Torque Control Strategy for High Performance SR Drive

Jin-Woo Ahn†

Abstract – This paper attempts to summarize torque control strategy for high performance SR drive. There are primarily two strategies for torque control. One method is direct torque control, which uses the simple control scheme and hysteresis controller to reduce the torque ripple. Another method is indirect torque control, which uses the complicated algorithms or simple distribution function to distribute each phase torque and obtain current command. The current controller is used to control phase torque by a given current command. In order to compare these two strategies of torque control, five torque control methods are introduced. The advantages and disadvantages of each method are presented. At last, they are verified by some simulations and experimental results.

Keywords: direct instantaneous torque control, switched reluctance motor, torque control

1. Introduction

The switched reluctance motor (SRM) is a simple low-cost and robust motor suitable for variable-speed and high speed drive applications [1]. But the magnetic saturation of SRM leads to a nonlinear characteristic that causes difficulty in implementing precise torque control. And the simple double saliency construction and the discrete nature of torque production by the independent phases result in high torque ripple compared with other machines.

The inherent high torque ripple is one of the demerits of SR drive, which restricts constant output torque and high dynamic response. In order to overcome inherent torque ripple, many advanced control methods have been proposed in recent years [3-13].

This paper attempts to summarize torque control strategy for the high performance SR drive. There are primarily two strategies of torque control: one method is direct torque control [3-5], which uses the simple control scheme and the torque hysteresis controller to reduce the torque ripple. Based on a simple algorithm, the short control period can be used to improve control precision. The direct instantaneous torque control (DITC) and advanced DITC (ADITC) are introduced in this method.

Another method is indirect torque control [6-13], which uses the complicated algorithms or distribution function to distribute each phase torque and obtain current command. And then, the current controller is used to control phase torque by a given current command. The linear, cosine, and non linear logical torque sharing function (TSF) are introduced.

Moreover, comparisons of these five torque control methods, as well as their advantages and disadvantages, are presented. At last, some simulations and experimental results are presented.

† Corresponding Author: Dept. of Electrical and Mechatronics Engineering, Kyungsung University (jwahn@ks.ac.kr)
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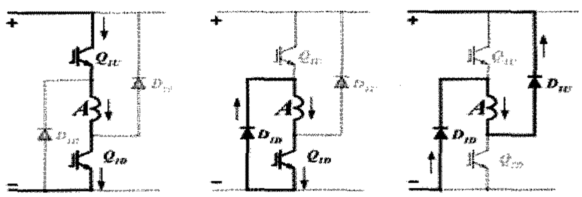
2. Direct Torque Control Method

2.1 Direct Instantaneous Torque Control

The asymmetric converter is very popular in the SRM drive system. The operating modes of the asymmetric converter are shown in Fig. 1. The asymmetric converter has three states, which are defined as state 1, state 0, and state -1 in the DITC method, respectively.



(a) state 1 (b) state 0 (c) state -1

Fig. 1. Operation modes of asymmetric converter

In order to reduce a torque ripple, the DITC method is introduced. By the given hysteresis control scheme, the appropriate torque of each phase can be produced, and constant total torque can be obtained. The phase inductance has been divided into 3 regions, as shown in Fig. 2.

The regions depend on the structure geometry and load. The boundaries of the 3 regions are θ_{on1}, θ_1, θ_2 and θ_{on2} in Fig. 2. θ_{on1} and θ_{on2} are turn-on angles in the incoming phase and the next incoming phase, respectively, which depend on load and operation speed. The θ_1 is a rotor position which is the initial overlap of stator and rotor.

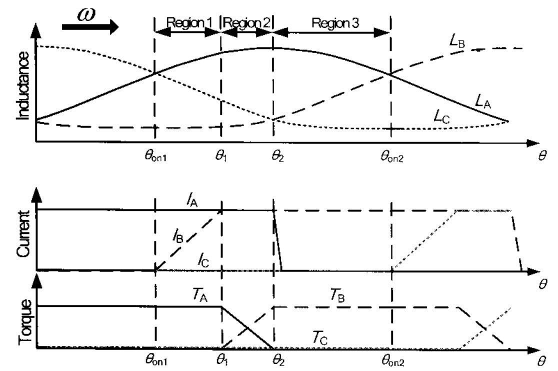
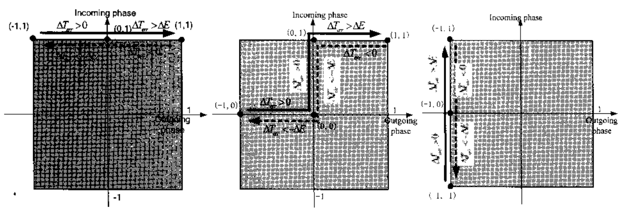


Fig. 2. Three regions of phase inductance in the DITC method

And θ_2 is the aligned position of inductance in the outgoing phase. Total length of these regions is 120 electrical degrees in 3 phases SRM. Here, outgoing phase is phase A and incoming phase is phase B in Fig. 2. When the first region 3 is over, outgoing phase will be replaced by phase B in the next 3 regions.

