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A Study on Voltage and Switching Angle for Maximum Torque / Efficiency and Minimum Torque Ripple of SRM by using SIMULINK®

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ABSTRACT

This paper presents the switching angle and voltage for maximizing the torque or efficiency and minimizing torque ripple of an 8/6, SRM. The approximate analysis and computer simulation determine the switching angle and voltage by using SIMULINK®. This is performed as a function of the speed and torque required by the load. From the results, new three facts can be known: First, the maximum torque depends on voltage and speed depends on switching angle. The others, the maximum efficiency and minimum torque ripple rely on switching angle. We control the switching angle and voltage of an asymmetrical inverter for the SRM with one-chip micro controller.

Key Words : SRM(Switched Reluctance Motor), switching angle, voltage control, maximum torque, maximum efficiency, minimum torque ripple.

1. Introduction

An useful SRM (Switched Reluctance Motor) was developed in the beginning of 1980's. Until now, it has been actively researched as an SRM has a simple structure with a variable topology. The SRM inverter control is independent of the polarity of the current, so it is low cost. And the SRM has a high torque density and efficiency compared with that of the standard induction motor. With these features, SRMs are being applied to household appliances as well as industrial use. For an electric vehicle, the switching angle can be adjusted in order to maximize the torque and to increase the efficiency. For household applications, the minimum torque ripple for quietness is likely to be the most important characteristic.

This paper analyzes the effect of switching angle and voltage, taking into account the nonlinear inductance profile, current and torque.

SRM modeling was done to allow a steady state SIMULINK® simulation to obtain the optimum switching angle and average dc link voltage for the maximum torque or efficiency and the minimum torque ripple. The inductance profile was modeled using FLUX2D®. The one-chip micro controller, Siemens SAB C167, controls the experimental system.

2. Torque Characteristics as a Function of Switching Angle Control

The torque characteristics in an SRM depend on the

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switching angle and applied voltage, which affects the waveform of the phase current according to the operating speed. Generally, for high efficiency operation, the shape of the phase current should be flat topped[1]. This current waveform may produces the switching angle, or chopping control of the phase voltage to regulate the current [1].

These studies focus on the selection of the switching angle. The selection is performed by adjusting the switching angle to obtain a flat-top current. The switching angle is shown in Fig. 1 and Fig. 2 The turn-on angle is referred to as the advance angle as it is the angle with respect to the current and is given by eq. (1) to form a flat topped current

$$\theta_{ad} = \frac{\omega L_{\min}}{E} I \tag{1}$$

where, Θad : advance angle
E : dc supply voltage
ω : angular speed
I : current
L_{min} : minimum inductance

Eq. (1) is obtained using the assumption that the resistance can be neglected and that the inductance is fixed at its minimum value (because the inductance is constant in the advance angle region that is, dL/dt= 0).

It is necessary to adequately control the advance angle in order to form the flat-top shape current[1]. But the choice of the turn-off angle is divided into two branches: the constant torque angle control method (Fig. 1) and the constant dwell angle control method (Fig. 2) [1]. As shown in Fig. 2, the dwell angle is constant and the switching angle should be controlled[2].

In the linear section of the inductance function, as shown in Fig. 1, the current is to be maintained as long as possible, limited by the requirement that the turn-off current does not enter an area of negative torque. However, increasing the load current draws the saturation point before turn-off, and further increases the current at that point.

The saturations cause the iron loss to increase and lengthen the time required for the current to turn-off, so that the efficiency reduces. With the constant torque angle control, the switch should be turned off before the saturation point, and hence the maximum load current must be limited. As the result of this, it is characterized by a limited maximum power and current limit [3].

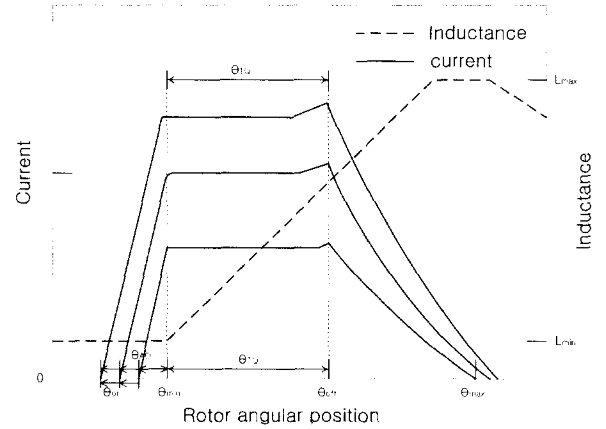


Fig. 1. Current waveform under constant Torque angle control.

