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A New Two-degree of Freedom switched Reluctance Motor for Electric Vessel

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Abstract - This paper introduces a new 2-degree of freedom (2-DOF) switched reluctance motor for an electric vessel. The configuration, operation principle and algorithm of the new motor are described in detail. Moreover, the electromagnetic characteristics have been illustrated by using finite element method (FEM), and the simulation of the electric vessel also has been realized. A modified control method has been suggested as the control scheme to ensure innovation and stability of the electric vessel's operation. Finally, the experimental results have suggested that the innovation and conveniences of the new electric vessel are better than that of conventional electric vessel, then the results of theoretical analysis and experiments has been proved the improvements of the electric vessel.

Index Terms—2-DOF, switched reluctance motor, electric vessel, FEM

I. Introduction

Electric vessel, as a new type of electrical propulsion transportation, has been investigated for years. The motors are practically used for the high power transportations with a high degree of reliability, such as electrical vehicles, aircrafts and electric vessel.

A two - dimensional rotating linear motor is usually used for the industrial motion control equipment. The two-degree switched reluctance motor is an alternative to be selected to drive this motion, such as boring mill, drill press and carving machine, etc [1].

The two-degree motions are required in surface motion or multi-axis applications, such as concentrating photovoltaic generation system in capturing the solar direct light to enhance power generation efficiency. The solar tracking is 2-dimension as the solar path varies throughout a year. Conventional 2-degree of freedom motions are realized by combining two rotary or linear (RL) motors in two directions, integrating screw rods and mechanical gears. For example, helical motion induction machines are reported in ref [2] and [3]. By using those mechanical gears, both the position precision and efficiency of the motion system could be reduced because there are backlash, axis-coordination and losses generated by mechanical gears. This 2-degree switched reluctance motor can realize two-degree movements-rotary and linear movements, directly, which is similar to the multilayer SR motor reported in [4]. This proposed direct-drive scheme is able to solve the problem of the low efficiency and position control caused by backlash and extra mechanical losses in conventional 2-degree of freedom motion platform and hence the whole system efficiency is significantly improved.

In addition, due to the simple mechanical structure of the proposed 2-degree of freedom switched reluctance motor characterized by low cost, high robustness, variable speed regulation, etc., the cost of the whole system could be reduced. Meanwhile, the 2-degree of freedom switched reluctance motor can operate well under high temperature as well as deteriorated working environment because this motor has no permanent magnet.

The invention is the 2-degree of freedom switched reluctance actuator that consists of the frame, stator cores, stator coils, mover cores, air gaps between the stator poles and the mover poles, and the mover shaft, that integrates the longitudinal magnetic structure with the transverse magnetic structure, and relates to electromagnetic rotary-linear actuators. Besides, combining pole structure and small tooth structure can further enhance the efficiency of the rotary-linear actuator that can realize linear motion and rotary motion simultaneously.

The traditional form of rotating linear motion adopts two rotating motors or the combination of a linear motor and a rotating motor for implementation [5]-[7]. However, this combination not only increases size and weight of the drive, but also reduces working accuracy of the equipment. Therefore, to explore an integrated rotating linear motor, an optimized rotary-linear motor based on switched reluctance principle is presented. The structure of the motor for the vessel electrical propulsion system is also discussed and the structure of the motor is optimized in this paper. Until now, the integrated rotating linear motor is based on switched reluctance principle, which has been preliminary researched. A rotating linear switched reluctance motor presented in [8], is to integrate rotating motion and linear motion based on the minimum reluctance principle, while to achieve rotating linear motion, and to reduce volume of the driver and increase accurate position control. However, the coupling of this linear motor has occurred when both rotating motion and linear motion, and the motion of rotating and linear are produced by the same coils, so the motor will produce unwanted linear directional force upon the movement of rotating motion, and vice versa. A method of decoupling control for the reduction of coupling effect of the motor's operation has been proposed [9]; to excite reasonable distribution control current of the motor stator coil, and the decoupling of both rotating motion and linear motion have been implemented. Therefore, the control accuracy has been improved. Since the motor is based on the principle of switched reluctance, so the efficiency of switched reluctance is lower than other motors, and the force volume ratio is relatively poor [10]. Even the rotating linear motor has been controlled by the method of the decoupling, but cannot solve the problems of the lower conversion efficiency, the smaller torque and linear direction force [11], [12].

