New Estimation Scheme of the Arbitrary Rotor Position at Standstill for the Sensorless Switched Reluctance Motor Drive

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***Abstract*—A new scheme to estimate the rotor position at standstill for the sensorless switched reluctance motor drive is presented in this paper. This scheme utilizes the accurate estimation modelling based on the two-dimensional least squares and bisection methods. Furthermore, the optimal sensing phase that is detected via exciting each phase in sequence with a DC voltage for a short duration is used to estimate the mathematical rotor position at standstill. According to the developed logic rules, thus, the physical rotor position at standstill can be determined on the basis of the obtained mathematical rotor position at standstill. The simulation and experimental results validate the presented scheme.**

I. INTRODUCTION

Both starting and running of the switched reluctance motor drives depends on the rotor position information. Rotor sensors or encoders are one of the approaches to acquire the position information. However, mounting such sensors or encoders increases the size and cost of the switched reluctance motor drives. Moreover, sensors or encoders are also a source of unreliability. Thus, low cost, small package size, and reliability is the primary motivation for research in the sensorless switched reluctance motor drives. For the sensorless switched reluctance motor drives, the estimation of the rotor position at standstill (named as the initial rotor position in this paper) is the same important as the rotor position estimation at running (at low or high speed), because the starting performance and the expected rotation direction of the switched reluctance motor drives depend on the information of the initial rotor position. Furthermore, the accurate determination of the initial rotor position will be much helpful to the next rotor position estimation at running. Whereas, most of the reported publications on the sensorless switched reluctance motor drives are interested in the rotor position estimation at running. Only few publications discussed the initial position estimation.

Reference [1] presented an active probing method to estimate the rotor position at low speed and at standstill via look up table with respect to the inductance. It uses the sinusoidal high frequency (600Hz) current signal which is injected into the idle phase. In [2], Suresh, Fahimi, and et al proposed also the active probing method to estimate the rotor position at all speeds via the analytical expression of the inductance. This method utilizes the sinusoidal voltage sensing signal with 36 kHz frequency. Exciting two phases using a short pulse of current, the rotor position at standstill is estimated based on fuzzy logic, in [3]. Reference [4] presented the passive probing method to estimate the initial rotor position through applying a DC voltage to the all phases for a short moment and the look up table. In the meantime, it uses also the optimal sensing phase technique. Gao, Salmasi, and Ehsani presented a passive probing method to estimate the rotor position at standstill. In this method, exciting each phase in sequence with a narrow voltage pulse, the starting phase is detected by comparing the amplitudes of the resultant phase currents [5].

Flux linkage (or inductance) characteristics within a rotor period for the switched reluctance motor drives are symmetrical about the position of the half a rotor period. Hence, at a given instant, the rotor position cab be uniquely determined only within the half a period if the phase current and flux linkage (or inductance) are acquired. Such a detected rotor position is named as the mathematical rotor position, in this study. Consequently, it is not sure that the mathematical rotor position does be the physical rotor position that is most closed to the actual rotor position. However, the estimated physical rotor position just can ensure that the switched reluctance motor drive runs with the large starting torque and the expected rotation direction. The methods presented in [1][2][4] only can estimate the mathematical rotor position at standstill via look up table with respect to both the current and the flux linkage (or inductance), and does not describe how determining the physical initial rotor position. Furthermore, the mutual coupling between phases has an effect on the initial rotor position for that excitation approach in [4]. For the estimation scheme presented in [3], the two mathematical initial positions must be estimated and consequently the physical initial position can be determined. The optimal sensing phase technique can be not utilized because of only exciting two phases. Reference [5] discussed the detection of the starting phase according to the amplitudes of the current and does not deal with the mathematical and physical rotor position estimation.

A good estimation scheme of the initial rotor position should have the following features: a) Accurate estimation model with respect to both the current and the flux linkage (or inductance); b) Selecting the optimal sensing phase; c) Estimating not only the mathematical position but also the

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physical position; d) few stored data and rapid computation.