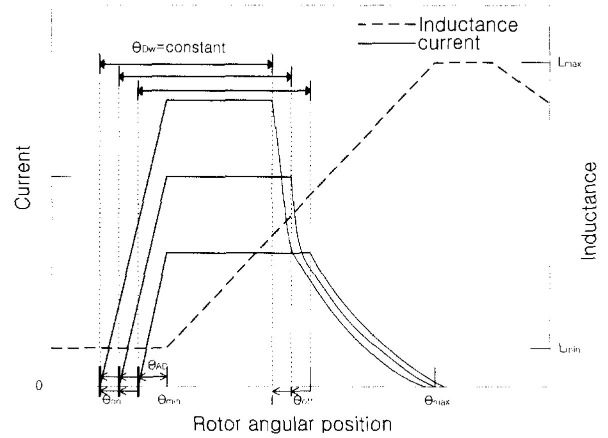


Fig. 2. Current waveform under constant dwell angle control.

Fig. 2 shows the constant dwell angle control method, in which the turn-off angle is adjusted to maintain a constant dwell angle, independent of any variation of speed or load. This method increases the efficiency because the phase current is tuned off before the saturation point, however the specified period of switching causes the limitations.

Actually, Fig. 1 and Fig. 2 explain the non-linear characteristic of current. But we want to explain the concept of constant angle control and dwell angle control in these figures. So it is linearly plotted.

The turn-off angle does affect the maximum torque, the maximum efficiency and the minimum torque ripple, all as a function of the speed and load. The switching angle determined by the conventional control method is not optimal as it neglects the non-linearity of the inductance. So, in order to obtain the maximum torque, efficiency and minimum torque ripple, the optimum switching angle and voltage is found by taking into account the non-linear inductance using SIMULINK® and FLUX2D® programs. The switching angle and voltage are stored in the ROM of one chip micro controller to enable rapid changing of the switching angle in response to the commanded speed and power. Therefore, the SRM can be driven among the maximum torque, maximum efficiency and minimum torque ripple points, making it suitable for a range of applications, such as EV, industrial applications and household appliances.

3. SRM Model using SIMULINK®

3.1 Mathematical model

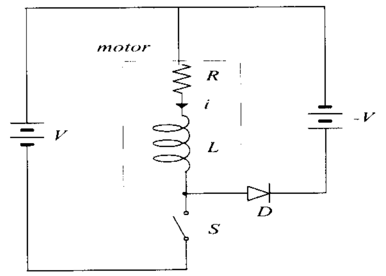


Fig. 3. Equivalent circuit of the reluctance motor.

Fig. 3 is the equivalent circuit for an SRM. The voltage equation is as follows [2].

$$E = ri + \omega \frac{dL(\theta,i)}{d\theta} i + L(\theta,i)\frac{di}{dt} \qquad (2)$$

where, i : instantaneous current

E : dc supply voltage

ω: rotor speed (rad/s)

L(θ,i) : inductance as a function of rotor angular position and current

t : time

The generating torque equation and the mechanical equation are eq. (3) and eq. (4), respectively.[2]

$$T_{em} = \frac{d\omega_m}{dt} J + B\,\omega_m + T_f + T_l \qquad (3)$$

$$T_{em} = \frac{1}{2} i_a^2 \frac{dL(\theta)}{d\theta} + \frac{1}{2} i_b^2 \frac{dL(\theta - 15°)}{d\theta} + \frac{1}{2} i_c^2 \frac{dL(\theta - 30°)}{d\theta} + \frac{1}{2} i_d^2 \frac{dL(\theta - 45°)}{d\theta} \qquad (4)$$