The paper presents an optimized rotating linear motor, and it is applied to the electric vessel. In the paper, firstly, a new structure of the motor is proposed. The mathematical model of the two - dimensional rotating linear is established. Secondly, through the finite element analysis of the motor, internal electromagnetic field distributions of the motor and force characteristics of the motor are obtained. Experiments are carried out to study the accurate control of motor. Thirdly, to control the position of motor and to realize the angle and position control, an optimization is needed to resolve the electrical propulsion performance, and also to improve the force to volume ratio.

II.CONSTRUCTION OF THE SYSTEM

A. Mechanical structure and basic control method of the electrical propulsion system

The new electrical propulsion system is only based on one two-degree switched reluctance motor to complete all propulsion operation, the two-degree switched reluctance motor have connected with propellers, which is shown in Fig.1. Therefore, in the Fig.2, the direction control is achieved by the linear motion of the motor and the linear acceleration control is achieved by the rotating motion of the motor. To compare with traditional electric vessel propulsion system, not only the operation of electric vessel is more hommization and convenience, but also the operation precision is improved. The electric vessel is readily for industrialized production.

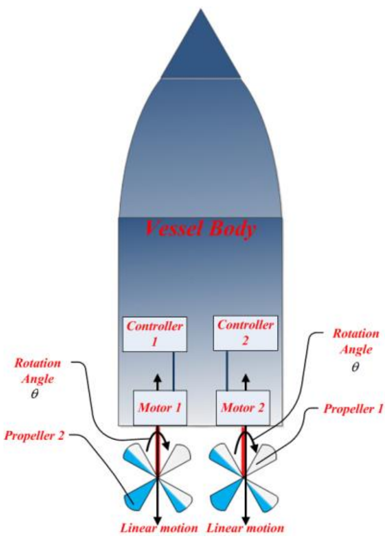


Fig.1 Mechanical structure of the electrical propulsion system

B. Actual structure of the motor

Fig.3 (a) is the mechanical configuration of the two degrees of freedom switched reluctance motor; Fig. 3 (a) is left view of the motor. It mainly consists of a linear guider, the first part and the second part. Both parts have teeth and slots. When each phase is excited, the second part will rotate to the position at which all teeth of the two parts are directly opposite. Fig.3 (b) is front view for the motor. As shown in the figure, the first part has three phases named as phase A, B and C, respectively. The second part has five units fixed on the linear guider. Two bearings are used to guider the movements of the second part both in rotary and linear directions. When phase A is excited, the second part will shift to left. Also, if phase C is excited, it will move to right. Therefore, the second part can realize linear motion to left by exciting phase A, C and B in sequence. The main specifications are listed in Table I.

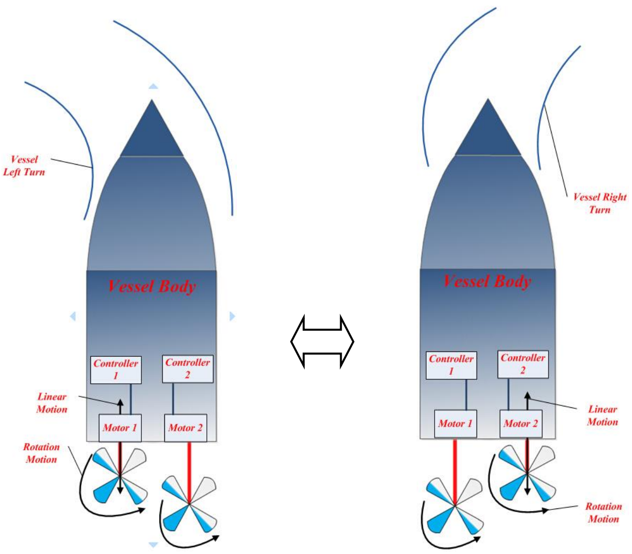
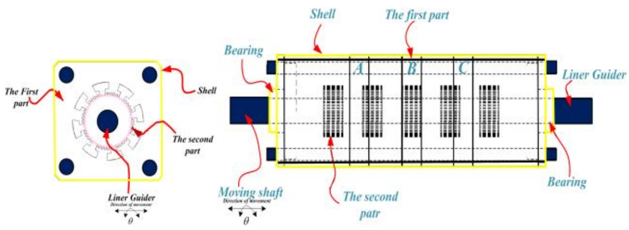


