Design, modeling, prototyping, and comparison of a low-cost, small-size, and accurate sensorless driver for switched reluctance motor

Alireza Siadatan¹,² | Hossein Torkaman³ | Mehran Rafie³

¹Energy Systems Group, Faculty of Applied Science and Engineering, University of Toronto, Toronto, Ontario, Canada
²Department of Electrical Engineering, College of Technical and Engineering West Tehran Branch, Islamic Azad University, Tehran, Iran
³Faculty of Electrical Engineering, Shahid Beheshti University, A.C., Tehran, Iran

Abstract
A switched reluctance motor (SRM) is a low-cost motor with a simple structure and variable speed industrial and home applications. This article presents the design, simulation, and development of a low-cost, accurate, and small-size sensorless driver for a 6/4 three-phase SRM. In the algorithm, the (nonlinear) relation of the flux, current, and rotor (FCR) position is linearized to achieve a modified FCR model, in which the values of the most important points of the primary FCR are emphasized. The SRM parameters required for the design process are obtained using a 3D finite-element method (FEM). The proposed method is simulated and then tested under different load and speed conditions. The results are compared with a conventional sensorless algorithm’s results, and the reference data are obtained by a direct with-sensor algorithm. The algorithm estimates the rotor position (error of 1.3%) between low to nominal speed of the selected SRM under both nominal and no-load conditions. In comparison with the conventional algorithm, the proposed FCR model significantly reduces the calculation cost and memory demand by 66%. Finally, the proposed algorithm decreases the driver size and price by 64% and 85%, respectively.

KEYWORDS
energy efficiency, rotor position detection, sensorless drive, switched reluctance motor

1 | INTRODUCTION
Switched reluctance motor (SRM) has a lot of merits such as high performance, simple and low-cost structure, and ability to operate under harsh conditions with high speed.¹,² The rotor can achieve high speed because it does not include any winding and has low weight.³,⁴ Since power electronic devices and transistors are utilized in the SRM driver, SRM had not been used for many years until the developments in power electronics technology in the past decades.⁵,⁶ In SRM control, the rotor position is required since the stator pole should be energized in a rotor position where positive torque can be generated to rotate the rotor.⁷,⁹ Basically, two main strategies are suggested for detecting the rotor position: direct (with position sensor) and indirect (sensorless) strategies.¹⁰,¹² In indirect methods, different types of position sensors such as encoder and Hall effect sensor can be used to detect the location of the rotor. Although this method is very accurate, the
use of position sensors in the motor structure has some drawbacks such as increasing the costs, reducing the performance and reliability due to an increase in the complexity of sensor wiring.\textsuperscript{13-15}

Some sensorless techniques are declared below, which have been suggested in the literature so far. Note that, in this article, these techniques are classified according to the range of the motor speed in which they have the highest performance. As shown in Figure 1, the classification is based on three ranges of speed: (a) from standstill, (b) in low speed (less than 1000 rpm), and (c) in high speed (more than 1000 rpm). These methods include\textsuperscript{15-18}:

1. Polynomial regression strategy: In this method, the nonlinear characteristic of the SRM inductance profile is simplified by polynomial regression. It originally is a statistical technique for data analysis in order to model a nonlinear relationship between variables and understand the trend of them. Then, the simplified model is utilized in order to estimate the rotor position during startup.
2. Lock rotor strategy: In this method, one of the SRM phases is switched-on, which may make the rotor to be aligned with the stator pole. After alignment, the rotor position is detected, and using an affordable switching algorithm, the motor can operate. The rotor may rotate in reverse direction in this technique.
3. Training pulse technique: In this method, each phase of the motor is applied by trains of gate pulses, which make the rotor to rotate. In this method, the rotor may rotate some degrees in reverse direction at the start point.
4. Pulse detection method: In this technique, each phase winding is energized by low-level gate pulses with high frequency. The resulted current of windings shows their location with respect to the rotor pole.
5. Modulation strategies: In these strategies, rotor position detection is done after the calculation of the phase inductance from the modulated signal of the phase current. These methods are classified into three general groups: frequency modulation (FM), amplitude modulation (AM), and phase modulation (PM).
6. Chopping method: In the chopping method, the chopped current variations of a phase are used in rotor position detection.
7. Observer strategy: In this method, real SRM and its unreal (mathematical) model in computer are run simultaneously. The rotor location that is achieved for the mathematical model is used for controlling the real motor.
8. Mutual voltage technique: During motor operation, the active winding induces some energy to other inactive windings. The amplitude of the induced energy can be used in estimating the rotor location.
9. Resonance technique: In the resonance method, a pulse with specific frequency and low amplitude is applied to an unenergized winding. The specific frequency of the pulse is determined so that a resonance is created in the phase winding when the rotor is in unaligned position with respect to the stator pole.
10. Series capacitor method: The phase winding is connected to a capacitor in series in this method. Afterward, the phase is energized by pulses with low amplitudes. The capacitor discharging/charging time can be helpful in detecting the rotor location.

