Rotor Position Sensing and Estimation Techniques for Switched Reluctance Motors: Overview

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Abstract: Switched Reluctance Motors (SRMs) are fast gaining attraction towards industrial applications since they are less costly in construction and have robust performance in harsh environments. However, for speed, current and torque control in SRMs, rotor position sensing is indispensable. Over the last decade, there have been extensive research on rotor position determination using different techniques. Discrete sensors and indirect rotor position estimation both have merits and drawbacks depending on speed ranges, size of motor and principle of operation. This paper will analytically classify and discuss different techniques applied under rotor position estimation. These techniques are compared with regards to complexity of mathematical models, estimation error, complexity of the algorithm and need for storage memory. Additionally, this work also discusses rotor position determination using sensors with a proposition of a new technique using Magnetostrictive Amorphous Wire. Instead of the conventional position sensor encoders to sense the position of the rotor pole, this scheme proposes the application of Magnetostrictive Amorphous Wire (MAW) as the position sensor. The conventional position sensor is expensive and unreliable. It has been found to be affected by vibrations, temperature fluctuations, dirt and dust. With proper physical arrangement, the MAW sensor has been proven to provide amplifiable signals from the rotor. The discussion is geared towards facilitation in selection of potentially effective techniques in rotor position sensing and estimation in SRM drives.

Keywords: Switched Reluctance Motor; Sensor-based detection; Sensor-less estimation; Magnetostrictive Amorphous Wire

1 Introduction

The SRM has advantages such as wide speed range operation, high torque and robustness. Its construction is also less costly since its rotor is not made of rare earth metals. Presently, SRMs have been successfully applied in household appliances, textile industry and electric drives for other industrial applications [1]. However, apart from torque ripples and acoustic noises experienced with the motor, the need for rotor position information is indispensable. The rotor positon information is needed for accurate switching of currents through the respective phases. The sequential switching of the phases also determines the direction of rotation. The position information can be obtained in two ways: sensor based detection and sensor-less estimation as depicted in Figure 1.

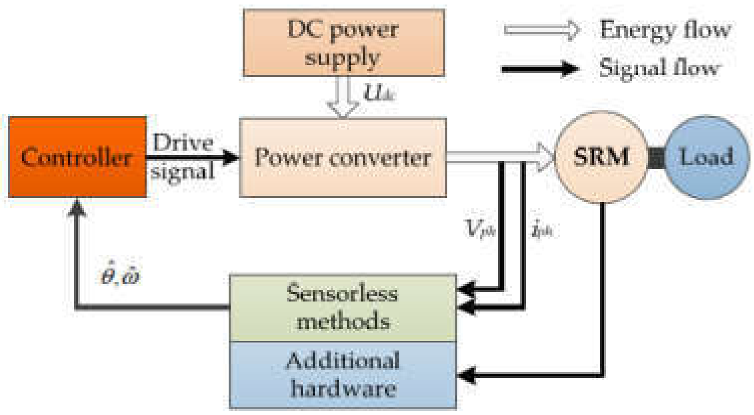


Figure 1
Sensorless and sensor based configuration for rotor position determination [10]

Sensor based detection provides rotor positon information through hall sensors, resolvers or encoders attached to the rotor shaft. According to [2], the rotor position can be determined using Giant Magneto Resistive sensors in between the motor air gaps. [3] Connects two SRMs on one shaft where one SRM acts as the rotor position sensor, also known as Switched Reluctance Position Sensor. For high speed operations, [4] utilizes a contactless optical sensor for the detection of the relative positon between the stator and the rotor. However, physical sensors have presented reliability challenges in unfavorable environments such as dust, electromagnetic interference and high temperatures. The drive system also incurs additional costs when the physical sensors are utilized.

