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Pressure Control of SR Driven Hydraulic Oil-Pump Using Data based PID Controller

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ABSTRACT

This paper presents a practical method of pressure control for a hydraulic oil-pump system using an SR (Switched Reluctance) drive. For a 6Mpa grade hydraulic oil-pump, a 2.6kW SR drive is developed. In order to get high performance pressure dynamics in actual applications, a data based PID control scheme is proposed. The look-up table from a pre-measured data base produces an approximate current reference based on motor speed and oil-pressure. A PID controller can compensate for the pressure error. With the combination of the two references, the proposed control scheme can achieve fast dynamics and stable operation. Furthermore, a suitable current controller considering the nonlinear characteristics of an SRM (Switched Reluctance Motor) and practical test methods for data measuring are presented. The proposed control scheme is verified by experimental tests.

Keywords: Switched reluctance motor, Hydraulic pump, Data based PID control, Pressure control

1. Introduction

Hydraulic-oil pumps are very widely used for building machinery, the brake systems of vehicles and automatic control systems in industrial applications due to their high dynamic force and smooth linear force control performance. Recently there has been a lot of interest in variable speed drive systems for hydraulic pumps due to their smooth and fast dynamic power supply to the load[1]. Induction motors for hydraulic pumps are very simple and have a good cost benefit. But the operating efficiency and control dynamics are not sufficient.

SRMs (Switched Reluctance Motors) are a simple, low-cost and robust structure suitable for variable speed and traction applications[2]-[4]. SR drives are investigated for a wide range of industrial applications due to their mechanical strength and cost advantages[5]-[9]. When compared with squirrel cage induction motors, SRMs have high efficiency with a high starting torque and excellent high speed characteristics. In addition, SRMs are excited by a pulse wave voltage source rather than a sinusoidal one which is for induction motors. Therefore, the excitation of SRMs is easier with lower switching frequencies. Also power loss can be reduced in the converter system in the high speed range. For these reasons, SRMs are considered for practical industrial applications[7]-[9].

This paper presents a hydraulic oil-pump system using a SR drive with a data based PID controller for oil-pressure

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control in practical applications. The operating conditions of a hydraulic oil-pump are very complicated due to flow rate and oil-pressure. When the cylinder moves, the motor speed is changed, and the operating speed is adjusted by the flow rate valve. In fixed operating conditions, PID controllers can make sufficient control performance, but they have trouble in wide operating conditions. Furthermore, the pressure sensor of a hydraulic-pump has a low dynamic response. As, the output signal of the pressure sensor has a time delay from the actual pressure, the control gains of a PID are limited for stable operation.

In this paper, a 2.6kW SR drive is designed for a 6Mpa hydraulic-oil pump system. A data based PID controller for a SR drive is presented in order to get a fast dynamic response from the hydraulic-oil pump. The proposed control scheme for a hydraulic-oil pump using a SR drive is very simple. The base torque command for pressure control is determined by a pre-measured data base, and the pressure error is controlled by a conventional PID controller. If only a PID pressure controller is used, it is very difficult to get a sufficient dynamic response in a wide operation range. The pre-measured current can be easily determined by using a look-up table and linear interpolation according to motor speed and oil-pressure. A fast dynamic response is possible. But the actual oil-pressure still has an error from the measured data base. The error can be compensated for by the PID controller. The proposed control scheme needs an auxiliary measuring process, and the data is acquired from an off-line pre-test.

The proposed proto-type SR drive for hydraulic-oil pumps and the data based PID pressure control scheme are verified by the practical experiments.

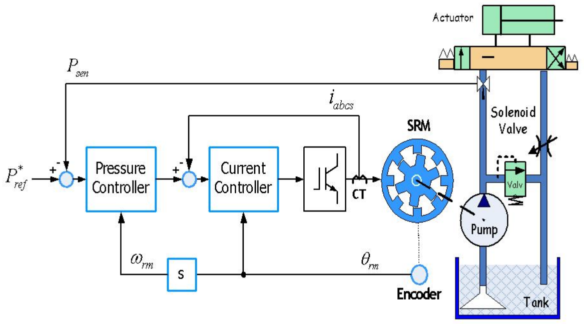


Fig. 1. Block diagram of hydraulic oil-pump system using SR drive.

