations to obtain new model HSM in (d-q) reference frame as:

$$v_{ds} = \mathrm{R}\ i_{ds} + \mathrm{L}\ \frac{di_{ds}}{dt} - \mathrm{L}\ \mathrm{N}_r\ \omega_m\ i_{qs} \tag{8}$$

$$v_{ds} = \mathrm{R}\ i_{qs} + \mathrm{L}\ \frac{di_{qs}}{dt} + \mathrm{L}\ \mathrm{N}_r\ \omega_m\ i_{ds} + \mathrm{K}_m\ \omega_m$$
(9)

$$\mathrm{K}_m\ i_{qs} - \mathrm{T}_l = \mathrm{J}\ \frac{d\omega_m}{dt} + \mathrm{B}\ \omega_m \qquad \textbf{(10)}$$

$$\frac{d\theta_m}{dt} = \omega_m \qquad \textbf{(11)}$$

- VECTOR CONTROL PRINCIPLE

During the past decade, several authors have presented the principles of vector control of AC motors [3, 8]. However, the vector control principle consists of controlling the angle and amplitude components of the stator field. For ease of motor equation representation, the components of the stator current are represented in a rotating reference frame (d-q) aligned with the rotor axis, i.e., with the magnet flux. The motor torque for a permanent magnet machine as in HSM depends only on the quadrature (q) current (torque) component. In this case, the most convenient control strategy is to set to zero the direct (d) current components to minimize the torque versus the current ratio and then increase the motor (and converter) efficiency. The control of current components requires the knowledge of the instantaneous rotor position. It can be seen that field orientation can be implemented when the winding current are adjusted so as to produce a current space vector that lies exclusively in the quadrature direction by setting direct current component equal to zero (id = 0). Torque will then be proportional to the magnitude of the current space vector. The block diagram of the proposed method of vector controlled HSM is shows in Fig. 3.

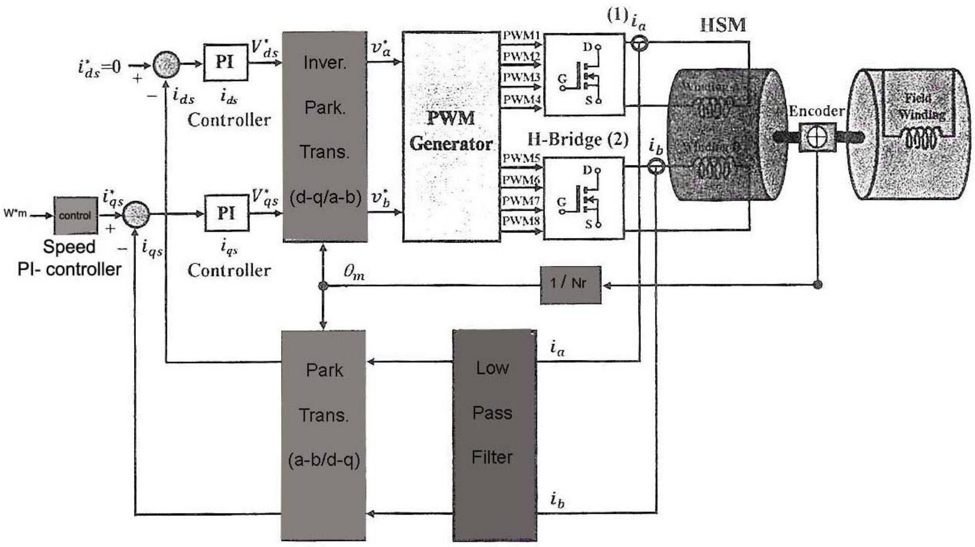

Fig. 3: Block diagram of vector controlled HSM [3].

This vector control scheme consists of a speed PI controller and two current PI controllers in the synchronous reference frame. The rotor speed is measured using encoder and the rotor position is calculated by integrating rotor speed (1/Nr) with respect to time. A low Pass Filter (LPF) has been used to eliminate the effect of unwanted high frequency signals that may be introduced during the measurements processes. However, for the conventional modules of vector control such as Park and Inverse Park transformation, sinusoidal PWM generation module, and a double H-Bridge power inverter are also included as well as the controlled HSM .

- POWER CONVERTER DESIGN

The HSM will be supplied by two identical H- bridge bipolar voltage source inverters as shown in Fig.4 (a, b).

