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FLOW RATE CONTROL IN CLOSED HYDRAULIC CIRCUIT BY ADDITION OF SERVO FUNCTION TO SR MOTOR DRIVING HYDRAULIC PUMP

Tomoya NAKAMURA*, Yasukazu SATO**

* Department of Mechanical Engineering, Graduate School of Engineering
Yokohama National University
** Department of Mechanical Engineering, Faculty of Engineering
Yokohama National University
79-5 Tokiwadai Hodgayaku, Yokohama, Kanagawa, 240-8501 Japan
(E-mail: sato-yasukazu-zm@ynu.ac.jp)

Abstract. A switched reluctance motor (SRM) outputs the reluctance torque without the power of permanent magnet. It is one of the candidates to be a rare-earth free motor. However, it is generally inferior to a permanent magnet synchronous motor in the point of controllability, torque ripple, and noise. On contrary, a SRM has advantages of the use in high temperature environment with its robust structure. In recent power-saving hydraulic system, in which the flow rate is controlled by rotational speed of a hydraulic pump driven by a permanent magnet synchronous servo motor, has been conducted for the closed hydraulic circuit. In this study, the controllability of SRM has been improved compared to a permanent magnet synchronous servo motor. Furthermore, hydraulic power control using rotational speed control of a hydraulic pump driven by the SR servomotor has been carried out.

Keywords: Pump, Actuator, Switched reluctance motor, Servomotor, Closed hydraulic circuit

INTRODUCTION

Flow rate control by rotational speed control of a hydraulic pump not using any control valves is one of the solution to improve the power transmission efficiency in fluid power system. By removing control valves, which act as a flow resistance and generate some leakages, a valveless control system utilizing a hydraulic pump driven by a high performance electric servomotor provides high power transmission efficiency without pressure drop and leakage power loss, as shown in Fig. 1.

Usually, a permanent magnet synchronous motor (PMSM) is used to drive the hydraulic pump in the closed hydraulic circuit as a high performance electric servomotor. However, A PMSM is expensive and has problems resulting from permanent magnets such as a lack of properties resisting to heat and vibration, and much rare-earth use, etc.

For solving the problems, a servomotor function is added to a conventional switched reluctance motor (SRM) control. A SRM shown in Fig. 2 is robust and uses no permanent magnet and rare-earth in its drive principle. Generally, a SRM is used in drive system requiring high torque output in wide speed range, one directional rotation, and rough speed control. This paper presents a driving method of the SRM as a bi-directional rotation torque and speed controllable servomotor. Furthermore, its performance is evaluated by flow rate control of hydraulic pump driven by the SR servomotor in a closed hydraulic circuit.

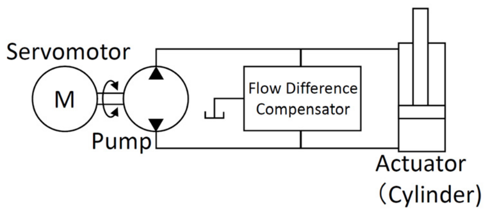

FIGURE 1. Valveless control system for hydraulic actuator drive (Closed circuit)

BI-DIRECTIONAL ROTATION CONTROL OF SR SERVOMOTOR FOR HYDRAULIC PUMP DRIVE IN CLOSED CIRCUIT

The SRM has a salient pole structure for both the rotor and the stator, and the windings are wound only on the stator as shown in Fig. 2. The sets of opposing poles of the stator are called phase A, phase B, phase C, phase D, respectively. The stator windings that generate the magnetic flux penetrating the airgap between the rotor and stator are wound in series in each phase and four phases are connected in parallel. In this study, 8-6 type structure that the number of phases is 4-phases, 6-teeth rotor and 8-teeth stator is used. In the SRM, when the winding is excited, a force attracting the salient poles of the rotor and the stator is generated, thereby producing a reluctance torque. Fig. 3 shows inductance distribution due to rotor angular position.

