A Low-Cost Linear Switched Reluctance Motor with Integrated Position Sensor for General-Purpose Three-Phase Motor Controller

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Abstract— **This paper presents a novel linear switched reluctance motion system that can be driven by a general-purpose motor controller hardware. This is achieved by two methods: a low-cost position sensor is first integrated into the linear switched reluctance motor (LSRM) by making use of the unique open structure feature of the motor. The resolution of the position sensor is further enhanced via sine-cosine interpolation. The output of the proposed position sensor is a standard quadrature (A,B) signal for industrial encoder interfacing. Then with a proper reconfiguration of the three-phase motor windings and the insertion of three diodes, the LSRM can be driven by a standard three-phase bridge inverter with two current feedback sensors only. By combining the proposed low-cost position sensor and the novel driving scheme, the LSRM can directly replace any three-phase linear AC permanent magnet (PM) motors or linear AC induction motors without any hardware reconfiguration. This would increase the popularity of applying LSRM in motion control system.**

I. Introduction

Linear switched reluctance motor (LSRM) has never been a popular choice for direct-drive linear motion control system; because it is difficult to control and its output has high torque ripples. It is also due to the fact that the actuator's characteristic is highly dependent on its complex magnetic circuit, which is difficult to model, simulate, and control. There is little in recent literature which concerns with high performance motion control of switched reluctance linear drive systems. It was only until recent years which we see a general surge of interest in the switched reluctance motor [1]. This was mostly due to the advancement of power electronics and digital signal processing, and the continuous trend of "simplifying the mechanics through advance control strategy".

In comparison to the linear AC permanent magnet(PM) motor or the linear AC induction motor, LSRM serves many advantages that other actuators do not have. Firstly, manufacturing of the LSRM is simple, and it is very suitable for high-precision travel over long distances. Secondly, unlike other types of motion actuators, mechanical couplings, lead screws, magnets, and brushes are not required in LSRM. Special mechanical adjustments or alignments are also not necessary. Finally, in comparison to PM linear motor, the proposed actuator has a much simpler structure and is less expensive. It is also more robust and more fault tolerant, and has less overheating problem. Therefore, LSRM is a potential candidate for high performance linear motion drive.

Fig. 1 shows a general-purpose three-phase motor controller. The main component of the controller is either

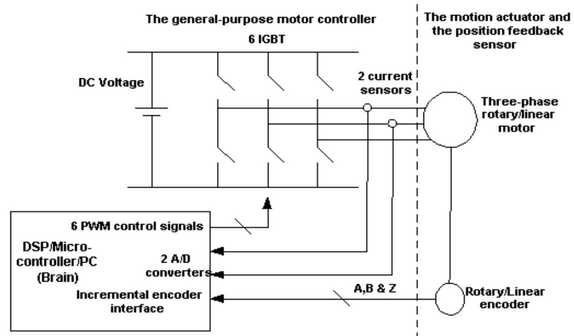

Fig. 1. Block diagram of a general-purpose three-phase motor controller.

a digital signal processor, a microcontroller or a personal computer (PC) which serves as the brain of the overall system. It performs the profile generation, the complex control algorithm and the PWM control, etc. The standard hardware interface for a three-phase motor system consists of a three-phase bridge inverter (6 IGBTs) and six PWM driving signals, two current sensors and two A/D converters, as well as the quadrature (A,B) and index Z encoder signal interface. By using the structure in Fig. 1, both three-phase linear/rotary PM/induction motors can be driven by only changing a proper control algorithm in the host controller but without any hardware reconfiguration. However, a hardware change is needed in order to drive a three-phase rotary/linear SRM. For example, the drive stage may be reconfigured as three asymmetric bridges [1] and uses three current sensors and three A/D converters. The lost of the generality for a three-phase LSRM drive is an obstacle to promote its popularity in industrial applications. Sensorless control for SRM driver has been studied rigorously in [2], [8]; however, these sensorless algorithms require another A/D converter or digital I/O for interfacing with the host controller. In other words, extra hardware is needed and the hardware generality is lost. In addition, presently reported research on sensorless control does not provide an all round answer for accurate and reliable position control of LSRM. A general solution remains to be found. In summary, if a reliable and low-cost position sensor as well as a three-phase bridge driving scheme can be developed for the LSRM, the popularity of applying LSRM in industrial motion control system can be promoted.

