Research on Extraction and Analysis of Characteristic Conditions of Hub Motor for Electric Vehicles

Guohui Yang, Shuo Zhang, Chengning Zhang* and Yongxi Yang
National Engineering Laboratory for Electric Vehicles, Beijing Institute of Technology (No. 5, Zhongguancun South Avenue, Haidian District, Beijing, China, 100081)

*Corresponding author: mrzhchn@bit.edu.cn

Abstract: The traditional electric machine optimization design technology is generally based on continuous power or overload conditions. It is difficult to fully consider the entire operating domain of the machine, and it is difficult to effectively improve the overall efficiency of the motor. In order to achieve an effective improvement of the overall efficiency of the electric motor under the operating conditions of the vehicle, the motor drive system is well matched with the vehicle design. This paper proposes an electromagnetic optimization design technology for multiple working conditions, uses NEDC working conditions to simulate the actual running conditions of the vehicle to the motor, and optimizes the design of the motor with the highest comprehensive efficiency (lowest comprehensive energy consumption) under the working conditions. By using statistical method, more than 1000 working points of the motor in the whole operating range are simplified into 11 characteristic working conditions. By calculating and comparing the overall energy consumption of the motor under NEDC working condition and 11 characteristic points, the effectiveness of the extraction method of characteristic working conditions is verified.

1. Introduction

The electromagnetic loss of the motor under different working conditions is different. The traditional design method is based on the rated working point for the electromagnetic design of the motor. However, the motor for the vehicle does not have a fixed rated working point. The motor has a wide working range and a large torque/speed change. The electromagnetic design method of the motor at the working point is difficult to ensure that the comprehensive efficiency of the motor for the vehicle under the actual operating conditions of the vehicle is the highest, and even the efficiency of the motor at the rated design point is high, and the overall efficiency is low under the actual operating conditions of the vehicle.

In the traditional motor design method, 80% of the area is larger than 80% of the total working area of the motor. This method can be used to evaluate the motor efficiency distribution characteristics. However, it is difficult to ensure a good match between the motor and the whole vehicle. It is difficult to ensure that the motor drive system has a higher overall efficiency in the actual operating conditions of the vehicle. The efficiency of the motor in the low speed and high torque field is relatively low, the motor matching design is unreasonable, and it is easy to cause the motor to work in the low efficiency area for a long time and reduce the efficiency of the motor drive system. In order to improve the overall efficiency of the motor under the actual operating conditions of the vehicle, the actual working condition of the vehicle should be considered in the motor design stage, and the comprehensive efficiency under the working condition is optimal as a performance optimization index in the motor.
design process.

The operating conditions of the automobile are relatively complicated. At present, the general urban and suburban working conditions for electric vehicles have not yet met the standards. Therefore, the typical working conditions of the traditional gasoline vehicles are used, and the NEDC working conditions of both urban and suburban conditions are used as the simulation operation of the vehicle to carry out the hub motor optimization design. Through technical combination, it is found that there are technical problems to be solved in the research of the subject: the motor optimization design is a cycle iterative process, and the NEDC contains 1180 working conditions, even if the motor is configured for more than 1000 finite elements. The time is also very large and unacceptable. How to simplify the working conditions to meet the engineering calculation requirements is a technical problem that needs to be solved.

2. Analysis of vehicle operating conditions

Motor performance indicators in this study:

Rated power ≥10kW, peak power ≥20kW (30s); maximum speed 1400rpm, output rated torque ≥150Nm, peak torque ≥280Nm (30s); torque density ≥9Nm/kg; effective mass power density ≥1.5kW/kg.

2.1 The choice of simulation cycle conditions

The performance of the vehicle has a lot to do with the actual driving conditions. During the actual driving process, the vehicle constantly experiences acceleration and deceleration and uniform speed. In the evaluation and analysis of automobile-related performance, a vehicle speed-time curve that is more suitable for the local actual situation is often selected as the driving condition of the vehicle, so that the analysis result is closer to the actual performance level of the vehicle.

The operating speed of the whole vehicle under NEDC cycle conditions is shown in Figure 1.

![Figure 1 NEDC cycle condition](image)

Figure 1 NEDC cycle condition

Under the condition of NEDC, the deceleration condition is simplified to separate the electric brake of the motor, regardless of the mechanical brake. It is assumed that the efficiency of the motor is the same as the efficiency under the driving state, and the generated energy can be completely recovered.

