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Difference in maximum torque-speed characteristics of induction machine between motor and generator operation modes for electric vehicle application

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ABSTRACT

This paper explains the reason for the difference in maximum torque-speed characteristics and power factor of IM between the motor and generator operation modes and investigates the influence of machine design parameters on the difference, such as stator resistance, rotor resistance and iron loss etc. An analytical mathematical model based on the *dq* reference frame is employed for investigation. It is shown that the difference in torque-speed characteristics between the motor and generator operation modes is mainly caused by the opposite direction of *q*-axis current and affected by stator and rotor resistance values. Finally, analytically calculated torque-speed characteristics of a 12 kW IM in the motor and generator operation modes are verified by finite element analyses.

1. Introduction

Induction machines (IMs) are widely used for many applications due to simplicity, robustness and mature manufacturing technology without using any permanent magnets [1]. IMs have been widely used for line-fed operation, and the attention has been given to variable-speed IM design since 1990s. For some variable-speed applications, such as electric vehicles (EV), the maximum torque/power-speed characteristic is an important design criterion, which determines the size of electrical machine and power rating of inverter. A high torque in low speed region and a wide constant power region are both required [2,3]. Usually, a constant power region around 3–4 times the base speed needs to be satisfied [4]. For some cases, the required constant power region may be much wider.

Bianchi and Bolognani [5] studied the design process of IM for variable-speed applications. Harson et al. [6] and Song et al. [7] investigated the influence of some design parameters on torque-speed characteristic of IM, such as airgap length, slot opening, skew bars and slot combination, etc. Many comparisons on the torque-speed characteristics have been done between conventional three-phase IM and other types of machines [8–13]. In addition, some new motor topologies and control strategies have been proposed for EV applications, to enhance the flux-weakening performance of IM, such as six-phase pole-changing IM [14,15] and IMs with reconfigurable winding arrangements [16,17]. Kim et al. [18] presented a dual-inverter control strategy for IM for EV application. These new IM topologies and control strategies can realize very wide constant power region, together with relatively complicated inverter or motor configuration.

The calculation of maximum torque/power-speed characteristic of IM should be conducted in the whole speed region and both the stator voltage and current amplitudes should be within the limitation. In this case, traditional transient finite element analysis (FEA) is not suitable for torque/power-speed characteristic prediction of IM at design stage, because it takes quite a long time, although it may give more accurate results [19]. Alberti et al. [20,21] and Pellegrino et al. [8] proposed a FEA using magnetostatic analysis especially for variable-speed IM analysis. As for equivalent magnetic circuit (EMC), it may be a good choice for calculation of IM for EV application, in terms of calculation speed and accuracy [22]. Although, FEA and EMC are appreciated for their accuracy, the classic single-phase lumped parameter equivalent circuit is still the most favorable method to predict the torque/power-speed characteristic of IM, especially at design stage, in terms of calculation speed due to its analytical nature [23–28].

Most of the literature above mainly focuses on IM in the motor operation mode, while not much attention is paid to the generator

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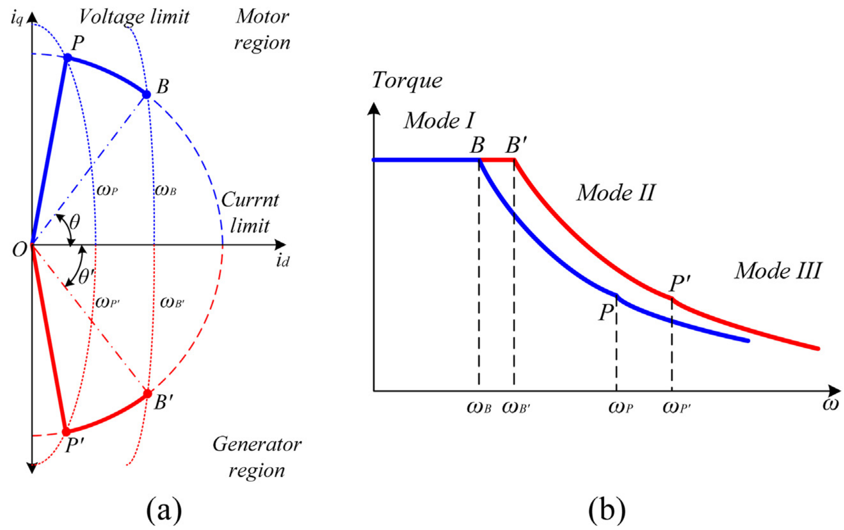

