Accurate Rotor Position Detection and Sensorless Control of SRM for Super-High Speed Operation

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***Abstract*—Based on the general nonlinear magnetizing model (GNMM) from our previous research work, an improved method of detecting rotor position for sensorless control of SRMs in super-high speed operation has been developed. With minimum input data, the approximated GNMM is obtained and the rotor speed estimated. Then the rotor position is detected by the motion equation. To remove rotor position error, the proposed scheme updates the reference at critical points using the flux observation. Further, the GNMM is adaptively tuned based on the updated information. The improved rotor position detection method has been implemented by fully exploring the computation power of the modern DSP. Laboratory verification on different types of SRMs with sensorless control up to 20,000 rpm is accomplished.**

***Index Terms*—Adaptive, DSP, general nonlinear magnetizing model (GNMM), sensorless, super-high speed, switched reluctance machine.**

I. INTRODUCTION

SWITCHED reluctance machine has been getting much attention in recent years due to its simple and solid structure, no rotor excitation, and high speed capability. Particularly in super high speed applications like washing machine, centrifuge for blood separation, and aerospace craft, a SRM has advantages over other machines. In terms of control, due to the separate stator phase excitation, the inverter for SRM is simple and easy to build. However, in order to provide correct excitation, the SRM rotor position must be known. An encoder or resolver can be used for rotor position detection, which will increase cost and reduce reliability of the entire SRM drive system. Sensorless control has been applied in other machines like induction and PM machines for years. Though, in principle, the sensorless control techniques for induction and PM machines could be applied to SRM, there are some differences. For example, it is more difficult to build an analytical model for a SRM than for an induction or PM motor.

For the sensorless control of SRMs, generally speaking, there are two basic types of position estimation methods, active probing and nonintrusive estimation. In active probing [1]–[3], special testing signals are injected into an unenergized phase. The position-dependent information is extracted by additional decoding circuit. In nonintrusive ways, the dependence of phase current and phase winding flux linkage on rotor position is utilized [4]–[6]. Recently, intelligent estimation like artificial neural networks (ANN) and fuzzy logic has been used in speed estimation in [7]–[10]. Either in an active probing or nonintrusive method, the dependence of the sensed information on rotor position must be predetermined. In ANN and fuzzy logic, offline training based on prestored data is required. Further, no much attention has been given to address special issues associated with super high speed application where fast and timely estimation of rotor position is extremely important.

A popular method of sensorless control of SRM is to look up a prestored table that closely relates the winding flux linkage and current level to the rotor positions. To avoid complicated and sometimes impossible measurements for setting up the magnetizing characteristic table at numerous different rotor positions and current levels, the concept of general nonlinear magnetizing model (GNMM) has been developed and realized in our previous research work [8]. In GNMM, only two measurements at the rotor-stator pole aligned and unaligned positions are needed at different current level, which can be conveniently accomplished. Theoretical analysis and experimental testing verified that in a normal rotor speed range (lower than 5,000 rpm) including standstill, the sensorless control based on GNMM is very successful. However, our most recent investigation also indicates that the GNMM based rotor position estimation is not sufficiently accurate for super-high speed operation. While GNMM provides boundaries at aligned and unaligned positions, the rotor position information in critical areas near the two boundaries is not adequate. As a result, for super high-speed operation, the errors in position estimation cause serious problem and limit the SRM potentials in super high speed applications where sensorless control is most necessary.

In this paper, an improved scheme of rotor position detection is developed and verified specifically for super high speed applications. The paper is organized as follows. First, the concept of a general nonlinear magnetizing model is reviewed for a given SRM and the principle of accurate rotor position detection based on GNMM explained. Then, the DSP-based implementation procedures are described. Finally, experimental testing results are presented.

II. ESTABLISHMENT OF GENERAL NONLINEAR MAGNETIZING MODEL (GNMM)

Fig. 1 depicts the measured magnetizing mapping of a 6 stator pole/4 rotor pole (6/4) SRM, in which, all factors, including rotor positions and current levels are considered. In the figure, the position difference between any two adjacent curves is 3 mechanical degrees.