This study presented a new scheme to estimate the initial rotor position for the sensorless switched reluctance motor drives, which uses the passive probing method. The proposed modelling based on two-dimensional (2-d) least squares needs few given data and is used to describe accurately the flux linkage characteristics of the switched reluctance motor drive. Exciting each phase in sequence with a DC voltage for a short duration, the voltage and the current are acquired. According to the amplitudes of the phase currents, the phase having the largest current and the optimal sensing phase are detected. Consequently, the flux linkage in the optimal sensing phase is only computed by using the trapezoid integration method. Furthermore, the optimal sensing phase is employed to estimate the mathematical initial rotor position with high resolution, and the phase having the largest current is used to determine the physical initial rotor position from the proposed logic rules. The bisection algorithm is utilized to solve the mathematical rotor position accurately and rapidly. The simulation and experimental results validate the presented new scheme. The presented new scheme has the salient features, which are the accurate estimation modelling, few stored data, the rapid computation, and only to need to estimate the initial rotor position to the optimal sensing phase.

II. Estimation Modelling

A. Analytical modelling based on 2-d least squares

Assuming that $N\times M$ flux linkage data ψ_{kj} with respect to rotor position θ_k and current i_j are obtained through the measurements on existing motor or through the numerical computations ($k=0,1,\ldots,N$-1; $j=0,1,\ldots,M$-1), the analytical modelling proposed in this study can be expressed by (1).

$$\psi(\theta,i)=\sum_{k=0}^{p-1}\sum_{j=0}^{q-1}a_{kj}(\theta-\bar{\theta})^k(i-\bar{i})^j \qquad (1)$$

where $N\geq p, M\geq q$, and

$$\begin{aligned}\bar{\theta}&=\sum_{k=0}^{N-1}\theta_k\,/\,N\\ \bar{i}&=\sum_{j=0}^{M-1}i_j\,/\,M\end{aligned} \qquad (2)$$

Equation (1) shows that the proposed model is the 2-d polynomials, in which the highest order of the rotor position θ is (p-1) and the highest order of the phase current i is (q-1). The least squares are widely applicable to science and engineering. This technique is an efficient tool to precisely fit discrete data. In this study, the coefficients a_{kj} in (1) are determined by using 2-d least squares technique [6] [7].

At standstill, the flux linkage characteristics to both the rotor position and the current are obtained through the experiment on the exiting prototype of a four-phase switched reluctance motor drive, in this study. There are 13 rotor position data ($N=13$) from 0 to 30 degree (half a rotor period) with the step of 2.5degree, 7 current data ($M=7$) from 0 to 3 A with the step of 0.5 A, and 13×7 flux linkage data. p and q is selected to 8 and 7, respectively. $\bar{\theta}$ and $\bar{i}$ is equal to 15 degree and 1.5 A, respectively. The computed coefficients from the above given data are shown in Appendix. Consequently, the flux linkage characteristics of the switched reluctance motor drive can be modeled accurately only by these 56 coefficients.

Fig.1 illustrates the flux linkage characteristics from the experiment roughly, whereas Fig. 2 depicts the fux linkage characteristics from the presented analytical modelling smoothly.

