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Method Controlling Two or More Sets of PMSM by One Inverter on a Railway Vehicle

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Abstract – If two or more Permanent Magnet Synchronous Motors (PMSM) can be controlled by one inverter, a train can be driven by less energy than the present Induction Motor (IM) drive system. First, this paper proposes a method for simulating the movement of wheels and a vehicle to develop a control method. Next, a method is presented for controlling two or more PMSMs by one inverter.

Keywords: Multi Motor Drive, Railway Vehicle, Synchronous Machine

1. Introduction

Trains are now being driven by mainly operating two or more induction motors by one inverter. However, trains could be made more efficient by using a permanent magnet synchronous motor (PMSM) instead of an induction motor. Fig. 1 shows a railway vehicle model that can be run by plural PMSMs and one inverter. This paper proposes a method for simulating movement of wheels and a vehicle for an electricity system package program (PSIM) and a control method in which one inverter is used to control two or more PMSMs that have different magnetic pole positions.

2. Modeling of Driving Part

Fig. 2 shows a wheel movement simulation model. The wheel sits on the disk (called a rail disk) equivalent to an endless rail, and the disk is rotated by friction between the wheel and the disk. The wheel is joined to the axis of the PMSM. (In practice, in the structure of a railway vehicle, motor power is transmitted to wheel through reduction gears. However, it is transmitted directly in this simulation.) Fig. 2 explains the of motion caused by the side of a wheel and a rail disk. The positive rotation direction is defined as the direction of the arrow in Fig. 2. (1) shows the of motion for a wheel. Jr is the moment of inertia of a wheel.

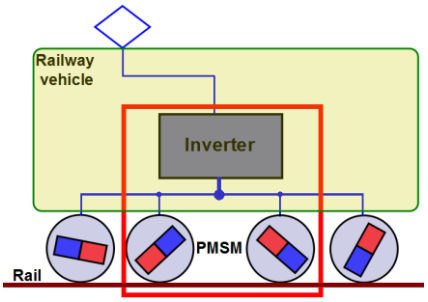

Fig. 1. Vehicle model to be controlled by plural PMSM and single inverter

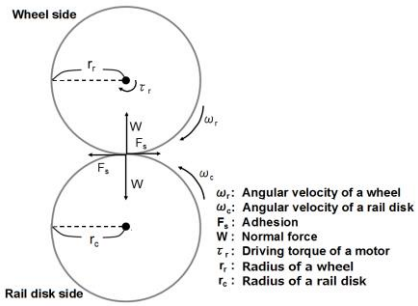

Fig. 2. Wheel movement simulation model

$$J_r \frac{d\omega_r}{dt} = \tau_r - \tau_s \quad (1)$$

(2) shows the of motion for a rail disk. Jc is the moment of inertia of a rail disk.

$$J_c \frac{d\omega_c}{dt} = \tau_s - \tau_c \quad (2)$$

The power Fs committed between a wheel and a rail disk is explained. Fs is a power called the adhesion, which arises at the contact point of a wheel and a disk. (3) shows the

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formula that calculates Fs. μ is the adhesion coefficient, and W is the normal reaction.

$$F_s = \mu W \tag{3}$$

If the wheel is faster than the rail disk, the adhesion coefficient μ is a value determined by the slip ratio s of the rail disk speed and wheel speed.

(4) shows the formula that calculates slip ratio s.

$$s = \frac{\omega_r r_r - \omega_c r_c}{\omega_r r_r} \tag{4}$$

Fig. 3 shows a general relationship between the adhesion coefficient μ and slip ratio s [1]. The value of slip ratio s is less than 1% where the adhesion coefficient μ maximizes. The adhesion hinders rotation of a wheel, but it rotates a rail disk. The simulation method for movement of wheels and a vehicle is described. (5) shows the fundamental of rotational motion. J expresses the moment of inertia, ω expresses rotary speed, and τ expresses torque.

$$J \frac{d\omega}{dt} = \tau \tag{5}$$

(6) shows the fundamental electrical of a capacitor circuit. C expresses capacitance, V expresses a voltage, and I expresses an electric current.