Research developments have been geared towards elimination of the position sensor for the sensor-less position estimation. Sensor-less methods require lesser hardware as compared to sensor based techniques. Additionally, low cost and low risk advantages are realized for the SRMs implemented on sensorless rotor position estimation. Some of the techniques in sensorless detection of rotor position discussed in [5] include non-opening phase test, intelligent control test, additional components control and opening phase test. Other methods include pulse injection and simplified flux techniques. Development of finite element analysis methods, power electronics, control theory and flux linkage measurement technology has rapidly facilitated sensorless technology [6]. Novel methods of sensorless rotor position estimation are continuously being developed to coincide with the need for wider speed ranges, superior versatility and better accuracy in position estimation. The advantages and shortcomings of the sensorless positon estimation methods will be explored in this paper.

This paper presents a comparative analysis of both the sensor based and sensor less rotor position detection techniques. This work classifies different types of sensor less methods while also discussing their development process. The performance of each method is compared based on various metrics: range of speed regulation, memory space requirement and need for model accuracy. Sensor based methods still have other advantages which can address the challenges faced by sensorless techniques, for instance determination of the starting position of the rotor. Additionally, this paper discusses various categories and development of sensor based methods. Furthermore, the work introduces a new method of position detection using Magnetostrictive Amorphous Wire (MAW) to address some of the challenges presented by the conventional encoders and optic sensors.

2 Significance of Rotor Position Determination in SRMs

2.1 Alignment and Inductance profile

Figure 2 depicts the structure of a 3 phase 6/4 SRM [7]. Individual phases are subjected to current pulses sequentially which are then energized consequently. Rotor position determines which stator phase is energized by the current pulses.

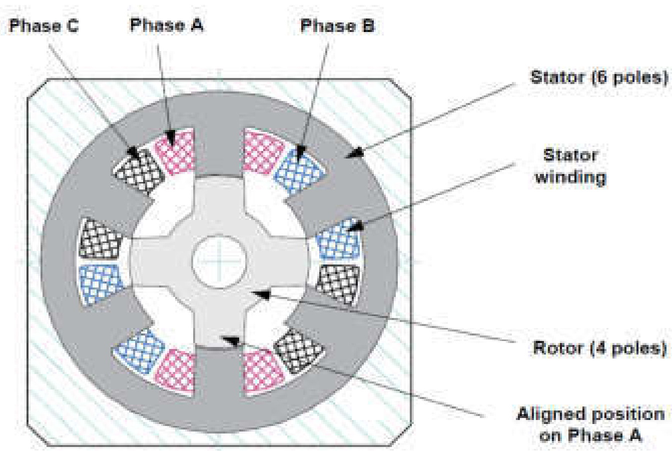


Figure 2
6/4 SRM [7]

Maximum stator inductance is achieved when a pair of rotor pole is aligned with an energized pair of stator poles. The phases are unaligned when the interpolar rotor axis is in-line with the energized phases of the stator poles as shown in Figure 3. In this way, the inductance profile achieves minimum stator inductance as shown in Figure 3 [7].

