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New Positioning Control of Stepper Motor using BP Neural Networks

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ABSTRACT

This paper presents a new approach based on the use of a knowledge base, in order to improve the angular resolution of the permanent magnet (PM) stepper actuator. The use of this technique is justified by the limits of the conventional technique when the static torque characteristic is high nonlinear. The conventional open loop microstepping technique which realised by a Pulse Width Modulation is described and discussed, in first part. In second part, a design of a new approach based on the use of back propagation neural network is proposed. The obtained simulation results confirm the efficiency of the new proposed approach.

Keywords: *permanent magnet stepper motor, Micro stepping control, knowledge base, Neural network, detent torque, load torque.*

1. INTRODUCTON

The permanent magnet stepping motor (PMSM) is a potential candidate for high performance positioning drive. Recently, PM stepping motors were being used for different computer peripheral equipments such as optical disk drives, printers and optical equipments. Moreover, these devices need precise PM type stepping motors as a source of its drives. The PM stepping motors was being dominant in these various applications due to its simple and robust structure, low manufacturing cost and high endurance [1], [2], [5].

These performances added to the very elevated torque produced, are at the principal advantages given to this machine compared to other stepping actuators type [1], [2]. Hence, PMSM has obtained a new attention for positioning fields. Moreover, for each electrical pulse input, results an incremental movement called step.

A small step is commonly found in greater field in industrial applications such as biomedical systems, push-syringe, nutrition pump, robot arms, machine tool feed drives. However, the regular movement step of a PMSM, which is fixed by mechanical construction, is the main disadvantage for the use of this actuator in some microstepping applications.

In addition, such applications require smoother displacement with a good accuracy. Hence, Saturation effects and presence of harmonics are not acceptable for applications where microstepping mode is applied [5], [6]. In literature, the microstepping control consists to subdivide the full steps, which are fixed by mechanical construction. For this purpose, the rotor is solicited by two antagonistic forces. The first force provokes the advance of the mobile part in the positive sense. The second one breaks the movement of the rotor. Hence, the rotor is immobilized at the some position where the resultant of the two antagonistic forces is null [7].

The detent torque is the several disadvantages limiting the significant use of this motor in micro stepping control applications. Moreover, the detent torque is the main cause of the high nonlinear relevant torque characteristics of the PM stepper motor.

In the present work, a methodological approach based on the study of static torque characteristic, is considered, in order to develop a new microstepping control strategy based on the use of a knowledge base which improve the angular resolution.

The static torque characteristic is an indispensable required data in modelling the machine behaviour. Taking into account this necessary requirement, our works are based on analysis of torque characteristic considering the effect of the detent torque.

This paper is organized as follow. The description and mathematical model of the PM stepper motor are presented in section 2. Section 3 is reserved to the study of microstepping control obtained by conventionally technique. The proposed Neural Network concept is developed in section 4. Finally, conclusions are summarized in section 5.

2. THE PM STEPPER MOTOR DESCRIPTION AND STATIC ANALYSIS

The permanent magnet stepper motor under investigation has step resolution of 0.39 radian. It has 4 stator poles and 2 coils wound around them and 8 rotor poles. Each diagonal pair of stator windings is connected in series to build the two stator phases.The PMSM structure is given in fig. 1. Only one coil is energized for normal stepping and the 2 coils are simultaneously energized at a time for micro stepping.

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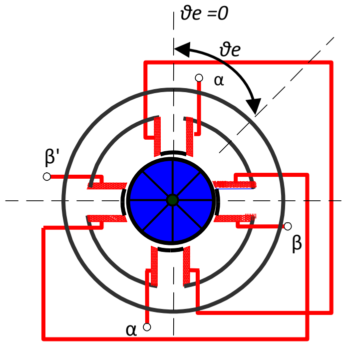