Despite the fact that the magnetizing characteristics of the SRM are both magnetically and spatially nonlinear, it is shown

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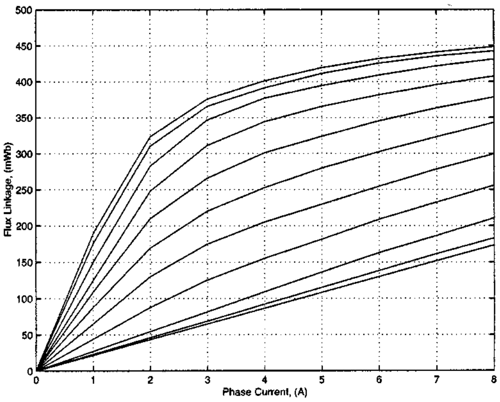

Fig. 1. Measured magnetizing curves of an 6/4 SRM.

in the following that a comprehensive magnetizing model can be conveniently established by the proposed fuzzy algorithm based on minimum inputs to GNMM from measurement.

Starting with a given current level, for example $I = 5$ A, a normalized flux linkage can be defined as

$$\lambda_5' = \frac{\lambda_5 - \lambda_{u5}}{\lambda_{a5} - \lambda_{u5}} \tag{1}$$

which is a function of λ_{a5} and λ_{u5}, the flux linkages at aligned and unaligned rotor positions at current level of 5 A. In the equation, λ_5 is the flux linkage at current level of 5 A before normalization at an arbitrary rotor position.

Normalizing all flux linkages for different rotor positions and current levels, it is interesting to observe that the normalized flux linkage model from a particular SRM holds true for almost any other SRMs:

a) the variation rate of the normalized flux linkage is very small when the rotor is near aligned and unaligned positions;
b) away from aligned and unaligned regions, the normalized flux linkage variations are large.

The above observations suggest that a general nonlinear magnetizing model (GNMM) to characterize nearly all SRMs is possible. Of course, since each SRM is built with its unique pole numbers, commutation angles, and saturation levels, solutions have to be found to link a specific SRM to the GNMM.

Dropping the subscript "5" and rearranging (1), it follows that:

$$\lambda = \lambda_u + \lambda'(\lambda_a - \lambda_u) \tag{2}$$

(2) clearly indicates that with the two magnetizing curves at aligned and unaligned rotor positions (λ_a, λ_u) for a given machine, the comprehensive magnetizing characteristics of any specific SRM can be derived from the normalized flux linkage (λ') which is available from the GNMM data base.

Because of the high nonlinearities in the magnetizing characteristics, fuzzy logic is used to represent the GNMM. The advantage of the fuzzy approach is that it does not require elaborated analytical equations, Fourier series, interpolations, or numerical derivatives. Instead, all the information is incorporated into the fuzzification, fuzzy knowledge base, and defuzzification. To let the proposed GNMM universal to other SRMs, all the variables are normalized. The normalized current i' and rotor position θ' are

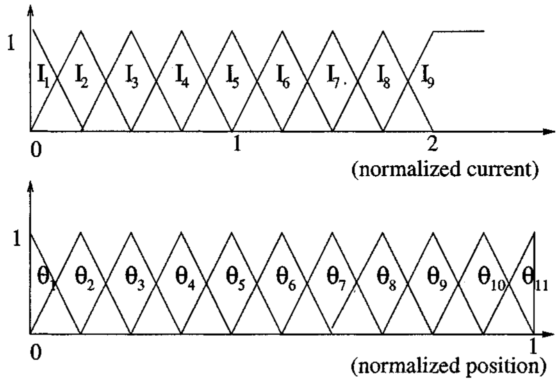

Fig. 2. Input membership functions.

