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A Modulation Technique for Sensorless Control of Switched Reluctance Motor

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ABSTRACT

The switched reluctance motor (SRM) uniquely bears several merits with respect to other motor configurations. Especially, the construction of the rotor is simple in the sense that it neither contains copper not contains permanent magnets. Because of this construction, likelihood of rotor's failure is less than the other motor configurations. This makes this motor more suitable for harsh environments. On the flip side, this motor cannot directly operate with AC or DC power source and needs electronic commutation. For commutation, the information on instantaneous orientation of the rotor is essential. Since inclusion of appropriate sensor adds to the cost and complexity of the system, sensor-less commutation of SRM gained interest among the researchers and has been studied extensively in literature. The techniques for sensorless control of SRM can be broadly classified into Active phase and Idle phase techniques. Idle phase techniques are generally believed to be not suitable for high speed operation beause of tail current in a phase, i.e., because of inductive nature of the phase, it takes time for flow of current to stop. This paper proposes a novel idle phase technique that is conducive for high speed operation of switched reluctance motor.

Keywords: Switched reluctance motor; SRM; Sensorless control; Electronic commutation; Idle phase techniques

1. INTRODUCTION

The switched reluctance motor (SRM) bears unique merits with respect to other motor configurations:

- There is no coil or current carrying element in the rotor (therefore, no copper loss).
- There is no permanent magnet in the rotor.

These aspects make the construction of rotor for SRM significantly simpler than other motors. Therefore, the SRM is more suitable than the other motors for harsh working environments. The use of SRM for vehicle propulsion and hybrid electric vehicle is well appreciated in literature[1-4]. There is considerable research motivation for eliminating rare earth permanent magnets[2,4,5] The SRM configuration can also operate in generator mode and this is also well studied in literature[6,7]. The SRM is useful for various applications including position tracking[8]. The SRM shares some similarity with modern electrical machines like brushless DC (BLDC) motor in the sense that it needs electronic commutation for operation. This section explains the principle, construction and operation of switched reluctance motor and the need for estimation of angular position of the rotor. The configuration of a switched reluctance motor (SRM) is shown in Fig. 1. The extremely simple construction of the rotor is the characteristic feature of SRM. In DC motors, the rotor includes the armature core, the armature coils and commutator. Even the simplest induction motor does contain squirrel cage type rotors. The modern contemporary machines which depend on electronic commutation for operation like Brush-less DC (BLDC) or Permanent Magnet Synchronous Motor (PMSM) do contain permanent magnets in the rotor. On the contrary, the rotor of a SRM is merely a piece of metal (of high permeability) with well defined shape. Thus, the machine is more suitable for hostile working environments.

Figure 1 illustrates a SRM with 6 stator poles and 4 rotor poles (Let n_s and n_r represent the number of poles in the stator and rotor respectively). Each stator pole bears a coil and it would be convenient to connect (with appropriate polarity) the coils of diametrically opposite poles so that the resultant torque gets reinforced. With such an arrangement, the commutation can be achieved with just three switches (like

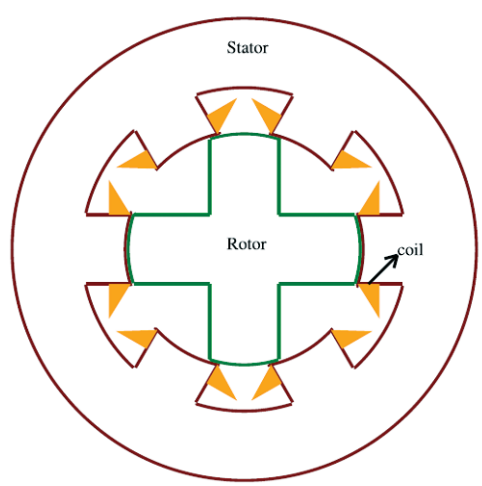

Figure 1. Construction of switched reluctance motor.

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MOSFETs or IGBTs) or $\frac{n_s}{2}$ switches in general. In an SRM, the torque depends only on the magnitude of the current and not on the direction. Because, the Torque τ equals $\frac{1}{2}i^2\frac{\partial L}{\partial\theta}$ as given by (1), where i is the instantaneous current through coil. Since torque depends on i^2, the direction of current does not matter. Since flow of current in one direction is sufficient for the operation of the motor, the *Shoot-through* fault gets eliminated naturally. But, on the flip side, it is necessary for the core material (on which the stator and rotor are made of) should be sufficiently *soft* in its magnetic characteristics. Yet, the magnetic *Hardness* could be catered for by having a drive system with capability for bi-directional current. Certain modifications like segmentation of the rotor[9], winding configuration & excitation waveform[10] and incorporation of magnetic bearing[11] are also studied in literature.

