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RESEARCH ON RESTART METHOD OF PERMANENT MAGNET SYNCHRONOUS TRACTION MOTORS DURING COASTING FOR HIGH-SPEED TRAIN

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ABSTRACT

Permanent magnet synchronous motors（PMSMs）have been more and more interesting for railway vehicle traction system because of their high efficiency and light weight. For the existing of permanent magnet material, the back EMF can be generated during coasting. The inverter components may be destroyed without proper control, when the peak value of back EMF is higher than its withstand voltage. Presently, there are two ways to solve the problem: reducing synthesized air-gap flux linkage by adding negative d-axis current during coasting which can reduce the efficiency, or adding some contactors between inverter and PMSM which is commonly used. But when close the contactors, the phase and frequency of the output voltage of inverter should agree with that of the back EMF to ensure system security.In this paper, an integrated control method of PMSMs during coasting when applied to high speed train is proposed. Based on the mathematical model of PMSM in the synchronous rotating reference frame, the relationship between stator currents, stator voltage and back EMF is analyzed. Then a closed-loop restarting control method after coasting is designed: add an gradual voltage to ensure the smooth switching from coasting to traction or brake. As it has turned out by the simulation results, the method is correct and effective.

KEYWORDS

High speed train, PMSM, coasting, back EMF, contactors, re-closing, voltage gradual regulation.

I. INTRODUCTION

Permanent magnet synchronous motors (PMSMs) have been widely used in industrial manufacture and civil products with the merits such as little volume, light weight, high efficiency and power factor and high reliability, etc. With the emergence of new permanent magnet material, modern PMSM has been developed to the direction with high power and speed and has been widely used in traction system(Jianghua Feng et al., 2007).

For the existing of permanent magnet material, the coupled flux linkage between stator and rotor can be generated even without supply of exterior power. When PMSM is applied to railway vehicle traction system, the back EMF can be generated during coasting. The inverter components may be destroyed, when the peak value of back EMF is higher than its withstand voltage. During coasting, if the flux-linkage produced by permanent magnet material is so high that the peak value of back EMF is higher than the DC input voltage value of inverter, the regeneration brake may appear for the back EMF commutated by the circuit which is composed of diodes reverse paralleled with the inverter switch components (Hao Zhu et al., 2007). On the other hand, it is difficult to re-close the PMSM for the existing of high back EMF. In order to apply PMSM to railway vehicle traction system, the problem of high back EMF must be solved.

When PMSM is applied to railway vehicle traction system, in order to solve the high back EMF and the difficult of re-closing, the easy way may be thought is to reduce the back EMF of PMSM. We should guarantee the maximum back EMF value of PMSM less than DC input voltage value of the inverter.

To restrict back EMF, a negative d-axis current must be added even without output torque during coasting. The copper loss is generated when negative d-axis current added during coasting, which can result in a lower efficiency.

Usually, there are another way for the back EMF problem, adding some contactors between the inverter and the PMSM. In this situation, when the PMSM is coasting, we break the contactors, the generation operation or destroying of inverter components won’t happen of course. But when reclose the contactors, the phase and frequency of the output voltage of inverter should agree with that of the back EMF to ensure system security.

In this paper, we suggest a new restart method for high-speed train during coasting with contactors between the inverter and PMSM. In the proposed control method, the phase angle and frequency of back EMF is observed in order to match the angle and frequency of the output voltage from the inverter. Furthermore, we proposed the design method with gradual voltage regulation. Finally, we verified the novel control method to ensure that it is feasible enough.

II. MATHEMATICAL MODEL OF PMSM

Permanent magnet synchronous motors are usually modelled in the d−q reference frame fixed to the rotor. The following assumptions are made in the derivation:

1) Saturation is neglected although it can be taken into account by parameter changes;
2) The back EMF is sinusoidal;
3) Eddy currents and hysteresis losses are negligible (Jun Liu et al., 2009).

