

# AUTOMATIC PHASE ADVANCING IN SWITCHED RELUCTANCE MOTOR BY EMPLOYING AN ELECTRONIC GOVERNOR FOR A DESIRED SPEED/ANGLE PROFILE

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**Abstract** Switched reluctance motor (SRM) drive has remarkable characteristics that make it attractive for high-speed applications. As the motor's speed increases the shape of the current waveform changes in such way that limits the production of motoring torque. At high speeds, it is possible for the phase current never reaches the desired value due to the self e.m.f. of the motor, therefore, the torque falls off. In order to remedy this problem, the phase turn on angle is advanced in such way that the phase commutation begins sooner. Advancing the commutation angle offers the advantages of getting the current into the phase winding while the inductance of the phase is low, and also of having a little more time to get the current out of the phase winding before the rotor reaches the negative torque region. Since the SRM drive is a variable speed motor then, the amount of advancing for the turn on angle should be accomplished automatically according to the speed of the motor, meaning, as the motor speed increases so should the turn on angle and vice versa. In this respect, this paper introduces an electronic governor using a P.L.L. module in conjunction with a micro controller to achieve this task for a desired speed/advancement angle profile, which is considered to be linear in this study. The governor causes 0-14 degrees automatic adjustment in the turn on angle from stand still to a pre-set speed for a SR motor. A linear analysis of the current waveform for the motor under different advancements of the turn on angle has been performed and the plots are shown. Finally, the experimental results of employing the governor on a 6 x 4 SRM drive are presented.

**Key Words** Switched Reluctance Motor, SRM, Switched Reluctance Drive, Motors, Electronic Governor in SRM

**چکیده** موتور رلوکتانس سویچی با مشخصات قابل توجه، کاربردهای مختلفی در سرعت بالا دارد. با افزایش سرعت بعلت e.m.f. موتور شکل جریان نیز تغییر می کند بطوریکه این جریان ممکن است هرگز به مقدار حداکثر خود نرسد که این امر موجب کاهش گشتاور می گردد. برای حل این مسئله زاویه آتش هر فاز همزمان با افزایش سرعت به مقدار مناسبی به جلو کشیده می شود این عمل باعث افزایش جریان قبل از محدود شدن آن بوسیله اندوکتانس سیم پیچ موتور می گردد و به همین ترتیب موجب تقلیل جریان به صفر قبل از رسیدن روتور به ناحیه گشتاور منفی می گردد. بدین ترتیب در سرعت های بالا امکان ایجاد جریان های بالاتر و گشتاور بیشتر فراهم می شود. از آنجایی که موتور رلوکتانس سویچی در سرعت های متغیر به کار می رود بایستی زاویه آتش نیز همزمان با سرعت تغییر نماید به همین منظور این مقاله یک گاورنر الکتریکی رامعرفی می نماید که با استفاده از یک میکرو کنترلر میتوان منحنی های مختلف سرعت و زاویه آتش را به مدار راه انداز موتور اعمال می نمود. همچنین تاثیر مطلوب این کار بر عملکرد یک موتور رلوکتانس ۶/۴ را نیز ارائه می دهد.

## 1. INTRODUCTION

The switched reluctance motor has been extensively investigated and developed in the past decades by several research organizations with results that are more promising than those obtained in the previous

work [1-3]. Although invented over 150 years ago, the SRM drive did not realize its full potential until the modern era of power electronics and computer-aided electromagnetic design [4]. SRM drives have been used extensively in clocks and phonograph turntables before but nowadays; they have been

