High Performance Speed Control of Switched Reluctance Motor

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Abstract–Advantages of switched reluctance motor(SRM) drives make it an attractive candidate for replacing adjustable speed ac and dc drives in both industrial and consumer applications. Furthermore, a simple, low cost and robust SRM drive can be efficiently operated in the hostile environment of an automobile.

Generally, the speed control of SRM has a large step change or large torque reference, the output of its PI controller is often saturated. When this happens, the integral state is not consistent with the SRM input, while may give rise to the windup phenomenon.

This paper proposes anti-windup control method for SRM speed control system by hysteresis current controlled asymmetry bridge converter.

The experimental results show that the speed response has much improved performance, such as a small overshoot and fast settling time at the acceleration and particulary deceleration period with braking mode.

Index Terms—SRM, anti-windup proportional-integral Control, braking operation

1. INTRODUCTION

Recently, switched reluctance motors (SRMs) become popular in industrial applications, especially for drives in low and medium level. It is because SRMs have the advantages of low manufacturing cost, good reliability, wide range operation of speed and torque, and good dynamic response.

Generally, it is possible to control speed only at the positive torque of the load. But in case of the large inertia, braking operation is needed for speed control.

The structure and idealized inductance profile of SR motor are shown in Fig.1 and 2. As Fig. 2, the positive torque is produced in the increasing period of inductance and negative torque in the decreasing period. Torque does not depend on direction of the current, but only on the magnitude of the phase currents.

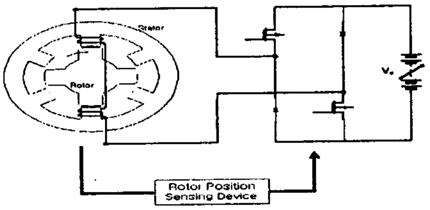

Fig 1. Structure of SRM and drive system

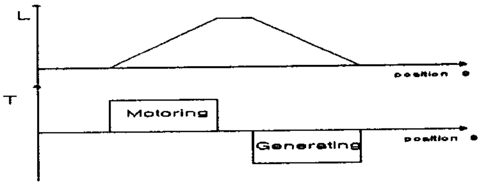

Fig 2. Inductance and torque generation of SRM

In this paper, speed control response characteristic is shown to prove the improvement at the speed reduction and the negative torque through the braking operation. To elevate speed response, anti-windup PI controller is used. Speed error and reference of the anti-windup PI controller are compared and the signal of braking motion is decided at the reasonable point.

80c196kc is used for the test set-up. Pulse obtained from the incremental encoder is analyzed to calculate the speed of SRM and the encoder signal and data of the EPROM are used to detect rotor position. Moreover asymmetric bridge converter and hysteresis current control is applied to reduce torque ripple.

2.1 Hysteresis Current Controller

Hysteresis control is commonly used in Switched Reluctance Motor drives in the low speed region for limiting the current to the desired value.

Hysteresis current controller is very simple hardware realizing the robust system with variable parameters and the fast response. In the hysteresis current controller method, the current is allowed to chop within a tolerance band, around the desired level of current.[7]

SRMs have a considerable inherent torque ripple and non-linearity due to the driving characteristics of waveform of current and the non-linearity inductance profile. The torque ripple causes a motor vibration and noise and inhibits wide application. To overcome these drawbacks, various control methods have been proposed. Torque of SRM is proportional to the square of the current. Therefore it is important to keep current Flat-topped.

In this paper, hysterisis current control comparing real current gained by feed back with calculated reference value is applied for variable speed range. The error between real current obtained from CT and current reference of 80c196kc is applied to the first OP-Amp's input and output of the second OP-Amp divided by R1 and R2 gets into the non-inverting terminal, making up hysteresis band. Gate signals keep on and off to maintain the steady current between reference values and real current into the band.

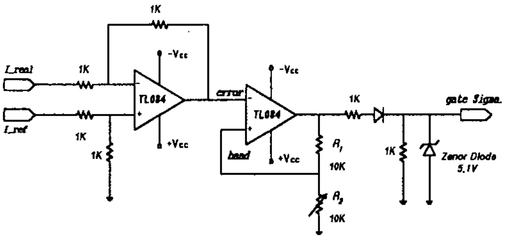

Fig 3. Hysterisis current controller

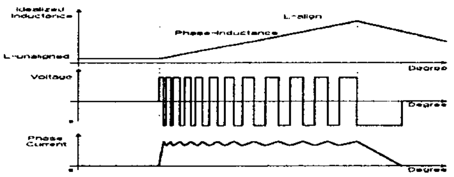

Fig 4. Waveforms by hysteresis control

Fig. 5 shows a sequence of switching with respect to the rotary direction. From the principle of reluctance torque, the positive torque is produced when each phase is excited on the increasing period of inductance. Oppositely, the negative torque is produced on the decreasing period.

