A LOW COST SENSORLESS CONTROL DRIVE CIRCUIT FOR A LOW VOLTAGE SWITCHED RELUCTANCE MOTOR

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Abstract Shaft position sensing is an essential part of switched reluctance (SR) motor drive In order to synchronize the pulses of phase current with the period of rising inductance of the proper motor phase. Direct sensors such as, Hall effect and optical encoder are commonly used in SR motors. The purpose of this paper is to present an indirect shaft positioning sensing known as "sensorless " control for switched reluctance motor. It uses stator inductance measurement technique by multiplexing each phase inductance to predict the rotor position and also using a micro controller to produce proper gate pulses for the motor phases. This circuit has the ability of controlling the proper advancement of firing time for each power transistor (adjusting the dwell angle) in the drive circuit either manually or automatically for different speeds. It has also the option of selecting the direction of rotation for the motor and uses a PWM scheme for variable speed as well as, a full stop braking system. This control circuit in conjunction with a two switch per phase configuration converter drive has been tested on a 35W, 12V; 3-phase switched reluctance motor and the test results are presented.

Key Words Switched Reluctance Motor Drive, Sensorless, Indirect Rotor, Position Sensing Scheme

چکیده دانستن موقعیت روتور یکی از ضروریات لازم برای راه اندازی و چرخش صحیح موتور رلوکتانس سوئیچی می‌باشد. سنسورهای اثر میرانی و اینکودرهای نوری بصورت فراوانی برای این منظور بصورت مستقیم بر روی شفت این نوع موتورها تعبیه می گردند. این مقاله مدار راه اندازی موتور رلوکتانس سوئیچی را با استفاده از سنسور موقعیت بصورت غیر مستقیم برای بدست آوردن مکان روتور ارائه نموده است. این مدار با اندازه گیری سلف هر یک از فازهای موتور بصورت مالتی پلکسینگ موقعیت روتور را تعیین نموده و با استفاده از یک میکرو کنترولر فرمان آتش هر یک از فازها را صادر می نماید. آوانس و ریتارد آتش ترانزیستورهای قدرت نسبت به موقعیت روتور در هر دو جهت چرخش، تغییر سرعت موتور و ترمز ناگهانی از قابلیتهای این مدار می باشد. راه اندازه گیری برای یک موتور ۳۵ وات، ۱۲ ولت ، سه فاز آزمایش و نتایج حاصله ارائه گردیده است.

INTRODUCTION

The widespread interest in switched reluctance motor for its ruggedness and durability in harsh environment, the need for eliminating the direct position sensors, which are the source of unreliability and failure in such environment, arises.

The rotor position information is an essential part of SR motor drive. It is used to generate precise firing command for the power switches in converter ensuring drive circuit stability, direction of rotation, and fast dynamic response. In general, there are two types of rotor position sensing in SR motor, namely direct sensing and indirect sensing techniques. In direct sensing scheme, discrete sensors such as, hall effect devices or optical encoders mounted on the back of the motor are used to produce necessary pulses in relation to rotor position [1-2]. In the indirect sensing method, the information about rotor position is obtained through different motor characteristics such as, inductance or flux/current [3].

It is shown in [4] that the rotor position can be detected by decoding the output signal out of a FM converter. Measuring the inductance of a non-conducting phase by using a linear modulated (FM) converter produces this signal. The technique presented in [5] relies on the principle that the incremental phase inductance varies as a function of phase current and rotor position thus, by monitoring the phase current rise-time or fall-time it is possible to detect the rotor position.

The detection of rotor position is discussed in Reference 6 where it uses an estimator to produce unexcited phase with short voltage pulses from an inverter, and evaluates the resulting currents to measure the phase inductances and from these inductances, instantaneous rotor position is estimated. It is reported in Reference 7 that, one of the most useful indicators of rotor position are current rise-time arising from chopping an unexcited phase at low current. The methods outlined in Reference 8 for sensing inductance are based on the following principles:

A - Phase Pulsing A voltage pulse V is applied to an unenergized phase of the motor for the period of time ΔT and the change in coil current ΔI is measured. The inductance is then obtained from

$$L = V \frac{\Delta T}{\Delta I} \tag{1}$$

B - Frequency Modulation Inductance information is encoded in frequency-modulated signal using a low voltage analog circuit.