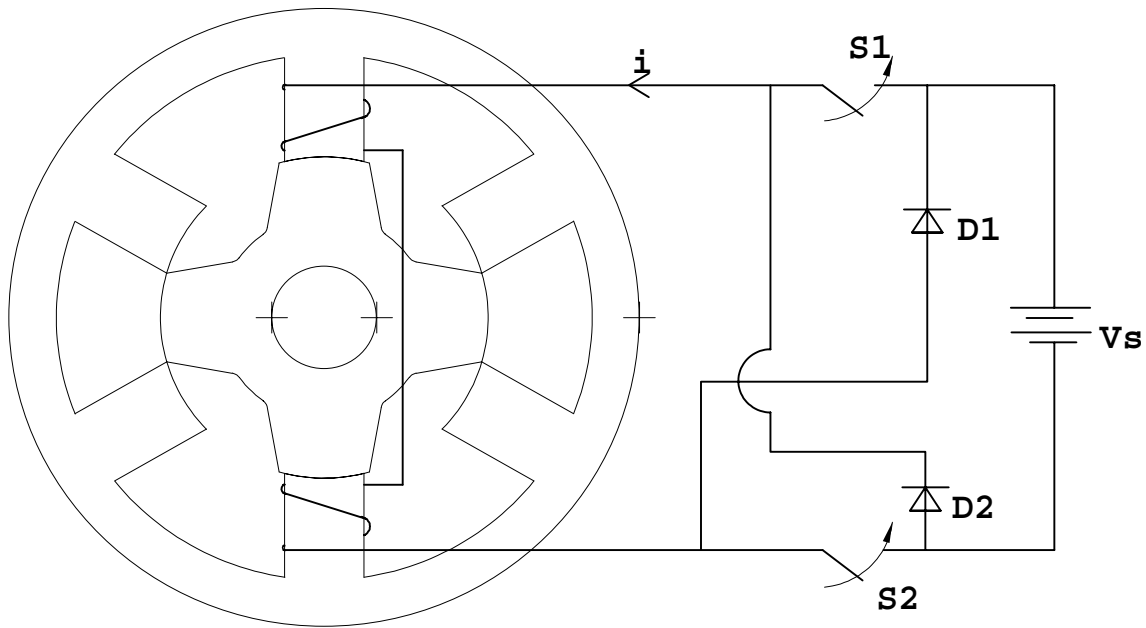


Figure 1. A 6 x 4 SRM drive, showing the phase one winding and its drive circuit.

employed in many different industrial applications such as Electric Vehicle [5]. The motor development has matured to the point that its performance has been raised to levels competitive with that of dc and variable speed ac motors especially in high-speed [6]. The performance prediction and different design aspects of the motor has been discussed by researchers [7-8].

The start and duration of current pulses for each phase in a switched reluctance motor is controlled and synchronized with rotor position by means of a direct or an indirect shaft positioning scheme [9]. The control strategies become an important issue in the motor behavior [10]. The performance of SRM drive can be greatly influenced by choosing the proper starting time for the phase turn on angle at different speed [11] and also selecting the proper turn off time can greatly effect its performance [12]. The time duration  $\tau$  available for current in each phase winding is directly related to the speed of the motor. As the motor's speed increases the amount of time,  $\tau$ , decreases and at some point, it can reach a certain value such that, the control of the winding current to the desired value is impossible.

At this high speed the current can neither rise nor decay quickly enough in the winding to reach the preferred level. Due to this reason, it is desirable to get current into the motor phase winding while the phase inductance is still relatively small. There are two methods to achieve this objective [13]

- 1 - Varying the dwell angle (difference between the firing angles) such that the phase commutation begins sooner and ends sooner.
- 2 - If possible, switch from full number of turns in phase winding to half of that value, so the current rise time is reduced.

The idea of phase advancing was realized in the earliest work in variable reluctance motor and its effectiveness on the motor performance was discussed and clarified [14].

It is important to realize that the amount of advancing for the turn on angle should be accomplish according to the motor's speed in order to get the high performance expected out of the motor [15].

In this respect, an electronic governor is introduced to change the dwell angle just enough under different speeds, so that the phase commutation begins