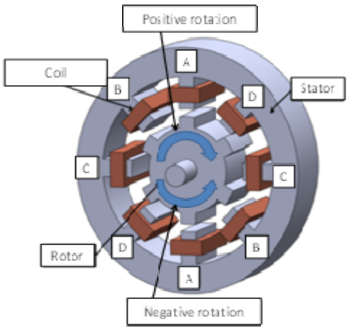

FIGURE 2. 8-6 type SRM structure

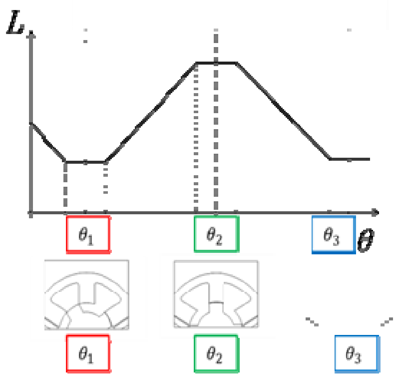

FIGURE 3. Conceptual self-inductance distribution between aligned and unaligned position

Fig. 4 shows the operating range of a hydraulic pump driven by an electric servomotor. ① is a region where supplies hydraulic power to the hydraulic actuator by positive torque and forward rotation, and energizes the phase current in the region of $dL/d\theta$ positive in Fig. 3. ② is a region where braking is applied to the hydraulic actuator with negative torque and forward rotation. At the time of transition to the region of $dL/d\theta$ negative in Fig. 3, leave the magnetic flux and disconnect it from the power supply, generate negative torque by regeneration in power generation, and when the negative torque is insufficient, connect with the power supply and energize the phase current to increase the negative torque. ③ is the state in the reverse rotational direction of ①, ④ is the state in the reverse rotational direction of ②.
To realize the four quadrants drive in *N-T* coordinated plane in Fig. 4, the control method for SR servomotor should contain the following controls[1];

A) Firing order control (Rotational direction control)
The SRM rotates forward direction by the firing order of A-B-C-D-A, reverse direction by the order of A-D-C-B-A, in Fig. 2.

B) Torque amplitude control
The torque amplitude of a SRM is expressed by Eq. (1)[2].

$$T = \frac{1}{2} i^2 \frac{dL}{d\theta} \tag{1}$$

where, T, i, L, and θ are output torque of SRM, electric current of winding, inductance, and rotor teeth angular position of SRM, respectively. The amplitude of output torque is controlled by the current of winding in each phase. The magnitude of the phase current is controlled by PWM (Pulse Width Modulation) switching under constant voltage supply.

C) Torque direction control

The torque direction is determined by the rotor teeth position in firing. The region of $dL/d\theta$ positive - the range where L in Fig. 3 increases upward to the right - is called the motor region, and in case the firing in the region, the positive torque is generated, and the SRM accelerates. The region of $dL/d\theta$ negative - the range where L in Fig. 3 decreases downward to the right - is called the generator region, and the negative torque is also generated in the same manner in the region, and the SRM decelerates. Further, if magnetic flux remains at the time of transition to this region, an electromotive force that generates a magnetic field that hinders a decrease in magnetic flux due to a decrease in inductance is generated in the winding, and power generation - regeneration - that continues to flow a phase current without connection with the power supply is performed.

