Harmonics Reduction in the High-Speed Synchronous Reluctance Motor by Space-Vector PWM Control

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ABSTRACT – *Many harmonics components are contained within the stator currents of the high-speed synchronous reluctance motor, SynRM, with salient pole rotor. They cause the power factor of SynRM to get worse.*

In this paper, the mathematical model of SynRM is investigated, and SV_PWM control method is applied to reduce harmonics components in the stator current.

Simulation results show the fast response of speed and the reduction of harmonics components at steady state.

1. Introduction

According to the need of the increase for the load requiring high speed rotation, and the need of the miniaturization for units in the scale and weight, the demand of high speed motors is increasing. Although induction motors have been mainly used for high speed motors, they have the crucial defects under the high speed rotation; the separation of the rotor windings and the heat loss of the rotor due to secondary copper loss and harmonics secondary copper loss.

Because SynRM is simpler in construction and solider than reluctance motor, researchers are vigorously proposed to utilize SynRM for high-speed applications.

SynRM has the bad power factor but substantially it is applied to the small size motors under the high speed up to 100,000 rpm and not more than 10KW.

Therefore, even though SynRM has been used for the special use of motors with small output power, the applications of the conventional SynRM are expected due to the development of inverter recently.

It is the method to improve the power factor of SynRM that we need to put the gap close between rotor's salient-pole and stator in order to make inductance in the d-axis big and inductance in the q axis small.

Also laminate of rotors is requires optimizing those.

However, in that case, it has the big problem that under the high-speed rotation, the separation of the rotor winding could be happened due to centrifugal force.

PWM control techniques to control AC motors have been studied to raise usable DC voltage in order to reduce harmonics component and to get the maximum torque. Among these techniques, SV_PWM is the control technique to satisfy the above conditions.

In this paper, we analyze SynRM with the salient-pole rotor numerically, and modelize the system. Also we apply SV_PWM control method to reduce the harmonics included in SynRM current waveform, and then consider the validity with simulation and experiment.

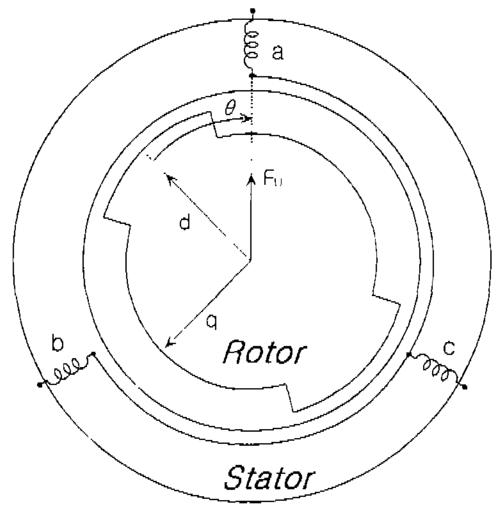


Fig. 1 The structure of the salient-pole SynRM

2. Modeling of SynRM

SynRM has the structure similar to salient-pole synchronous motor without stator winding, therefore it has the same vector control as the salient-pole synchronous machines have theoretically that it divides rotor, current components into main flux current (I_d) and torque current (I_q). The voltage equation of SynRM without rotor starting cage is as follow.

$$\bar{V}_s = R_s \bar{I}_s + p\bar{\lambda}_s + j\omega\bar{\lambda}_s \qquad (1)$$

Where, V_s is rotor voltage, R_s is rotor winding resistance, I_s is rotor current, λ_s is rotor linkage flux, ω is angle speed, and p is differential factor. Also we can say

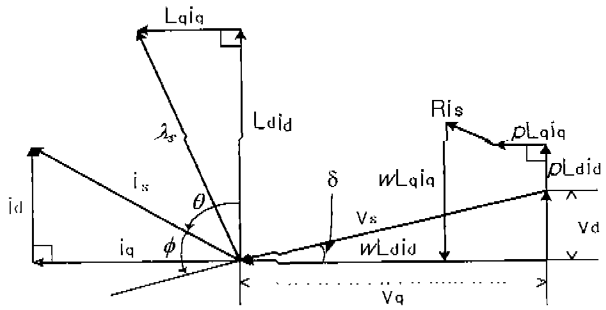


Fig. 2 Vector diagram of SynRM

The Fig. 2 shows the 1 phase vector diagram of SynRM.

where, L_d and L_q are inductance in d axis and q axis individually. Rotor linkage flux λ is the vector sum of flux λ in d axis result from d axis's magnetomotive force and flux λ in q axis resulted from rotor reaction. It can be said that $\lambda_d = L_d I_d$ and $\lambda_q = L_q I_q$.