Fig. 1. Circle diagram of IM in motor (Solid blue line) and generator (Solid red line) operation modes. The solid line in (a) is the current trajectory under maximum torque control. The curves in (b) are the corresponding torque-speed characteristics. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

operation mode. Usually, electrical machines for EV applications need to work at both the motor and generator operation modes. In fact, the maximum torque/power-speed characteristics of IM in the motor and generator operation modes are sometimes quite different, which can be seen from the calculation or test results in some literature [29]. This paper mainly focuses on investigating the difference of maximum torque-speed characteristics of IM between the motor and generator operation modes. First, the reason for the difference is explained. Then the influence of some design parameters on the difference is investigated using analytical method. Finally, the analytically calculated torque-speed characteristics of a 12 kW IM in the motor and generator operation modes are verified by tests.

2. Maximum torque-speed characteristics in motor and generator operation modes

The circle diagram and corresponding torque-speed characteristics of IM in the motor and generator operation modes are shown in Fig. 1, which typically divides the torque-speed characteristics into three modes by rated and critical operating points B (or B') and P (or P'). The current trajectories of IM in the motor and generator operation modes are symmetrical about d-axis. IM in the generator operation mode has better torque-speed characteristic than in the motor operation mode, because for the same current vector, i.e. electromagnetic torque, the corresponding frequency of voltage limit ellipse in the generator operation mode is larger than that in the motor operation mode. IM in the motor and generator operation modes has identical electromagnetic torque value in constant torque region, because the d- and q-axis current amplitudes are the same. It should be mentioned that the torque/power value in the generator operation mode is usually negative. However, it is transformed to positive value in this paper to make the difference between the motor and generator operation modes clearer.

The frequency difference of the voltage limit ellipse of IM in the motor and generator operation modes, for the same d- and q-axis current values, can be explained from the voltage vector diagram. Two voltage vector diagrams for points B(or B') and P(or P') are shown in Fig. 2. The voltage equations of IM in dq-axis reference frame are listed in (15) and (16) in Appendix A. $\vec{U}(M)$ and $\vec{I}(M)$ are the stator voltage and current vectors in the motor operation mode, $\vec{U}(G)$ and $\vec{I}(G)$ are the stator voltage and current vectors in the generator operation mode, φ and φ' are power factor angles in the motor and generator operation modes. It can be seen that with the same d- and q-axis current values and stator frequency, the stator voltage amplitude of IM in the generator operation mode is always smaller than that in the motor operation mode, while the power factor in the generator operation mode is always lower than that in the motor operation mode, which are both caused by the opposite directions of q-axis currents. That is also the reason why for the same electromagnetic torque, the frequency of voltage limit ellipse in the generator operation mode is larger than that in the motor operation mode. It also can be seen that the magnitude of voltage difference has a close relationship with the stator resistance value.

3. Influence of stator and rotor resistances

The calculation method in [30] is utilized to calculate the torque/power-speed characteristics. In this section, the influences of stator and rotor resistances R_s and R_r on the difference in the maximum torque/power-speed characteristics between the motor and generator operation modes are investigated. It is assumed that the iron saturation level does not change along the whole speed region, i.e. L_s and L_t are constant, and the iron loss is zero, to simplify the analysis. The influence of variable inductances and iron loss will be investigated in Section 4.

3.1. Stator resistance

The electromagnetic torque/power-speed characteristics of IM with different R_s are shown in Fig. 3(a) and (b). The rotor resistance is set to be quite small ($1 \times 10^{-6}\,\Omega$) to exclude the influence of R_r. The electromagnetic torque in flux-weakening region decreases with R_s in the motor operation mode, while increases with R_s in the generator operation mode. Consequently, the difference between them increases. It is due to the opposite directions of q-axis currents, which has been explained in last section. Although the difference of electromagnetic power between the motor and generator operation modes in the flux-weakening region increases with R_s, the difference of output power does not change obviously, as shown in Fig. 3(c). The output power in the motor and generator operation modes can be expressed by (1) and (2), respectively. The output power difference between the generator and motor operation modes is (3). Although $(P_{\text{em\_}G} - P_{\text{em\_}M})$ in flux-weakening