2. Hydraulic Pump System using SR Drive

The oil pressure is detected by a pressure sensor. The pressure controller produces a torque or current command to keep a constant reference oil-pressure. A speed limiter is included in the pressure controller to protect the pump and motor. The current controller generates PWM switching signals to control the reference current for constant pressure.

2.1 Basic Principle of SR Drive

Fig. 2 shows a general SRM drive system. With a constant phase current, ideal phase torque is produced according to the square of the current and the inductance slope of the motor. The two basic equations of an SRM can be derived in terms of phase voltage and torque as follows [4-5].

$$v = L_{(\theta_{rm},i)}\frac{di}{dt} + i\frac{dL_{(\theta_{rm},i)}}{d\theta_{rm}}\cdot\omega_{rm} \tag{1}$$

$$T_m = \frac{1}{2}\cdot i^2\cdot\frac{dL_{(\theta_{rm},i)}}{d\theta_{rm}} \tag{2}$$

where, θ_{rm} is the rotor position, ω_{rm} is the rotor speed and $L_{(\theta_{rm},i)}$ is the inductance according to rotor position and current.

Due to the magnetic nonlinearity in an SRM, the phase inductance is nonlinear with respect to the rotor position and phase current. Therefore, constant torque profiling for torque ripple reduction is difficult compared to conventional AC motors such as PM and induction motors.

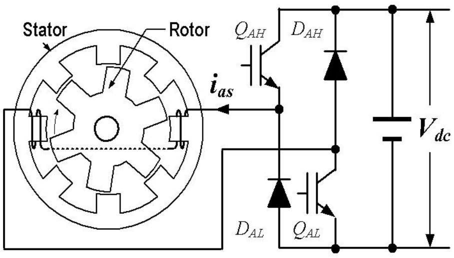


Fig. 2. SRM drive system.

2.2 Design of an SRM

In this paper, an SRM is designed for a 6Mpa hydraulic oil-pump. The outside dimensions of the SRM are determined by the induction motor size of a conventional hydraulic pump to simplify the changing of motor drives. For the detail design of an SRM, the maximum torque and rated speed are obtained from the mechanical specifications of the hydraulic pump. The maximum flux of the hydraulic pump is determined by volume efficiency and pump speed as follows[1].

$$Q_{\max} = n_m \cdot v_p \tag{3}$$

where, $Q_{\max}$ is the maximum output flux, n_m is the pump speed [rpm] and v_p denotes the pump capacity [cm^3/min]. The oil pressure is determined with the assumption of a constant output flux and no loss from the hydraulic pump as follows.

$$p_p = T_m / v_p \tag{4}$$

where, p_p is the oil-pressure [Mpa] and T_m is the pump torque [Nm].

From (3) and (4), the maximum torque and rated speed of the SRM are determined as 9.7[Nm] and 2500[rpm] respectively.

Table I shows the specifications of the prototype SRM for a hydraulic oil pump.

Table 1. Specification of the prototype SRM.

Parameter	Value	Parameter	Value
Stack Length	95 [mm]	Air-Gap	0.25 [mm]
Dia. Of Stator	135 [mm]	Turn	80 [trun]
Dia. Of Rotor	70 [mm]	Rated Torque	10.2 [Nm]
Stator pole arc	15 [deg]	Rated Speed	2500 [rpm]
Rotor pole arc	16 [deg]	Efficiency	91.4 [%]

Fig. 3 shows the rotor and stator assembly of the designed prototype SRM for a hydraulic pump application. The rated output power is 2.6[kW] at 220[Vac] of input voltage. The stack length is 95[mm] and the turn number of phase windings is 80[turn].