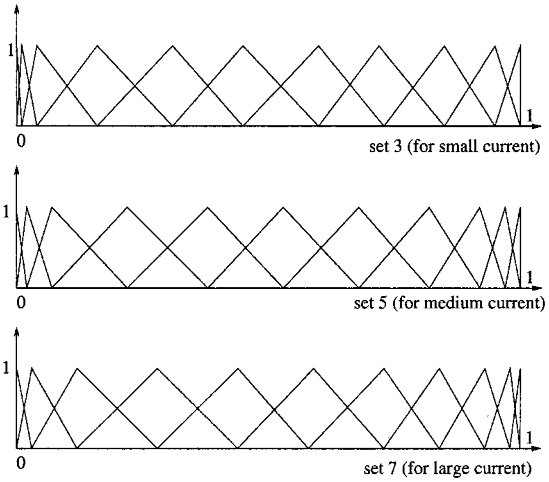

Fig. 3. Output membership functions.

$$i' = \frac{i}{i_b} \tag{3}$$

$$\theta' = \frac{\theta}{\theta_b} \tag{4}$$

where i is the phase current, θ the rotor position. To reflect the degree of saturation, the current base i_b is chosen at a value where the SRM enters deep saturation at the aligned rotor position and the base rotor position θ_b half the electrical cycle of the SRM. For example, θ_b is 22.5 mechanical degrees for an 8/6 SRM, and 30 mechanical degrees for a 6/4 SRM.

In the GNMM, the normalized current and rotor position are chosen as the fuzzy inputs, and the normalized flux linkage the fuzzy output. Fig. 2 shows the membership functions for the fuzzy inputs. In the figure, I_1 means zero current, I_2 is very small current$\cdots$and I_9 is very large current; θ_1 means the unaligned position, θ_2 is very close to the unaligned position$\cdots\theta_{10}$ is very close to the aligned position, and θ_{11} means the aligned position.

In contrast to a traditional fuzzy algorithm where only one output membership function set is specified, nine output membership function sets are used here corresponding to nine membership functions of the input current as specified in Fig. 2. The reason for choosing different output membership function sets is to fully consider both spatial and magnetic nonlinearities in the SRM magnetizing characteristics. Fig. 3 shows three of the nine typical output membership function sets.

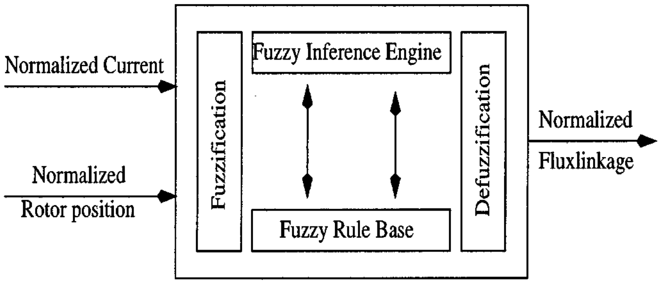

Fig. 4. Fuzzy algorithm.

In the proposed fuzzy algorithm, all the fuzzy rules are expressed as below: **if i$'$ is m and θ' is n, then λ' is (m, n)** which means that if i' belongs to membership function "I_m" and θ' membership function "θ_n," then λ' belongs to the membership function "n" of the output membership function set "m."

As shown in Fig. 4, from the normalized current and position, the fuzzification determines which membership functions are activated. The fuzzy inference engine then determines which rules are used. Finally, the normalized flux linkage is given by defuzzification algorithm.

Once the normalized flux linkage is known, the actual flux linkage can be obtained from (2). In this way, the comprehensive magnetizing characteristics of a specific SRM can be reconstructed, using only the aligned and unaligned magnetizing curves as the inputs. It should be emphasized that the fuzzy knowledge base is universal to all conventionally designed SRMs.

III. ROTOR POSITION DETECTION BASED ON GNMM

Taking currents and winding flux linkages as the inputs, GNMM can be used to detect rotor positions as discussed in [8]. Note that, the measured curves at stator-rotor poles aligned and unaligned positions only provide the boundaries for the rotor position estimation. However, in reality, it is the information near these two boundary positions, not exactly these two positions, to be directly used for commutation. In other words, the incoming phase is usually turned on after the rotor passes its unaligned position and similary the adjacent outgoing phase is turned off prior to its aligned position. Therefore, the information of aligned and unaligned positions obtained by direct measurements are not effective for optimal commutation. On the other hand, if performed based on the information in nearby areas of these two positions that is synthesized from the GNMM, the commutation is not optimal either and sometimes even fails. That means, an error exists to use the GNMM for a particular SRM. It is noted that this error is so small that it does not affect the operation of a SRM at a low or medium speed. However, in high speed, the resolution for rotor position estimation decreases and the error becomes severe if the sampling time is not changed. This is evidenced by nonsmooth and distorted rotor position estimation shown in Fig. 5.