Where, ia ,ib ,ic, id : phase currents

J : moment of inertia

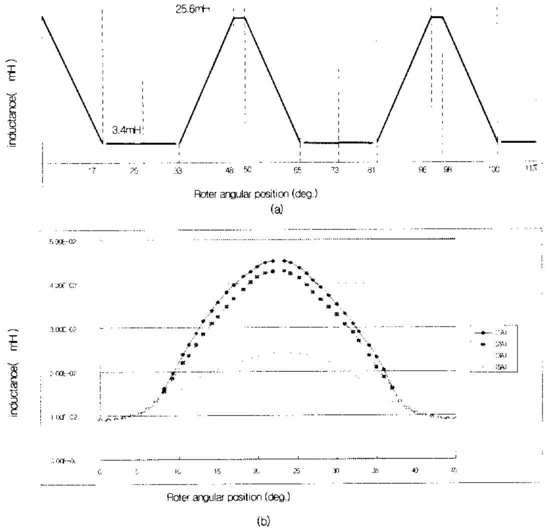
B : viscous damping coefficient

Tem : General electromagnetic torque

T_f : Static friction torque

T_l : load torque

3. 2 Inductance profile



(a)

(b)

Fig. 4. Inductance profile : (a) simplified ideal case (b) obtained from FLUX2D®.

In this paper, the FEM software FLUX2D® taking into account the inductance non-linearity of the SRM calculates the inductance profile. A database of the inductance profile is formed from the simulation results. Fig. 4(a) shows the approximate linear inductance profile. Fig. 4(b) shows the calculated inductances. The calculated inductance profiles do not have the ideal trapezoid linear form like Fig. 4(a). Therefore, the nonlinear inductance profile obtained from FLUX2D® can provide exact optimum current and torque. Also, we can determine the proper switching angle for maximum torque, efficiency or minimum torque ripple.

3.3 Simulation Results

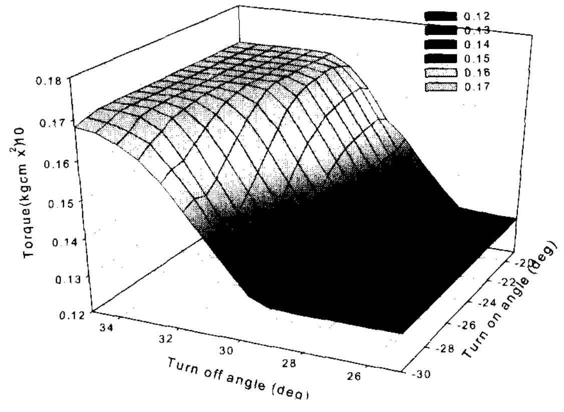


Fig. 5. Maximum torque curve.

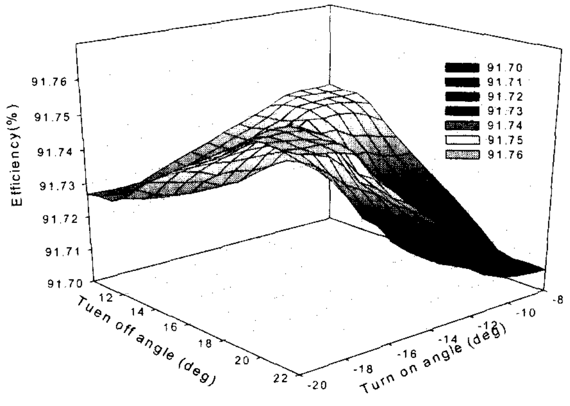


Fig. 6. Maximum efficiency curve.

SIMULINK® provides for linear and nonlinear system analysis. It is convenient software to analyze nonlinear system such as an SRM[3].

Fig. 5 shows maximum torque curve. This curve was found using iterated simulation. First, the maximum torque point was found, with a varying switching angle with a constant voltage and speed. Subsequently, the voltage and speed were changed. As shown in Fig. 5, the switching angle that produces the maximum torque is affected only by the rotor speed and the input voltage only determines the torque for a given load.

In Fig. 6, the maximum efficiency curve is found to vary with the load torque and switching angle at constant speed and voltage. These curves show that efficiency is not a function of the voltage.

On the other hand, the efficiency is very sensitive to a variation of the switching angle. This can be represented as a function of the speed and load torque from simulation results. If the maximum efficiency points are connected together at a constant voltage, a constant efficiency line can be produced for various speeds.