Fig.1 Basic control method of the electrical propulsion system



(a) (b)

Fig.3 The mechanical configuration of motor

The magnetic field generated by the concentrated coils passing current, rounding the core in the first part, attracts the second part. Based on the minimum reluctance principle, a unit of the second part will move to the position, which has the minimum reluctance, thus producing electromagnetic propulsion or torque. By controlling currents passing in the coils of the first part, the generated propulsion and torque will drive the second part and then it will realize rotary and linear motions simultaneously. As shown in Fig.3 (b), when the second part shifts linearly, phases A, B and C should be excited in turns. For example, phase B is totally aligned in the figure. At the position the second part would move left if phases A, C and B are excited in sequence and vise versa. For the first part, there are several small teeth in each pole and there are eight poles of each phase of the motor. The working rules probably the same as common switched reluctance drives, namely through controlling the ON/OFF conditions of the first pole. All of A, B and C phrase positions were fixed with one shaft, which would be led by two bearings in order to realize linear and rotational motions.

1) *Mathematic mode*

Equation (1) is the voltage equation for both rotary and linear parts [13].

$$V_{\mu} = R_{\mu} I_{\mu} + \frac{f_{\mu} dv}{dt} \tag{1}$$

And V_μ is the input voltage and I_μ is current for the u^{th} coil (u is1-6). R_μ is winding resistance for the coil, and f_μ is flux-linkage confirmed during excitation.

The rotary-linear machine consists of a coupled RL electromechanical system. From the rotary part with each stator ring, and equation (2) is the machine generalized torque characteristic T as,

$$T = Q\ddot{\theta} + G\dot{\theta} + T_L \tag{2}$$

where the moment of inertia is Q , rotational friction coefficient is G . Angular position is θ and load torque is T_L . For the linear motion, the generated force F is

$$F = S\ddot{z} + N\dot{z} + F_L \tag{3}$$

whereas mass of the moving shaft is m , and linear friction factor is L . The linear position and thrust force are X and F_L , respectively. Assume the magnetic circuit is not saturated in the linear motion region. Toward the phase inductance, the influence can be neglected for the phase current [22], also force can be estimated as,

$$\begin{cases} T = \dfrac{1}{2} \cdot \dfrac{\partial L_1}{\partial \theta} \cdot i_1^2 + \dfrac{1}{2} \cdot \dfrac{\partial L_2}{\partial \theta} \cdot i_2^2 \\ F = \dfrac{1}{2} \cdot \dfrac{\partial L_1}{\partial x} \cdot i_1^2 + \dfrac{1}{2} \cdot \dfrac{\partial L_2}{\partial x} \cdot i_2^2 \end{cases} \tag{4}$$

And L_1 and L_2 are total inductances, and i_1 and i_2 are the two stator rings current, respectively. It can be found that the torque and force generation are both dependent on phase current of the stators. The stator ring for linear motion in the mean time can generate the torque. Consequently, the magnetic paths are nonlinear and highly coupled.

2) *Electromagnetic characteristics*

In order to analyze the magnetic field distribution and properties of the motor, FEM is employed. The mesh model of the motor as shown in Fig.4, actually, it is a model with symmetrical structure, which subdivides the computational nodes and reduces calculation time. It can be concluded from the figure, subdivision of the air gap between two parts is intensive, and the more unions of subdivision were set, the higher quality of computation could be obtained.