One scheme has been developed to improve the accuracy of rotor position estimation based on GNMM method. The approach is to detect the rotor position directly based on the system motion equation after the motor is started using the approximated GNMM.

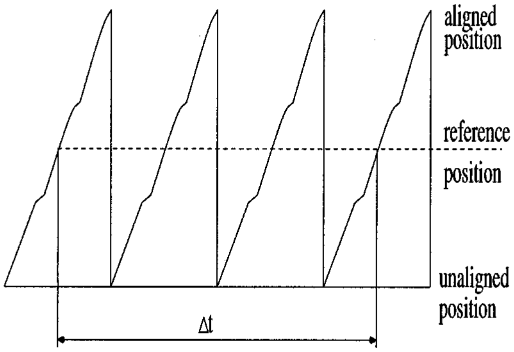

Fig. 5. Speed estimation based on reference positions.

To explain the concept, firstly the algorithm assumes a certain rotor position θ_{ref} estimated by GNMM as a reference point (Fig. 5). A middle point between aligned and unaligned position is preferred because the so-chosen point is very stable and repeatable. For rotor position estimation including the reference position, the input current is directly measured. The phase flux linkage is computed by

$$\psi = \int (V - Ri)dt. \tag{5}$$

Based on the approximated rotor position estimation, the speed ω can be calculated with

$$\omega = \frac{\Delta\theta}{\Delta t}. \tag{6}$$

For accuracy improvement, the number of strokes ($\Delta\theta$) between the reference points can be several at a higher speed. The time interval Δt during these strokes can be readily obtained by counting the sampling cycles. It is important to realize that even though the so estimated reference position is not a trully accurate position relative to the stator/rotor pole alignment, the speed estimation is accurate because the reference points of the same rotor position are used to count electric strokes.

Thereafter, another improved version of rotor position θ could be detected directly by the speed integration based on system motion equation

$$\theta(k+1) = \theta(k) + \omega(k)T_s \tag{7}$$

where, T_s is the sampling period. Since the integration always begins from the assumed reference rotor position and is reset at each cycle of stator excitation, there is no integration drift. However, there is an offset between the real and assumed reference rotor positions because of the approximation of GNMM.

To ensure accurate rotor position detection, one calibration mechanism is proposed to correct the reference position and therefore to minimize the detection error. In this scheme, the SRM magnetizing characteristics at aligned position can be effectively utilized as shown in Fig. 6.

The normalization of the winding flux linkage by the phase current is online performed and the periodic maximum of the results is examined. Note that the maximum value occurs only at the moment when the rotor and stator poles are aligned. This aligned position ${\theta_a}^*$ is just the position we want to use to correct the assumed reference position. If inconsistency exists at the

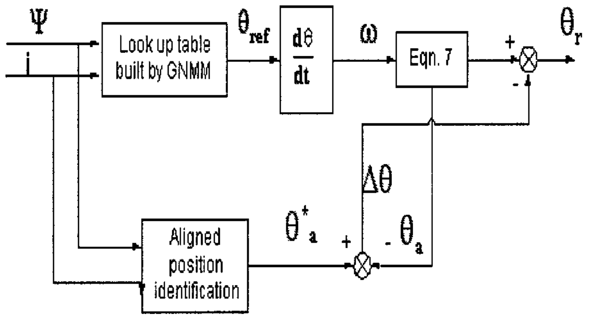

Fig. 6. Accurate rotor position detection by calibration.

aligned points between the rotor position θ_a obtained by motion equation and $\theta_a{}^*$ identified from flux-current profile, the assumed reference position will be corrected by the angle difference $\theta_a{}^* - \theta_a$.

After the speed is obtained and the reference position corrected, the online adaptive tuning of the GNMM is possible based on Model Reference Adaptive mechanism [9]. This is explained in the following.