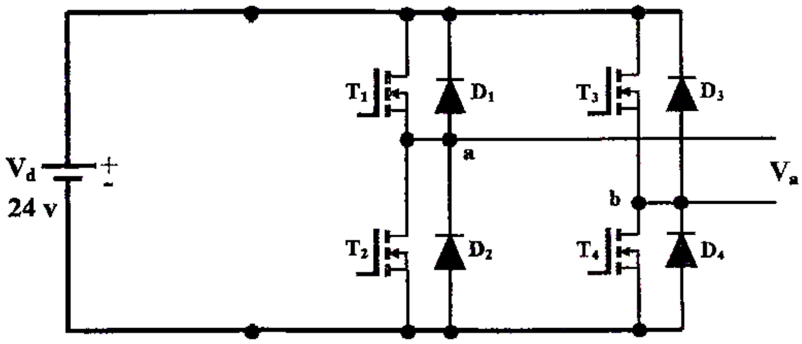

Fig.4.a: H- bridge (1) bipolar voltage source inverter [1].

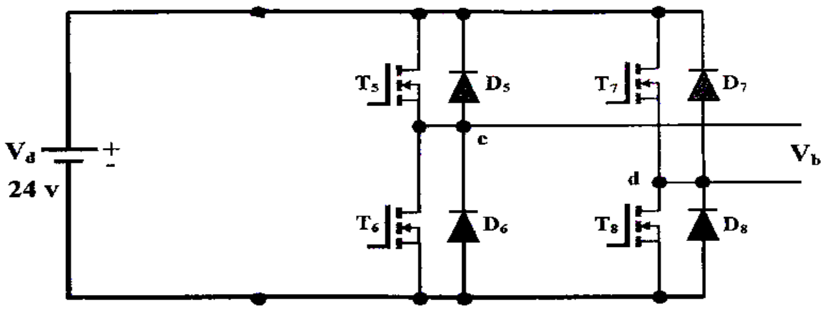

Fig.4.b: H- bridge (2) bipolar voltage source inverter [1].

Transistor (MOSFET) has been used as switching elements in the H- bridge inverter. These elements will control using the well known Sinusoidal Pulse Wave Modulation (SPWM) technique. However, the output voltage and the reference voltage waveforms from H- bridge inverters (1) and (2) are obtained using MATLAB/ Simulink as shown in Fig.5 and Fig.6.

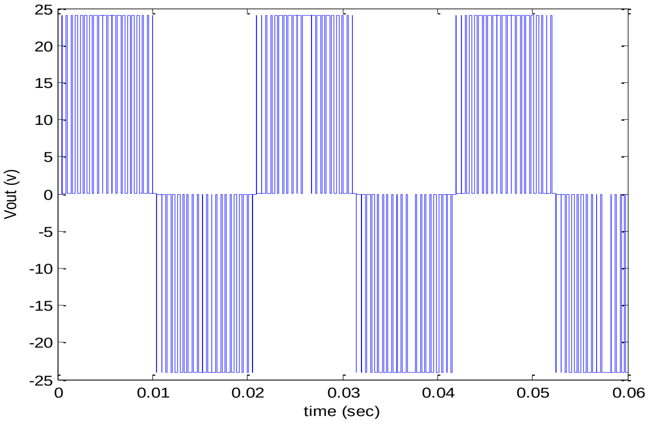

Fig.5: Output voltage from H- bridge (1).

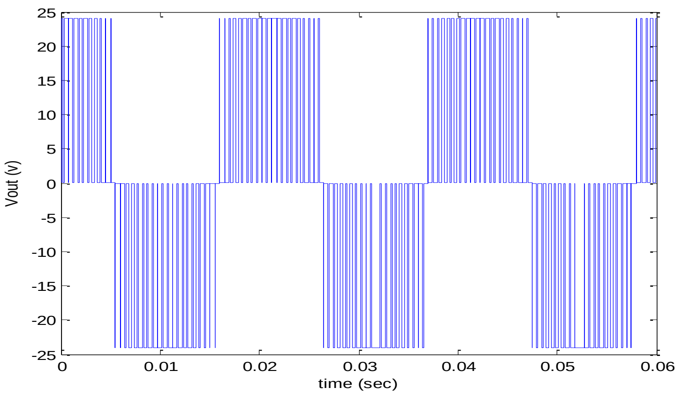

Fig.6: Output voltage from H- bridge (2).

From these results, it should be noted that the output phase voltage is shifted by (90º) due to the fact that the supplied HSM consist of two phase windings.