If the rotor is rotated by an angle of $\frac{2\pi}{n_r}$ radians, all characteristics of the motor would be same. In other words, the magnetic characteristics of the SRM repeats every $\frac{2\pi}{n_r}$ radians. A typical profile of coil inductance with respect to angle is as shown in Fig. 2. The inductance profile could be more accurately estimated with finite element analysis[12-14]. Studies on optimising the profile of the rotor is also proposed in literature[15]. A scheme for optimising the profile for torque ripple minimisation is presented in[15], whereas[16-18], attempt to achieve the same by modulating the excitation current. The inductance of the coil varies between a minimum value of L_{min} and a maximum value of L_{max}. The profile of inductance is periodic with respect to angular position of the rotor and repeats every $\frac{2\pi}{n_r}$ radians. The inductance of a coil is maximum when the rotor core is perfectly aligned with the stator. This maximum inductance is referred as *Aligned* inductance L_a. Similarly the inductance would be minimum when there is a perfect mis-alignment between the stator and rotor cores. Hence, the minimum inductance L_{min} is referred as *Un-aligned* inductance L_{ua}. For any angular position of the rotor (say θ), if the corresponding inductance is $L(\theta)$ and the current through the coil (whose inductance is $L(\theta)$) is i, the instantaneous torque is given by:

$$\tau = \frac{1}{2}i^2\frac{\partial L}{\partial\theta} \tag{1}$$

A SRM would have certain number of stator poles and associated windings. Each coil would have its own $L(\theta)$ profile because, aligned positions for each coil would be shifted in phase so as to cover the entire 360° about the axis of rotation. For proper operation of SRM, right coil, i.e., a coil which has positive value for $\frac{\partial L}{\partial\theta}$ must be made to carry current. This brings a demand on electronic commutation for appropriately *switching* the currents among the set of coils.

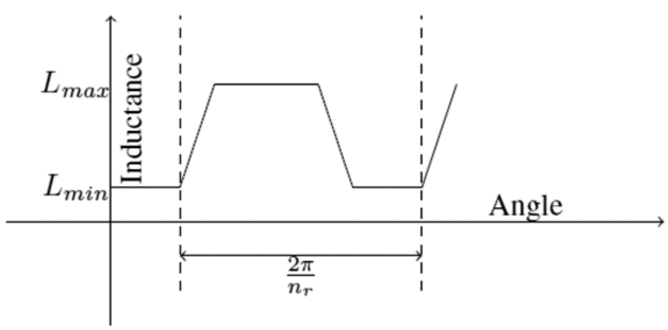

Figure 2. Typical inductance profile of SRM.

Certain salient positions on the inductance profile of SRM were identified in[19]. These are:

- *U* is the *Un-Aligned* position, wherein, the inductance is minimum.
- 1 is the position where the stator pole and rotor pole *begin* to overlap.
- *HR* is the position where the front edge of the rotor pole aligns with the axis of the stator pole.
- *A* is the *Fully Aligned* position.

To avoid retardation of the motor, the current in the coil must be stopped before the rotor reaches position *A*.

The torque exerted on the rotor is such as to align the *Saliency* of the rotor to that of the stator pole which is excited. Once the saliencies are aligned, the inductance of the stator coil attains its maximum value. Since $\frac{\partial L}{\partial\theta}$ becomes zero at the maximum value of *L*, the torque becomes zero irrespective of the current. If the rotor were already in motion and overshoots this position of maximum inductance, it would experience a *negative torque* opposing its motion proportional to i^2. Since the negative torque is undesirable, the current must have been stopped before this happens and *another* coil (housed in an another pole) which provides a positive torque to the rotor should be made to carry current. Thus the electronic commutation becomes vital for functioning of the SRM. The key aspect of the commutation is exciting the *correct* coil. To achieve this, we need to know the angular position of the rotor. Though it can be measured online with a suitable sensor, it adds the vulnerability of the system for failure defeating the main advantage of SRM, i.e., simplicity of the rotor and suitability for harsh environments. Therefore, a substantial amount of research efforts were carried out[6,20-27] towards *Sensor-less* control of switched reluctance motor which forms the subject matter of this paper. Methods for sensorless control can be broadly classified into *Idle* phase techniques and *Active* phase techniques. Idle phase techniques involve insertion of sensing signal in one of the idle phases to sense the angular orientation of the rotor. As the speed increases, the tail of current pulse in an active phase stretches out and thus occupies a significant portion of the idle phase. Thus, the idle phase is effectively not available for sensing. Therefore, literature generally favours active phase technique for control of SRM at higher speeds. To the contrary, this paper proposes a modulation encoding technique which is largely an idle phase technique for sensorless control of SRM. The proposed technique is amenable for higher speeds.