A LSRM control system for high-precision accuracy was developed by the authors and the results can be found

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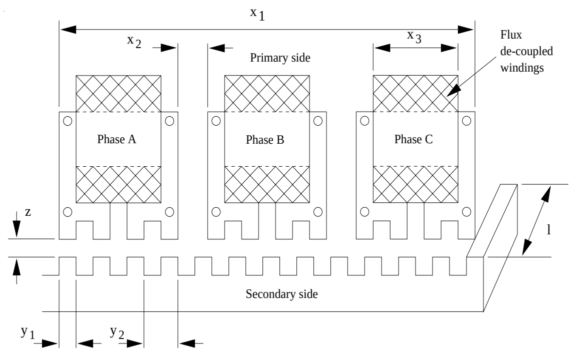

Fig. 2. LSRM design schematic.

in [3], [4]. In this paper, a low-cost position sensor with reasonable resolution is first developed for the LSRM by using its unique open structure feature, and then the resolution of the position sensor is enhanced via sine-cosine interpolation. The output of the proposed position sensor is a standard quadrature (A,B) signal for industrial encoder interfacing. Then with a proper reconfiguration of the three-phase motor windings and the insertion of three diodes, the LSRM can be driven by a standard three-phase bridge inverter with two current feedback sensors only. By combining the proposed low-cost position sensor and the novel driving scheme, the LSRM can directly be driven by the general-purpose three-phase motor controller structure as shown in Fig. 1 without any hardware reconfiguration. The only change is the easily reconfigurable control software inside the motion controller.

The paper is organized as follows. Section II gives a brief review on the construction and development of the LSRM. In Section III, the low-cost position sensor is introduced to sense the motor position by making use of the open structure of the proposed LSRM, and the sine-cosine interpolation algorithm is employed to increase the sensor resolution. In Section IV, the three-phase motor winding reconfiguration and the novel winding excitation scheme are described, so that the proposed LSRM can be driven by a standard three-phase bridge inverter. The system integration and experimental results are shown in Section V to validate the proposed LSRM, the low-cost position sensor and the novel driving scheme. Some concluding remarks are given in Section VI.

II. Review on the Construction and Modeling of the LSRM

The novel actuator design is based on switched reluctance technology [4]. The magnet-free structure makes this actuator particularly suitable for harsh environment such as high temperature and high pressure. The flux de-coupled rotor arrangement leads a more simple motor model because there are no mutual inductances between windings. Fig. 2 shows the design schematic of the LSRM system.

The motor is integrated on a precision linear motion guide. The tracking guide and the core of the windings are laminated with 0.5mm silicon-steel plates. Table I shows the design parameters of the proposed LSRM.

The switched reluctance linear drive system has a highly nonlinear characteristic due to its non-linear flux behavior. Following is the nonlinear mathematical model of the LSRM:

$$v_j = R_j i_j + \frac{\partial \lambda_j(x,i_j)}{\partial x}\frac{dx}{dt} + \frac{\partial \lambda_j(x,i_j)}{\partial i_j}\frac{di_j}{dt} \quad (1)$$

$$f_e = \sum_{j=1}^{3} \frac{\partial \int_0^{i_j} \lambda_j(x,i_j) di_j}{\partial x} \quad (2)$$

$$f_e = M\frac{d^2x}{dt^2} + B\frac{dx}{dt} + f_l \quad (3)$$

where v_j, i_j, R_j and λ_j are the phase voltage, phase current, phase resistance and phase flux linkage respectively, x is the travel distance, f_e is the generated electromechanical force, f_l is the external load force, M and B are the mass and the friction constant respectively.

The 3-D force-current-position function $f_e(x, i_j)$ and the 3-D current-force-position function $i_j^*(x, f_j)$ are measured experimentally and stored in a table for the purpose of force linearization control which will be described in Section V.