- SIMULATION OF HYBRID STEPPER MOTOR

The open loop pulse width modulation HSM system consists of the test input in the form of sine and cosine of 50Hz frequency and SPWM has been used to control the magnitude and frequency of AC output voltage of an inverter are shown in Fig.7. The simulated hybrid stepper motor is shown in Fig. 8, HSM can be divided into two subsystems, the electrical system and the mechanical system. In the open-loop control scheme, there is no feedback information of a position to the controller, and therefore it is imperative that the motor must respond correctly to each excitation change. If the excitation changes are made too quickly, the motor is unable to move to the new demanded position and consequently there is a permanent error in the actual position compared to the position expected by the controller. The vector controller is applied for closed-loop system to avoid the problems in open one. The idea of vector control is to study the effect of motor controller (speed and current controllers) on the performance of overall system, and to demonstrates how the value of switching frequency can contribute to change the performance of the proposed vector control of HSM, one technique have been studied through simulation by using MATLAB/ Simulink. High switching frequency is used to avoid the ripple in low frequency. The proposed vector control of HSM will be simulated using MATLAB. The values of PI controllers are used in the simulation. System's simulations were performed using a model of the HSM as shown in Fig. 9. The parameters of the motor are used in the modeling of HSM. These parameters are the same as that for real motor and they are used in the experiments and will be kept constant during simulations.

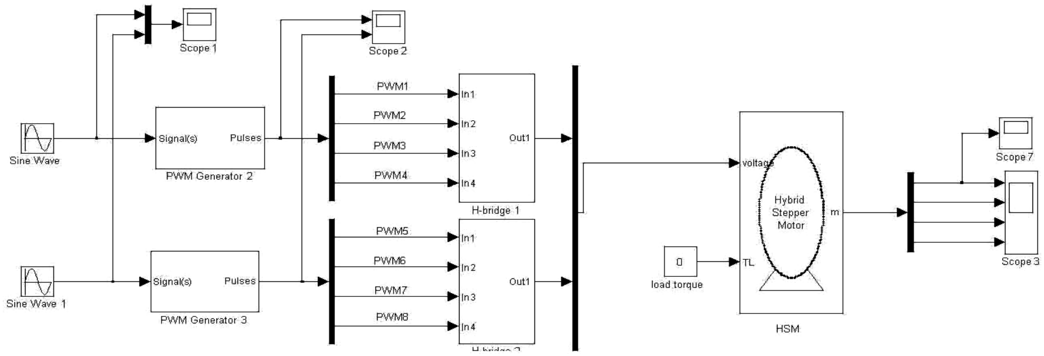

Fig.7: Open loop system.

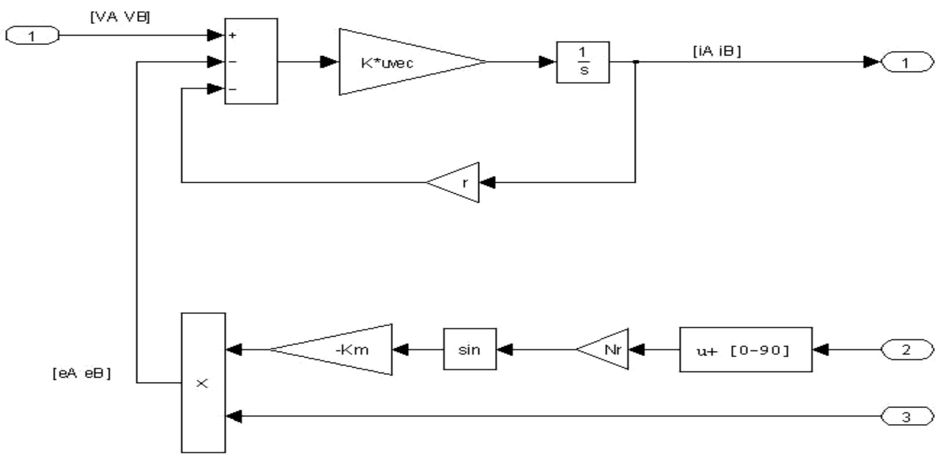

Fig. 8.a: Hybrid Stepper Motor Electrical part.

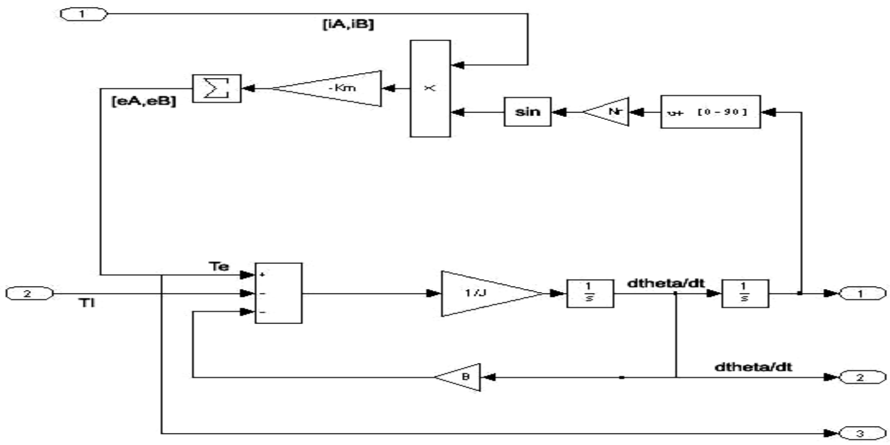

Fig. 8. b: Hybrid Stepper Motor Mechanical part.