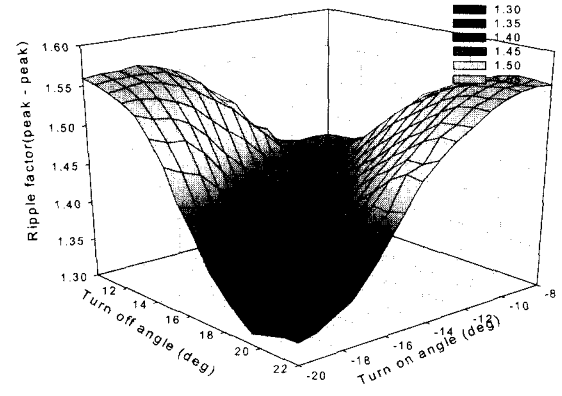


Fig. 7. Minimum torque ripple curve.

Fig. 7 shows the minimum torque ripple curve as a function of the switching angle. The SRM has a larger inductance non-linearity than that of other motors, so it has a higher torque ripple. The minimum torque ripple is produced when turn-on angle and turn-off angles are 6° and 31° respectively. The locus of the minimum torque ripple is related to the switching angle and is not related to the voltage. The SRM may have negative torque when it is driven at the maximum efficiency operating switching angle. However, the SRM does not have any negative torque when it is driven at the maximum torque operation point. So, there is a difference between the turn on and off angle for maximum torque operation and that for maximum efficiency operation.

If the SRM is used in an EV as a traction motor, the switching angle and voltage to start the EV should be determined by Fig. 6 to produce the maximum torque.

If the SRM is operated at a constant speed, the operation should be with the switching angle to suit maximum efficiency, as shown in Fig. 6.

Because low noise and vibration are required for household appliances, it is necessary to drive the SRM with the switching angles as shown in Fig. 8 for minimum torque ripple.

4. Maximum torque, efficiency and minimum torque ripple operation

4.1 Maximum torque operation

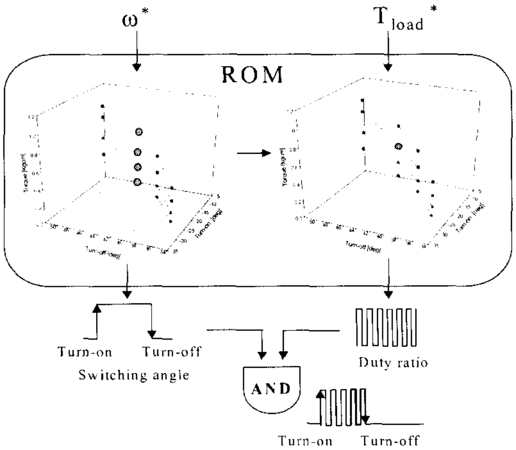


Fig. 8. Maximum torque searching algorithm.

This method will be used for traction operation. It is illustrated in Fig. 8. It was found that the motor speed was related to the switching angle at maximum torque operation, and the torque is related to the voltage.

The maximum torque operation is determined using this concept. First, the switching angle that produces the commanded speed is determined. The 4 operating points are found in the left figure of Fig. 8.

Of these 4 points, only one point produces the required torque. This point produces the maximum torque at the appropriate switching angle and voltage. This method is more efficient than the constant voltage-variable switching angle control and the variable voltage-constant switching angle control. It is able to adjust both voltage and the switching angle.

4.2 Maximum efficiency operation

This method expected to be used for steady driving of an electric vehicle. It is found that the efficiency is dependent on not the voltage, but the switching angle. As shown in Fig. 9, the 3 points are meeting the commanded requirement.

In the Fig. 10, the curved line is a constant torque line. However, only one point produces the desired speed and torque with maximum efficiency. Maximum efficient operation is at the supply voltage and switching angle corresponding to this point.

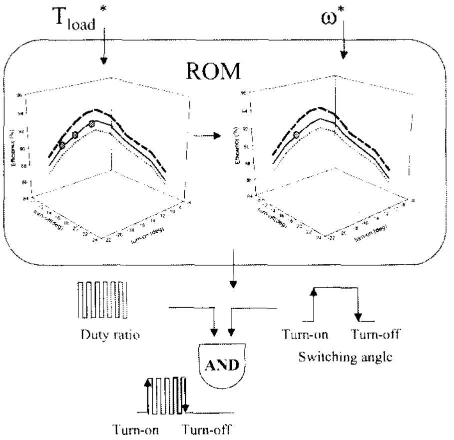


Fig. 9. Maximum efficiency searching algorithm.