In the vector diagram, the synchronous model of voltage-current equations is as follow

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R + pL_d & -\omega L_q \\ \omega L_d & R + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \qquad (2)$$

Torque of SynRM and synchronous machines are identical. Therefore, the torque equation is showed in the steady state like this.

$$T = \frac{3}{2}\frac{P}{2}(\lambda_d i_q - \lambda_q i_d) \qquad (3)$$

Where P is pole number.

If we put $\lambda_d = L_d I_d$ and $\lambda_q = L_q I_q$ to the equation (3), the torque equations are showed as follows

$$T_e = \frac{3}{2}\frac{P}{2}(L_d - L_q) I_d I_q \qquad (4)$$

$$T_e - T_L = J\frac{d\omega}{dt} + B\omega \qquad (5)$$

Where J is the moment of inertia.

When the d-q components of rotor voltage are constant, the equation of voltage and current doesn't change.

Here, the d-q components of current are as follows

$$I_d = \frac{(\omega L_q V_s - R V_d)}{R^2 + \omega^2 L_d L_q} \qquad (6.a)$$

$$I_q = \frac{\omega L_d V_d + R V_s}{R^2 + \omega^2 L_d L_q} \qquad (6.b)$$

We can get the maximum torque equation, when we put equation (6.a) and (6.b) into the equation (4), where winding resistance, Rs, can be ignored.

$$T_{max} = \frac{3}{2}\frac{P}{2}\left(\frac{1}{L_q} - \frac{1}{L_d}\right)\left(\frac{V_s}{\omega}\right)^2 \qquad (7)$$

3. Control method of SV_PWM

The available eight different switching states of the 3-phase inverter are depicted in the Fig. 4. All the machine terminals are connected to each other electrically and no effective voltages are applied to machine when the zero voltage vectors presented by V0 and V7 is selected. In Fig. 4, the effective voltage vector which is 2 over 3V_dc and its phase margin 60° generates the hexagon.

For the more precise voltages and the minimization of current ripple, SV_PWM control scheme produce the symmetrical ON, OFF one sampling period. In sector 1, the switching pattern is V0→ V1→ V2→ V7→ V2→ V1 → V0.

The table 1 presented the gating sequences of sector I and gating time means the time delay.

Fig. 5 presented the effective voltage in one sampling period and Fig. 6 is voltage reference.

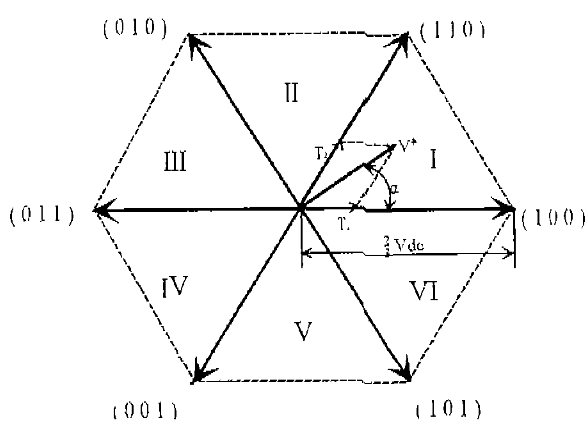


Fig. 4 State space vector diagram

Table. 1 Gating time on the sector I

ON Gating Time	OFF Gating Time
$T_{ga} = T_0/2$	$T_{ga} = T_0/2 + T_1 + T_2$
$T_{gb} = T_0/2 + T_1$	$T_{gb} = T_0/2 + T_2$
$T_{gc} = T_0/2 + T_1 + T_2$	$T_{gc} = T_0/2$

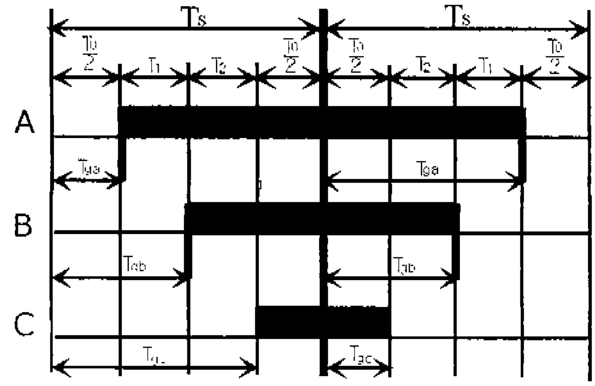


Fig. 5 Effective voltage per one period (Sector I)

