Study of Developing Control Algorithm for Pumped-storage Synchronous Motor Drive

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Abstract - This paper presents a control algorithm for a large salient-pole synchronous motor fed by a Load Commutated Inverter (LCI). Many papers have been presented in the past few years on the justification, design, and application of variable-speed drive. The focus of this paper is on high torque operation and the estimation of initial rotor position. The results of simulation indicate that it is possible to produce the maximum torque and estimate the initial rotor position.

Keywords: maximum torque, initial rotor position, large synchronous motor

1. Introduction

The large synchronous motor for the pumped-storage plant (or SFC: Static Frequency Converter) must be brought up to 100% rated speed and synchronized with the AC power network. Starting the motor from the rest position is achieved by switching the current into the stator winding so that interaction between this stator current and the rotor flux will cause the correct amount of torque to be developed, allowing the motor to turn in the required direction. The information pertaining to the rotor position is essential to obtain the required direction of the maximum motor torque. Driving ranges of the synchronous motor are divided into three regions. The first region is at standstill, the second, known as forced commutation is from standstill to 5-8% of rated speed, and the third, known as natural commutation, is from 5-8% of rated speed to 100% rated speed. So this paper describes the control techniques of the pumped-storage synchronous motor drive. In the first region the initial rotor position can't be achieved from the wheel-gear or the stator voltage at standstill. The transient of the stator voltage is generated by injecting the voltage of the static excitor to the rotor winding. The information of the initial rotor position can be achieved from the transient stator voltage. In the second region the amplitude of emf is too small for proper commutation, and a pulse mode of operation must be employed in the source side converter. At very low frequencies of the second region, a three phase auxiliary signal voltage is derived from the rotor position of the wheel-gear. This auxiliary voltage controls the firing pulses for the motor side converter and through a logic circuit, the pulses of the supply side converter. In this mode the forced commutation is performed by the motor side converter. In the third region the motor itself determines the output frequency of the synchronous motor by means of its motor side converter that is an inverter. The stator voltage is sufficient to naturally commutate the inverter. The synchronous motor then runs up to the rated speed and is synchronized with the AC power network.

In this paper, an efficient initial rotor position estimation method without a position sensor, and the maximum torque control method of the large salient-pole synchronous motor are described. Simulation results are presented to verify the effectiveness of the proposed methods.

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2. Initial Rotor Position Estimation

The initial rotor position should be determined in order to accelerate the motor with the full torque. To estimate the initial rotor position before starting, the transient voltages are applied from the exitor to the rotor winding during a short period. When these voltages are applied, the stator voltage responses are different according to the rotor position because the three-phase winding inductances are a function of the rotor position. The initial rotor position can be estimated by using the stator transient voltages measured by the volatage sensor.

Two stationary reference frames can be used for modeling the synchronous machine. One is a 3phase (a-b-c) stationary frame, the other is a 2phase (d–q) stationary frame. If the motor quantities are transformed from the three phase variables to the two phase dq -frame, the voltage equations of the machine become:

$$v_{dq} = Ri_{dq} + e_{dq} \tag{1}$$

$$e_{dq} = \frac{d\psi_{dq}}{dt} \tag{2}$$

where, v_{dq} : motor terminal voltage,

i_{dq} : stator current,

R : stator resistance,

e_{dq} : back emf.

The flux linkages ψ_{dq} are

$$\psi_d = Li_d + \psi_f \cos(\theta) \tag{3}$$

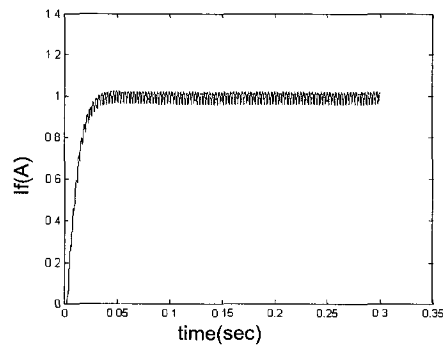
$$\psi_q = Li_q + \psi_f \sin(\theta) \tag{4}$$

where θ is the rotor position.