The DITC schemes of the asymmetric converter are shown in Fig. 3. The combinatorial states of outgoing and incoming phase are shown as a square mesh. The x and y axis denote the state of outgoing and incoming phase, respectively. Each phase has 3 states, so the square mesh has 9 combinatorial states. However, only the black points are used in the DITC scheme.



(a) region 1 (b) region 2 (c) region 3

Fig. 3. DITC scheme of asymmetric converter

The control diagram of the DITC SR motor drive is shown in Fig. 4. The torque estimation block is generally implemented by 3-D lookup table according to the phase currents and rotor position. And the digital torque hysteresis controller, which carries out the DITC scheme, generates the state signals for all activated machine phases according to torque error between the reference torque and estimated torque. The state signal is converted to switching signals by switching the table block to the control converter.

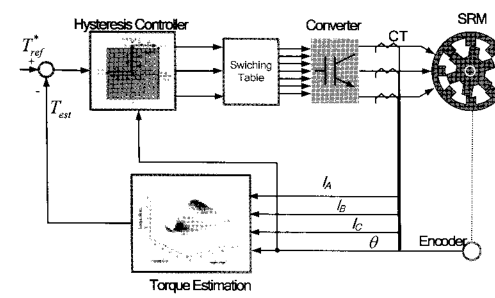


Fig. 4. DITC control diagram

Through estimation of instantaneous torque and a simple hysteresis control, the average of total torque can be kept in a bandwidth. And the major benefits of this control method are its high robustness and fast toque response. The switching of power switches can be reduced.

However, based on its typical hysteresis control strategy, switching frequency is not constant. At the same time, the instantaneous torque cannot be controlled within a given bandwidth of the hysteresis controller. The torque ripple is limited by the controller sampling time, so torque ripple will increase with increased speed.

2.2 Advanced Direct Instantaneous Torque Control

The conventional DITC method uses a simple hysteresis switch rule, so only one phase state is applied according to torque error at every sampling period. The torque variation with sampling time and speed under full dc-link voltage is shown in Fig. 5. There are two methods used in order to guarantee the torque ripple within a range. One method reduces sampling time, which will increase the cost of hardware. The other method controls the average voltage of phase winding in sampling time. The PWM method can be used.

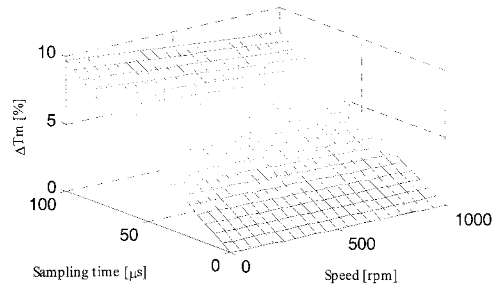
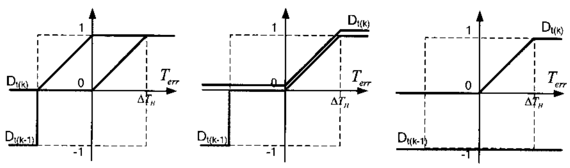


Fig. 5. Torque variation with sampling time and speed

ADITC combines the conventional DITC with the PWM method. The duty ratio of the phase switch is regulated according to the torque error and simple control rules of the DITC. Therefore, the sampling time of the control can be extended, which allows implementation on low cost microcontrollers.

ADITC is improved from the conventional DITC, so the divided region of phase inductance is similar to the DITC method. The control scheme of ADITC is shown in Fig. 6, *Dt(k)* means incoming phase, *Dt(k-1)* means outgoing phase. The x-axis denotes torque error, and the y-axis denotes switching state of *Dt(k)* and *Dt(k-1)*.

