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Automatic Phase Advancing in Switched Reluctance Motor by Employing a Mechanical Governor

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Abstract

Switched reluctance (SR) motor 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 SR motor 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 a mechanical governor mounted on the shaft of a SR motor to achieve this task. The opening of the governor's arms causes 0-14 degrees automatic adjustment in the turn on angle from stand still to a pre-set speed.

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 SR motor are presented.

I-Introduction

The switched reluctance motor has been extensively investigated and developed in the pasted 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 SR motor did not realized its full potential until the modern era of power electronics and computer-aided electromagnetic design. SR motors have been used extensively in clocks and phonograph turntables before but nowadays, they have been employed in many different industrial applications [4]. 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 [5].

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. The SR motor performance can be greatly influenced by choosing the proper starting time for the phase turn on angle at different speed [6]. The time duration τ 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, τ, 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 [7]

1-Varying the dwell angle (difference between the firing angle) 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 [8].

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.

In this respect, a mechanical governor mounted on the motor shaft is introduced to change the dwell angle just enough under different speeds, so that the phase commutation begins 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.

II- The Basic Model

The principles of operation of SR 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. Fig. 1 illustrates a 3-phase, 6 x 4 SR motor showing only phase one winding and its drive circuit.

Although saturation plays an important role in obtaining the exact behavior of the SR motor and also, is necessary for the detailed motor design, but analysis of magnetically linear SR motor can provide useful and broad understanding of the influence of the many motor parameters. Fig. 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 Fig. 1.

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

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

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

where, Vs is the source voltage
i is the phase current
R and L are resistance and inductance of the phase
ω is the motor speed.

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

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

where; I_0 is the initial current, and

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

In order to be able to plot the current profile for a SR motor, the parameters in equation 2 are found by r numerically for a 6 x 4 , three phase, 24 V switched reluctance motor

In the numerical part, the magnetic field analysis has been performed using a Magnet CAD package [9] 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 (λ / I). Values based on this definition are presented in Fig. 3 for the motor.

In the analysis the rotor moves from unaligned (i.e. 0^o) to aligned (i.e. 28^o) 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

$L_{max} \approx 49$ mH
$L_{min} \approx 6.5$ 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. Fig. 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 Figs. 4a and 4b may be explained with reference to the idealized inductance profile of Fig. 2. 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, thus permitting current build up at almost linear rate until the phase inductance begins to increase. 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.

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 SR motor. Figs 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.

III-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. A mechanical governor mounted on the motor shaft is used to accomplish this task. A picture of the governor on the shaft of the SR motor is shown in Fig. 7.

The opening of the governor arms is directly related to the speed of the motor, which controls the positioning of the shaft decoder with respect to the shaft sensors. As the speed increases so does the advancement of the shaft decoder, 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 at 14 degrees in advance while the governor's arms are locked so there will be any changes in these angles, then the torque, speed, and current are measured and plotted. Figs. 8 and 9 show the plots of speed versus torque and torque versus current, respectively.

As seen from Fig. 8, higher speed - torque curve has been obtained for the 14 Deg. advancement while Fig. 9 shows larger torque-current has been achieved for the same setting.

Test 2: The governor is used for the 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. Fig. 10 shows the speed-toque characteristics of the motor under the same loading condition for the different settings of the governor.

As shown in Fig.10, the curves have converged to a point at full load since, the governor's arms have closed 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.

Fig. 11 shows the torque-current characteristics of the motor with the same conditions mentioned for the Fig. 10. 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 Figs.10 and 11.

IV-Conclusion

The mechanical governor has been built and mounted on a 6 x 4 motor. 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 opening of the governor's arms is directly proportional to the amount of phase commutation advancing which is related to the speed of the motor. 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.

