Optimal design of the drive motor based on the road condition of the electric vehicle

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Abstract
Due to the progressive prevalence of electric vehicles (EV) in the last few decades, more concerns have been focussed on the drive motor efficiency and its manufacturing cost. This article presents an optimisation design method for EV’s motor based on road condition to achieve more practical optimisation design. First, the magnetic circuit model of motor is established which can calculate the efficiency map. The correctness of the circuit model can be verified by comparing the calculated map with the testing map. Second, the objective function can be established by considering the feature of New European Driving Cycle (NEDC) cycle road condition into motor conditions and the time proportions for different motor conditions as the weights. Then, the optimisation design for the motor can be carried out by setting constraints of optimisation including the loss limitation, volume, and other geometrical feasibility. Two objective functions with efficiency as the single objective and efficiency–weight as the dual objective are constructed, and the difference between the two objective functions corresponding to the optimisation scheme is analysed at the end. The optimisation method proposed in this article can be employed in the optimal design of the drive motor under any road condition. The designed scheme obtained from optimisation can achieve the best performance in target under whole road conditions, and by weighing the contradiction between material optimisation and thermal design.

1 | INTRODUCTION
The popularity of an electric vehicle is closely related to the advantages of environmental protection and its excellent performance, but it still confronts the challenge of reduced autonomy for the electric vehicle (EV). Improving the efficiency and reducing motor weight are the effective means to solve the mentioned problem [1].

At present, the efficient design of the permanent magnet synchronous motor (PMSM) for EV is a widely employed and well-developed method. Engineers and scholars pay attention to the efficient design of motor in a wide torque and speed range [2]. Stipetic et al. proposed a fast efficiency map calculation method based on the electromagnetic saturation model. This method can also be used in simulation of EV systems. Based on this method, the motor is optimised and a sequence of motor loss and efficiency maps is obtained [3]. Wu et al. proposed a new method for parameter modelling and optimisation of brushless DC motors. Based on the neural network, the geometrical feasibility was optimised to achieve the purposes of efficiency maximising, material cost minimising, and higher power density [4].

Some scholars also evaluated the performance of motors in combination with cycle test conditions of EV. Liu et al. proposed a loss prediction model based on the relationship between temperature and motor loss. Taking the New European Driving Cycle (NEDC) as sample driving cycle, a lumped parametric heating model is established, and the working performance of outer-rotor I-shaped flux-switching permanent magnet switched reluctance motor is predicted [5]. In Ref. [6], it is aimed at the research of two types of high-speed, low-torque cycle—Highway Fuel Economy Test and low-speed, high-torque cycle—Artemis Urban Driving Cycle. The influence of motor parameters such as tooth width, slot depth, split ratio, and V-shaped permanent magnet (PM) angle on energy consumption during entire driving cycle is analysed.
Zhu et al. proposed a new method of motor optimal design in combination with NEDC conditions. The PM memory motor with controllable stator flux is selected as the research object, and the driving modes of EV are divided into start, normal cruise, acceleration, high speed cruise, and heavy load climb which correspond to the five normal operating conditions of motor, magnetising operating condition, weak magnetic operating condition, open circuit fault, and short circuit fault. The optimisation constraints and boundaries are given according to operating conditions, and the importance of optimisation variables in five driving modes is distinguished according to the sensitivity. Finally, the effectiveness of optimisation method is verified through experiments. The optimisation content is shown in Figure 1. The optimised design method based on PM memory motor proposed in Ref. [7] is highly targeted and is an effective method to improve the applicability of EVs.

In Ref. [8], Krasopoulos et al. proposed a multi-criteria and multi-disciplinary design optimisation strategy for light-duty EV PM-SM considering entire driving cycle. The optimisation strategy includes three parts in Figure 2. These three parts are evolutionary optimisation, fuzzy inference system adjustment based on adaptive network, and archive update. They are used to improve Pareto front of each generation and accuracy of each generation, and update standard values of archived members. This novel optimisation method greatly reduces the workload of efficiency map calculated by finite element.