2. SENSOR-LESS OPERATION OF SWITCHED RELUCTANCE MOTOR

2.1 Active Phase Technique

Let us assume that in every coil, the current, its rate and voltage across it are measured. Let R_c be the resistance of the coil and R_s be the resistance of the part of circuit except the coil. Then the Kirchoff's voltage law for j^{th} pole becomes:

$$V_j = i_j(R_{cj} + R_{sj}) - e$$

$$= i_j(R_{cj} + R_{sj}) + \left(\frac{\partial\phi}{\partial i}\frac{\partial i}{\partial t} + \frac{\partial\phi}{\partial\theta}\dot{\theta}\right)$$

$$\Rightarrow \dot{i}_j = \frac{V_j - i_j(R_{cj} + R_{sj}) - \frac{\partial\phi_j}{\partial\theta}\dot{\theta}}{\frac{\partial\phi}{\partial i_j}}$$

$$\dot{i}_j = \frac{V_j - i_j(R_{cj} + R_{sj}) - \frac{\partial\phi_j}{\partial\theta}\dot{\theta}}{\frac{\partial\phi}{\partial i_j}} \quad (2)$$

Then, rearranging (2), we get:

$$V_j = i_j\left(R_{cj} + R_{sj}\right) + \frac{d\phi_j}{dt} \quad (3)$$

By rearranging (3) and integrating, we get:

$$\phi_j = \int\left(V_j - \left(R_{cj} + R_{sj}\right)i_j\right)dt \quad (4)$$

We know that flux ϕ is a function of current and orientation. Knowing $\phi(i,\theta)$ (from (4) and i , θ can be estimated. Though, apparently, the estimation of angular position looks straight-forward and simple, there are intricacies related to speed of the machine. The methods for sensorless switched reluctance motor drives have been classified into three categories in[23] depending on *Hardware* or *Data* or *MIPS* intensive. Since the sensing scheme is influenced substantially by the speed of the motor, different sensing strategies are employed[23]. This method for estimation of instantaneous orientation is called as *Active Phase* technique, because, it does not require an idle phase for sensing circuitry. But, it may be pointed out all phases in an SRM are not simultaneously excited, therefore, an idle phase is generally available, which is made use of by *Modulation Encoding Techniques* for sensing the instantaneous orientation of the rotor.

2.2 Modulation Encoding Techniques

Several modulation encoding techniques were presented in[28,29]. These are based on the dynamic behaviour of inductive circuit and uses an inactive phase for sensing. At an instant, one of the phases is excited and the other phases are not. The idea is to excite the inactive phase with a sinusoidal *carrier* signal. The transfer function of the coil can be written as:

$$I(s) = \frac{V(s)}{R + L(\theta)} \quad (5)$$

Assuming $L(\theta)$ as constant, (5) represents a basic first order system with a time constant L/R and a gain of $1/R$. The frequency response of a first order system is well known. For any carrier frequency ω_c , the current $I(j\omega_c)$ bears a definite relation in terms of gain and phase with respect to the voltage $V(j\omega))$. Either by measuring the gain or by measuring the phase, instantaneous inductance $L(\theta)$ can be estimated and in turn, the angular orientation θ . The gain can be estimated with AM (amplitude modulation) detector like what is used in AM communication. Phase can be estimated by zero-crossing detector which could be built with comparator. The instantaneous phase lag of the current with respect to the voltage is $\tan^{-1}(\frac{\omega L}{R})$. At low values of *L*, the phase lag is more *sensitive* to variation in $L(\theta)$ caused by change in θ. Whereas at larger values of *L*, the amplitude $\frac{1}{\sqrt{1+(\frac{\omega_c L}{R})^2}}$ becomes more sensitive to variation in $L(\theta)$. To exploit this fact[28], proposes that we can use a *level-crossing* detector instead of zero-crossing one. It is was also described in[28] how to choose the optimum value of series resistance R in (5). Besides the value of series resistance, the frequency is of carrier is also important[29].

