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A STUDY ON TWO-DEGREE OF FREEDOM SPEED CONTROLLER FOR SYNCHRONOUS RELUCTANCE MOTOR

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Abstract

Recently, due to increasing adoption of energy-saving policy, SynRM (Synchronous Reluctance Motor) is used as machinery, home appliance, automotive and robotic applications. The features of SynRM are high power, high efficiency and high performance. To obtain a high performance in a direct vector controlled SynRM, it is essential to obtain robust control system of railway vehicle. Two degree of freedom controller is applied to SynRM in order to resist disturbance, error of system. The proper control scheme possesses a prominent aspect in that it can force the systems to follow the desired reference model. The proposed method utilize the combination of PID controller and PD controller. The validity of proposed algorithm is verified through the MATLAB/Simulink and the experimental results.

Introduction

Recently, because of energy saving policy, SynRM(Synchronous Reluctance Motor) which has high efficiency, power and performance is chosen more in robotic application industry for example machinery, home appliance and automotive. As following this, it is getting more activated to trying to improve efficiency of products.

SynRM drives fast or derives in low speed with torque, and it needs high output density. In this paper, it introduces control method that insensitive to rapidly changing loads and frequently varying velocity in train vehicles through two degree-of-freedom controller.

As synchronous reluctance motors have small torque ripple and do not include permanent magnets there is no chance of affecting their performance by decreasing magnetic flux. Without second circuit on rotor side, it has advantage of manufacturing and does not drop off in control efficiency which is bothered with secondary circuit factor. In addition, SynRM can set up same stator structure to existing one, so it has merit to using existing facilities.

For high efficiency of motor controller, we need to make small response overshoot and to reduce recovery time. but traditional speed controller had problem with realizing it.

To solve this problem, parameters of existing PI controller need organic tuning method. Designing PID speed controller which is insensitive to noise is complicated because you need to consider lots of parameters. Therefore, it can be solved by using the two degree-of-freedom controller. This paper suggests control method that is insensitive to rapidly changing loads and frequently varying velocity while maintaining the form of existing PID controllers by applying the two degree-of-freedom control method. IPMSM, PWM 3 phase-invertor current controller and speed controller models are designed and simulated by MATLAB/simulink.

Structure and Mathematical Modeling of the Synchronous Reluctance Motor

The synchronous reluctance motor consists of three-phase stator windings and the rotor of which the reluctance is different from the stators. Below is the representation of the voltage equations in the d-q axes.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_s + pL_d & -\omega L_q \\ \omega L_d & R_s + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \qquad (1)$$

Here,

R_s : resistance of the stator
L_d, L_q : d-axis and q-axis stator inductance
v_d, v_q : d-axis and q-axis stator voltages in rotor frame
i_d, i_q : d-axis and q-axis stator currents in rotor frame
ω : electrical angular velocity
p : differential coefficient

The right-hand side of equation (1) signifies voltage drops by the stator's winding resistance and the d-q inductance. And it shows the interaction between the d-q axes.

SynRM generates torque by using the difference of reluctance. The mathematical modeling of the reluctance torque can be derived by the relationship between current and magnetic flux of the d-q axes and it is represented as follows.

$$T = \frac{3}{2}\frac{P}{2}\left(L_d - L_q\right) i_d i_q \qquad (2)$$

Where P is the number of poles.

Contrary to interior permanent magnet synchronous motor which has reverse-saliency ($L_d<L_q$), SynRM has the forward-salient structure ($L_d<L_q$) as shown in Fig. 1. Therefore

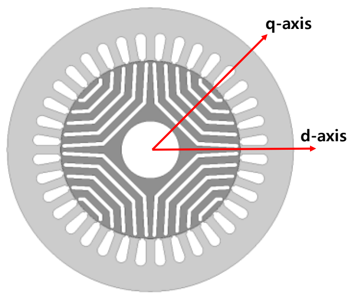


Fig. 1. The d-q axes of SynRM

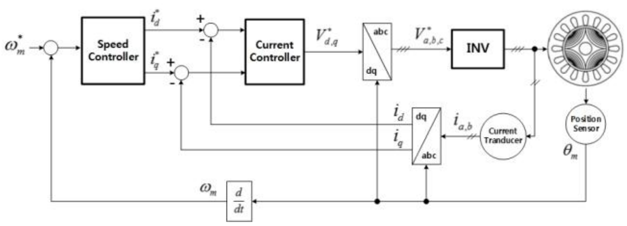


Fig. 2. Block diagram of speed-controlling system for SynRM

positive current should be applied to the d-q axes in order to generate torque. Because SynRM doesn't have permanent magnets, it generates only the reluctance torque but not the magetic torque. And the following equation indicates the d-q current that makes the maximum torque per unit current.

$$i_d = i_q = \frac{I_a}{\sqrt{2}} \tag{3}$$

I_a is the value of the stator's current. Fig. 2 shows SynRM's speed-controlling system using (3).