Fig.1: PM stepper motor structure

Considering the Faraday's law, the applied voltages $U_{\alpha\alpha'}$ and $U_{\beta\beta'}$ to a stator phases are equal to the sum of the resistive voltage drop and the rate of change of flux linkage. Hence the dynamic model is expressed in [3], [4] as:

$$U_{\alpha\alpha'} = R i_{\alpha\alpha'} + L\frac{di_{\alpha\alpha'}}{dt} - k_\varphi \Omega \sin(p\theta_m) \quad (1)$$

$$U_{\beta\beta'} = R i_{\beta\beta'} + L_0\frac{di_{\beta\beta'}}{dt} + k_\varphi \Omega \cos(p\theta_m) \quad (2)$$

$$J_0\frac{d\Omega}{dt} + D_{r0}\frac{d\theta_m}{dt} = T_{\alpha\alpha'} + T_{\beta\beta'} + T_{detent} - T_r \quad (3)$$

$$\frac{d\theta_m}{dt} = \Omega \quad (4)$$

The produced torques by the winding αα' and the winding ββ' has respectively the following expressions [4]:

$$T_{\alpha\alpha'} = -k_\phi I_{\alpha\alpha'} \sin(p\theta_m) \quad (5)$$

$$T_{\beta\beta'} = k_\phi I_{\beta\beta'} \cos(p\theta_m) \quad (6)$$

The detent torque describes the interaction between the rotor magnets and the statoric windings. Then, it's present with or without phase currents applied [3], [4].

This torque can be calculated by the partial derivative of magnetic co-energy with respect to the angular displacement. Then, the detent torque is given by [5]:

$$T_{detent} = \frac{\partial W_f}{\partial \theta} \quad (7)$$

Where, W_f is the total co-energy of the field. The detent torque can be expressed by the following expression [3], [4]:

$$T_{detent} = -T_{detentMax} \sin(4p\theta_m) \quad (8)$$

With $T_{detent\ Max}$ is approximately given by [4]:

$$T_{detentMax} = \frac{k_\phi I_n}{5} \quad (9)$$

In order to obtain an intermediate position (θ_j) between steps, two current intensities must be injected in two adjacent statoric windings simultaneously. In this case, two antagonistic torques are produced [7].

In steady micro step operation, the currents $I_{\alpha\alpha'}$ and $I_{\beta\beta'}$ are given by the following expressions:

$$I_{\alpha\alpha'} = I_n \cos\theta_j \quad (10)$$

$$I_{\beta\beta'} = I_n \sin\theta_j \quad (11)$$

With I_n is the nominal current.
So, using the last equation, we can obtain the following torque expressions:

$$T_{\alpha\alpha'} = -k_\phi I_n \cos\theta_j \sin(p\theta_m) \quad (12)$$

$$T_{\beta\beta'} = k_\phi I_n \sin\theta_j \cos(p\theta_m) \quad (13)$$

The obtained equations show that the first phase produces a positive torque taking the rotor in the positive sense. However, the second phase produces a negative torque which brakes the rotor in the inverse sense. The resultant torque, which is the sum of these two partial forces, allows immobilizing the rotor in an intermediate position. The gradual variations of the commutation times and the currents control signal confers to the rotor a positioning by microsteps[7].

Then the torque produced by the windings (αα') and (ββ') is expressed by:

$$T_{\alpha\beta} = -k_\phi I_n \sin(p\theta_m - \theta_j) \quad (14)$$

The desired micro step is obtained when the two statoric windings (αα') and (ββ') are simultaneously excited by the necessary currents and the detent torque is neglected.

In order to test the effect of the detent torque in microstepping operation and simulate some control techniques applied to the permanent magnet actuator, we consider the bipolar permanent stepping motor which is characterized by the principal parameters indicate in Table1.

Table.1 PM Stepper motor parameters

Stator coil resistance	R	32 Ω
Stator coil inductance	L	12.2mH
Rotor inertia	J_0	6.67 10^{-7} kg.m^2
Number of pair poles	p	4
Viscous friction constant	D_{r0}	0.2 10^{-4} m^2.s^{-1}
Motor torque constant	k_Φ	0.03 rad.s^{-1}

The results given in figure 2 shows that the obtained position is superposed to the desired one. So, the proposed validation scheme results on a high accuracy position tracking.

