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Design Characteristics of Torque Harmonics Reduction of Induction Motors for Electric Vehicle Propulsion

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This paper deals with torque harmonic characteristics and its reduction design of induction motors for electric vehicle (EV) propulsion. For calculating the stator harmonic flux of squirrel-cage induction motor, the numerical methods have been employed on the structural configuration design of stator and rotor teeth. In particular, torque ripples including spatial harmonics are obtained by Finite Element Method (FEM), and their individual harmonic components are identified with Fast Fourier Transform (FFT). In this paper, design modification on the teeth surface gives rise to the significant reduction of torque ripples including spatial torque harmonics, which have been obtained with FEM.

Keywords : induction motor, torque ripples, torque harmonics, finite element method, fast fourier transform

1. Introduction

Induction motors have been used for EV propulsion that requires high torque density, high power density, and low cost at the same time. In fact, PMSM has been regarded as one of the most attractive candidate for EV propulsion so far [1]. However, finding out the alternative candidate replacing rare-earth Permanent Magnet (PM) has been in effort owing to the rapid increase of PM price, thus induction motors with the superiority on mechanical robustness, low price and covering wide operational speed range become much highlighted nowadays [2].

Torque ripple of induction motor applied for EV propulsion is mainly produced by space harmonics by teeth configuration of stator and rotor core along air-gap, which can be clarified with inductance much influenced by air-gap variation between stator and rotor. In fact, spatial harmonics are essential ones for torque ripples of induction motor, resulting in significant harmonic loss, vibration and noise in vehicle after all [3, 4].

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In this paper, magnetic design based on FEM has been performed to reduce torque ripples of induction machine with 65 kW for EV propulsion by modifying teeth surface configuration of stator and rotor core. In particular, numerical evaluation on torque ripples and harmonics identified with FFT is done at the specified load condition, where it is running with the representative control strategy for EV propulsion, Maximum Torque Per Ampere (MTPA) Control and Flux Weakening Control [5, 6]. It is found that the employed design methodology has dedicated the reduction of torque ripples and the specific n-th order torque harmonics of induction motor for EV propulsion significantly.

2. Design of Induction Motors

2.1. Specification of Induction Motors

In this paper, induction motors have been applied for EV propulsion, which specification is summarized in Table 1. As shown in Table 1, the design specifications are as follows: the constant output power is 65 [kW] covering 355-2219 [rpm], line input voltage is 500-600 [V], 4-poles and 3-phases, stator outer diameter is 500 [mm] and rotor outer diameter is 307 [mm], air gap is 0.8 mm, number of stator slots and rotor slots are 36 and 42, respectively.

For reference, the performance curve of induction motors

Table 1. Specifications of Induction Motor for EV propulsion.

Output Power		65 kW, 355-2219 rpm
Operation Range		0-3600 rpm
Line Input Voltage		500~Max. 600 V
No. of Pole / Phase		4 / 3
Stator Outer Diameter		500 mm
Rotor Outer / Inner Diameter		307 / 60 mm
Stack Length / Air-Gap		300 / 0.8 mm
No. of Stator Slot and Rotor Slot		36 / 42
End Ring	Outer / Inner	306 / 246 [mm]
	Width	30 [mm]

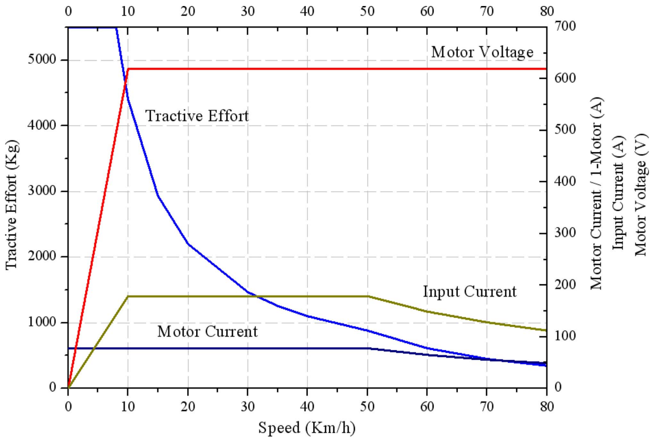


Fig. 1. (Color online) Performance curve of induction motors for EV propulsion.