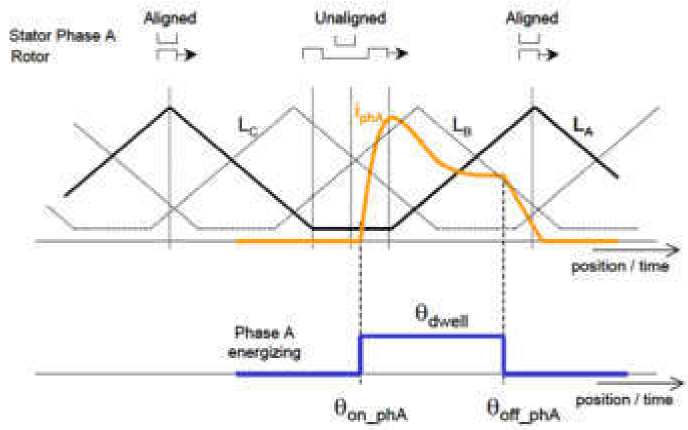


Figure 3
SRM inductance profile

The phase shift between A, B and C is 120 degrees and a dwell angle is developed in between intervals of energization of the respective phase. The dwell angle is defined by turn-off and turn-on angles. The phase current, assuming constant voltage, becomes maximum when the rotor pole starts to align with the energized stator phase and the inductance starts increasing. De-energizing the phase implies that the phase current will fall to zero. When inductance decreases as the alignment is gradually lost, the phase current present at that particular region will result into a negative torque. Therefore, it is imperative that the stator phase be energized when the rotor position assumes the increasing inductance region to achieve positive torque. The torque generated influences the efficiency of the SRM. A large positive torque and a small negative toque guarantees better SRM performance as discussed from Eqns. (1) to (12)

According to Kirchhoff's voltage law, the rotor position contributes to individual phase loops as follows:

$$v = Ri + \frac{\partial \lambda(\theta, i)}{\partial t},$$

(1)

where i, R, θ, λ and e are the phase current, phase resistance, rotor position, flux linkage and back EMF. The supplied power is a function of dissipation and summation of stored magnetic energy, W_f and an output of mechanical power W_m:

$$vi = Ri^2 + i\frac{\partial \lambda(\theta, i)}{\partial t}$$

(2)

Where,

$$i\frac{\partial \lambda}{\partial t} = \frac{\partial W_m}{\partial t} + \frac{\partial W_f}{\partial t}$$
(3)

We can relate the torque T and developed power P_m as:

$$P_m = \frac{\partial W_m}{\partial t} = T\omega = T\frac{\partial \theta}{\partial t}$$
(4)

Therefore, torque T from Equation 4 simplifies to:

$$T = i\frac{\partial \lambda}{\partial \theta} - \frac{\partial W_f}{\partial \theta}$$
(5)

The field energy, W_f and the co-energy, W_c

$$W_f = \int_0^{\lambda} i(\theta, \lambda)\partial\lambda$$
(6) $W_c = \int_0^{i} \lambda(\theta, i)\partial i$
(7)

The co-energy concept discussed in [8] can be summarized as:

$$W_f + W_c = \lambda i$$
(8)

Also

$$W_f = \frac{1}{2}Li^2$$
(9)

Substituting Eqn. (9) into Eqn. (5) yields the SRM torque as in Eqn. (12)

$$\frac{\partial W_f}{\partial \theta} = Li\frac{\partial i}{\partial \theta} + \frac{1}{2}i^2\frac{\partial L}{\partial \theta}$$
(10)

$$T = i\frac{\partial(Li)}{\partial\theta} - \frac{\partial W_f}{\partial\theta}$$
(11)

$$T = \frac{1}{2}i^2\frac{\partial L(\theta)}{\partial\theta}$$
(12)

From Eqn. (12), the developed torque is also a function of rotor position as much as it is directly proportional to the phase current. Considering Eqn. (1), then the flux linkage λ, is a nonlinear function comprised of phase current and rotor position.

For sensorless position estimation, the phase current i can be directly measured, however, θ can only be determined by a position sensor. Integrating Eqn. (1) provides flux linkage measurements which can then be utilized in obtaining the rotor position [9]:

$$\lambda = \int(v - iR)\,dt$$
(13)

With λ and i known, θ can be determined through numerical method or directly through lookup table. For small changes in flux linkage, current and rotor position angle, and for a small neighborhood of a point in the flux linkage profile, then:

$$\Delta\lambda = \frac{\partial\lambda}{\partial i}\Big|_{\theta=const}\Delta i + \frac{\partial\lambda}{\partial\theta}\Big|_{i=const}\Delta\theta$$
(14)

Measuring the current directly implies that Δi can be assumed as zero. Meaning,

$$\theta - \hat{\theta} = \frac{\partial\theta}{\partial\lambda}\Big|_{i=const}(\lambda - \hat{\lambda})$$
(15)