(a) Rotor (b) Stator

Fig. 3. The prototype SRM for hydraulic pump.

In order to keep the target oil-pressure in a low speed range, the rated output is 10.2[Nm] which is larger than the required maximum torque, 9.7[Nm]. The maximum drive efficiency of the SR drive at full load is 87.6[%] which is lower than the designed value 91.4[%] due to manufacturing error and the control conditions of a classic inverter system.

3. The Proposed Control System for a Hydraulic Pump

Fig. 4 shows a conventional oil-pressure PID control block diagram. K_P , K_I and K_D denote the proportional, integral and differential gain of the PID controller, respectively. As shown in Fig. 4, the PID controller generates a torque command T_1^* using pressure error P_{err} and a PID control loop. The torque command T_1^* is limited by the actual motor speed ω_{rm} to protect the oil-pump and motor system.

The control performance is dependent on the pressure and torque controller. But, the control gains of the pressure controller are limited by the pressure sensor dynamics in actual applications. In restricted conditions,

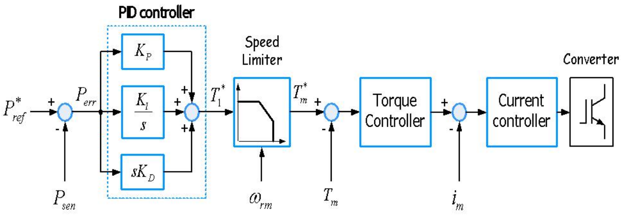


Fig. 4. Conventional oil-pressure PID control block.

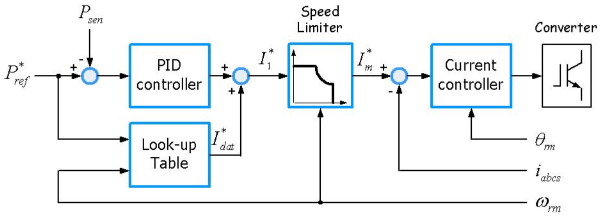


Fig. 5. Proposed control scheme for hydraulic pump.

the control gains can be selected to get excellent control performance. However, motor speed is changed by the flow-rate valve in actual application, and pressure variation is dependent on the load condition. So, proper control gains selection is very difficult in a wide operation range.

Fig. 5 shows the proposed pressure control scheme in a hydraulic oil-pump system. Compared with a conventional pressure control system, the proposed method has an additional look-up table and the torque controller is removed. Because SRMs have nonlinear torque characteristics to phase current, the torque reference cannot be changed to the current reference directly. In this paper, the primary torque reference is determined by a look-up table and the auxiliary error can be compensated for by the PID controller. In order to reduce control complexity the torque controller is removed, and a direct current controller is used.

The pressure controller is designed as follows:

$$P_{err} = P^*_{ref} - P_{sen} \tag{5}$$

$$I^*_1 = \left(K_P + \frac{K_I}{s} + sK_D \right) \cdot P_{err} + I^*_{dat}(P^*_{ref}, \omega_{rm}) \tag{6}$$

$$I^*_m = f_x\left(I^*_1, \omega_{rm}\right) \tag{7}$$

where, $f_x\left(I^*_1, \omega_{rm}\right)$ denotes the speed limiter function. And $I^*_{dat}\left(P^*_{ref}, \omega_{rm}\right)$ is the output of the look-up table which is from the pre-measured data base. In the proposed control scheme, the pre-measured data base is very important. The proper current is obtained by an actual hydraulic oil-pump test with a current controller of a SR drive according to motor speed and load variation. In this paper the current controller of an SR drive is designed with the consideration of the nonlinear characteristics of SRMs.