With these assumptions the stator d, q equations in the rotor reference frame of the PMSM are the following set of equations:

Stator voltage equations:

$$\begin{aligned} u_d &= R_s i_d + p\psi_d - \omega\,\psi_d \\ u_q &= R_s i_q + p\psi_q + \omega\,\psi_d \end{aligned} \tag{1}$$

Stator flux equations:

$$\begin{aligned} \psi_d &= L_d i_d + \psi_f \\ \psi_q &= L_q i_q \end{aligned} \tag{2}$$

The inverter frequency is related to the rotor speed as:

$$\omega = n_p \omega_m \tag{3}$$

The electromagnetic torque can be described as

$$T_e = \frac{3n_p}{2}\left[\psi_f i_q + \left(L_d - L_q\right) i_d i_q\right] \tag{4}$$

For constant flux operation when id equals zero, the electric torque Te, $T_e = \frac{3n_p}{2}\psi_f i_q = k_t i_q$, where k_t is the motor torque constant. Note that this torque equation for the PMSM resembles that of the regular dc machine and hence provides ease of control.

The dynamic equation of the PMSM drive is described as:

$$J\frac{d\omega_m}{dt} = T_e - T_L - R_\Omega \omega_m \tag{5}$$

Where R_s is the resistance of the stator phase winding, L_d and L_q are the d-, q- axis inductances; u_d and u_q are the d-, q- axis voltages; i_d and i_q are the d-, q- axis currents; ψ_d and ψ_q are the d-, q- axis flux linkages of stator winding. ψ_f is the rotor permanent magnet flux linkage, ω_m is the Mechanical angular speed, and ω is the electrical speed of the PM motor and n_p is the number of pole pairs. For a non-salient PMSM, the d- and q- inductors are considered to be equal(Pwgasan Pillay, 1988).

III. CURRENT CONTROLLER WITH VOLTAGE GRADUAL REGULATION

Coasting is a situation of inertia running without power supply. The contactors break at the beginning of this running condition and reclose when we recover the power supply. Before the re-closing, the locomotive itself has a certain speed. Unlike the induction motor, due to the magnetic field of the permanent magnet synchronous motor rotor, a back EMF rotating with the rotor and with a certain amplitude is generated on the stator winding. If the output voltage from the inverter is not controlled precisely, it will cause the impact or oscillation of the motor current. Therefore, when the inverter and the contactors are reclosed, to ensure the security of the system, the phase and frequency of the output voltage from the inverter must correspond that of the back EMF. And the output voltage of the inverter should have a gradual adjustment progress.

The back EMF can be represented like this:

$$E_o = n_p \omega\,\psi_f \tag{6}$$

Where ω is the motor speed, n_p is the pair of poles, ψ_f is the flux-linkage produced by permanent magnet material.

In this simulation model, we can observe the phase and frequency of the rotor, according to formula (6), they are also the phase and frequency of the back EMF. So in this model, though it has a big impact when the inverter and contactors close, it is not because of the phase and frequency disagreement of the output inverter voltage and the back EMF. We should think of another way to settle the current impact problem.

The stator voltage equation of PMSM can be described by this equation:

$$u = E_0 + L_s \frac{di_s}{dt} + i_s R_s \tag{7}$$

Where u is the stator voltage, E_0 represents the back EMF, L_s is the stator inductance, i_s is the stator current and R_s is the stator resistance.

As is known already, the back EMF increases along with the increasing of the rotor speed, so when we close the contactors during coasting, the back EMF is not zero, so this must have an effect on the change rate and value of the current. Besides, the voltage change influences current rate of change too.

In order to lower the impact of the current, we can add gradual voltage to the regulator when the contactors reclose at first, then after a period of time, we supply the original voltage again, which can be seen from the figure below.