11. Flux calculation method: In SRM, there is a flux, current, and (FCR) rotor positions' relation. As a result, by knowing the phase current, its flux value, and using the FCR relation, the rotor location is detected.

12. Current profile strategy: For each rotor position, the current profile (waveform) of the active winding is significantly different. The difference can be helpful in the rotor position detection process.

13. Intelligent method: In intelligent strategies, the methods such as fuzzy logic controller, neural networks, and Fourier series are used to detect the rotor location.

Most of the existing sensorless techniques require a computer or high-frequency controller chip to drive the motor, which are expensive components. This problem significantly prevents these types of motor from broadly entrance to household appliances (such as fans, washing machine, and vacuum cleaner) and industrial equipment (such as robots, pump, drill, scooter, and mixer).

In this article, a low-cost, small-size, and accurate sensorless driver circuit is designed, simulated, and developed, which is able to control SRM in wide ranges of speed. In the presented driver, a control algorithm is introduced based on the linearized FCR relation of SRM that only needs the sampled current of the phase. The method significantly decreases the size, calculation cost, and memory demand in comparison with a common sensorless algorithm, while the value of accuracy is kept in close match. This article is organized as follows. Section II explains the specifications of the selected 6/4 three-phase SRM and the FCR curve of the SRM is obtained using a three dimensional (3D) finite-element method (FEM) analysis. In section III, specifications of the selected converter and the design process of the proposed sensorless method are explained. In section IV, the designed sensorless driver is simulated in the speed of 300 and 5000 rpm. Section V illustrates the operational results of the fabricated sensorless driver that is tested on the selected SRM in the laboratory. In section VI, the results of the proposed sensorless driver under different load and speed conditions are compared with results of a common sensorless algorithm and the reference data achieved by a direct with-sensor driver. The article is then followed by the conclusion in section VII.

2 | THE SPECIFICATIONS AND FEM ANALYSIS OF THE 6/4 THREE-PHASE SRM

In this article, a 6/4 three-phase SRM is chosen to simulate and test the presented sensorless driver. The selected motor, its rotor shape, and windings are demonstrated in Figure 2. As shown, the motor includes six salient stator poles and four salient rotor poles. The specifications of the used SRM are given in Table 1. The rotor pole and stator pole arcs are 32° and 30°, respectively. The difference helps the motor to produce less noise and torque ripple, which help the motor to achieve the nominal speed of around 5000 rpm.

The parameters of the SRM can be obtained by the simulation to perform 3D FEM analysis to find the solution for integral and partial differential equations, in which two methods are utilized to solve problems. One of them is based on using electric vector potential and the other is based on magnetic vector potential. Here, the first method is implemented whose final equations are:

\[ \nabla^2 T - \mu \sigma \left( \frac{\partial T}{\partial t} \right) = -\mu \sigma \nabla \left( \frac{\partial \Omega}{\partial t} \right), \]  
\[ \nabla^2 \Omega = 0. \]

**Figure 2** The selected 6/4 three-phase switched reluctance motor (SRM, front opened view)
TABLE 1 The specifications of the 6/4 three-phase SRM

| Parameter                          | Value   |
|------------------------------------|---------|
| Nominal power                      | 50 W    |
| Nominal voltage                    | 12 V    |
| Nominal speed                      | 5000 rpm|
| Stator core outer diameter         | 60 mm   |
| Stator core inner diameter         | 52 mm   |
| Stator pole arc                    | 30°     |
| Air gap                            | 0.25 mm |
| Rotor core outer diameter          | 35 mm   |
| Rotor shaft diameter               | 8 mm    |
| Rotor pole arc                     | 32°     |
| Number of turns per pole           | 200     |
| Phase resistance                   | 3.7 Ω   |
| Maximum inductance (in fully aligned) | 31 mH   |
| Minimum inductance (in unaligned)  | 5.9 mH  |

Abbreviation: SRM, switched reluctance motor.