2.2 Calculation of motor operating conditions

According to the basic parameters of the vehicle and the cyclical conditions of the vehicle, the basic equations of the vehicle theory can be used to calculate the speed/torque/power of the motor at each time point t=t, respectively, n(t), T(t), p(t), the speed/torque of the motor and the power distribution. Figure 2 shows.

\[
\begin{align*}
F - mg \cos \theta - \frac{C_d \rho A v^2}{2} - mg f &= ma \\
T &= \frac{P}{9549} \\
P &= \frac{F \cdot v}{r} \\
F &= \frac{r}{a}
\end{align*}
\]

(1)

Where, F is the driving force, T is the driving torque, m is the conditioning quality, C_d is the drag
coefficient, \( A \) is the windward area, \( n \) is the wheel speed, and \( P \) is the output power;

From Fig. 2, it can be seen that in the whole NEDC working condition, the rotational speed, torque and power demand at different time points, obviously the torque demand under the whole working condition is below 150Nm, most of which is concentrated around 100Nm, in the urban cycle. Under the circumstance, the power demand of the motor is about 3kW, and the torque and power demand in the suburban high-speed working conditions are relatively large, at around 150Nm and 12KW. Further analysis, in the NEDC working condition, the motor's speed-torque demand is matched, according to the index requirements of the project, the external characteristic requirement curve of the motor is established, and the motor speed-torque demand under the NEDC condition is combined. The demand is shown in Figure 3.

Since the energy consumption of the electric vehicle drive system is mainly reflected in the loss of the motor, or the energy consumption of the whole vehicle is reflected in the energy consumption of the motor drive system. According to the power \( P(t_i) \) and time \( \Delta t_i \) of the motor at each point, the energy \( E_i \) in the unit time interval is defined to represent the energy consumption of the motor at that point.
3. Analysis and study on the extraction method of characteristic working conditions

3.1 Equivalent feature point extraction

Obviously, under the whole cycle condition, the corresponding energy consumption of the motor under different working conditions is different, and the amount of data is huge, which cannot be directly applied to the optimal design of the motor. Analysis of the energy consumption of the motor under various working conditions can be seen: the energy consumption of each working point has a certain regularity, the energy consumption of the motor in the medium and high speed area and the low speed heavy load area is high, and the energy of the low speed light load area is relatively low, and the distribution of working conditions shows regularity, which is relatively concentrated within a certain range. Project the operating point under the NEDC condition to the external characteristic curve of the motor as shown in Figure 5.

Excluding the several points where the energy consumption is too high, the energy consumption distribution under various working conditions of the motor is shown in Fig. 6. Obviously, in different speeds and torque ranges, the motor energy consumption has a certain regularity, and hundreds of
operating points in a certain area have relatively similar energy consumption. To reduce the overall number of operating points, the motor is based on the speed, torque and energy consumption are divided into several areas, and the energy consumption in different areas is processed.

Specific division principle:
1. The motor is relatively concentrated in the area;
2. The speed/torque change is not large;
3. The difference in energy variation of the motor in this area is within a certain range.

Figure 6 NEDC operating point distribution map

According to the above principle, the working point of the motor under the NEDC condition is divided into 11 regions, and the specific divided regions are shown in Table 2. The number of working points of the motor under low load is small, the energy consumption is low, and two regions are divided according to the speed interval below 40Nm; in the torque range of 40-90Nm and 90-130Nm, the number of motor operating points is large, and different speeds The motor energy consumption in the range is quite different. Therefore, this part of the area needs to be divided into thin sections. It is divided into 7 sections according to energy consumption and speed. In the interval where the torque is greater than 130Nm, the working points are mainly concentrated in two parts, divided into 2 parts. A total of 11 work areas, as shown in Table 1.

Table 1 Speed/torque area division

| Region | Tm (Nm) | n (r/min) | Number of working points |
|--------|---------|-----------|--------------------------|
| 1      | 0-40    | 0-600     | 435                      |
| 2      | 0-40    | 600-1400  | 30                       |
| 3      | 40-90   | 0-200     | 88                       |
| 4      | 40-90   | 200-400   | 100                      |
| 5      | 40-90   | 400-600   | 48                       |
| 6      | 40-90   | 600-1400  | 77                       |
| 7      | 90-130  | 0-400     | 88                       |
| 8      | 90-130  | 400-660   | 8                        |
| 9      | 90-130  | 660-1400  | 16                       |
| 10     | 130-150 | 0-200     | 4                        |
| 11     | 130-150 | 200-1400  | 6                        |

The speed and torque in each area of the motor are analyzed based on statistical methods. The rotational speed and torque center of gravity in each area are calculated. The center of gravity value is used to replace the points in each area. The energy loss is calculated for the total energy under all working conditions. Consumption, used to characterize the overall energy consumption in each area.

