Application of SR Drive for Locomotive Traction

Jin-Woo Ahn, Dong-Hee Lee, Chen Hao, Sang-Hun Lee*, and Heon-Ho Lim*

Kyungsung University, KT Electric*

ABSTRACT

The developed locomotive in coal mine drawn by the parallel drive system of the double Switched Reluctance motors is introduced. The operational principles, the control pattern and the component parts of the traction and the regenerative braking operation are proposed. The drive system contributes to reduce the cost of utilization of the locomotive per ton kilometer.

1. Introduction

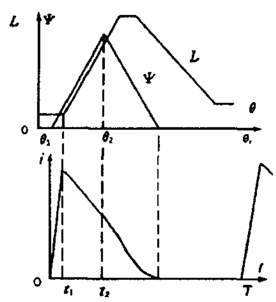
The Switched Reluctance motor drive has been developed for many years[1]. The control theory and the systematical design method of the drive have been researched in some literatures[2-4].

The mechanical properties of the Switched Reluctance motor drive with the rotor speed open-loop control are soft[5], so that the drive could be used as the locomotive traction in coal mine. The Switched Reluctance motor drive could be operated in four quadrants so that the regenerative braking operation of the locomotive could be implemented. The soft mechanical properties of the drive contribute to paralleling the double Switched Reluctance motors drive with balanced distribution of loads. Instead of the locomotive drawn by one motor, the locomotive drawn by paralleling double motors has the high reliability. If there are some trouble in one motor, the parallel drive system could be operated continuously at the condition of reducing the tractive power by removed the broken motor. The parallel drive system of the double Switched Reluctance motors has the advantages in arranging the space of placing the motors rationally and improving the tractive properties of the drive with composition of the properties of the two motors.

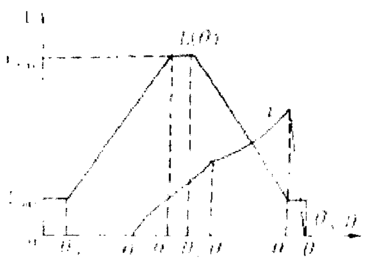
This paper introduces the locomotive developed for a coal mine drawn by the parallel drive system of the double Switched Reluctance motors.

2. Operational Principles

If the resistance of the phase windings is neglected, the magnetic circuit of the Switched Reluctance motor is unsaturated, and the leakage flux is neglected, the phase inductance, $L(\theta)$, the flux linkage, ψ, and the phase current, i , of the Switched Reluctance motor drive at the operational state of traction, are is shown in Fig.1(a).



(a) The operational state of traction



(b) The operational state of braking

Fig. 1 Analysis of the phase inductance and the phase current

The phase inductance, $L(\theta)$, and the phase current, i , of the Switched Reluctance motor drive at the operational state of braking, are is shown in Fig.1(b).

While the phase current is at the ascending region of the phase inductance ($\partial L/\partial \theta > 0$), the direction of electromagnetic torque is the same as the rotational direction of the rotor, the property of the torque is traction torque.

While the phase current is at the descending region of the phase inductance ($\partial L/\partial \theta < 0$), the direction of electromagnetic torque is in the opposite direction of the rotational direction of the rotor, the property of the torque is braking torque. While the phase current is at the rotor position that the axis of the rotor pole is aligned with the axis of the stator pole, or at the rotor position that the axis of the rotor slot is aligned with the axis of the stator pole, the electromagnetic torque is zero because $\partial L/\partial \theta$ is zero. While the motor is operated at I-quadrant and at III-quadrant, the greater part of the phase current is at the ascending region of the phase inductance. The direction of the average electromagnetic torque of the motor is the same as the rotational direction of the rotor, so that it is the operational state of traction. While the motor is operated at II-quadrant and at IV-quadrant, the greater part of the phase current is at the descending region of the phase inductance. The direction of the average electromagnetic torque of the motor is in the opposite direction of the rotational direction of the rotor, so that it is the operational state of braking.

The average electromagnetic torque, T_{av}, the average supplied voltage of the phase winding, U, and the rotor speed, n, have the relationship [6] as follows,

$$T_{av} = K_1 \frac{U^2}{n^2} \qquad (1)$$

Where, K_I is a coefficient that is related to the structure parameters of the motor, the turn-on angle and the turn-off angle of the main switches in the power converter. The greater part of the phase current could be at the ascending region of the phase inductance or at the descending region of the phase inductance by regulating the turn-on angle and the turn-off angle of the main switches in the power converter, so that the operational state of the motor could be changed as traction ($K_I>0$) or braking ($K_I<0$) .