III. Low-Cost Position Sensor for LSRM

With an expensive and accurate optical encoder installed, the proposed LSRM can achieve accurate position tracking responses [3]. However, the cost of the optical encoder alone is about one third of the overall system. Therefore, a novel low-cost position sensor with reasonable resolution is developed in this section to reduce the cost of the LSRM system further.

To eliminate the delicate and expensive linear optical encoder, position sensing for switched reluctance motors can be achieved through indirect position estimation or observer based position estimation. Indirect position estimation involves obtaining position from a second variable. Current signal, flux, inductance, mutual inductance and di/dt of PWM waveform [7]- [11] have been used for the position information estimation. However, the above type of position sensing methods suffer from one or more of the following deficiencies:

- Inoperative at low or zero speed.
- Inaccurate during large speed dynamics.

TABLE I
Design parameters of the LSRM.

Power output	100 W
Traveling distance	300 mm
Maximum load	5kg
Pole width	5 mm (y_1)
Pole pitch	10 mm (y_2)
Coil separation	8.333 mm (x_2)
Winding width	15 mm (x_3)
Track width	25 mm (l)
Air gap width	0.4 mm (z)
Aligned phase inductance	19.8mH
Unaligned phase inductance	11.4 mH

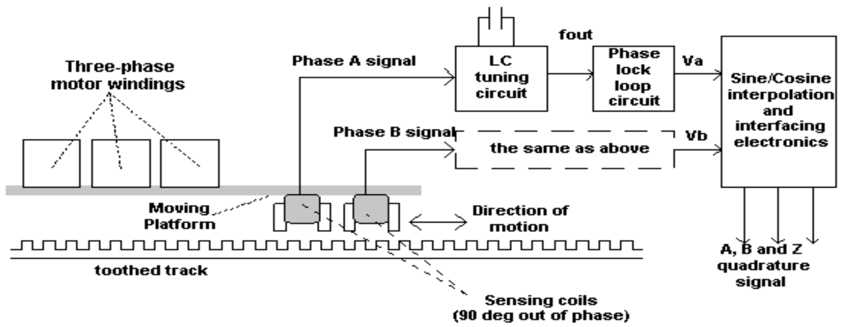

Fig. 3. Structure of the position sensor for the LSRM.

- Unreliable readings under frequent direction reversals.
- Cannot operate at high speed.

Thus the above methods are unsuitable for high acceleration/deceleration trajectory control of limited stroke LSRM.

To overcome the above problems, we propose to measure the inductance change on the tooth track of the LSRM to obtain the position information. The proposed method takes advantage of the fact that the LSRM is an "open structure" and inductance-sensing coils can easily be incorporated into the motor. Additionally, the tooth track is an ideal "ruler" for position measurement. To provide a reliable position output under frequent direction reversals, two search coils are needed, and they should be aligned 90 degrees out of phase.

Fig. 3 shows the block diagram of the position sensing system. Since the main coils of the LSRM are located far away from the sensing coils, there is no cross-interference between the motion coils and the sensing coils.

A. Signal Processing and Information Extraction

To measure the inductance variation of the tooth track, a low current and high frequency signal is injected into the sensing coils. This prevents errors due to hysteresis and saturation effects. A phase lock loop interface circuit shown in Fig. 3 is used to detect the change in frequency. An output voltage, which is proportional to the frequency, is produced for each channel.

In general, the inductance variation along the tooth track is not a pure sinusoidal function and hence tradition circuits for sine-cosine interpolation cannot be applied. In addition, the voltages output from the phase lock loop (V_a,V_b) are shifted by a constant DC offset. To compensate the offset value, a trail run calibration is performed and an offset value is added to the two outputs.

B. Resolution Enhancement via Sine-Cosine Interpolation

The resolution of the tooth track is inadequate for the commutation process of the LSRM and a smooth trajectory motion tracking. Thus a simple and effective method of resolution enhancement needs to be proposed to enhance the sensor resolution. The method employed in this paper is the extension work of [5] and this proposed method uses very few components to accomplish the sine-cosine interpolation task, and does not need to use any expensive resistor networks, additional computing overheads, or data acquisition units.