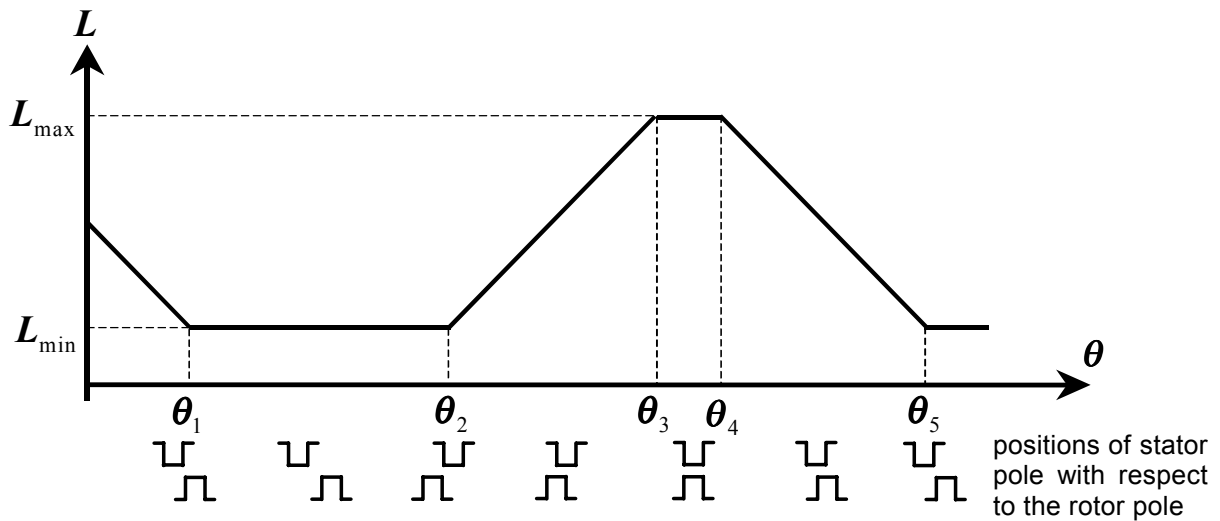


Figure 2. Inductance variation of one motor phase.

sooner and ends sooner. This method is very effective in creating sufficient time for the phase current to rise to the desired value therefore, the motoring torque will not fall off, and also, the current will be out of the winding before the rotor reaches the negative torque region.

## 2. THE BASIC MODEL

The principles of operation of switched reluctance motors have been widely explained and understood; hence it will not be explained here. It is appropriate, however to use a linear model of the motor, to develop simplified expressions for the current waveforms under different advancement of the phase turn on angles. Figure 1 illustrates a 3-phase, 6 x 4 SRM drive showing only phase one winding and its drive circuit.

Although saturation plays an important role in obtaining the exact behavior of the SRM drive and also, is necessary for the detailed motor design, but analysis of magnetically linear SRM drive can provide useful and broad understanding of the influence of the many motor parameters. Figure 2 shows the variation of inductance with respect to the rotor position for only one pair of stator poles in an ideal linear motor shown in Figure 1.

The positions of rotor pole with respect to the stator pole corresponding to the different parts of inductance profile are also shown in Figure 2.

The current flowing in the phase winding of Figure 1 can be described by the following equation

$$V_s = R \cdot i + L(\theta) \frac{di}{dt} + i \frac{dL(\theta)}{d\theta} \omega \quad (1)$$

where  $V_s$  is the source voltage,  $i$  is the phase current,  $R$  and  $L$  are resistance and inductance of the phase and  $\omega$  is the motor speed.

The solution to Equation 1 yields the following result for the current,  $i$

$$i = \frac{V_s}{R + \frac{dL}{d\theta} \omega} + [I_0 - \frac{V_s}{R + \frac{dL}{d\theta} \omega}] e^{-\frac{t}{\tau}} \quad (2)$$

where  $I_0$  is the initial current, and

$$\tau = \frac{L(\theta)}{R + \frac{dL(\theta)}{d\theta} \omega}$$

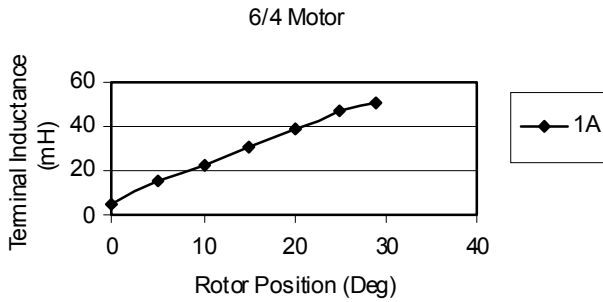


Figure 3. Terminal inductance vs. rotor position.

In order to be able to plot the current profile for a SRM drive, the parameters in equation 2 are found by either numerically or experimentally for a 6 x 4, three phase, 24 V switched reluctance motor with the following specifications:

- stator core outer diameter = 72mm
- stator core inner diameter = 62mm
- rotor pole arc = 32°
- stator pole arc = 28°
- stack length = 35mm
- air gap = 0.25mm
- rotor core outer diameter = 39.5mm
- rotor shaft diameter = 10mm
- number of turns per pole = 115.

In the numerical part, the magnetic field analysis has been performed using a Magnet CAD package [16], which is based on the variational energy minimization technique to solve for the

magnetic vector potential. This simulation directly yields prediction of flux linkages. The so-called “effective” inductance has been defined as the ratio of each phase flux linkages to the exciting current ( $\lambda / I$ ). Values based on this definition are presented in Figure 3 for the motor.

