

Design Analysis of Six-phase Permanent Magnet Motor for Electric Vehicles

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Abstract

With the increasing development of electric vehicle technology, the research on the drive motor is also in-depth. Permanent magnet synchronous motor has the advantages of high power density, wide speed regulation range, high efficiency and small size, and has a broad application prospect in electric vehicles. Compared with the traditional three-phase motor, the multi-phase permanent magnet synchronous motor has the dual advantages of permanent magnet synchronous motor and multi-phase motor, which can reduce the torque fluctuation, has unique fault tolerance, and the phase deficiency can still work stably, greatly improving the reliability of the motor. According to the requirement of motor performance of electric vehicle, six-phase Y-shift 30 winding as stator winding and V-type structure as motor, and then the size design of permanent magnet is studied. At the same time, a 22kw six-phase permanent magnet synchronous motor was designed and the torque performance was analyzed with finite element software.

Keywords

Electric Vehicle; Permanent Magnet Synchronous Motor; Fault Tolerance; Torque Fluctuation; Six-phase Double Y Shift 30 Winding.

1. Introduction

The drive motor is the power core of electric vehicles, and it should possess the highest possible power density, torque density, excellent control capability, high reliability, and high efficiency across a wide speed range. Permanent magnet synchronous motors, characterized by high efficiency and torque density, good torque smoothness, and low vibration and noise, are ideal choices for electric vehicle drive systems[1].

Currently, three-phase permanent magnet synchronous motors are commonly used in the drive systems of electric vehicles. However, considering passenger comfort and safety, the development of multi-phase fault-tolerant permanent magnet synchronous motors for electric vehicles has garnered attention. Multi-phase motors refer to those with more than three supply phases. Since the 1990s, electric vehicles, electric ships, electric aircraft, and high-power industrial devices have experienced rapid development[2]. These application fields have imposed stricter requirements on drive motors. Multi-phase motors, with their inherent advantages, have gained attention in these fields and have gradually become a research hotspot in the current motor field. Compared to three-phase motors, multi-phase motors exhibit advantages such as small torque ripple, high torque density, the ability to achieve high power at low voltage, and high reliability[3] [4]. The literature [5] studied the four-phase motor applied to electric vehicles, proving that the four-phase motor can still provide output torque to maintain vehicle operation under the faults of one phase open circuit and two phase open circuits, thereby improving the reliability of the vehicle. The literature [6] designed a half-twelve-phase outer

rotor fault-tolerant permanent magnet synchronous motor for electric vehicles, which adopts an open winding and fractional slot concentrated winding structure, improving the torque density and field weakening speed expansion capability of the motor[7].

This article first introduces the theoretical composition of the six-phase double Y-shift 30° winding, and based on the performance requirements of electric vehicles, designs a six-phase permanent magnet synchronous motor. Then, using the finite element software Ansoft, the target motor is modeled, and its performance is simulated and analyzed.

2. Design of Electric Vehicle Motor

In traditional three-phase motor drive systems, any malfunction in the motor or controller often leads to a sudden system shutdown, potentially endangering the safety of operators. Therefore, in certain applications where high reliability is required, such as in industry, aerospace, medical fields, etc., the motor drive system must maintain rated or derated operation even in the event of a fault, demonstrating fault tolerance.

This chapter focuses on an in-depth exploration of six-phase permanent magnet fault-tolerant motors. Based on the fundamental principles followed in the design of multi-phase permanent magnet fault-tolerant motors, research is conducted on their electromagnetic design methods. The scope of research covers multiple key aspects: from the careful selection of the number of phases, to the precise coordination of the number of pole slots, to the reasonable arrangement of windings, as well as the stator structure and many other aspects[8]. The aim is to comprehensively create a motor model with excellent performance, and to verify the rationality of the design through simulation.

2.1 Motor Performance Parameters

In the process of motor design, it is first necessary to determine the rated parameters of the motor, and then use these parameters to determine the main dimensions of the motor. The rated parameters of the motor mainly include rated torque, rated speed, rated power, and rated current, while the main dimensions of the motor include armature diameter, armature length, and permanent magnet volume. Subsequently, adjustments and corrections are made based on the installation space requirements and in conjunction with motor simulation results. The rated torque of the motor can be expressed as:

$$T_N = \frac{P_N \times 9.55}{n_N} \quad (1)$$

In the formula, P_N , n_N and T_N represent rated power, rated speed, and rated torque, respectively. When the speed is constant, power is proportional to torque.