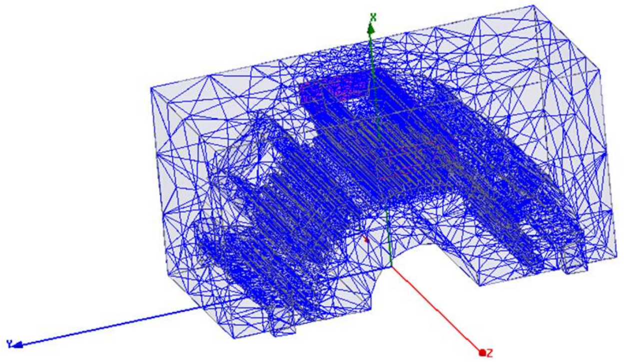


Fig.4 is the distribution of magnetic flux lines in the motor When it works, it is clear to see that the electromagnetic torque or propulsion is produced when the magnetic flux lines are closed from the first part to the second. The flux linkage will be built when the coils are excited. When the motor moves, the magnetic lineation of the field coil is in the same flat with the second part. Fig.5 describes the distribution of magnetic lineation when the second part moves in the position that is not aligned with the first part. When the motor works in the linear direction, magnetic flux line is vertical with the direction of the linear direction, which is different from the principle of producing tension when the motor moves. So the motor can produce not only torque, but also the propulsion in the linear direction, thus decreasing the volume of the two dimensional motions actuators and simplifying the execute components. In addition, there is no need to add any intermediate mechanical converters because both of the torque and linear propulsion of the motor are direct-drive mode, which can realize the precise position control.

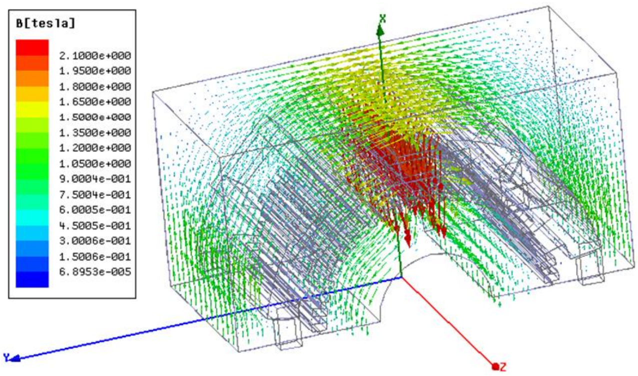


Fig.5Magnetic field distribution of the motor in rotary direction

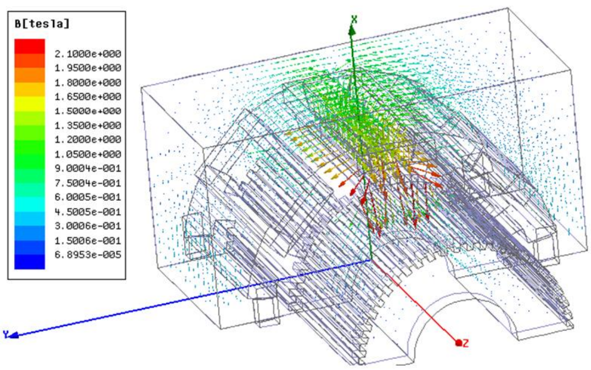


Fig.6 Magnetic field distribution of the motor in linear direction

From the distribution of magnetic field, the rectilinear motion of the motor and the magnetic field both come from the same coil, thus, the motor in rectilinear motion will produce the torque of rotational motion. There is coupling between them, however, it is acceptable to avoid the coupling by a kind of decoupling controlling method, in order to realize the high quality controlling.

Fig.7 and Fig.8 are the waveforms of FEM calculation from the torque and rectilinear directions. Fig.7 is the waveform of measured torque data. Any phrase position excites, the maximal torque is 0.71N.m, and the torque will not increase accordingly under large current, because the motor has saturated, the permeability of magnetic material and the volume of motor limit the increase in magnetic field intensity, which can make the increase in torque inconspicuous.

TheFig.8,that the propulsion of the motor is increased with therising of phase current because it is hard to reach the sa turated point to the motor as it moves from unaligned Posit ionton aligned position, during which the reluctance is big enough. This figure shows the propulsion profiles corresponding to all positions during a stroke. The linear propulsion is relatively low and up to 10N at the rate current.