The method takes advantage of the fact that both channel A and channel B waveforms decrease by the same ratio when the vector rotating speed is increased, and the shape of the semi-circular profile remains the same. Therefore, instead of comparing the waveforms to reference voltages, the two waveforms can be compared with each other to find out the angle of the rotating vector, and deduce the immediate position values. The problems of non-circular locus and signal variation at different speeds can be effectively eliminated. To provide maximum resolution enhancement while minimizing the circuit complexity, a 16-fold resolution enhancement is chosen. The interpolation unit divides the sine-cosine cycle into 16 sections, with an angular distance of 22.5° for each section.

Fig. 4 shows the concept of non-sinusoidal interpolation/sectioning. Due to the fact that both outputs are non-sinusoidal, the locus of the X-Y plot is not an ideal circle. After acquiring the two voltage levels from the phase lock loop outputs, a simple interpolation circuit is used to determine the angle of the rotating vector.

The rotating vector diagram shown in Fig. 4 is sectioned into 16 equal parts. Boundary lines ($L0$-$L7$) are used to divide the 16 sectors ($S0$-$S15$). The position of the search coils are represented by a rotating vector in Fig. 4. In this

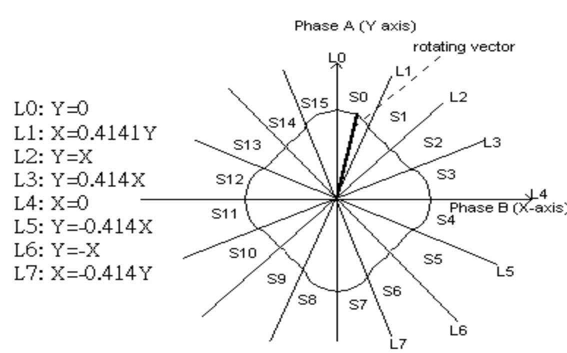

Fig. 4. Non-sinusoidal interpolation/sectoring.

TABLE II

MATCHING THE OUTPUT TO THE BOUNDARY CONDITIONS.

O/P	I/P	O/P Sector
Ch. A	$(X > 0)$ & $(Y > X)$	$S0$, $S1$ high
	$(Y < 0)$ & $(-Y < X)$	$S4$, $S5$ high
	$(Y < 0)$ & $(Y < X)$	$S8$, $S9$ high
	$(Y < 0)$ & $(-Y < X)$	$S12$, $S13$ high
Ch. B	$(0.4141Y < X)$ & $(Y > 0.414X)$	$S1$, $S2$ high
	$(-Y > 0.414X)$ & $(-0.414Y < X)$	$S5$, $S6$ high
	$(0.4141Y > X)$ & $(Y < 0.4141X)$	$S9$, $S10$ high
	$(-Y < 0.414X)$ & $(-0.414Y > X)$	$S12$, $S13$ high

way the change of signal amplitude will merely change the magnitude of the rotating vector; the angle of the rotating vector remains the same. By testing boundary conditions of the rotating vector, one can find out which sector the rotating vector resides.

By setting the conditions for each of the sector (e.g. $S0 \Rightarrow Y > 0$ and $X < 0.414Y$), all 16 sectors can be identified. Since the interpolation unit is designed to be interfaced with conventional quadrature decoding unit, the interpolation unit should output 90° phase-shifted A-B digital pulse-trains, as shown in Fig. 5. The figure shows that for channel A, the output is high at $S0$, $S1$, $S4$, $S5$, $S8$, $S9$, $S12$, and $S13$. For channel B, output is high at $S1$, $S2$, $S5$, $S6$, $S9$, $S10$, $S13$, and $S14$. These output criteria can be matched with the boundary conditions of Fig. 4, to form a Table II. The 16 sectors can then be translated into A-B pulse-trains (with ×4 resolution increase) for industrial incremental encoder interface. The present system uses 16 times interpolation enhancement and the circuit is built by using standard logic gates and operational amplifiers [5]. However, under the proposed method, sine-cosine interpolation units with much higher resolution increase (×32 or ×64) can be easily designed and implemented by using a mixed-signal ASIC chip. Table III summarizes the electrical characteristic of our proposed position sensor.