$$C \frac{dV}{dt} = I \tag{6}$$

[Mechanical-Electrical interface block] can be used in PSIM, which makes it possible to think the electric (6) is equivalent to the mechanical (5). By this interface, the equivalent circuit of the exercise can be made electrically on PSIM. Therefore, the wheel movement is simulated on the simulator by simulating the circuit of motion of the wheel movement. The following description explains that a capacitance C, an inertia moment J, a voltage V applied to C, are equivalent to a rotation speed ω, a current I, and a torque τ, respectively. (7) shows the electric that is equivalent to (1).

$$C_r \frac{dV_r}{dt} = I_r - I_s \tag{7}$$

(8) shows the electric that is equivalent to (2).

$$C_c \frac{dV_c}{dt} = I_s - I_c \tag{8}$$

Fig. 4(a) and (b) show equivalent circuits of (7) and (8). As shown in Fig. 4, the wheel movement was si mulated on the simulator by simulating the circuit of m otion of the wheel movement. For a simulation metho d for the adhesion, Fig. 5 shows a circuit outputting th e adhesion. Wc and Wr in Fig. 5 represent angular vel ocity of a rail disk ωc and angular velocity of the whe el ωr. To operate the circuit in Fig. 5, first rate s from (4) is calculated using angular velocity. Next, the adhe sion coefficient μ is calculated from the

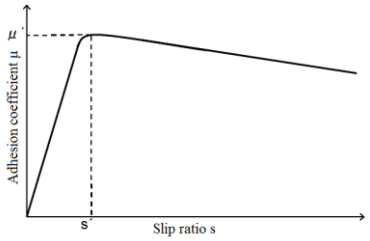
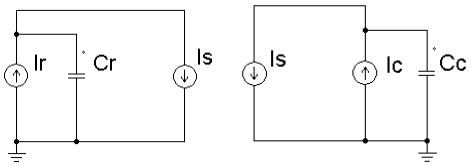


Fig. 3. Relationship between adhesion coefficient μ and slip ratio s



(a) Case of (7) (b) Case of (8)

Fig. 4. Equivalent circuits of (7) and (8)

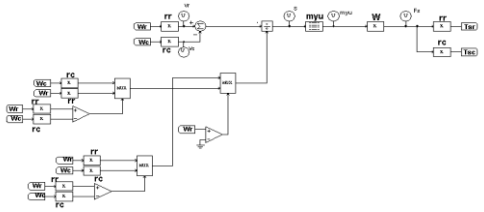


Fig. 5. Circuit of outputting the adhesion

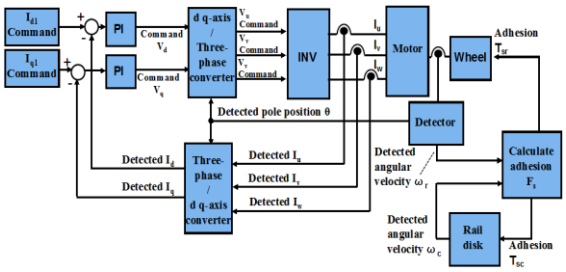


Fig. 6. Block diagram of wheel motion simulation for one wheel

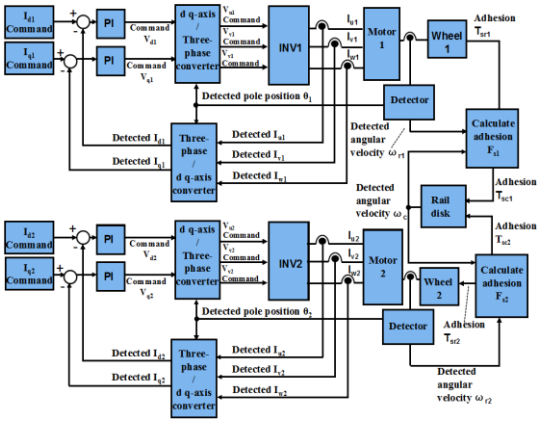


Fig. 7. Block diagram of wheel motion simulation for two wheels

calculated slip ratio s. Myu in Figure 5 represents the function block, and it outputs the adhesion coefficient μ corresponding to that in Fig. 3 by inputting the value of the calculated slip rate s.