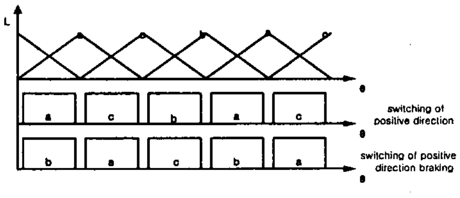

Fig 5. Commutation signal of forward starting and forward braking

Switching sequence of positive direction : a→ c→ b →a →c
Positive direction braking operation : b→ a→ c→b →a

Moreover, switching sequence of negative direction is determined with same method. These switching patterns are easily acquired by use of EPROM with position information. Switching pattern of braking operation in positive direction is similar to positive torque in negative direction. As a result, rotation in negative direction may increase when braking operation occurs unnecessarily. To prevent this, control signal should be composed to change promptly for mode.

2.2 Development torque of the SRM[1]

The voltage equation of the SRM is given as

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

The first term of (1) is voltage drop of winding resistance, the second is variable inductance voltage drop and the last is speed emf. The torque of SRM can be determined from the co-energy (Wc) as

$$W_c = \frac{1}{2} i(\theta)^2 \cdot L(\theta) \tag{2}$$

$$T = \frac{\partial W_c}{\partial \theta} = \frac{1}{2} i(\theta)^2 \frac{dL(\theta)}{d\theta} \tag{3}$$

Note that the torque is proportional to the square of the phase currents and the slope of the inductance. [1]
dL/dθ term in equation (1) reduces current at positive torque in the positive direction. But at braking operation, generation(current) occurs as dL/dθ falls to minus.

Fig 6. Current waveform of positive torque

In Fig.7, supply of exciting current is sufficient to restore the energy. But in Fig. 8, exciting current is not sufficient. As such, the amount of generated current is dependent to turn-off angle.

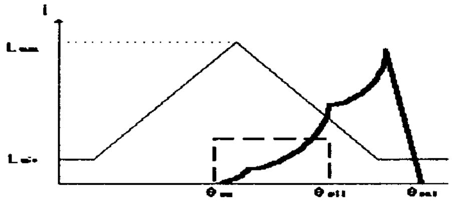

Fig 7. Current waveform of braking mode
(Over-excitation)

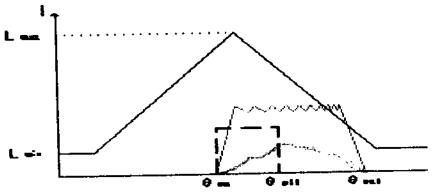

Fig 8. Current waveform of braking mode (Under excitation)

2.3 Design of controller

Usually, anti-windup PI control is adapted to overcome the windup phenomenon. The windup phenomenon appears and the performance degrades when the proportional integral (PI) controller output is saturated.

An anti-windup PI controller is proposed to improve the control performance of variable-speed motor drives.

It operates the same as PI control if output isn't limited, oppositely limited, the error between output(V) of the control and real given output(u) is feed back and reduced the integral clause.

Although the operating speed command changes, similar control performance can be obtained by using the PI gains selected in the linear region.

Fig. 9 shows block diagram of the tested anti-windup PI controller generating the braking operation signal and the plant dynamics.

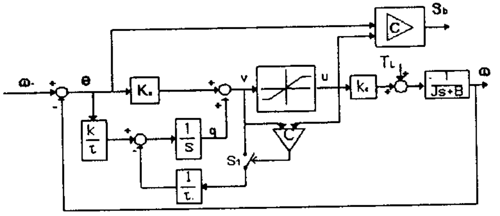

Fig 9. Block diagram of anti-windup PI controller

The integral state of block diagram of anti-windup PI controller is given as

$$\dot{q} = \begin{cases} \dfrac{k_p}{\tau_I} e & \text{if} \quad u = v \\ \dfrac{k_p}{\tau_I} e - \dfrac{1}{\tau_I} V & \text{if} \quad u \neq v \end{cases} \qquad (4)$$

When the speed command or the external load changes in a large step, speed controller may operate in the saturation region. In this region, the plant input is clamped at a prescribed maximum value and the integral state rapidly converges to zero and prevent from windup phenomenon. Besides, it is composed of the braking operation signal Sb, the output u and the error of controller.

2.4 Simulations

With the objective of evaluating the employed method, simulation of the system was made using PSIM program as fig 10.