Equation 15 gives the estimated rotor positon and the flux linkage. The flux linkage is negligible initially since there are no magnetizing winding and permanent magnets. The flux linkage is a nonlinear relationship between the phase current and rotor position. Neglecting mutual inductance and expressing stator flux by self-inductance, then:

$$\lambda(\theta, i) = iL(\theta, i)$$
(16)

Substituting Eqn. (16) into (1) and considering back EMF and magnetic saturation, then Eqn. 1 becomes

$$v = Ri + L_i(\theta, i)\frac{\partial i}{dt} + e$$

(17)

Where $e = i\omega\frac{\partial L(\theta, i)}{\partial \theta}$ is the back EMF and $L_i(\theta, i) = L(\theta, i) + i\frac{\partial L(\theta, i)}{\partial i}$ is the incremental inductance. For low speed rotor position estimation, the incremental inductance has to be determined through current variation measurements as a consequence of the injected voltage:

$$L_i(\theta, i) = \frac{V_{inj}}{di/dt}$$

(18)

3 Overview of Major Categories of Sensorless Position Estimation Techniques in SRMs

3.1 Classification based on speed range operation and magnetic model

The general form of sensorless position control is as shown in Figure 4. [24]

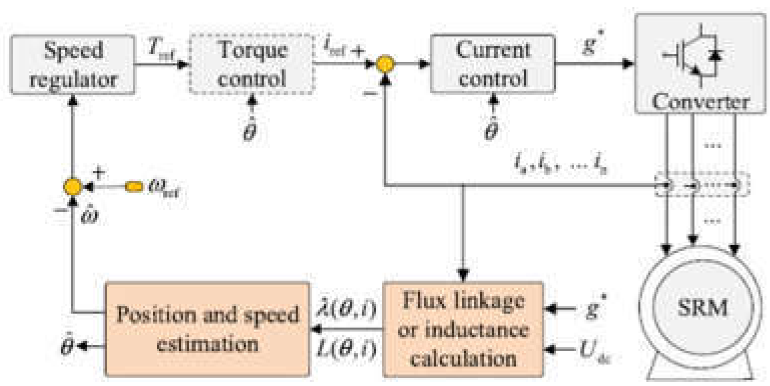


Figure 4
SRM control with sensorless rotor position determination [24]

This section reviews various related sensorless techniques with an objective of providing technical understanding of past, present and future direction in the development of these methods. Quantification of the performance of these methods is discussed based on metrics such as estimation error, need for prestored parameters and range of speed regulation.

There are several ways of categorizing sensorless position estimation, for example, intrusive and nonintrusive methods, low speed and high speed methods or magnetic parameter based methods. Researchers in [5] and [6] have roughly categorized these methods into non-opening phase test, additional component test and opening phase test. This paper presents categorization of the position sensorless techniques under low speed and high speed operation, standstill control and need for memory space. Summary of position sensorless techniques based on speed of operation is presented in Figure 5.