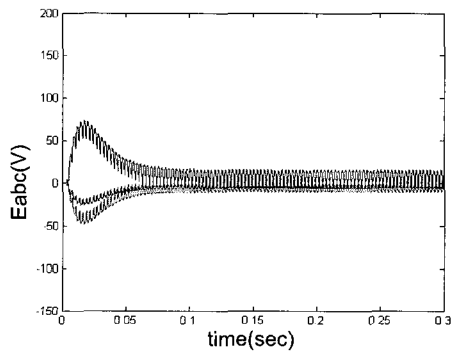
The current is not switched , therefore $i_{dq} = 0$

$$v_{dq} = e_{dq} = \frac{d\psi_{dq}}{dt} \tag{5}$$

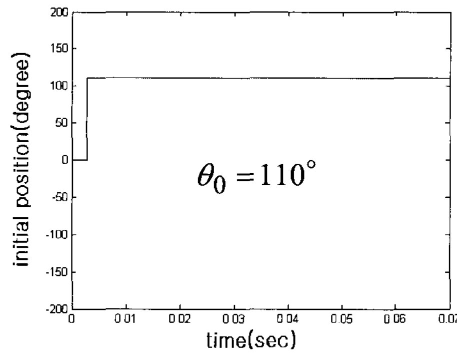
Therefore, the initial rotor position can be calculated using Eq(7) as shown in the following:



(a) the field current injected by the static excitor



(b) the transient 3phase stator voltages



(c) Estimation result when the rotor position is 110 (deg)

Fig. 1 The rotor position estimated from the transient stator voltages

$$\frac{-e_d}{e_q} = \frac{\psi_f \sin(\theta)}{\psi_f \cos(\theta)} = \frac{\sin(\theta)}{\cos(\theta)} = \tan(\theta) \tag{6}$$

$$\therefore \theta = \tan^{-1}(-e_d, e_q) \tag{7}$$

From Fig. 1, it is verified by simulations that the estimation algorithm is suitable.

3. Maximum Torque Operation

The current phase angle is controlled in order to utilize the reluctance torque of the salient pole effectively. As far as we know, in the $i_d = 0$ control method, reluctance torque is not produced even if a salient-pole synchronous motor has saliency. Therefore, there is no need to be bound to the $i_d = 0$ control method. Several control methods that control not only q-axis current but also d-axis current are proposed to improve the ability of a salient-pole synchronous motor system.

In this paper, the effective control method and the drive system, in which the current phase angle is controlled, are implemented for high torque, power factor, efficiency, power capability and so on and are examined in detail by the computer simulations results. The performance characteristics are affected by the motor parameters, which depend on the rotor configurations. This motor will be analyzed using the normal d-q axis representation. In this examination, the d axis is always assumed to be aligned with a rotor pole. When a salient pole motor is analyzed, the motor parameters are functions of the rotor position unless the d-q reference frame is assumed to be rotating synchronously with the rotor. In addition, the field circuit will generate a back EMF only in the q axis if the d axis alignment is along a rotor pole. The back EMF generators in each axis are controlled by the flux linkage in the other axis. They are

$$\psi_{qs} = w_b\left[L_{ls}i_{qs} + L_{mq}\left(i_{qs} + i'_{qr}\right)\right] \quad (8)$$

$$\psi_{ds} = w_b\left[L_{ls}i_{ds} + L_{md}\left(i_{ds} + i'_{dr} + i_{fd}\right)\right] \quad (9)$$

Note the ψ_{qs} and ψ_{ds} represent the base frequency times flux linkage.

The electromagnetic torque developed is given by

$$T = \frac{3}{2}\frac{P}{2}\frac{1}{w_b}\left(\psi_{ds}i_{qs} - \psi_{qs}i_{ds}\right) \quad (10)$$

The rotor currents i'_{dr} and i'_{qr} will be zero in steady state.

Therefore, the eletrictorque in steady state is given by.

$$T = \frac{3}{2}\frac{P}{2}\left[L_{md}i_{fd}i_{qs} + \left(L_{md} - L_{mq}\right)i_{ds}i_{qs}\right] \quad (11)$$

where, L_{ls} : Stator leakage inductance

L_{md} L_{mq} : The magnetizing inductance of d-q axis

w_b : Base frequency

i'_{dr} i'_{qr} : The rotor current of d-q axis

i_{ds} i_{qs} : The stator current of d-q axis

The d and q axes components of the armature current are represented as

$$i_{ds} = -I_a \sin\beta, \quad i_{qs} = I_a \cos\beta \quad (12)$$

where, $I_a = \sqrt{3/2}\, I_p$, I_p is the magnitude of the armature current per phase, and β is the leading angle of armature current from the q-axis.