IV. Three-phase bridge inverter for LSRM

In general, SRMs are driven by special inverters such as asymmetric bridge, unipolar converter and C-Dump converter [1], [12], [13]. There is not much concern on designing a SRM driver by using a standard three-phase bridge before [14], [15]. The advantages of using a standard three-phase bridge are the reduction in the size and cost of the motor driver, the reduction in stray inductance and EMI problem, and the direct compatability to other three-phase motors. The dwell angle limitation in [14] is not suitable for the current tracking control in an accurate position control system. The inverter topology and the motor winding configuration employed in this paper is based on [15] with

TABLE III

ELECTRICAL CHARACTERISTIC OF THE POSITION SENSOR.

Resolution Output	$625\mu m$
Track pitch	10mm
Output Signal	A,B TTL quadrature signal

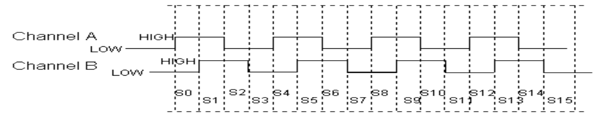

Fig. 5. The quadrature output waveform of the 16-fold interpolation unit.

modification on the phase current excitation sequence for the proposed LSRM.

Fig 6 shows a general three-phase bridge inverter for a three-phase linear/rotary PM/induction motor. The current loop controllers such as PI compensators are assumed to be appropriately designed or well-tuned so that the closed-loop bandwidth is adequate for an accurate command tracking. As the summation current of a three phase system is equal to zero, i.e. $I_r + I_s + I_t = 0$, the control of three phase current is equivalent to the control of two phase currents, I_r and I_s, and the third current is slave to the other two as $I_t = -I_r - I_s$. Hence only two current sensors are enough for feedback purpose. However, the zero current summation assumption is not valid for SRM in general. The phase current excitation for the proposed LSRM is shown in Table IV.

Electromechanical force generation in the LSRM is a function of current magnitude only. By making use of this “unipolar” current driven feature, the LSRM can still be driven by the standard three-phase bridge inverter as shown in Fig. 6 with a proper motor winding reconfiguration. Firstly, the diode insertion in each phase is to guarantee unipolar current flowing, i.e. $I_a > 0$, $I_b > 0$ and $I_c > 0$. Secondly, the delta connection of the three-phase windings is to guarantee $I_r + I_s + I_t = 0$ with the current relations shown below:

$$I_r = I_c - I_a, I_s = I_a - I_b, I_t = I_b - I_{c.} \tag{4}$$

Finally, by using (4), the magnitude of I_a, I_b and I_c can be independently controlled by two phase current I_r and I_s. The detail excitation table is shown in Table V.

In summary, with the help of the delta motor windings reconfiguration, the insertion of the diodes and the two phase command current excitation table, the LSRM can be driven by a standard three-phase bridge with only two current sensors for feedback purpose. Hence the proposed LSRM is now ready for connection to any general-purpose three-phase motor driver without any hardware change.

TABLE IV

CURRENT EXCITATION TABLE FOR A SINGLE POLE PITCH.

Region	Range(mm)	For +ve force	For-ve force
1	0-1.667	I_b	I_c, I_a
2	1.667-3.333	I_b,I_c	I_a
3	3.333-5	I_c	I_a, I_b
4	5-6.667	I_c,I_a	I_b
5	6.667-8.333	I_a	I_b, I_c
6	8.333-10	I_a,I_b	I_c