C- Phase Modulation A low alternating voltage is applied to an Unenergized phase of the motor and the phase angle difference between the input voltage and the resulting current is detected. The inductance is given by L = R tan θ/ω where θ is the phase angle and ω is the frequency in rad/s.

D - Amplitude Modulation A low level alternating voltage is applied to an unenergized phase and the amplitude of the resulting current is mapped to the coil inductance. The inductance can be expressed as

$$L = \frac{1}{\omega} \sqrt{\frac{V_M^2}{I_M^2} - R^2} \tag{2}$$

Where Vm is the voltage amplitude of the input voltage; Im is the current amplitude and R is the resistance of the circuit.

E - Self-Voltage Technique The inductance of active phase is estimated in real time form measurements of the active phase current and phase flux. If Io is the current in the active phase linking a flux Φo then the phase inductance is given by Lo = Φo/Io.

The rotor position can also be found from magnetic characteristics provided that Φ and I can be measured. Some flux/current based sensorless methods are given below [8]:

A - The Waveform Detection technique which monitors the phase current raise and fall times due to change in the phase inductance.

B - The State Observer that is based on terminal voltage current and voltage measurements.

As the motor's speed increases and reaches to a certain speed, it becomes difficult to regulate the winding current to the desired value. The practical phase current waveform at low and high speeds controlled by chopping or PWM is shown in Figure 1a and 1b, respectively [1].

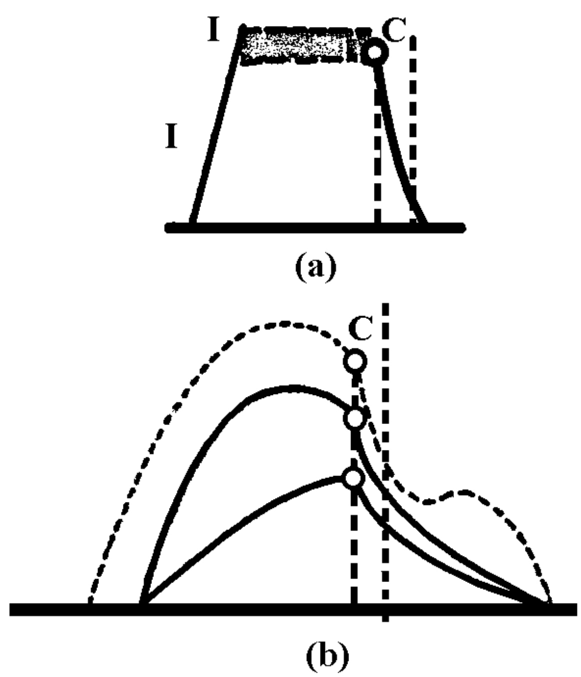

Figure 1. (a) Practical phase-current at low speed and (b) Practical Phase-Current At high speed.