2.3 Factors Influencing Modulation Encoding Techniques

Though the modulation techniques are useful for sensorless operation of switched reluctance motor, the application of such techniques is subject to the following considerations:

- It requires that the value of resistance R to be known. Though it is known in general, it is subject to variations based on environmental conditions. The variations in R lead to variation in gain and phase of current with respect to that of voltage and can potentially mislead the estimation of angular position of the rotor.
- The modulation techniques require that $L(\theta)$ changes at a rate significantly slower than the carrier frequency ω_c . Thus, at higher speeds, i.e., higher rpm, the carrier frequency must be made sufficiently high. For higher values of ω_c , the RC circuit (5) largely behaves as an inductive circuit and $I(j\omega)$ becomes too small to measure reliably. For example, if the motor rotates at 48k rpm, i.e., 800 rps, an 8/6 SRM (which completes an electrical cycle every 60°) effectively runs at 4800 rps. If we say that carrier signal shall have a frequency atleast ten times of it, it shall be atleast 48 kHz. Where a typical PWM frequency would be less than 20 kHz, the carrier frequency would be significantly higher than this. At such a high carrier frequency, the reactance $L\omega_c$ would be higher than 6 $k\Omega$. This leads to a very low current and sensing mechanism becomes less sensitive to change in inductance because of angle.
- Further at higher rpms, the dwell period of each phase increases virtually leaving no phase available for sensing.
- The coils are already connected to the driver circuit and during sensing, the circuit must be detached from this circuitry and connected to the sensing circuit. This was achieved by a multiplexer in[28]

With the due consideration of the above factors, this paper proposes a novel sensorless technique for control of switched reluctance motor. Contrary to other methods reported in literature, the proposed method is amenable to higher speeds since it enhances the availability of idle phase even at higher speeds.

3. PROPOSED CARRIER ENCODING TECHNIQUE FOR SENSORLESS CONTROL OF SRM

According to the classification presented in[23], the proposed technique is based on inclusion of additional control hardware. Idle phase techniques are limited by the tail current in the inactive phase. That is, because of inductive nature of the windings, the current continues to flow even after de-excitation of the winding. This is illustrated in Fig. 3.

The proposed technique includes a resistance in series with the coil in sensing circuit which bears a larger value. The carrier frequency in[29] is arrived based on desired resolution and update rate of inductance estimation. Lower is the carrier frequency, lower has to be the series resistance for effective estimation of the inductance. In contrast, the proposed technique uses a carrier of a substantially higher frequency. This offers two advantages. First, because of a high carrier frequency, the accuracy of inductance estimation improves substantially. Next, the time constant of the sensing circuit L/R, gets reduced substantially leading to shorter tail current. This enhances the availability of a phase for sensing, therefore, the proposed technique is better suitable than other idle phase techniques for high speed operation. The high level circuitry of the proposed technique is presented in Fig. 4.

The distinguishing features of the proposed technique are:

- The sensing signal is always present and thereby the problem of reconfiguring a phase of the motor from power (actuation) mode to sensing mode is eliminated. It has been described in[20], that, for sensorless control of SRM, the problem of including the phase winding alternatively into power and sensing circuitry has to be addressed.
- Compared to other modulation techniques, the frequency is deliberately chosen to be high. For a reasonable estimation of inductance of the coil, it is necessary that reactance $L\omega$ and the resistance of the circuit R_{sense} have to be close. Otherwise, the circuit largely behaves either inductive or resistive whichever dominates. At the core of sensorless control of SRM, we need to estimate instantaneous inductance online, necessitating that resistive and inductive constituents of the circuit should be roughly equal. As ω becomes large, R_{sense} has to be made large to match with $L\omega$.
- Since R_{sense} is large, it can be connected in parallel with the phase windings in power circuitry and in series with the phase windings in sensing circuitry as shown in Fig. 3.
- Because of large value of R_{sense}, the power *wasted* by it $\frac{V^2_{supply}}{R_{sense}}$ would be small and therefore, the sensing circuitry and power circuitry can co-exist.
- When the power to a phase winding is switched off, the large resistance R_{sense} appears in series with the phase windings, which has been in parallel so far. Large value of R_{sense} leads to a low value of time constant L/R, leading to early elimination of tail current (Fig. 3).
- Shorter duration of tail current leads to a better availability of a phase for sensing the inductance.

