Performance of SR Drive for Hydraulic Pump

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Abstract—**This paper proposed a hydraulic pump system which uses a variable speed SR drive and constant capacity pump. The base and maximum speed, torque are determined from the mechanical specifications of hydraulic pump. The drive system is set to have minimum power consumption during the keeping of preset oil-pressure. In order to save the power consumption of hydraulic pump, power and oil-pressure signals are feedback to DSP controller, and SR drive controls the operating speed of SRM. A 2.2Kw, 12/8 pole SR motor and DSP based digital controller are designed and tested with experimental set-up. The test results show that the system has some good features such as high efficiency and fast response characteristics.**

I. Introduction

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

In a conventional hydraulic pump system, 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 system, and it is required additional inverter system for variable speed control of conventional induction motor.

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

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

The proposed SR drive system for 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 system.

II. SR Drive For Hydraulic Pump

A. Design of SRM

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

The maximum flux of hydraulic pump is determined by volume efficiency and pump speed as follows[1].

$$Q_{\max} = n_m \cdot v_p \tag{1}$$

Where, $Q_{\max}$: maximum output flux

n_m : pump speed [rpm]

v_p : 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.

$$p_p = T_m / v_p \tag{2}$$

Where, p_p : oil-pressure [Mpa]

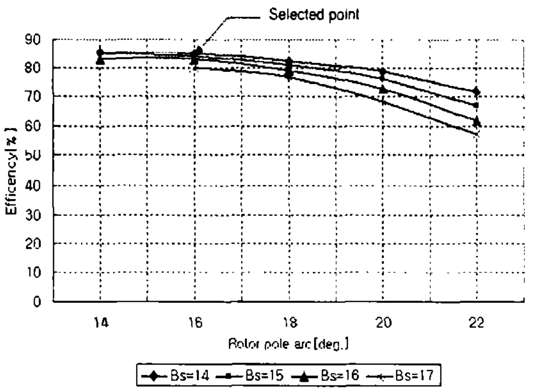
T_m : pump torque [Nm]

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

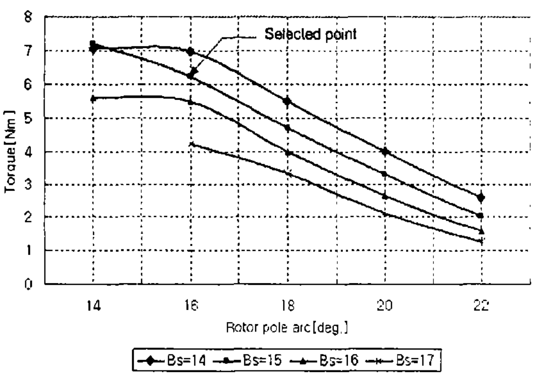
Although many advantages of SRM, the actual application of SRM such as hydraulic pump is much restricted because of acoustic noise and mechanical vibration. The design process of SRM is different from DC and AC motors. Because of SRM use reluctance torque and the characteristics are much different according to stator and rotor pole array.

The general combination of stator and rotor pole array of 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 four-phase inverter system and cost problem. In this paper, the number of stator and rotor combination is selected 12/8 SRM because of torque ripple and acoustic noise.

In order to get a good performance of SRM for 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.