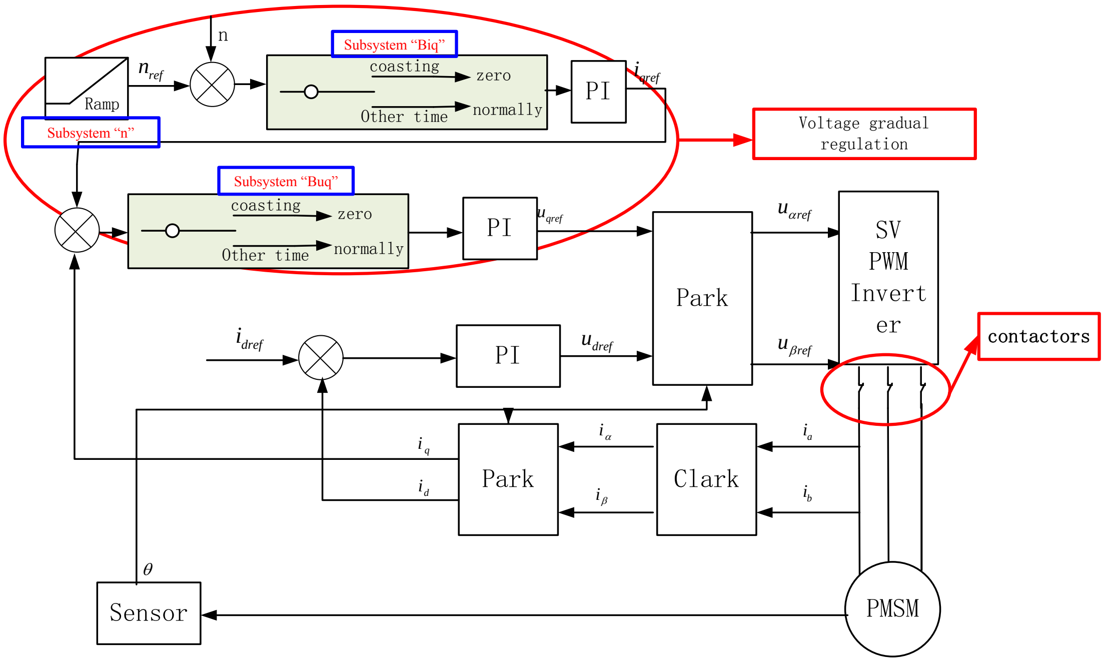

Fig.1 vector control system of PMSM with voltage gradual regulation

As the figure shows, at the very beginning, we add a ramp signal till it reaches n_{ref} instead of an immediate step signal as given rotating speed, and the starting current can be reduced; Besides, after reclosing the contactors, we add the ramp signal with its initial value equaling to the current speed; in order to minish the changing range of u_{qref}, we simply make it zero during coasting. At this point, if we reclose the contactors, the current impact appears the same. Though we minish u_{qref} during coasting, it returns to a big value when reclose the contactors, because $i_{qref} - i_q$ is not zero, and it increases greater through PI controller, so during coasting, $n_{ref} - n$ should be zero too.

IV. SIMULATION RESULTS

The proposed voltage regulation strategy is examined by MATLAB simulation.

In the model, we use three breakers between the inverter and PMSM to simulate the contactors. As to cutting off the power supply, we create a subsystem consisting of switches and clocks to imatate practical situation.

During 0.3s to 0.33s, there is no power supply and the breakers are opened.

Space vector control is adopted and the torque command comes from the speed PI controller, where a speed referenced value of 1000 rpm is used.

In this paper, simulation parameters used in PMSM are as follows: $L_q = L_d = 8.5mH$, $\psi_f = 0.35V.s$, $R_s = 2.875\Omega$, n_p = 2, J=0.0008, $J = 0.0008kg{\bullet}m^2$, $T_L = 2N.m$, the given speed is $n_{ref} = 1000rpm$

In figure 1, subsystem "n": 0s-0.05s, ramp signal with an initial output of 0 rmp and slope of 20000;0.05s-0.33s, 1000 rmp;0.33s-0.34s, ramp signal with an initial output of 282 rmp and slope of 71800.