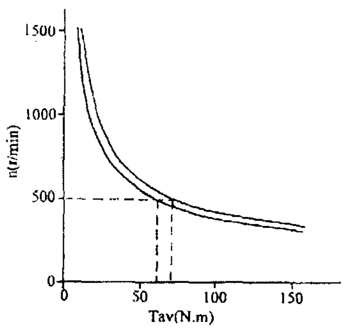
The main switches of the power converter are turned on at θ_{1K} (turn-on angle), and turned off at θ_{2K}(turn-off angle), (K= *I, II, III, IV*). At the operational state of traction, the triggering signals of the main switches at I-quadrant θ_{1I} θ_{2I} are advanced as follows,

$$\theta_{f1} = \theta_{1I} + \theta_{2I} \qquad (2)$$

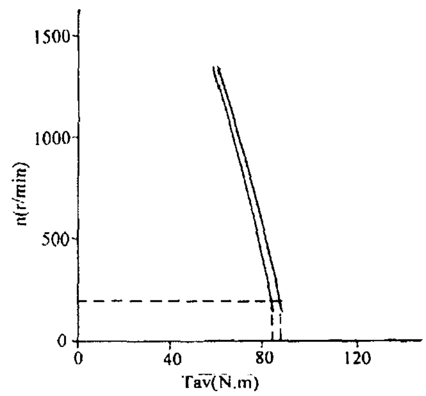
and those could be used as the triggering signals of the main switches at III-quadrant (θ_{1III}, θ_{2III}) , so that the symmetrical traction at I-quadrant and III-quadrant could be implemented. At the state of regenerative braking, the triggering signals of the main switches at II-quadrant (θ_{1II}, θ_{2II}) are advanced as follows,

$$\theta_{f2} = \theta_{1II} + \theta_{2II} \qquad (3)$$

and those could be used as the triggering signals of the main switches at IV-quadrant θ_{1IV} θ_{2IV} , so that the symmetrical regenerative braking control at II-quadrant and IV-quadrant could be implemented. The fixed angle PWM control strategy is adopted for the adjustable speed control and the regenerative braking control of the drive.



(a) The fixed angle PWM control strategy



(b) The phase current chopping control strategy

Fig. 2 Mechanical properties of the two same output volume motors

In the control strategy, the turn-on angle and the turn-off angle of the main switches in the power converter are fixed, the triggering signals of the main switches are modulated by the PWM signal. The phase winding average voltage, U , could be adjusted by regulating the duty ratio of the PWM signal. So the output torque and the rotor speed of the motor are adjustable at the operational state of traction, and the braking torque are adjustable at the operational state of regenerative braking, by regulating the phase winding average voltage. It is important for the parallel drive system with two motors to balance the distribution of the loads at the operational state of traction. There is the difference in the mechanical properties of the two motors because of the difference in the manufacture of the two motors. The mechanical properties of the two same output volume motors adopted the fixed angle PWM control strategy or the phase current chopping control strategy are shown in Fig. 2. Based on Fig. 2, the mechanical properties of the two motors are soft at the high rotor speed range with the fixed angle PWM control strategy so that the difference in the average electromagnetic torque of the two motors at the same rotor speeds is small.

3. Component Parts of the System

The developed five Ton locomotive in coal mine is drawn by the parallel drive system of the two 7.5KW Switched Reluctance motors. The motor is a kind of 3-phase 6/4 structure double-salient pole reluctance motor as shown in Fig. 3.

The two motors are applied to draw the front wheel and the rear wheel of the locomotive by the two gear boxes, respectively, which are installed on the chassis of the locomotive There is also the rotor position detector installed on the motor, respectively.

The power supply source is a group of storage battery shown in Fig. 4, which is installed in the power sources box carried on the locomotive. The rated supplied voltage is 88Vdc, and the rated capacity is 330Ah. The power converter consists of the power electronic switching components that convert the DC supply to pulse supply unidirectionally and energizes the motors.

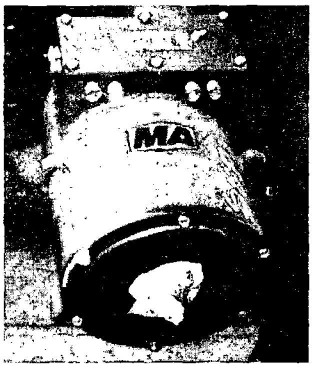


Fig. 3 Photograph of the motor

The two 3-phase asymmetric bridge power converters in parallel are used in the drive system. The power converter and the controller are together installed in the control box fixed in the driver's cab. The Intel 80C196KB single chip computer is adopted as the core of the controller.