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The torque produced by the windings (αα') and (ββ') added to the detent torque is:

$$T_{em} = -k\phi I_n \sin(p\theta_m) - T_{detentMax} \sin(4p\theta_m) \qquad (15)$$

The detent torque causes vibration and acoustic noises to the PM stepper motors; also the detent torque is the main cause of the high nonlinear torque characteristics, which degrade the positioning control. Fig 3 shows the simulation results of holding torque characteristics with consideration of the detent torque. These results show the appearance of an angular variation, which affects positioning in microsteps. So, all depends on the importance of the detent torque, several microsteps can be missed.

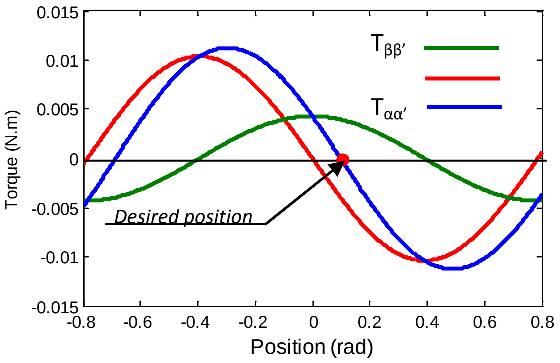


Fig. 2: Torque characteristic in microsteps, the detent torque is neglected

In fact, the equilibrium is reached by the equality between the torque machine *Tem* and the torque *Tr* opposed by the coupled load. However, in positioning with considering the detent torque, which is not neglected in reality, the satisfaction of this condition shows an important inaccuracy, which affects the precision positioning.

This undesirable positioning is confirmed by the simulation tests, which are consigned in the next section.

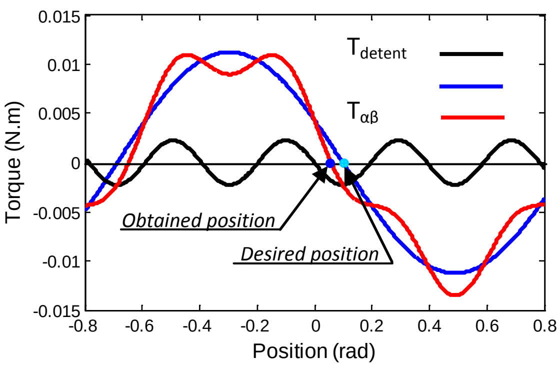


Fig.3: Torque characteristic in microsteps positioning with the detent torque

In fact, the equilibrium is reached by the equality between the torque machine *Tem* and the torque *Tr* opposed by the coupled load. However, in positioning with considering the detent torque, which is not neglected in reality, the satisfaction of this condition shows an important inaccuracy, which affects the precision positioning.

This undesirable positioning is confirmed by the simulation tests, which are consigned in the next section.

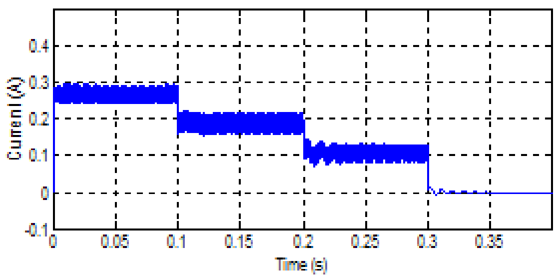
3. MICROSTEPPING APPROACH BY PULSE WITH MODULATION (PWM)

In this control approach, the both phase windings (αα') and (ββ') must be excited simultaneously by two PWM signals. The first phase produces a positive torque allowing pulling the rotor in the positive sense. And the second phase produces a negative torque and drags the rotor in the inverse sense. The global torque allows to immobilize the rotor in an intermediate position. The gradual variations of the commutation times of the PWM control signal confers to the rotor a positioning by microsteps[7].