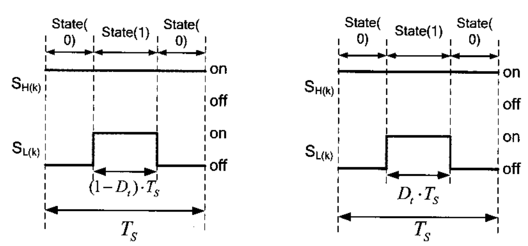
Profit from the effect of PWM, the average voltage of phase winding, can be adjusted from 0 to V_{dc} in one sampling time. And the hysteresis rule is removed from



(a) Region 1 (b) Region 2 (c) Region 3

Fig. 6. ADITC scheme of asymmetric converter

the control scheme. Now, the current state can select the phase state between state 0 and 1 by duty ratio of the PWM.



(a) incoming phase (b) outgoing phase

Fig. 7. Switching modes of incoming and outgoing phase

The duty ratio of switching modes is decided by the torque error as shown in Fig. 7, and D_t is expressed as follows:

$$D_t = Abs(T_{err}) / \Delta T_H \tag{1}$$

Where, T_{err} is torque error and ΔT_H is torque error bandwidth.

The control block diagram of ADITC is similar to Fig. 8. The hysteresis controller is replaced by the Advanced DITC controller, and the PWM generator is added.

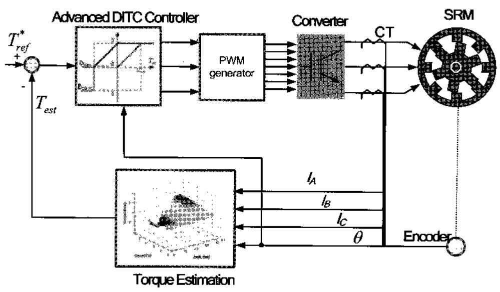


Fig. 8. Control diagram of ADITC

The ADITC method can adjust the average phase voltage to control a variety of phase currents in one sampling time, which can extend the sampling time and obtain smaller torque ripple than the conventional DITC. However, the PWM generator is added, and the switching frequency of the ADITC is double that of DITC's with uniform sampling time in the worst case. So the switching loss and EMC noise are increased in the ADITC method.

3. Indirect Torque Control Method

3.1 Traditional Torque Sharing Function Control

Besides the direct torque control method, another method is indirect torque control. TSF is a simple but powerful and popular method. It is simply divided by a torque sharing curve that is used for constant torque generation. And the phase torque can be assigned to each phase current to control torque smoothness. But phase torque has the relationship of square current. As such, the current ripple should be kept small enough to generate torque smoothness. Therefore, the frequency of the current controller should be increased.

Fig. 9 shows the traditional torque control block diagram with the TSF method. The input torque reference is divided into each phase torque command according to rotor position. Torque references of each phase are calculated to current command signal in the "Torque-to-Current" block according to rotor position. Since the output torque is determined by the inductance slope and phase current, and the inductance slope is changed by rotor position, the reference currents of each phase are determined by the target torque and rotor position. The switching rule generates an active switching signal of the asymmetric converter according to current error and hysteresis switching tables.

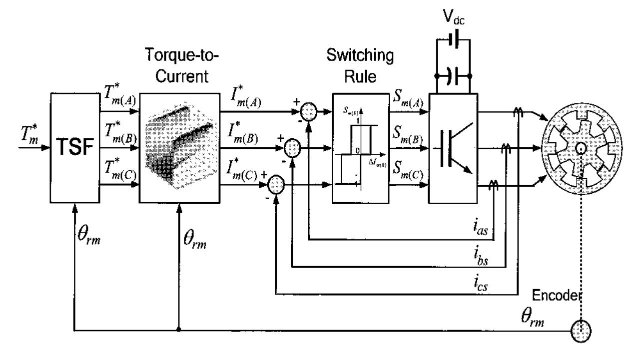


Fig. 9. The traditional torque control block diagram with TSF method

The overlapped region of operation is very important to torque control of the SR motor. Therefore, some proposals have been put forth to distribute each torque phase for constant torque generation in a commutation region. The traditional torque sharing control consists of two types, linear sharing function and cosine sharing function.

Fig. 10 gives the inductance profiles of the three-phase SR Motor having traditional TSF curves. As shown in Fig. 10, Region 2 denotes the one phase activation area. Region 1 and Region 3 each have a two phase activation area explained as the commutation region. In the one phase activation region, TSF is constant in each of the torque sharing functions. But it is different in commutation regions.