Thereafter, the adhesion Fs is calculated from (3). Next, the adhesion torque Tsr and Tsc is calculated from the radius of the disk. Finally, the value of calculated adhesion torque is outputted to the circuit as current source Isr and Isc.

Fig. 6 shows a block diagram of wheel motion simulation for one wheel. Vector control is used to control PMSM. Also, if two or more wheels ride on the rail, they are simulated as well. Fig. 7 shows a block diagram of wheel motion simulation for two wheels. Two inverters control the PMPM, and the adhesion arises between each of the rails and wheels.

3. Consideration of Control Method

Fig. 8 shows the model of two PMSMs in which the magnetic pole position differs and one inverter. If PMSM is controlled using the vector control, PMSM is controlled on the dq-axis coordinates that are calculated by the detected magnetic pole position. When two PMSMs that have different magnetic pole positions are driven by a single inverter, if the vector is controlled in accordance with the magnetic pole position of one side of PMSM, the other side of PMSM is controlled by an angle that deviates from the actual position of the magnetic pole. For the other side of PMSM, when PMSM is controlled by an angle that deviates from the actual position of the magnetic pole, considering how the deviation affects the output torque. Evaluation is carried out by giving an error of an angle X to the angle θ that is actually detected. Fig. 9 shows a block diagram of granting a magnetic pole position error X. In this case, vector control is performed in one PMSM by the error detection angle θ '(= θ + X) using one inverter. Simulating in Fig9 in the case that giving the detected angle error X = [0,10,20,30, ... ,360]. Measuring the output torque τR and q-axis current Iq in this simulate.

Fig. 10 shows the relationship between the output torque τr and the detection error angle X. The vertical axis in Fig. 10 shows the percentage of the output torque to the current when the percentage is defined as 100% at X = 0. In Fig. 10, the relationship between detection angle error X and output torque τr becomes τr=cosX. The relationship between the output torque and the detection error X became cos waveform. For this reason, the output torque is determined by the size of Iq. However, the q-axis current Iq of the detection error direction is controlled in a direction shifted θ from the no error direction. Therefore, it is considered that real Iq becomes a value that is multiplied by cosθ to the Iq of the detection error direction. Therefore, the decrease in output torque is acceptable to some extent if there is detection error X in the range of around +-20 degrees. However, further error is hard to permit.

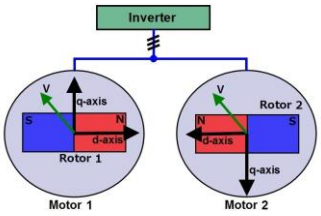


Fig. 8. Model of two PMSMs

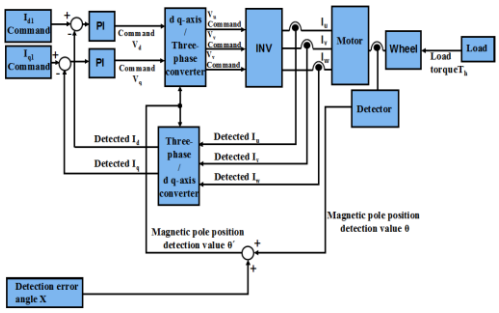


Fig. 9. Block diagram of granting a magnetic pole position error X

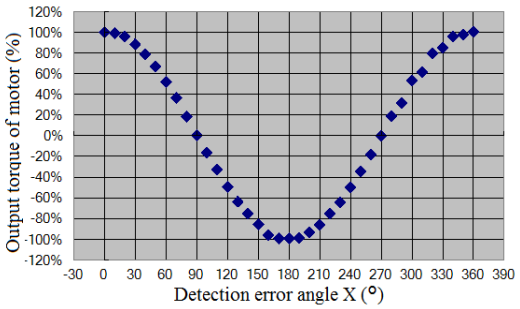


Fig. 10. Relationship between output torque of the motor and detection error angle X