In the analysis the rotor moves from unaligned (i.e. 0°) to aligned (i.e. 28°) positions hence, all “effective” inductance values for these points in between are computed.

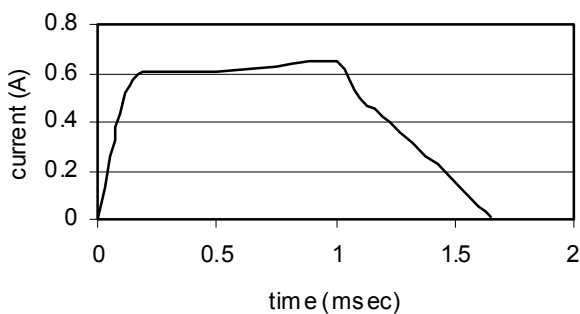
In the unaligned position the “effective” inductance is at its lowest value and increases as the motor goes into aligned position. This inductance increase is due to the fact that the reluctance of the motor magnetic circuit decreases as the rotor moves into the aligned position. For a dc current of 1A the “effective” inductance values are:

$$L_{\max} = 49 \text{ mH}$$

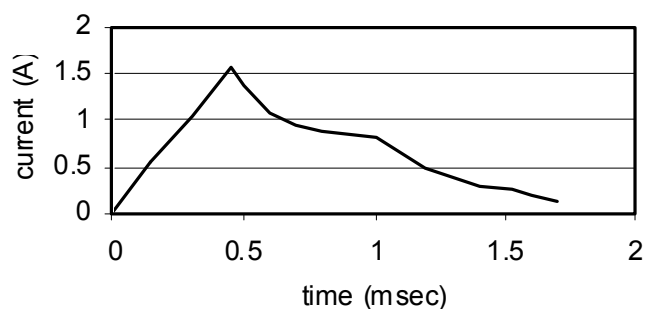
$$L_{\min} = 6.5 \text{ mH.}$$

Substituting these inductance values into Equation 2, and for a speed of 5000 rpm the current for the different regions of inductance profile has been evaluated. The current computed for the time when the switches  $S_1$  and  $S_2$  are open, during this time the polarities of the power supply is reversed and current flows through diodes  $D_1$  and  $D_2$ . Figure 4 a and b show the current waveforms for different advancements in conduction angle. It is worth mentioning here that, for comparison purposes, all the current curves have been plotted starting at  $t = 0$ .

The different parts of current waveforms of Figures 4a and 4b may be explained with reference

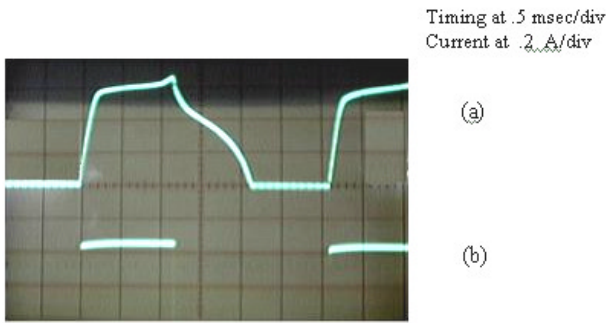


(a)

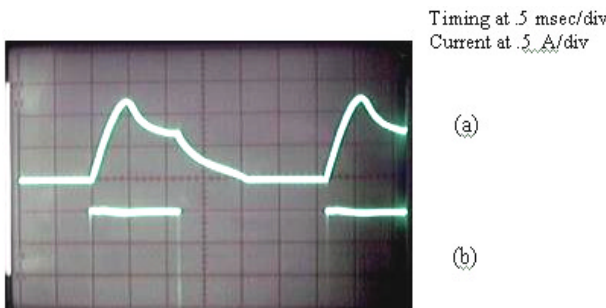


(b)

Figure 4. (a) Current waveform for 5 Deg. of Advancement and (b) Current waveform for 14 Deg. of Advancement.