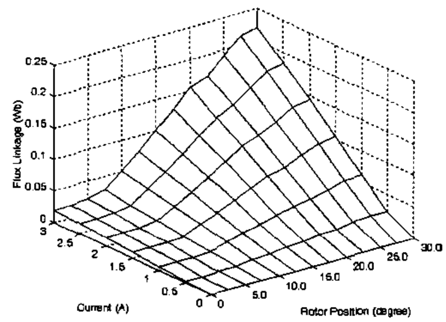


Fig. 1. Flux linkage characteristics from the experiment

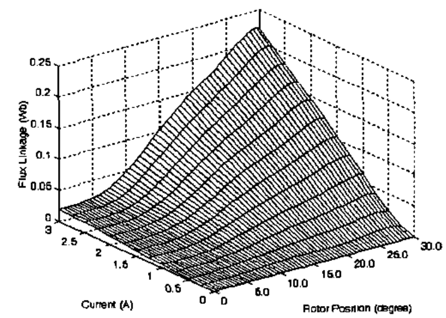


Fig. 2. Flux linkage characteristics from the presented analytical modelling

B. Solving rotor position using bisection algorithm

The rotor position can be solved on the basis of the above analytical modelling of the flux linkage with respect to the rotor position and the current, if the information of both the flux linkage and the current is obtained. The analytical modelling is the high-order polynomials with the 2-d variables. Hence, it is difficult to directly solve the rotor position if the flux linkage and the current are known. In this study, the bisection algorithm is utilized to solve the rotor position from (3).

$$f(\theta)=\sum_{k=0}^{p-1}\sum_{j=0}^{q-1}a_{kj}(\theta-\bar{\theta})^k(i-\bar{i})^j-\psi=0 \qquad (3)$$

where p=8, q=7, i and ψ are the acquired values at standstill.

III. Scheme of Initial Rotor Position Estimation

A. Optimal sensing phase

The four-phase (8/6 poles) switched reluctance motor drive is regarded as the analytical case study in this paper. Fig. 3 illustrates the typical relationship between the rotor position, the flux linkage, and the current, where the rotor period is 60 degree and the flux linkage within a period is symmetrical about the position of 30 degree.

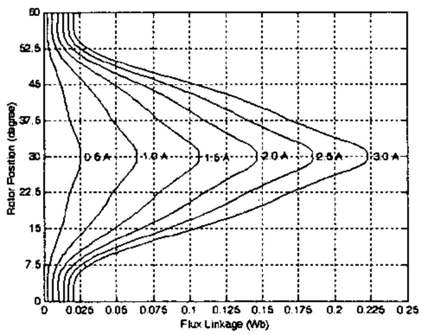


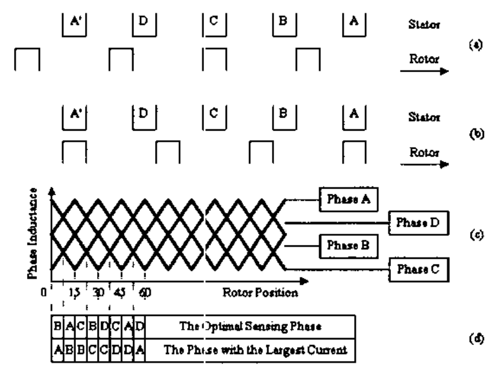
Fig. 3. Relationship of the rotor position versus the flux linkage at various currents

From Fig. 3, it can be observed that a pair of values of the flux linkage and the current determines a unique rotor position within the half period, such as from 0 degree to 30 degree. However, the rotor position estimation has the greatly different resolutions if the estimated rotor positions locate in the different regions. Clearly, in the regions where the rotor position is near the position of 0 degree or 30 degree, the rotor position estimation resolution is low because the small errors in the flux linkage and the current measurements will lead to a large error in the rotor position estimation. However, in the region from 7.5 degree to 22.5 degree (or from 37.5 degree to 52.5 degree), the rotor position estimation resolution is high because the small errors in the flux linkage and the current measurements will only result in the negligible error in the rotor position estimation. It can be seen that the rotor position has high resolution if such a phase is selected to measure the flux linkage and the current and to estimate the rotor position. This phase senses the rotor position accurately and thus is named as the optimal sensing phase in this paper.

B. Detecting optimal sensing phase at standstill

At standstill, the back EMF in the switched reluctance motors is zero. Thus, the magnitude of the phase current at standstill depends on the phase inductance because the all phase windings have the same resistance and the same DC voltage is applied to the all phase windings during the same time. Consequently, the phase with the smallest inductance must have the largest current and the phase with the largest inductance must have the smallest current, at standstill.