In this method, rotor positions are declared as problems. Afterward, the winding is energized by direct current. At the same time, the rotor is rotated in the defined direction and the parameters of SRM are calculated for each problem.

In the presented article, the winding of the selected SRM is excited by rated current between 0.1 and 3 A and the motor is simulated from the beginning of alignment position to fully aligned location. Two poles (as one phase) are energized in this SRM. The flux starts to flow from the stator pole tooth, air gap, the rotor pole, the other stator pole tooth and closes the path from the motor yoke. Different parameters can be achieved by FEM analysis, such as torque ripple, torque, flux, winding losses, and energy. Here, the information about the FCR relation is required. Figure 3 demonstrates the FCR curve obtained by the FEM analysis for the winding rated current of 0.1 to 3 A and in different locations of the rotor.
3 | SELECTING THE CONVERTER AND THE DESIGN PROCESS OF THE PROPOSED SENSORLESS ALGORITHM

3.1 | Selecting the SRM converter

There are many converter topologies to drive SRM. The simplest topology is one-switch-per-phase (OSP) converter. One leg model of OSP converter is shown in Figure 4A. As shown, the phase winding of SRM is modeled by a series resistance and inductance. In the OSP converter, only one transistor (T1) and one Schottky diode (D1) are used in each phase, which significantly decreases the cost and size of the converter in comparison with other converter topologies.25

Figure 4B illustrates different operational steps of the OSP converter. When T1 is switched-on, the phase winding is energized and the motor generates some positive torque. Afterward, the phase is switched-off. Note that D1 is used in order to discharge the phase winding energy when the phase is switched-off; otherwise, after switching off the phase, the energy stored in the winding is appeared as a high voltage (spike) on metal-oxide-semiconductor field-effect transistor (MOSFET) (according to the equation $V = L \left( \frac{di}{dt} \right)$), which can severely hurt the MOSFET.

3.2 | Design process of the proposed sensorless algorithm

In order to design the presented sensorless driver, the basic relations of SRM, FCR relation, and the sampled current of the motor are required. The basic relations of SRM are originated from the $RL$ model of the phase winding. Equation (3) can be written for this model:

$$V = ri + \frac{d\psi}{dt}, \quad (3)$$

where $V$ is the phase applied voltage, $r$ is the winding resistance, $i$ is the phase current, and $\psi$ is the flux linkage and is calculated by:

$$\psi(\theta, i) = L(\theta) \times i, \quad (4)$$

**Figure 4** One-switch-per-phase (OSP) converter: (A) one leg model and (B) operational steps
where $\theta$ is the rotor position angle in radian, and $L$ is the winding inductance that varies with the variation of rotor position.

As shown in Figure 5, $L(\theta)$ has different values in any position of the rotor. In the start of alignment position (where the air gap between the rotor and stator poles is high), the value of the winding reluctance ($R$) is also high. According to the equation $L = N^2/R$, higher reluctance means that the phase has less inductance; as a result, in the start of alignment position, the value of inductance is minimum. On the other hand, in fully aligned position (where the air gap between the rotor and stator poles has its minimum value), the inductance has its maximum amount. Note that, in the motor mode, the phase winding has to be energized in the positive torque region, and in the generator mode of SRM, the phase should be switched-on in the negative torque region.

Using Equations (3) and (4), Equation (5) is obtained for unsaturated SRM:

$$V = ri + L\frac{di}{dt} + i\frac{dL}{dt}.$$  \hspace{1cm} (5)

The angle speed of the rotor is $\omega = \frac{d\theta}{dt}$; hence, Equation (5) is can be written in the form of:

$$V = ri + L\frac{di}{dt} + i\omega \frac{dL}{d\theta}.$$  \hspace{1cm} (6)

Expression $e = i\omega \frac{dL}{d\theta}$ is the back-Electromotive force (EMF) voltage of the motor. At low speed (small $\omega$), the value of back EMF is negligible. In SRM driving, the rotor position is the most important required parameter. Other parameters such as the current, voltage, flux linkage, resistance, and the motor speed are required in rotor position detection. In the presented method, the motor speed is calculated using the switching frequency. The supplied voltage and the value of the winding resistance are known, and the current value is sampled by the controller chip.