On the basis of approximated GNMM, fuzzy reasoning is used to estimate the rotor position [8]. In each sampling cycle, the belonging degree of the current $\mu_I(i,j)$ and the belonging degree of the flux linkage $\mu_\psi(i,j)$ are determined respectively by current measurement and flux linkage calculation. The rule bases are activated according to these belonging degrees. The belonging degree of one activated output membership function for $\theta(i,j)$ is

$$\mu(i,j) = \mu_I(i,j)\mu_\psi(i,j). \tag{8}$$

To obtain the rotor position, the method of center of average (COA) is used in the defuzzification.

During online tuning, the motion equation with a corrected reference position can be regarded as the reference model. The position error between that obtained by motion equation and by approximated looking-up table is used to adaptively update the GNMM. Thus, the activated output of position can be revised by a recursive least-mean-square algorithm (RLS) [9] as

$$\theta(i,j)^{new} = \theta(i,j)^{old} + k(\theta_m - \theta_e)\mu(i,j) \tag{9}$$

where $i, j =$ 1,2 indicate the activated terms in the looking-up table; k is an empirical learning factor, $0 < k < 1$; θ_m is the position obtained by motion equation; θ_e is the position obtained by approximated GNMM.

In essence, the initial GNMM has been online modified. The significance of the tuned model is that once tuned, the rotor position estimation from the GNMM can be used directly for sensorless control. From this moment, it is not necessary to execute the online adaptive tuning if the same motor is to be controlled. For different SRMs, the proposed procedure is also applicable in similar manner. In other word, the on-time tuning makes the general nonlinear magnetizing model truly general.

IV. DSP-BASED IMPLEMENTATION PROCEDURES

The SRM rotor position estimation algorithm based on GNMM and motion equation has been implemented using Motorola DSP56005. This DSP is very suitable in digital control with sophisticated algorithms due to its powerful calculation capability and high speed. In DSP56005, one instruction cycle with a 50 MHz clock only takes 20 ns, and it also has convenient interface for PWM outputs.

Using the scheme described in the above sections, the steps to implement the sensorless control of SRM at super high speed application are described as follows.

A. Measurement of Magnetizing Curves at Aligned and Unaligned Positions

For each SRM, first we need to measure or already have two curves at aligned and unaligned rotor positions. For example, in a three-phase 6/4 SRM, in aligned measurement, we simply apply current to one phase and sample the voltage and current; in unaligned measurement, first we apply current to two phases equally for a moment and the rotor pole will be pulled exactly to the unaligned position with respect to the third phase stator pole. Switching current to the third phase with the other two phases open, then we can measure the unaligned flux-current curve. In spite of the unaligned position being an unstable equilibrium, the rotor will be stable at this position for a short moment. The obtained data from one sampling can be used to build the flux/current characteristic because of the linear relationship between the flux and current at unaligned position.

B. Building the Approximated Table Based on GNMM

Now that the basic data of flux linkage and current at the aligned and unaligned rotor positions have been obtained, the magnetizing table in terms of winding flux linkage and phase current is built using fuzzy reasoning based on GNMM. The purpose of building this table is to be able to run SRM smoothly without rotor position sensor and therefore the rotor speed can be estimated.

C. Speed Estimation and Assumed Reference Correction

After Steps A and B, the preliminary sensorless operation is realized. Once the SRM is running, the speed is estimated by counting the time interval while the rotor passes the assumed reference positions. The speed estimation will be satisfactory even though the approximated table is not sufficiently accurate for rotor position estimation. At this point, the rotor position estimated by motion equation starts to replace the results from the initial table. Also, the flux normalization by current is computed. Thus, the maximum point in normalized flux profile can be identified to correct the estimated rotor position.

D. Obtaining Adaptively Tuned GNMM

To make the GNMM accurate and truly universal, the GNMM will be adaptively online tuned based on the accurate position obtained by Step C. The model reference adaptation approach is adopted and the obtained position information from the corrected motion equation is considered as that from the reference model.

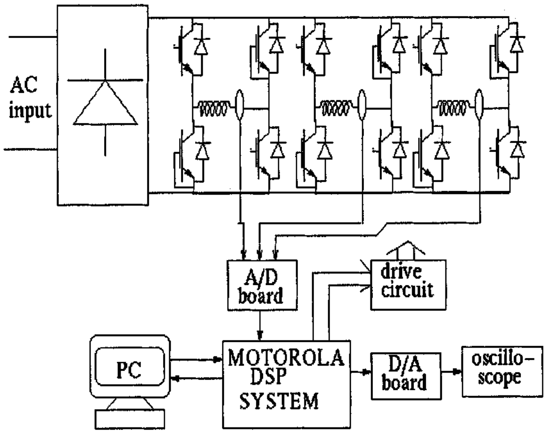

Fig. 7. Setup of SRM drive.