Design of a Two Degree-of-Freedom Speed Controllers for Synchronous Reluctance Motors

For existing PID speed controllers, tuning of control parameters are necessary to cope with frequent speed change and rapidly varying loads. Using the existing PID controllers for systems with conditions mentioned above requires additional designs of controllers to satisfy all specifications given. However, you can avoid additional designs of controllers by using the two degree-of-freedom speed controllers. Such two degree-of-freedom speed controlling method are suggested in this paper.

In Fig. 3, you can observe step responses of D, PI, and PID controllers. PD controllers show fast response but large overshoot. In contrast, PI controllers show small overshoot but slow response. PID controllers exhibit intermediate characteristics between PD and PI controllers. In these three controllers, overshoots and speed of responses are inversely proportional to each other. On the other hand, PID-PD controllers constructed by combining PID and PD controllers

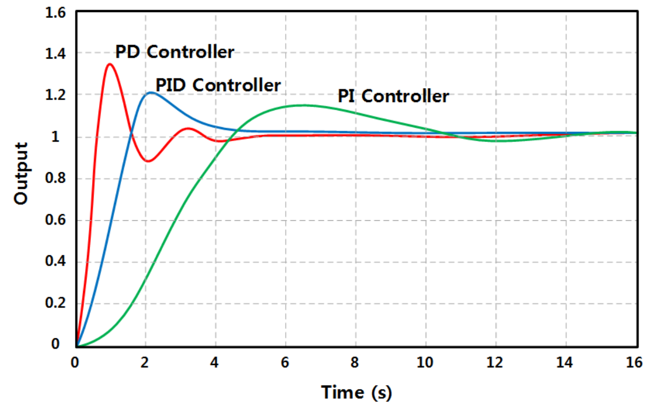


Fig. 3. Step response of PD, PI, PID controllers

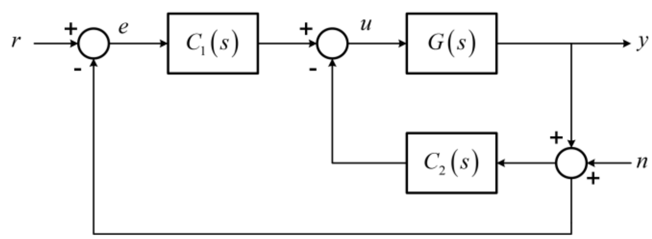


Fig. 4. Block diagram of modified PID controller

improve speed of responses in an acceptable range of overshoot. PID-PD controllers have another benefit in that you can change the gain of the controllers in accordance with varying loads. Fig. 4 shows the block diagram of PID-PD controllers suggested in this paper. $C_1(s)$, $C_2(s)$ are respectively PID and PD controllers which have transient responses as shown in Fig. 3. They can be obtained by

$$C_1(s) = C_{pid}(s) = K_{p1}\left(1 + \frac{1}{T_{i1}s} + T_{d1}s\right) \tag{4}$$

$$C_2(s) = C_{pd}(s) = K_{p1}\left(1 + T_{d2}s\right) \tag{5}$$

Closed-loop transfer functions of PID, PI-PD, PID-PD controllers are respectively expressed in equations (6), (7) and (8). G(s) is transfer fuction of SynRM.

$$G_{pid}(s) = \frac{C_{pid}G(s)}{1 + C_{pid}(s)G(s)} \tag{6}$$

$$G_{pipd}(s) = \frac{C_{pi}G(s)}{1 + \left(C_{pi}(s) + C_{pd}(s)\right)G(s)} \tag{7}$$

$$G_{pidpd}(s) = \frac{C_{pid}G(s)}{1 + \left(C_{pid}(s) + C_{pd}(s)\right)G(s)} \tag{8}$$

Convex set C is defined as follows.

① In set C where it satisfies $C \subseteq R^n$, if $x_1, x_2 \in C$ and $0 \le m \le 1$, then $mx_1 + (1-m)x_2 \in C$.

Table 1. Specifications of SynRM

Parameter	Value
Power rating [KW]	2.2
Phase Current [Apk]	8.484
DC Link Voltage [V]	540
Induced voltage [Vpk]	279.71
R_s [mΩ]	1.08
L_d [mL]	205
L_q [mL]	29
Pole	4

② $mx_1 + (1-m)x_2$ is located somewhere between x_1 and x_2.

It applies to time domain responses of systems such as one in equation (7) which satisfies $0 \le m \le 1$. Step response of system $G_m(s)$ which is equation (7) shows intermediate response between reponses of systems $G_1(s)$ and $G_2(s)$.

$$G_m(s) = mG_1(s) + (1-m)G_2(s) \qquad (9)$$

This property has been proved by Haitham and applied to design of controllers. However, this controller is dependent on two systems $G_1(s)$ and $G_2(s)$ that constitute the convex set and as a result, orders and structure fo the controller are not consistent. This problem can be solved by transforming PID controllers which are widely used now. PID-PD system can be expressed by using convex set of PID and PI-PD systems.