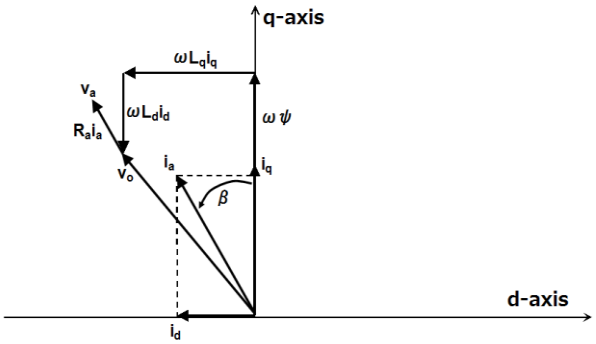


Fig. 11. Vector plot of PMSM

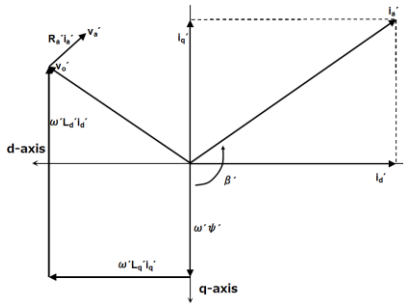


Fig. 12. Vector plot of PMSM in which there is the difference in magnetic pole position of 180 degrees in the case of Fig.11

Simultaneous s of dq-axis coordinate system of the PMSM is given by

$$\cdot\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R_a + pL_d & -\omega L_q \\ \omega L_d & R_a + pL_q \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega\psi \end{bmatrix} \quad (9)$$

In (9), ψ is the effective value of the armature flux linkage by the permanent magnet, ω is the angular velo city electricity, Ra is the armature winding resistance, p is the differential operator, Vd and Vq are dq-axis co mponents of the armature voltage, Id and Iq are dq-axi s components of the armature current, and Ld and Lq are dq axis inductances.

Figs. 11 and 12 show each vector plot of PMSM that has a difference in the magnetic pole position of 180 degrees. In Figs. 11 and 12, vector of the induced voltage ωψ differs with magnetic pole position. Therefore, the voltage applied (= Vo + Va-ωψ) is different at motors 1 and 2. Therefore, the current Ia' flowing through motor 2 and the current Ia flowing through motor 1 have different phases and amplitudes.

For d-axis and q-axis current, Iq' is a negative value whereas Iq is positive. Furthermore, both Id and Id' are negative values, but they have different values. It is considered that since both directions of the d and q axes of two motors may be changed by the magnetic pole position, the value of d-axis and q-axis current flowing to motor 2 and the d-axis and q-axis current flowing to motor 1 become different values.

4. Control Algorithm

The method to control two PMSMs that have different magnetic pole position using one inverter is considered by using the vector plot. The differences in torque and current of two motors are caused by the difference in magnetic pole position. Therefore, the control method is proposed by adjusting the position of magnetic poles, and next the vector control is performed for motor 1. The voltages injected into motors 1 and 2 by the inverter are the same. Therefore, Id and Iq of the controlled motor can be controlled by using a current sensing value of the controlled motor. Therefore, this method mainly controls motor 1 by using its current value.

It is considered that to adjust the magnetic pole position, motors 1 and 2 should be rotated separately so that the magnetic pole position approaches the others. The difference in the magnetic pole position of two motors is in the range of $-180 < (\theta 2\text{-}\theta 1) \leq 180$. In the range of $-180 < (\theta 2\text{-}\theta 1) < 0$, θ2 is more delayed than θ1. Therefore, the magnetic pole position can be adjusted by rotating motor 1 in reverse and motor 2 forward. Also, in the range of $180 \geq (\theta 2\text{-}\theta 1) > 0$, θ2 advances more than θ1.