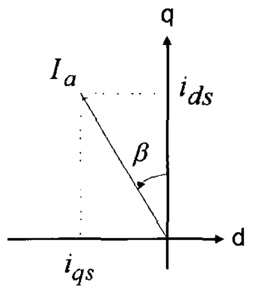


Fig. 2 Phase diagram of current

The Total torque T is represented as follows using I_a and β.

$$T = \frac{3}{2}\frac{P}{2}\left[L_{md}i_{fd}I_a \cos\beta + \left(L_{md} - L_{mq}\right)I_a^2 \sin 2\beta\right] \quad (13)$$

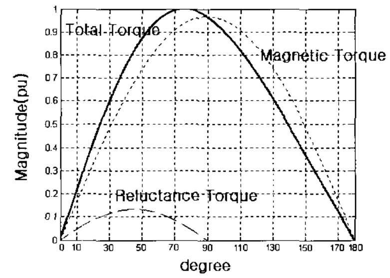


Fig. 3 Comparison of the torque component

Table 1 Specifications of tested salient-pole motor

L_{md}	**723(mH)**
L_{mq}	**494(mH)**
I_{fd}	**1.15(A)**
I_a	**2(A)**

Fig. 3 presents the torque characteristic versus a current phase angle β at the rated current and rated speed. The specifications of the tested salient-pole synchronous motor are listed in Table 1. It can be seen that a suitable current phase angle to improve the characteristics such as torque exists. The optimum current phase angle to produce the maximum torque per current is about 82° in Fig. 3 This phase angle is optimum for high torque operation considering the maximum current constraint. This control method can be applied in the constant torque region of the synchronous motor.

4. Simulation Results

The LCI drive uses a phase controlled rectifier and DC link inductor to provide a smooth unidirectional current to the motor side converter. The motor side converter, a phase controlled thyristor bridge inverter, distributes the DC link current to the three phases of the synchronous machine. When the LCI drive is operating in the steady state, inverter thyristors fire in sequence, one every 60 electrical degrees of operation, and cause the stator MMF vector to rotate by 60 degrees with every switching event. As a result, the complete steady-state operation of the drive can be described by analysis of any interval that is 60 electrical degrees in duration. For starting the motor, the choice of

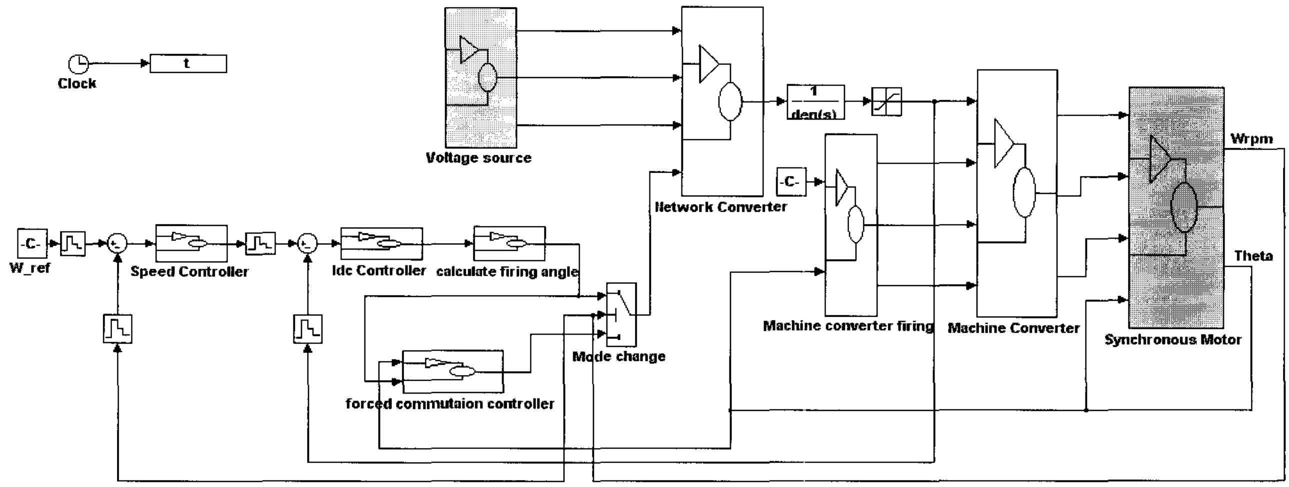


Fig. 4 Simulated models of the synchronous motor drive fed by LCI

switching mode is according to the initial position of rotor obtained by the proposed algorithm.

