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The high-speed operation of single phase switched reluctance motor considering magnetic saturation

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In the high-speed operation of SRM, the conventional pulse width modulation (PWM) drive method is not available because of the limitation of switching speed; therefore the single-pulse drive method is commonly employed. On the contrary, the use of the single-pulse drive method cannot avoid the overcurrent in the low-speed operation because of the insufficient back emf and the difficulty of duty control. With these reasons, the switching method is commonly changed from PWM at the low-speed operation to the single-pulse method at the high-speed operation. In the fan application, the required load torque increases as a square of the fan speed; it requires more current for the torque generation. Therefore at the mode transition between PWM and single-pulse drive, it is unavoidable that the phase current rapidly increases if the nonlinearity of inductance to the current is not considered. In this paper, by using finite element method (FEM) which is considered with the nonlinearity of the inductance with respect to the current, the speed of mode transition is calculated (18 000 rpm) and verified by the experiment.
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I. INTRODUCTION

The fan drive application turbo fan or vacuum cleaner requires high-speed operation. For the high-speed operation, following points are necessarily considered. The first requirement is the wide operation range of the control scheme. The pulse width modulation (PWM) drive method is common because it easily implements, the current control. However, in the high-speed operation, the PWM drive method is difficult to perform, as it is in the low-speed operation, because of the limitation of the switching frequency. However, the single-pulse control can endure high-speed operation because the switching frequency of the single-pulse control (dwell time control) is far low than the PWM control. Therefore for the wide speed operation, the control mode must be changed from PWM control mode to single-pulse control mode in a certain operation speed. In choosing the speed of mode transition, the experimental method is conventionally used. The conventional method is implemented by experiments under all load conditions. The transition speed is decided by the look-up table in which all the speeds of mode transition are tabularized. The conventional method is simple and easy to implement, but it is not proper to use this method in various load conditions because it requires experiments for all load conditions. Therefore the theoretical selection method of the mode transition speed is necessary which must be available in various load conditions.[1]

The second one is the magnetic saturation and corresponding losses. If the magnetic saturation has occurred, the current in the circuit increases rapidly which causes the increment of copper loss.[2]

In this paper, the way to select the speed of mode transition from PWM control mode to single pulse is proposed. The conventional method requires experiments for all load conditions. Moreover, the magnetic saturation is hardly considered in the conventional method because this method obtains the transition speed by experiments. On the other hand, the proposed method considers the load condition, torque production, and magnetic saturation simultaneously. For the validation of the proposed method, simulation using MATLAB is performed as well as experiment with load condition.

II. OPERATION PRINCIPLES

A. Numerical modeling

Table I shows the specification of the single phase SRM model. The voltage equation of SRM is related to the linkage flux of phase winding by Faraday's law, described by (1),

$$V = Ri + \frac{d\lambda(\theta,i)}{dt}, \tag{1}$$

where λ is linkage flux, R is phase winding resistance, i is phase current, and θ is rotor position.

SRM is doubly salient; the flux linkage is a function of the rotor position and phase current. (1) can be described by (2),

TABLE I. Specifications of the single phase SRM.

Items	Values
Rated output [W]	1,500
Rated voltage	220
Pole number ratio	6/6
Rated speed [rpm]	33,000
Rated torque [Nm]	0.35
Inductance (minimum) [mH]	0.484
Inductance (maximum) [mH]	1.887

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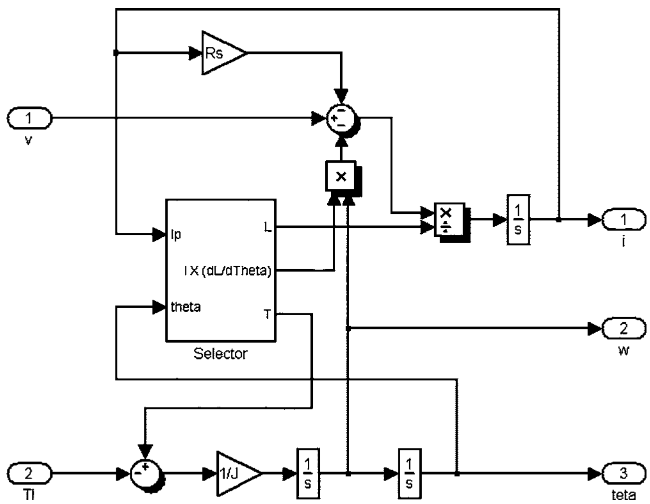

FIG. 1. The block diagram of single phase SRM.

$$V = Ri + \frac{\partial \lambda}{\partial i}\frac{di}{dt} + \frac{\partial \lambda}{\partial \theta}\frac{d\theta}{dt} = Ri + L(\theta,i)\frac{di}{dt} + i\omega\frac{dL(\theta,i)}{d\theta}. \quad (2)$$