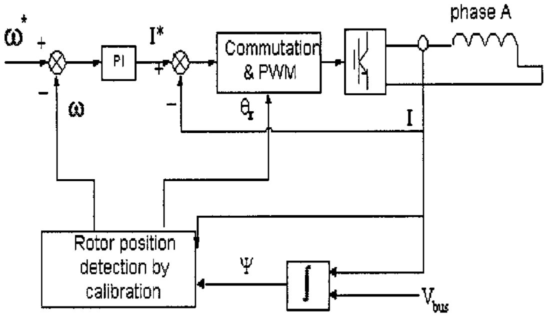

Fig. 8. Diagram of SRM control system.

TABLE I
SPECIFICATION OF SRMS

	SRM1	SRM2
Stator/rotor poles	6/4	12/8
Power rating	3 hp	1.5 hp
Voltage (AC)	240 v	120v
Phase current	6.5 A	3.0A
Speed range	0-24,000 rpm	0-10,000 rpm

V. EXPERIMENTAL RESULTS

To verify the improved scheme of rotor position estimation for SRM sensorless operation at super high speed, a SRM drive system has been set up as shown in Fig. 7. The controller is based on MOTOROLA DSP 56 005. The closed-loop control is implemented with the speed loop as the outer loop and current inner one, as shown in Fig. 8. Two different types of SRM are used to demonstrate the versatility of the control algorithms. The specification of the two SRMs are listed in Table I

Experimental results on the 6/4 SRM are obtained from our lab testing. In Fig. 9, from the top to bottom, it shows the phase current, normalized flux linkage, estimated rotor position based on the untuned GNMM and estimated rotor position by motion equation at a speed of 7000 rpm. As can be observed, the maximum of the normalized flux from motion equation does not coincide with the estimated rotor position. The angle difference between the maximum of normalized flux linkage and the rotor position from motion equation is used to correct the assumed reference rotor position. The updated results are show in Fig. 10. It is evident that the position estimation from motion equation is now accurate.

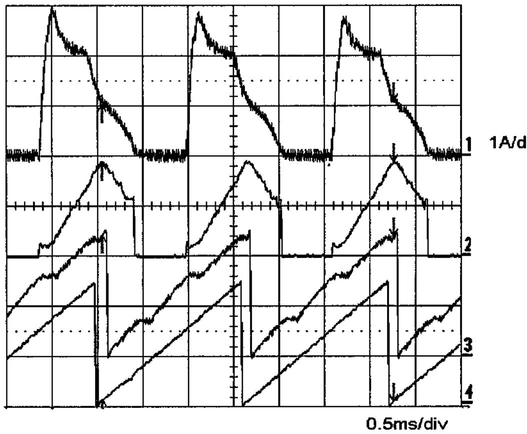

Fig. 9. Estimated rotor position before reference correction (Ch1: phase current, 1 A/div; Ch2: normalized flux linkage, 25 mH/div; Ch3: estimated rotor position by GNMM, $(\pi/5)$/div; Ch4: estimated position by motion equation, $(\pi/5)$/div).

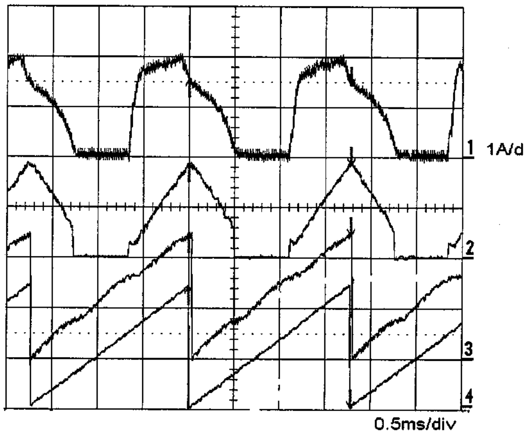

Fig. 10. Estimated rotor position after reference correction (Ch1: phase current, 1 A/div; Ch2: normalized flux linkage, 25 mH/div; Ch3: estimated rotor position by GNMM, $(\pi/5)$/div; Ch4: estimated position by motion equation, $(\pi/5)$/div).