Fig. 6 shows the inductance profile and phase current of an SRM. Unlike other motors, SRMs use a pulse wave phase current to produce reluctance torque during phase inductance changing as shown in (2). Phase torque can be produced from θ_1, when the starting position of the rotor and the state pole are aligned to θ_2 as shown in Fig. 6. In order to get a constant and sufficient torque, the phase current should be excited before the θ_1 position due to inductance. Similarly, the phase current should be demagnetized before θ_3, when the starting position of the rotor and the state pole are unaligned. An unsuitable advance angle can result in insufficient torque production or low driving efficiency, and an unsuitable demagnetization angle can result in a torque dip or negative torque production. So, the advance angle θ_{adv} and demagnetization angle θ_{dem} should be determined by the operating conditions.

Fig. 7 shows phase currents with an unsuitable advance and turn-off angle.

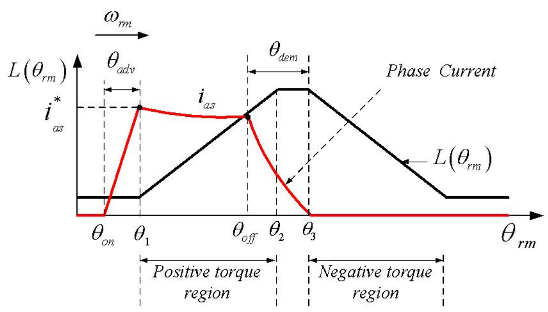


Fig. 6. Inductance profile and phase current of SRM.

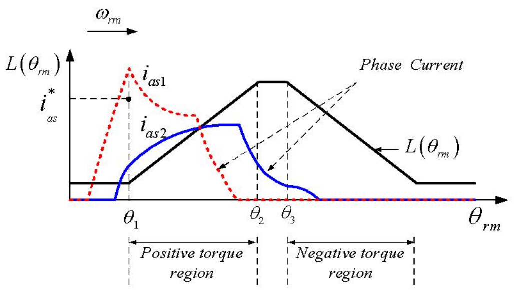


Fig. 7. Phase current with an unsuitable advance and turn-off angle.

In the case of an advanced turn-on angle, the phase current has an undesired over-shoot and copper loss with a torque spike. And in the case of a delayed turn-on angle, the phase current cannot keep the desired current and torque dip. Similarly, a fast turn-off angle can produce a torque dip, and a late turn-off angle can produce a negative torque as shown in Fig. 7.

In order to secure enough time to build-up the desired phase current i_{as}^*, the advance angle θ_{adv} can be adjusted according to motor speed ω_{rm}. From the voltage equations of the SRM, the proper advance angle can be calculated by the current rising time as follow regardless of phase resistance at the turn-on position.

$$\Delta t = L(\theta_1)\cdot\frac{i_{abcs}^*}{v_{abcs}} \tag{8}$$

where, i_{abcs}^* denotes the desired phase current of the current controller and v_{abcs} is the terminal voltage of each phase winding. The advance angle is determined by motor speed and (8) as follows:

$$\theta_{adv} = \omega_{rm}\cdot\Delta t \tag{9}$$

The determination of a proper turn-off angle is very difficult due to the nonlinear characteristics of SRMs. Because inductance is changed by the rotor position and phase current, the proper turn-off angle cannot be determined by a simple calculation in a wide operating range.

In this paper, the advance and turn-off angle are determined as nonlinear functions which are based on pre-tests according to motor speed and phase current. In order to take into consideration the phase voltage effect, the weighting factor K_{vdc} is used. If the DC-link voltage of the converter is lower than the tested value, the weighting factor K_{vdc} is increased to compensate for the insufficient advance and turn-off angle from low DC-link voltage. The weighting factor is decreased when the DC-link voltage is higher than the tested value.

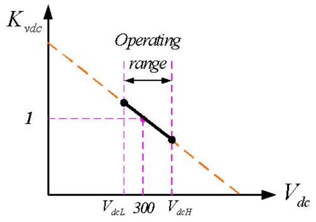


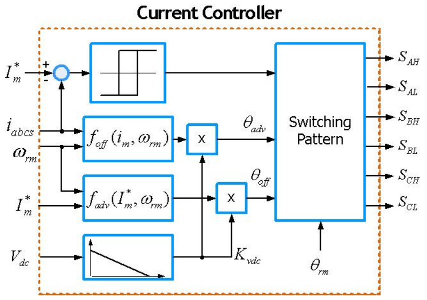
Fig. 8. Weight factor for DC-link voltage effect in control angle function.

