Performance of SR Drive for Hydraulic Pump

Sang-Hun Lee*, Dong-Hee Lee, Young-Joo An*** and Jin-Woo Ahn†**

Abstract - This paper proposes a hydraulic pump system that uses a variable speed SR drive and constant capacity pump. For the design of the SRM (Switched Reluctance Motor) and digital controller, base speed and rating torque are determined from the mechanical specifications of the hydraulic pump. In order to minimize the power consumption during the maintaining of preset oil-pressure, the pressure control system changes the maximum oil-pressure band and flow rate according to the motor speed. The DSP control system adjusts the oil-pressure and the speed of the SRM from the pressure sensor signal, due to conservation of power consumption by the hydraulic pump. A 2.2Kw, 12/8 pole SR motor and DSP based digital controller are designed and tested with experimental set-up. The test results indicate that the system has some good features such as high efficiency and rapid response characteristics.

Keywords: Digital pressure control, High performance, Hydraulic pump system, SR drive

1. Introduction

Hydraulic pump systems are very widely used in building machinery, brake systems of vehicles and automatic control systems of industrial applications. The hydraulic pump system can supply high dynamic force and smooth control of force with rapid dynamic characteristics. The load torque of a hydraulic pump system is dramatically changed during operation and a motor of the pump is generally started with full load condition in order to get the high operation efficiency. Recently, high performance motor drive for hydraulic pump systems is of great interest due to the smooth and fast dynamic power supply to the load [1].

In a conventional hydraulic pump system, the induction motor is much used due to the cost and simplicity of the motor driving. However, the speed control performance of the general induction motor system with variable load condition is not suitable in high performance hydraulic pump systems, and it requires the use of an additional inverter system for variable speed control of the conventional induction motor.

The SRM (switched reluctance motor) has recently been under investigation for a wide range of industrial applications due to its mechanical strength and cost advantages [2-6]. The SRM is a simple, low-cost, and robust structure suitable for variable-speed and traction applications. As well, it has a simple structure and is stable for shoot-through fault because of each phase being separated [7-8]. In addition, the SRM has high power-to-weight and torque-to-weight ratios as well as a wide speed range and excellent starting characteristics. Therefore, it is suitable for hydraulic pump systems that are frequently stopped and started under full load condition [9-11].

In this paper, the SR drive system with a proper oil-pressure control method is proposed for the constant capacity hydraulic pump system. From the basic mechanical specifications of the hydraulic pump, base speed and torque of the motor are obtained and the prototype SRM is designed by FEM. In order to obtain the proper operating performance, the speed and torque of the motor are controlled by a power saving mode that reduces the increase of oil temperature.

The proposed SR drive system for the hydraulic pump is tested with the conventional hydraulic pump and the experimental results show that the proposed SR drive is suitable for high performance hydraulic pump systems.

2. SR Drive for Hydraulic Pump

2.1 Design of SRM

The outer dimensions of the SRM are determined by the induction motor size of the conventional hydraulic pump due to the easy change of the motor drive. For the detail design of the SRM, the maximum torque and rated speed are obtained from the mechanical specifications of the hydraulic pump. The maximum flux of the hydraulic pump

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is determined by volume efficiency and pump speed as follows [1].

$$Q_{\max} = n_m \cdot v_p \qquad (1)$$

Where, $Q_{\max}$ is the maximum output flux, n_m is pump speed [rpm] and v_p denotes pump capacity [cm^3/min].

And the pressure of oil is determined with the assumption of constant output flux and no loss of hydraulic pump as follows.

$$p_p = T_m / v_p \qquad (2)$$

Where, p_p is oil-pressure [Mpa], T_m is pump torque [Nm].

From Equations (1) and (2), the maximum torque and rated speed of the SRM are determined as 9.7[Nm] and 3000[rpm] respectively.

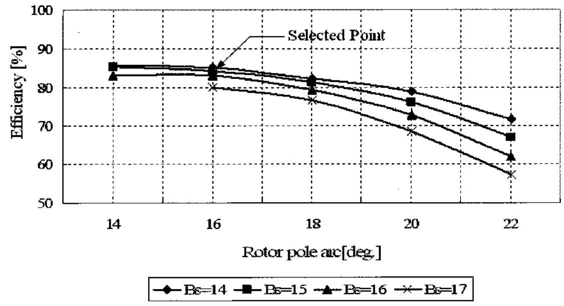
Although there are many advantages of the SRM, its actual application is significantly restricted because of acoustic noise and mechanical vibration. The design process of the SRM is different from DC and AC motors. This is due to the fact that the SRM uses reluctance torque and the characteristics are quite different according to stator and rotor pole array.