In the motor mode, the phase of SRM has to be turned-on in the beginning of alignment region and turned-off in the fully aligned region. By looking at the FCR curve of the selected 6/4 SRM (Figure 4) deeply, it is realized that in the region between the beginning of alignment and fully aligned points (which are the most important points in SRM control), the FCR curve can be modified into a linear curve. The modified FCR curve is shown in Figure 6.

Using the modified FCR curve, the relations of the machines are modified to very simple equations. This dramatically decreases the computational costs; accordingly, a low-cost microcontroller chip with low frequency is able to drive the motor. The modified relations are obtained as follows.
FIGURE 6 Modified flux, current, and rotor (FCR) curve of the selected 6/4 switched reluctance motor (SRM)

FIGURE 7 The reference flux, current, and rotor (FCR) curve of the selected 6/4 switched reluctance motor (SRM)

The flux linkage of the phase winding can be calculated by the controller using the value of sampled current at each time instant, the value of the supplied voltage, and winding resistance, which are known:

\[ \psi(t) = \int [V - (r_i(t))] dt. \]  \hspace{1cm} (7)

In the next step, one of the flux-rotor position curves of the modified FCR curve is selected as a reference curve. In the presented article, the flux-rotor position curve in the current of 100 mA is chosen as the reference curve, which is shown in Figure 7. As shown, it is a linear curve between two points of \([\psi_1, \theta_1] = [128 \times 10^{-6}, 0^\circ]\) and \([\psi_2, \theta_2] = [418 \times 10^{-6}, 28^\circ]\).

For the presented reference curve, the flux linkage equation can be written as follows:

\[ \psi_{ref, \theta} - \psi_1 = \frac{\psi_2 - \psi_1}{\theta_2 - \theta_1} (\theta - \theta_1) \rightarrow \]

\[ \psi_{ref, \theta} = (10.36 \times 10^{-6} \times \theta) + (128 \times 10^{-6}). \] \hspace{1cm} (8)

where \(\psi_{ref, \theta}\) is the value of flux in the reference FCR curve in the rotor position of \(\theta\). Equation (8) is only useful in the current of 100 mA. In order to achieve a comprehensive equation, the modified FCR curve (Figure 7) should be studied.
As is illustrated in the curve, the variations of the flux linkage curves in two different values of current, in each rotor position, are linear. In fact, the following relation can be seen in the FCR curve:

$$\psi_{i, \theta} = i \times \psi_{\text{ref}, \theta},$$  \hspace{1cm} (9)

where $\psi_{i, \theta}$ is the value of flux in the FCR curve of the current of "$i$" with the rotor position of $\theta$. For instance, as shown in Figure 7, with $\theta = 28^\circ$, the flux linkage in the current of 1 A is $418 \times 10^{-5}$ Wb, which is 10 times greater than that in the current of 100 mA ($418 \times 10^{-6}$ Wb), which is obtained by Equation (9) as:

$$\psi_{1A, 28^\circ} = \frac{1}{0.1} \times \psi_{\text{ref}, 28^\circ} = 418 \times 10^{-5} \text{ Wb.}$$  \hspace{1cm} (10)

Hence, the following equation can be written:

$$\psi_{i, \theta} - \left( i \times \psi_{1} \right) = \left( \frac{i}{0.1} \right) \frac{(\psi_{2} - \psi_{1})}{\theta_{2} - \theta_{1}} (\theta - \theta_{1}),$$

$$\psi_{i, \theta} = i \times [(10.36 \times 10^{-5} \times \theta) + (128 \times 10^{-5})].$$  \hspace{1cm} (11)

Equation (11) is the comprehensive modified FCR equation between FCR position for the selected 6/4 three-phase SRM, which is a linear equation. $\theta$ (radian) can be calculated by Equation (11) as follows:

$$\theta = \frac{\psi_{i, \theta} - (128 \times 10^{-5})}{10.36 \times 10^{-5}}.$$  \hspace{1cm} (12)

In summary, the current of the phase is sampled by the microcontroller; afterward, $\psi_{i, \theta}$ is calculated by Equation (7) and then $\theta$ is calculated by the linear Equation (12). After rotor position detection, adequate command pulses are generated to control the motor in the desired speed. These simple steps create an accurate, low-cost, and small-size sensorless driver for SRM. Equation (12) is obtained for the presented SRM; however, the proposed method can be implemented to estimate the value of $\theta$ for any SRMs using their FCR curve.