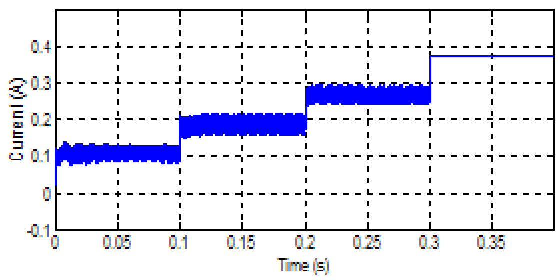
The numerical simulation results show the relationship of the machine behavior, between the statoric currents and the angular position. Indeed, Fig.4 illustrates a fragmentation of the one mechanical step in four microsteps using a PWM technique.

The response indicated by fig.4 shows that a fragmentation in4micro steps/step reduced considerably the overshoot and improves clearly the angular resolution. However, the principal disadvantage of this command is the error of positioning when the detent torque is not neglected. Moreover, the detent torque acts to the rotor in the first and the third micro steps that causes degradation in the performances of the Microstepping control approach.

To solve this problem, a new approach is proposed in the next section.



a. current i_β



b. current i_α

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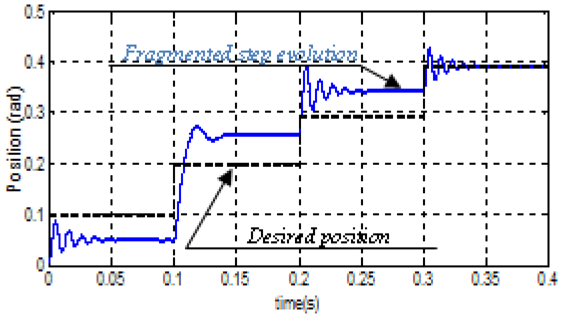


c. position

Fig.4: Fragmentation of a one step by PWM Technique

4. NEW POSITIONING APPROACH

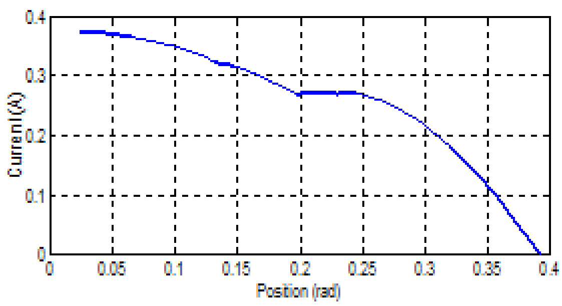
The interest of the Neural Network Controller lies in their capacity of generalization and their ability to model nonlinear functions. The Artificial Neural Network is recognized as a very efficient approach contributing to control with a high accuracy the electrical actuators.

For these reasons, we interest to Neural Network to model the variation of the currents according to the desired position.

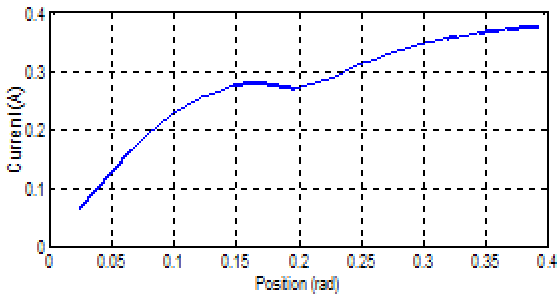
The microstepping motion of the studied motor can be obtained when two successive phases are exited. Indeed, the winding ββ' allows the drive of the motor and the winding αα' insure the braking. Hence, the inputs of the proposed Neural Network are the desired position and the load torque applied to the PM actuator.

This new controller is a decision algorithm based on an operator's expertise. So, this type of control strategy is described by a knowledge base. The desired position of the studied motor can be obtained when the two voltages $U_{\alpha\alpha'}$ and $U_{\beta\beta'}$ are updated.

In order to determine the necessary currents required to have a micro stepping movement, several simulation tests were carried out for different positions rotor. For each position, the value of applied voltage, respectively the value of current for each winding is readjusted in order to stabilize the rotor on the desired position. Hence, the value of currents depends on the equilibrium position. The results obtained are summarised by the curves given on figure 5. The curves show the variations of the currents in the two windings with the rotor position. It is clear that the value of the currents is non linear characteristics with the rotor position.



a. current i_α



b. current i_β

Fig.5: Variation of the currents with position

The output control signals of the new controller are the voltages $U_{\alpha\alpha'}$ and $U_{\beta\beta'}$ that should be applied to the motor windings. These signals well increase or decrease the statoric current of the studied motor.