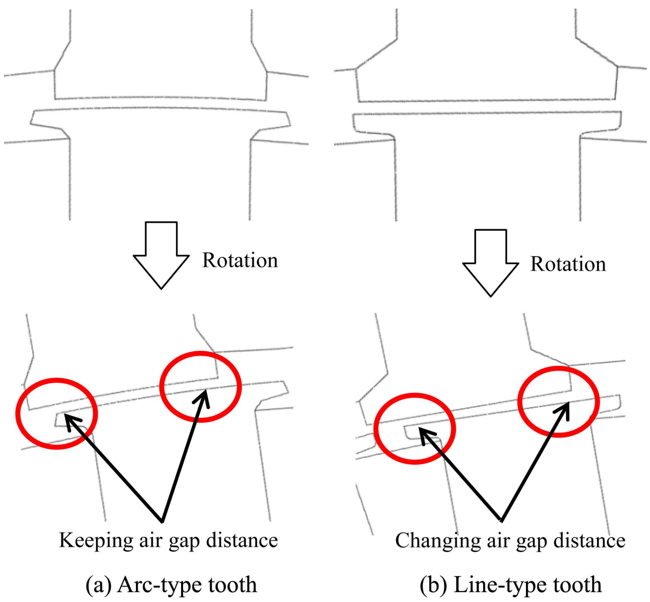


Fig. 2. (Color online) Structural comparison of arc-type and line-type tooth.

specified with the running speed is shown in Fig. 1. As shown in Fig. 1, the operation range of induction motors can be characterized with the different control strategies, where the constant torque region is controlled with MTPA and the constant power region controlled with Flux Weakening.

2.2. Structural configuration of arc-type and line-type tooth

Fig. 2 shows the comparison of structural configuration with arc-type and line-type tooth at the stator and rotor core. It is employed to realize the air-gap length modification resulting in the change of torque harmonics. Actually, line-type tooth are obtained from the sliced arc-type tooth, whereby the different air-gap distance is realized contrary to the arc-type teeth with the uniform air-gap distance, while induction motor is running.

3. Numerical Design Characteristics of Induction Motors

3.1. Reduction of Torque Ripples

Magnetic design has been performed to modify the tooth surface of stator and rotor from arc-type to line-type one. In Fig. 3, numerically obtained flux lines are com-