To match the electric vehicle drive motor mentioned earlier, the rated power of the six-phase motor studied in this paper is determined to be 22KW, with water cooling and a rated speed of 3900r/min (revolutions per minute). Its main parameters are calculated according to equation (1), and the relevant parameters are shown in Table 1 below.

Table 1. Main design parameters of the six-phase motor

Parameter	Value (unit)	Parameter	Value (unit)
Rated power	22 KW	Rated torque	50 N·m
Rated speed	3900 r/min	Rated torque	6

2.2 Motor Structure Design

2.2.1 Main Dimensions of Motor

The electromagnetic energy existing in the air gap of a motor plays a crucial role as it is the core element for achieving internal energy conversion within the motor. Essentially, motor power is electromagnetic power. At the beginning of the motor design process, it is necessary to first determine the stator armature diameter and axial length. The determination of these two key dimensions lays the foundation for subsequent design steps. After clarifying these two dimensions, other dimensions of the motor can be determined in an orderly manner based on relevant design criteria and calculation methods, gradually constructing a complete and performance-compliant motor to meet the requirements for motor power and various performance indicators in different application scenarios. The expressions for the armature diameter and length are shown in Equation (2).

$$D^2 L_{ef} = \frac{6.1 P'}{\alpha_p' K_{NM} K_{dp} A B_\delta n} = C_A \quad (2)$$

In the formula, $P' = [(1 + 2\eta_N) / 3\eta_N] * P_N$, $\alpha_p' = B_{\delta av} / B_\delta$. The symbols in formula (2) are explained in Table 2 below.

Table 2. Parameters related to size calculation

Symbol	Description	Symbol	Symbol
P	Calculated power (W)	n	Motor speed (r/min)
α_p'	Calculate pole-arc coefficient	P_N	Rated power (W)
K_{NM}	Air gap magnetic field waveform coefficient	η_N	Motor efficiency
K_{dp}	Winding Factor	C_A	Motor Constant
A	Line load (A/mm)	D	Armature diameter (m)
B_δ	Air gap magnetic density (T)	L_{ef}	Armature length (m)
$B_{\delta av}$	Air gap average magnetic flux density (T)		

For motors within a certain range of power and speed, the variation range of electrical load and electromagnetic load is not large, and the variation range of other parameters is even smaller[9]. Therefore, C_A is referred to as the motor constant.

Electrical load and electromagnetic load typically determine the main dimensions of a motor. The selection of electrical and electromagnetic loads directly affects the materials and structural parameters used in the design, and also impacts the electrical performance of the motor, such as its rated operating point, efficiency, and reliability. The selection of electrical load is closely related to the heat dissipation of the motor. A higher electrical load leads to a higher power density of the motor, which can save materials. However, a higher electrical load also results in a higher temperature rise of the motor, affecting its operating efficiency, and in severe cases, even causing the motor windings to burn out[10].

The selection of electrical load A and air gap magnetic density B_δ not only affects the performance of the motor but also has a significant impact on its economic performance. When the line load A is high and the air gap magnetic density remains unchanged, the motor size and volume will decrease, saving steel and reducing the weight of the iron core, which in turn leads to lower iron loss. However, as the motor size decreases and the air gap magnetic density remains unchanged, the magnetic flux per pole decreases. To generate a certain amount of induced electromotive force, the number of winding turns must be increased, resulting in an increase in copper usage. In addition to not selecting an excessively high A or B_δ , it is also necessary to consider the appropriate ratio between the two. This ratio not only affects the motor parameters and characteristics but is also closely related to the distribution of copper and iron losses in the motor, as well as influencing the motor's maximum efficiency point. For this reason, for motors that often operate under light loads, it is advisable to choose a larger A value and a lower B_δ value, so as to achieve higher efficiency under light loads[11].

The value of electric load A (A/m) is:

$$A = \frac{2mNI_{rm}}{\pi D} \quad (3)$$

In the formula, m represents the number of motor phases, N denotes the number of series turns per phase of the armature winding, I_{rm} signifies the effective value of the armature winding phase current (A, ampere), and D stands for the armature diameter.