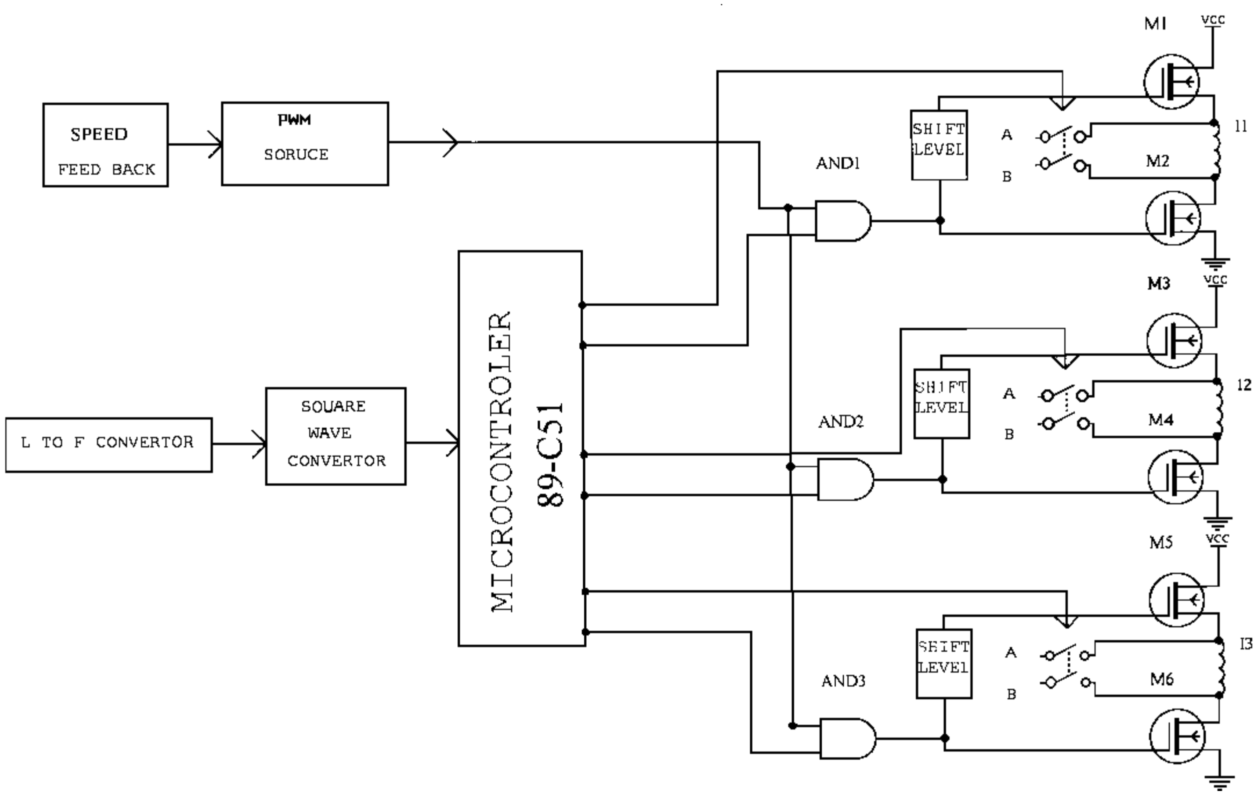

Figure 2. Sensorless control diagrams for SR motor.

As seen from Figure 1b the lower solid curve is at higher speed than the upper solid curve, because the current at high speed cannot build up quickly, hence the current magnitude is much lower and torque produced falls off at high speed. If it was possible to advance the turn on angle, the current waveform would have been as shown in Figure 1b by the dotted curve, which shows higher current magnitude hence, higher torque produced. In order to change the conduction angle, a mechanical governor is mounted on the motor shaft [9]. The opening of governor arms is directly proportional to the motor speed, which controls the positioning of the shaft decoder with respect to the discrete shaft sensors.

In order to change the direction of rotation in SR motor and having equal speed in both directions for the same duty cycle, two sets of position sensors are required. One set is positioned such that, the angle difference between proper rotor and stator poles are less than half of the angle O_d. Where the angle O_d is defined as the angle produced by the end of one stator pole to the beginning of the next consecutive stator pole. The other set is positioned exactly in the mirror image of the first set with respect to the imaginary line going through the center of motor and cutting angle O_d in half. Commercial direct shaft positioning module is available in the market place today (even in Iran). However, in some industry with harsh environments, the position-sensing module proves to be not so reliable and practical, especially in very high temperature areas. It is therefore desirable to detect the positioning information through other sensorless means. This paper describes one method of such an indirect position sensing techniques.

CONTROL CIRCUIT

The switched reluctance motor is a doubly salient, singly excited motor. As the rotor turns, the phase inductance of the motor, L, varies between two extreme values. The maximum inductance, L_{max} occurs when the rotor and stator poles are aligned. The minimum inductance, L_{min} occurs when a rotor Interpol axis is aligned with the stator poles. The idealized sinusoidal approximation of each phase inductance for a 6 by 4 SR motor can be estimated roughly in a linear magnetic circuit as [10]

$$L(\theta) = \frac{1}{2}[(L_{MAX} + L_{MIN}) + (L_{MAX} - L_{MIN})COS4\theta] \quad (3)$$

Where, θ is the angle between rotor and stator poles.

