

Damage Prediction for the Starter Motor of the Idling Start-Stop System Based on the Thermal Field

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ABSTRACT

A coupled magnetic-thermal model is established to study the reason for the damage of the starter motor, which belongs to the idling start-stop system of a city bus. A finite element model of the real starter motor is built, and the internal magnetic flux density nephogram and magnetic line distribution chart of the motor are attained by simulation. Then a model in module Transient Thermal of ANSYS is established to calculate the stator and rotor loss, the winding loss and the mechanical loss. Three kinds of losses are coupled to the thermal field as heat sources in two different conditions. The thermal field and the components' temperature distribution in the starting process are obtained, which are finally compared with the already-burned motor of the city bus in reality to predict the damage. The analysis method proposed is verified to be accurate and reliable through comparing the actual structure with the simulation results. The approach in this paper provides the basis for optimizing the idling start-stop system in the future, and its key point lies in the modification of the control program to prevent the control system from sending discontinuous high frequent on-off driving signals.

KEYWORDS: starter motor, magnetic-thermal coupling, thermal field, damage mechanism

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1. INTRODUCTION

In idling condition, the combustion efficiency of the common internal combustion engine is relatively low[1], due to the fact that the fuel is not used for driving the car. And the internal combustion engine exhausts more waste because of insufficient combustion. The idling start-stop system, a device designed to optimize the idling condition, is gaining more and more attention from auto companies and environmentalists, and it is considered to be a key technology for energy saving and emission reduction for cars in the future. When a car stops, the idling start-stop system shuts down the engine. And when sensors detect the driver's intention to start the car, the system then starts the engine automatically by starter motor[2]. Idling start-stop system can effectively reduce the fuel consumption rate while reducing emissions of pollutants, especially for idling condition on urban roads. According to a research, the pollutant emission and fuel consumption rate will respectively be reduced by 20% and 7% on urban roads[3]. Therefore, the idling start-stop system is of greater significance for city bus running on the urban roads.

For the idling start-stop system, starter motor is the core and the main actuator, whose life and reliability play a direct and significant role on the performance of the system and of the whole car. However, there are still some technical problems for starter motor to solve, one of which is the short service life caused by high temperature. The heat is generated by the internal losses including copper loss, iron loss, eddy current loss, mechanical loss, etc. City bus running on the urban road needs to be started frequently due to the complex traffic, under which circumstance quantities of heat will be generated in the internal motor. And the life expectancy of the motor will be lowered to a great extent. At present, the optimization for the idling start-stop system mainly concentrates simply on the battery and the control strategy of the system, lacking damage prediction for different working conditions. Research on idling start-stop system begins with companies like Bosch, Delphi and Strategy Analytics and they have finished a lot of research and verification[1, 2, 3, 4]. Their studies focus on the matching of different cars with different working conditions[6, 7, 8, 9,11], research and optimization about control

strategies[5,10], and improvement for vehicle NVH performance. Up to now, some achievements have been made in spite of starting relatively late[12]. For example, in 2015 an idea of constrained optimization for piston ring-cylinder bore contact was proposed by Chao Cheng and the three-dimensional model can be used as a ring design tool to predict the ring free shape with a specified constraint force distribution pattern[13]. The idea raised by Chao Cheng could also be a guide for optimization of starter motor. However, the damage mechanism analysis under certain working conditions is still in shortage. And the control signals under those conditions are unstable, resulting in motor damage due to strong current. Hence, it is of great significance for the starter motor in idling start-stop system to analyze its thermal fields and conduct damage prediction under certain conditions.

In terms of thermal field analysis, the achievements focus on the coupling between magnetic field and thermal field, through which the internal motor thermal field can be attained[14, 15, 16, 17, 18, 19, 20, 21]. Qin Ren, from Harbin Institute of Technology, calculated the magnetic field and the thermal field of the permanent magnet motor with high power density, and further optimized the motor[22]. Weili Li, from Harbin University of Science and Technology, analyzed the sensitivity of stator copper loss, height of fins and impregnation quality of stator winding based on the thermal field of motors, laying a foundation for motor optimization[23]. Based on the magnetic-thermal coupling analysis of high-speed PM brushless DC motor, Xiaojun Chen optimized the design of the high-speed PM brushless DC motor by using genetic algorithm, and effectively reduced the core loss and significantly improved running efficiency of the motor[24]. However, the existing studies usually focus on the steady-state magnetic fields and their coupling with thermal fields, while the thermal fields under unsteady-state conditions are not taken into account. Therefore, it is necessary for this paper to predict the damage for the starter motor in the idling start-stop system, based on the thermal field obtained from unsteady-state condition. Damage mechanism can be worked out through comparing thermal field with the real object of the burnt motor.

A finite element model for the starter motor is built with Ansoft Maxwell and a simulation is performed for the magnetic field. Finite element model is applied for modeling automotive powertrain system. For example, Xia Hua[25, 26, 27] creatively performed finite element modeling and simulation of automotive driveline systems to investigate the dynamic characteristics which is critical for determining the component damage mechanism. Then the stator and rotor loss, the winding loss and the mechanical loss in two different conditions are attained and coupled to the thermal field as heat sources. By simulating the starting process in two different conditions and comparing the damaged components in simulation with the real starter motor which have been damaged, the damage mechanism can be determined and the method proposed will provide the basis for optimizing the idling start-stop system.