The simulated models of the drive based on MATLAB SIMULINK toolbox are shown in Fig. 4 The magnitude commands I_{dc} and V_{dc} of the DC link are decided through the Controller, which is a familiar proportional-integral (PI) compensator. The stator current is switched according to the position of the rotor in order to obtain maximum torque. The simulation results for the motor speed, 3phase stator current, DC link voltage and DC link current are as shown in Fig. 5-8 respectively.

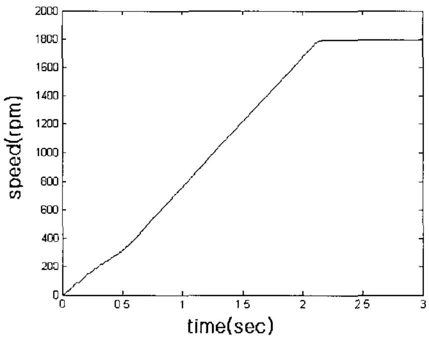


Fig. 5 Motor speed

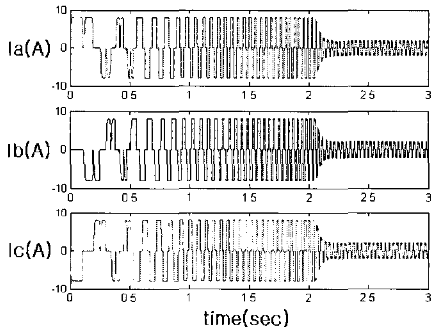


Fig. 6 3phase stator current

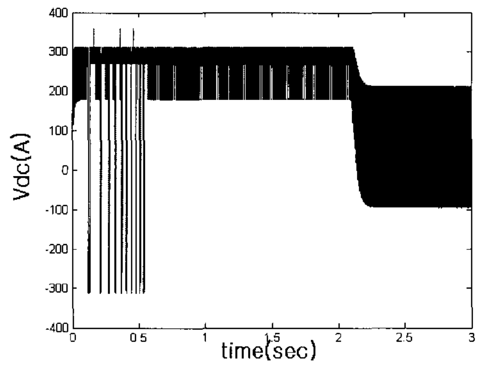


Fig. 7 DC link voltage (Vdc)

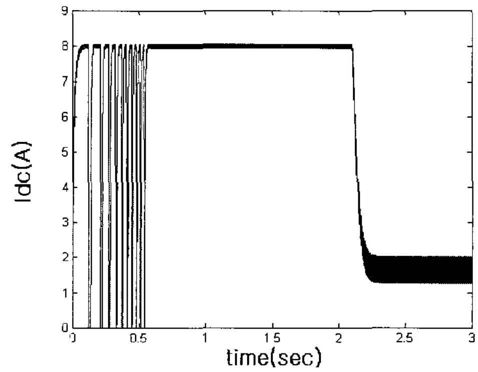


Fig. 8 DC link current (Idc)

At very low frequencies (0~0.5 sec), when the amplitude of the motor voltage is too small for netural commutation, the forced commutation mode of operation is employed. At higher frequencies (0.5~3 sec), the motor itself determines the output frequency of the converter by means of its own stator voltage. And the synchronous motor runs up to the rated speed and is synchronized with the AC power network. When the amplitude of the motor voltage is enough to commutate the motor side converter, the netural commutation mode of operation begins.

Figs. 9 and 10 indicate the simulation results of the d-q axes current waveforms controlled by the $i_d = 0$ control and the maximum torque control. Figs. 11 and 12 show the torque characteristics controlled by the $i_d = 0$ control and the maximum torque control. The torque controlled by the maximum torque control is larger than the $i_d = 0$ control, and the maximum torque control method has a faster speed response than the $i_d = 0$ control method. (see Fig. 13)

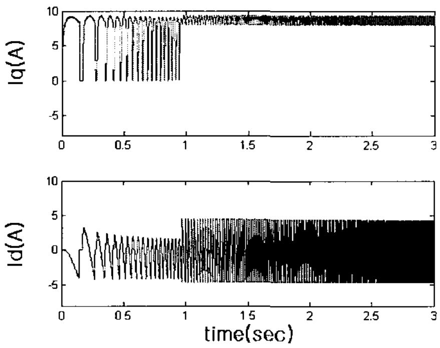


Fig. 9 The stator current in synchronous reference frame by $i_d = 0$ control method