Fig. 8 shows the weighting factor K_{vdc} according to input DC-link voltage. In order to stabilize operation of the SRM and protect the power devices, the input DC-link voltage is limited. The low voltage V_{dcL} is set to 250[V] for full load and the high voltage V_{dcH} is set to 390[V] for the protection of the power devices in this paper.

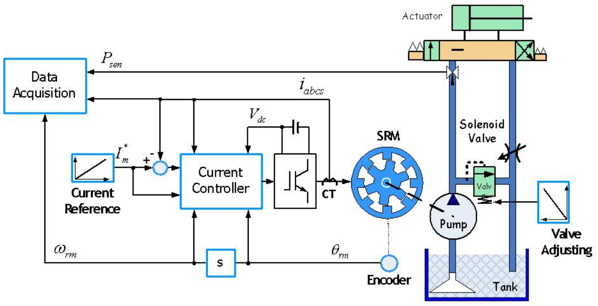
According to the weighting factor, the advance and turn-off angle can be determined as follows:

$$\theta_{adv} = K_{vdc}\cdot f_{adv}(I_m^*, \omega_{rm}) \tag{10}$$

$$\theta_{off} = K_{vdc}\cdot f_{off}(i_m, \omega_{rm}) \tag{11}$$



(a) Proposed current controller



(b) Practical test block for data base and look-up table

Fig. 9. Proposed hydraulic oil-pump system test block.

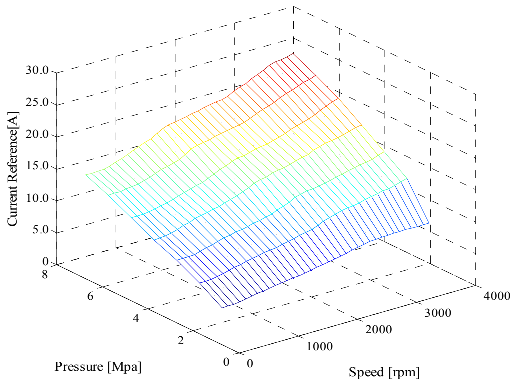


Fig. 10. Current reference look-up table for hydraulic oil-pump system.

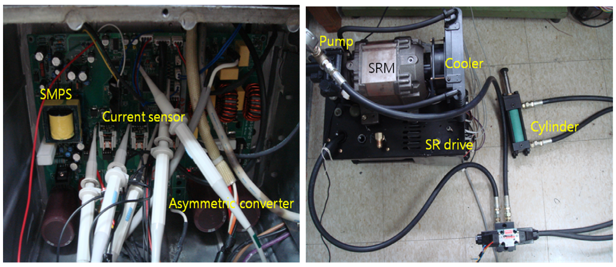
where, $f_{adv}(I_m^*, \omega_{rm})$ and $f_{off}(i_m, \omega_{rm})$ are nonlinear functions from the pre-measured data.

Fig. 9 shows the proposed current controller and the hydraulic oil-pump system test block for making the data base and look-up table.

The main controller is designed with the hysteresis method, and the advance and turn-off angles are determined by the nonlinear function as stated. The current reference is changed from 1 to 30[A] and the motor speed is changed by the flow-rate valve. In the practical test, the oil-pressure according to motor speed and phase current is measured. From this data base, $I_{dat}^*\left(P_{ref}^*, \omega_{rm}\right)$ a function can be decided as shown in Fig. 10.