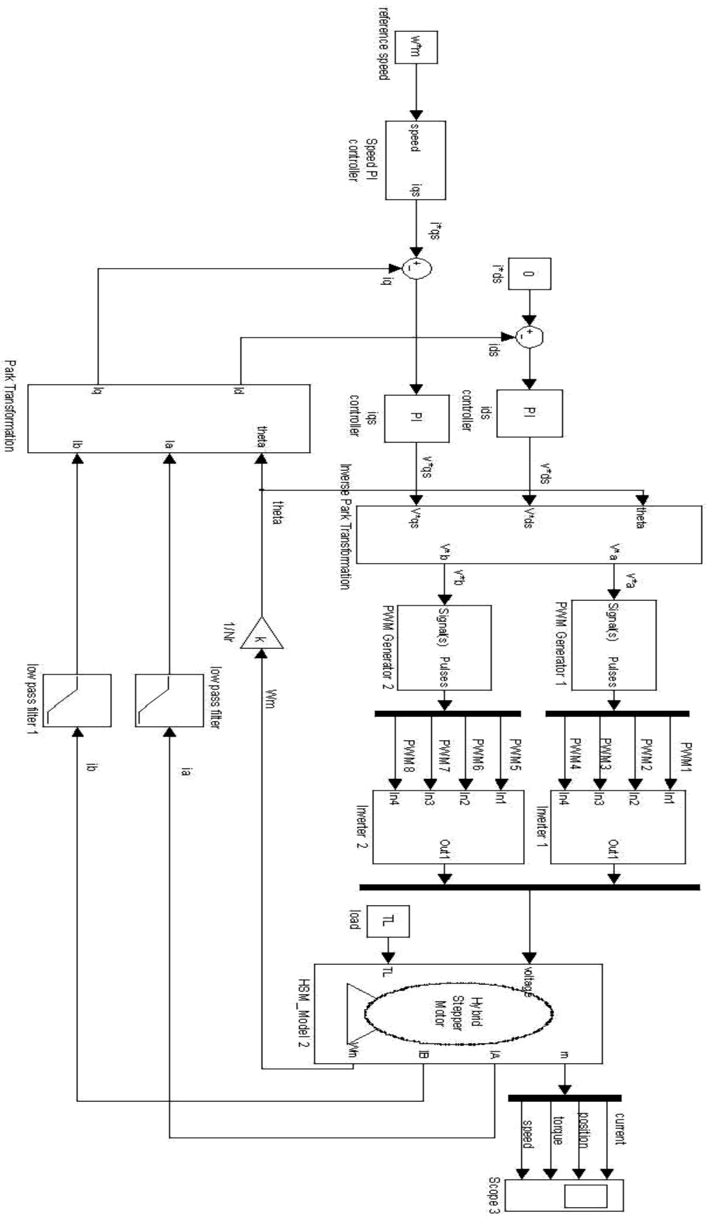

Fig. 9: Closed loop system.

- SIMULATION RESULTS

The simulation system consists of open loop system and closed loop system

OPEN LOOP RESULTS

Fig. 10 shows the currents for phase A and B of the stepper motor when load torque is 0.25 (Nm) and carrier frequency is 20 (KHz) sinusoidal current. The phase current oscillations occur as effect of PWM inverter.

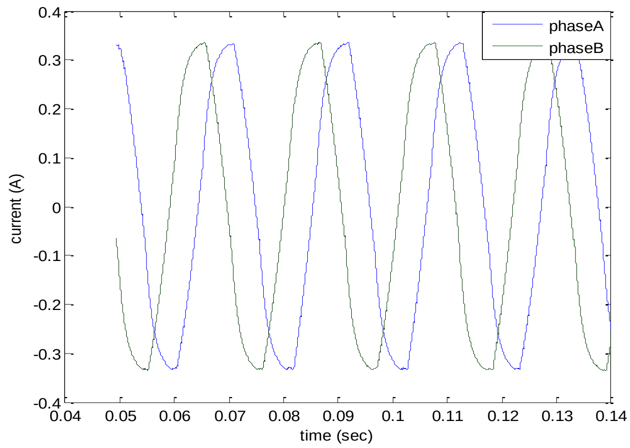

Fig. 10: Simulated windings current for phase (A,B) at 0.25 Nm load torque.

Fig. 11, Fig. 12 and Fig. 13 illustrate the dynamic behaviour of the motor when the load torque is 0.25 (Nm) and carrier frequency is 20 (KHz). The motor torque and speed contain oscillations due to PWM inverter.