The article presents an optimisation method of motor efficiency and consumable cost based on the actual operation condition of EV. The optimised flow chart is shown in Figure 3. The parameters such as speed, acceleration, climbing angle, and vehicle mass are transformed into different operating conditions and working time of the motor. After that, the performance of motor at various torques and speeds can be obtained through the magnetic circuit calculation shown in Figure 5, and the time ratio of different working conditions define the weight of objective function. As for constraint of optimisation, it includes loss limitation, volume, and geometrical feasibility. The optimal solution finally can be found by optimisation algorithm.

The optimisation method proposed in the article is different from traditional single operating point or high-efficiency interval optimisation. The optimised design plan is based on the optimal design of EV operating conditions. Adjusting parameters for different types of vehicles and operating road conditions can effectively increase the cruising range of EVs. Hence it is a new method for evaluating EV motor optimisation plan and it can realise the optimised design of materials saving, efficiency improvement and prevention of loss limitation.
2 | MAGNETIC CIRCUIT DESIGN AND EXPERIMENTAL VERIFICATION OF PMSM USED IN EV

2.1 | Motor parameters

The PMSM drive motor of commercial EV used for express transportation is taken as an example to carry out research in this article. For this section, the motor magnetic circuit model is constructed and its accuracy is verified by the test results.

The basic parameters of motor are shown in Table 1. Correspondingly, Figure 4 is an exploded view of geometrical feasibility, which includes the structure of rotor parts and casing. It can be seen that the cooling method of motor is natural cooling.

2.2 | Magnetic circuit calculation of motor

The calculation of magnetic circuit of a PMSM is a relatively mature and common method for calculating electromagnetic performance of motor. It has high speed and slightly worse calculation accuracy than finite element and suited for occasions where the number of calculation schemes is large and accuracy requirement is not high. In the optimisation calculation process, there needs to be constant iteration calculations until calculation converges, so the article uses magnetic circuit method to calculate the performance of motor under different working conditions.

The magnetic circuit calculation mainly includes the calculation of main dimensions, PMs, winding parameters, no-load magnetic circuit, circuit parameters, and working characteristics, as well as the cycle calculation of no-load working point of PM and cross-axis current, as shown in Figure 5. Equation (1) is the convergence condition of the cycles. When the error is less than ε, it will jump out of the loop. After that, the dimension, weight, and working characteristic curve can be obtained [9,10].

\[
\left| \frac{b_{m0} - b_{m0}}{b_{m0}} \right|, \left| \frac{I_q' - I_q}{I_q} \right| < \varepsilon
\]  

Figure 5 The flow chart of magnetic circuit calculation

where, \( b_{m0} \) represents the no-load operating point of PM. \( I_q \) represents the quadrature axis current. \( b_{m0}, I_q \) represents the new variable in iteration process.

2.3 | Analysis of theoretical calculation and measured results

The original prototype was tested on electric dynamometer, as shown in Figure 6. The variable frequency driver controls the test motor which drives electric dynamometer through rotating shaft, and the data such as voltage, current, torque, and speed of motor under different working conditions was collected by sensors.

The efficiency of motor was obtained through tests under different working conditions. By fitting the torque, speed and
efficiency under multiple working conditions, the efficiency map shown in Figure 7 was obtained. The efficiency values corresponding to different working conditions can be read by colour of legend.

The efficiency map shown in Figure 7 was obtained by testing motor’s efficiency under different working conditions. Among them, the speed range is 500–8000 rpm, the torque range is 10–178 Nm, the maximum power is 76.5 kW, the highest efficiency obtained by test is 95.46%, and the corresponding operating point with highest efficiency is 5000 rpm–62.8 kW.

Based on the electromagnetic model mentioned above, the same working point as Figure 7 is calculated to obtain the corresponding efficiency, and then the efficiency map shown in Figure 8 is fitted. It can be seen from the comparison between calculated value and test value of efficiency map that the distribution law of high-efficiency area of calculated map is basically consistent with test map. It shows that electromagnetic calculation results are basically consistent with test results, but the calculation value of some high-efficiency areas in map is about 1% higher. Difference values of mechanical losses and stray losses in magnetic circuit calculations are the main reasons for this phenomenon, especially when the torque is large. It should be noted that the size of mechanical loss and stray loss is 1.5% of output power in the calculation.