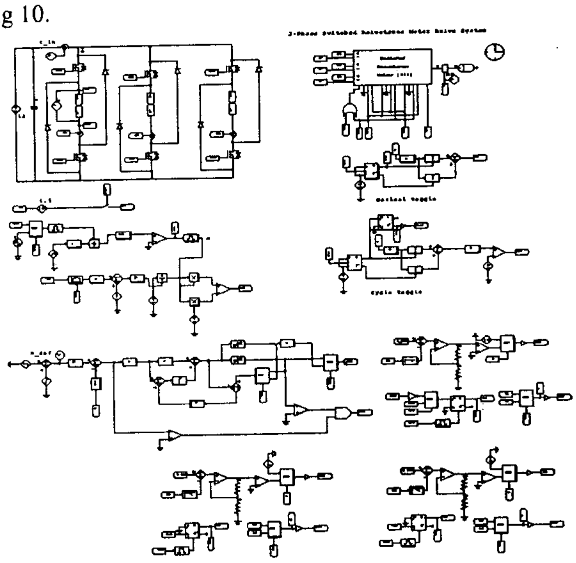

Fig 10.Configuration of simulation

In Fig. 11, 12, 13, speed and current waveform of each controller is illustrated.

For conventional PI controller, overshoot occurs at both acceleration and deceleration speed period. As a result, it takes long time for deceleration speed period. Otherwise, anti-windup PI controller, speed response is faster without overshoot than the others as speed increases.

Fig 13 shows response of anti-windup controller with braking mode. We can show that acceleration speed period is the same as the response of fig 12, while deceleration speed period is faster than mode compared with fig 12 in response time.

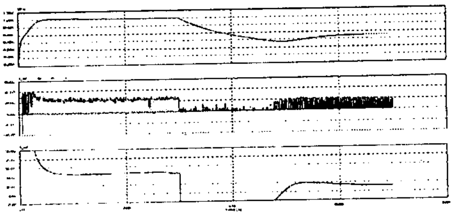

Fig 11. Conventional PI Controller

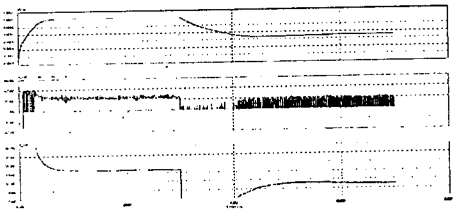

Fig 12. Anti-windup Controller

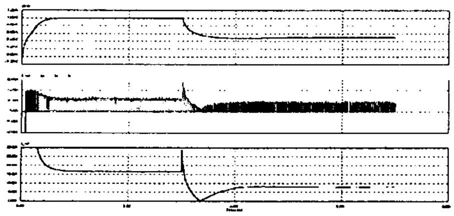

Fig 13. Anti-windup Controller with braking mode

2.5 Experimental Results

Tested SRM (6/4pole, 12V, 250W) is controlled by 80c196kc. The control algorithm is fully implemented in software with an 80c196kc, which includes an A/D converter. The sampling time of the speed control loop is 1ms and the shaft encoder has 600 pulses per revolution.

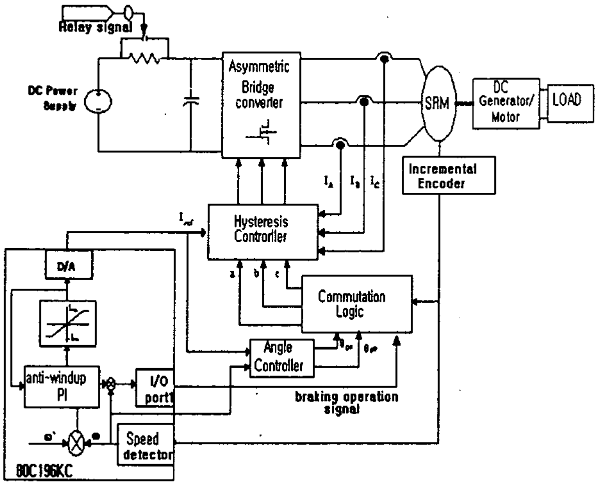

Fig 14. Set-up of SRM driving system

Asymmetry bridge converter and hysteresis current control are adapted. Fig. 14 shows the set-up of SRM driving system.

Fig.15, 16 and 17 show the experimental results of conventional PI, anti-windup PI controller and anti-windup PI with the braking operation, respectively, as reference $\omega^* = 500$rpm and $\omega^*=1500$rpm.

In comparison of PI and anti-windup PI controller, anti-windup PI with braking operation shows much faster in that speed response for the different speed commands.