2. BASIC CONCEPT

2.1. Loss Analysis for the Motor

To perform the thermal analysis for the motor, it is necessary to analyze the various kinds of losses, which compose the heat sources of the motor. The losses for the motor mainly consist of four parts--the copper loss, core loss, eddy loss and the mechanical loss. The total loss is presented by the following field variable expansion,

$$P_z = P_{Cu} + P_{Fe} + P_{me} + P_m \quad (1)$$

where P_z is the total loss, P_{Cu} is the copper loss and P_{Fe} is the core loss. P_{me} and P_m are the eddy loss and the mechanical loss, respectively[28]. The loss caused by the leakage magnetic field and the leakage current field is too small so it can be ignored.

The copper loss equals multiplying the current in the winding by its resistor, according to the Lenz's Law. The starter motor analyzed in this article is a DC motor with double-layer windings, whose copper loss can be represented by the following copper loss calculation equation,

$$P_{Cu} = 2I^2 R_\tau \quad (2)$$

where I is the current in each phase of the windings, R_τ is the resistance value of the windings under temperature of τ . In the transient condition, the thermal field in the internal of the motor changes constantly, as well as the resistance value of the windings. In this circumstance, the motor copper loss P_{Cu} is a time-dependent variable. The following equation can approximately describe the discipline that the resistance value changing with the temperature[29],

$$R_\tau = R_0(1 + \lambda\tau) \quad (3)$$

Where R_0 is the resistance value of the windings under temperature of 0 °C, and λ is the temperature coefficient.

The core loss will be generated by the iron core in alternating magnetic field. And in practical engineering, the theory proposed by Bertotti can usually be used to analyze the core loss[30]. According to different mechanisms of heat generation, the core loss can be divided into core eddy loss, magnetic hysteresis loss and extra loss, and the three kinds of losses can be calculated respectively and superimposed into the following field variable expansion,

$$P_{Fe\mu} = P_h + P_e + P_{ex} = k_h f B_m^2 + k_e (f B_m)^2 + k_{ex} (f B_m)^{1.5} \quad (4)$$

where $P_{Fe\mu}$ is the total core loss per unit mass, P_h , P_e and P_{ex} are respectively the magnetic hysteresis loss, the core eddy loss and the extra loss per unit mass.

When performing the transient analysis, the permanent magnetic eddy loss P_{me} is ignored in consideration of the small effect the eddy loss has on the whole thermal analysis.

The mechanical loss consists of bearing friction loss and ventilation loss[31]. There are many factors affecting bearing friction loss, including machining precision, quality of assembly, quality of bearing and the grease. The mechanism can be expressed by the following equation,

$$P_f = 1.5 \times 10^{-6} \frac{F}{d} v \quad (6)$$

where P_f is the bearing friction loss. The ventilation loss is mainly affected by the motor structure, the speed and the air gap. And it's usually characterized by the damping coefficient.

2.2. Mathematical model for thermal field analysis

For isotropic material, its heat conductivity is a constant, meaning that it is invariant with time. According to the Energy Conservation Law and basic laws of heat transfer, the transient thermal field of the motor in the Cartesian coordinate system can be represented as the following equations[32],

$$\frac{\partial}{\partial x} \left(K_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial T}{\partial y} \right) + q_s - \rho c \frac{dT}{dt} = 0 \quad (7)$$

$$\frac{dT}{dt} = v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + \frac{\partial T}{\partial t} \quad (8)$$

where T is the temperature, ρ and c are respectively the density and specific heat of the material. q_s is the heat flux, indicating the heat transferred per unit area and unit time.

The internal heat conduction and heat convection on the external surface should be taken into consideration when conducting thermal analysis. And the boundary conditions can be established based on the principle of heat transfer[33],

$$\begin{cases} T|_{S_1} - T(t) = 0 \\ K_n \frac{\partial T}{\partial n}|_{S_2} + q_0 = 0 \\ K_n \frac{\partial T}{\partial n}|_{S_3} + \beta(T - T_{ev}) = 0 \end{cases} \quad (9)$$

Where $T_{(t)}$ and T_{ev} are respectively the temperature functions of boundary S_1 and boundary S_3 . q_0 is the heat flux of the boundary S_2 .

The transient internal thermal field can be determined by the above governing differential equations and boundary condition equations.

Table 1. The meanings of the symbols used in Section 2.

Symbols	Meanings
k_h	Hysteresis loss coefficient
k_e	Eddy loss coefficient
k_{ex}	Extra loss coefficient
f	Actual flux frequency of the core
B_m	Maximal magnetic flux density
F	Force applied on the bearing
d	Diameter of bearing
v	Peripheral speed of center of ball in the bearing
t	Time
K_x	Heat conductivity along x direction, $K_x = K_y$
K_y	Heat conductivity along y direction
v_x	Heat transfer rate along x direction
v_y	Heat transfer rate along y direction
β	Convective heat transfer coefficient on the boundary S_3
n	Unit normal vector with positive orientation away from the boundary surface
K_n	Heat conductivity along vector n