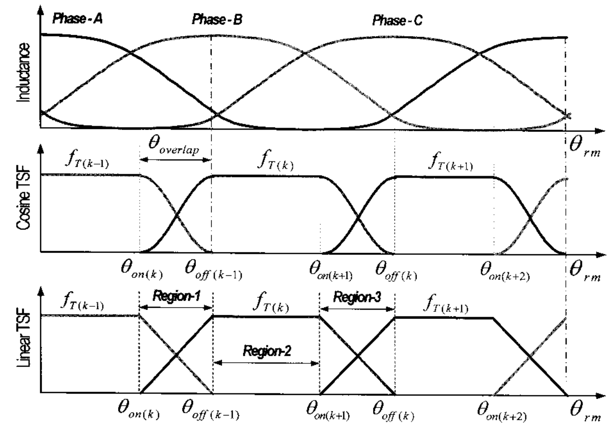


Fig. 10. Phase inductances, conventional cosine, and linear TSF curves

In the linear TSF method, the TSF of each phase can be obtained as follows.

$$f_{T(k)} = \frac{\theta_{rm} - \theta_{on(k)}}{\theta_{overlap}} \tag{2}$$

$$f_{T(k-1)} = 1 - f_{T(k)} \tag{3}$$

$$f_{T(k+1)} = 0 \tag{4}$$

Although it is very simple, it cannot consider nonlinear phenomena of the SR Motor. Therefore, torque ripple is very serious according to rotor speed.

In the cosine TSF, the TSF of each phase in the commutation region is defined as follows:

$$f_{T(k)} = \frac{1}{2}\left[1 - \cos\left(\frac{\theta_{rm} - \theta_{on(k)}}{\theta_{overlap}}\pi\right)\right] \tag{5}$$

$$f_{T(k-1)} = 1 - f_{T(k)} \tag{6}$$

$$f_{T(k+1)} = 0 \tag{7}$$

The cosine function is relatively simple and it is similar to the non-linear torque characteristics. However, the non-linear characteristic of SRM is very complex, and as such, a simple cosine torque function cannot be satisfied in the aspect of torque ripple and efficiency.

3.2 Non-linear Logical Torque Sharing Function

Compared with traditional TSF, the non-linear logical TSF offers greater advantage. In the commutation region, only one phase torque under commutation is controlled to produce a constant total torque, and the other phase torque is remained as the previous state under the current limit of the motor and drive. If the minimum changing of a phase torque reference cannot satisfy the total reference torque, the two-phase changing mode is used.

In order to improve torque ripple, the lagging of sampling time is considered. A prediction of estimated position for the next sampling time is implemented by estimated position block. So the phase torque and the phase current commands are predicted by position of the next sampling time to reduce the torque ripple. The proposed control block is shown in Fig. 11.

$$\hat{\theta}_{rm} = \theta_{rm} + \omega_{rm} \cdot T_S \tag{8}$$

The actual torque can be obtained by inductance slope and phase current. So the torque equation can be derived as follows.

$$T_m^* = T_{m(k)}^* + T_{m(k+1)}^* \tag{9}$$

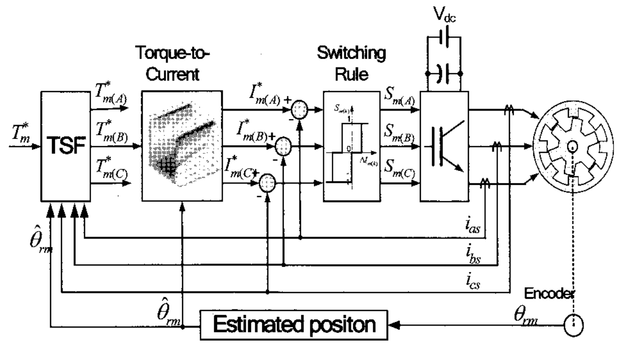


Fig. 11. The proposed torque control block diagram with TSF method

$$T_m^* = \frac{I_{m(k)}^{*\,2}}{a^2} + \frac{I_{m(k+1)}^{*\,2}}{b^2} \tag{10}$$

where, $a = \sqrt{\dfrac{2}{\partial L_{(k)}/\partial \theta_{rm}}}$, $b = \sqrt{\dfrac{2}{\partial L_{(k+1)}/\partial \theta_{rm}}}$

This equation is similar to an ellipse equation. The semi-major and semi-minor axes have the relation of torque reference and inductance slope. The current of outgoing phase and incoming phase are placed on the ellipse trajectory in the commutation region.