The energy consumption in each region is represented by the sum of the energies in the following equation:
The centers of angular velocity $\omega_{mci}$ and torque $T_{mci}$ are given by:

$$
\omega_{mci} = \frac{1}{E_i} \sum_{j=1,2,...}^{N_i} E_{ij} \omega_{ij}
$$

(4)

$$
T_{mci} = \frac{1}{E_i} \sum_{j=1,2,...}^{N_i} E_{ij} T_{ij}
$$

(5)

Where $N_i$ is the number of operating points in the i-th region.

The energy consumption, rotation speed and torque under various working conditions of the motor are calculated as shown in Table 2.

| Region | $n$ (r/min) | $Tm$ (Nm) | $E$ (kJ) | Percentage |
|--------|-------------|-----------|---------|------------|
| 1      | 472.5046    | 17.7585   | 286.2   | 18.16      |
| 2      | 854.0395    | 35.1862   | 94.36   | 6.32       |
| 3      | 124.3280    | 80.2412   | 77.8    | 5.21       |
| 4      | 314.4887    | 66.6050   | 214.3   | 14.15      |
| 5      | 494.3554    | 65.7768   | 157.64  | 10.55      |
| 6      | 872.6665    | 57.2749   | 319.4   | 22.4       |
| 7      | 182.9250    | 101.5762  | 123.2   | 8.25       |
| 8      | 550.8427    | 117.7544  | 53.13   | 3.56       |
| 9      | 860.6012    | 100.9883  | 142.14  | 9.51       |
| 10     | 128.2133    | 139.9125  | 6.25    | 0.42       |
| 11     | 311.6451    | 142.8539  | 22.35   | 1.5        |

It can be seen from the analysis in Table 2 that the equivalent point condition represents the energy consumption of the motor under different working conditions and the equivalent speed and torque. The total energy consumed in each working condition accounts for a percentage of the total energy, among which, the torque The energy consumption at the operating point below 40Nm accounts for about 25% of the total energy consumption, of which the low speed (472r./min) light load (about 17.7Nm) accounts for 19% of the total energy consumption, and the motor efficiency at this moment is relatively low. Therefore, it is necessary to pay attention to the motor design process. At medium and low speeds (300-500r/min), the energy consumption of the motor torque below 70Nm accounts for about 25% of the total energy consumption; at medium and high speeds (around 700-900r/min), the medium and low torque (The energy consumption of 60Nm and 100Nm accounts for about 35% of the total energy consumption; for some of the above-mentioned several energy consumption conditions, it is necessary to pay attention to the motor design stage to ensure that the efficiency of the motor is relatively high under this condition. High to achieve a higher overall efficiency of the motor system. The motor consumes about 2% at low speed (100-300r/min) heavy load (about 140Nm), but the efficiency of the motor is low at this time, and it needs to be considered in design.

Through the above 11 feature points, the energy loss of the whole vehicle under the whole NEDC condition is greatly reduced, and the calculation amount of the motor energy utilization rate in the motor design optimization process is greatly reduced, especially when calculating the efficiency by using the finite element method. Ascension is unimaginable.

### 3.2 Effectiveness Analysis of Equivalent Operating Point

The use of 11 equivalent operating conditions to replace the 1180 operating conditions under the entire NEDC operating conditions, whether the equivalent method is reasonable or not will be highlighted in this section.

1. Analysis of the compatibility of working conditions

The NEDC operating point and 11 characteristic operating points are projected into the external characteristic curve of the motor, as shown in Fig. 7. The distribution of the speed/torque distribution
and the distribution of the characteristic points of the motor under the NEDC operating conditions are compared and analyzed. Obviously, the characteristic point distribution can well represent the working conditions in different speed/torque ranges.

![Figure 7 NEDC operating point and characteristic operating point](figure7.png)

(2) Energy loss analysis

The energy consumption of 11 feature points is compared with the energy consumption under NEDC conditions to verify the rationality of using the feature point conditions instead of the entire NEDC operating conditions.