In this model, the coasting time is 0.03s, when it's the end of coasting time-0.33s, the rotor speed is 282rmp. So if we want to order a ramp signal when the contactors reclose, the initial value of ramp2 signal should be 282 rmp, and if the rising time is set as 0.01s, then the slope can be calculated as 71800.

The slope of ramp1 is obtained just the same way as what we mentioned above.

Subsystem "Biq": 0.3-0.33s,0;other time, $n_{ref} - n$.

Subsystem "Buq": 0.3-0.33s,0;other time, $i_{qref} - i_q$.

The inverter and the contactors are cut off at 0.3s, and re-invested at 0.33s. The simulation results are shown in Fig.2.

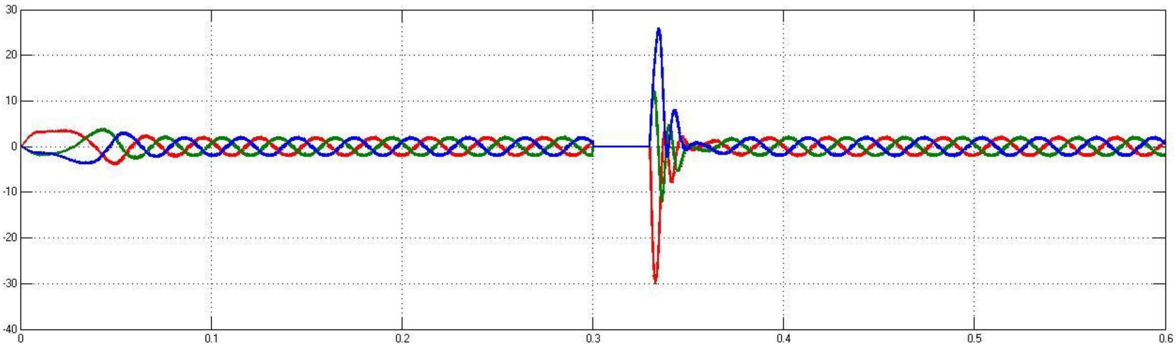

Fig. 2 Simulation: stator currents before voltage gradual regulation

Fig. 2 shows the simulation results when there is no voltage gradual regulation. Due to the existence of the back EMF, the control of the PM motor can not guaranty an ideal state. As simulation result shows that current impact can reach 26.16A when the contactors closed, which can cause an over-current protection that stop the motor from operating well. This is because that the output voltage of the inverter is not increasing slowly. As shown in figure 3, the voltage rises from 79V to 330V in only 0.03s, which will surely have an effect on the current. So there is an impulse current when the inverter runs into operation and the contactors reclose. The partial wave form of the stator three phase currents are shown in Fig.4.