If the rotor position to a phase is near the position of 0 degree, the phase inductance has the smallest value and consequently the phase has the largest current among the all phases, such as the phase-A shown in Fig. 4. In this case, the rotor positions to two phases next to the phase having the largest current will locate within the region from 7.5 degree to 22.5 degree or from 37.5 degree to 52.5 degree, such as the phase-B and the phase-D shown in Fig. 4. Hence, anyone of these two phases can be selected as the optimal sensing phase according to the above analysis. This study suggests that the phase with the larger current among these two phases is determined as the optimal sensing phase at standstill. The rotor position to the optimal sensing phase is the estimated initial rotor position. Fig. 4(d) shows the distributions of the phase with the largest current and the optimal sensing phase within a period. For example, if the initial rotor position to the phase A is in the region from 0 degree to 7.5 degree, the phase with the largest current must be the phase-A because the phase-A has the smallest inductance, and thus theses two phases next to the phase-A having the largest current are the phase-B and the phase-D. The phase-B has the smaller inductance than the phase-D and consequently the phase-B has the larger current than the phase-D. Hence, the optimal sensing phase must be the phase-B, as shown in Fig. 4(c) and 4(d). Furthermore, Fig. 4(c) and (d) show that the optimal sensing phase commutates every 7.5 degree and the phase having the largest current commutates every 15 degree.



(a) Position of the stator pole and the rotor pole at the rotor position to the phase-A = 0 degree
(b) Position of the stator pole and the rotor pole at the rotor position to the phase-A = 30 degree
(c) Ideal profiles of phase inductances
(d) Distribution of the optimal sensing phase and the phase with the largest current at standstill
Fig. 4. Relationship between the optimal sensing phase and the

C. Determining physical initial rotor position

To solve the unique mathematical solution from (3), the known flux linkage (or inductance) characteristics should be limited within the half period. Thus, the analytical modelling presented in this study is active within the half period from 0 degree to 30 degree. In this case, the estimated initial rotor position from (3) is the mathematical initial rotor position, because it always locates within the region from 0 degree to 30 degree. However, it is not sure that the mathematical initial rotor position leads to the best starting feature and the expected rotation direction. Therefore, the physical initial rotor position to the optimal sensing phase must be determined. The physical initial rotor position just is the actual initial rotor position.

The physical initial rotor position to the phase having the largest current has to satisfy the given constraint, which depends on the numbers of both the phases and poles in the switched reluctance motor drives. For the four-phase, 8/6 poles switched reluctance motor drive, the physical initial rotor position to the phase having the largest current should satisfy (4).

$$0 \le PIPL \le 7.5, or \\ 52.5 \le PIPL \le 60 \quad (4)$$

where *PIPL* represents the physical initial rotor position to the phase having the largest current.

D. Logic rules

Table I shows the logic rules for detecting the phase having the largest current and the optimal sensing phase from the amplitudes of the phase currents.

TABLE I
LOGICS FOR DETECTING THE OPTIMAL SENSING PHASE

Current	Phase having the largest current	Optimal sensing Phase
$i_a > i_b \ge i_d > i_c$	A	B
$i_a > i_d > i_b > i_c$	A	D
$i_b > i_c \ge i_a > i_d$	B	C
$i_b > i_a > i_c > i_d$	B	A
$i_c > i_d \ge i_b > i_a$	C	D
$i_c > i_b > i_d > i_a$	C	B
$i_d > i_a \ge i_c > i_b$	D	A
$i_d > i_c > i_a > i_b$	D	C

According to the estimated mathematical initial rotor position to the optimal sensing phase and the phase having the largest current, the physical initial rotor position to the optimal sensing phase can be determined. Fig. 5 depicts the logic rule for determining the physical initial rotor position to the optimal sensing phase-A. Similarly, the logic rules to determine the physical initial rotor positions to the other optimal sensing phases can be deduced.