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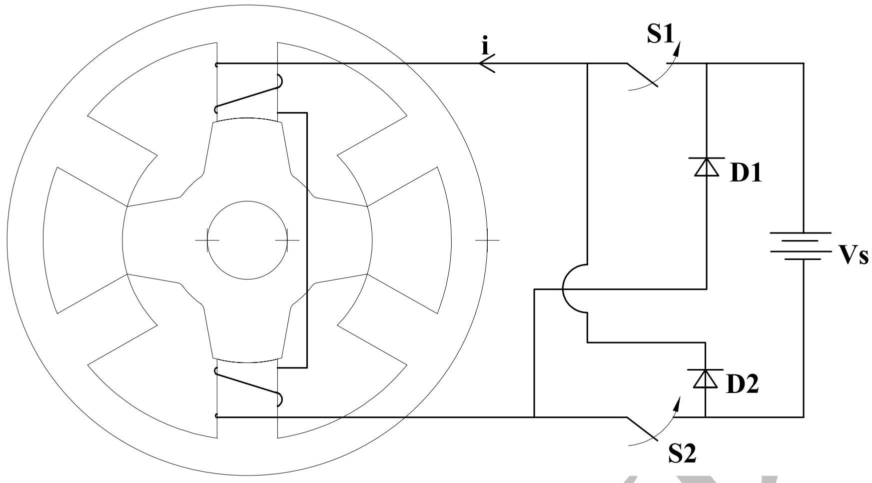


Fig. 1 A 6 x 4 SR motor, showing the phase one winding and its drive circuit

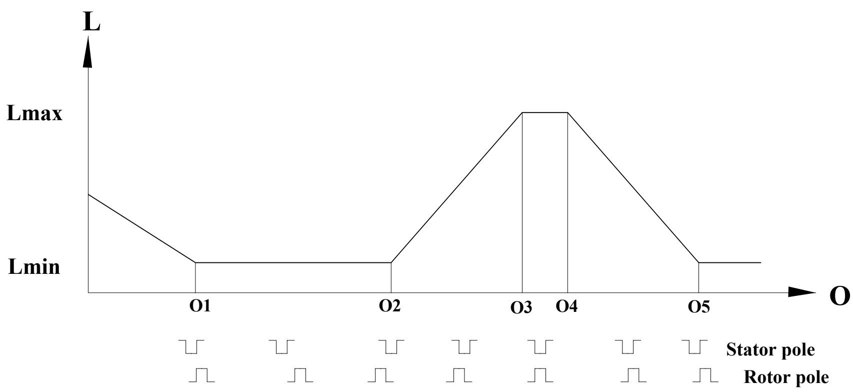


Fig. 2 Inductance variation of one motor phase

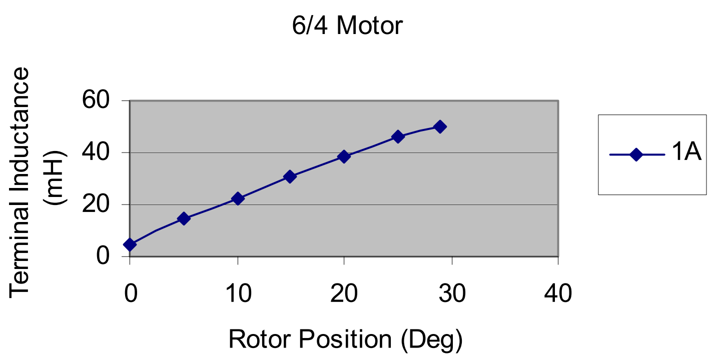
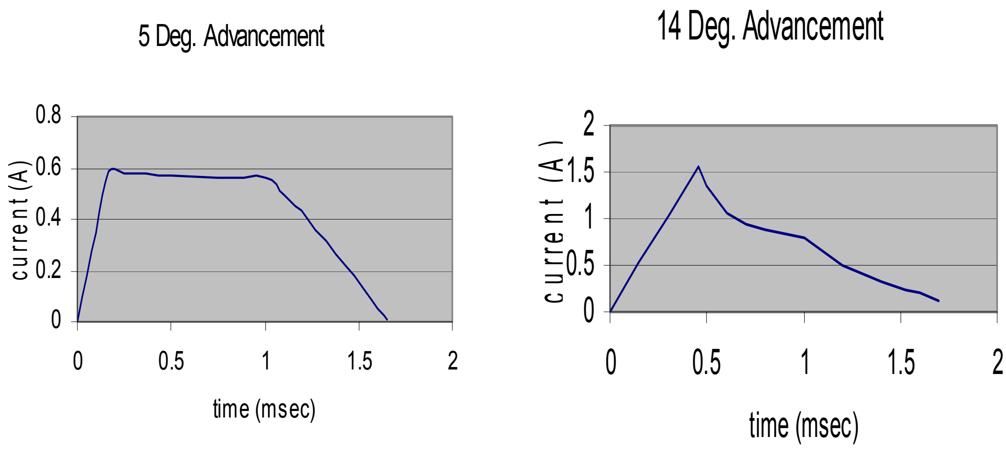
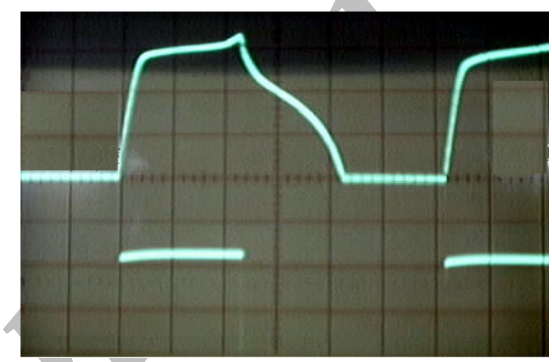