**Figure 5.** (a) Actual current waveforms for 5 Deg. of Advancement and (b) Power switches turn on time duration.



**Figure 6.** (a) Actual current waveforms for 14 Deg. of Advancement and (b) Power switches turn on time duration.

to the positions of idealized inductance profile of Figure 2 using the circuit shown in Figure 1. The phase winding is connected via switches  $S_1$  and  $S_2$  to the voltage source  $V_s$  at  $t = 0$  while the phase inductance is low (i.e.  $\theta_1 < \theta < \theta_2$ ), thus permitting current build up at almost linear rate until the phase inductance begins to increase (i.e.  $\theta_2 < \theta < \theta_3$ ). The positive rate of change of phase inductance with time causes the current to fall. From then on the switches are open and the voltage source is connected to the phase winding via the diodes  $D_1$  and  $D_2$ . The current now is flowing through the diodes and also decaying fast. As seen from the current waveforms, more advancement in conduction angle produces larger current in high speed. Hence, higher torque is obtainable. Phase advancing can also cause the phase commutation to end before the rotor reaches the negative torque region (i.e.  $\theta_4 < \theta < \theta_5$ ).

In order to see the shape of the actual current waveforms under different turn on angles, a set of optical sensors, having adjustable positions with

respect to rotor pole is fixed at the end of the 6 x 4 switched reluctance motor. Figures 5a,b and 6a,b show the actual motor phase current waveforms and the on time duration of the power switches under 5 and 14 degrees of advancing for the phase turn on angles at a speed of 5000 rpm, respectively.

Comparisons of the actual current waveforms in figs. 5a and 6a with the computed ones in Figs. 4a and 4b show close agreement in general shape of the waveforms and a difference of less than 16% in the magnitudes. The reason for the difference is due to the assumptions made in writing and solving Equation 1.

### 3. EXPERIMENTAL STUDY

Advanced conduction angle at the motor start (i.e.  $\omega_m = 0$ ) can have adverse effect on torque production mechanism since there are no overlapped areas between the rotor and the stator poles at the beginning. At low speed, high advanced turn on angle results in higher current in the region of constant inductance where no torque is produced. Also, at high speed but low advanced turn on angle, higher current due to the breaking effect is produced. Therefore, a means of producing variable advancements in commutation angle for different speeds is required. An electronic governor is used to accomplish this task. A block diagram of the governor for the SRM drive is shown in Figure 7.

There are three  $30^\circ$  pulses are produced by the motor shaft position sensors and each pulse appears 4 times in one rotation. These pulses are fed into a pulse-shaping unit in order to get 12 pulses of  $30^\circ$  width per revolution. Figure 8a, shows one of the motor pulses produced by the shaft position sensors while, Figure 8b illustrates the output pulses from the pulse shaping unit which is synchronized with the motor pulses.

The frequency of this pulse train is increased to 30 times higher by employing a P.L.L. module. The P.L.L. module comprises of a CMOS 4046 and a 40102 counter integrated circuits. The P.L.L. output produces a pulse train with one-degree resolution in comparison with the original  $30^\circ$  motor pulses. In another word, there are thirty pulses embedded in each pulse of motor phase as shown in Figure 9.

Now a unit exists that provides the measurement

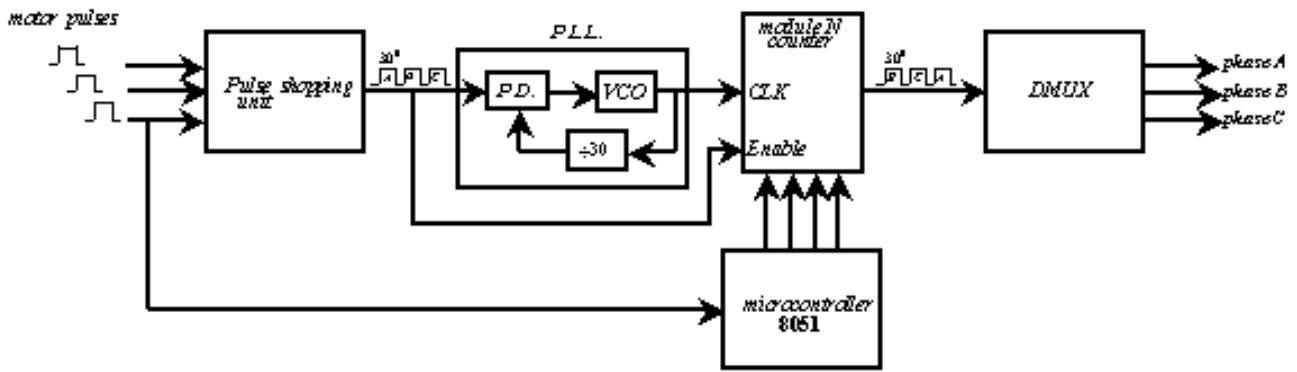


Figure 7. The block diagram of the governor.