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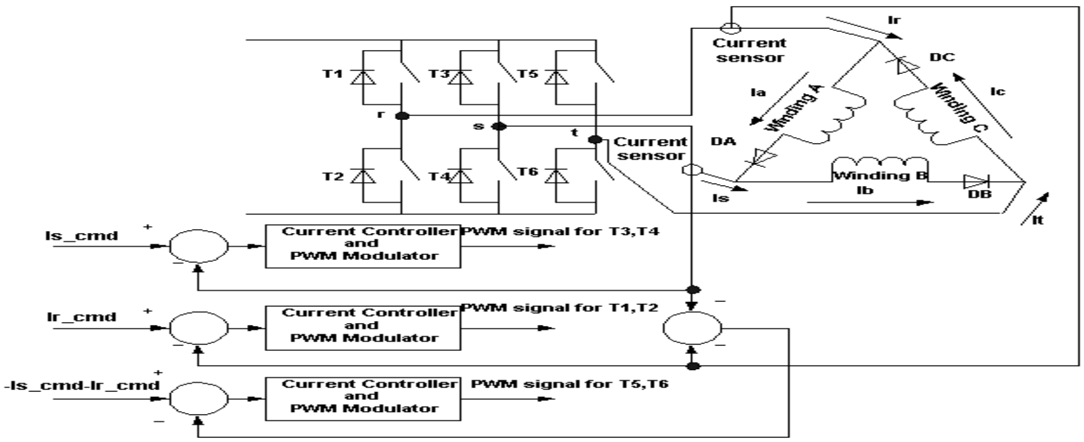

Fig. 6. Three-phase bridge inverter for LSRM.

TABLE V

Current excitation table by using I_r and I_s only.

Region	For +ve force	For-ve force
1	$I_r = 0$,$I_s = -I_b$	$I_r = I_c - I_a$, $I_s = I_a$
2	$I_r = I_c$,$I_s = -I_b$	$I_r = -I_a$,$I_s = I_a$
3	$I_r = I_c$,$I_s = 0$	$I_r = -I_a$, $I_s = I_a - I_b$
4	$I_r = I_c - I_a$,$I_s = I_a$	$I_r = 0$,$I_s = -I_b$
5	$I_r = -I_a$,$I_s = I_a$	$I_r = I_c$,$I_s = -I_b$
6	$I_r = -I_a$, $I_s = I_a - I_b$	$I_r = I_c$,$I_s = 0$

V. System Integration and Experimental Results

With the proposed low-cost position sensor and the driving scheme by using a standard three-phase bridge, the overall system was integrated as shown in Fig. 7. The dSPACE DS1102 was employed as the motion controller with only two A/D converters, six PWM driving signals and one quadrature encoder interface.

Force linearization is the backbone in a LSRM position control system. A simple but effective look-up table for force linearization is employed in this paper [3]. Fig. 8 shows the 21×21 current-force-position look-up table that is stored in our motion controller. The required current i^* can be evaluated via bi-linear interpolation. From the position x_{in} and force F_{in} inputs, two pairs of data in the look-up table $i_{(F_1,x_1)}$, $i_{(F_2,x_1)}$ and $i_{(F_1,x_2)}$, $i_{(F_2,x_2)}$ are located. For each pair, a linear interpolation is done, according to the ratio of F_1, F_2, and F_{in}. As a result two intermediate elements $i_{(F_{1-2},x_1)}$ and $i_{(F_{1-2},x_1)}$ are obtained. The output current command i^* is obtained by interpolating the two intermediate elements with x_1, x_2, and x_{in}. The outer position loop controller is a standard PID type with velocity and acceleration feedforward control.

To test the performance of the proposed system, a 50mm third order position profile was used as the test signal. Fig. 9 and 10 show the experimental results. Fig. 9(a) shows the comparison between the output position measured by the proposed low-cost sensor and the command reference, the output position tracks closely with the command reference with only a small overshoot and a small time lag in the transient region. In the steady state, the error is equal to the sensor's resolution (625μm). Fig 9(b) shows the output position comparison between the proposed sensor and an accurate optical encoder (2μm resolution) which has already been installed in the LSRM, it can be seen that the two curves are very close to each other. This demonstrates the functionality of the proposed position sensor. Fig. 10 shows the current signals of the three-phase bridge inverter for the LSRM. The measured unipolar current for phase winding A is depicted in Fig. 10(a) while the phase current $I_r = I_c - I_a$ is shown in Fig. 10(b), which has both positive and negative values. The promising experimental results demonstrate that the proposed system can be used as an accurate position tracking system.