The general combination of stator and rotor pole array of the SRM are 6/4, 8/6 12/8 and 16/12. However, 8/6 and 16/12 SRM are not suitable for hydraulic pump application because of the complexity of the four-phase inverter system as well as the economic factors involved. In this paper, the number of stator and rotor combinations is selected as 12/8 SRM because of torque ripple and acoustic noise.

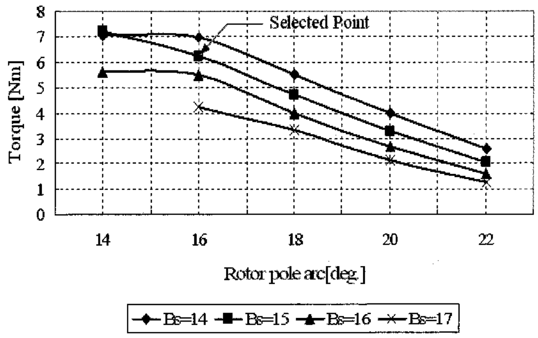
In order to obtain a good performance of the SRM for the hydraulic pump, the efficiency and torque characteristics are analyzed according to stator and rotor pole arc. Fig. 1 shows the simulation results of efficiency and output torque characteristics according to stator and rotor pole arc.

The simulation is implemented by changing of the stator pole arc according to rotor pole arc. In Fig. 1, the output torque and efficiency are superior in the low stator and rotor pole arc. However, under the critical stator and rotor arc, self-starting is impossible in some rotor positions due to the dead-zone where output torque is zero. In this paper, stator and rotor pole arc are determined as 15 and 16 [deg] with the consideration of efficiency, torque and dead-zone.

Fig. 2 presents the torque and efficiency variation in the fixed outer dimension of the SRM according to the depth rate of the stator and rotor pole and yoke. Although, the SRM with low rotor pole depth rate has better torque and efficiency characteristics. However, the manufacturing difficulty and heat problem are serious due to the low occupation rate and high current density in the SRM with low rotor pole depth rate.

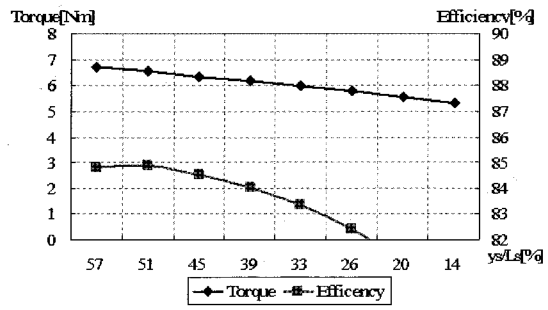


(a) Efficiency characteristics



(b) Torque characteristics

Fig. 1. The simulation results of SRM according to rotor and stator pole arc



(a) Torque and efficiency with the depth of stator pole

(b) Torque and efficiency with the depth of rotor pole

Fig. 2. Torque and efficiency characteristics of SRM with the depth of rotor and stator pole

Since the mechanical vibration is increased with thin stator yoke and thick stator teeth, stator yoke is selected in the range 2/3 of stator teeth width. The torque and efficiency of the prototype SRM describes parabola characteristics according to the rate of rotor pole depth and yoke as shown in Fig. 2(b). The efficiency is decreased in a high rate of rotor pole depth and yoke due to the concentration of magnetic flux density. The fringing effect is increased in the other case.

In the prototype SRM, the rate of stator pole depth and yoke is 40[%], while it is 54[%] for the rate of rotor pole depth and rotor yoke with the considerations of efficiency and torque characteristics.

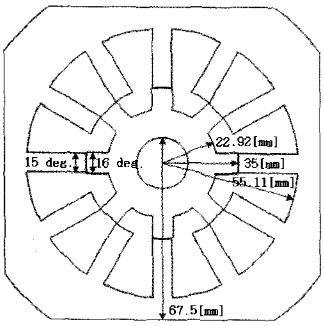
2.2 Design Results

Table I shows the specification and simulation results of designed prototype SRM.