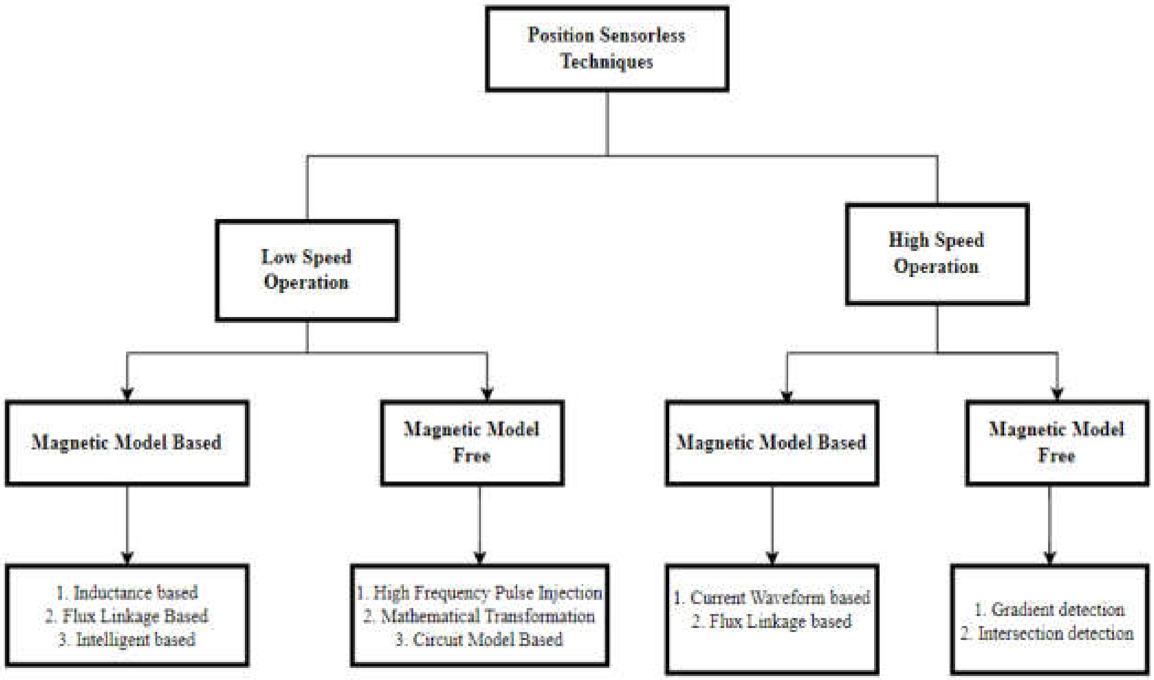


Figure 5
Categories of sensorless techniques based on range of speed operation

3.2 Low Speed Position Sensorless Estimation Techniques

Low speed estimation methods are categorized into magnetic model based and magnetic model free techniques. These include: inductance based method, flux linkage based method, high frequency pulse injection and mathematical transformation models.

Inductance based method

The incremental self-inductance of a given phase m can expressed as a function self-inductance $L_{m,m}$ [10]:

$$L_{inc\_m,m} = L_{m,m} + i_m \frac{dL_{m,m}}{di}$$

(19)

As depicted in Eqn. (19), at given rotor positions, phase inductance varies with current. Therefore, incremental self-inductance, $L_{m,m}$ can be represented as a function of phase current and rotor position as in Eqns. (20) and (21).

$$L_{inc\_m,m} = f(i_m, \theta)$$
(20)

$$\theta = f^{-1}(i_m, L_{inc\_m,m})$$
(21)

Several research works, have adopted inductance model of position sensorless method to save memory space since there is no storage of complex magnetic characteristics. However, this method is only suitable for applications of low speed operations. Ignoring other harmonic components, as in [11] and [12], to only consider first harmonic of a simple inductance through Fourier series with the objective of eliminating the need for interpolation and controller memory. However, neglecting of other components of the harmonics may lead to model mismatch. Enhancing inductance model accuracy is solved through mutual inductance, online calibration and magnetic saturation.

3.2.1 High Frequency Pulse Injection

Here, a series of high frequency voltage pulses are injected into unenergised phases of the stator. Different rotor positions lead to changes in the magnetic circuit of the individual phases. Therefore, when high frequency voltage pulses are injected into non-conducting phases, the corresponding current pulses will subsequently vary with rotor positions. This method operates on a theoretical basis presented in Eqn. (22) where Δt and Δi are the detection coil time interval and rate of change of current.

$$U_k \approx L(\theta_{ph}) \frac{\Delta i}{\Delta t}$$
(22)

A short duration pulse injection into 3 phases is proposed in [13] to mitigate the effects of startup hysteresis. Ehsani et al [25], presents a technique of injecting a high frequency carrier into a non-energised phase. Relative to the carrier signal, smaller frequency variations are recorded for signals that contain phase inductance data. The frequency variations were then decoded using a demodulator for the estimation of the rotor position. High frequency pulse injection method is cheaper to implement since there are no complex computations and additional hardware. However, there is need for a substantial amount of storage space [26]. Furthermore, several studies have combined pulse injection and current waveforms based technique to achieve wider speed range operation. However, operation of pulse injection at high speed range affects the torque quality of the motor.