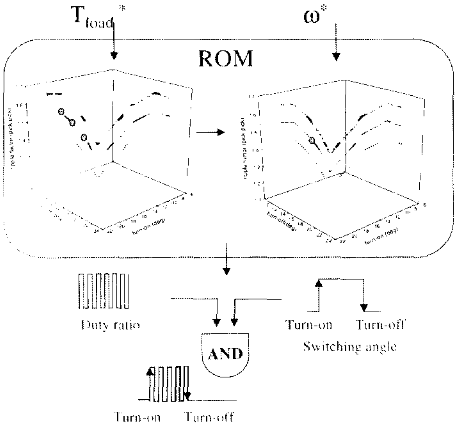


Fig. 10. Minimum torque ripple searching algorithm.

4.3 Minimum torque ripple operation

Minimum torque ripple driving can be used for precision control applications, such as numerically controlled lathes and milling machines. Minimum torque ripple operation is not dependent on the voltage, but rather it is dependent on the switching angle. Minimum torque ripple operation is similar to maximum efficiency operation. Firstly, the operating points that meet the required speed needs to be found. Then the one point that is on the required constant torque line needs to be selected. Hence, with the corresponding voltage and switching angle, minimum torque ripple operation can be achieved.

5. Experimental results

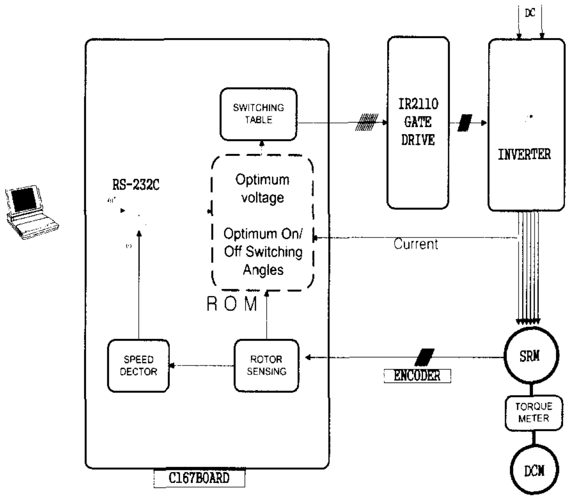


Fig. 11. Block diagram for experiments.

The simulation results are also confirmed with the experiments. Fig. 11 shows the block diagram for experiments.

Since the torque $T = \frac{1}{2}i^2 \cdot dL/d\theta$, as shown in Eq. (4), the measured phase currents which informs the load torque are used looking for ROM data which stored the optimum average voltage. The absolute encoder is used for detection of rotor angular position and motor speeds. Also it refers to ROM address, which is stored PWM duty ratio, that is the optimum switching angle. One-chip micro-controller C167 makes the gating signals of the asymmetric bridge type inverter.

Because the component of the gating driver, IR2110, has superior feature of insulation than any other, it results in reducing the power loss and minimize the system size.

The SIMULINK® provides the linear/nonlinear system analysis through continuous/discrete time. So it is convenient software to analyze nonlinear system as a SRM.

Fig. 12 shows a SIMULINK® model. This model consists of the voltage source part, the current calculating part, the torque calculating part, and the inductance referring part. And Fig. 13 is simulation flowchart. It draws up a table of contents of SIMULINK® model.

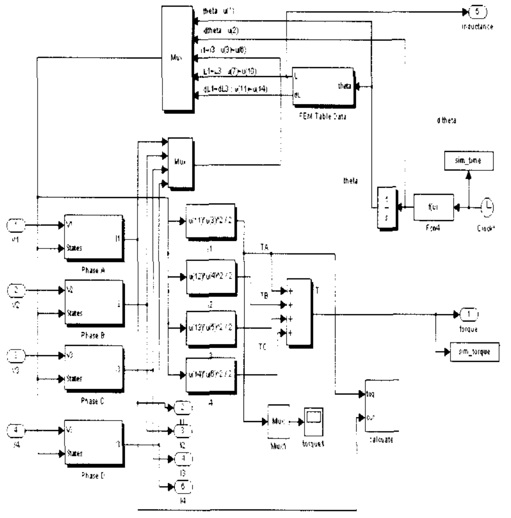


Fig. 12. SIMULINK® model for simulation.