The ratio of maximum inductance to minimum inductance in SR motor is definitely much greater than one; therefore it is possible to sense the rotor position by monitoring the phase inductance. The block diagram of sensorless control circuit for a 6 by 4 SR motor is shown in Figure 2.

As shown in Figure 2, there is only one block called L to F unit that is common to all three phases. This unit is an oscillator that utilizes one of the motor phase inductances to produce a waveform with a frequency proportional to the value of that phase inductance. Figure 3 shows the L to F output waveform.

As shown in Figure 3 the waveform has variable frequency since the motor phase inductance changes as the motor turns. It has the lowest frequency at the beginning of the period, which translates to a high inductance value, L_{max}, and then gradually reaches its highest frequency in the middle, which means it has achieved the lowest phase inductance value, L_{min}.

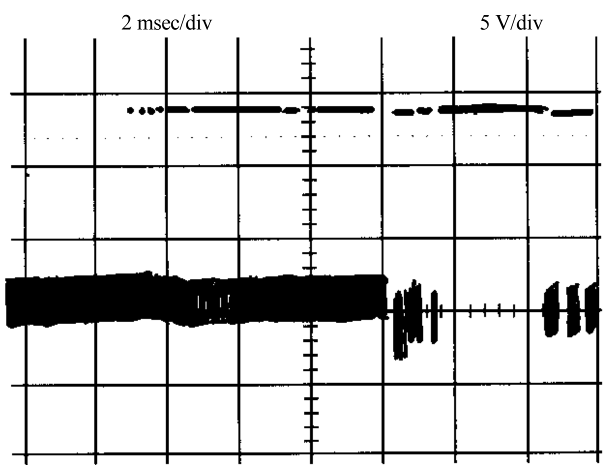

Figure 3. Waveform out of L to F unit.

Finally at the end of period, the frequency has decreased again since; the phase inductance as reached to its highest value, L_{max} The micro controller, using multiplexing technique provides the oscillator with the direct sampling of proper motor phase inductance, by employing analog switches in order to produce the waveform shown above (Figure 3). Figure 4 shows the two sets of signal generated by the micro controller for the control of analog switches utilized in phases A and B, respectively.

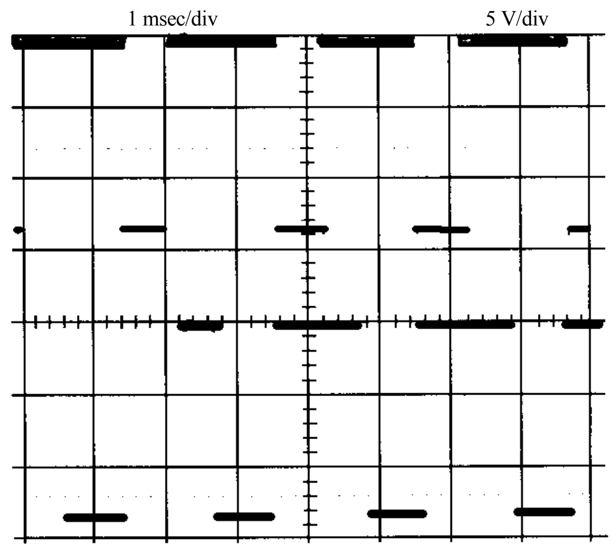

Figure 4. (a) Control signal for analog switch of phase A and (b) control signal for analog switch of phase B.

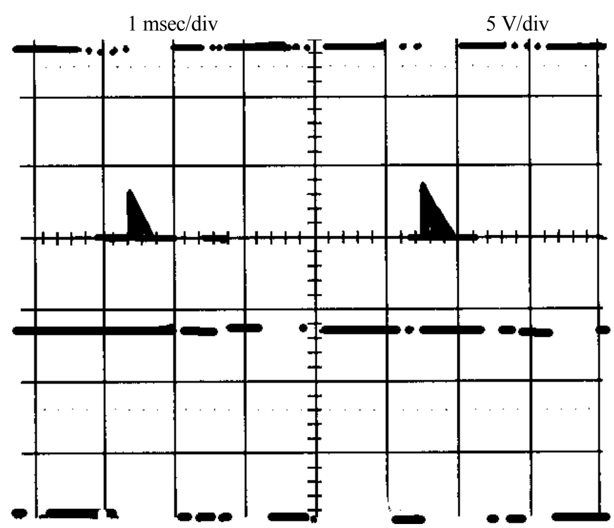

Figure 5. (a) Waveform out of L to F unit and (b) waveform out of square wave converter.