The proposed control algorithm that can be used for any SRM is shown in Figure 8. As shown, one phase of the SRM is excited at first. Afterward, the current of the phase is measured and transmitted to the control section. Then, the value of flux is calculated using Equation (7).

In the next stage, the rotor position value is achieved by Equation (12). If the rotor is placed in the fully aligned location ($\theta_{\text{desired}}$), the phase will be switched-off and the next phase will be excited; otherwise, the processes will be repeated till the rotor will be placed in the desired position. The presented SRM has three phases; hence, after energizing the third winding (phase), the first winding is energized again. Note that, during operation, the motor starts rotating from standstill using a training pulse strategy. Afterward, the controller changes the driving algorithm to the proposed method.

4 | SIMULATION OF THE PROPOSED SENSORLESS DRIVER

The complete simple block diagram of the simulation is presented in Figure 9. As shown, the current of the phase is sampled by a controller; afterward, the rotor position is detected after flux calculation and according to the modified FCR equation.

Then, the pulse generator section creates appropriate gate pulses based on the detected rotor position and the value of the desired speed. The gate pulses trigger the transistors of OSP converter that drives the selected SRM.

The simulation is done in two ranges of speed. Figures 10 and 11 demonstrate the calculated rotor position and the real value of rotor position in the speeds of around 300 and 1000 rpm, respectively.

The estimated rotor positions in each phase are shown based on the alignment and nonalignment positions of the rotor and the stator poles, where with $\theta = 30^\circ$, the rotor and stator are fully aligned and with $\theta = 0^\circ$, they are unaligned. In each electrical period ($T_p$), the real rotor position is $90^\circ$ ($3 \times 30^\circ$). As shown, the rotor positions of all phases are estimated in each phase $T_p$ (which is around 0.05 and 0.015 s in 300 and 1000 rpm, respectively), which perfectly match the real
FIGURE 8  The general control algorithm of the proposed sensorless technique

FIGURE 9  The complete block diagram of the implementation
**FIGURE 10**  The estimated and real values of the rotor position under 300-rpm speed in simulation

**FIGURE 11**  The estimated and real values of the rotor position under 1000-rpm speed in simulation
rotor position. The main reason of this precise estimation is that the information of the vital points (start of alignment and fully aligned points) of the FCR curve is considered in the modified FCR.

5 PROTOTYPING AND EXPERIMENTAL TEST RESULTS

The designed sensorless driver is then constructed and tested in the laboratory, as shown in Figure 12. As illustrated, the driver is very small size since it is very simple. An AT-Mega16 AVR microcontroller is utilized as the controller and pulse generator chip of the driver. The supplied voltage of the board is 12-V DC. Lm7805 voltage regulator is used for generating 5 V to feed the microcontroller and other digital chips. The microcontroller operates with 16-MHz clock frequency. The SRM phase excitation is done by the OSP convertor that includes IRF540 N-channel MOSFETs and TC427 MOSFET drivers.

The desired pulses are generated using the pulse-width modulation (PWM) technique in the microcontroller to drive the SRM. The current of phases is measured by 1-MHz sampling frequency using an ASC712 chip that is a Hall effect-based linear current sensor. The analog output of the current sensor has low amplitude. It is converted from analog to digital data by the analog-to-digital converter of the microcontroller that has 10-bit resolution.

**FIGURE 12** The constructed sensorless driver: (A) top view, (B) bottom view, and (C) test bench
Figure 13 shows the experimental results of two consecutive phases for 1000 rpm: (A) pulse-width modulation (PWM) output signal of the microcontroller and (B) output waveform of the current sensor.