After selecting A and B_δ , D^2L_{ef} can be preliminarily determined based on equations (2) and (3). However, motors with the same D^2L_{ef} can be categorized as slim, long, short, or thick. To reflect the geometric shape of the motor and ultimately determine the armature diameter and length, the concept of dimensional ratio is introduced, with a value of:

$$\lambda = \frac{L_{ef}}{\tau} \quad (4)$$

In the formula, τ represents the pole pitch, $\tau = \frac{Z}{2P}$ and Z represent the number of stator slots, and P represents the number of pole pairs of the motor. For synchronous motors, generally, λ increases with the increase in the number of poles. Typically, for small and medium-sized synchronous motors, λ is taken as 0.6 to 2.5, with the upper limit belonging to multi-pole motors. When the motor size is larger, the motor tends to be slender, with the end phase being shorter than the axial length, which can improve the utilization rate of winding copper wire; when the size is smaller, the motor tends to be short and thick, with the end phase being longer than the axial length, resulting in an increase in the amount of useless copper and a decrease in the utilization rate of winding copper wire.

2.2.2 Slot Pole Coordination Selection

The selection of slot pole fit has a significant impact on the power, efficiency, torque, vibration, and noise of the motor. For a six-phase motor, the number of stator slots Q must be an integer multiple of 12. If the motor has a double Y-offset 30° winding, the stator slot pitch angle should be a multiple of 30° .

When the number of poles of a motor increases with the increase in slot number Q , the least common multiple $\text{LCM}(Q, P)$ of the motor slot number and pole number also increases accordingly. In this case, the order of the cogging torque increases, while its amplitude decreases. However, a higher

number of pole pairs requires a controller equipped with power devices with higher switching frequencies, which not only increases the difficulty of control but also increases system costs[12]. Therefore, when selecting the combination of pole and slot numbers, it is necessary to comprehensively consider the above factors.

The motor designed in this paper adopts a double Y-offset 30° winding configuration, hence its slot pitch angle should align with the offset angle. The relationship between the slot pitch angle is as follows:

$$\alpha = \frac{P \cdot 360}{Z} \quad (5)$$

2.2.3 Stator Winding and Core Design

The six-phase double Y-shift 30° winding utilizes a 30° phase belt, referred to as the "30° phase belt winding in spatial distribution". It consists of two sets of three-phase windings that are 120° out of phase with each other, and the two sets of windings are 30° out of phase with each other in electrical angle. The spatial distribution diagram is shown in Fig. 1:

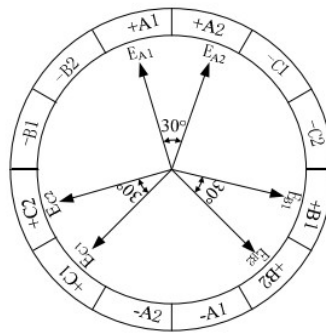


Fig. 1 Spatial distribution diagram of six phase double Y-shifted 30 ° winding

For a six-phase double Y-shifted 30° winding motor, assuming that the stator winding current contains harmonics of 1, 3, 5, 7, 9, 11, ..., with the axis of the stator A1 phase winding as the spatial coordinate origin, at a certain instant t , the six-phase pulsating magnetomotive forces are added at a distance θ_s (mechanical angle) from the axis of the A1 phase winding, resulting in the stator synthetic magnetomotive force waveform:

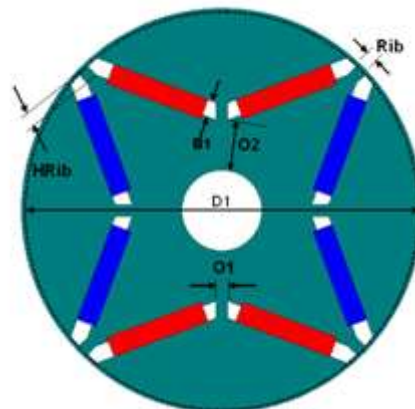
$$\begin{aligned} f_s &= f_{A_1}(t) + f_{B_1}(t) + f_{C_1}(t) + f_{A_2}(t) + f_{B_2}(t) + f_{C_2}(t) \\ &= \frac{6}{2} \sum_{\mu=\nu=1,3,5,\dots} F_{\phi\mu\nu} \cos(\mu\omega t - \nu\theta_s) + \frac{6}{2} \sum_{\mu\pm\nu=\pm 12n} F_{\phi\mu\nu} \cos(\mu\omega t \pm \nu\theta_s) (n=0,1,2,3,\dots) \end{aligned} \quad (6)$$