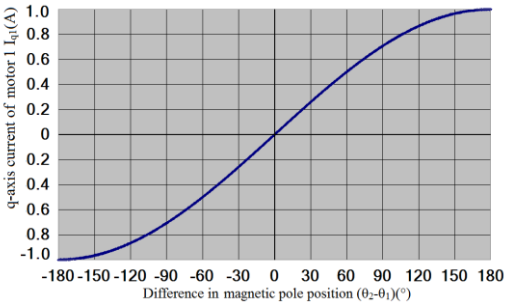


Fig. 13. Relationship between q-axis current of motor 1 I_{q1}(A) and difference in magnetic pole position $(\theta_2\text{-}\theta_1)$(°)

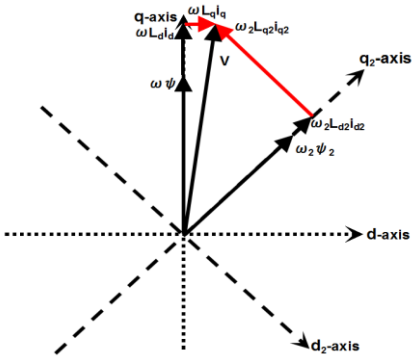


Fig. 14. Vector diagram that is plotted by (11) when proposed control method is perfor med in the range of $-180 < (\theta 2\text{-}\theta 1) < 0$

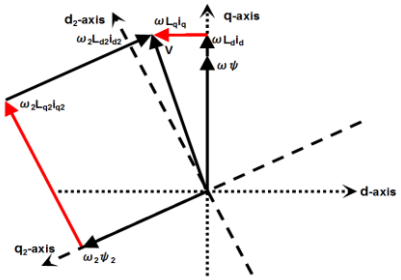


Fig. 15. Vector diagram plotted by (11) when control is performed to be proposed in the range of $180 \geq (\theta_2\text{-}\theta_1) > 0$