In order to reduce the torque ripple and increase drive efficiency, a minimum changing method is applied in the non-linear TSF. The current reference of the outgoing or incoming phase is fixed, and another phase current reference is controlled to generate a suitable torque and maintain constant torque in the commutation region.

There are two cases to consider when comparing the actual torque and torque reference: a). When $T_m \leq T_m^*$, the outgoing phase current is fixed, and the incoming phase current is increased to satisfy the reference torque. If the incoming phase current is limited by the current limit, the auxiliary torque is generated by the outgoing phase current.

b). When $T_m > T_m^*$, the incoming phase current is fixed, and the outgoing phase current is decreased to reach the constant torque. If the outgoing phase current reaches zero, and the actual torque is over the reference value, the incoming phase current is decreased to satisfy the reference torque. Table 1 shows the non-linear logical TSF in the commutation.

Due to the minimum changing state of the phase, the switching number of active phases can be reduced, and the drive efficiency can be improved. When the state of another phase is kept, the torque ripple is only controlled by one phase. Compared with traditional TSF, the outgoing phase has fast demagnetization to reduce negative torque when the incoming phase can satisfy to generate the torque.

Table 1. The non-linear logical TSF in the commutation region.

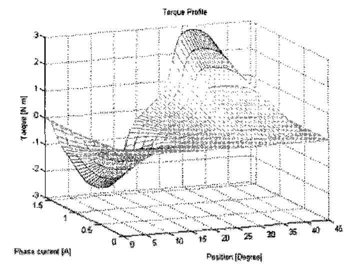
Conditions	Step	References of incoming and outgoing phase
$T_m \le T_m^*$	First	$T^*_{m(k+1)} = \begin{cases} T^*_m - T_{m(k)} & (if\ \ I^*_{m(k+1)} < I_{\max}) \\ T_{m(k+1)} & (if\ \ I^*_{m(k+1)} > I_{\max}) \end{cases}$
	Second	$T^*_{m(k)} = T^*_m - T_{m(k+1)}$
$T_m > T_m^*$	First	$T^*_{m(k)} = \begin{cases} T^*_m - T_{m(k+1)} & (if\ \ I^*_{m(k)} > 0) \\ 0 & (if\ \ I^*_{m(k)} < 0) \end{cases}$
	Second	$T^*_{m(k+1)} = \begin{cases} T_{m(k+1)} & (if\ \ I^*_{m(k)} > 0) \\ T^*_m - T_{m(k)} & (if\ \ I^*_{m(k)} < 0) \end{cases}$

Because of estimated torque feedback, this method can be suitable to divide the phase torques, and the minimum changing state of the phase can improve the efficiency of the SR drive. However, because two tables are required for torque and current profile, a large memory is used to store the profile data.

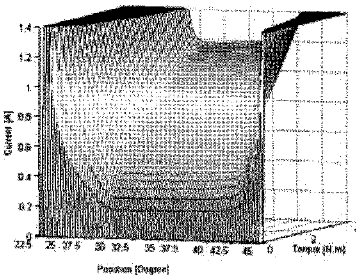
4. Simulation Results

In order to compare torque control methods, computer simulations are executed. Matlab and simulink are used for simulation. The static torque characteristic of prototype SRM are analyzed from FEA described in Fig. 12. There are used in the simulation and the experiment.

Fig. 13 shows the simulation comparison results at 500 [*rpm*] with direct torque control. The simulation results show the total reference torque, actual total torque, reference phase torque, actual phase torque, actual phase current and phase voltage, respectively.

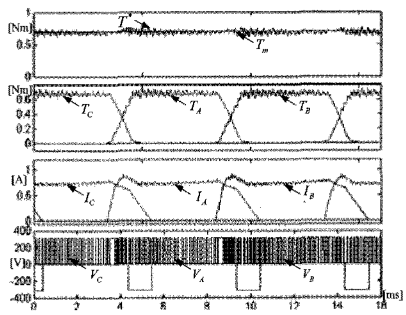


(a) Current-position-torque profile

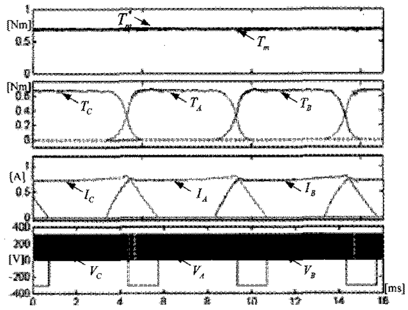


(b) Torque-position-current profile

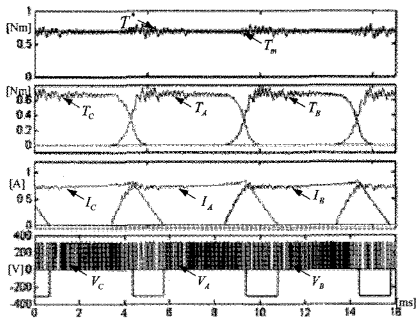
Fig. 12. Profile of the prototype SR motor