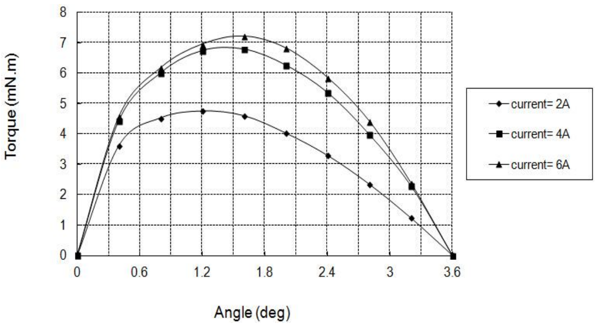


Fig.7 Torque output with different currents

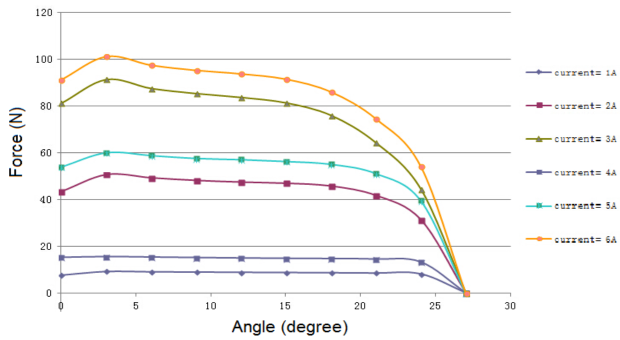


Fig.8 Force output profiles corresponding to position

From the analysis above, this two-degree of freedom stabilized platform motor can directly realize the motions of linear and rotary movements.

III.POSITION CONTROLLER DESIGN FOR THE TRACKER

Two PID controllers are employed for linear and rotary motions [14] for the tracking system and the whole control scheme is expressed in Fig.9.

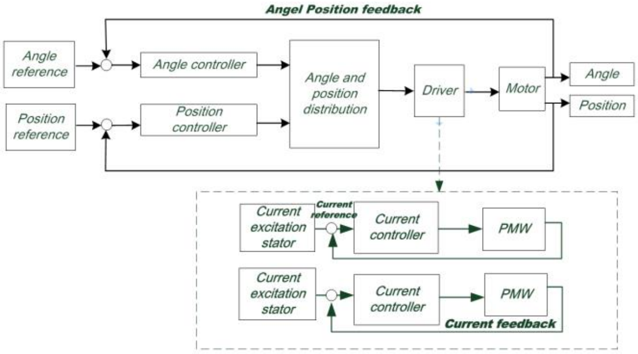


Fig.9 Control block of the motor

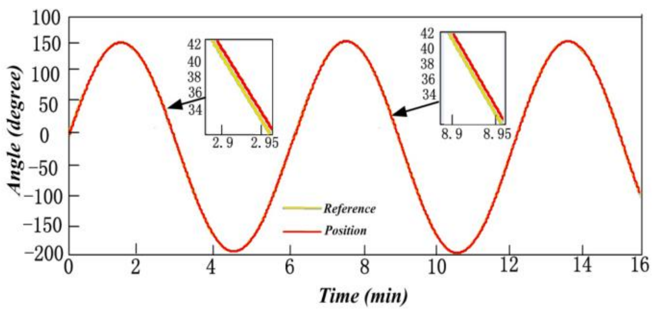
The control system is divided into two parts. On one hand, a controller regulates the linear motion whose axis is responsible for the perpendicular motion for the electric vessel. On the other hand, another controller gives the horizontal movements for the system controls in rotary motion. The feedbacks of both the two axis positions of angle and linear displacement are sampled by a sensor which tracks movements of the sun. Controllers output the force and torque reference commands for the force to current and torque to current distribution parts [15]-[17]. Finally, the two distribution parts output current commands for the divers to the motor. The trajectories of the two axes for the motor are obtained in the end as shown in Fig.9. The simple PID controller can be applied in angular and linear position control with control parameters in Table I.