The proposed control, with an open loop strategy, is presented in Figure 6.

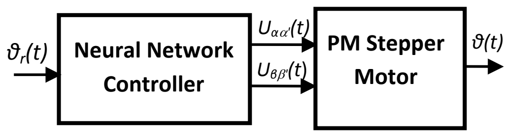
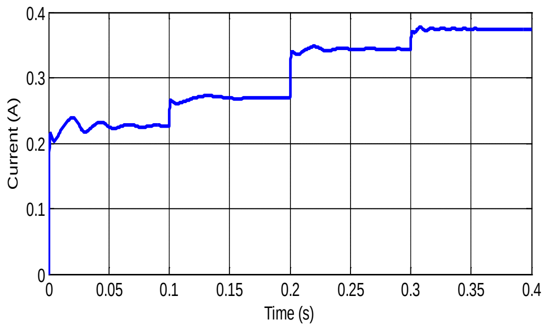
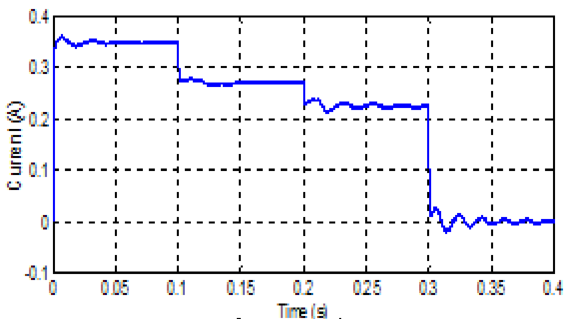


Fig.6: Structure of the proposed control strategy

In this part of section, we interest to validate of the proposed controller approach. The result given in Figure 7 illustrates a fragmentation of the one full mechanic step into 4 microsteps for a positioning without load. This result shows the efficiency of the new approach in the improvement of the positioning precision.



a. current i_β



b. current i_α

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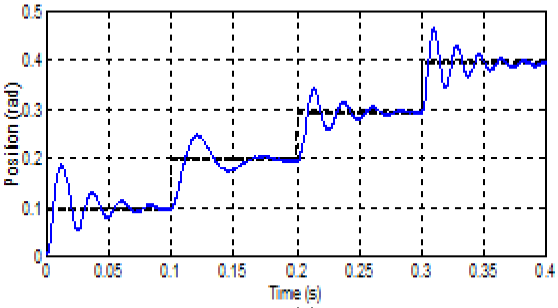

c. position

Fig.7: Fragmentation in 4 microsteps without load

In order to test the efficiency of this proposed Neural Network controller in positioning with load, we applied a nominal torque. It is under these conditions that the result consigned in the Figure 8 is obtained. It describes a positioning in 4 micro steps/step. This response shows the appearance of an angular variation, which affects positioning in load. So, all depends on the importance of the applied load, several microsteps can be missed. In fact, when the desired number of microsteps is high and the coupled load is significant, the actuator can position in opposite direction during some step.

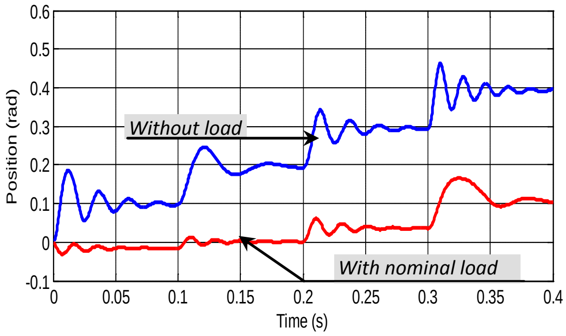

Fig.8: Fragmentation in 4 microsteps with nominal load

In positioning with load, the equilibrium is reached by the equality between the torque machine T_{em} and the load torque T_r opposed by the coupled load. The satisfaction of this condition reveals an inaccuracy, which affects the precision positioning [8], [9]. The study in static mode of the torque angular curves confirms these results. Thus, the positions reached by the rotor under load, presents a positioning error ($\Delta\vartheta$).