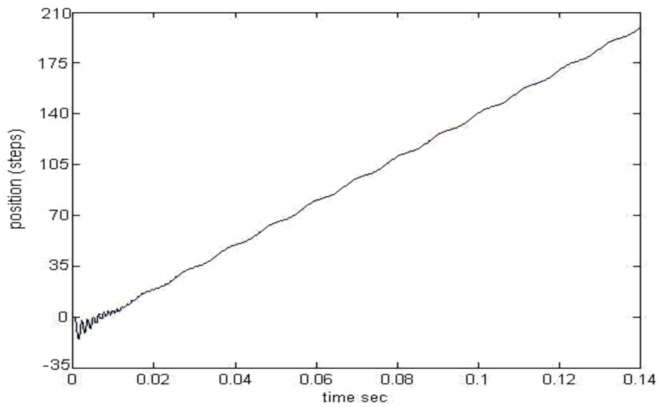

Fig. 11: The position of HSM at 0.25 Nm load torque.

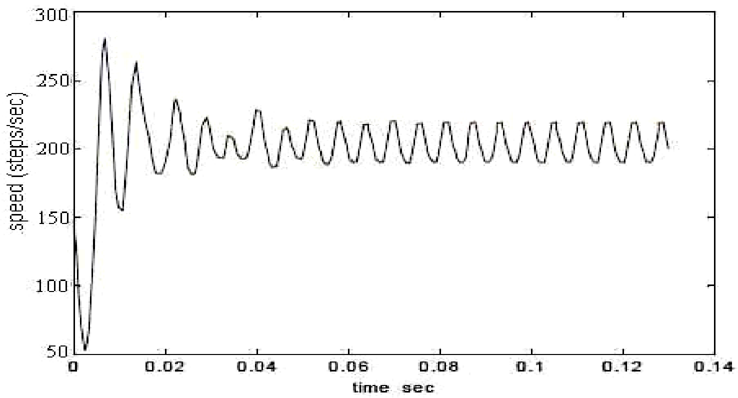

Fig. 12: The speed of HSM at 0.25 Nm load torque.

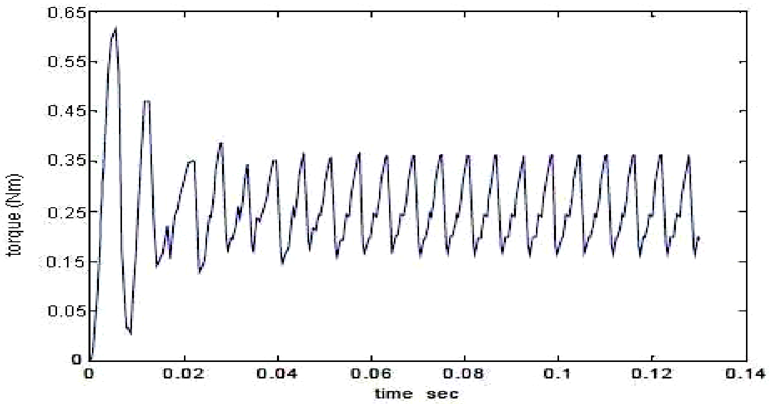

Fig. 13: The torque of HSM at 0.25 Nm load torque.

CLOSED LOOP RESULTS

The switching frequency of the PWM inverter is 20k Hz. According to the vector control principle, the stator currents can be transformed into a frame of reference which is moving with the rotor flux. Therefore, optimal utilization of the machine is achieved if the stator current is only fed in the quadrature axis (id = 0). This condition can be attained by selecting suitable value of speed and current controller parameters through tuning procedures. However, this idea has been confirmed when we obtained the winding current in (d-q) reference frame. Fig.14 shows the winding current in (d-axis), and Fig.15 illustrates the winding current in (q-axis).

From these result, it can be observed that after 0.01 sec the winding currents remain constant and thus the motor is in steady state mode. Also, the current waveforms have few harmonics because the selected value of switching frequency was high enough to eliminate these harmonics. During startup, the speed of the motor will increase until reaching the desired speed at 0.25 sec as shown in Fig.16. In Fig.17, the rotor position is reported in steady state with a desired speed of 100 (rad/sec).

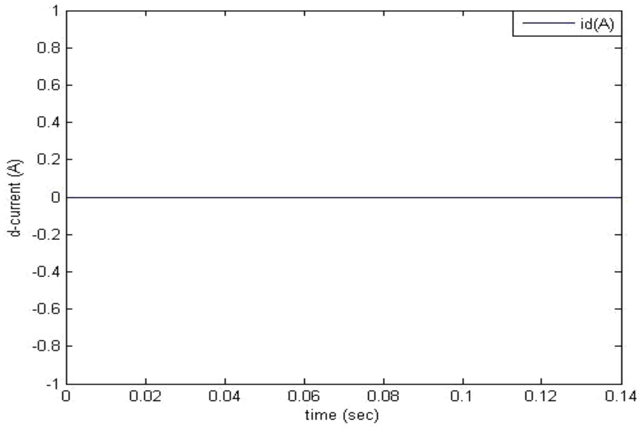

Fig.14: Simulated winding current in (d-axis) with high switching frequency.