(a) Efficiency characteristics



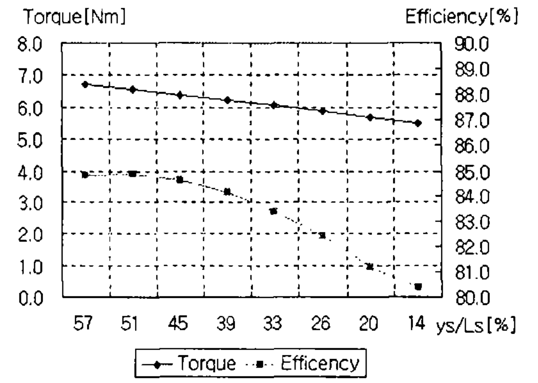
(b) Torque characteristics

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

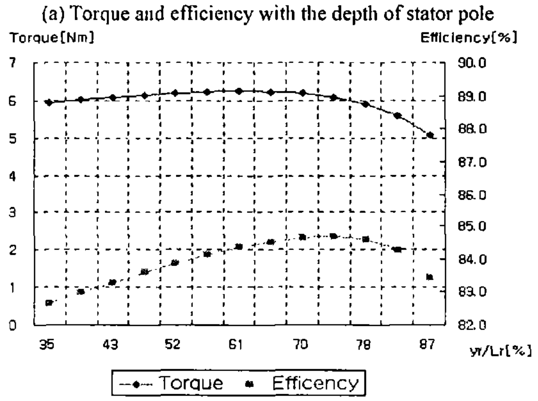
The simulation is implemented by changing of stator pole arc according to rotor pole arc. In the Fig. 1, the output torque and efficiency is better in low stator and rotor pole arc. However, under the critical stator and rotor arc, self-starting is impossible in some rotor position due to the dead-zone 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 shows the torque and efficiency variation in the fixed outer dimension of SRM according to the depth rate of stator and rotor pole and yoke. Although, SRM with a low depth rate of rotor pole 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 SRM with low depth rate of rotor 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 prototype SRM describe parabola characteristics according to the rate of rotor pole depth and yoke shown as Fig. 2(b). The efficiency is decreased in 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[%] and 54[%] rate of rotor pole depth and rotor yoke with the considerations of efficiency and torque characteristics.



(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 stator and rotor pole

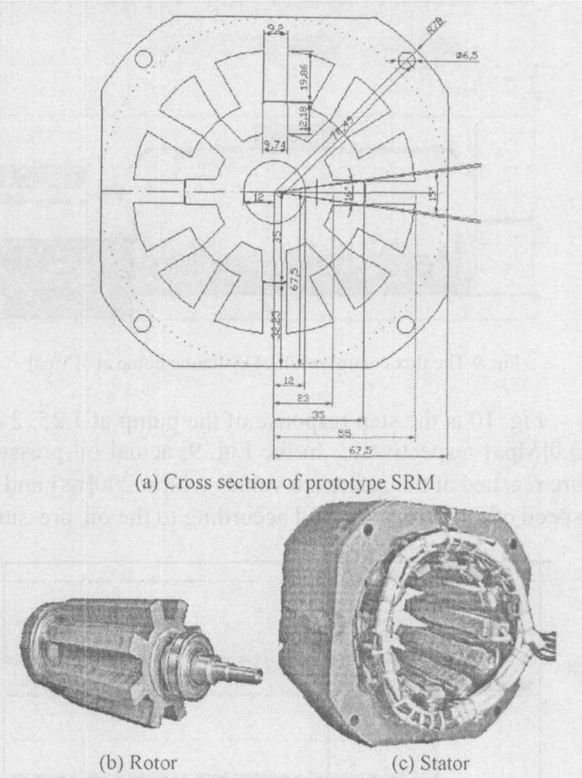
B. Design Results

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

TABLE I
SPECIFICATION OF THE PROTOTYPE SRM

Parameter	Value	Parameter	Value
Stack Length	95 [mm]	Air-Gap	0.25 [mm]]
Dia. Of Stator	135 [mm]	Turn	52 [turn]
Dia. Of Rotor	70 [mm]	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