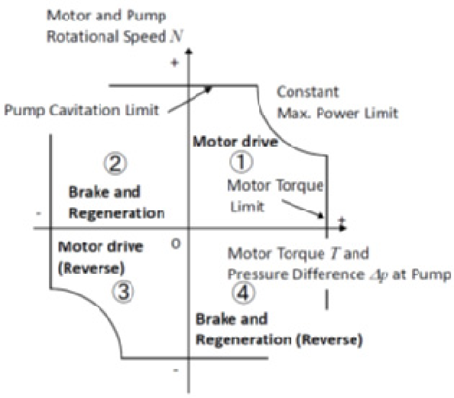

FIGURE 4. Operation range of hydraulic pump driven by servomotor

The angular position of the rotor is detected by a rotary encoder. The controller of the SRM determines an appropriate angle and angle range for generating a positive torque or a negative torque based on the command. As shown in Fig. 2, the datum of the angle of the rotor position was set to 0 ° when the rotor and the salient poles of the stator faced each other - allied position. Based on the previous study, in the motor region, when exciting on the plus side than the excitation range from -30 ° to -15 °, the current starts to be applied to the generator region and prevents rotation, so it was set to -30 ° to -15 °. In the generator region, since the braking force was the largest, it was set to 0 ° to 15 °.

SRM DRIVE SYSTEM

Fig. 5 and Fig. 6 show a schematic diagram of SRM controller. The magnitude of the phase current is determined by the PI control according to the difference in the response speed between the SRM and the command speed, and the direction of the torque is determined by the positive or negative of the difference between the command speed and the response speed and the positive or negative of the response speed itself. Further, it is determined by the command rotational direction and the response speed direction in the servo-drive control. Further, the control signal for switching the FET is sent from the DSP installed with the driving program of the SRM.

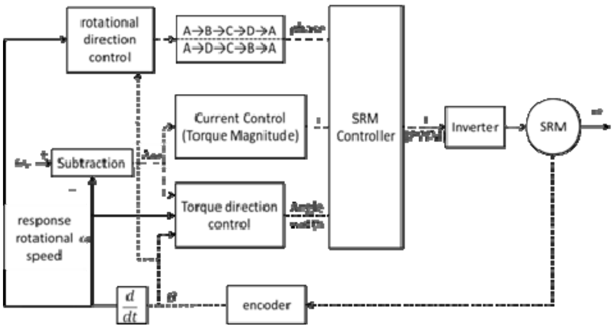

FIGURE 5. Bi-direction rotational speed control system of SRM

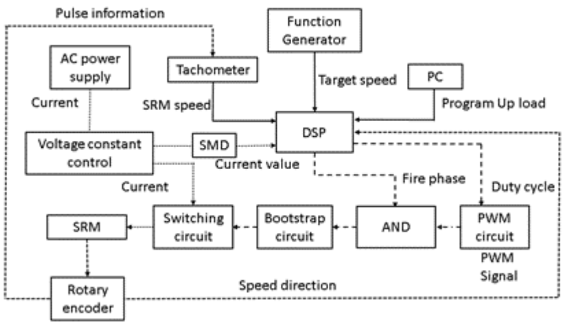

FIGURE 6. System flow of SRM drive system

FLOW RATE CONTROL OF HYDRAULIC PUMP DRIVEN BY SR SERVOMOTOR IN CLOSED CIRCUIT

Experimental Apparatus

Fig. 7 shows a schematic diagram of the experimental apparatus for flow rate control of the hydraulic pump driven by the SR servomotor in the closed circuit. In the experimental apparatus, a 4-phase 8-6 type SRM and a fixed displacement bi-direction rotation axial piston pump / motor are connected, and the SRM controls the flow rate and direction of the pump discharge flow rate of the closed hydraulic circuit by controlling the rotation speed and the rotational direction of the pump. A variable orifice is used for the load. However, the load is not an inertial load, and there is no hydraulic power input from the outside to the pump in this apparatus, so the regeneration region ② and ④ in Fig. 4 cannot be reproduced. Therefore, the hydraulic power of the drive region ① and ③ in Fig. 4 is controlled by the SRM rotational speed servo system.