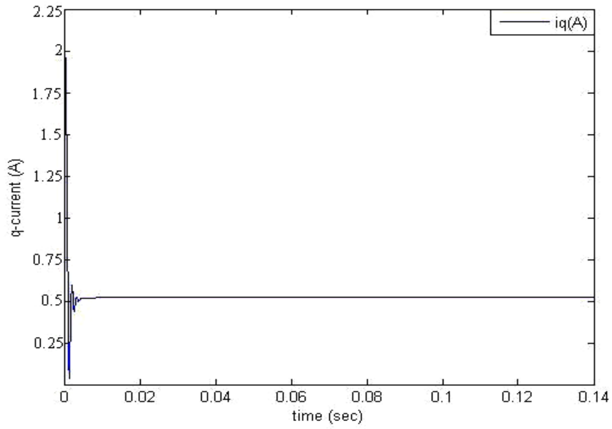

Fig.15: Simulated winding current in (q-axis) with high switching frequency.

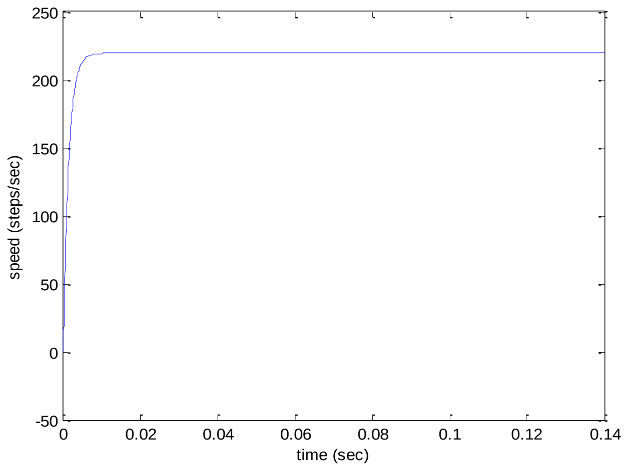

Fig.**16: Motor speed response with high switching frequency.**

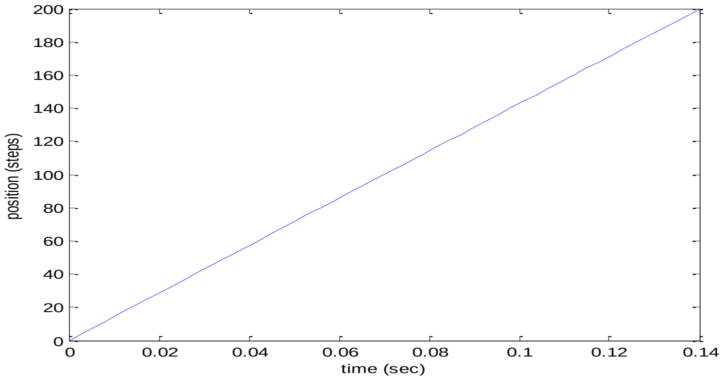

Fig. 17: Motor rotor position with high switching frequency.

- EXPERIMENTAL SETUP

The Stellaris stepper motor control reference design kit (RDK) contains all the necessary hardware and software design, and integrate stepper motor applications. The stepper RDK design kit consists of a board containing a Stellaris® microcontroller, motor drive electronics, a stepper motor, and firmware to run the motor. The stepper RDK microcontroller is shown in Fig. 18. The stepper RDK includes the following product features:

- Advanced PWM control of bipolar HSM.
- Software-based PWM control to operate high-torque steppers at high step rates.
- Fast and slow decay modes.
- Full-step, half-step, micro-step, and wave modes.
- High step rates up to 10000 steps / sec.
- Programmable holding current.

The stepper RDK firmware is designed to show how stepper motor control can be done using a Stellaris microcontroller and motor drive circuits. All of the stepper sequencing is performed in the microcontroller; no external stepping logic is required. The stepper RDK firmware provides maximum flexibility by implementing three different methods for controlling the stepper motor winding current. It also provides a number of user adjustable parameters which allows experimentation to find the best **settings for use in a particular application. The firmware is implemented as several layers, with a well defined stepper Architecture Programming Interface**

(API) to make it easy to integrate with a user's application code. It includes, as the application, a user interface which is used for demonstrating how to use the stepper firmware. The user interface can be used initially for experimenting with the motor and settings, and can later be replaced by the real application software. There are two user interfaces: an on-board interface, and an off-board interface. The on-board interface uses a potentiometer knob, a button, and two LEDs to operate the stepper motor. The off-board interface uses a USB-connected serial port and graphical application which provided extensive control of the firmware. Refer to the stepper RDK user's manual for details of using the on-board and off-board interfaces.