Multiplexing causes the use of only one L to F unit instead of one for each phase. The waveform out of L to F unit is put into a square wave converter to yield a square wave with the voltage level and frequency suitable for the use by the micro controller. Figures 5a and 5b show the resulting waveforms out of L to F unit and the square wave converter, while multiplexing is being performed.

Figure 5(a and b) shows the waveforms with seven times of multiplexing completion. The reason for not observing the complete output waveforms out of L to F unit in Figure 5a (such as the one shown in Figure 3) and also, the corresponding waveform out of square wave converter 5b is due to the multiplexing process. After the micro controller finds the minimum inductance for one phase, it generates the necessary pulses and then picks the next motor phase and begins with the process of searching for the next minimum phase inductance therefore, the waveforms shown in Figure 5(a and b), are only presented up to the point of minimum inductance. Minimum and maximum frequencies generated by the square wave converter are 4KHz at highest inductance value (aligned case) and 10KHz at lowest inductance value (non-aligned case), respectively. It is worth mentioning that, it is possible to have different limits for the frequency values produced by the square wave converter. The reason this particular frequency range has been chosen is because this motor shows much less susceptibility to noise that disrupts the micro controller under different loads over the speed range. A low cost 8051 micro controller is used to generate the necessary pulses needed to run the SR motor. The motor has six stator poles and 4-rotor poles configuration. The cross section of the motor is shown in Figure 6.

The motor has three phases named A, B, and C, respectively. When the motor is in operation, there is always one phase energized and the other two are unenergized. The method of detecting rotor position is to measure the inductance of one unenergized phase and from there finding the rotor position. There are two techniques on Phase inductance selection for sampling and energizing:

1-sampling one unenergized phase and turning the other unenergized phase on. For example, sampling phase A until micro controller senses the L_{min} position, then, turning phase C on and Phase B off.

2-sampling one unenergized phase and turning the same unenergized phase on. For example, sampling phase A until L_{min} is sensed by micro controller, then turning phase A on and phases B or C off.

In this paper, the second method is employed because, it would give sufficient time to the micro controller to set the advance and retard adjustment. The flow chart of the micro controller program is shown in Figure 7.

Since it is not possible to set the firing time in advance electronically while the measurement is being done in real time therefore, detecting phase inductance is set for some L much greater than L_{min} but the gate pulses for the power transistors in the drive circuit are delayed by the micro controller. The delay time is set by the motor speed and executed by the micro controller when, the rotor has reached to its the proper position. Figure 8a shows the pulses generated by the micro controller after sampling phase A while, Figure 8b displays the gate pulses produced by the same micro controller for the power transistors without applying any delay to them.

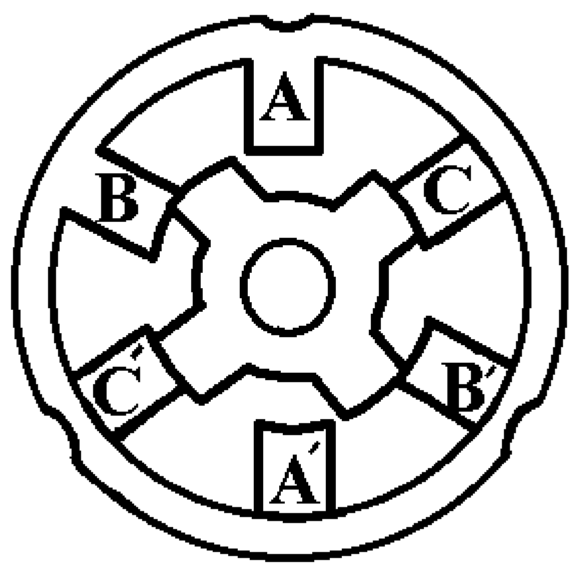

Figure 6. Cross section of a 6 by 4 SR motor.