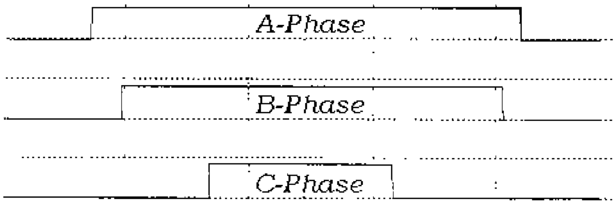


Fig. 6 Voltage signal for SV_PWM

4. Simulations

Fig. 7 presented the system block diagram, SynRM are manufactured for the experiments. SynRM parameters are presented in Table 2. To verify SynRM model which is applied to mathematical notations in chapter 2, Fig. 8 shows the speed (a), output current (b) and the harmonics spectra of phase current (c) with sinusoidal voltages.

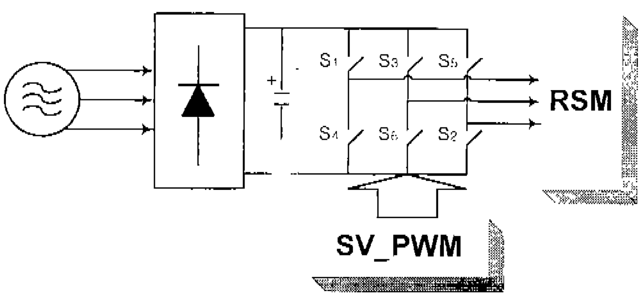
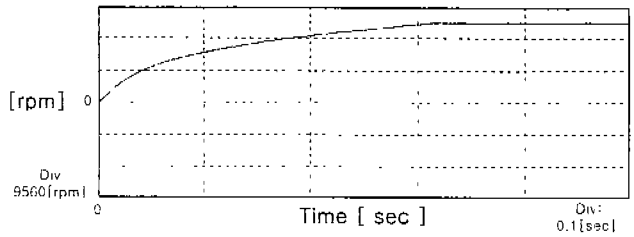


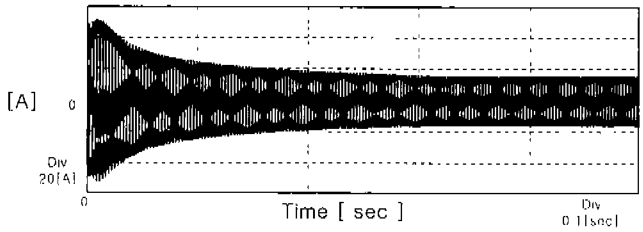
Fig. 7 System configuration

Table. 2 Variable of Reluctance Synchronous Motor

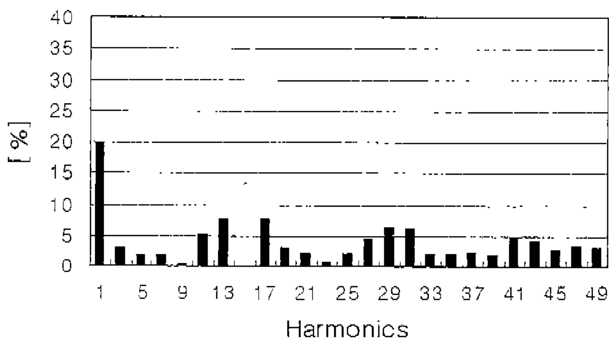
Rated Voltage	220[V]	R_s	0.18[Ω]
Current Rating	16[A]	L_d	3.22[mH]
Frequency	1000[Hz]	L_q	1.04[mH]