The motor efficiency map is constantly changing as the electromagnetic structure parameters of the motor change, and the efficiency changes of different motors at different operating points directly affect the energy consumption. The efficiency map of the motor proposed in this project is a special one, which is assumed to have little change during the motor optimization design process, or is understood to have a fixed efficiency map during the process of changing the electromagnetic parameters of the motor. All use this map as a benchmark.

Obviously, this assumption is not the same as the actual situation, but whether it can reflect certain problems to a certain extent. In the process, you need to make certain compromises and trade-offs. Choosing the right motor efficiency map is the first step in the analysis. The efficiency map of a certain motor selected in the previous design is shown in Figure 8.

![Figure 8 Efficiency map](figure8.png)

Calculate the energy consumption of the motor under the entire NEDC characteristic condition using equation (6).

\[
EL = \sum_{i=1}^{N} \omega_{m}(t_{i}) T_{m}(t_{i}) \Delta t_{i} (1 - \eta_{i}) / \eta_{i} \quad (6)
\]

Where \( \eta_{i} \) is the efficiency at \( \omega_{m}(t_{i}) \) and \( T_{m}(t_{i}) \) in the motor energy efficiency diagram.
The energy consumption of the motor under 11 characteristic point conditions is calculated by formula (7).

\[ EL = \sum_{j=1}^{11} E_{nj}(1 - \eta_j) / \eta_j \]  

(7)

Where \( E_{nj} \) and \( \eta_j \) represent the energy consumption and efficiency at the j-th point, respectively.

The total energy consumption of the motor under NEDC conditions and the energy consumption under 11 characteristic points are calculated by MATLAB as shown in Table 3.

| Table 3 Comparison of energy consumption |
|-----------------------------------------|
| NEDC energy consumption at all operating points (kJ) | 1784.1 |
| Energy consumption of 11 feature points (kJ) | 1875.9 |
| Error comparison | 4.89% |

Obviously, the total loss calculated by the characteristic point working condition can well characterize the loss characteristics of the motor under the whole NEDC condition. In the motor optimization design stage, the characteristic point condition is used for motor performance check, comparative analysis, and iterative optimize the design of the motor, greatly reducing the amount of calculation in the motor optimization design process.

The alternatives to the working conditions mentioned in this paper are not limited to NEDC operating conditions, and their ideas are still applicable to other typical operating conditions. The difference lies only in the division of specific characteristic working conditions. The division principle of working conditions will affect the representativeness of the characteristic points to the whole to a certain extent. In principle, the more regional, the more representative, the better the better. The energy consumption characteristics of the whole working condition, but the corresponding calculation amount will also increase, so the trade-off between the working conditions should be properly weighed.

In the process of motor optimization design, the variation of electromagnetic parameters must lead to the variation of motor efficiency distribution characteristics, and the distribution of motor efficiency map must be different.

In essence, multi-operating condition electromagnetic optimization design technology is to carry out motor electromagnetic parameter design based on the actual operating conditions of the whole vehicle, or motor efficiency map design movement problem, so as to ensure the motor operating efficiency as high as possible under the comprehensive operating conditions of the whole vehicle.

4. Summary
In this paper, by means of statistical method, more than 1000 operating points of hub motor NEDC for electric vehicles in the whole working condition range are simplified into 11 characteristic working conditions. Moreover, the energy consumption comparison between the whole working condition and characteristic points is calculated to verify the effectiveness of the feature point extraction method. It provides the foundation for improving the comprehensive efficiency of the motor vehicle under the operating condition, and also provides the idea for the motor drive control system to match the good design of the vehicle.

Acknowledgement
This research was financially supported by the National Natural Science Foundation of China (Grant No. 51677005).

References
[1] C. Zhang, S. Zhang, G. Han, H. Liu, Power Management Comparison for a
Dual-Motor-Propulsion System Used in a Battery Electric Bus.[J] IEEE Transactions on Industrial Electronics, vol.64, pp3873-3882(2017).

[2] C. Zhang, H. Liu, X. Wu, Y. Yang, X. xin, A Computationally Efficient PM Power Loss Derivation in Thermal Modelling for Surface-mounted Brushless AC PM Machine[C], ICAE2016, vol.105, pp2891-2897(2017).

[3] Y. Ji,L. Ren,J. Zhou, Boundary conditions of active steering control of independent rotating wheelset based on hub motor and wheel rotating speed difference feedback.[J] Vehicle System Dynamics, vol.56, pp1883-1898(2018).