Figure 5 shows the inductance tracking performance of the proposed technique. This figure contains three profiles, each representing the instantaneous inductance of individual phases. The true value of instantaneous inductance is plotted along with the value estimated using the proposed technique. It can be seen from Fig. 5, not only that estimated inductance matches with the actual one, but also that, inductance estimation is available from two of the phases most of the times. This is achieved because of low time constant of the sensing L-R circuitry. Active phase techniques require a more elaborate computation which consume time while idle phase technique require the availability of idle phase. Thus, both class of techniques for sensorless control of SRM are limited by the speed of operation. Table 1 describes the speed of the motor reported in literature.

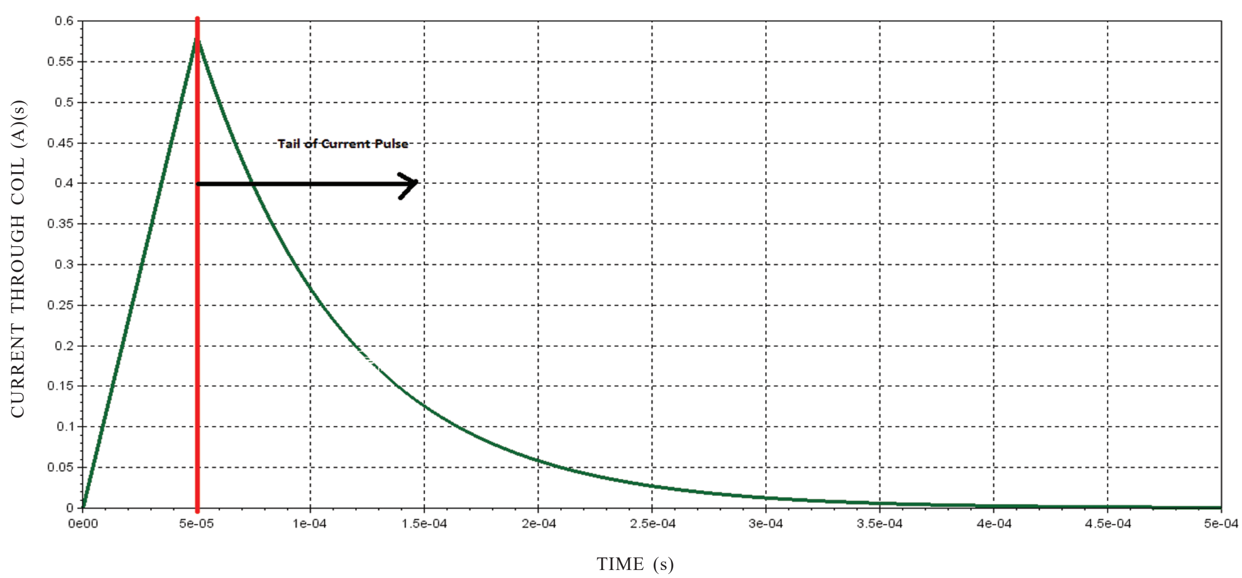

Figure 3. Tail current in SRM winding.

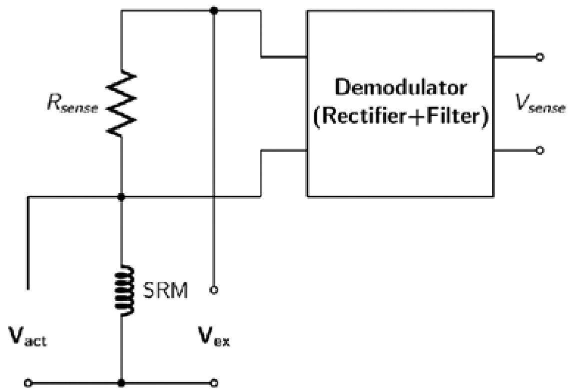

Figure 4. Sensing circuitry for sensorless control of switched reluctance motor.