(a) Speed waveform



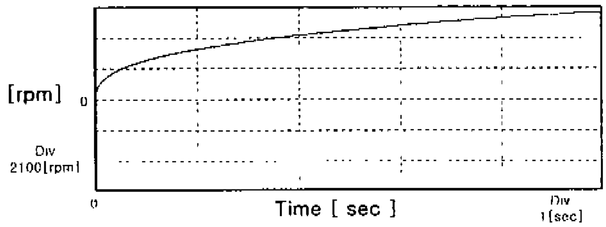
(b) Three phase current



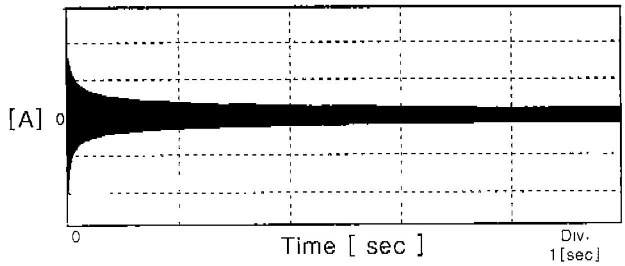
(c) Spectra analysis of phase current

Fig. 8 Output waveform at commercial source

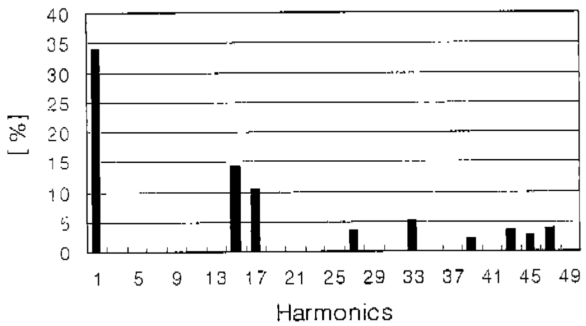
Fig. 9 is the speed (a), output phase current (b) and the harmonics spectra of phase current (c) at 1 ㎑ input frequency.



(a) Speed waveform



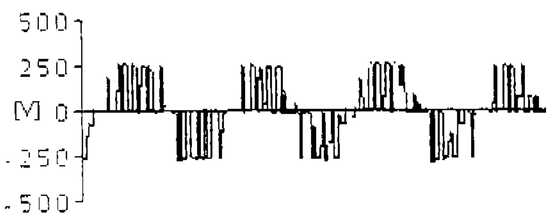
(b) Three phase current



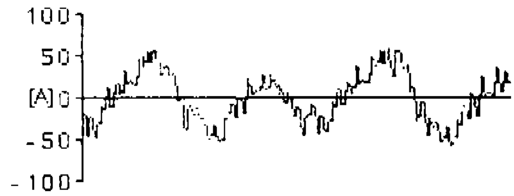
(c) Spectra analysis of phase current
Fig. 9 Output waveform at SV_PWM

5. Experimental Result

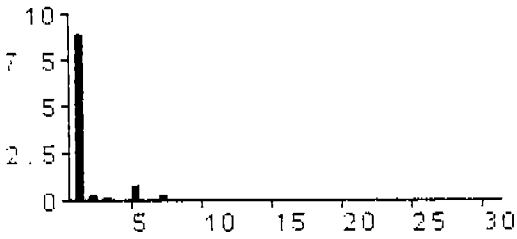
Fig. 10 shows the voltage (a), current (b) and the harmonics spectra of phase current (c) at commercial source.



(a) Voltage

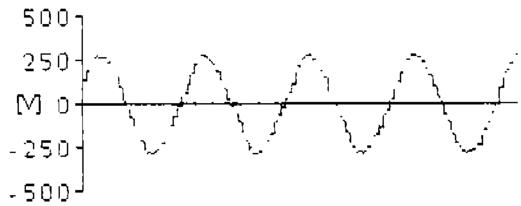


(b) Cuurent

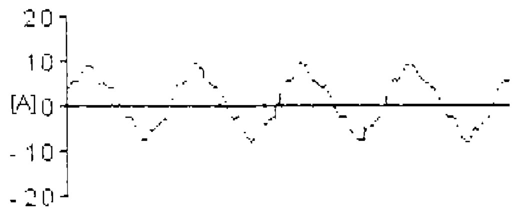


(c) Spectra analysis of phase current
Fig. 10 Output waveform at commercial source

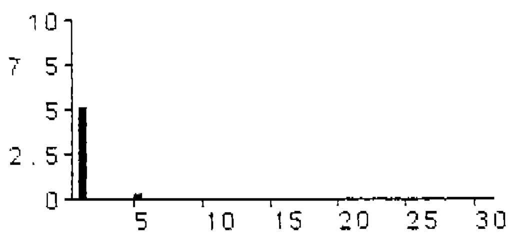
Fig. 11 is the voltage (a), current (b) and the harmonics spectra of phase current (c) at the SV_PWM.



(a) Voltage



(b) Current



(c) Spectra analysis of phase current
Fig. 11 Output waveform at SV_PWM

6. Conclusions

In this paper, SynRM with salient rotor is investigated mathematically and proposed the system model. For the reduction of harmonics, SV_PWM is applied to the proposed system.

Simulation results described the fast speed response (4.8sec at 60,000rpm) and reduction of harmonics components.

7. References

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