6 | DISCUSSION AND COMPARATIVE STUDY

The proposed sensorless driver was tested under different load and speed conditions. The results were compared with the results of a traditional sensorless driver, in which the original FCR of the SRM was used. Figure 15A compares the rotor position estimation accuracy of both sensorless drivers with reference data achieved by a direct with-sensor driver while the SRM is working under no-load conditions over different ranges of speed. As shown, the accuracy of both sensorless drivers are in close match before the nominal speed of the motor (5000 rpm), which is due to considering the vital points of the FCR curve in the modified FCR curve. After the nominal speed, the difference between the accuracy of the proposed and common sensorless drivers is increased, which shows that the common sensorless driver can be more accurate in higher speed ranges. However, the accuracy of both sensorless drivers is significantly decreased in high-speed ranges, which is due to the impact of nonlinear parameters such as vibration and torque ripple that are increased in high speed.26-29

Figure 15B compares the rotor position estimation accuracy of all drivers in nominal speed (5000 rpm) under different load conditions. As shown, the accuracy of the proposed and common sensorless drivers is in close agreement with all ranges of the load. The accuracy of all drivers is near unity before around 95% of the nominal load (0.95 per unit load). However, the accuracy of both sensorless drivers is decreased exponentially by increasing the load, which shows that the sensorless drivers are not able to precisely estimate the rotor position under postnominal load conditions.

Table 2 compares the statistical results achieved by both sensorless drivers. The maximum value of the estimation error in nominal speed and no-load conditions is 0.78% and 0.81% for the common and proposed sensorless drivers, respectively, which are in close match (around 0.03% discrepancy). Moreover, the estimation errors of both drivers are in close agreement under nominal load and speed as well (around 0.11% discrepancy). The common sensorless driver can
**Figure 14** Experimental results of two consecutive phases for 5000 rpm (maximum speed): (A) pulse-width modulation (PWM) output signal of the microcontroller and (B) output waveform of the current sensor.

**Figure 15** Estimation accuracy resulted by the existing (red-dot) and proposed sensorless (blue-line) drivers in comparison with the reference sensor data (black-dash) under: (A) different speeds (no load) and (B) different load conditions (nominal speed).
TABLE 2 Statistical results achieved by the existing and proposed sensorless drivers

| Description                                      | Sensorless driver | Proposed sensorless driver | Discrepancy (%) |
|--------------------------------------------------|-------------------|-----------------------------|-----------------|
| Maximum estimation error (no load/nominal speed) | 0.78%             | 0.81%                       | +0.03%          |
| Maximum estimation error (nominal load and speed)| 1.22%             | 1.33%                       | +0.11%          |
| Maximum no-load speed                            | 6300 rpm          | 6230 rpm                    | −0.012%         |
| Maximum load (nominal speed)                     | 1.07 p.u.         | 1.06 p.u.                   | −0.01%          |
| Memory demand and calculation costs              | 87.5%             | 21.2%                       | −66.3%          |
| Board size                                       | 56.25 cm² (7.5 × 7.5 cm²) | 20 cm² (5 × 4 cm²)       | −64.5%          |
| Microcontroller chip price                       | At-Mega128 (£ 8.95) | 1 × At-Mega16 (£ 1.31)    | −85.4%          |

control the SRM to the maximum no-load speed of around 6300 rpm, while the proposed methods can drive the SRM to around 6230 rpm. In addition, both sensorless methods are able to drive the SRM under the maximum load of around 1.06 per unit.

The results prove that the achieved results of both sensorless drivers are in a close agreement; however, the memory demand and calculation costs of the proposed sensorless driver are around 66% less than that of the common sensorless driver, which is due to the less calculations and simpler algorithm used in the proposed sensorless method. Moreover, the size of the circuit board is decreased by around 64% in the proposed sensorless driver in which only one At-Mega16 AVR microcontroller was used, whereas in the common sensorless driver, an At-Mega128 AVR microcontroller was required to implement the complex algorithm. In addition, based on the price of the microcontroller chips to date, the circuit of the proposed algorithm is fabricated around 85% cheaper than the common method.