[4] J.Dai, Z.Zhao,T. Liu,C. Wang,X. Hu, Review of research on AFPM hub motor[J], Journal of Hebei University of Science and Technology, vol.39, pp 17-23(2018).

[5] R. Wrobel, P. H. Mellor, M. Popescu, D. A. Staton, Power Loss Analysis in Thermal Design of Permanent Magnet Machines – A Review[J], IEEE Transactions on Industry Applications, vol.52, pp 1359-1368(2016).

[6] R. Wrobel, G. Vainel, C. Copeland, T. Duda, D. Staton, and Phil H. Mellor, Investigation of Mechanical Loss Components and Heat Transfer in an Axial-Flux PM Machine, [J], IEEE Transactions on Industry Applications, vol.14, pp 3000-3011(2015).

[7] J. Goss, R. Wrobel, P.H. Mellor, D. Staton, The Design of AC Permanent Magnet Motors for Electric Vehicles: A Design Methodology[C], IEEE International Conference on Electric Machines and Drives, pp 871 – 878(2013).

[8] R. Wrobel, J. Goss, A. Mlot, P.H. Mellor, Design Considerations of a Brushless Open-Slot Radial-Flux PM Hub Motor[J], IEEE Trans. Ind. Appl., vol. 50, pp. 1757-1767(2014).

[9] J. Goss, P.H. Mellor, R. Wrobel, D.A. Staton, M. Popescu, The Design of AC Permanent Magnet Motors for Electric Vehicles: A Computationally Efficient Model of the Operational Envelope,[C], 6th IET International Conference on Power Electronics,Machines and Drives, PEMD’12, pp. 1–6(2012).

[10] X. Wu, Research on Method of Electromagnetic Loss Derivation over the Entire Torque-Speed Envelope and Thermal Field in Permanet Magnet Synchronous Motor[D],Beijing Institute of Technology(2016).

[11] R. Wrobel, D.E. Salt, A. Giffo, P.H. Mellor, Derivation and Scaling of AC Copper Loss in Thermal Modeling of Electrical Machines[J], IEEE Trans. Ind. Elect., vol. 61, pp. 4412 – 4420(2014).

[12] P. Zhang, G.Y. Sizov, J. He, D.M. Ionel, N.A.O. Demerdash, "Calculation of Magnet Losses in Concentrated-Winding Permanent-Magnet Synchronous MachinesUsing a Computationally Efficient Finite-Element Method[J], IEEE Trans. Ind. Appl., vol.49, pp. 2524 - 2532 (2013).

[13] D. A. Howey, A. S. Holmes, K. R. Pullen, Measurement of Stator Heat Transfer in Air-Cooled Axial Flux Permanent Magnet Machines[C], 35th IEEE Industrial Electronics Annual Conference, IEECON’09, pp. 1197 – 1202(2009).

[14] A. C. Malloy, R. F. Martinez-Botas, M. Jaensch, M. Lamperth, Measurement of Heat Generation Rate in Permanent Magnet Rotating Electrical Machines[C], 6th IET International Conference on Power Electronics, Machines and Drives, PEMD’12, pp.1– 6, 2012(2012).

[15] X. F. Ding and C. Mi, Modeling of Eddy Current Loss in the Magnets of Permanent Magnet Machines for Hybrid and Electric Vehicle Traction Application[C] Vehicle Power and Propulsion Conference, pp. 419-424(2009).

[16] K. Yoshida, Y. Hita, K. Kesamaru, Eddy-Current Loss Analysis in PM of Surface-mounted-PMSM for Electric Vehicles[J], IEEE Trans. Magn., vol. 36, pp. 1941-1944(2000).

[17] L. J. Wu, Z. Q. Zhu, D. Staton, M. Popescu, and D. Hawkins, Analytical Modelling and Analysis of Open-circuit Magnet Loss in Surface-mounted Permanent Magnet Machines[J], IEEE Trans. Magn., vol. 48, pp. 1234-1246(2011).

[18] K. Atallah, D. Howe, P. H. Mellor, and D. A. Stone, "Rotor Loss in Permanent-magnet Brushless AC Machines[J], IEEE Trans. Ind. Appl., vol. 36, pp. 1612-1618(2000).
[19] P.H. Mellor, R. Wrobel, D. Holiday, A Computationally Efficient Iron Loss model for Brushless AC Machines that Caters for Rated Llux and Field Weakened Operation[C]. IEEE International Conference on Electrical Machine and Drives, IEMDC’09, pp. 490-494(2009).