Precise zero speed positioning control technology of permanent magnet synchronous motor based on dual-motor planetary coupled driving

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Abstract:

During the braking process of the dual-motor planetary coupled driving system which is applied to Blade Electric Buses, the outer gear rim need to be locked at the moment that the high gear turns to the low gear. For achieving the aim that there is no power interruption at that time, the locking action of the locking mechanism needs to be precise zero speed positioning controlled under the condition that the permanent magnet synchronous motor is with load. This control method uses the Faraday principle as its theoretical basis, and uses space voltage vector control method as basic control framework, with leading into the closed-loop control to establish the zero speed braking control method. On this basis, the position ahead of torque compensation control is used to achieve precise zero speed position.

Keywords: dual-motor planetary coupled driving; permanent magnet synchronous motor; position control

1 Introduction

The dual-motor planetary coupled driving mode of EVs that two motors couples through planetary is a novel driving mode, which outputs large torque by locking the outer gear rim when the speed is low and outputs large power by two motors coupling when the speed is high. Through analysis and experimental verification, compared with the mode that single motor connects AMT, the capacity of each motor of the dual-motor planetary coupled driving mode is half as that of one motor. Moreover, owning to the small capacity, the motor achieve high speed and the volume is just 40% of single motor. Meanwhile, there is no power interruption and no impact when this method is used to shift, and compared with AMT, the mechanical structure of this system is simpler. Therefore, it is an important direction of driving mode of EVs.

In order to reduce the mechanical complexity as well as the cost, and to facilitate the application by a large scare, a clasp is used to lock and unlock the outer gear rim. By controlling the PMSM with various novel control strategies and controlling the action of the clasp, the control proposes can be achieved easily, and it is essential to achieve precise zero speed position control under the condition that the permanent magnet synchronous motor is with load, which is different with the conventional PMSM control of EVs. Only by achieving the control objective, can the process of locking the outer gear rim succeed when the regenerative braking is conducted. Hence, to achieve the control objective is a prerequisite to take the advantages of the dual-motor planetary coupled driving system.

2 Technical control requirements for locking mechanism

In order to reduce the mechanical complexity, the cost and the volume, a clasp is used. The basic requirement of using this structure to lock out is to let clasp face a slot of the gear plate precisely. If there is a part of a tooth beneath the clasp, the locking action will not be completed. Meanwhile, according to the principle of conservation of energy, components will release energy from rotating to stop. Because the structure which uses clasp cannot store energy and cannot absorb energy, it cannot be used to stop the rotating components. Therefore, the PMSM which is connected with the gear rim should enable the rotating outer gear rim to stop and make the slot under the clasp stably when the PMSM is with load. This is so-called precise zero speed position control technology of permanent magnet synchronous motor.

3 Control Strategy

3.1 The Structural Characteristics and Electromagnetic Properties of PM Motor

The rotor of PM motor is composed of permanent magnet and the stator is the same as the composition of induction motor formed by distribution windings and silicon steels. When the stator has three-phase alternating current, the space rotating magnetic is produced which has the same frequency as alternating current. According to Faraday's principle, the permanent magnet will rotate with the rotating magnetic and the value of permanent magnet torque is sinusoidal distribution with the angle of permanent magnet and rotating magnetic.

$$\mathrm{Te} = \mathrm{P} \cdot \mathrm{K} \cdot \mathrm{Sd} \cdot Bd \cdot Sc \cdot Bc \times \sin\theta / r \quad (1)$$

Where *Te* is electromagnetic torque; *P* is number of pole pairs; *K* is coupling coefficient; *Sd* is valid area under a pair of stator pole; *Bd* is stator flux density; *Sc* is valid area under a pair of rotor pole; *Bc* is stator flux density; *Θ* is the angle between the stator and rotor magnetic field of electromagnetic; *r* is rotor radius. Where *Te, P, K, Sd, Sc, Bc, r* are constants, which can be obtained when the motor's manufacturing is completed. *Bd* can be derived by the following formula.