7 | CONCLUSION

In this article, the design, simulation, and fabrication of an accurate, low-cost, and small-size sensorless driver were presented for a 6/4 three-phase SRM over a wide range of speed. In the new method, the modified FCR curve of the selected SRM was used in order to design the modified FCR equation, which was a linear equation and placed in the memory of the microcontroller chip. This dramatically decreased the calculations related to the rotor position detection; consequently, a low-cost At-Mega16 AVR microcontroller could implement the control and rotor position estimation process of the selected SRM. In the control algorithm, the phase current was sampled by the microcontroller, which was used for calculating the value of flux during the SRM operation. Then, using the calculated value of flux, sampled current, and the modified FCR equation, the rotor position was estimated. Since the most important points (start of alignment and fully aligned positions of the rotor) of the FCR curve were used in the modified FCR curve, the rotor position estimation was implemented precisely over low to nominal ranges of the speed. This was confirmed by the simulation results and operational results in the laboratory. The method significantly decreases the size, calculation cost, and memory demand in comparison with a common sensorless algorithm, while the value of accuracy is kept in a close match. The results and accuracy of the proposed method were compared with a common sensorless driver and a direct with-sensor driver. The results proved that the proposed method can estimate the rotor position with high accuracy (maximum error of 1.3%) under nominal load and speed conditions. In addition, the method can significantly reduce the calculation cost and memory demand by around 66%, decrease the driver size by around 64%, and reduce the final fabrication price by around 85% in comparison with the common sensorless driver.

ACKNOWLEDGEMENT
This work was supported by research grants from the Iran National Science Foundation (INSF) under Grant No. 93036047.

CONFLICT OF INTEREST
The authors declare no potential conflict of interest.
**NOMENCLATURE**

\[ V \] voltage (V)

\[ i \] current (A)

\[ L \] inductance (H)

\[ r \] winding resistance (Ω)

\[ \psi \] flux linkage (Wb)

\[ e \] back-EMF voltage (V)

\[ \omega \] speed (rad/s)

\[ \theta \] rotor position (degree)

**ORCID**

Alireza Siadatan 🐦 https://orcid.org/0000-0002-3843-0458

**REFERENCES**

1. Afjei E, Siadatan A, Torkaman H. Magnetic modeling, prototyping, and comparative study of a quintuple-set switched reluctance motor. *IEEE T Magn*. 2015;51(8):1-7.

2. Siadatan A, Afjei E, Torkaman H, Rafiee M. Design, simulation and experimental results for a novel type of two-layer 6/4 three-phase switched reluctance motor/generator. *Energ Conver Manage*. 2013;71:199-207.

3. Gan C, Jianhua W, Yihua S, Shiyou Y, Wenping C, James KL. Online sensorless position estimation for switched reluctance motors using one current sensor. *IEEE Trans on Power Electron*. 2016;31(10):7248-7263.

4. Siadatan A, Torkaman H, Afjei E. Septi-segment switched reluctance machine: design, modeling, and manufacturing. *Int T Electr Energy*. 2016;26(8):1673-1684.

5. Dong J, Howey B, Danen B, et al. Advanced dynamic modeling of three-phase mutually coupled switched reluctance machine. *IEEE Trans Energy Conver*. 2018;33(1):146-154.

6. Zhu Y, Wei W, Yang C, Zhang Y. Multi-objective optimisation design of two-phase excitation switched reluctance motor for electric vehicles. *IET Electr Power Appl*. 2018;12(7):929-937.

7. Cheng H, Chen H, Xu S, Yang S. Four-quadrant sensorless control in switched reluctance machine drive using pulse injection based on special flux linkage curves. *IET Electr Power Appl*. 2017;11(9):1566-1574.

8. Li C, Wang G, Li Y, Xu A. An improved finite-state predictive torque control for switched reluctance motor drive. *IET Electr Power Appl*. 2018;12(12):144-151.

9. Siadatan A, Afjei SE, Torkaman H. Analytical design and FEM verification of a novel three-phase seven layers switched reluctance motor. *Prog Electromagn Res*. 2013;140:131-146.

10. Cao X, Zhou J, Liu C, Deng Z. Advanced control method for a single-winding bearingless switched reluctance motor to reduce torque ripple and radial displacement. *IEEE Trans Energy Conver*. 2017;32(4):1533-1543.

11. Wang Q, Chen H, Dou Y, Abbas S. Improved current control scheme with online current distribution and DFA regulation for switched reluctance generator. *IET Electr Power Appl*. 2018;12(3):388-397.