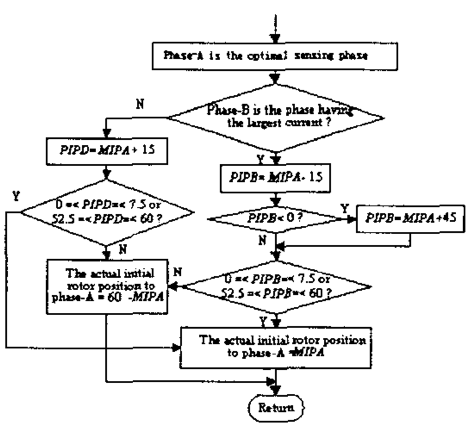


Fig. 5. Flowchart to determine the physical initial rotor position to the optimal sensing phase-A

In Fig. 5, *PIPB* denotes the physical initial position to the phase-B having the largest current, *PIPD* denotes the physical initial position to the phase-D having the largest current, and *MIPA* denotes the mathematical initial position to the optimal sensing phase-A. The estimated mathematical initial rotor position must be located within the half period (from 0 to 30 degree) and the estimated physical initial rotor position is limited within a period (from 0 to 60 degree). The phase having largest current must be the phase-D if the phase-B is not the phase having the largest current, because the phase having the largest current is adjacent to the optimal sensing phase-A. For the four-phase switched reluctance motor drive, it is clear from (4) that the physical initial rotor position to the phase having the largest current is not smaller than 0 degree and not larger than 7.5 degree, or not smaller than 52.5 degree and not larger than 60 degree.

E. Scheme of the initial rotor position estimation

In general, the phase voltage and the phase current of the switched reluctance motor drive can be acquired directly on line. Hence, the flux linkage has to be computed according to the measured voltage and current. Here, the flux linkage is computed by using the trapezoid integration method, which is described by (5).

$$\psi(l+1) = \psi(l) + \frac{1}{2}T_s[V(l+1) + V(l) - ri(l+1) - ri(l)] \\ \psi(0) = 0 \quad (5)$$

where $\psi(l+1)$ and $\psi(l)$ are the flux linkage values at sampling instants $(l+1)$ and (l), $V(l+1)$ and $V(l)$ are the voltage values applied to the phase winding at sampling instants $(l+1)$ and (l). $i(l+1)$ and $i(l)$ are the phase current values at sampling instants $(l+1)$ and (l), r is the resistance of the phase winding, T_s is the sampling time, and $l = 0, 1, 2, :$

Based on the above analyses, the scheme to estimate the initial rotor position can be presented and illustrated by the block diagram in Fig.6.

In Fig. 6, the DC voltage v_p is used to excite each phase in sequence during the same short time. The rotor is not disturbed at all because the exciting duration is very small. This excitation approach is better than the exciting all phases for a short time proposed in [4] because exciting each phase in sequence can eliminatethe effect ofthe mutual coupling. From the resultant phase currents (i_a, i_b, i_c, and i_d), the optimal sensing phase can be detected, based on the proposed logic rules where i_o denotes the current in the optimal sensing phase. Then, integrating both the voltage and the current in the optimal sensing phase with respect to the time, the flux linkages ψ_o of the optimal sensing phase can be computed. Hence, the mathematical initial rotor position $?_o$ to the optimal sensing phase can be estimated, according to the presented estimation modelling based on the 2-d least squares and the bisection solution algorithm. Based on the established logic rules, the physical initial rotor position $?_p$ to the optimal sensing phase can be determined. At last, the other physical initial rotor positions to the other phases can be computed from the estimated physical initial rotor position to the optimal sensing phase.

IV. APPLICATION

A. Simulation

Using the above proposed scheme to estimate the initial rotor position, the prototype of the four-phase switched reluctance motor drive is simulated. Its magnetic characteristics from the experiment were given by Fig. 1. The DC link voltage is selected to 28.5 V. The sampling frequency is 20 kHz. The exciting duration is chosen as 0.5 ms. The phase resistance of the prototype is 0.687 ohm.