From the above formula, it can be seen that when $\mu=\nu=1, 3, 5, \dots$ (n equals zero), the synthetic magnetomotive force wave rotates in the forward direction, with a rotational speed of ω ; when $\mu+\nu=12n$ (n is a positive integer), the synthetic magnetomotive force rotates in the reverse direction, with a rotational speed of $\omega\mu/\nu$; when $\mu-\nu=12n$ (n is a positive integer), the synthetic magnetomotive force rotates in the forward direction, with a rotational speed of $\omega\mu/\nu$; for other combinations of ω and ν , the synthetic magnetomotive force is zero. From the above formula, it can be seen that when $\mu=\nu=1, 3, 5, \dots$ (n equals zero), the synthetic magnetomotive force wave rotates in the forward direction, with a rotational speed of ω ; when $\mu+\nu=12n$ (n is a positive integer), the synthetic magnetomotive force rotates in the reverse direction, with a rotational speed of $\omega\mu/\nu$; when $\mu-\nu=12n$ (n is a positive

For a three-phase motor, the fundamental current can generate spatial harmonics of magnetic motive force at orders such as 1, 5, 7, 11, 13, 17, and 19. In a six-phase motor, the fundamental current can generate spatial harmonics of magnetic motive force at orders such as 1, 11, 13, 23, 25, and 35, eliminating the harmonics at orders such as 5, 7, 17, and 19 found in a three-phase motor. This reduction in harmonics at these orders leads to a decrease in the motor's 6th-order ripple torque and torque fluctuation. In a three-phase Y-connected winding motor, harmonic currents at orders that are multiples of 3 only produce pulsating magnetic motive force. However, in a six-phase motor, harmonic currents at orders that are multiples of 3 produce spatial harmonic magnetic motive force at the same order, with the same speed and direction.

Electric vehicles require motors with high torque density, wide speed range, high reliability, and other performance characteristics. The rotor structure of permanent magnet synchronous motors is one of the important factors affecting motor performance.

The built-in rotor structure features a design where the permanent magnets are embedded within the rotor core, leading to a higher direct-axis magnetic circuit reluctance compared to the quadrature-axis magnetic circuit reluctance. This, in turn, results in a larger quadrature-axis inductance (L_q) than the direct-axis inductance (L_d). The reluctance torque generated by the asymmetry between the direct and quadrature axes is beneficial for enhancing the motor's overload capacity and power density, and it also facilitates the field weakening and speed expansion of electric vehicle drive motors[14]. Therefore, this paper chooses the V-shaped built-in rotor structure as the rotor design for permanent magnet synchronous motors used in electric vehicles. The schematic diagram of the rotor structure is shown in Fig. 2.



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2.2.5 Permanent Magnet Size Design

Despite the variety of permanent magnet materials, in order to achieve higher power density and a wider speed range, the permanent magnets in permanent magnet synchronous motors typically employ rare earth cobalt permanent magnet materials and neodymium iron boron permanent magnet materials, both of which exhibit high magnetic properties. Compared to the latter, the former has the best magnetic stability and is more suitable for manufacturing high-performance permanent magnet motors.

The dimensions of permanent magnets primarily include the magnetization direction length h_M , width b_M , and axial length L_M . Generally, the axial length L_M of the permanent magnet is equal to or slightly shorter than the axial length of the motor core, so in practice, only the dimensions of two permanent magnets (i.e., h_M and L_M) need to be designed. When designing a motor, the following factors also need to be comprehensively considered:

When determining h_M , the permanent magnet should be placed at the optimal operating point and have a reasonable direct-axis reactance value, as h_M is an important factor determining the direct-axis reactance, which in turn affects the motor's output power, electromagnetic torque, and other performance characteristics.

h_M cannot be too small. On the one hand, if h_M is too small, it will lead to an increased scrap rate of permanent magnets, resulting in higher costs and making them difficult to transport and assemble. On the other hand, if the permanent magnet is too thin, it will be prone to demagnetization, reducing the reliability and stability of the motor.

Determine b_M based on the requirements of magnetic load. b_M determines the magnetic flux area and can be selected according to the magnitude of the magnetic load, while also considering the limitations of the rotor size[15].