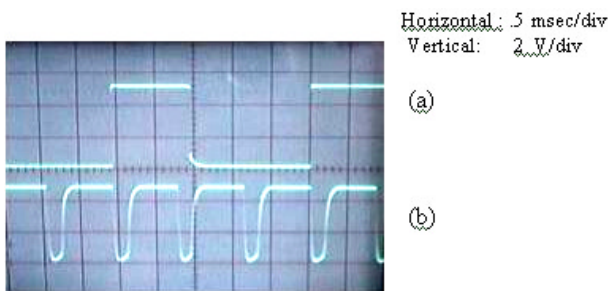


Figure 8. (a) Motor pulses of phase A and (b) Output of the pulse-shaping unit.

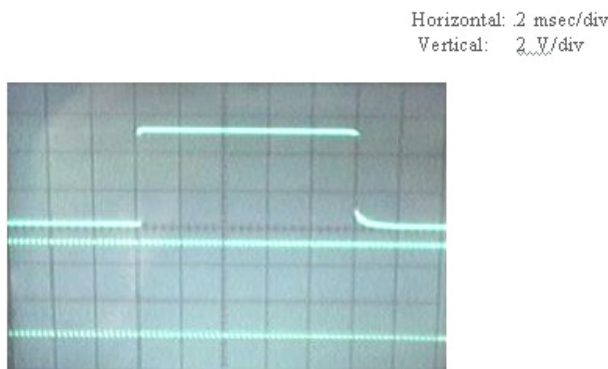


Figure 9. (a) Motor pulses of phase A and (b) Output of the P.L.L. module.

of motor firing time variations in degrees independent of motor speed.

This pulse train and the pulse shaping unit output signal are fed into a module N counter. The amount of phase turn on advancement variation is set by an 8051 Intel micro controller, which measures the motor speed, and then using a predefined

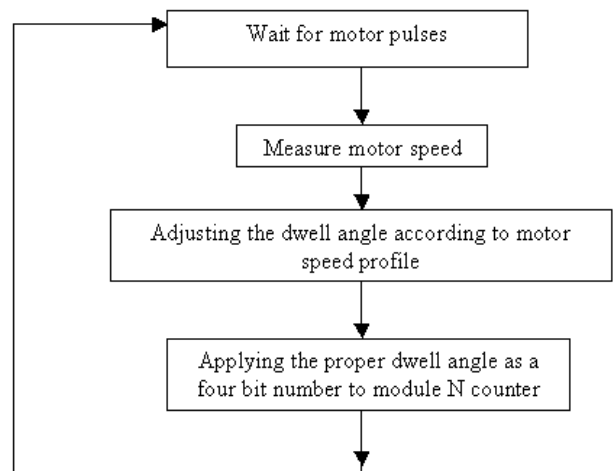


Figure 10. The program flowchart of the micro controller.

speed/advancement angle table comes up with the proper advancement angle. The user can define this table in any way desired. The program flowchart for the micro controller is shown in Figure 10.

The module N counter output pulses are separated into three independent advanced motor pulse trains by a demultiplexer. Figures 11a, 11b and 12 a, 12b show the original pulse trains from the motor shaft sensors after 5° and 14° degrees dwell angle adjustments for phase A, respectively.

As the speed increases so does the advancement in turn on angle, hence, sooner the phase commutation occurs. In order to see the effect of change in turn on angle experimentally, the following two tests have been performed:

**Test 1:** Setting the turn on angle first at 5 and then

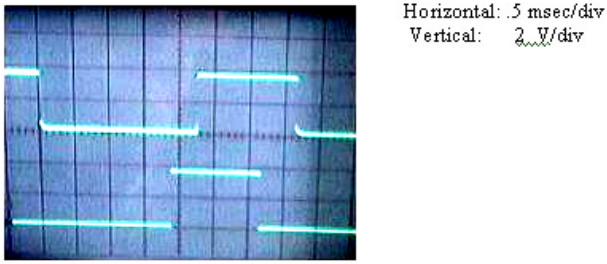


Figure 11. (a) Original motor pulses and (b) Pulses after 5° advancing.