4. Experimental Results

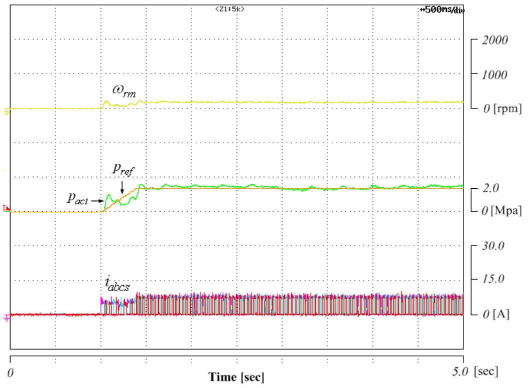
In order to verify the proposed control scheme, a hydraulic oil-pump using an SR drive is tested in a cylinder actuator load. The main controller is a TMS320F2811-120Mhz from TI (Texas Instrument) and the asymmetric converter which is a 50[A], 600[V] discrete IGBT. The phase currents are measured by a 30[A] grade current sensor, and an embedded AD converter of TMS320F2811. The rotor position is detected by an optical encoder and an embedded QEP module of DSP. The pressure of the hydraulic oil pump is fed to the AD converter, and used as a pressure controller. Two temperature sensors are used for heat protection of the motor and drive.



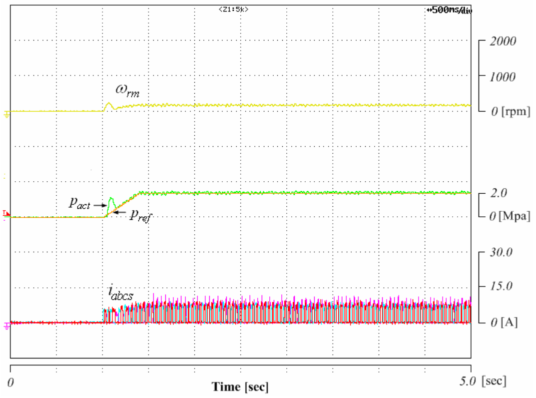
(a) SR drive (b) Load configuration

Fig. 11. Designed SR drive and experimental configuration.

Fig. 11 shows the designed SR drive and the experimental configuration. The SRM is directly connected to the hydraulic oil pump. The pumped oil flows to the actuator valve. If the valve turns on, the oil pushes out the cylinder shown as Fig. 11(b). If the valve turns off, the oil returns to the oil tank.



(a) Conventional PID controller



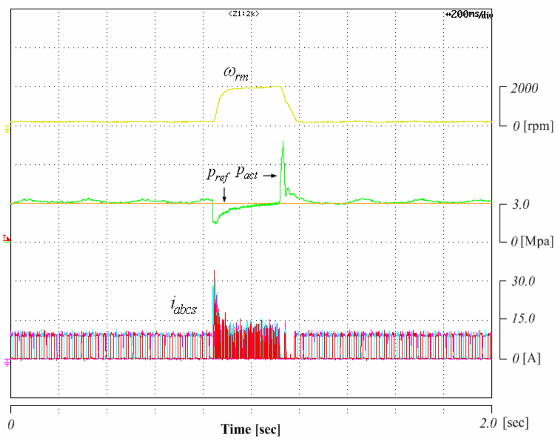
(b) Proposed controller

Fig. 12. Compared experimental results at the starting(2Mpa).

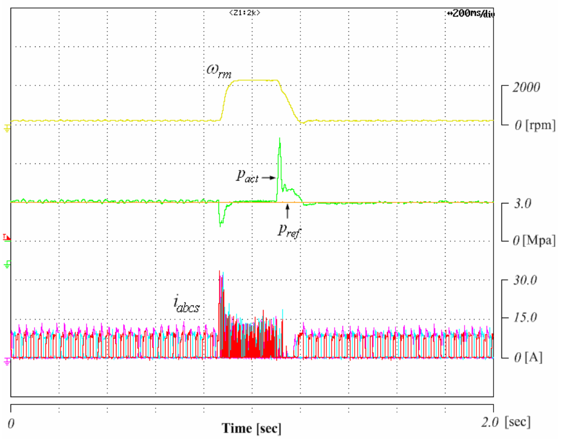
In order to verify the proposed control scheme, experiments are implemented and their results compared. Fig. 12 and Fig. 13 show the compared experimental results of a conventional PID and the proposed control scheme.