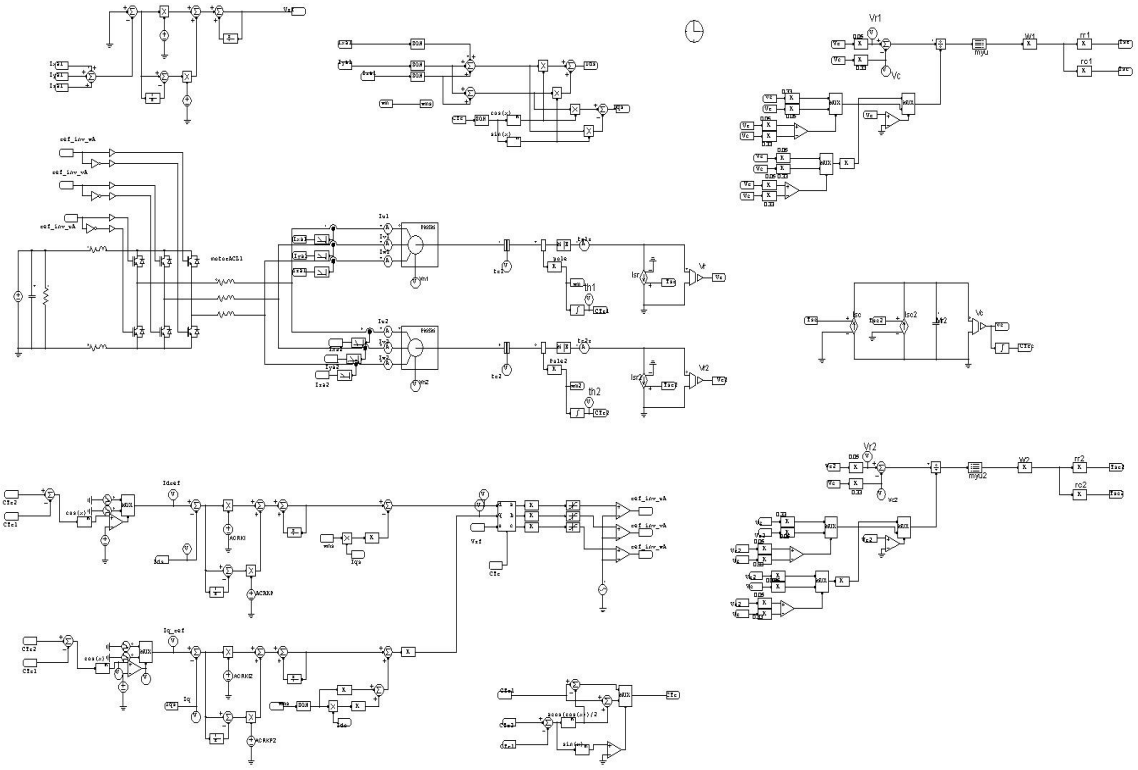


Fig. 16. Overall view of circuit on simulator (PSM)

Therefore, the magnetic pole position can be adjusted by rotating motor 1 forward and motor 2 in reverse. For Iq (q-axis current of the motor), by controlling the value of the negative Iq, the motor can be rotated in reverse. Additionally, by controlling the value of the positive Iq, the motor can be rotated forward. The direction of rotation is controlled by controlling Iq. Furthermore, it is considered that the position of the magnetic pole might be able to be adjusted faster by controlling Iq1 to a bigger value as the difference of the magnetic pole position becomes larger. Therefore, Iq1 is controlled to a bigger value as the difference in the magnetic pole position becomes larger.

The control method is described above. This method mainly controls motor 1 by using its current value. The magnetic pole position detection θ' to be used in the control is calculated as $\theta' = \theta 1 + (\theta 2 - \theta 1)/2$ in this method. When θ1 is different from θ2 ($\cos(\theta 2 - \theta 1) < 0.999$), to adjust the magnetic pole position of two motors by a large torque currents as soon as possible, d-axis and q-axis current command value is controlled to Id1=constant(A) Iq1=0(A). When θ1 and θ2 are adjusted ($\cos(\theta 2 - \theta 1) \geq 0.999$), d-q-axis current command values are controlled to Id1=0(A) Iq1=constant(A). The methods used are called "the proposed control method" and "the magnetic pole position adjustment control method". To explain the logic of the position adjustment that is performed by this control method. When the detection pole position θ ' is $\{\theta 1 + (\theta 2 - \theta 1) / 2\}$, Iq is 0, and Id is 1, torque component of motor 1 Iq1 is calculated by

$$I_{q1} = \sin\{(\theta_2 - \theta_1)/2\} \quad (10)$$

In (10), Fig. 13 shows the relationship between q-axis current of motor 1 Iq1(A) and the difference in the magnetic pole position (θ2-θ1)(°) in a graph. From Fig.13, it is possible to output a large torque current Iq1 as the difference in the magnetic pole position is large.

In the range $-180 < (\theta 2 - \theta 1) < 0$, negative torque current is output. In the range $180 \geq (\theta 2 - \theta 1) > 0$, positive torque current is output. Therefore, it is considered that control can be performed to adjust the magnetic pole position as described above by the proposed method. Because voltage Va applied to the armature winding resistance Ra is a small value, Vo of motors 2 and motor 1 are assumed to be a similar value. Furthermore, motors is assumed to be a steady state. In this case, simultaneous s of dq-axis coordinate system of the PMSM are given by

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R_a + pL_d & -\omega L_q \\ \omega L_d & R_a + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega\psi \end{bmatrix} \quad (11)$$

Fig. 14 shows the vector diagram that is plotted by (11) in the case of the performance of a control to be proposed in the range of $-180 < (\theta 2 - \theta 1) < 0$. Id and Iq of motor 2 are determined by the difference in the induced voltage of motor 2 ωψ and Vo. Because Id and Iq are controlled to Id1 > 0 and