In addition, the proportion of different efficiency segments in two maps is analysed. As shown in Table 2, it can be seen that agreement is higher in 80%–90% efficiency area. When the efficiency is greater than 90%, the calculation results are different. This is because the high-efficiency area is generally a point with a high rotation speed and large torque. When the rotation speed and torque become large enough, the calculated mechanical loss is different from the measured value, resulting in difference in efficiency.

3 | OPTIMISED MOTOR DESIGN BASED ON STANDARD DRIVING CONDITIONS

In this section, the optimisation architecture based on the road conditions of NEDC (Extra Urban Driving Cycle) is constructed. The optimisation design is carried out in combination with road conditions and example models, which mainly includes road condition analysis, EV parameters, the change from road condition to working condition, objective function construction, constraints and optimisation algorithm.

3.1 | Analysis of NEDC standard road condition and motor drive working point

NEDC road conditions include Urban Driving Cycle (UDC) representing low speed and low load and Extra Urban Driving Cycle (EUDC) at high speed and high load, as shown in Figure 9. By adjusting the ratio of UDC and EUDC, the actual driving situation can be simulated [11]. The article takes UDC and EUDC in NEDC conditions as examples to carry out optimised design of motor, and the obtained motor design schemes are the best in UDC and the best EUDC, respectively. The optimisation method can also be applied to the entire NEDC road conditions or the design based on other road conditions.

The UDC and EUDC were analysed separately in the article, and the characteristics of vehicle’s operation at zero speed, acceleration, uniform speed, deceleration, gear shifting, clutch action etc., were obtained. Tables 3 and 4 give operation content and time under different road conditions.

**FIGURE 6** Motor test bench

**FIGURE 7** The test efficiency map
In order to clearly describe the optimisation method in the article, the following idealised treatments were made in analysis of road conditions. (1) It is believed that there is only mechanical braking during deceleration, and motor cannot provide braking force as a power generation state. (2) Since the shifting process lasts for a short time and the motor speed does not change suddenly, it is considered that the motor still maintains the state of previous gear. (3) According to the actual working state of EV, the motor does not work during idling. Therefore, only the two road conditions corresponding to operations of uniform speed and acceleration are considered in the optimisation.

Based on the actual vehicle model, this article selects the parameters of business EV shown in Table 5, and vehicle weight refers to the weight including goods.

From knowledge of dynamics, when the vehicle is driving on a non-slope, the driving force of motor is equal to rolling resistance, air resistance, acceleration resistance, and ramp resistance. Since the road conditions selected in the article do not involve slopes, the balance equation of vehicle traction is shown in Equation (2) [12].

\[
F = mgf + \frac{C_DA\nu_a^2}{21.15} + ma \tag{2}
\]

\[
T_e = FR/(\lambda \eta_t) \tag{3}
\]

\[
n = \lambda \nu_a/(0.377R) \tag{4}
\]

where, \(F\) is driving force of motor, \(m\) is vehicle weight, \(f\) is rolling resistance coefficient, \(C_D\) is air resistance coefficient, \(A\) is frontal area, \(\nu_a\) is vehicle's speed, \(a\) is acceleration, \(T_e\) is torque, \(\lambda\) is transmission ratio, \(\eta_t\) is transmission efficiency, \(R\) is tire radius, and \(n\) is rotating speed.

The driving force of motor is calculated by Equation (2), and the speed and torque of motor are obtained by Equations (3), and (4). Following this process, convert the EV data in Tables 3 and 4 to the speed, torque in Table 6. Then, the vehicle speed during acceleration is obtained by averaging method, and the proportion of operating conditions is determined by the time corresponding to road conditions.