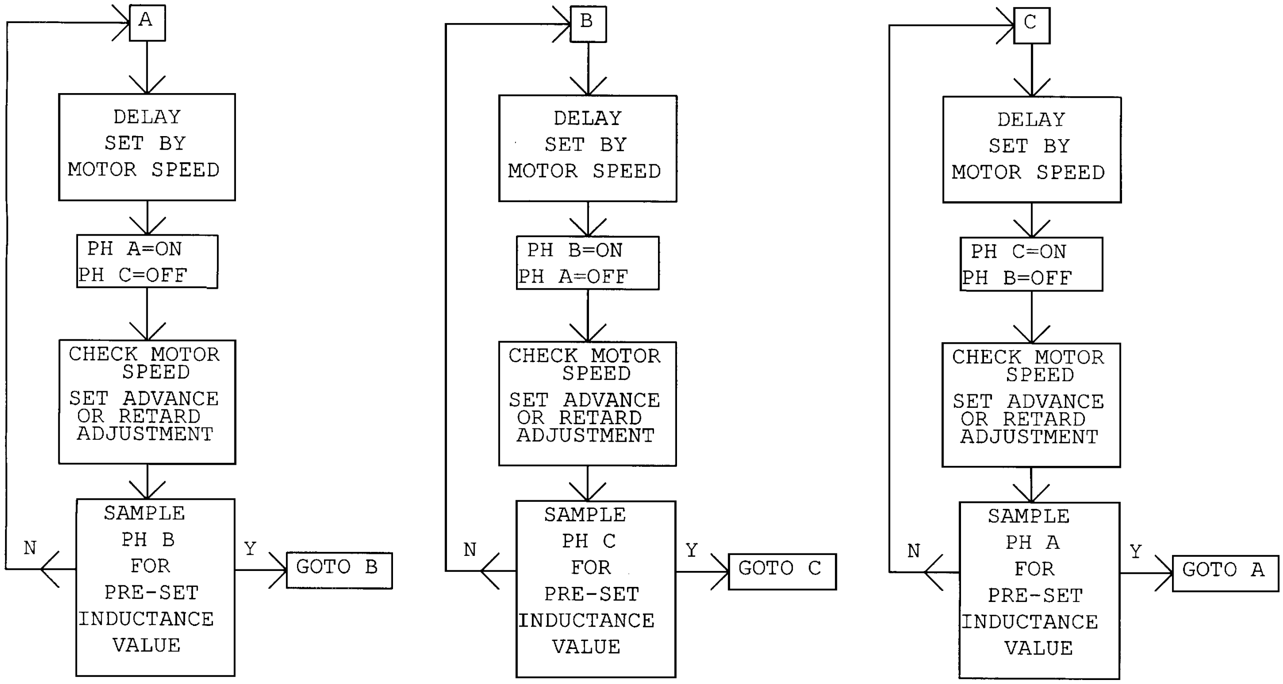

Figure 7. Flow chart of the micro controller program.

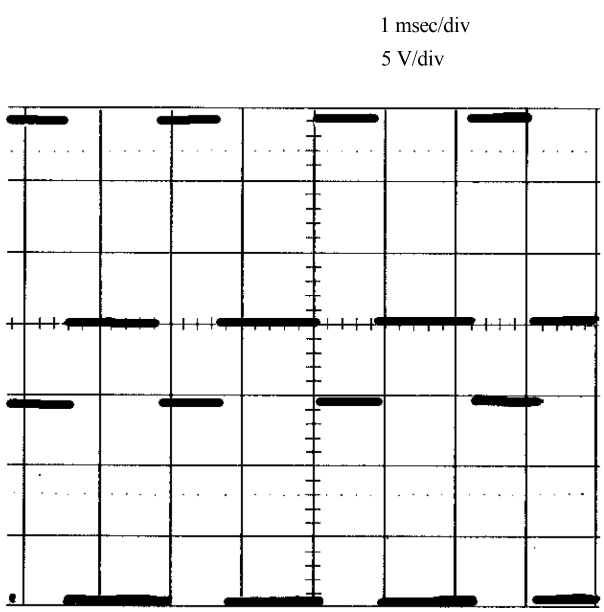

Figure 8. (a) Pulses generated by micro controller after finding a pre-set inductance value and (b) gate pulses produced by micro controller for the power switches without applying any delay.