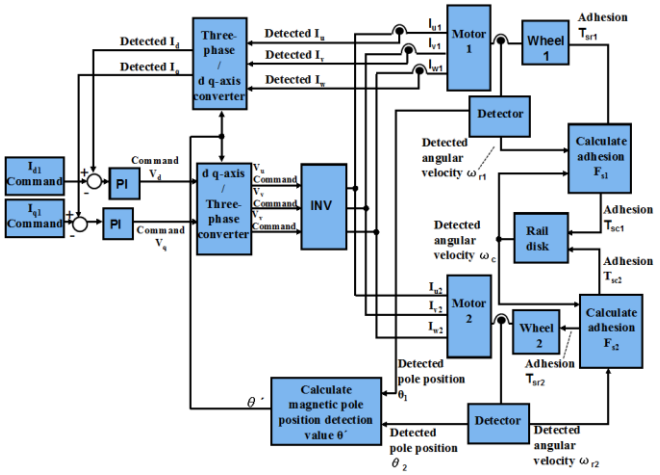


Fig. 17. Overall structure of proposed method

Iq1 < 0, Iq2 of motor 2 is positive from Fig. 14 in this range. Therefore, motor 1 rotates in reverse, and motor 2 rotates forward.

Fig. 15 shows the vector diagram that is plotted by (11) when the proposed control method is performed in the range of 180 ≥ (θ2-θ1) > 0. Because Id and Iq are controlled to Id1> 0 and Iq1 >0, in this range, Iq2 of motor 2 is negative from Fig. 15. Therefore, motor 1 rotates forward, and motor 2 rotates in reverse.

After adjustment, for θ1 = θ2, the magnetic pole position detection value becomes θ'= θ1 + (θ2-θ1) / 2 = θ1 = θ2.

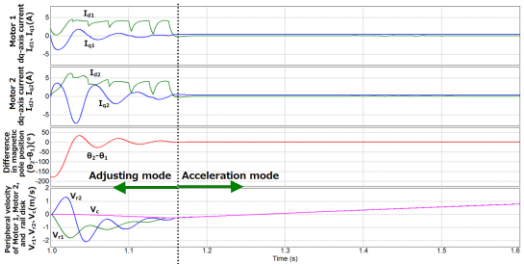


Fig. 18. Results in the case of (θ_2-θ_1=180(°))

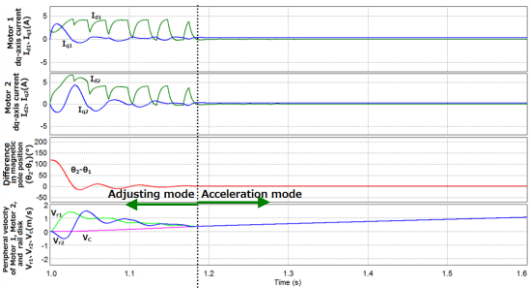


Fig. 19. Results in the case of (θ_2-θ_1=120(°))

From this, it is considered that by controlling Iq1=1 and Id1=0, q-axis current of motors 1 and 2 will be Iq1 = Iq2 = 1, and d-axis current of motors 1 and 2 will be Id1 = Id2 = 0, and motors 1 and 2 will be similarly rotated. Fig. 16 shows the overall view of the circuit on the simulator (PSIM).Fig.17 shows the overall structure of the proposed method.

One inverter controls two PMSMs. Control of the motor is vector control using the current value of motor 1 and the magnetic pole position detection value θ´.

5. Simulation Results

Figs. 18, 19, and 20 show graphs of the results of simulation of dq-axis current of motors 1 and 2, Id1 (A), Iq1 (A), Id2 (A), Iq2 (A), pole position of motor 1 and 2, θ1 (°), θ2 (°), difference in the magnetic pole position θ2-θ1 (°), peripheral velocity of the wheel of motors 1 and 2 Vr1 (m / s), Vr2 (m / s), and peripheral velocity V_c of the rail disk (m / s). Fig. 18 shows the results when the difference in the initial magnetic pole position of θ1 and θ2 is 180 degrees. Fig. 19 shows the results when the difference in the initial magnetic pole position of θ1 and θ2 is 120 degrees. Fig. 20 shows the results when the difference in the initial magnetic pole position of θ1 and θ2 is -120 degrees. Since the control is performed to shift the pole position until t = 1(s), the figures show results for after t = 1(s).