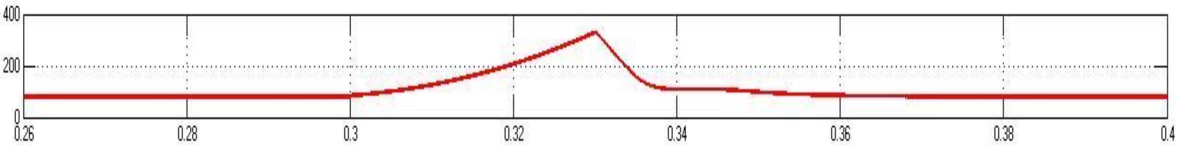

Fig. 3 Uref of the model before voltage gradual regulation

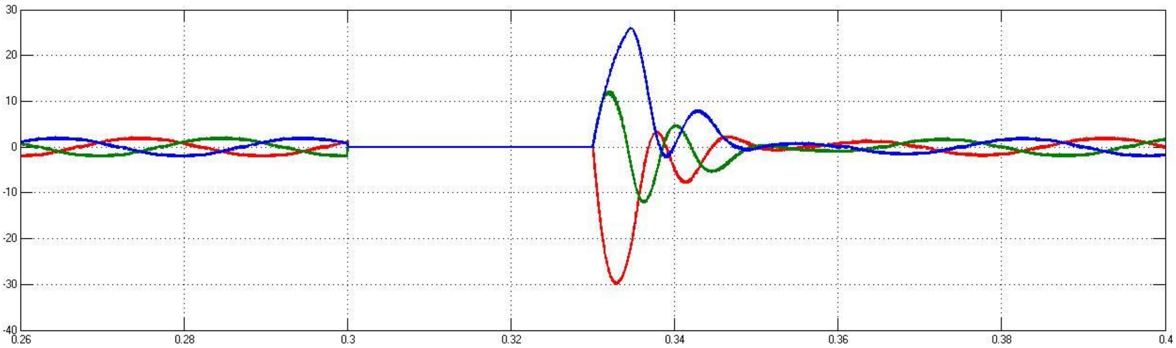

Fig.4 Simulation: partial stator currents before voltage gradual regulation when reclose the contactors

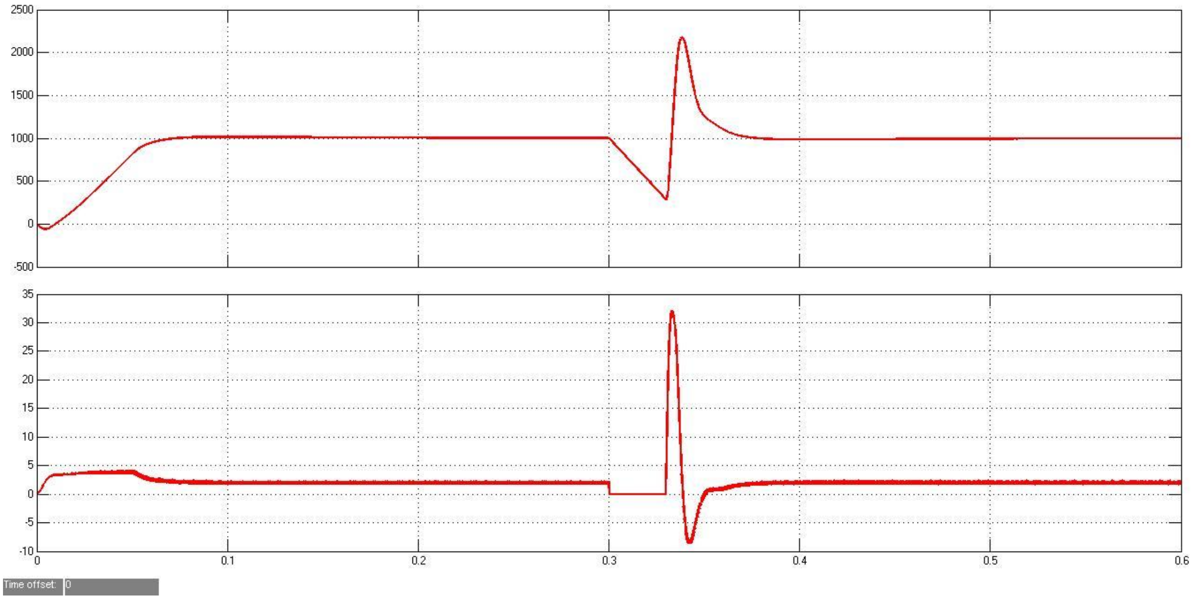

Fig.5 The speed and electric torque of PMSM without voltage gradual regulation

Just as the three phase stator current, the speed and Te of PMSM all have their large impact when reclosing. Then Fig. 5 gives the simulation after voltage gradual regulation. The q-axis voltage is changing gradually from 80V to 51V then to 80V again, and it can be seen that the three phases currents have been reduced obviously. The current impact decreases from 19.16A to 8.5 A.