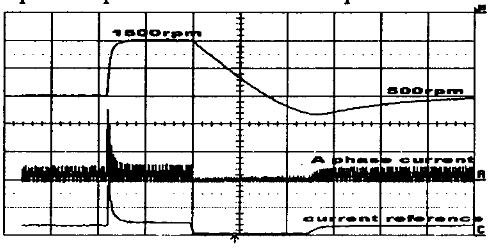

Fig 15. Conventional PI Controller (2s/div, 10A/div)

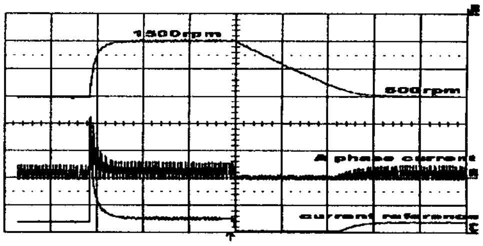

Fig 16. Anti-windup PI controller (1s/div, 10A/div)

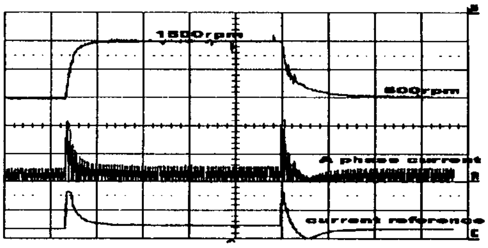

Fig 17. Anti-windup PI with braking operation (1s/div, 10A/div)

Fig.18, 19, 20 shows the current waveform in case of positive torque and negative torque respectively.

Fig. 18 shows the flat-topped current waveform controlled by hysteresis control at positive torque. Fig.19, 20 shows the current waveform of negative torque at the low speed and high speed.

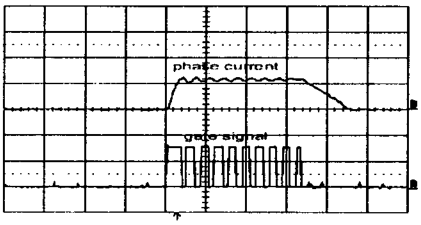

Fig 18. Phase current and gate signal waveform at positive-direction and positive-torque.

During the low speed driving shown as Fig 19(Fig.8), current is controlled by the hysteresis controller and then flat-topped current can be performed reducing current, but the peak of the tailing current can arise much during the high speed driving shown as Fig 20(Fig.7) because of the generated current. As a result, hard chopping is required at braking operation point to overcome this tailing current.

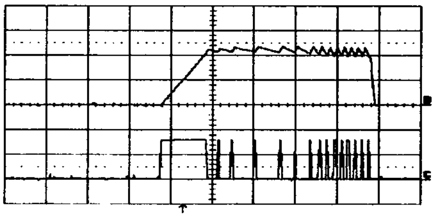

Fig 19. . Phase current and gate signal waveform in 500[rpm] in case of braking operation

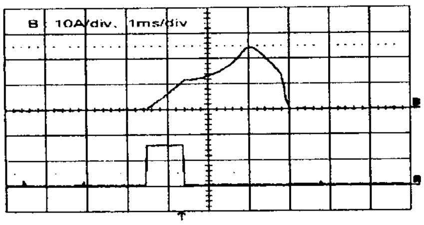

Fig 20. Phase current and gate signal waveform in 1500[rpm] in case of braking operation

Fig. 21 shows the waveform of speed response when SRM driving at 1500rpm is loaded by DC machine at 2000rpm. When load is applied, speed arises in a moment by DC motor(load) and then speed is responded by braking mode operation at 1500rpm of reference.

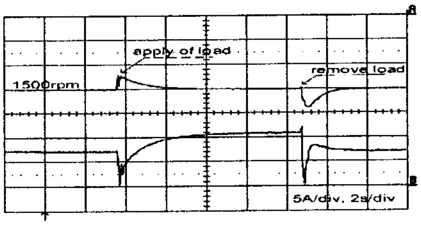

Fig 21. Speed waveform and current reference as load variation

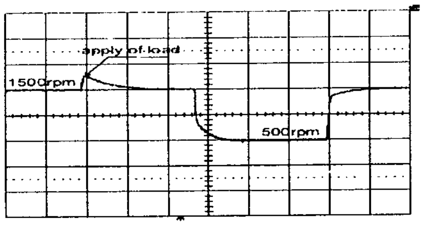

Fig 22. Variable speed waveform at the state of negative load

Fig. 22 shows the speed waveform at variable speed driving under the same condition of fig 21.

3. Conclusion

An anti-windup PI with braking operation for variable speed motor drives has been proposed, in order to overcome the windup phenomenon.

This paper describes the torque ripple reduction using hysteresis current control among of current control techniques.

The 80c196kc, low-cost one-chep microcontroller is used for designing SRM drive controller board which include the speed controller and the starting sequence.

The simulation and experimental results show that the anti-windup PI with braking operation has much improved performance, such as small overshoot and fast settling time.

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