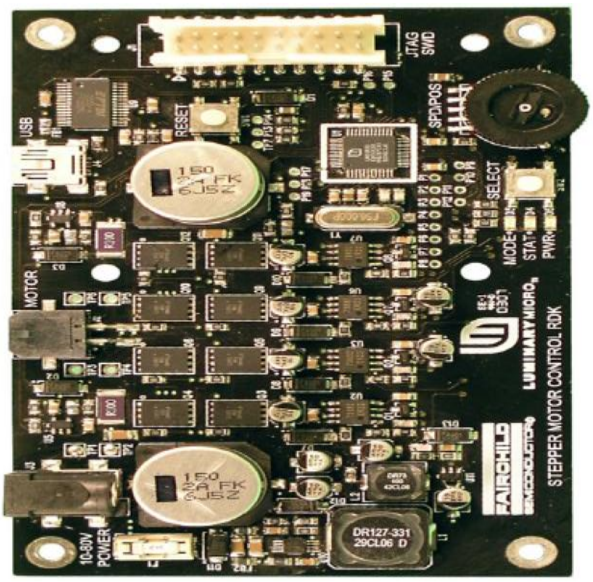

Fig. 18: Stepper Motor Control Board.

- EXPERIMENTAL RESULTS

The experimental results introduced in this section will be used to verify the effectiveness and performance of the proposed vector control of HSM. However, the proper information about rotor speed and position is required and essential for real time implementation of the high performance vector control. In closed loop PWM stepper motor system, Fig. (19, 20, 21) show the current and speed of the steady state of the motor when target speed is 221 (steps/sec), target position is 3475 steps, carrier frequency is 20 (KHz) and constant load torque is 0.25 Nm when the mode of phase excitation is full-step, half-step, micro-step. In full step excitation, two phases HSM has a step size of 1.8 degrees and 50 rotor teeth **corresponding to 200 steps per** revolution. In half step excitation, two phases HSM has 400 steps per revolution causing the rotor to rotate at half distance so that amplitude of the current will be reduced. Advantage of a step motor operation in half step mode is position resolution increased by a factor of two compares to full step mode. In micro step excitation, the current is change in the windings in fraction of rated current so that increased step position resolution as result of a smaller step angle.

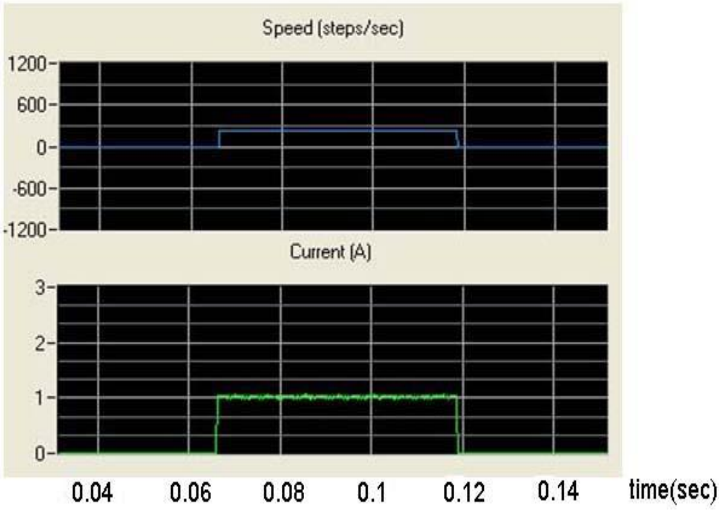

Fig. 19: Current and speed of HSM for full-step and 221(steps/s).