### 3.2 Optimised architecture composition

#### 3.2.1 Objective function

The optimisation goal consists of motor’s efficiency under different working conditions, and weight is composed of the proportion of corresponding working conditions. After

**FIGURE 8** The calculated efficiency map

**TABLE 2** Proportion of area with different efficiency zones in two efficiency maps

| Proportion of efficiency zone (%) | Calculated map | Test map |
|----------------------------------|----------------|---------|
| ≥95                              | 38.67          | 13.19   |
| 95–90                            | 45.76          | 65.99   |
| 90–85                            | 10.31          | 12.81   |
| 85–80                            | 3.68           | 3.95    |

**FIGURE 9** NEDC standard cycle conditions

is frontal area, \(\nu_a\) is vehicle's speed, \(a\) is acceleration, \(T_e\) is torque, \(\lambda\) is transmission ratio, \(\eta_t\) is transmission efficiency, \(R\) is tire radius, and \(n\) is rotating speed.
### TABLE 3  Analysis of EV driving content under UDC

| Number | Operation    | Acceleration (m/s²) | Equivalent speed (km/h) | Cumulative time (s) |
|--------|--------------|---------------------|-------------------------|---------------------|
| 1      | Uniform speed| 0                   | 15                      | 8                   |
| 2      | 0            | 32                  | 24                      |
| 3      | 0            | 50                  | 12                      |
| 4      | 0            | 17.5                | 13                      |
| 5      | Acceleration | 1.04                | 7.5                     | 4                   |
| 6      | 0.83         | 7.5                 | 5 + 5 = 10              |
| 7      | 0.94         | 23.5                | 5                       |
| 8      | 0.62         | 25                  | 9                       |
| 9      | 0.52         | 42.5                | 8                       |
| 10     | Deceleration | −0.69               | 12.5                    | 2                   |
| 11     | −0.75        | 21                  | 8                       |
| 12     | −0.52        | 42.5                | 8                       |
| 13     | −0.86        | 22.5                | 7                       |
| 14     | Zero speed   | 0                   | 0                       | 11 + 21 + 21 + 7 = 60 |
| 15     | Clutch separation | −0.92           | 5                       | 3 + 3 +3 = 9 |
| 17     | Shift        | /                   | /                       | 2 + 2 + 2 + 2 = 8   |

### TABLE 4  Analysis of EV driving content under EUDC

| Number | Operation    | Acceleration (m/s²) | Equivalent speed (km/h) | Cumulative time (s) |
|--------|--------------|---------------------|-------------------------|---------------------|
| 1      | Uniform speed| 0                   | 70                      | 50 + 50             |
| 2      | 0            | 50                  | 69                      |
| 3      | 0            | 100                 | 30                      |
| 4      | 0            | 120                 | 10                      |
| 5      | Acceleration | 0.83                | 7.5                     | 5                   |
| 6      | 0.62         | 25                  | 9                       |
| 7      | 0.52         | 42.5                | 9                       |
| 8      | 0.43         | 60                  | 13 + 13                 |
| 9      | 0.24         | 85                  | 35                      |
| 10     | 0.28         | 110                 | 20                      |
| 11     | Deceleration | −0.69               | 60                      | 8                   |
| 12     | −0.69        | 100                 | 16                      |
| 13     | −1.04        | 65                  | 8                       |
| 14     | Zero speed   | /                   | /                       | 20 + 13             |
| 15     | Clutch separation | −1.39           | 25                      | 10                  |
| 16     | Shift        | /                   | /                       | 2 + 2 + 2 = 6       |
accumulation, the objective function is obtained as shown in Equation (5).
\[
\text{Max } \sum_{i=1}^{N} \alpha_i f_i(X)
\]  

(5)

where, \(N\) represents the number of characteristic operating conditions, taking 9 for UDC and 10 for EUDC. For example, in Equation (6), \(\text{Max } F_1\) consists of 9 items. \(\alpha_i\) represents the weight of each working condition, \(f_i(X)\) represents optimisation objectives, the optimisation objectives in the article is efficiency, which can also be set to other single or multiple goals. It should be noted that the efficiency is expressed as less than 1, such as 0.9, 0.88 in the calculation process.