Equation (10) is transfer function of the PID-PD controller derived by mathematical modeling suggested above.

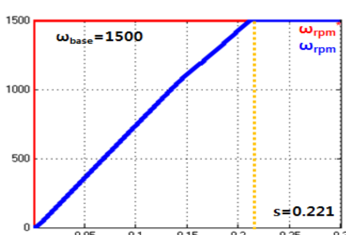
$$G_{pidpd}(s) = \frac{\left(K_{p1} + \frac{K_{i1}}{s} + K_{d1}s\right)G(s)}{1 + \left(K_{p1} + \frac{K_{i1}}{s} + K_{d1}s + K_{p2} + K_{d2}s\right)G(s)} \qquad (10)$$

Equations (11), (12) can be used to express equation (10) by collecting the terms with P gain and D gain together. Assuming that sum of them are constants, they are left with one variable *m*.

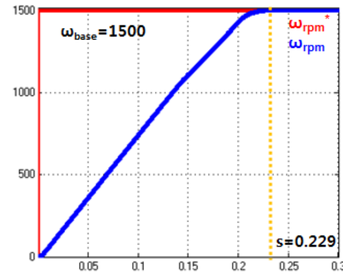
$$K_p = mK_{p1} + (1-m)K_{p2} \qquad (11)$$

$$K_d = mK_{d1} + (1-m)K_{d2} \qquad (12)$$

Simulation and Experiment



(a)



(b)

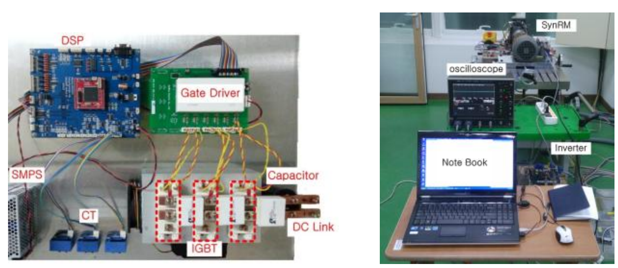
Fig. 5. Reponses in rated speed (a) The traditional speed controller (b) The suggested speed controller

A. Simulation results

The mechanical specifications of SynRM used in the simulation are the same as Table 1. and it was modeled using MATLAB/Simulink. The results of 1500rpm reference speed are indicated in Figure 4. Fig. 5(a) shows results using just PID controller, whereas Fig. 5(b) reveals results using PID-PD controller. In comparison with settling time of both controllers through Fig. 4, settling time of PID-PD controller is shorter than that of PID controller. that is, in rapid response, it is faster when PID-PD controller is used. Also, it is found that overshoot of PID-PD is smaller 0.9% than that of PID.

B. Test results

To verify the validness of suggested PID-PD controller, 2.2kW SynRM like Table 1. used in test. As indicated in Fig. 6(a), through PWM inverter, it applies a voltage to the motor and TMS320F28335 DSP of TI company is used for motor control. Fig. 6(b) illustrates test environment for this experiment.



(a) (b)

Fig. 6. SynRM test set (a) The motor drive system (b) The test enviroment

Fig. 7. presents response of traditional PID controller and suggested PID-PD controller. Likewise simulation results, it indicated that settling time of PID-PD is shorter than that of

PID. In case of overshoot, that of PID-PD is smaller 0.87% than that of PID.

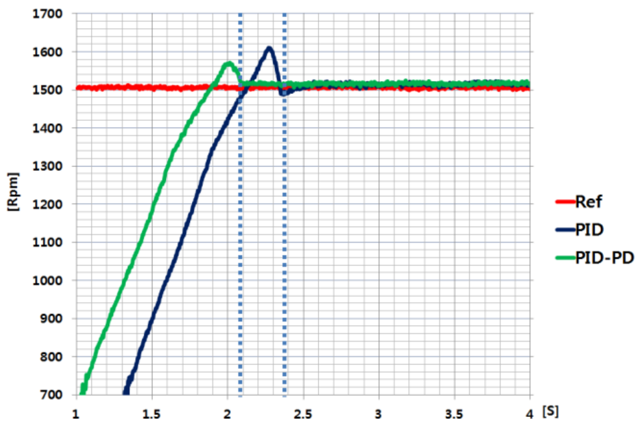


Fig. 7. SynRM test control response results

Conclusion

From the above results, this paper indicates that it is possible to perform optimal control regardless of fluctuation of Load varying value as a system required performance if suggested PID-PD controller is used. Particularly, in railway vehicles with the frequent speed variation and rapidly changing load, robust control is possible.

PID control has been widely used due to simplicity of design along with excellence of performance in system control. However, there is a case unable to demonstrate sufficient performance with only this PID control. So, a revised PID control with inner feedback has been issued. This paper suggests the way using feature of block-type set to controller design by setting PID-PD controller, one of the revised PID controller to form block-type set of closed-loop transfer function, with PID controller and PD controller. Also, taking advantage of one parameter variation through two-dimension of Freedom speed controlling method, it is possible to select and use excellent performance.

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