From Figs. 18, 19, and 20, Iq1 is positive when (θ2 -θ1) is positive, Iq1 is also negative when (θ2-θ1) is n egative, and Iq1 is greater when the value of (θ2-θ1) is larger. That is, Iq1 has a value nearly proportional to t he difference in the magnetic pole position (θ2-θ1).

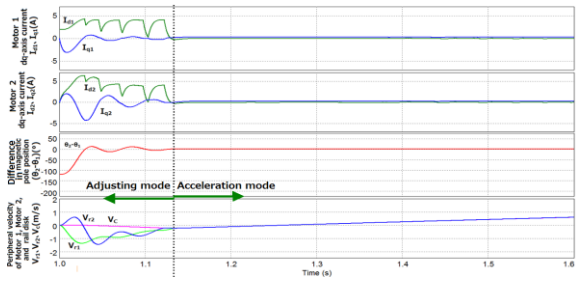


Fig. 20. Results in the case of (θ_2-θ_1=-120(°))

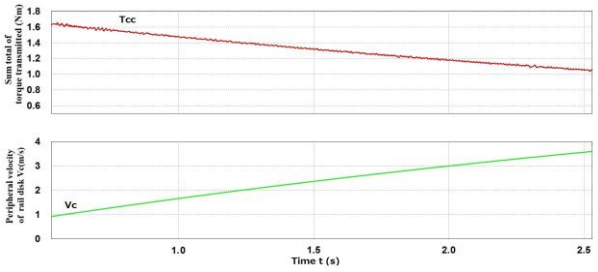


Fig. 21. Results for individual control in two inverters

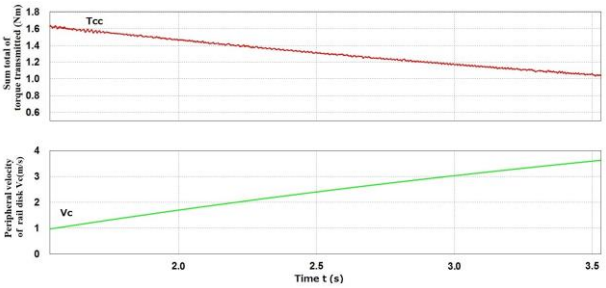


Fig. 22. Results of proposed control method

Also, for Iq2, when the difference in the magnetic po le position is large enough, Iq2 moves to the opposite sign of Iq1. It is thought that this behavior is caused b y the proposed control method and Iq1 and Iq2 were o perated as proposed. From Figs. 18, 19, and 20, motor 2 and motor 1 are put into a state of idling slip by lar ge Iq flows. Thus, magnetic pole positions can be adjus ted in states in which the rail wheel is little affected. I t is found that motor 2 and motor 1 rotate in different directions of the magnetic pole position in a state of id ling slip. The magnetic pole position of the motor and circumferential speed of the wheel appear to vibrate. Th is is because the magnetic pole position of the two mot ors was adjusted abruptly from different locations. Ther efore, it is considered that magnetic pole positions of t he two motors would pass each other because there is no torque to act as a brake in the reverse direction. Af ter the two magnetic pole positions pass each other, tor que is applied to both in the opposite direction in order to make them match. Thus, both magnetic pole positio ns as appear to vibrate. Since the difference in the ma gnetic pole position (θ2-θ1) becomes 0 at t ≈ 1.2 (s), i t turns out that the magnetic pole positions can be adju sted.

6. Comparison with Individual Control

After magnetic pole positions were adjusted, the proposed control method and the individual control in two inverters were compared in terms of the sum total of the torque transmitted from two wheels to a disk by adhesion. Fig. 21 shows the results of the individual control in two inverters. Fig. 22 shows the results of the proposed control method. From Figs. 21 and 22, both methods transmitted the same adhesion torque. Therefore, two sets of PMSM can be controlled by one inverter in the proposed control methods.

7. Conclusion

This paper proposes a control method for two or more PMSMs using a one inverter. In the simulation results, two sets of PMSM were able to be controlled by using one inverter.

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