For rotors with built-in structures, the formula for calculating the size of permanent magnets is:

$$h_M = \frac{K_S K_\alpha b_{M0} \delta}{(1 - b_{M0}) \sigma_0} \quad (7)$$

$$b_M = \frac{2\sigma_0 B_{\delta 1} \tau L_{ef}}{\pi b_{M0} B_r K_\phi L_M} \quad (8)$$

L

In the above formula, the coefficient K_α is related to the structure of the rotor and is generally taken as 0.7~1.2. K_S represents the saturation coefficient of the permanent magnet motor, σ_0 denotes the no-load leakage coefficient, $B_{\delta 1}$ signifies the fundamental magnetic density of the air gap, τ stands for the pole pitch of the motor, b_{M0} indicates the no-load operating point of the permanent magnet, L_{ef} is the axial length of the iron core, B_r is the remanent magnetic density of the permanent magnet, K_ϕ is the waveform coefficient of the air gap magnetic density, and L_M is the axial length of the permanent magnet.

3. Final Design Scheme

Based on the design specifications for electric vehicle motors and the analysis of the motor structure mentioned above, this paper designs a 22kw built-in permanent magnet synchronous motor for electric vehicle drive. The motor stator adopts a six-phase double Y-shaped winding with a 30° shift, and the rotor adopts a built-in V-shaped structure. The main design parameters of the motor are shown in Table 3. The motor model and the distribution of air gap magnetic flux are shown in Fig. 3.

Table 3. Main design parameters of the six-phase motor

Parameter	Value	Parameter	Value
Rated power (KW)	22	Rotor inner diameter (mm)	60
Rated voltage V	325	Number of stator slots	36
Rated torque (Nm)	50	Number of pole pairs	3
Rated speed (r/min)	3900	Number of phases	6
Speed range (r/min)	0~7200	Permanent magnet width (mm)	40
Stator outer diameter (mm)	208	Permanent magnet thickness (mm)	6
Stator inner diameter (mm)	120	Core length (mm)	140
Rotor outer diameter (mm)	118	Air gap length (mm)	1

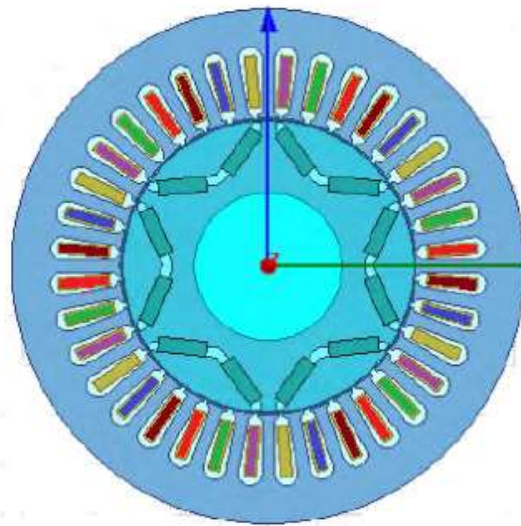


Fig. 3. 2D model of motor

4. Torque Analysis

This article conducts simulation analysis using a 36-slot, 6-pole six-phase and three-phase permanent magnet synchronous motor as examples (the specifications and dimensions of the three-phase permanent magnet synchronous motor are consistent with those of the six-phase motor). The study explores the impact of the number of motor phases on load torque performance. Compared to three-phase motors, six-phase motors offer the advantage of achieving high power with low voltage. Therefore, when simulating the load torque of six-phase and three-phase motors, the current load applied to the six-phase motor is half of that applied to the three-phase motor. The simulation diagram is shown below.

By comparing the torque output waveforms of a three-phase motor and a six-phase fault-tolerant motor, we can observe that the three-phase motor has an output torque of 51.04 Nm with a torque fluctuation of 3.89%. In contrast, the six-phase motor exhibits an output torque of 51.33 Nm with a torque fluctuation of 1.41%, which is significantly lower than that of the three-phase motor. This demonstrates that the six-phase motor can achieve high power at low voltage, reduce motor torque fluctuation, and enhance motor performance and the comfort of electric vehicles.