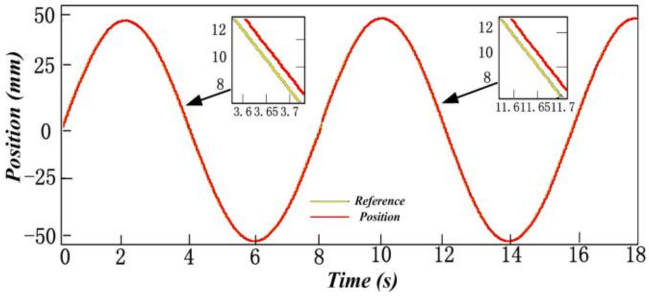
Table I. Parameters of position controllers

Parameters controller	Angular position controller	Linear position
P	0.410	32.5
I	6.006	2.2
D	0.005	0.008

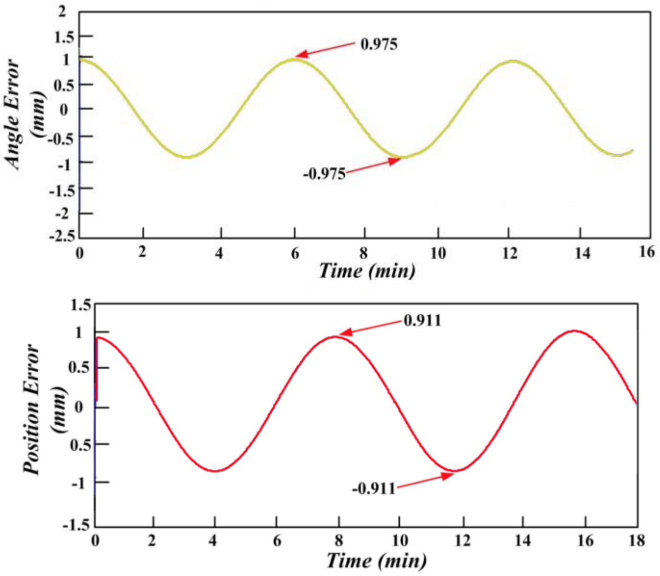
IV.EXPERIMENTAL RESULTS

The achievements of experimental is shown in Fig.10, with A DSPACE DS1104 controller card, the encoders collect the position feedback with two channels of quadrature encoder pulse interface, also for each stator, the controller card generates the current reference of any phase. Lastly, the six current drivers generate the phase current outputs.





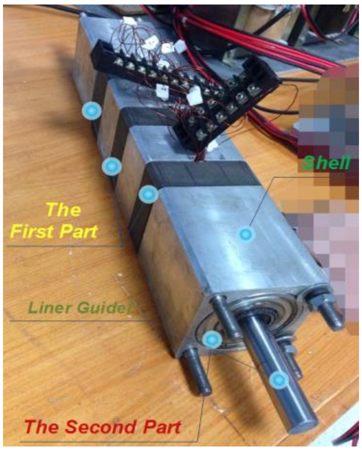
(a)



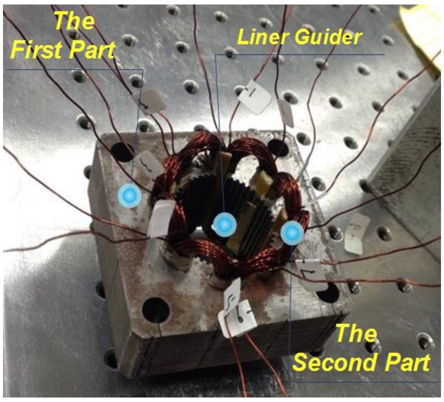
(b)

Fig.10(a) Position control performance for rotary and linear motion (b) Dynamic error response

In Fig.10 (a) and (b) proved the position control performance and the theory of dynamic tracking error response. The results shows that the proposed two-degree freedom of SR motor not only has a high position tracking precision of less than 0.4°, but also the performance of the period of working is stable and reliable. Consequently, the achievements of theory analysis and FEM have been proved by the improvements of the proposed setup



(a)



(b)

Fig.10 (a) and (b) are the prototype of the 2-degree freedom of SR motor

The structure of the proposed motor is shown in (b) and (C), its features and operated performance have been discussed in detail above.