Fig. 4 The power supply source

The rotor position detector installed on the no shaft extension consists of three photoelectric transducers and a slotted disk. The three photoelectric transducers are fixed on the endshield of the motor with 30^0 interval. The slotted disk has four teeth with 45^0 width per tooth and four slots with 45^0 width per slot, which is fixed on the shaft. While the rotor of the motor is rotated, the three photoelectric transducers could provide the square wave signals, P, Q and R, with 300 interval, which represent the information of the rotor position. P, Q and R signals could be used as the basic triggering signals of the main switches of A, B and C phase, respectively. By regulating the rotor position detector, the turn-on angle of the main switches in the power converter is fixed at -5.0^0 (θ $=0^0$is defined as the rotor position while the axis the rotor slot is aligned with that of the stator pole of the conducted phase), while the motor is operated at I-quadrant. The distribution of the basic triggering signals of the main switches at four quadrants is shown in Table 1. The Switched Reluctance motor drive system could be operated conveniently at four quadrants with traction at I-quadrant and at III-quadrant symmetrically, with regenerative braking at II-quadrant and at IV-quadrant symmetrically, based on Table 1. In the controller, the over current protection and the under voltage protection could be implemented.

Table 1 Distribution of the basic triggering signals of the main switches

Quadrant	θ_{1k}	θ_{2k}	A phase	B phase	C phase
I	-5.0^0	35.0^0	P	Q	R
II	25.0^0	65.0^0	Q	R	P
III	-5.0^0	35.0^0	R	P	Q
IV	25.0^0	65.0^0	Q	R	P

4. Operational Test

The locomotive developed for coal mine drawn by the parallel drive system of the double Switched Reluctance motors was tested. The tractive effort of the locomotive at the scale of hour is 7.1 kilo Newton, and the tractive effort at the scale of long-time is 5.0 kilo Newton. The velocity of the locomotive at the scale of hour is 7.0 kilometers per hour, and the maximum velocity of the locomotive is 10.0 kilometers per hour. The maximum braking distance is 14.0 meter. The developed locomotive with the loads is shown in Fig. 5. The tested maximum difference in the output torque of the two motors at the same rotor speeds is within *10%.*

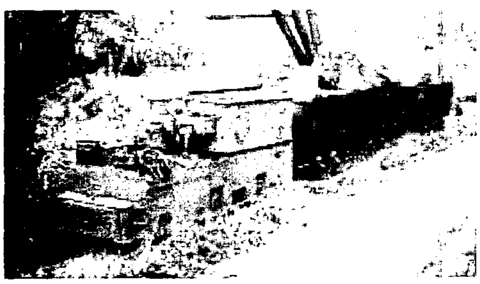


Fig. 5 Photograph of the developed locomotive

5. Conclusions

The 5-ton locomotive developed for a coal mine drawn by the parallel drive system of the double Switched Reluctance motors has been designed and parallel drive system has the high reliability. The regenerative braking operation of the locomotive could be implemented easily by the Switched Reluctance motor drive so that electric energy could be saved. All those contribute to reduce the cost of utilization the locomotive per ton kilometer. The parallel drive system of the double Switched Reluctance motors is suitable to draw other electric vehicles.

ACKNOWLEDGMENTS

This work was supported by a grant No. R01-2001-000300-0 from Korea Science and Engineering Foundation.

References

[1] P. J. Lawrenson, J. M. Stephenson and P. T. Blenkinsop et al, Variable-speed Switched Reluctance Motors, IEE Proc. B, vol. 127, no. 1, 1980, pp. 253-265.

[2] G. S. Buja, R. Menis, M. I. Valla, Variable Structure Control of An SRM Drive., IEEE Transactions on Industrial Electronics, vol. 40, no. 1, 1993, pp. 56-63.

[3] H. Chen and G. Xie, A Novel Fixed Angle Control Strategy for Three-phase Switched Reluctance Motor Drive, Proceedings of the 8th International Power Electronics & Motion Control Conference, 1998. vol. 3, pp. 68-71.

[4] H. Chen and G. Xie, A Systematic Design Method for Switched Reluctance Motor Drive, Proceedings of the 8th International Power Electronics & Motion Control Conference, 1998, vol. 3, pp. 72-74.

[5] H. Chen and G. Xie, Open-Loop Speed Control for Switched Reluctance Motor Drive, Proceedings of the 3rd Asia-Pacific Conference on Control & Measurement, 1998, pp. 287-290.

[6] H. Chen and G. Xie, The Hardware Controller of Switched Reluctance Motor Drive, in Proceedings of 3rd International Symposium on Advanced Electromechanical Motion Systems, 1999, vol. I, pp. 561-566.