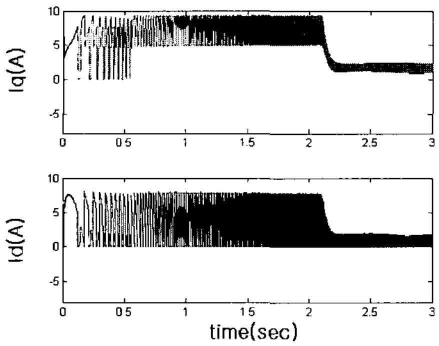


Fig. 10 Stator current in the synchronous reference frame by maximum torque control method

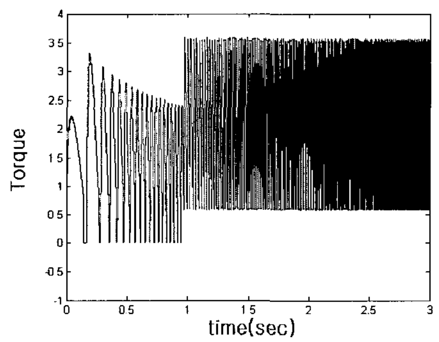


Fig. 11 Motor torque by $i_d = 0$ control method

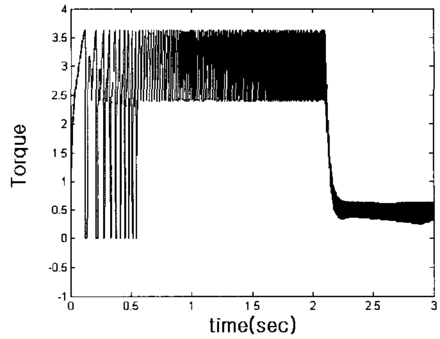
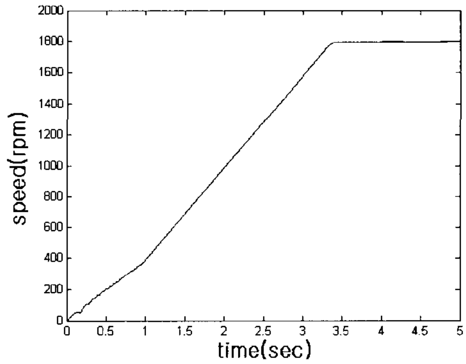
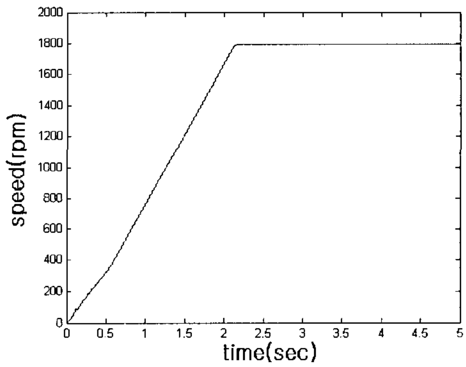


Fig. 12 Motor torque by maximum torque control method



(a) $i_d = 0$ control method



(b) Maximum torque control

Fig. 13 Motor speed

5. Conclusions

This paper has presented the modeling and simulation of a large synchronous motor LCI drive system. The maximum torque control method was proposed for the salient-pole synchronous motor. Through the simulations results, the ability of the maximum torque control is clarified. After the initial position of the rotor is estimated, the stable starting for the reference speed of 1800rpm is achived. The usefulness of the algorithm for the initial position estimation is verified through the computer simulations.

Acknowledgements

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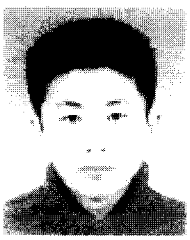

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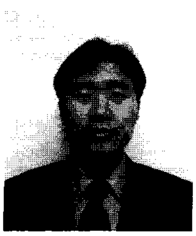

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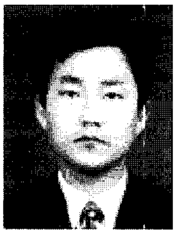

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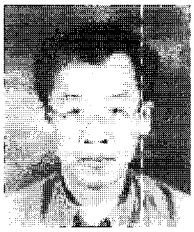

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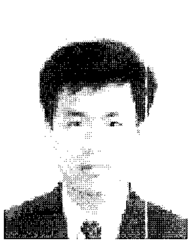

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