3.2.2 Mathematical Transformation and Circuit Model based methods

To estimate rotor positon at standstill, linear regression positon-sensorless method with Type-V exponent and quadratic polynomial are proposed in [14]. The bootstrap and linear regression methods are however not applicable for sensorless estimation during driving operations. In circuit model based methods, a circuit is needed to perform voltage measurements required for position-sensorless estimation. A real time position-sensorless estimation can also be achieved through a resonant circuit. The position of the rotor is estimated using the peak resonance as shown in Eqn. (23)

$$U_R = \frac{U_k}{1 + jQ[(f_1/f_0)^2 - 1]} \quad , \; f_0 = 1/\left(2\pi\sqrt{LC}\right) \text{and } Q = 1/\left(2\pi f_1 RC\right)$$

(23)

However, real time estimation requires predefined motor circuit parameters.

3.2.3 Intelligent based methods

This method presents an accurate modelling of nonlinearity in inductance and flux linkage in rotor position estimation. Fuzzy logic can be used to replace the conventional 3D lookup table used in flux linkage estimation methods. This results into a considerable reduction in the prestored data. Fuzzy logic algorithm based method does not need complex mathematical modelling of the SRM. The use of fuzzy logic has been limited by the need for complex fuzzy rules that are not clear and takes a considerable amount of time to design. Studies involving neural networks have used phase voltage and phase current as input to estimate the rotor position as output.

In [15], rotor position is estimated using neural network with sampled voltage and current. Thereafter, the performance of the model is improved through additional layers and pretreatment sections to realize a general improvement in accuracy of the position estimation method. As much as neural networks present an outstanding modelling accuracy, it needs a lot of measurement data to achieve the accuracy.

3.2.4 Current Waveform based method

This method involves direct current measurements as discussed in [27]-[29]. Reasonable performance from current waveform based methods have been realized at low speeds. [30]-[32] proposes an online back EMF estimation techniques derived from the ratio of fall time and rise time of the phase current during the chopping periods. However, this method is only efficient for accurate model of analytical inductance.

3.3 High Speed Position Sensorless Estimation Techniques

The pulse injection methods incur inaccuracies in position estimation at higher speeds due to narrow idle phase cycles which present shorter durations of injection at these speeds. Pulse injection methods also result in torque ripples, power losses and acoustic noises. High speed position estimation techniques have become more attractive since stator inductance and flux linkage are observable in conduction phases. One of the magnetic free based methods for high speed position sensorless techniques is the gradient detection method. Here, geometric location of the rotor is monitored to identify the rotor positon in real time. [16]- [17] proposes current gradient detection based on phase current regulation via adjustment of phase commutation angles. A nonlinear variation of phase current is realized with the rotor pole and stator pole relative position. Therefore, phase commutation is determined for direct position sensorless control and calculation of rotor positon value is achieved through rotor and stator pole arcs without need for complex magnetic characteristics. However, this method incurs inaccuracies at low speeds and standstill due to noise in the calculation of current differentials. To solve for the shortcomings of current gradient detection methods, inductance gradient based techniques can be used. However, this technique works with fixed commutation angles which may not achieve reasonable current and speed performance.

3.4 Wider Speed Range Estimation methods

There are methods that provide rotor positon estimation over a wide speed range, from low speed operations to high speed operations. These methods are mainly magnetic model based and include the flux linkage based method and observer based techniques.

3.4.1 Flux linkage based method

If mutual coupling is neglected, estimation of the rotor position can be determined from Eqn. (25) [10].

$$\lambda_m = f(i_m, \theta) \tag{24}$$

$$\theta = f^{-1}(i_m, \lambda_m) \tag{25}$$

This method uses look up table (LUT) to store magnetic characteristic values. 3D LUT and flux linkage modelling is presented in [13] and [18] to detect position signal through flux linkage and current information. Position estimation in wide speed range is achieved. However, there is need for pre-storage space and dependence on torque and speed control strategy.