(a) Conventional DITC (sampling time 25[μs])



(b) ADITC (sampling time 25[μs])

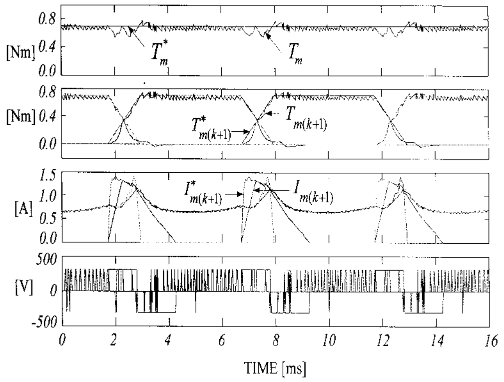


(c) ADITC (sampling time 75[μs])

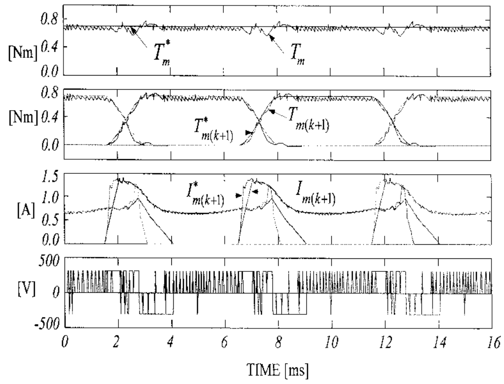
Fig. 13. Simulation results at 500rpm with direct torque control

Compared with the DITC method, the torque ripple of ADITC is smaller when the sampling time is the same. From Fig. 13(b), the phase torque and the phase current are smooth, but the switching frequency is very high, being produced by the PWM module. The sampling time 75[μs] is used in the ADITC as shown in Fig. 13(c). Although the sampling time is increased, the torque ripple is similar to DITC at 25[μs].

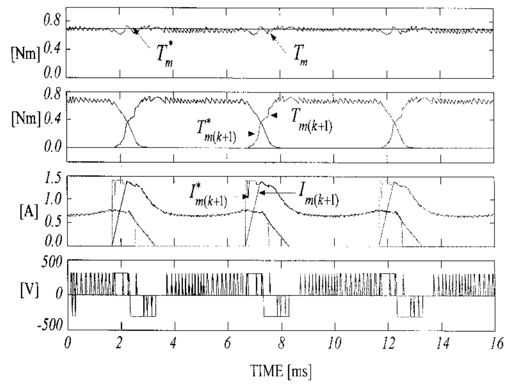
Fig. 14 shows the simulation comparison results at 500 [*rpm*] with indirect torque control. Smooth torque is generated by the TSF method. In order to follow the reference phase current, the state -1 is used to reduce the instantaneous current and torque ripple.



(a) Linear TSF



(b) Cosine TSF



(c) Non-linear logical TSF

Fig. 14. Simulation results at 500rpm with indirect torque control

5. Experimental Results

Fig. 15 shows the experimental setup. The main controller is designed by TMS320F2812 from TI (Texas Instruments) and phase current and voltage signals are feedback to 12bit ADC embedded by DSP.