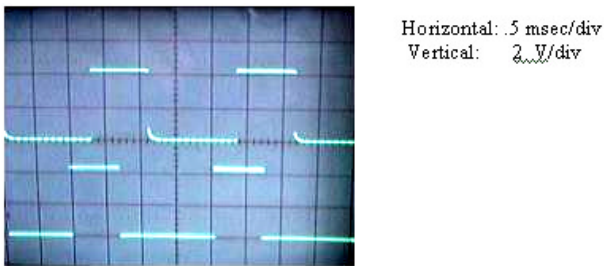


Figure 12. (a) Original motor pulses and (b) Pulses after 14° advancing.

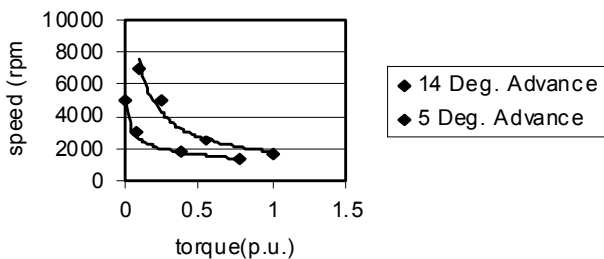


Figure 13. Speed vs. torque.

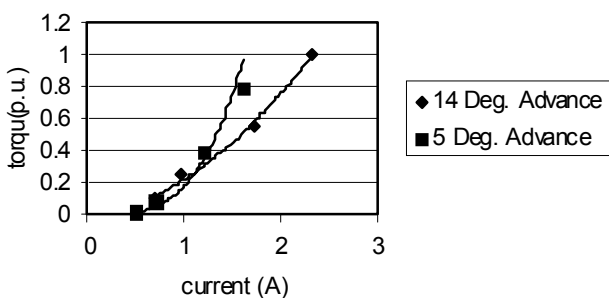


Figure 14. Torque vs. current.

at 14 degrees fixed in advance meaning, the electronic governor is locked so there will be any changes in these angles, then the torque, speed, and

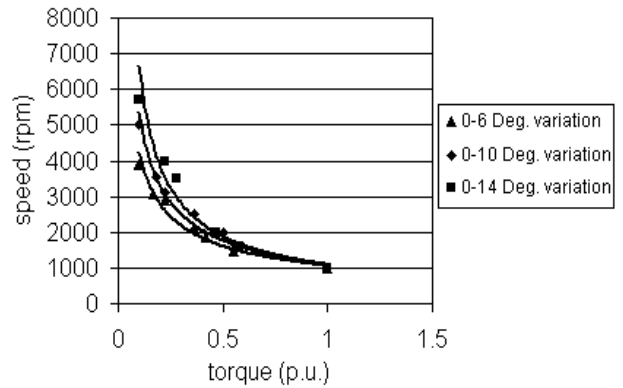


Figure 15. Speed torque characteristics of the motor under different governor settings.

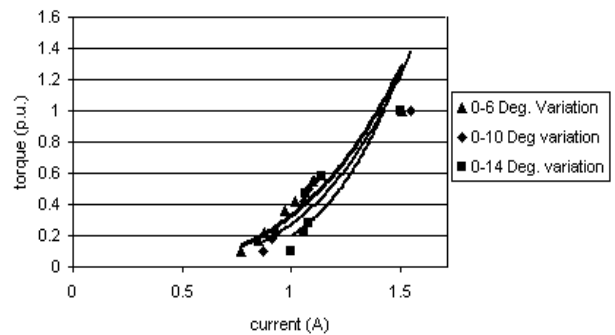


Figure 16. Torque current characteristics of the motor under different governor settings.

current are measured and plotted. Figures 13 and 14 show the plots of speed versus torque and torque versus current, respectively.

As seen from Figure 13, higher speed -torque curve has been obtained for the 14 Deg. advancement while Figure 14 shows larger torque has been achieved only for the current less than 1.1 A, but higher output power.

**Test 2:** The governor is used for the automatic advancement of firing time with three different settings for the governor such that, the advancement of the turn on angles are adjusted for 0-6, 0-10, and 0-14 degrees, respectively under the same loading condition. Figure 15 shows the speed-torque characteristics of the motor under the same loading condition for the different settings of the governor..

As shown in Figure 15, the curves have

converged to a point at full load since; the governor has reached its final setting completely at 1000 rpm. At light loads in high speed, the curves have been separated apart since; the advancing angle for each one is different. The curve for the 0-14 degrees variation shows the highest torque value for the same speed.

Figure 16 shows the torque-current characteristics of the motor with the same conditions mentioned for the Figure 15.