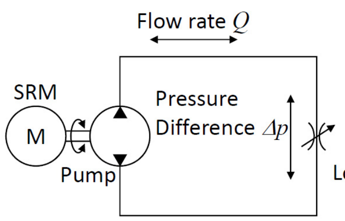

FIGURE 7. Testing hydraulic closed circuit for bi-directional flow rate control using hydraulic servo pump driven by SR servomotor

Flow Rate Control Experiment of Hydraulic Pump Driven by SR Servomotor in Closed Circuit

Table. 1 shows the specifications of the testing SRM and the testing hydraulic pump motor. The discharge flow rate of the pump was converted from the product of pump rotational speed and pump displacement volume since the pump is driven at a rotational speed of 2000 rpm or less at which the pump can be operated without cavitation. (Eq. (2)) Since the control flow rate is converted from the pump rotational speed or the speed of the hydraulic actuator to be driven without directly detecting by using the flow rate sensor even in the capacity control system of a general hydraulic closed circuit, also in this test, the discharge flow rate Q is converted from the pump rotation speed N and displacement D_m.

$$Q = D_m \times N \tag{2}$$

TABLE 1. Specifications of SRM and hydraulic pump / motor

Switched Reluctance Motor	
Topology	4-Phase 8-6 Switched Reluctance Motor
Rated Power	490W
Rated Rotational Speed	8000rpm
Input Voltage	24V
Hydraulic Pump / Motor	
Type	Axial Piston Pump / Motor
Displacement	1.6cm^3/rev
Max. Rotational Speed	2000rpm (Bi-direction)
Max. Pressure	16MPa

Fig. 8 shows the experimental result of the flow rate control of the hydraulic pump driven by the SR servomotor. Since the maximum rotational speed is 2000 rpm according to the specification of the testing pump, the pump drive was set to rotate in bi-directions sinusoidally with an amplitude of ± 1000 rpm to ensure self-suction performance of the pump and to prevent from cavitation.
As shown in Fig. 8, the pump flow rate follows the sinusoidal command flow rate corresponding to forward rotation and reverse rotation of the SRM, it was confirmed that the direction of flow was switched smoothly even in the vicinity where the rotational direction of the SRM is switched and the flow rate is 0.
In this experimental apparatus, the load is a variable orifice in the hydraulic closed circuit, however, if this is replaced with a hydraulic actuator such as a hydraulic cylinder, it can be considered that expansion and contraction of the cylinder, position control and speed control of the cylinder rod are possible.

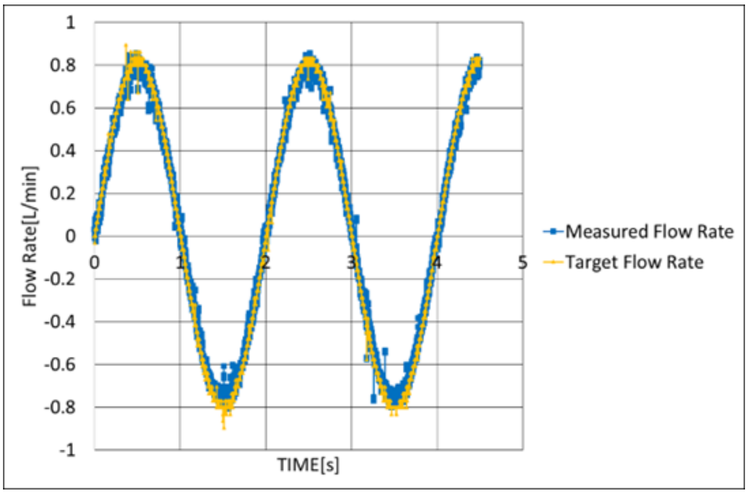

FIGURE 8. Sinusoidal bi-direction flow rate control of hydraulic pump driven by SR servomotor
（SRM speed -1000rpm ～ +1000rpm）

CONCLUSION

For solving the problem resulting from permanent magnets of motor in the hydraulic closed circuit capacity control system, which controls the rotational speed of the hydraulic pump by the permanent magnet synchronous servomotor, it was aimed to apply SRM of rare-earth free motor without using permanent magnet to drive hydraulic pump. This study proposed a motor control system that gives servo function to SRM, and presented closed circuit flow control performance of pump driven by SR servo motor.

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