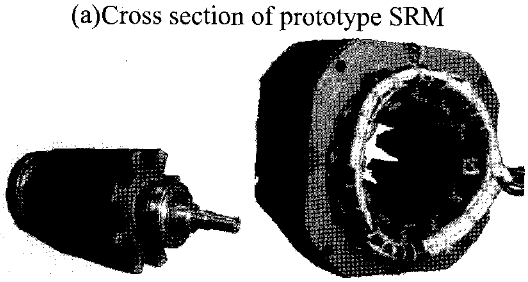
Table 1. Specification of the prototype SRM

Parameter	Value	Parameter	Value
Stack Length	95 [㎜]	Air-Gap	0.25 [㎜]
Dia. Of Stator	135 [㎜]	Turn	52 [trun]
Dia. Of Rotor	70 [㎜]	Max Torque	9.96 [Nm]
Stator pole arc	16 [deg]	Rated Speed	3000 [rpm]
Rotor pole arc	15 [deg]	Efficiency	87 [%]

Fig. 3 shows the cross section, rotor and stator assembly of a designed prototype SRM for hydraulic pump application. The rated output power is 2.2[kW] at 220[Vac] input voltage. The stack length is 95[㎜] and the turn number of phase winding is 52[turn].



(a)Cross section of prototype SRM



(b) Rotor (c) Stator

Fig. 3. The prototype SRM for hydraulic pump

3. Control of SRM for Hydraulic Pump

Fig. 4 denotes the relationships of flux and oil-pressure of the hydraulic pump. Under preset oil-pressure, the pump flux pump is limited maximum flux Q_{max}. Over the preset oil-pressure, flux is controlled by power saving mode indicated as shown in Fig. 4. Under high oil-pressure, oil temperature is rapidly increased with a friction of high flux. For this reason, the maximum flux is limited in high oil-pressure range.

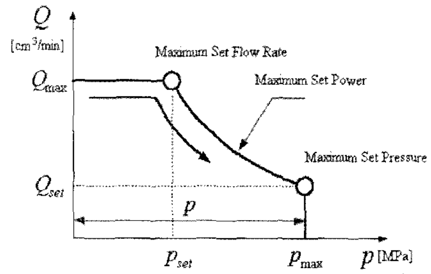


Fig. 4. The relationship of flux and oil-pressure

Because the flux of the constant capacity hydraulic pump system is proportional to the motor speed, the speed control of the motor can adjust the flux of the hydraulic pump.

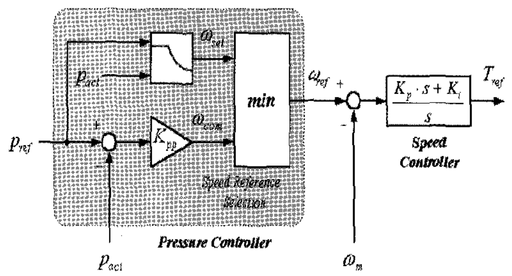


Fig. 5. The block diagram of flow and oil-pressure control

Fig. 5 shows the block diagram of flow-rate and oil-pressure control with power saving mode. The reference speed of the SRM that is proportional to flux is determined by the reference and actual oil-pressure P_{ref} and P_{act} respectively. In order to control oil-pressure, the proportional controller determines the reference speed of the pump in the outer control loop. And PI-speed controller adjusts the actual SRM speed in the inner control loop. The preset flux schedule in power saving mode is determined by the mechanical structure of the hydraulic pump and oil. In the oil-pressure controller in Fig. 4, if the reference speed of the P-controller is larger than the power saving mode speed, then the speed of the power saving mode is selected as a new reference value.

Fig. 6 explains the proposed control block diagram of the hydraulic pump system with SR drive. The SRM drives the pump gear, and the output flux of the oil-tank can be controlled by the speed of the gear.

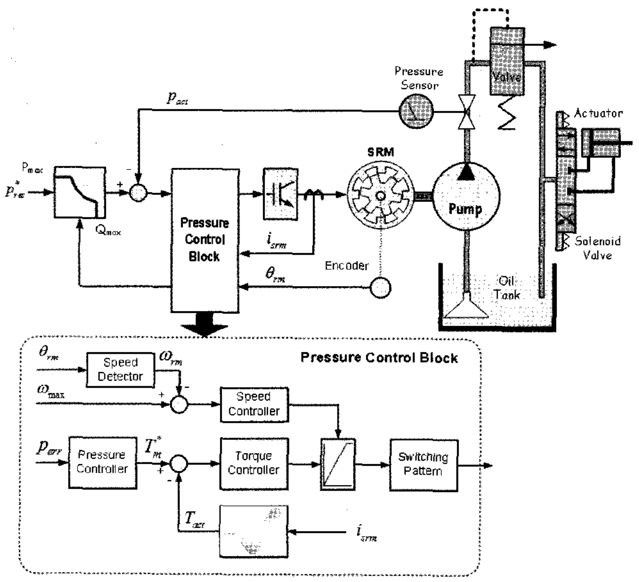


Fig. 6. The global block diagram of the hydraulic pump system with SR drive

The actual oil-pressure signal is fed back to the pressure controller in order to adjust the oil-pressure.