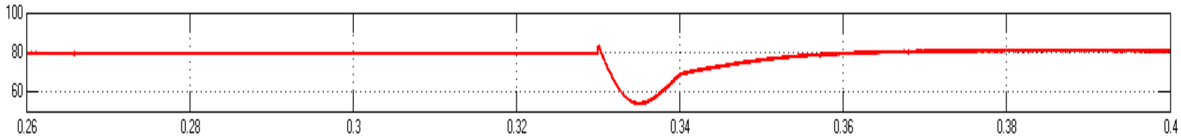

Fig. 6 Uref of the model after voltage gradual regulation

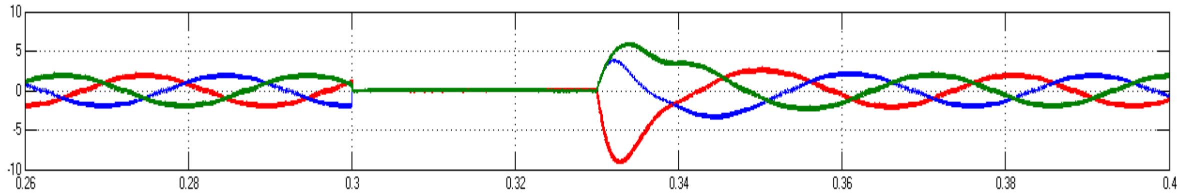

Fig. 7 Simulation: partial stator currents after voltage gradual regulation when reclose the contactors

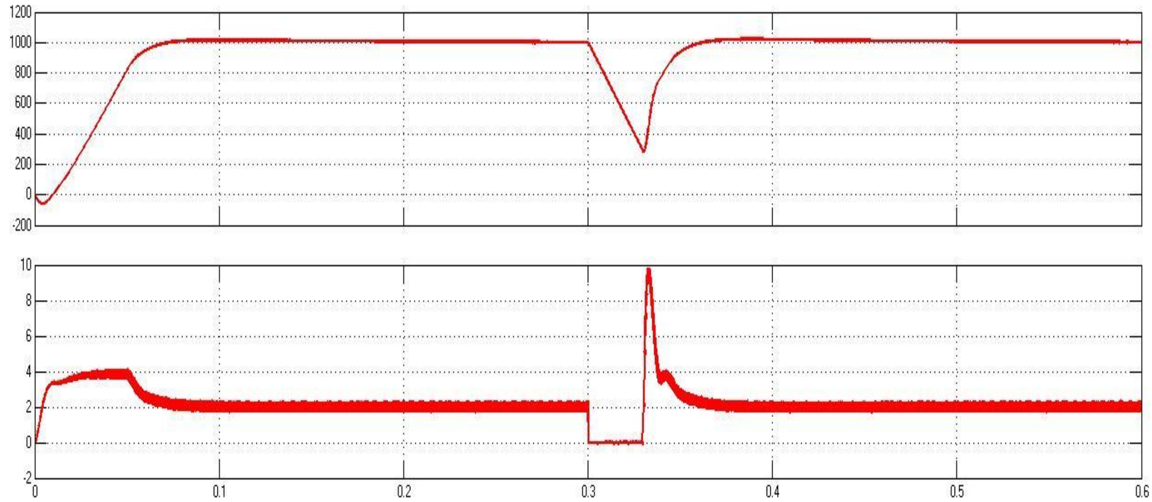

Fig.8 The speed and electric torque of PMSM after voltage gradual regulation

And the speed impact decreases from 2662 rpm to 1020rpm. Te of PMSM decreases from 28.5N.m to 9.1 N.m. Thus motor can be controlled more stably.

V. CONCLUSIONS

A PMSM space vector control system is discussed in this paper. The state of the rotor permanent magnet has a direct influence on motor overall performance. In order to reduce the influence of back EMF, this paper proposed a voltage regulation strategy. In the proposed method, a gradual voltage is acquired and fed to the motor when reclose the contactors between the inverter and the PMSM during coasting. Simulation results show that minor motor current impact is achieved using this compensation strategy, which verifies the effectiveness of proposed method.

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