Note that after the reference rotor position correction, the position information obtained from looking-up table is still not good. However, the rotor position based on the motion equation with reference correction is now sufficiently accurate for SRM to run up to the super high speed. Figs. 11 and 12 show the speed tracking responses at 18 000 rpm.

In order to verify the generality of the proposed scheme for rotor position estimation and sensorless control, we also tested the scheme on the three-phase 12/8 SRM. We follow the same procedure as described above. Figs. 13 and 14 show the speed step response and other variables in steady state at 10 000 rpm.

As stated before, after the rotor position estimation from motion equation integration is corrected, the approximated table

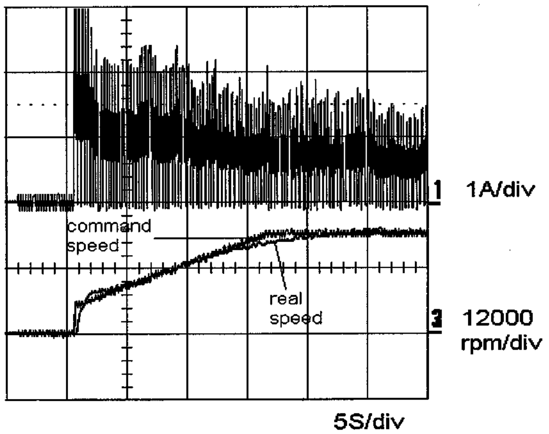

Fig. 11. Speed tracking of 6/4 SRM (Ch1: phase current, 1 A/div; Ch2: speed command, 12 000 rpm/div; Ch3: real speed, 12 000 rpm/div).

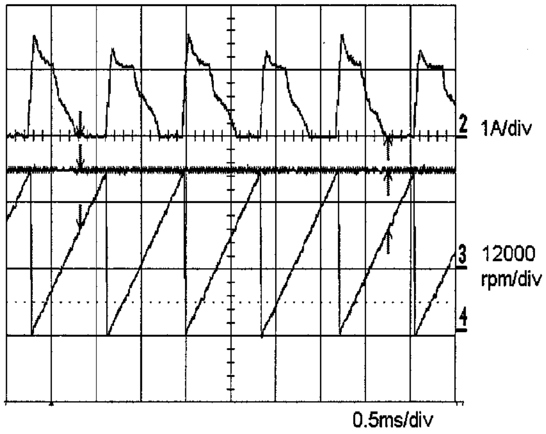

Fig. 12. Steady state responses of 6/4 SRM at 18 000 rpm (Ch2: Phase current, 1 A/div; Ch3: speed, 12 000 rpm/div; Ch4: estimated position, $(\pi/5)$/div).

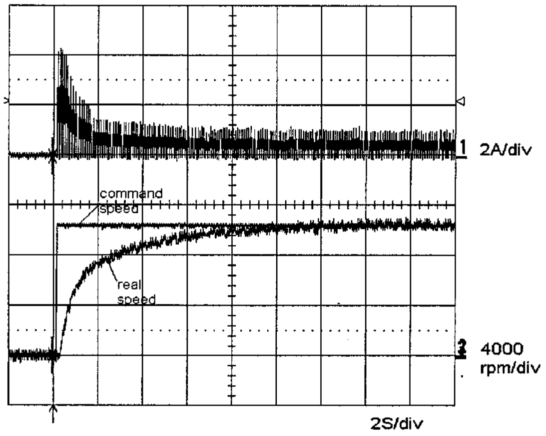

Fig. 13. Step responses of 12/8 SRM (Ch1: phase current, 2 A/div; Ch2: speed command, 4,000 rpm/div; Ch3: real speed, 4,000 rpm/div).

built on GNMM can be online tuned. The estimated rotor position by using the tuned GNMM is shown in Fig. 15. Evidently, the rotor position estimation based on the online tuned GNMM is as smooth and accurate as that from the corrected motion equation. Therefore, after adaptive tuning, the new GNMM can be used directly for sensorless control without using motion equation.