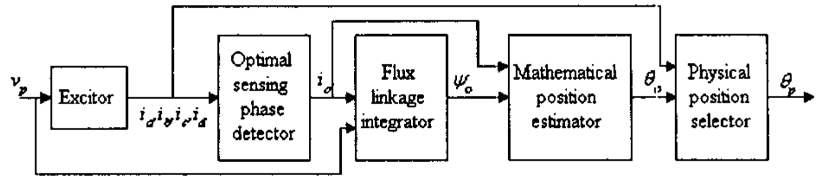


Fig. 6. Block diagram of the proposed scheme to estimate the initial rotor position

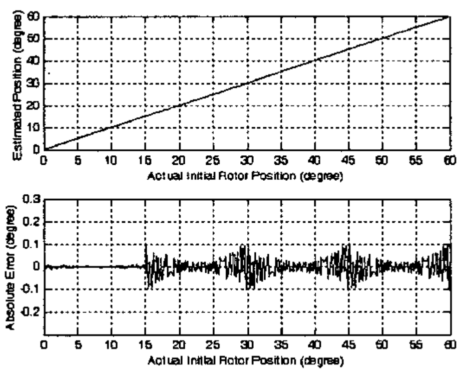


Fig. 7. Comparison between the estimated and actual initial positions from the simulation

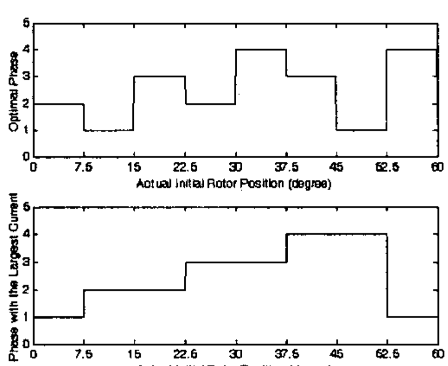
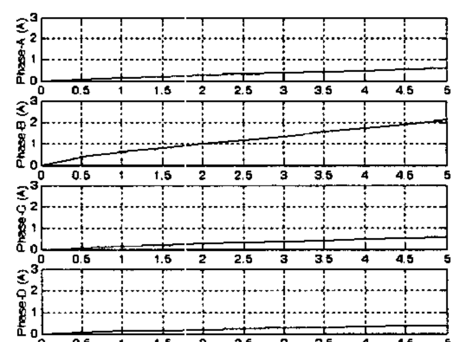
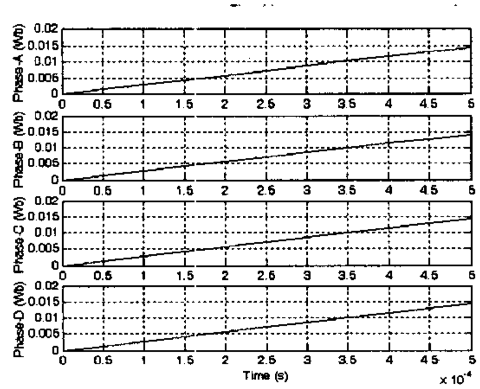


Fig. 8. Distributions of the optimal sensing phase and the phase having the largest current from the simulation

Fig.7 illustrates the simulation results of both the estimated initial rotor position to the phase-A and the absolute error, when the initial rotor position varies within a period. The top graph depicts the estimated initial rotor position, and the nether graph depicts the absolute error between the estimated and actual initial rotor position It is clear from Fig. 7 that the estimated initial rotor position from the simulation is agreement very well with the actual initial rotor position and that the absolute position error of the estimated initial rotor position is considerably small. It indicates that the estimation modelling presented in this study is accurate although this modelling only needs few known data. This also indicates that the proposed scheme to estimate the initial rotor position is able to estimate the arbitrary initial rotor position effectively and has the high resolution.