$$\begin{cases} \mathrm{Bd} = \mathrm{M} \cdot \sqrt{\mathrm{a}^2 + \mathrm{b}^2} \\ \mathrm{a} = \left(\mathrm{Ia} \cdot \sin\omega t - \mathrm{Ib} \cdot \sin\left(\omega t - \frac{2\pi}{3}\right) \cdot \frac{1}{2} - \mathrm{Ic} \cdot \sin\left(\omega t + \frac{2\pi}{3}\right) \cdot\right)^2 \\ \mathrm{b} = \left(\mathrm{Ib} \cdot \sin\left(\omega t - \frac{2\pi}{3}\right) \cdot \frac{\sqrt{3}}{2} - \mathrm{Ic} \cdot \sin\left(\omega t + \frac{2\pi}{3}\right) \cdot \frac{\sqrt{3}}{2}\right)^2 \end{cases} \quad (2)$$

Where *M* is excitation constant; *ω* is electrical angular velocity; *t* is time; *Ia* is peak value of a phase current; *Ib* is peak value of b phase current; *Ic* is peak value of c phase current.

It is AC motor, so *Ia=Ib=Ic*.

If *Im=Ia=Ib=Ic*,

$$\mathrm{Bd} = \sqrt{\frac{3}{2}} \cdot \mathrm{M} \cdot \mathrm{Im} \quad (3)$$

From formula （1 ） and (3), *Te* can be calculated as follows.

$$\mathrm{Te} = \sqrt{\frac{3}{2}} \cdot \mathrm{M} \cdot \mathrm{Im} \cdot \mathrm{P} \cdot \mathrm{K} \cdot \mathrm{Sd} \cdot Sc \cdot Bc \times \sin\theta / r \quad (4)$$

If *ω=0*, when the motor standstill, formula (3) is still set up.

$$\text{If } \mathrm{Q} = \sqrt{\frac{3}{2}} \cdot \mathrm{M} \cdot \mathrm{Im} \cdot \mathrm{P} \cdot \mathrm{K} \cdot \mathrm{Sd} \cdot Sc \cdot \frac{Bc}{r} \quad (5),$$

Q is constant; *Te* is a trigonometric function of *Θ* in the case of the above-mentioned conditions.

Because *P>2*, Mechanical angle from positive extreme to reverse extreme of Te is less than *2Π/3*.

When ω=0, *Im* is constant and torque from wheels to the motor is less than *Te*,

$$\cdot \mathrm{Te} = \sqrt{\frac{3}{2}} \cdot \mathrm{M} \cdot \mathrm{Im} \cdot \mathrm{P} \cdot \mathrm{K} \cdot \mathrm{Sd} \cdot Sc \cdot \frac{Bc}{r} \quad (6),$$

wheels only change a small angular displacement, not rotating. In this case, the driver feels that the vehicle is stationary.

3.2 The Principle of Control Strategy

According to the above conclusions, if keeping *ω=0* and *Im* is constant, zero speed braking can be achieved. As the Motor is stop, the electromotive force of motor is 0. Without considering the high-frequency carrier, and ignoring leakage inductance and mutual inductance of motor, so

$$Im = U/R \quad (7).$$

Where *U* is voltage; *R* is resistance of stator.

From formula (7), if ignoring the effects of temperature on resistance, stability of *U* will be able to stabilize *Im*. Through the DC chopper control, constant pressure and a fixed pulse width of the chopper, a stable *U* can be got.

$$\mathrm{U} = \mathrm{Us} \cdot \mathrm{D} \quad (8)$$

Where *Us* is supply voltage of high-voltage power; *D* is duty cycle.

Taking into account the change of *R* and *Us*, using control method of current closed-loop, and using *Im* as the feedback control variable, the transfer function can be expressed as follows.

$$\frac{\mathrm{Ku} \cdot \mathrm{Kr}(\mathrm{s} - \tau_i)}{(\mathrm{s} - \tau_i)(\mathrm{s} - \tau_u)(\mathrm{s} - \tau_r) + \mathrm{Ki} \cdot \mathrm{Ku} \cdot \mathrm{Kr}} \quad (9)$$

Where *Ki* is scale factor of current; *Ku* is scale factor of voltage; *Kr* is scale factor of resistance; *τi* is time constant of current filter; *τu* is time constant of voltage filter; *τr* is time constant of resistance filter.

3.3 Control Strategy for Zero speed Braking Based on SVPWM Method

The transfer function mentioned above can enable to achieve the function of zero speed braking, theoretically. However, the core control mathematical model of PM motor is space voltage vector method (PWM), so the DC chopped closed-loop control strategy for zero speed braking should be realized through PWM. Combined transfer function and PWM, the desired zero speed braking can be achieved.