V.CONCLUSION

This paper proposed a modified electric vessel based a new 2-degree of freedom SR motor, also its analysis of theory, configuration and control method are described in detail. Lastly, the achievements of experiment have proved the improvements of the modified electrical propulsion system of the vessel. Using a 2-degree SR motor to replace the two conventional motors is novel for such application.
The proposed electric vessel is not only simplifying the operation method, also promoting the direction precision. Consequently, the experiment has proved the improvements of the system, and it will be used for wider industrial applications with its attractive superiority.

REFERENCE

[1] G. Krebs, A. Tounzi, B. Pauwels, D. Willemot, and F. Piriou, “Modeling of a linear and rotary permanent magnet actuator,” IEEE Trans. Magn., vol. 44, no. 11, pp. 4357–4360, Nov. 2008.
[2] T. Onuki, et al., "Induction motor with helical motion by phase control," IEEE Transactions on Magnetics, vol. 33, pp. 4218-4220, 1997.
[3] J. Alwash, et al., "Helical motion tubular induction motor," IEEE Transactions on Energy Conversion, vol. 18, pp. 362-369, 2003.
[4] E.S. Afjei and H.A. Toliyat, "A novel multilayer switched reluctance motor," IEEE Transactions on Energy Conversion, vol. 17, pp. 217-221, 2002.
[5] C. T. Liu and T. S. Chiang, “Design and performance evaluation of a microlinear switched-reluctance motor,” IEEE Trans. Magn., vol. 40, no. 2, pp. 806–809, Mar. 2004.
[6] Y. Sato, “Development of a 2-degree-of freedom rotational / linear switched reluctance motor,” IEEE Trans. Magn., vol.43, no.6, 2007, pp.2564-2566
[7] Pan, Yu Zou, Cheng. N. C, “Performance analysis and decoupling control of an integrated rotary–linear machine with coupled magnetic paths”, IEEE Transactions on Magnetics, Vol. 50, Issue: 2, 2014
[8] X.D. Xue, K.W.E. Cheng and S.L. Ho, “Influences of output and Control Parameters on Power Factor of Switched Reluctance Motor Drive Systems”, Electric Power Components and Systems, Dec 2004, Vol. 32, No. 12, pp. 1207-1223.
[9] X.D. Xue, K.W.E. Cheng and S.L. Ho, “Improvement of power factor in switched reluctance motor drives through optimizing in switching angles”, Electric Power Components and Systems., Dec 2004, Vol. 32, No. 12, pp. 1225-1238.

[10] X.D. Xue , K.W.E. Cheng and S.L. Ho, "Simulation of Switched Reluctance Motor Drives Using Two-dimensional Bicubic Spline", IEEE Tran. Energy Conversion. Dec 2002, Vol. 17, Issue 4, pp. 471-477.
[11] Y. -C. Lai, Y. -L. Lee, and J. -Y. Yen, "Design and servo control of a single-deck planar maglev stage," IEEE Trans. Magn., vol. 43, no. 6, pp. 2600–2602, Jun. 2007
[12] G. Li, J. Ojeda, S. Hlioui, E. Hoang, M. Lecrivain, and M. Gabsi, "Modification in rotor pole geometry of mutually coupled switched reluctance machine for torque ripple mitigating," IEEE Trans. Magn., vol. 48, no. 6, pp. 2025–2034, Jun. 2012.
[13] X.D. Xue, K.W.E. Cheng and S.L. Ho, "Improvement of power factor in switched reluctance motor drives through optimizing in switching angles", Electric Power Components and Systems., Dec 2004, Vol. 32, No. 12, pp. 1225-1238.
[14] M. Bodson, J. Chiasson, R. Novotnak, and R. Ftekowski, "High-per-formance nonlinear feed back control of a permanent magnet stepper motor," IEEE Trans. Control Syst. Technol. , vol. 1, no. 1, pp. 5–14, Mar. 1993.
[15] D. Chen and B. Paden, "Adaptive linearization of hybrid step motors: Stability analysis," IEEE Trans. Autom. Control, vol. 38, no. 6, pp. 874–887, Jun. 1993.
[16] S. A. Stuart, J. E. McInroy, and R. M. Lofthus, "Closed loop low- velocity regulation of hybrid stepping motors amidst torque distur- bances," IEEE Trans. Ind. Electron. , vol. 42, no. 3, pp. 316–324, Jun. 1995.