4. Experimental Results

4.1 Experimental System Set-up

The prototype SR drive for the hydraulic pump system is tested in the view of speed-torque and speed response characteristics.

Fig. 7 shows the DSP control system for the hydraulic pump. The main controller is designed using TMS320LF2406 by TI (Texas Instrument) and an asymmetric converter, which consists of 50A, 600V IGBT.

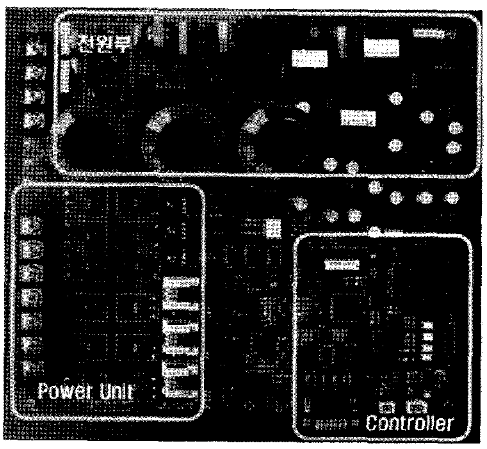


Fig. 7. The DSP control system for hydraulic pump

The speed of the SRM is calculated by the 2000[ppr] optical encoder and QEP function of TMS320LF2407 at every 1.6[ms]. Phase current signals and actual oil-pressure signal are detected by sensors and converted as digital data at internal 10bit ADC of DSP. The current control of the SRM is implemented by PWM method with 100[μs] sampling period.

Fig. 8 shows the experimental set-up of the hydraulic pump system with prototype SR drive.

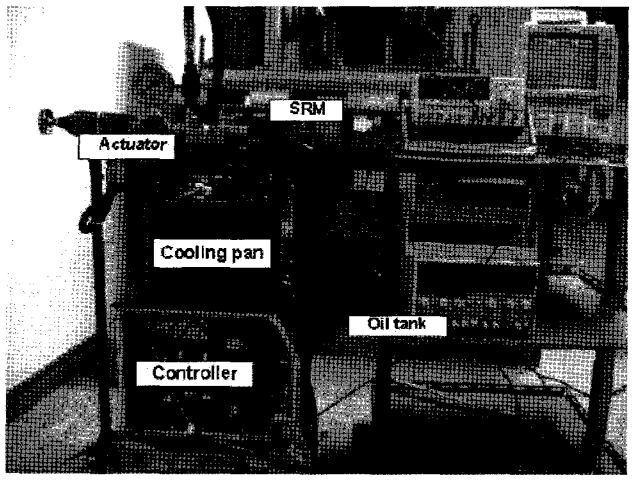


Fig. 8. The experimental set-up of hydraulic pump system with SR drive

4.2 Experimental Results

Fig. 9 shows the speed-torque and operating efficiency of the prototype SR drive in the hydraulic pump system.

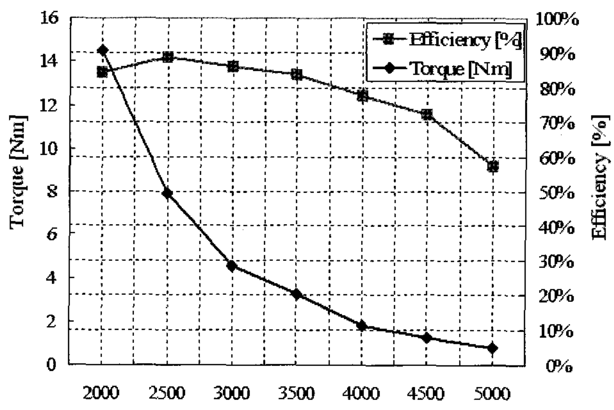


Fig. 9. Speed-torque and efficiency characteristics of prototype SR drive

In order to maintain the target oil-pressure at a low speed range, output torque of SRM is 13[Nm], which is larger than the required maximum torque of 9.7[Nm]. The maximum operating efficiency of the SR drive at full load condition is 84[%], which is lower than the designed value of 87[%] because of manufacturing error and control condition of the classic inverter system.

Fig. 10 shows the flux response of the hydraulic pump. The reference flux is changed from 15[L/min] to 5[L/min] at 5[Mpa] oil-pressure. The actual oil-pressure is limited as 2[Mpa] due to the reference flux being limited during power saving mode. In low flux, the actual oil-pressure is rapidly increased as reference value 5[Mpa] as shown in Fig. 10.