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PWM is from perspective of motor, and focus on how to make the motor obtain sine flux which has constant amplitude. It bases on ideal prototype flux's track of AC motor when three-phase symmetrical sine wave voltage supply power. Different switch patterns of inverter produce actual flux to approximate benchmark flux circle. It can get high control performance in this way. For example, 8 switch modes of inverter match 8 space vectors. It's shown in Figure.1. The goal of SVPWM control technology is making space voltage vector *Uout* rotate as the setting parameters circular by controlling the combination of these basic space vectors [2~5].

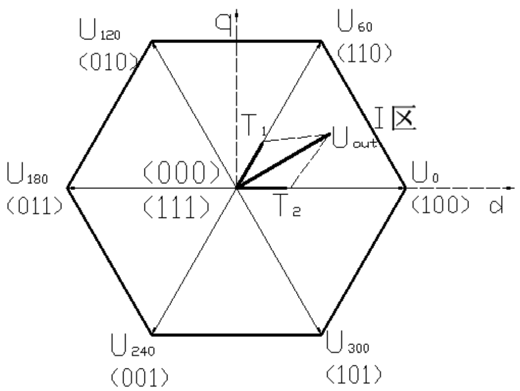

Figure.1 Space voltage vector graph

There are many ways to achieve SVPWM. For instance, one of the simplest ways is to use two non-zero vector and a zero vector to synthesize an equivalent voltage vector *Uout*. In Figure 1, at some point *Uout* rotates to a region, two non-zero vectors *Ux* and *Ux ± 60* which compose this region respectively act time of *T1* and *T2*. First role *Ux* is the main vector; *Ux ± 60* is the auxiliary vector. Time decomposition is shown in Figure.2. To compensate for the rotation frequency of *Uout*, zero vector is inserted, and act time of *T0*. The needs of *Uout* output can be obtained by controlling the ratio of *T1, T2,* and *T0*.

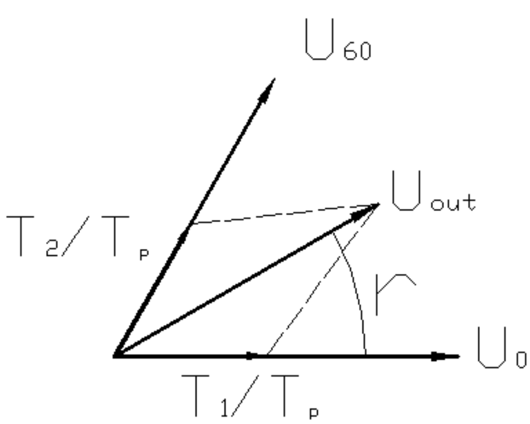

Figure.2 time decomposition of the voltage vector function

From above, as long as the space angle of *Uout* is locked, control output value of the transfer function of equation (8) changes as control of the *Uout*'s modulus. In the same time, *Im* as a feedback input is not a specific line current, but it's the current modulus of the synthesis of three-phase current space vector of motor.

4 Precise zero speed braking position control

The foregoing discussion merely describes the zero speed braking control, and we can see that, due to the effects from load, there is a deviation between the actual position and the position of zero load state. Through experiment and data analysis, although the PMSMs applied to EVs are equipped with Rotary transforms theoretically, which can achieve precise positioning by no-static difference position closed loop feedback control, we can see that the actual test results are not satisfied. The main reason is that the effect from inertia, causing a shocking and converging process when the stator is fixed in a certain position. If the feedback time constant is too small, the process divergent shock, and the control process will be too slow, causing a sense of stagnation when to ensure the time constant converge stably. Therefore, the delay compensation method of closed loop control is not satisfied for pursuing the good transient control effect during the adjusting process. If Im is kept as the maximum current modulo value, then we can know that Θ is the inverse trigonometric functions of Te from formula (3). Because of the specific structure of dual-motor planetary coupled, we can predict the amount of Te accurately through the outputting torque of motor connected with the sun gear. Calculating Θ through Te and conducting Lead compensation to Θ can help to achieve the precise zero speed braking positioning control quickly.

5 Conclusions

As a part of control functions of dual-motor planetary coupled driving system. This control strategy has completed the bench test, achieving the function of no power interruption during the regenerative braking process. And this research lays a solid foundation for the further practical tests on electric buses.

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