As shown in Fig. 12, the actual pressure of the pump has some ripple, and the response is not good at the starting 2Mpa pressure. But the actual pressure is well controlled in the proposed control scheme. In Fig. 12(b), the first over shoot of pressure is from the flow valve, and this over shoot is a natural characteristic of hydraulic pump systems at starting. Similarly, when the pressure responds to load variation, the proposed control scheme shows better results as shown in Fig. 13.

Fig. 14 shows the experimental result of the proposed control scheme when the cylinder load is changing. As shown in Fig. 14, the actual oil-pressure follows the reference value. The motor speed is changed to maintain oil-pressure, and the current reference is changed according to the data base and the PID controller.

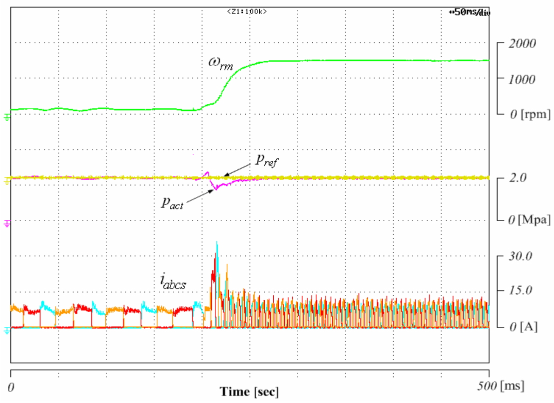


(a) Conventional PID controller

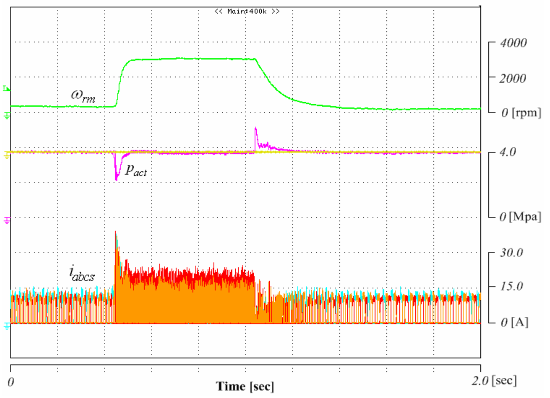


(b) Proposed controller

Fig. 13. Experimental results with the load variation(3Mpa).



(a) 2Mpa case

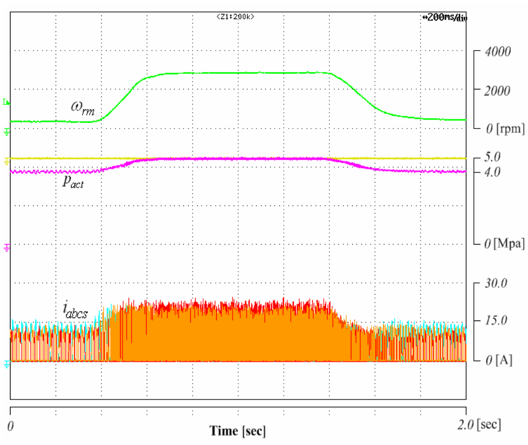


(b) 4Mpa case

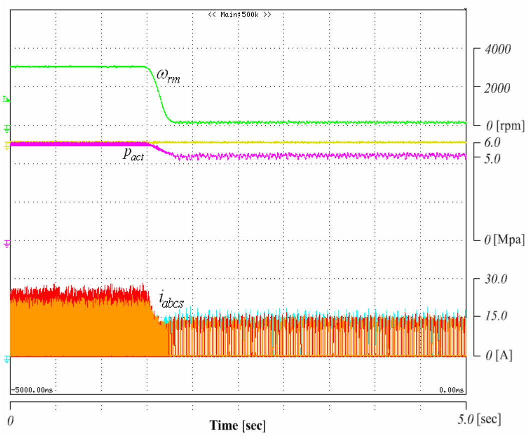
Fig. 14. Experimental result when load change.