Corresponding to road conditions in Table 6, the objective functions of UDC and EUDC can be obtained in Equations (6) and (7), respectively.

\[
\text{Max } F_1 = 0.043f(292, 85.9) + 0.086f(584, 10.5) + 0.054f(915, 78.7) + 0.097f(1656, 48.4) + 0.129f(1948, 10.7) + 0.14f(682, 10.5) + 0.108f(292, 70.7)
\]

(6)

\[
\text{Max } Y_1 = 0.016f(292, 70.7) + 0.029f(974, 55.5) + 0.026f(1656, 48.4) + 0.084f(2337, 42) + 0.32f(2727, 10.9) + 0.22f(1948, 10.7) + 0.112f(3311, 28.5) + 0.09f(3896, 11.4) + 0.064f(4285, 31.9) + 0.032f(4675, 11.8)
\]

(7)
where, \( F_1 \) and \( Y_1 \) represent the optimisation objective function of the motor under UDC and EUDC, respectively.

### 3.2.2 Constraints

The constraints of optimisation method include loss limitation constraint, volume constraint, and geometrical feasibility. The volume constraint is set according to motor’s application or other actual conditions. The feasible interval of optimisation variables is shown in Table 7. Among them, the maximum size of external dimensions, axial length, thickness, and width of PM are given according to the size of original motor, and the minimum value is given according to experience.

The structural relationship constraint refers to the relationship condition where dependent variable changes due to optimisation of independent variables. Furthermore, too many independent variables will result in slow convergence during optimisation, and it is difficult to find the global optimal solution set. Considering the limitation of computing resources and computing time, this article creates some dependent variables based on design experience. There are five dependent variables involved in this article, which are stator inner diameter, \( D_1 \), \( O_2 \), stator tooth width and yoke height in Figure 10. The stator inner diameter \( = \) stator outer diameter/1.387, \( O_2 = (\text{rotor outer diameter} - C_1)/2, D_1 = \text{rotor outer diameter} - C_2 \), where \( C_1 \) and \( C_2 \) are empirical constants. The stator tooth width and yoke height are determined according to tooth magnetic density and yoke magnetic density, and the judgement standard is that average magnetic density of each part is less than saturated magnetic density.

Dependent variables are used only to shorten computation time. When the dimension of independent variables is too low, the accuracy of optimisation results will be affected. Therefore, the use of dependent variables should be minimised when the computing capacity is sufficient.

In the optimisation process, it is easy to have a scheme with low total loss but relatively high copper or iron loss. For example, only the copper loss is higher than the normal value. Such schemes are easy to cause the problem of excessive local temperature. Therefore, in the optimisation process, according to the total loss under different working conditions, the loss of different parts is set as loss limitation constraint. The purpose is to achieve a relatively uniform loss distribution. In the calculation of magnetic circuit, the loss is composed of iron loss, copper loss, mechanical loss and stray loss. The setting of loss limitation constraint is composed of input power ratio, in which iron loss ratio is not more than 18%, copper loss ratio is not more than 10%.

### 3.2.3 Optimisation method

For projects with strong timeliness and large engineering volume, efficient optimisation algorithms can greatly reduce optimisation time. In this article, sequential nonlinear programming is used to optimise the set area, and convergence accuracy is set to 1%. After 175 iterations, the objective function value tends to be stable [13, 14].

### 4 ANALYSIS OF OPTIMISATION RESULTS

Based on the foregoing, this section analyses the optimisation scheme under UDC and EUDC, as well as the optimisation scheme under different target weights.