The motor current under 0-14 angle variation has highest value for the same torque and all curves reach to the same pint at full load. It is worth mentioning that the curve fitting has been used in plotting the data in Figures15 and 16. The reason for lower torque production in large variation angle is due to having smaller on time current period in the torque-producing region.

#### 4. COCLUSION

The electronic governor has been built and employed to a 6 x 4 SRM. The governor causes the phase commutation begins sooner and ends sooner, therefore the current has sufficient time to build up to the proper level and also, there is enough time to get the current out of the phase winding before the rotor reaches the negative torque region. The amount of phase commutation advancing which is related to the speed of the motor is obtained from a desired speed/angle table programmed into the micro controller. The test results using the governor show a great improvement in the speed torque characteristics of the motor. It prevents the motor not only from installing at the start but also producing higher starting torque due to larger overlapped area between stator and rotor poles caused by the governor. This technique solves one of the drawbacks of the switched reluctance motors.

The general shapes of the current waveforms found experimentally support the results obtained numerically. The difference in the values of current found by these two methods is within 16% and this variation is due to the assumptions made to the magnetic circuit of the motor in writing the current equation.

#### 5. REFERENCES

1. Lawrenson, P. J., Stephenson, J. M., Blenkinsop, P. T., Corda, J. and Fulton, N. N., "Variable-Speed Switched Reluctance Motor", *IEE*, Vol. 127, Pt. B, No. 4, (July 1980), 253-265.
2. Miller, T. J. E., "Switched Reluctance Motor Drive", Ventura, CA, Intertec. Communications Inc., (1988).
3. Krishnan, R., "Switched Reluctance Motor Drive: Modeling, Simulation, Analysis, Design and Application", Magna Physics Publishing, (2001).
4. Sugden, D. M., Blake, R. J., Randals, S. P., Stephenson, J. M. and Lawrenson, P. J., "High Performance MOSFET Switched Reluctance Drives", *IEEE Industry Applications Society Annual Meeting*, Atlanta, GA, (October 1987).
5. Housain, I. and Islam, M. S., "Design, Modeling and Simulation of an Electric Vehicle System", *SAE International Conference*, Detroit, Michigan, (March 1-4, 1999), 1-9.
6. Miller, T. J. E., "Switched Reluctance Motor and Their control", Magna Physics Publishing/Clarendon Press, Oxford, (1993).
7. Faiz, J., "A Review of the Performance Prediction and Design Techniques for Switched Reluctance Motors", *Journal of Electrical and Electronics Engineering*, Australia, IE Aust. and IREE Aust. Vol. 12, No. 3, (Sept. 1992), 258-266.
8. Faiz, J., "Prediction of Static Magnetization Characteristics of switched reluctance motors for general rotor positions", *Proceedings of 3rd European Conference on Power Electronics*, EPE'91, (Sept. 1991), Florence, Italy.
9. Vergalle, M. F., Melkebeek, J. A., Ghijselen, J. A., "Excitation Advance Control Schemes for Switched Reluctance Motor", *Annual Meeting IEEE-IAS*, Houston, (1992), 257-265.
10. Gallegos-Lopez, G., Walters, J., Jahekarta, K., "Switched Reluctance Machine Control Strategies for Automotive Applications", *SAE Technical Paper Series*, Number 2001-01-0995, (March 5-8, 2001).
11. Russa, K., Husain, I. and Elbuluk, M., "A Self-Tuning Controller for Switched Reluctance Machines", *IEEE-PESC Conf. Proc.*, Fukuoka, Japan, (1998), 1269-1275.
12. Orthman, R., Schoner, H. P., "Turn off Angle Control of Switched Reluctance Motors for Optimum Torque Output", The European Power Electronics Association, Germany, (1993), 20-25.
13. "Digital Signal Processing Solution for the Switched Reluctance Motor", Texas Instrument Literature No. BPRA058, (July 1997), 1-19.
14. Ray, W. F. and Davis, R. M., "Inverter Drive for Doubly Salient Reluctance Motor: Its Fundamental Behavior, Linear Analysis and Cost Implications", *Proc. Int. Elec. Engin.*, Pt. B, Elec. Power Appl., Vol. 2, (1979), 185-193.
15. Afjei, E. and Fallah, M., "An Efficient Drive Circuit For Switched Reluctance Motor", *International Journal of Engineering*, Vol. 12, No. 3, (August 1999), 137-143.
16. "Magnet CAD Package: User Manual", Infolytica Corporation Ltd., Montreal, Canada, (2001).