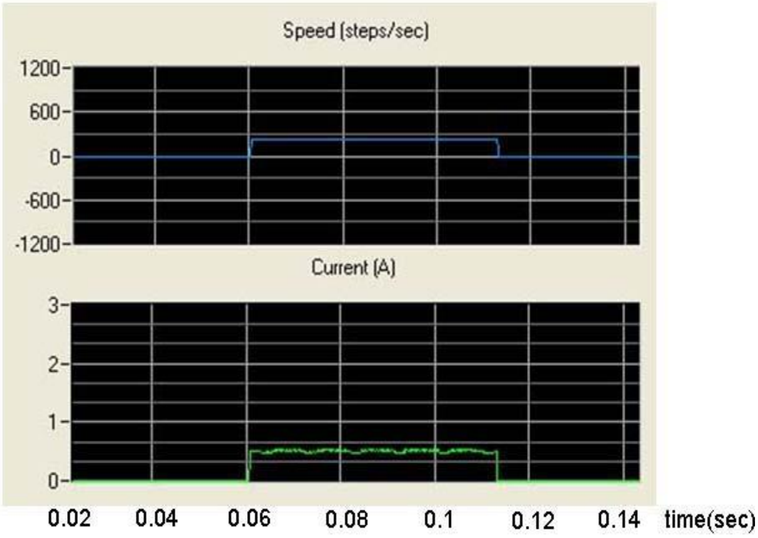

Fig. 20: Current and speed of HSM for half-step and 221 (steps/s).

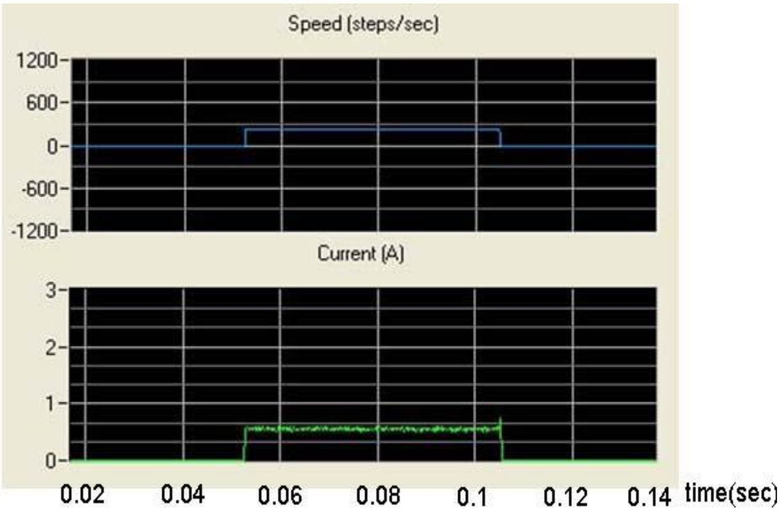

Fig. 21: Current and speed of HSM for micro-step and 221 (steps/s).

CONCLUSIONS

The proposed vector control of HSM using state estimation has been found to be well suited to the speed and rotor position estimation of the HSM. The developed method can be extended for the estimation of any other set of parameters/states in HSM control and may also be used with other control methods which require the accurate knowledge of a high number of parameters. It has been illustrates that the HSM can be transformed into a highly dynamic brushless DC- motor with vector control. This can lead to overcome the usual problems of HSM such as high currents, overheating and acoustic noise. To compare the results for speed and current between simulation and practical circuit, it found that the practical speed results are symmetrical to the simulation speed results but the current in practical results are less oscillation than simulation because simulation circuit used PI controller in closed loop system to control the current and speed of HSM while in practical circuit LM3S617 microcontroller is used to control the speed and current of HSM. PI controller depended on principle of trial and error to adjust the proportional and integral gain while LM3S617 depend on the accuracy of the software and electronic device.

REFERENCES

- P.P. Acarnely, Stepping Motors: A Guide to Modern Theory and Practice, 2nd ed. Stevenage, U.K.: Peregrinus, 1994.
- T. Kenjo, Stepping Motors and Their Microprocessor Control, Oxford, U.K. Clarendon, 1994.
- A. B. Behal, "Field Oriented Control of Step Motors", M.Sc. Thesis, Department of Electrical Engineering, Cleveland State University, Dec., 2004.
- N. M. Matsui, M. W. Nakamura, and R. T. Kosaka, "Instantaneous Torque Analysis of Hybrid Stepping Motor", IEEE Transactions on Industrial Electronic, Vol. 60, No. 6, Jan., 2009.
- A. S. Rubaai, M. F. Sitiriche, M. J. Garuba, and L. D. Burge, "Implementation of Artificial Neural Network Based Tracking Controller for High Performance Stepper Motor Drives", IEEE Transactions on Industrial Electronics, Vol. 54, No. 1, PP. 218-227, Feb., 2007.
- L. O. Hoang, P. H. Brunelle, and G. T. Sybille, "Design and Implementation of a Versatile Stepper Motor Model for Simulink's SimPower Systems", IEEE Transactions on Industrial Electronics, Vol. 20, No. 3, Dec., 2008.
- J. R. Frus and B. C. Kuo, "Closed loop Control of Step Motors Using Waveform Detection", Proceedings of the International Conference on Stepping Motors and System, University of Leeds, U.K., PP. 77-84, 1990.
- W. J. Douglas, " Stellaris® Stepper Motor RDK Software Reference Manual, Publication Number RDK Stepper", Luminary Micro, Inc., 2008.