12. Masoudi S, Soltanpour MR, Abdollahi H. Adaptive fuzzy control method for a linear switched reluctance motor. *IET Electr Power Appl*. 2018;12(9):1328-1336.

13. Li S, Cheng KWE, Zhu J, Zou Y. Design and application of a decoupled rotary-linear switched reluctance motor for concentrated photovoltaic power generation. *IET Electr Power Appl*. 2018;12(7):908-915.

14. Peng F, Ye J, Emadi A, Huang Y. Position sensorless control of switched reluctance motor drives based on numerical method. *IEEE Trans Ind Appl*. 2017;53(3):2159-2168.

15. Siadatan A, Afjei E, Torkaman H. Design trend of a novel three-phase five layers switched reluctance motor for high torque applications. *Int Rev Electr Eng*. 2012;7(6):6055-6061.

16. Cai Y, Wang Y, Xu H, Sun S, Wang C, Sun L. Research on rotor position model for switched reluctance motor using neural network. *IEEE/ASME Trans Mechatron*. 2018;23(6):2762-2773.

17. Wei W, Wang Q, Nie R. Sensorless control of double-sided linear switched reluctance motor based on simplified flux linkage method. *CES Trans Electr Mach Syst*. 2017;1(3):246-253.

18. Gong C, Li S, Habetler T, Restrepo J, Soderholm B. Direct position control for ultrahigh-speed switched-reluctance machines based on low-cost nonintrusive reflective sensors. *IEEE Trans Ind Appl*. 2019;55(1):480-489.

19. Cai J, Deng Z. Unbalanced phase inductance adaptable rotor position sensorless scheme for switched reluctance motor. *IEEE Trans Power Electron*. 2018;33(5):4285-4292.

20. Oshaha AS, Ali ES, Abd Elazim SM. Speed control of SRM supplied by photovoltaic system via ant colony optimization algorithm. *Neural Comput Appl*. 2017;28(2):365-374.

21. Tang Y, He Y, Lee DH, Ahn JW. Sensorless estimation of single-phase hybrid SRM using back-EMF. *J Electr Eng Technol*. 2017;12(1):198-206.

22. Kim JH, Kim RY. Sensorless direct torque control using the inductance inflection point for a switched reluctance motor. *IEEE Trans Ind Electron*. 2018;65(12):9336-9345.
23. Hu KW, Chen YY, Liaw CM. A reversible position sensorless controlled switched-reluctance motor drive with adaptive and intuitive commutation tunings. *IEEE Trans Power Electron*. 2015;30(7):3781-3793.

24. Nezamabadi MM, Afjei E, Torkaman H. Design, dynamic electromagnetic analysis, FEM, and fabrication of a new switched-reluctance motor with hybrid motion. *IEEE Trans Magn*. 2016;52(4):1-8.

25. Krishnan R. *Switched Reluctance Motor Drives: Modeling, Simulation, Analysis, Design, and Applications*. New York, NY: CRC Press; 2001.

26. Ding X, Rashed M, Bozhko S. Assessment of torque ripple minimization techniques for aircraft switched reluctance machine starter/generator. Paper presented at: 4th International Symposium on More Electric Aircraft Technology, Beijing, China. 2017: 1-8.

27. Deng X, Mecrow B, Wu H, Martin R. Design and development of low torque ripple variable-speed drive system with six-phase switched reluctance motors. *IEEE Trans Energy Convers*. 2018;33(1):420-429.

28. Ye J, Emadi A. Torque ripple reduction in switched reluctance motor drives. U.S. Patent 9742320B2, issued August 22, 2017.

29. Hui C, Li M, Hui W, Shen SQ, Wang W. Torque ripple minimization for switched reluctance motor with predictive current control method. Paper presented at: 20th International Conference on Electrical Machines and Systems, Sydney, Australia. 2017: 1-4.

30. Farnell Website. “Farnell.” Element14. http://uk.farnell.com/ (January 01, 2018).

---

**How to cite this article:** Siadatan A, Torkaman H, Rafie M. Design, modeling, prototyping, and comparison of a low-cost, small-size, and accurate sensorless driver for switched reluctance motor. *Engineering Reports*. 2020;2:e12072. https://doi.org/10.1002/eng2.12072