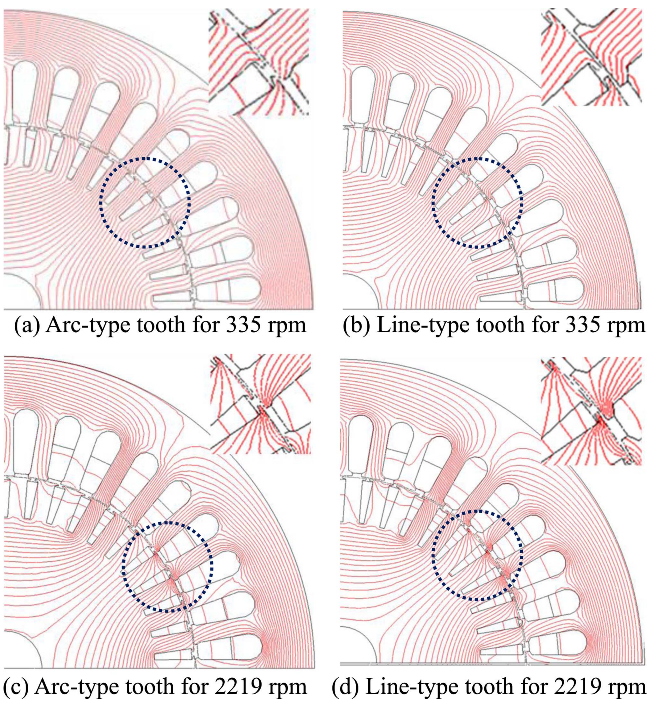
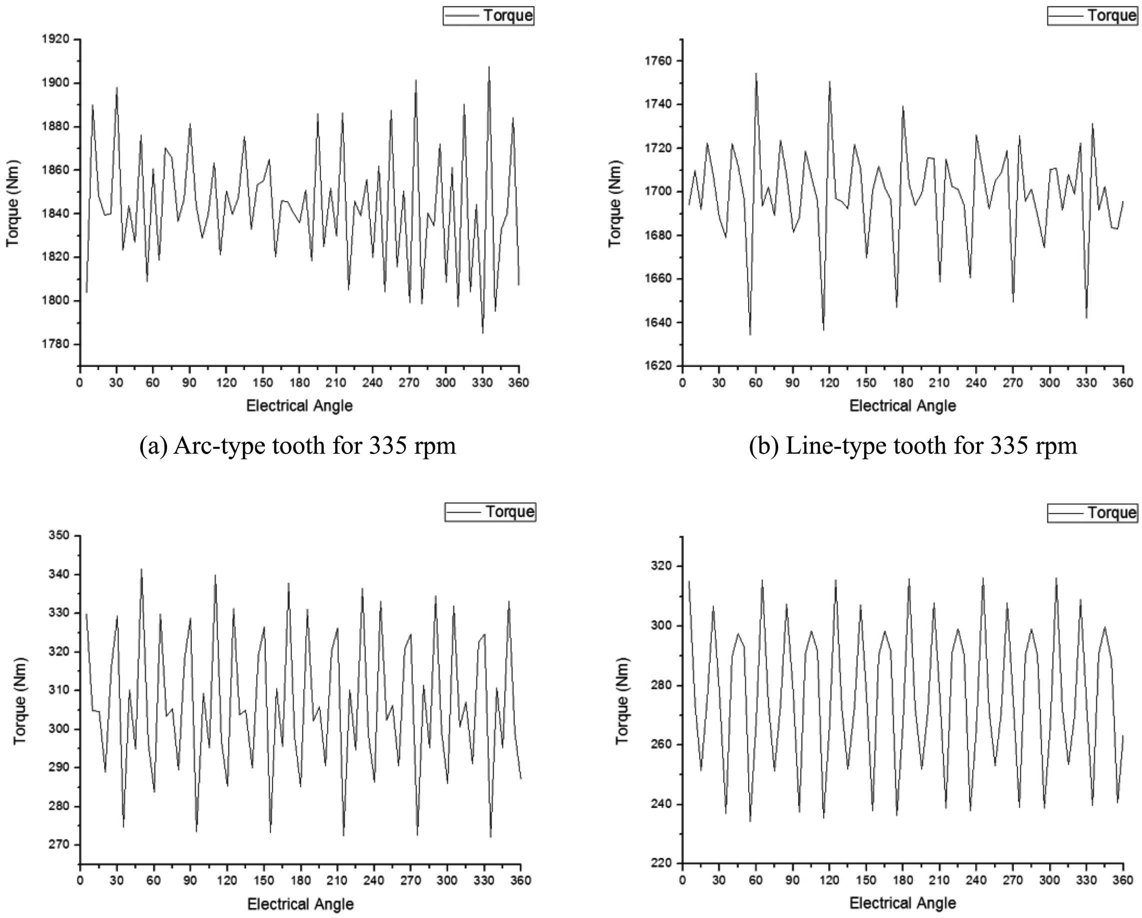


Fig. 3. (Color online) Magnetic flux line comparison with the different structural configuration and the running speeds specified with the different control strategies (MTPA control for 335 rpm and Flux Weakening control for 2219 rpm).



(a) Arc-type tooth for 335 rpm (b) Line-type tooth for 335 rpm

(c) Arc-type tooth for 2219 rpm (d) Line-type tooth for 2219 rpm

Fig. 4. Torque ripples comparison with the different structural configuration and the running speeds.

pared with the different structural configurations and the running speeds, where 335 rpm is operated with MTPA control and 2219 rpm with Flux Weakening control. It is shown that magnetic traveling path and pattern have been modified according to the modified air-gap distance and the different control strategy, where line-type tooth generates more sinusoidal air-gap flux waveform.

Meanwhile, Maxwell Stress Tensor is employed to identify the torque characteristics including torque harmonics, as shown in Fig. 4. Likewise, torque ripples are compared with the different structural configurations and the running speeds. It is shown that the line-type tooth has torque ripples, 6.5% at 355 rpm and 21.7% at 2219 rpm while arc-type one has 7.1% at 355 rpm and 29.1% at 2219 rpm, calculated with the maximum torque variation per the average torque. The improvement of torque ripples characteristics validates the effectiveness of the applied structural modification of stator and rotor tooth on.