Hence, in positioning with load, the positioning error must be solved. This operation can be realized by the action on the partial torques, which are produced by the actives phases $\alpha\alpha'$ and $\beta\beta'$. Consequently, the stator excitation must be regulated with the load torque In order to solve this problem.

The basic idea consists to slip the global static torque curve. This adjustment is conditioned by a judiciously controlled imbalance between the statoric currents.

A static study of the PM stepper motor torques, led to the representation of surfaces, binding the currents of each phase to the position and the load torque. The examination of this data base shows that the current developed by each phase varies according to the desired position and the load torque. So, it is very difficult to describe this function by analytical formula.

For this reason, the training data are organized as follows; a vector of 17 torque values in the range 0 N.m to 8. 10^{-3} N.m with a regular step of 5.10^{-4} , a vector of 24 positions values in the range 0 rad to 0.3925 rad and the corresponding current excitation $i\alpha$ and $i\beta$.

In order to validate the proposed modelling approach, we proceed by using a new controller as it is depicted in figure.11.

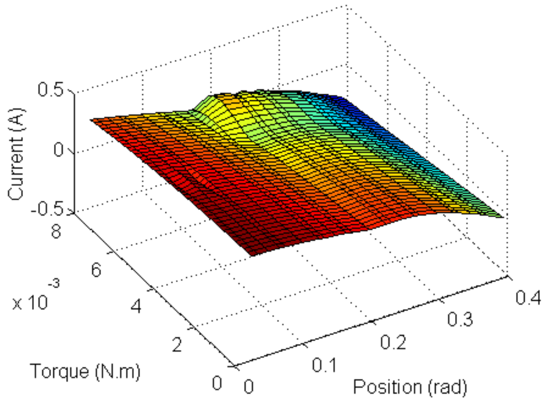

Fig.9: Non-linear control i_α surface

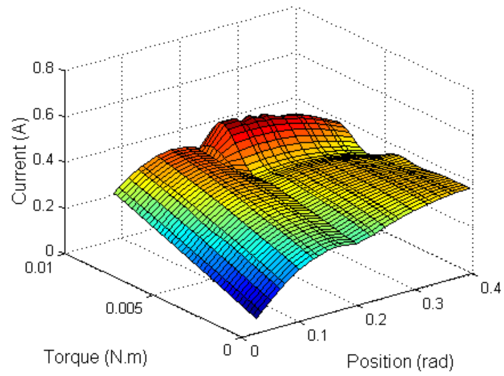

Fig.10: Non-linear control i_β surface

The inputs of the proposed scheme are load torque and the desired rotor position (θ_{ref}), the output are the statoric voltage excitation.