(2) can be written to (3) in the viewpoint of energy flow.

$$Vi = Ri^2 + \left(\frac{d}{dt}\frac{1}{2}Li^2\right) + \frac{i^2}{2}\frac{dL(\theta,i)}{d\theta}\omega. \quad (3)$$

Generally, disregarding magnetic saturation, coenergy and torque are described by (4) and (5).

$$W_c = \int \lambda(\theta,i)di = \int L(\theta)idt, \quad (4)$$

$$T = \frac{1}{2}i^2\frac{dL(\theta)}{d\theta}. \quad (5)$$

The speed is described by (6).

$$\omega = \int \frac{T_{\text{ph}} - T_L}{J}dt, \quad (6)$$

where T_{ph} is the torque at each phase winding, T_L is load torque, and J is inertia.

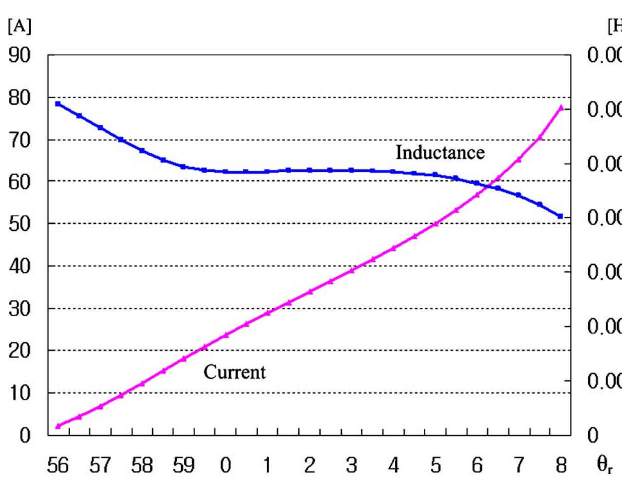

FIG. 2. The characteristics of inductance vs current (at 20 000 rpm).

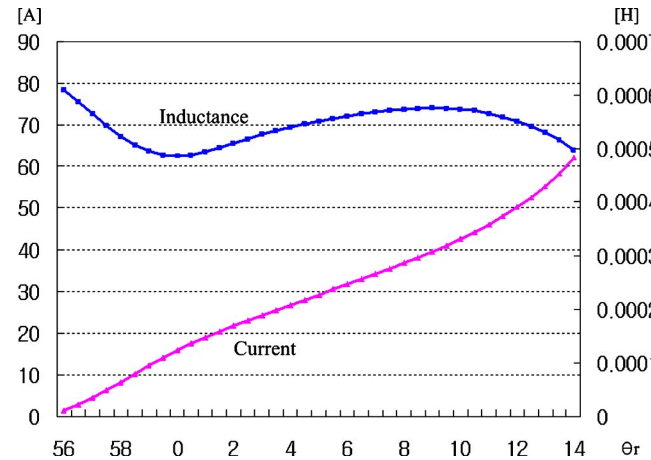

FIG. 3. The characteristics of inductance vs current (at 30 000 rpm).

From these equations, MATLAB simulink block diagram is composed and presented in Fig. 1.

B. Magnetic saturation

Magnetic saturation is influenced not only by the magnitude of magnetization current but also the mechanical dimensions of the magnetic circuit. With this reason if the dwell angle is increased by the speed controller for increasing the torque production in the high-speed operation, the aligned area of the rotor and the stator pole shoe also increases, so magnetic saturation occurs.[3] Figures 2 and 3 show the change of inductance versus the change of turn-on angle with fixed dwell angle at 20 000 and 30 000 rpm [y axis (main): phase current, y axis (auxiliary): phase inductance, x axis: turn-on angle, dwell angle: 21°]. In Fig. 2, the inductance starts to decrease at 60 A, but in Fig. 3, it starts to decrease at 50 A. This means that the magnetic saturation occurs easily in small current in the high-speed operation. Therefore the magnetic saturation must be considered in dwell angle control.

III. SIMULATION AND EXPERIMENT

Figure 4 shows the inductance profile versus current. This profile is the result of the finite element method (FEM)

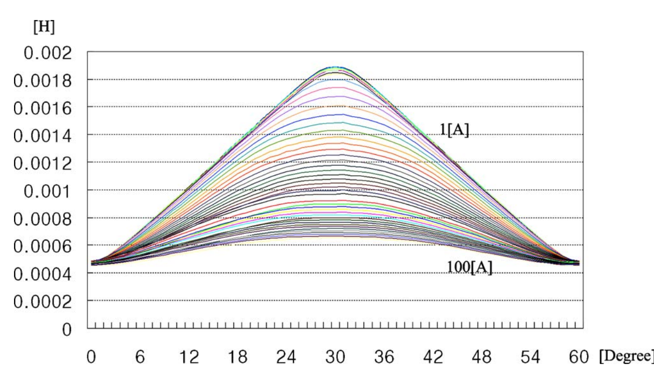

FIG. 4. The inductance profiles vs currents.