The simulation results of the optimal sensing phase and of the phase having the largest current within a period can be observed from Fig. 8, where the number represents the phase, such as phase-A = 1. It is clear that the optimal sensing phase commutates every 7.5 degree and that the phase having the largest current commutates every 15 degree. Furthermore, the distributions of the optimal sensing phases and of the phases with the largest current shown in Fig. 8 agree with the theoretical analytical results shown in Fig. 4.





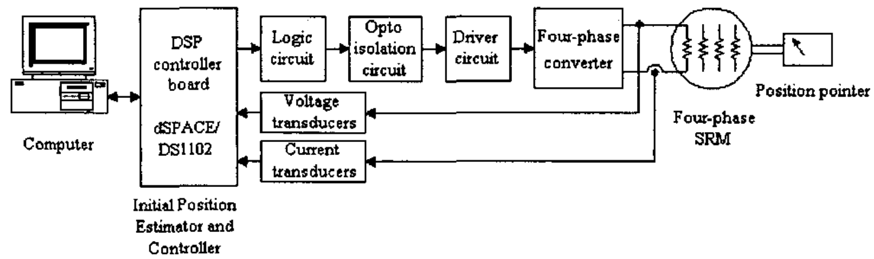


Fig. 11 Schematic diagram of the experimental set-up for the initial rotor position estimation

Fig. 9 and Fig. 10 depicts the simulation current and flux linkage waveforms in four phases at standstill, respectively, when the actual initial rotor position to the phase-A is equal to 15.0 degree. The estimated initial rotor position from the simulation is 15.003 degree. The absolute position error is equal to 0.003 degree. It can be observedfrom Fig. 9 and Fig. 10 that both the current and flux linkage almost changes linearly when estimating the initial rotor position by using the presented scheme.

B. Implementation

To test the scheme presented in this paper, the experimental set-up of a four-phase sensorless switched reluctance motor drive is designed and constructed, as shown in Fig. 11. It consists of the several sub systems: computer, the DSP controller board, the interfaces, the four-phase IGBT converter, current and voltage sampling circuit, 8/6 SRM, and the initial rotor position pointer. The sampling frequency is still selected to 20 kHz. The exciting duration is chosen as 0.6 ms.

Fig.12 and Fig. 13 shows the current and flux linkage waveforms from the experiment, respectively, under the same control as Fig. 9. and Fig. 10. The actual initial rotor position is 15 degree and the estimated initial rotor position from the real-time sensorless control is 13.668 degree. The absolute position error is equal to-1.332 degree. It can be seen from Fig. 12, Fig. 13, Fig. 9 and Fig. 10 that the experimental results are consistent with the simulation results.