Fig. 16 shows the experimental results of direct torque

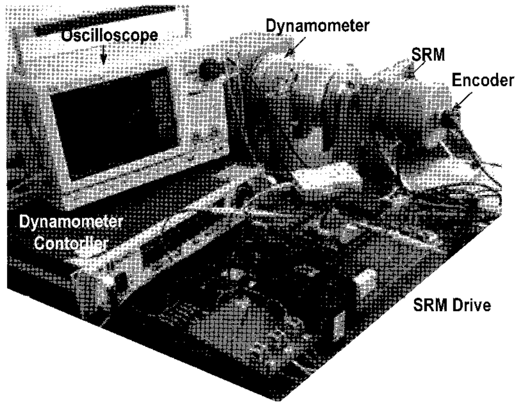
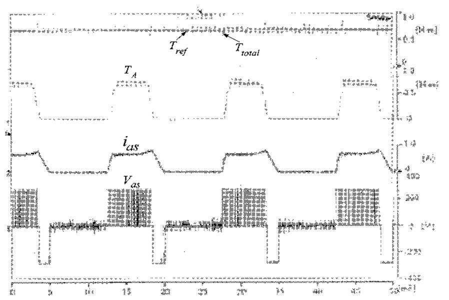
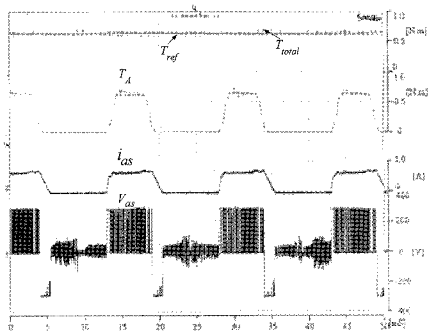


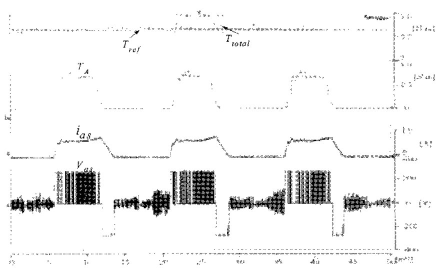
Fig. 15. The experimental configurations



(a) Conventional DITC (sampling time 25[µs])



(b) ADITC (sampling time 25[μs])

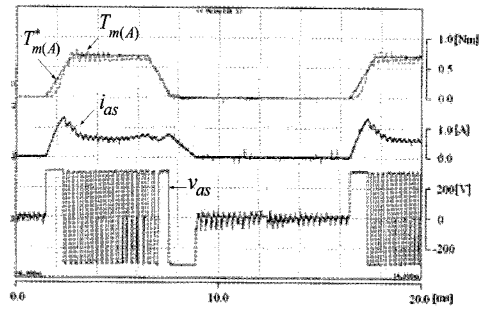


(c) ADITC (sampling time 75[μs])

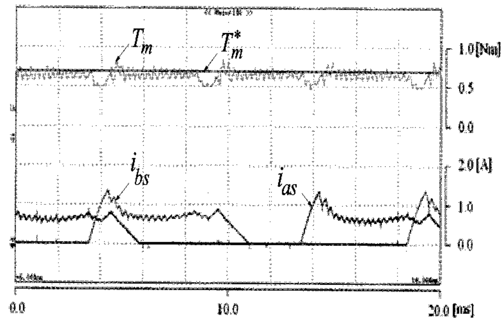
Fig. 16. Experimental results at 500rpm with direct torque control

control. The torque ripple of ADITC is smaller than DITC using uniform sampling time. But the higher switching frequency can be shown in voltage waveform.

Fig. 17, Fig. 18, and Fig 19 show the experimental results in case of linear TSF, cosine TSF, and non-linear logical TSF at 500[*rpm*], respectively. Torque ripple can be reduced in case of the indirect torque control method. The non-linear logical TSF is the best in the three TSF methods.

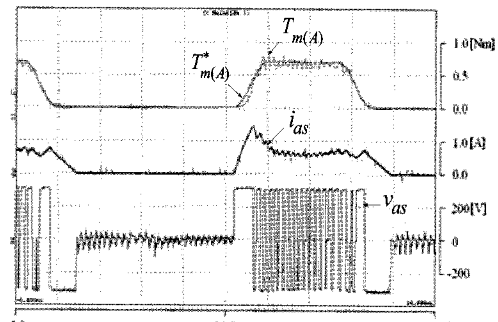


(a) Reference, actual torque, phase current, and voltage

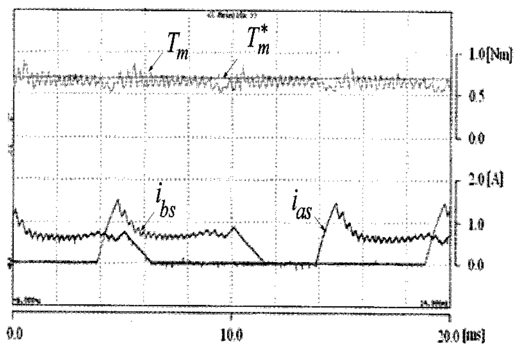


(b) Total reference torque, actual torque, and phase currents

Fig. 17. Experimental results of linear TSF (at 500[*rpm*])