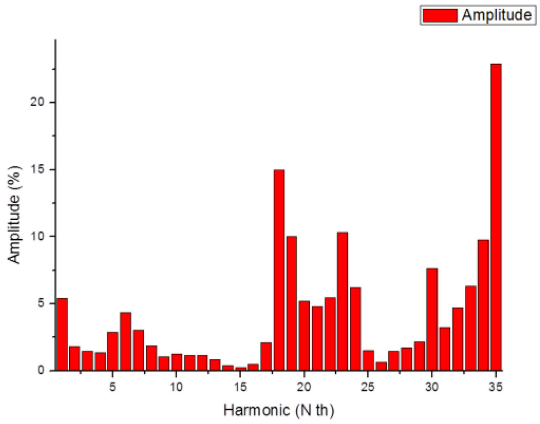
3.2. Reduction of Torque Harmonics

An obtained torque ripples are decomposed into the individual n-th order torque harmonics using FFT, as shown in Fig. 5. This emphasizes that the structural design modification gets rid of overall harmonic torque component while some specific harmonic components are increased as a trade-off influence.

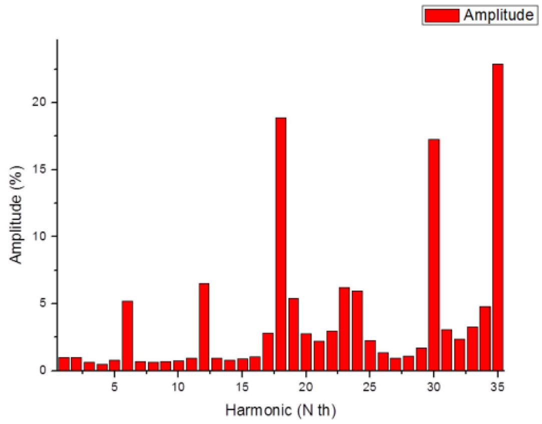
In addition, it is shown that the control strategy manifests its own individual harmonic occupation. The specific order of individual harmonic component still remains even after design modification. For instance, 18^{th} harmonic component occupies dominantly at 335rpm and 2219rpm in the arc-type and it is not suppressed after structural design modification throughout the control algorithm.

4. Conclusion

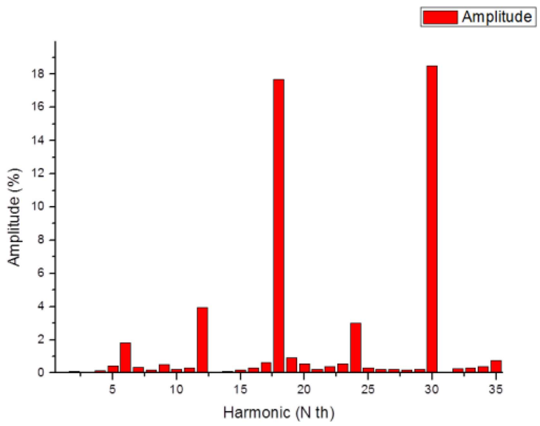
In this paper, torque ripples and harmonics of induction motor for EV propulsion are analyzed with FEM, and its reduction design characteristics are considered by employing the structural modification of tooth surface from



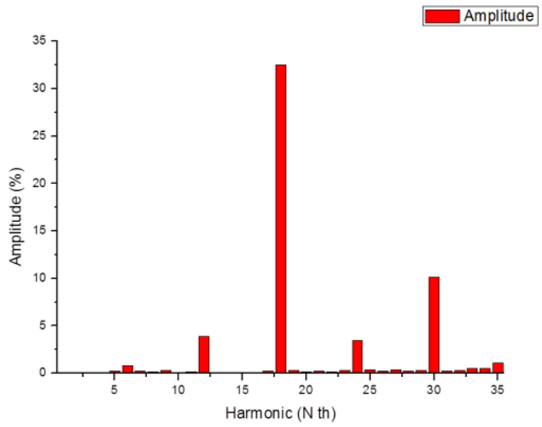
(a) Arc-type tooth for 335 rpm



(b) Line-type tooth for 335 rpm



(c) Arc-type tooth for 2219 rpm



(d) Line-type tooth for 2219 rpm

Fig. 5. (Color online) Individual n-th order torque harmonics comparison with the different structural configuration and the running speeds.

arc-type to line-type one. Furthermore, its effectiveness is also clarified according to the representative control strategies for induction motors, MTPA control and Flux-Weakening control. Based on the superiority of the proposed methods, more effort getting rid of the specific order of the individual torque harmonic components survived even after design modification and through control algorithms, should be made afterwards.

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