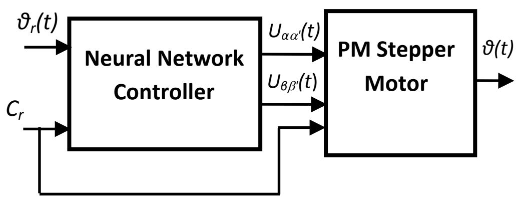

Fig.11: New Structure of the proposed control strategy

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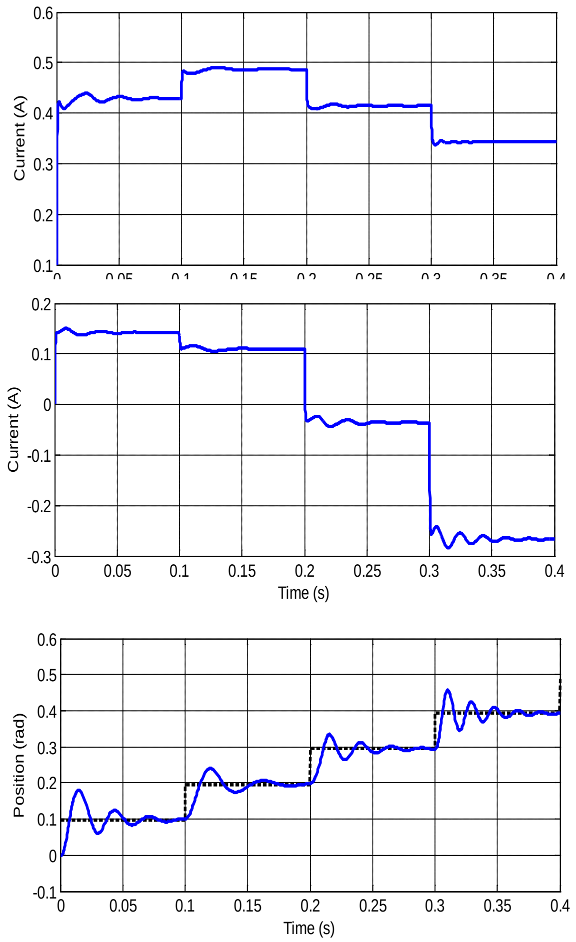
The integration of this correction module to the principal simulation programme, led to the results consigned in the Figure13 and Figure 14. These results show the potentiality of this new control approach in the improvement of the positioning precision with variable load.

These results confirm that the obtained position is superposed to the desired one. So, the proposed validation scheme results on a high accuracy position tracking.



c. position

Fig.12: Corrected positioning in nominal load

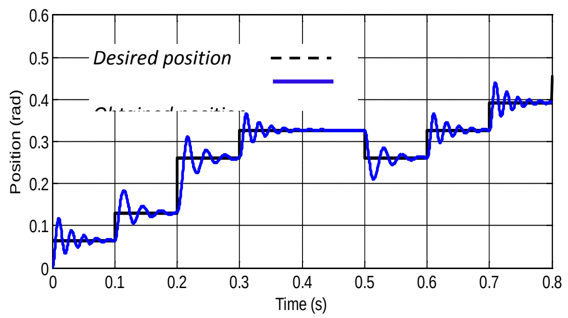


Fig.13: Position evolution versus desired position

5. CONCLUSION

In this paper, a new microstepping Controller is proposed in order to improve the performance of the permanent magnet stepper motor. This approach is based on the technique expertise. The application of this approach has improved the positioning applications using the PMSM. Results obtained by simulations confirm the validity of the proposed control.

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BIOGRAPHIES

El Manâa BARHOUMI was born in Kasserine, Tunisia, on April 16, 1981. He received the M.S. degree in Electrical Engineering from the Ecole Supérieure des Sciences et

Techniques de Tunis (ESSTT), Tunisia in 2005. Also, he received the master degree in Electrical System in 2008 from Ecole Nationale d'Ingénieurs de Tunis (ENIT), Tunisia. In September 2009, he joined the Department of Electrical Engineering at Institut Supérieur des Etudes technologiques de Kairouan, Tunisia, as assistant professor. He is now a researcher in Laboratory of Analysis Control of Systems (LACS) in ENIT. He works in the Ph.D. theses degree in the field of stepping actuators design and control.

Boujemâa Ben SALAH was born in Bizerte, Tunisia, on September 16, 1959. He received the Master degree in electrical engineering from Ecole Normale Superieure de l'Enseignement Technique de Tunis (ENSET) in 1986. Also, He received the Doctorat and Habilitation Universitaire (HDR) from Ecole Nationale d'Ingénieurs de Tunis (ENIT) in 1997 and 2003 respectively. From 1988 to 1997 he was employed at the ENIT as an Assistant. From 1997 to 2003, he has been Associate Professor in the same school. From 2003 up to now, he is a professor in electrical engineering at ENIT Univ, Tunis. From 2000 he is currently a visiting professor in the Ecole Centrale de Lille-FRANCE. He is now a researcher in Laboratory of Analysis Control of Systems (LACS) in ENIT. His main research interests are actuators design and control, power control, speed Ac