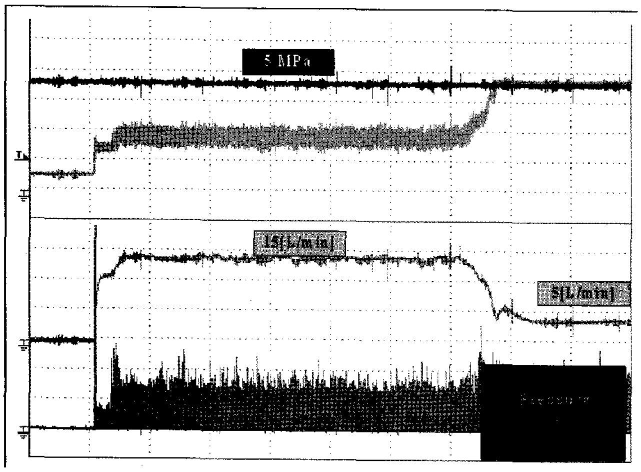


Fig. 10. The flow-rate control result of hydraulic pump at 5[Mpa]

Fig. 11 is the step response of the pump at 1.25, 2 and 3.0[Mpa] respectively. In the figure, actual oil-pressures are reached at the reference values within 200[ms] and the speed of the motor is regulated according to the oil-pressure.

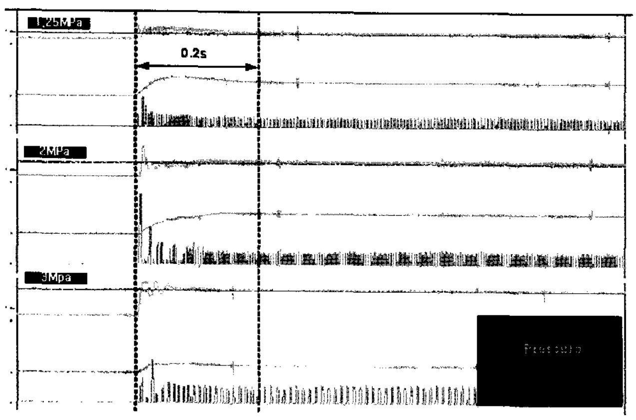


Fig. 11. The characteristics of oil-pressure control

In the hydraulic pump system, the temperature variation of the oil is very important because of oil viscosity. It is hard to keep the oil pressure with a low viscosity at a high oil temperature, and the fast response of pressure variation is disturbed by high viscosity of oil at a low temperature. In Fig. 12, the temperature variation of motor and oil shows a stable operation.

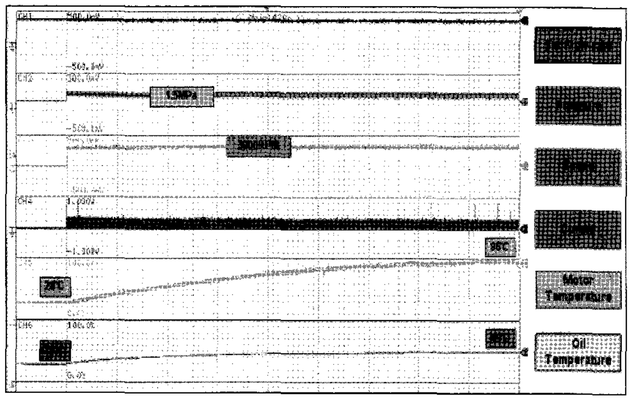


Fig. 12. Temperature variation of SRM and oil during continuous operation of hydraulic pump

5. Conclusions

In this paper, the performance of a hydraulic pump system with SR drive is investigated. In the conventional hydraulic pump system, the induction motor drive system is replaced with a prototype SR drive. A 12/8 SRM of 2.2[kW] is designed with consideration of efficiency and output torque.

The efficiency of the prototype SR drive has 84[%] at full load of the hydraulic pump system. The excellent dc series torque characteristics of the SRM can make a fast dynamic response of oil-pressure control.

A DSP controller with power saving mode that is limited to the actual oil-pressure and flux of the hydraulic pump due to the limit of oil temperature is proposed for the prototype SR drive. The inner loop PI-speed controller and outer P- pressure controller control the flux and oil-pressure with the optical encoder and pressure sensor.

The experimental results show some good advantages of the hydraulic pump system with SR drive.

Acknowledgment

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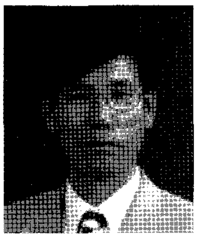

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