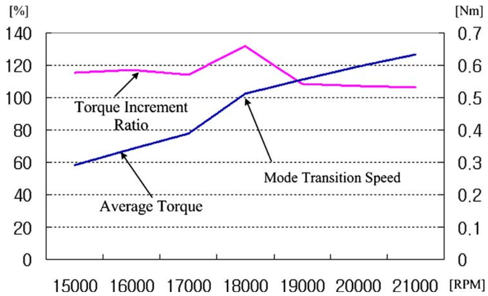

FIG. 5. The mode selection curves.

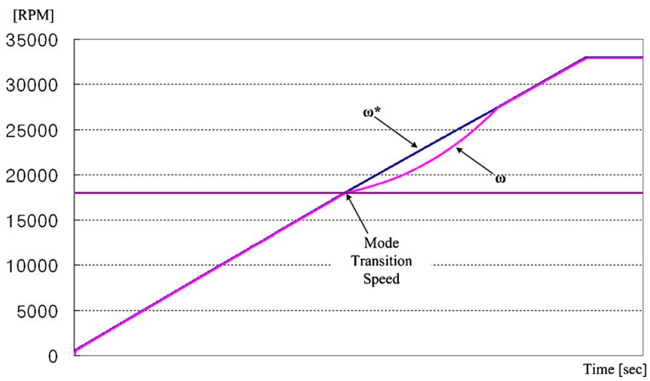

FIG. 6. The speed response with rated load.

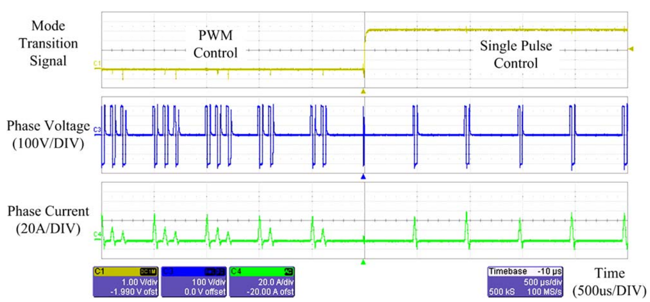

FIG. 7. The wave forms of voltage and current on the mode transition.

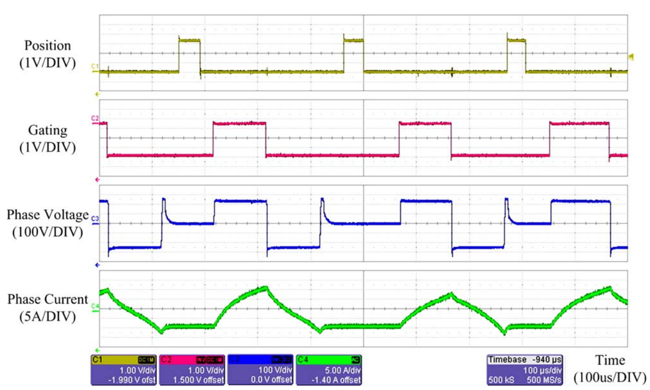

FIG. 8. The wave forms of voltage and current (at 32 000 rpm).

analysis and made into a table to be used in the simulation. The nonlinearity of the inductance versus current is considered in this table.

Figure 5 shows the FEM simulation result of the average torque versus speed. In Fig. 5 the increment ratio (main *y* axis) means the change of the average torque. The speed of mode change is selected when the average torque starts to decrease (at the point at which the increment ratio starts to decrease) and the produced torque is larger than the load torque. At this speed the generated torque is sufficient in the mode transition. Figure 6 shows that the SRM produces its maximum torque and reaches the rated speed with the condition of fixed turn-on, and maximum dwell angle of 21°. In Fig. 6, ω^* represents speed command, whereas ω represents real speed.

Figure 7 shows the wave forms of phase voltage and phase current during mode transition at 18 000 rpm. At the speed of 18 000 rpm, which is the result of the FEM analysis which considered the inductance nonlinearity and load torque, mode transition goes well. Figure 8 shows the wave forms of phase voltage, current, and position sensor signal and PWM gating wave forms at the rated speed of 32 000 rpm with fan load.

IV. CONCLUSIONS

In this paper the method of selection of the mode transition speed from PWM to single-pulse control is proposed. With this proposed method the load torque and the nonlinearity of inductance profile with respect to the current can be considered easily. This transition speed level is obtained from the FEM analysis without the experiment for each load condition. For the confirmation of its validation, simulations using MATLAB and the experiments are performed. With these simulations and experiments, it is confirmed that the selection of the speed level of the mode transition works well at the loaded condition.

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