VI. Conclusions

In this paper, a low-cost LSRM for position control application is designed, manufactured and verified. The LSRM does not equip with any expensive optical encoder for feedback purpose; instead, a low-cost position sensor with reasonable resolution is developed. The unique "open structure" of the LSRM makes the installation of the inductance variation sensing coils without any difficulties, and a reliable position sensing system can then be constructed. The resolution of the proposed sensor is further enhanced via the sine-cosine interpolation. The output (A,B) quadra-

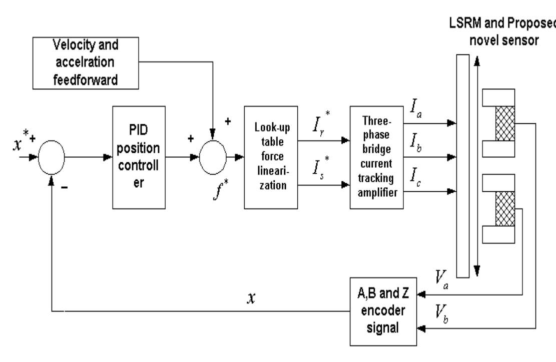

Fig. 7. System integration block diagram.

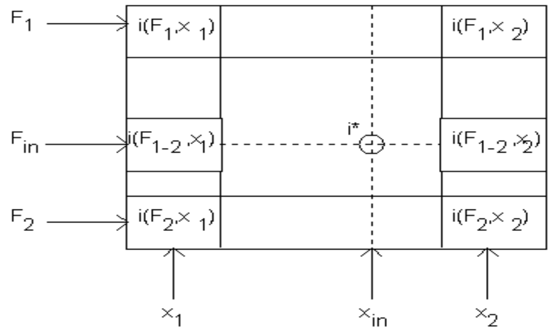

Fig. 8. Calculating i^* from the look-up table.

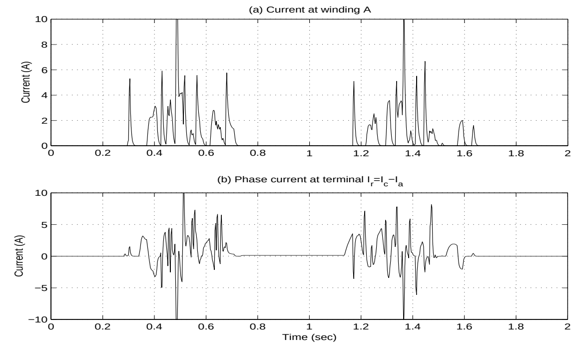

Fig. 10. Current signals for the three-phase bridge inverter.

ture signals can be synthesized by using simple logic and op-amp circuits.

The LSRM can be driven by a standard three-phase bridge inverter with the proposed driving scheme introduced in Section IV; therefore, the size of the overall driver can be reduced, the EMI problem can be alleviated and the cost of the whole system can further be reduced. The feasibility and the effectiveness of the proposed position sensor and the inverter are supported by the experimental results shown in Section V.

In conclusion, the LSRM described in this paper is robust, reliable and low-cost. The proposed LSRM can work with the general-purpose three-phase motor controller without any hardware change. Therefore, this LSRM is a direct replacement of any linear three-phase PM/induction motor. It is more reliable and robust in structure, and it has a lower manufacturing cost. The popularity of applying LSRM in industrial applications can definitely be promoted by the proposed system.

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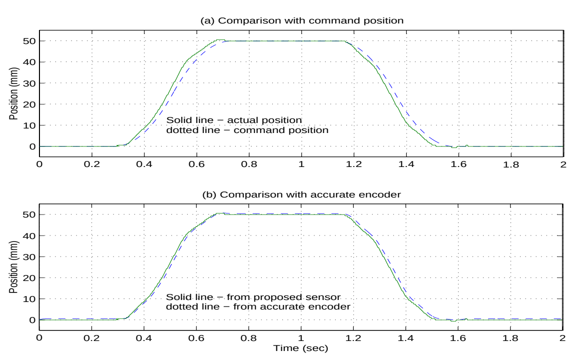

Fig. 9. Position tracking response.

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