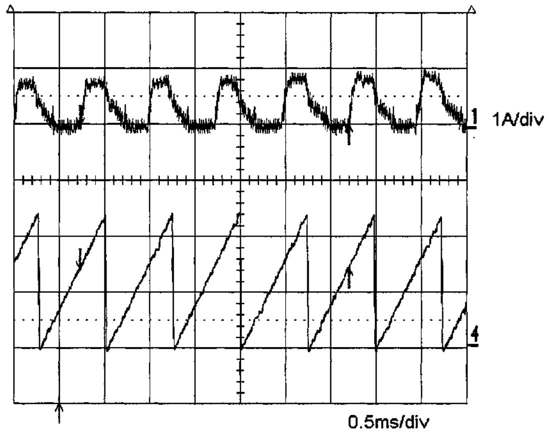

Fig. 14. Steady state responses of 12/8 SRM at 10 000 rpm (Ch1: phase current, 1 A/div; Ch4: estimated position by motion equation, $(\pi/10)$/div).

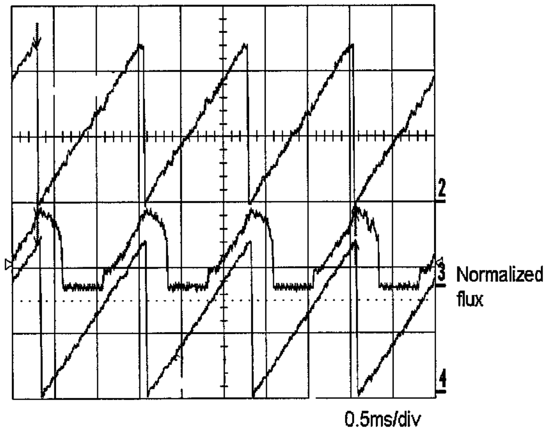

Fig. 15. Position after adaptive tuning (Ch2: estimated rotor position by corrected GNMM, $(\pi/10)$/div; Ch3: normalized flux Ch4: estimated rotor position by motion equation, $(\pi/10)$/div).

VI. DISCUSSION

The method of rotor position detection proposed in this paper combines the mechanisms of GNMM and the system motion equation. This method is favorably suitable for super high speed SRM operation because both electro-magnetic and mechanical characteristics of the SRM are effectively utilized to enhance the rotor position estimation. In practice, during super high-speed operation, the back EMF of the SRM is inevitably high and current overlapping among the phases causes substantial mutual coupling between the involved phases and is not negligible. Whenever the phases are mutually coupled due to the overlapping currents, pure electro-magnetic information of the SRM becomes complicated and not reliable for rotor position estimation. Thus, sensorless control is no longer robust. Incorporating independent signals extracted from system mechanical motion equations into estimation is a remedy, which creates another dimension in the information space. The ambiguity at the critical areas is avoided for commutation. Therefore, the method developed in this paper provides a logic solution to the problems of super-high speed, sensorless operation.

Note that the procedures for online updating reference position and tuning GNMM do not need to be executed as often as the rotor position detection. Also to be noted is that in order to obtain the normalized maximum flux at the aligned position, it is necessary for SRM to run at a relatively large dwell angle for a brief moment, with somewhat reduced average torque. However, for the rest of time during operation, the SRM torque production is not affected.

VII. CONCLUSIONS

An improved scheme of accurate rotor position estimation for sensorless control of SRM for super high-speed operation is proposed and verified with two different SRMs. The procedures to realize such a concept are simple and easy to be implemented. From measurement of only two magnetizing curves at aligned and unaligned positions, the implementation steps include setup of the approximated table based on GNMM, start-up of SRM, computation of speed, correction of reference position in terms of normalized flux linkage profile, and adaptively online tuning the approximated table. The online adaptively tuning the SRM GNMM is needed to perform only one time for different SRMs. Therefore, the tuned GNMM is becoming a truly general model for both normal and super high speed sensorless operation. The combination of electro-magnetic characteristics with the motion features of a SRM provides a promising route for super high speed SRM sensorless control.

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