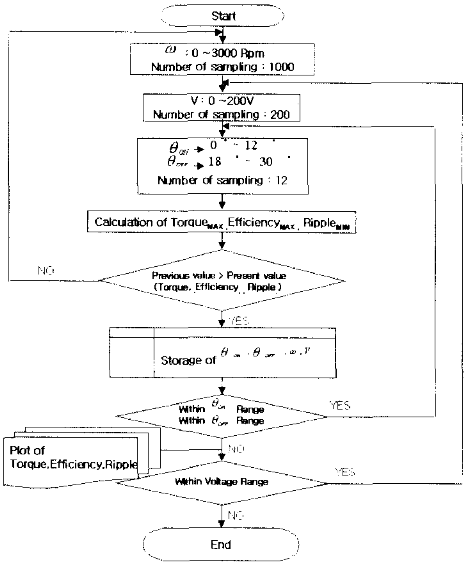


Fig. 13. Simulation flowchart.

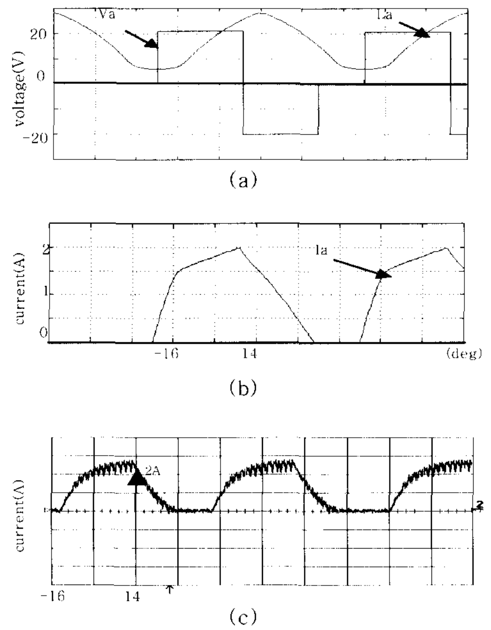


Fig. 14. Phase voltage of maximum torque for simulation result and phase ; (a) current of maximum torque for (b) simulation result and (c) experimental result.

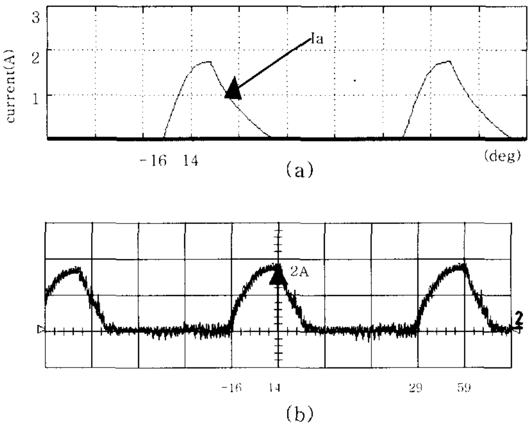


Fig. 15. Phase current of maximum efficiency for (a) simulation result and (b) experimental result.

Fig. 14 shows the simulated and experimental results respectively, of the SRM phase current during maximum torque operation. The motor speed is 1500rpm and the supply voltage is 200V. It can be seen that the experimental current waveform is similar to the simulation result. The current has wide dwell angle zone, as would be expected when achieving maximum torque operation.

Fig. 15 shows the simulated and experimental results of phase current operating at maximum efficiency of the SRM. The two waveforms are similar to each other. The maximum efficiency is known to occur with the condition that the current does not produce any negative torque [2].

Similarly, the minimum torque ripple current simulated and measured waveform is shown in Fig. 16(a) and Fig. 16(b) and (c) respectively. They are similar to each other. Fig. 16(b) and (c) show the current waveform of SRM. The peak dotted circle represents the torque ripple. From the experiment, the experiment result of phase current is not presented flat-top shape by the turn off angle after saturation point in Fig. 16(b). But the current in a phase has flat-top shape by the turn-off angle before saturation point in Fig. 16(c)[7][8].