3.4.2 Observer based method

Here, SRM state equation is first determined and then an observer is utilized in measurements of physical quantities that cannot be measured directly. Rotor position is determined indirectly in [19] using sliding mode observers, position observers and flux observers. These methods are independent of speed and torque control and do not require pre-stored data. However, the observers are difficult to design due mathematical complexities.

Table 1
Summary of Sensorless Estimation Techniques

	Position sensorless method	Speed operation Range	Standstill estimation ability	Need for Memory space
1	Inductance based method	Low speed	x	NO
2	High frequency pulse injection	Low speed	x	YES
3	Mathematical Transformation and circuit model based	Low speed	✓	NO
4	Intelligent based method	Low speed	✓	YES
5	Current waveform based	Low speed	✓	NO
6	Gradient detection	High speed	x	NO
7	Flux linkage based method	Wide speed	✓	YES
8	Observer based method	Wide speed	✓	NO

4 Sensor Based Position Detection Methods

In sensorless estimation, rotor position at standstill has to be known. An additional circuit is needed to achieve forced alignment during the motor start. Therefore, for application of these methods to unidirectional drives can be a great challenge. Sensor based methods such as hall sensors, resolvers and optical encoders are adequately utilized in industrial applications. Their performance is affected by dust, misalignments due to vibrations and they also increase the size of the motor. However, they guarantee continuous position detection and at standstill operation without extra circuitry.

Aydemir *et.al,* [20] presents a low cost nonintrusive Hall effect sensor system for an external rotor SRM. A90.8% cost reduction in comparison to absolute position encoder was realized. However, the system is too big to be applied to an inner runner SRM. Shin *et.al* [21], presents an inbuilt search coil that detects rotor position based on back EMF induced in coil during rotation. The performance of Hall sensors is generally affected by misalignments, and therefore optical sensors can be used as alternative. The optical sensors are highly sensitive to environmental conditions such as dust and dirt and hence demands proper sealing to guarantee reliability. Precise detection demands higher resolution encoders which turns out to be very costly. Low cost and low resolution encoders present challenges in detecting rotor positon at standstill and accuracy limitations. In [22], a high resolution position detection based on sinusoidal incremental encoders is presented. The technique is simple and less costly to implement. However, this method requires a look up table for calculation of uncorrected and real position for every sample during one cycle pointing towards the need for a large storage space if a huge number of cycles is considered.

5 Future development

Sensorless estimation techniques are limited by speed range operations, susceptible to estimation errors and require additional circuitry for initial position estimation. Hall sensor and optical encoders are also prone to faults due to environmental conditions and misalignments. In view of the above challenges, the author will be investigating a novel experimental method using Magnetostrictive Amorphous Wire (MAW) as the position sensor. The MAW has been successfully implemented in frequency control of microhydro power plants by [23] as shown in Fig 3(a) and (b). The MAW can be modelled into a pick up coil to harness the induced signals for the rotor poles. Consequently, develop the induced EMF equation as function of phase currents and the value of mutual inductance, which depends on the amount of overlap between the stator and rotor poles. The pick-up coil's EMF should contain information about rotor position.