III. Control Of SRM For Hydraulic Pump

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

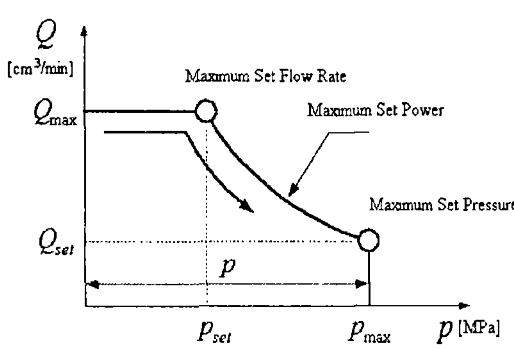


Fig. 4 The relationship of flux and oil-pressure

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

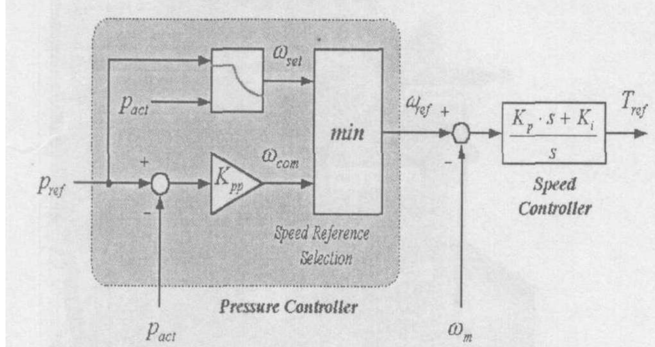


Fig. 5 The block diagram of flux and oil-pressure control

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

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

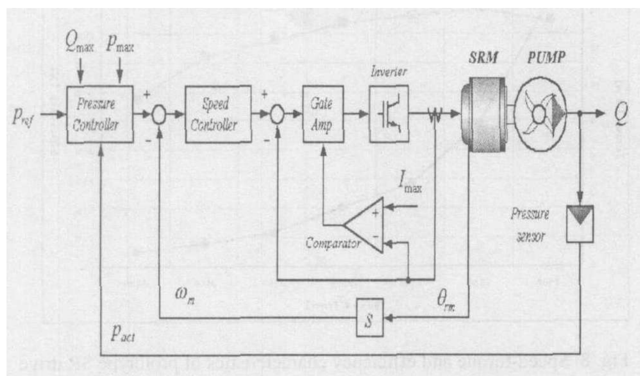


Fig. 6 The global block diagram of hydraulic pump system with SR drive

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

IV. Experiments And Results

A. Experimental System Set-up

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

Fig. 7 shows the experimental set-up of hydraulic pump system with prototype SR drive.

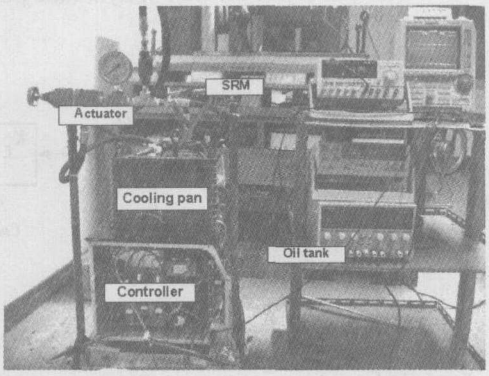


Fig. 7 The experimental set-up of hydraulic pump system with SR drive

The digital controller of SRM is implemented by TMS320LF2407 DSP of Texas Instruments. The speed of SRM is calculated by the 2000[ppr] optical encoder and QEP function of TMS320LF2407 at every 1.6[ms] period. 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 SRM is implemented by PWM method with 100[μs] sampling period. An asymmetric classic inverter with 600[V], 50[A] IGBT modules, supplies the pulse power to SRM.

B. Experimental Results

Fig. 8 shows the speed-torque and operating efficiency of the prototype SR drive in hydraulic pump system.

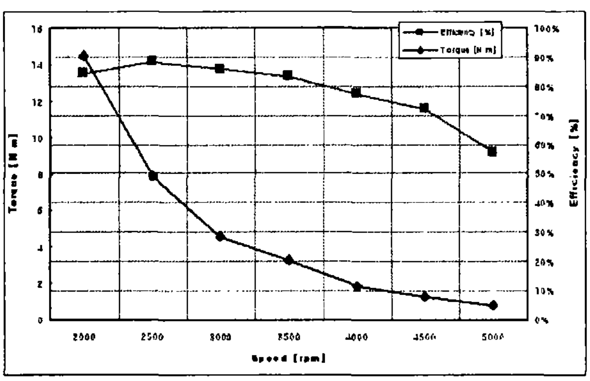


Fig. 8 Speed-torque and efficiency characteristics of prototype SR drive

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

Fig. 9 shows the flux response of 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 is limited in power saving mode. In low flux, the actual oil-pressure is fast increased as reference value 5[Mpa] shown as fig. 8.