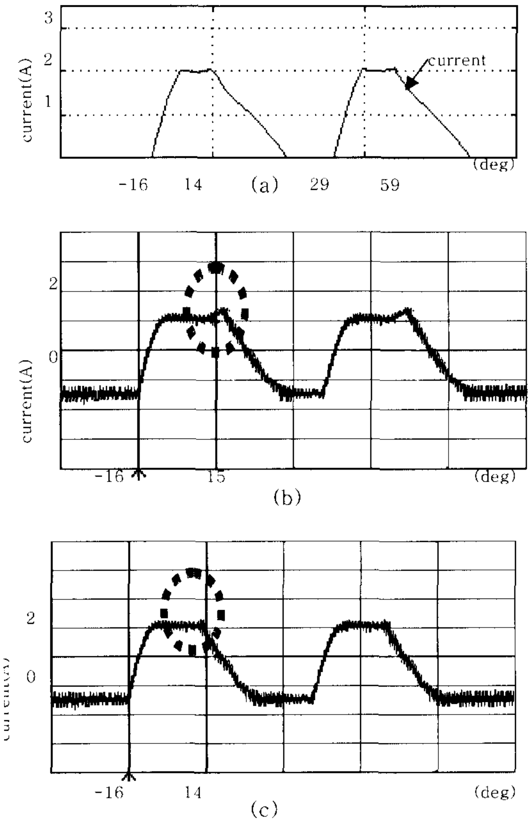


Fig. 16. Phase current of maximum torque ripple for (a) simulation result (b) Experimental result is in case of turn-off angle[15(deg)] not using (a) Simulation result. (c) Experimental result is in case of turn-off angle[14(deg)] using (a) simulation result.

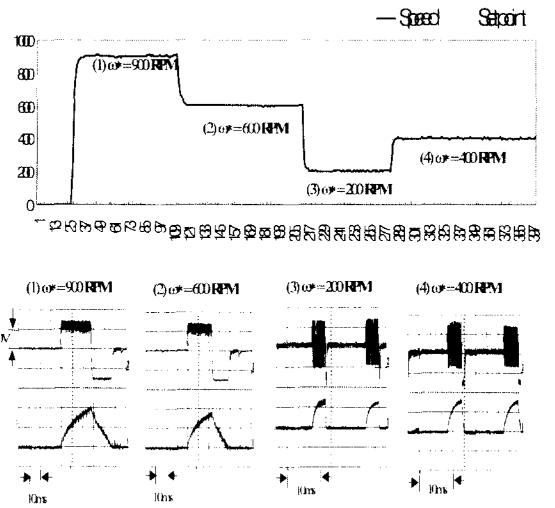


Fig. 17. Speed traction with maximum torque.

Fig. 17 shows that the motor speed follows the commanded speed well. The current and voltage waveforms for the different commanded speeds are also shown. In the case of an application for EV, it can be driven by maximum torque mode on starting and maximum efficiency mode during driving.

6. Conclusions

The optimum switching angle and voltage were determined from the simulation of the SRM for the operating conditions of maximum torque, efficiency and minimum torque ripple. From the simulation results, it is seen that only the load determines the optimum average supply voltage and the speed is determined only by the optimum turn on and off angle. The maximum efficiency and the minimum torque ripple locus depend only on the switching angle. In this paper, we propose a new operating method for the SRM, which is to obtain, maximum torque, or maximum efficiency, or minimum torque ripple.

From the experimental results, it can be seen that the simulation and measured current waveforms are similar and a good speed control is obtained. A one chip micro controller with ROM performed the implementation of the optimum switching angle and voltage. It is expected that these results will be useful if the SRM is to be used for a traction motor in an EV, an industrial motor or for household appliances

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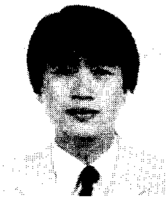

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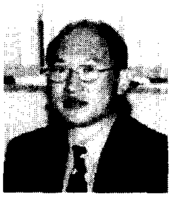

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