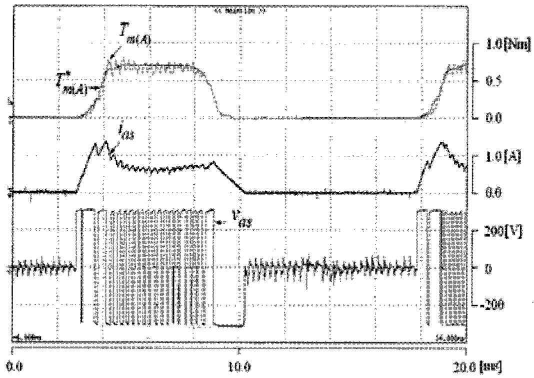


(a) Reference, actual torque, phase current, and voltage

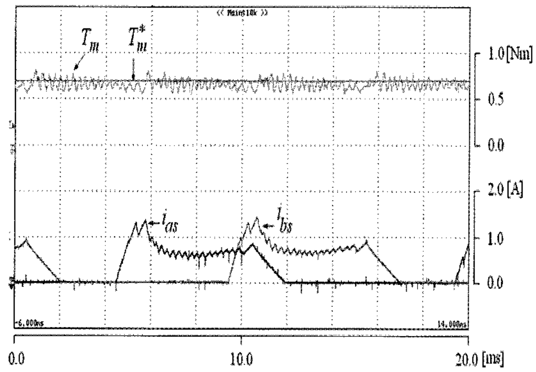


(b) Total reference torque, actual torque, and phase currents

Fig. 18. Experimental results of cosine TSF (at 500[*rpm*])



(a) Reference, actual torque, phase current, and voltage



(b) Total reference torque, actual torque, and phase currents

Fig. 19. Experimental results of the non-linear logical TSF (at 500[*rpm*])

6. Conclusions

In this paper, two torque control strategies of the SR drive are summarized. As regards direct torque control, DITC and ADITC are introduced. The advantage of direct torque control is simple, with the achievement of high performance. The feedback instantaneous torque and hysteresis controller allows high robustness and fast torque response in the SR drive. Although the performance of the DITC method depends too greatly on sampling time, ADITC can apply the PWM module to adjust the average phase voltage in one sampling time, which causes smaller torque ripple than DITC, and the sampling time can be extended.

For indirect torque control, linear TSF, cosine TSF, and non-linear logical TSF are introduced. Torque-position-current profile is used to create the indirect torque control loop. The torque sharing function and current controller determine the performance of this method. Based on the basic operation theory of the SR motor, phase torque has the relationship of square current. So the current ripple should be kept small enough to generate smooth torque. The simple linear TSF and cosine TSF cannot satisfy the non-linear torque characteristic. However, the non-linear logical TSF utilizes the feedback torque to create a more suitable sharing torque. Furthermore, minimum changing of phase torque causes the SR drive to have greater efficiency.

Acknowledgements

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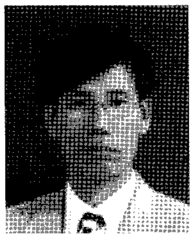

Jin-Woo Ahn

He was born in Busan, Korea, in 1958. He received his B.S., M.S., and Ph.D. degrees in Electrical Engineering from Pusan National University, Pusan, Korea, in 1984, 1986, and 1992, respectively.
He has been with Kyungsung University, Busan, Korea, as a Professor in the Department of Electrical and Mechatronics Engineering since 1992. He was a Visiting Researcher in the Dept. of ECE and Speed Lab, Glasgow University, U.K., and a Visiting Professor in the Dept. of ECE and WEMPEC, UW-Madison, USA. He has been visiting in the Dept. of ECE, Virginia Tech, since July 2006. He has also been Director of the Advanced Electric Machinery and Power Electronics Center since 2005. He is the author of five books including SRM, the author of more than 100 papers, and has several patents. His current research interests are advanced motor drive systems and electric vehicle drives.
Dr. Ahn received several paper awards including the Best Paper Award from the Korean Institute of Electrical Engineers and The Korean Federation of Science and Technology Society in 2003, respectively. He is a Senior Member of the Korean Institute of Electrical Engineers, a Member of the Korean Institute of Power Electronics, and a Senior Member of IEEE.