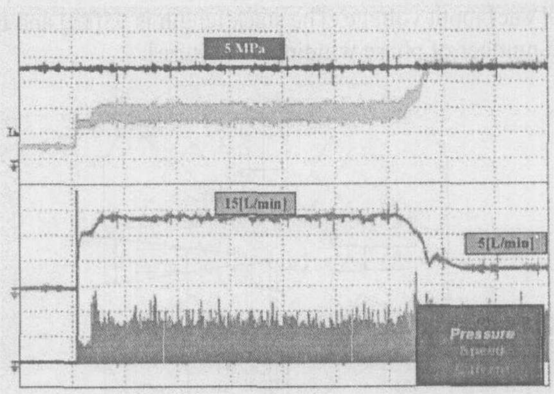


Fig. 9 The flux control result of hydraulic pump at 5[Mpa]

Fig. 10 is the step response of the pump at 1.25, 2 and 3.0[Mpa] respectively. In the Fig. 9, actual oil-pressures are reached at the reference values within 200[ms] and the speed of motor is regulated according to the oil-pressure.

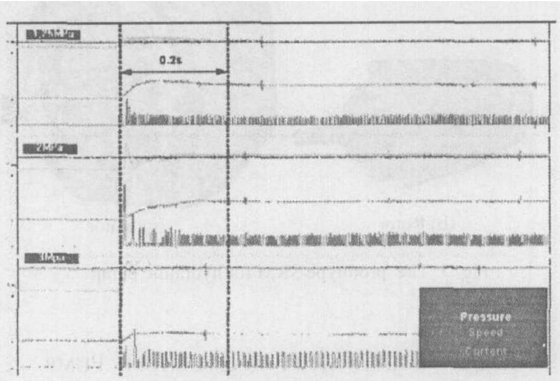


Fig. 10 The characteristics of oil-pressure control

In the hydraulic pump system, the temperature variation of oil is very important because of viscosity of oil. It is hard to keep the oil pressure with a low viscosity of oil at a high oil temperature, and the fast response of pressure variation is disturbed by high viscosity of oil at a low temperature. In the Fig. 11, the temperature variation of motor and oil shows a stable operation.

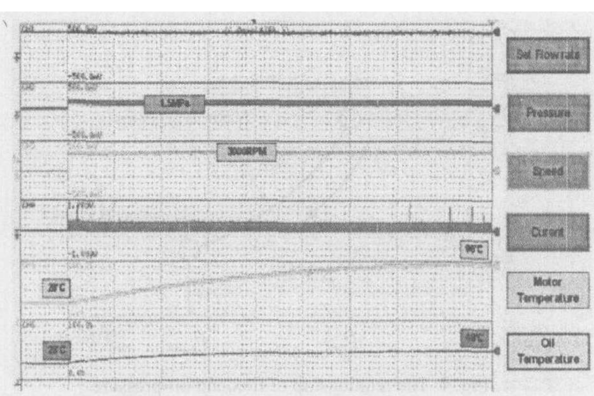


Fig. 11 Temperature variation of SRM and oil during continuous operation of hydraulic pump

V. CONCLUSIONS

In this paper, the performance of a hydraulic pump system with SR drive is investigated. In the conventional hydraulic pump system, 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 prototype SR drive has 84[%] efficiency at full load of hydraulic pump system. The excellent dc series torque characteristics of SRM can make a fast dynamic response of oil-pressure control.

A DSP controller with power saving mode that is limit the actual oil-pressure and flux of hydraulic pump due to the limit of oil temperature is proposed to 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 hydraulic pump system with SR drive.

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