Fig. 15 shows the experimental result when the reference changes. If the reference oil pressure is changed from 4 → 5 → 4Mpa and from 6 to 5Mpa and the motor speed is changed from 450 to 3200 rpm the actual oil pressure can keep the reference value.

Fig. 16 shows the experimental results when the load is changed at 5Mpa. The motor speed is determined by the flow rate valve and the oil-pressure. If the speed is limited, the actual oil-pressure is regulated marginally. The actual oil-pressure cannot keep the reference value as shown in Fig. 16(a). But, if the flow rate valve is adjusted, the motor speed can be changed at the same pressure. In this case the proposed controller can keep the reference pressure shown in Fig. 16(b).

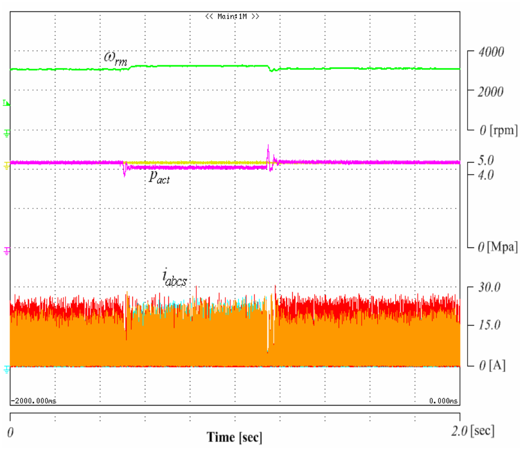


(a) Reference is changed from 4 to 5Mpa

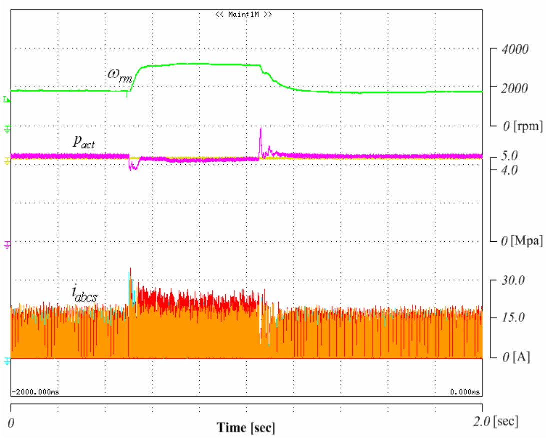


(b) Reference is changed from 6 to 5Mpa

Fig. 15. Experimental result with reference changing.



(a) Speed limited



(b) Speed is not limited

Fig. 16. Experimental results with load changing(5Mpa).

5. Conclusions

This paper presents the practical pressure control of a hydraulic oil-pump system using a SR drive for industrial applications. For a 6Mpa grade hydraulic oil-pump, a 2.6kW SR(Switched Reluctance) drive is developed and fabricated.

For the 100ms class of fast dynamic response hydraulic oil-pumps, a practical data based PID controller and current controller considering the nonlinear characteristics of SRMs is proposed. A look-up table from a pre-measured data base can produce an approximate current reference based on motor speed and oil-pressure.

Also a PID controller can compensate for the pressure error. With the combination of the two references, the proposed control scheme can achieve fast dynamics and stable operation.

Nonlinear functions for the advance and turn-off angle determinations are used to get a proper current waveform. In the current controller, the DC-link voltage effect is considered using a weighting factor, so a proper advance and turn-off angle can be obtained according to motor speed, load condition and dc-link voltage.

From the practical experiment using a cylinder load, the proposed control scheme is verified.

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