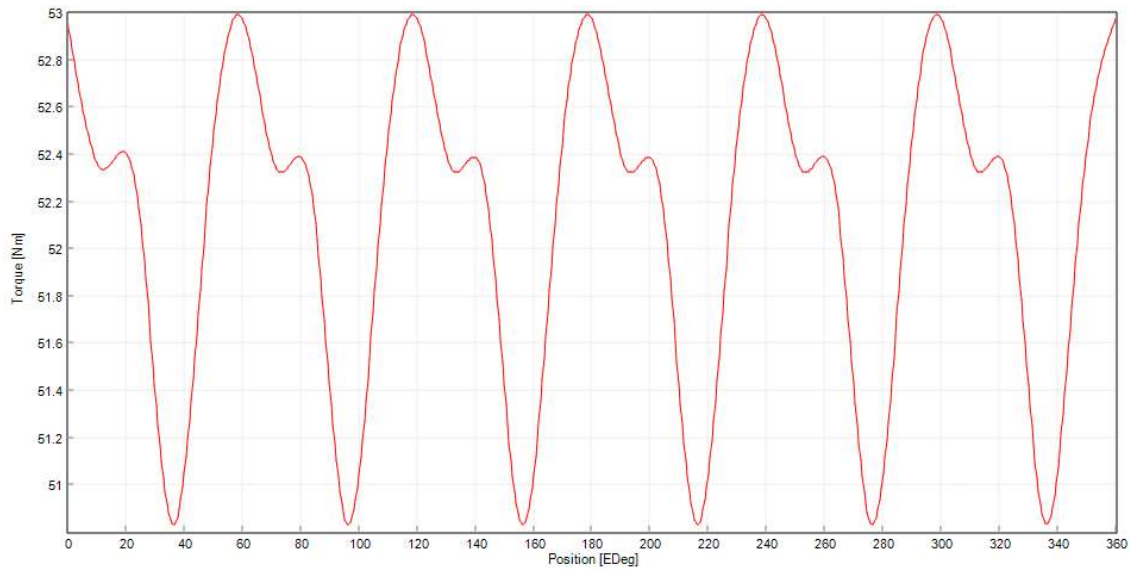


Fig. 4 Three phase motor torque fluctuation

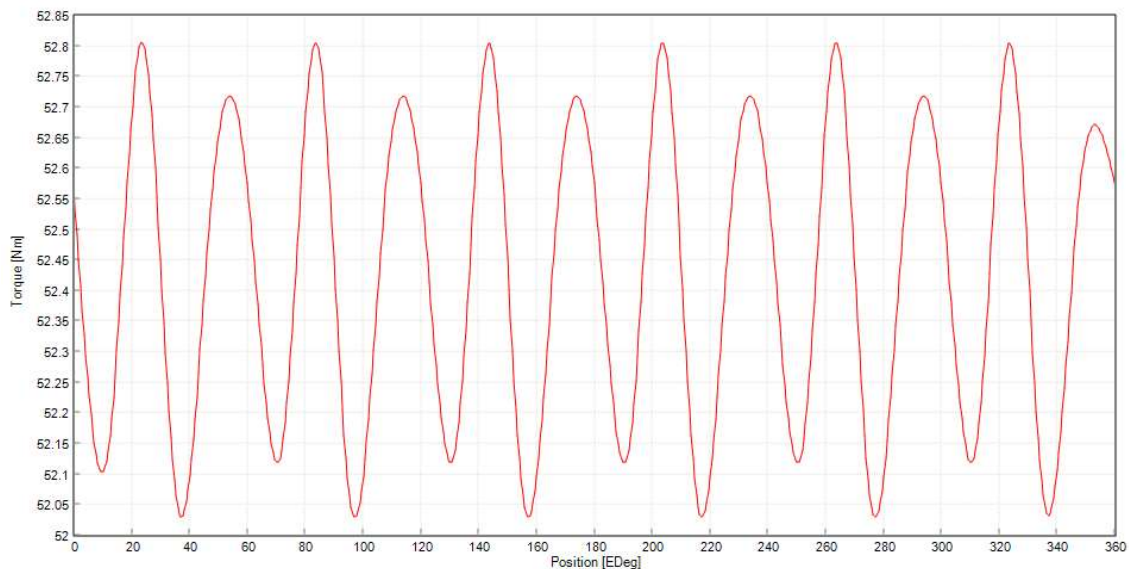


Fig. 5 Six phase motor torque fluctuation

5. Conclusion and Prospects

Based on the requirements of electric vehicle motors, which not only need to meet high torque density and low torque ripple but also a wide speed range, this paper adopts a six-phase permanent magnet synchronous motor design. Firstly, the structure and principle of the six-phase double Y-shifted 30° winding are introduced, and it is analyzed that the six-phase motor can reduce torque ripple. Secondly, a V-shaped structure is proposed as the rotor structure of the built-in permanent magnet synchronous motor to improve the motor's weak magnetic field speed expansion capability, and the design of the permanent magnet dimensions is analyzed. Finally, a finite element analysis of the motor is conducted using Maxwell software, verifying the high performance of the six-phase permanent magnet synchronous motor for electric vehicles.

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