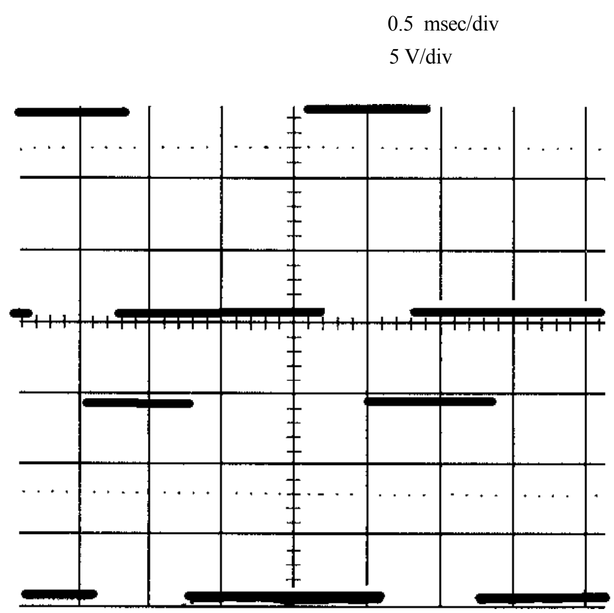

Figure 9. (a) Pulses generated by micro controller after finding pre-set inductance value and (b) gate pulses produced by micro controller for the power switches with applying proper delay time.

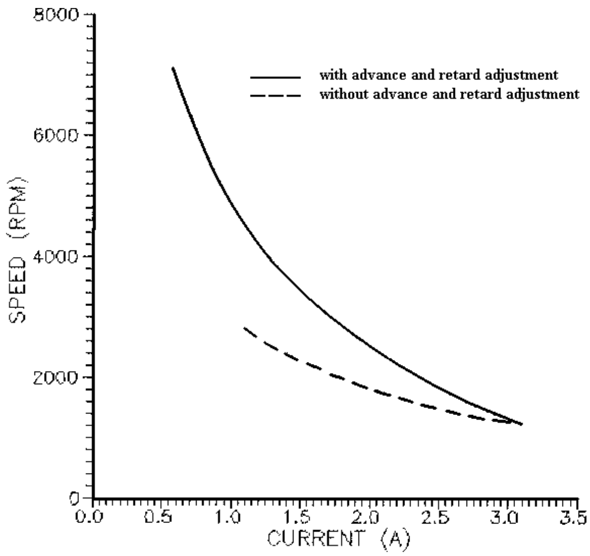

Figure 10. Speed versus current characteristic.

Figure 9a and 9b show the pulses resulted after micro controller finds the pre-set phase inductance value and the gate pulses generated by the micro controller after applying the proper delay time for the power switches, respectively.

The speed versus current curve for two different modes of operation namely, one with advance and retard adjustment (governor action) and the other one with fixed dwell angle are shown in Figure 10.

As seen from the Figure 10, the curve with the advance and retard adjustment has much higher speed.

The direction of rotation is set so that the sequence of firing the phases chosen by the micro controller for the clockwise direction is A-C-B and for the counter clockwise direction is A-B-C as marked on the motor cross section in Figure 6.

At standstill, the micro controller determines which phase should be energized by checking each phase inductance in a pre-determined sequence.

When the braking system is applied, the micro controller will keep the energized phase winding of the time, on for a while, till the motor stops running.

CONCLUSION

An indirect shaft position-sensing scheme using direct phase inductance measurement technique by multiplexing each phase inductance has been presented. The use of multiplexing has not only caused the elimination of many electronic components from the control circuitry but also, has increased the reliability of the drive system. The advance and retard adjustment system has made it possible for the motor current to build up in high speeds, and hence, causing better performance obtainable for the motor. The control circuit has the ability of turning the motor in either direction for any speed only by pushing a switch. The circuit has been built and tested on a 12 volts 35 Watts switched reluctance motor. The experimental results show the practicality of the circuit especially in harsh environment.

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