Table 1. Speeds with sensorless SRM

Literature	Speed (rpm)
20	1050
23	2120
21	1000
24	3500
27	3000
19	2050
28	2500
29	3000
30	1000
31	3000
Proposed	12000

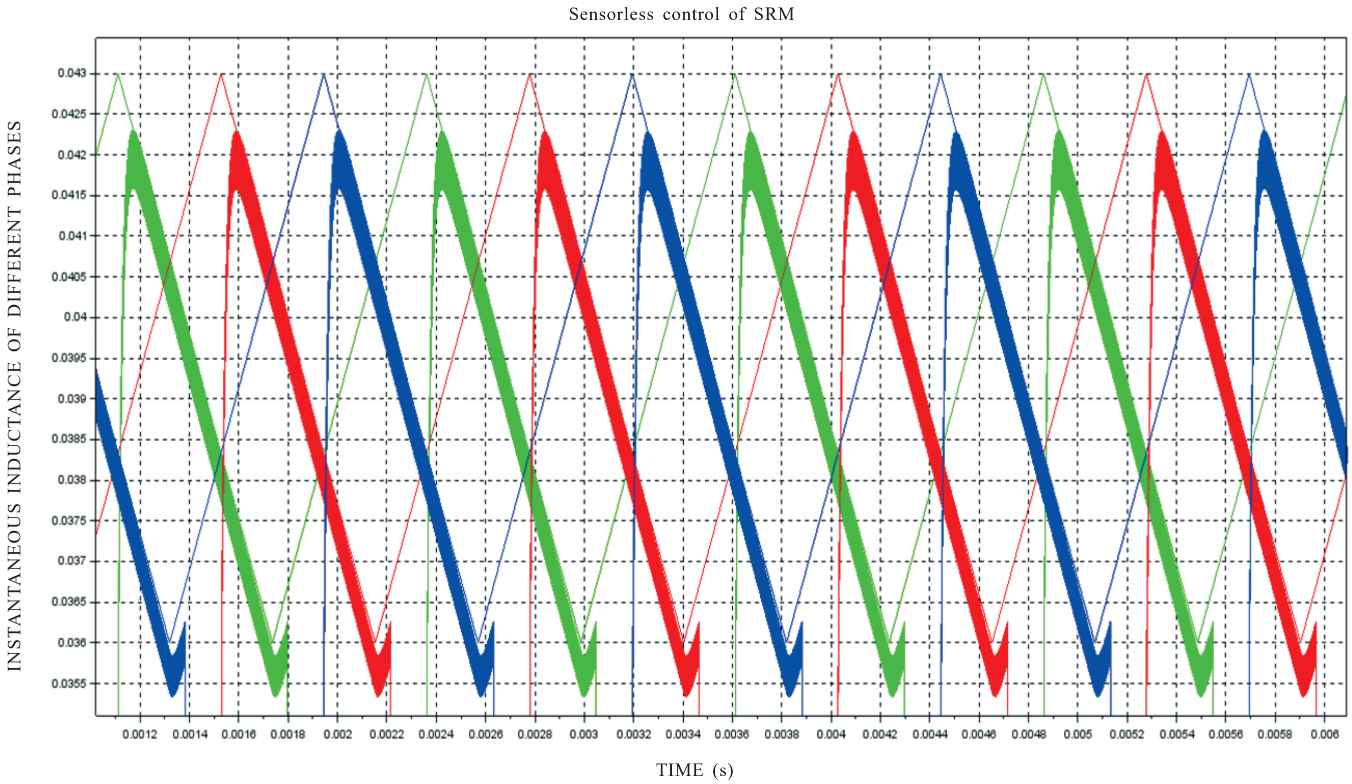

Figure 5. Sensing performance in individual phases of SRM.

4. CONCLUSIONS

The switched reluctance motors (SRM) bear an unique merit than other motor configurations because, its rotor is merely a piece of metal. Thus SRM is more suitable for hostile working environments. But, its application is greatly limited by the demand on drive electronics which needs to properly commute the power to the phase winding housed in the stator. Since the motor is driven by the saliency of the rotor (and stator), measurement of angular orientation of the rotor becomes essential. This requirement can potentially defeat the merit of SRM, hence, sensorless control of SRM attracts interest. Sensorless techniques attempt to estimate the position (through inductance) by observing the current through and voltage across the phase windings. Sensorless techniques are broadly classified into active and idle phase techniques which bear their own relative merits. Both these techniques limit the speed of operation of SRM. Active phase techniques require elaborate computation while idle phase techniques require availability of an idle phase. The inductive nature of the phase windings limit the availability of a phase as speed increases. This paper proposes a novel sensorless technique wherein, the availability of a phase for sensing the inductance is substantially enhanced.

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He devised and demonstrated the sensing circuitry in the present work.

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