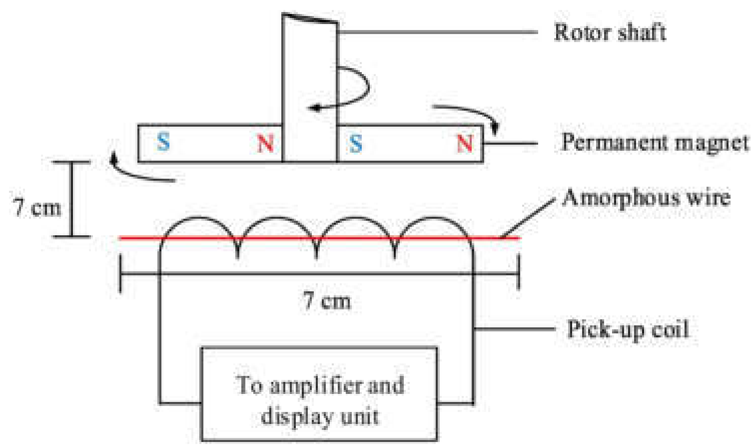


Figure 6
MAW coil configuration

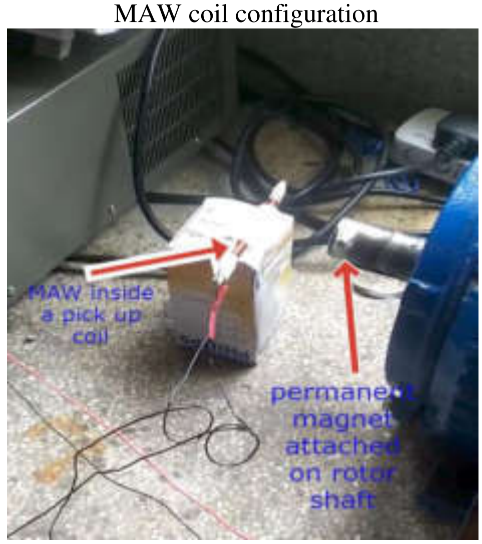
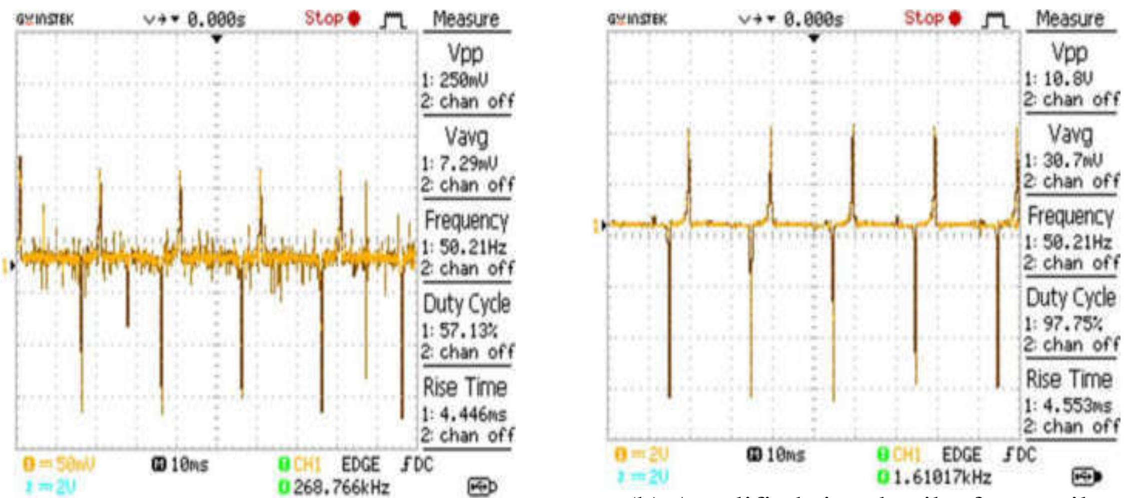


Figure 7
Experimental test bench



(a) Unprocessed induced spikes (b) Amplified signal spike from coil

Figure 8
Signals from the MAW coil

Conclusion

The author managed to classify the magnetic model based and magnetic model free position sensorless estimation techniques into various speed ranges, ability to estimate rotor position at standstill and need for pre-stored data. Through the discussion, the strengths of these techniques have been highlighted. The limitations of these techniques can be solved through hybridization of different methods and hardware compliments. It is in this regard that sensor based methods have been discussed to look for possibility of combining the fundamentals, as a future direction, from the two ideologies to maximize on the others advantages and compliment on the limitations.

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