Figure 3- Terminal inductance vs. rotor position



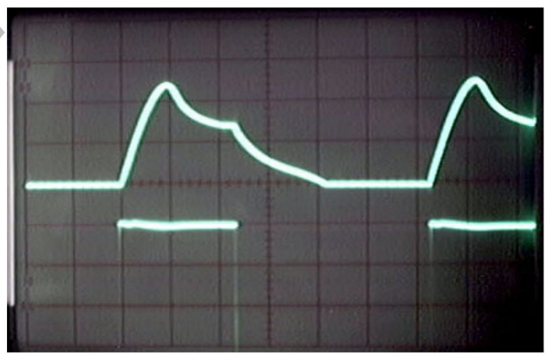
(a) (b)

Fig. 4 a- Current waveform or 5 Deg. of Advancement
b- Current waveform for 14 Deg. of Advancement



timing at .5 msec/div
current at .2 A/div

Fig. 5 a – Actual current waveforms for 5 Deg. of Advancement
b – Power switches turn on time duration



timing at .5 msec/div
current at .5 A/div

Fig. 6 a–Actual current waveforms for 14 Deg. of Advancement
b–Power switches turn on time duration

Fig. 7 The governor on the motor shaft

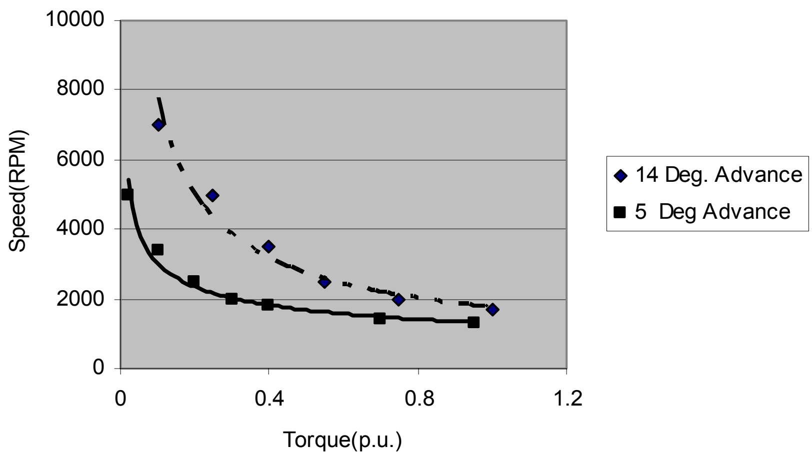


Fig. 8 Speed vs. torque

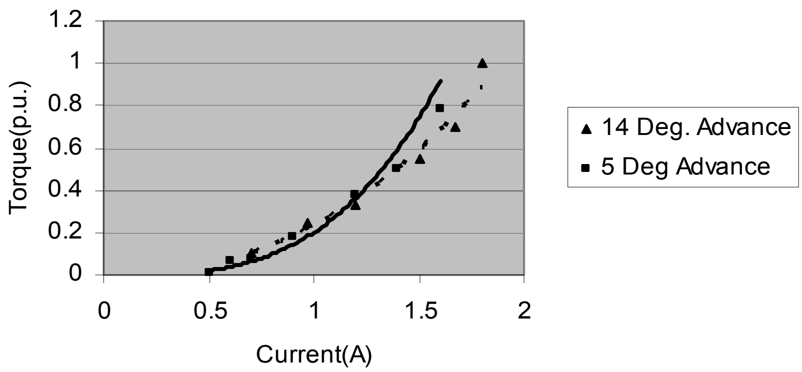


Fig. 9 Torque vs. current

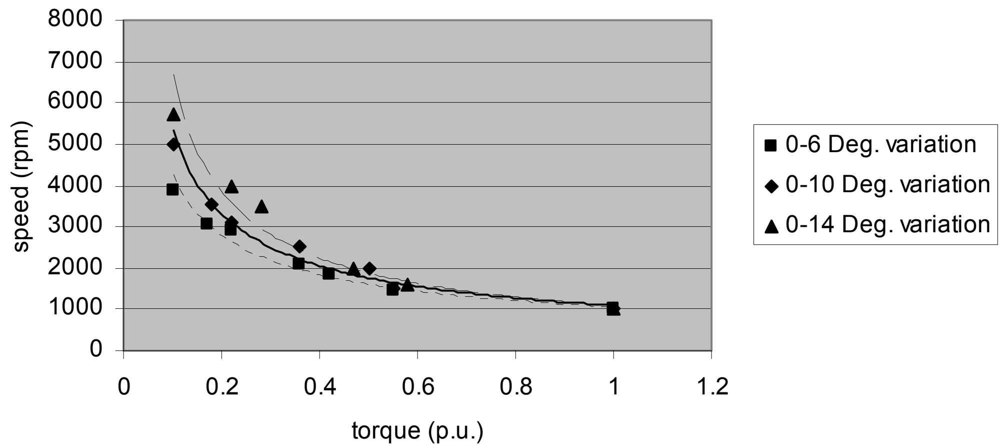


Fig. 10 Speed torque characteristics of the motor under different governor settings

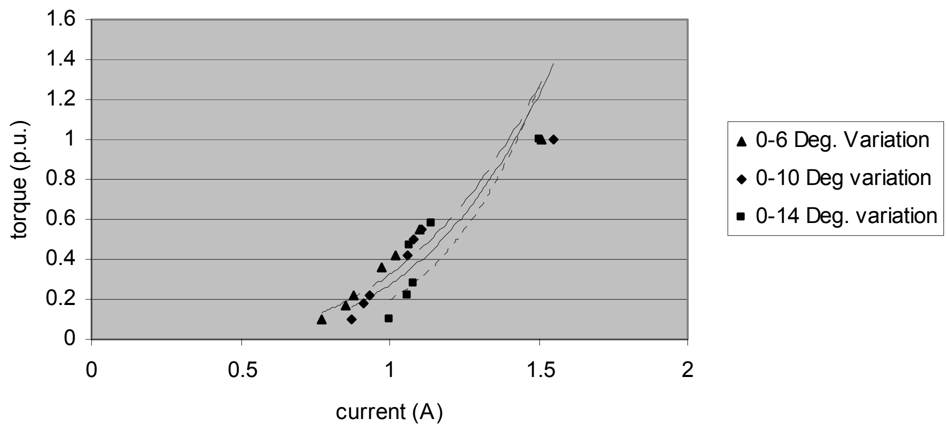


Fig. 11 Torque current characteristics of the motor under different governor settings