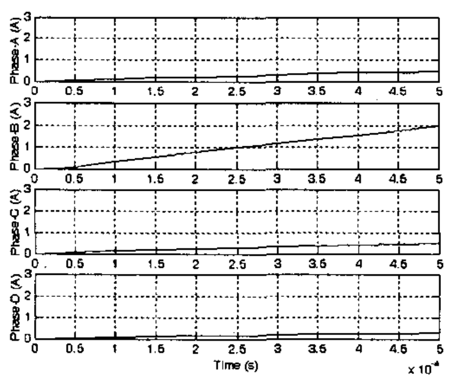


Fig. 12. Current waveforms at standstill from the experiment

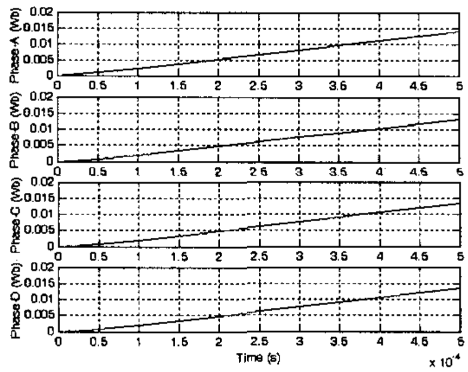


Fig. 13. Flux linkage waveforms at standstill from the experiment

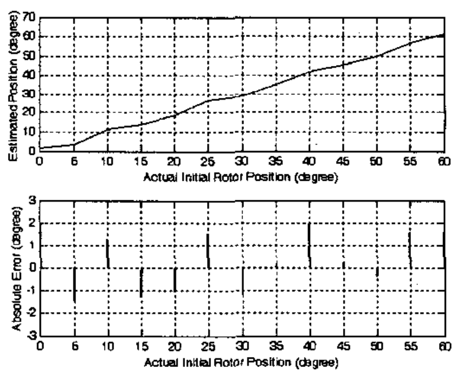


Fig. 14. Comparison between the estimated and actual initial rotor positions from the experiment

The estimated initial rotor position and the absolute position error within a period can be observed from Fig. 14. The actual initial rotor position is measured by using the initial rotor position pointer. The test approach of the rotor position pointer is described as the follows. Firstly, the phase-A winding is excited with the DC voltage for a proper duration so that the rotor is finally standstill at a position, which should be the position of 30 degree to the phase-A. Then, a pointer is fixed on the axis of the motor and aligned with the above position of 30 degree. Finally, a mechanical degree scale is mounted on the motor housing. Consequently, the pointer may point to a degree value if the rotor is located at someone position. Thus, the actual initial rotor position can be measured.

V. CONCLUSION

This paper presented a new scheme to estimate the initial rotor position for the sensorless switched reluctance motor drive. The estimation modelling is based on the 2-d least squares technique and the bisection algorithm. Consequently, this modelling only needs few coefficients, which can be computed off line or on line. The optimal sensing phase is detected through exciting each phase in sequence for a short duration. The mathematical initial rotor position to the optimal sensing phase only needs to be estimated. The physical initial rotor position can be determined from the developed logic rules, on the basis of the obtained mathematical initial rotor position. The simulation and experimental results validate that the scheme presented in this paper is effective and can estimate the initial rotor position fairly accurately.

The salient advantages of this scheme can be summarized as follows. 1) The estimation modelling only needs few given data and can be used to estimate the initial rotor position accurately. 2) The scheme senses the initial rotor position with high resolution because of using the optimal sensing phase. 3) The physical initial rotor position can be determined only from the estimated mathematical initial rotor position. 4) The estimation scheme takes up few memories and takes less computation time. 5) The effect of mutual coupling is eliminated.

APPENDIX

TABLE II
COEFFICIENTS IN THE PRESENTED MODELLING FOR THE PROTOTYPE

j \ k	0	1	2	3
0	.484601E-01	.494287E-02	-.116240E-03	-.148725E-04
1	.374061E-01	.411763E-02	-.593740E-04	-.153379E-04
2	-.335130E-02	.538422E-03	.138691E-03	-.144612E-04
3	-.797749E-03	-.399857E-04	.624083E-05	-.133682E-06
4	.415371E-02	-.701351E-03	-.193270E-03	.172676E-04
5	-.197630E-03	-.634557E-04	-.589302E-05	.128174E-06
6	-.880714E-03	.259503E-03	.588086E-04	-.548625E-05
j \ k	**4**	**5**	**6**	**7**
0	.183482E-05	.712824E-07	-.506973E-08	-.177530E-09
1	.109720E-05	.754539E-07	-.303131E-08	-.174327E-09
2	-.155645E-05	.843885E-07	.421729E-08	-.153535E-09
3	-.919989E-07	-.105944E-07	.300306E-09	.517894E-10
4	.219217E-05	-.945041E-07	-.614890E-08	.152094E-09
5	.524006E-07	.511125E-08	-.159012E-09	-.237951E-10
6	-.675771E-06	.292792E-07	.192867E-08	-.451590E-10

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