#### 4.1 Optimisation of motor efficiency based on NEDC road conditions

Through the above optimisation, the optimal electromagnetic design plan corresponding to UDC and EUDC is obtained. Table 8 lists three motor design solutions, of which \( A_1 \) is optimal solution optimised under UDC, and \( B_1 \) is the optimal solution optimised under EUDC. The motor design scheme of plan \( A_1 \) and plan \( B_1 \) has the characteristics of high efficiency under UDC and EUDC respectively. In order to explain the efficiency difference of plan \( A_1 \) and plan \( B_1 \) more clearly, the

![Figure 10: The parameters of PMs](image)

| Variates          | Min (mm) | Max (mm) | Variates          | Min (mm) | Max (mm) |
|-------------------|----------|----------|-------------------|----------|----------|
| Outer diameter    | 120      | 210      | Magnet thickness  | 1        | 5.5      |
| Length            | 57       | 114      | Magnet width      | 5        | 32       |
| Air gap           | 0.8      | 2        |                   |          |          |

Table 7 The interval of optimise variable
efficiency comparison of three motor solutions is also drawn in Figure 11 whose abscissa corresponds to the serial number in Table 6. It can be seen that the two optimised design schemes are more suitable for NEDC. At the same time, the design conditions of original scheme are not for NEDC, so the efficiency is not high. The article employs this motor as an example to evidence the effectiveness of the optimisation method.

It can be seen from objective function value of three schemes in Table 9 under two road conditions that the optimised two schemes have significantly improved motor's efficiency under corresponding road conditions. The value in red is the optimal objective function value. The efficiency of motor in UDC is about 2% lower than that in EUDC. This is because speed corresponding to UDC is low, and voltage is still given according to original scheme during the optimisation process, so the efficiency is relatively low. At the same time, this optimisation is only aimed at optimising efficiency, and reduction in weight is caused by limitation of volume constraint, so the optimisation of weight is small. In the following, weight will be used as part of objective function.

### 4.2 Efficiency and weight optimisation based on NEDC

The manufacturing cost is an important part of motor design. In the commercial application, reducing the weight of motor has an important role in enhancing products' competitiveness. Therefore, the weight is added to optimisation goal as a part of
optimisation goal. The weight of efficiency part is accumulated to 1, the weight of motor’s weight is 0.3. In engineering applications, different weight coefficients can be selected according to requirements of efficiency and manufacturing cost. In addition, other contents such as power density, power factor and copper weight can also be added as part of objective function.

When the motor weight is taken as part of optimisation goal, the objective functions of UDC and EUDC are as follows:

\[
\text{Max } F_2 = F_1 + 0.3 \frac{1}{W} \tag{8}
\]
\[
\text{Max } Y_2 = Y_1 + 0.3 \frac{1}{W} \tag{9}
\]

where, \(F_2\) and \(Y_2\) represent the optimisation objective function of motor under UDC and EUDC, respectively, and \(W\) represents the weight of motor under the corresponding optimisation scheme.

Similar to the optimisation process above, only optimisation goals have been modified here. \(F_2, Y_2\) are composed of the reciprocal of \(F_1, Y_1\) and the weight of motor, which can reflect the optimisation of both motor efficiency and weight. The proportion coefficient of 0.3 can be adjusted according to the actual optimisation requirements. After optimisation calculations, the design schemes suitable for both UDC and EUDC were obtained, as shown in Table 10. Among them, A2 is the optimal solution optimised under UDC, and B2 is the optimal solution optimised under EUDC. The motor design of plan A2 and plan B2 has the characteristics of high efficiency and light weight when operating under UDC and EUDC, respectively. Compared with the motor weight in Table 8, it can be seen that motor weight is significantly reduced when the weight is taken as part of optimisation goal. Compared with the objective function value in Table 9, it can be seen that the efficiency function value is reduced, which is due to the addition of weight into optimisation goal.

In order to explain the efficiency difference of plan A2 and plan B2 more clearly, Figure 12 is the comparison of efficiency for plan A2 and plan B2 under two road conditions. Through comparative analysis, it can be seen that motor’s weight becomes lighter than before when weight is used as a part of optimisation goal, and the efficiency in objective function becomes lower than before. The magnitude of change in weight and efficiency is related to their respective weights.

The speed ranges corresponding to UDC and EUDC are 292–1948 rpm and 292–4675 rpm. The overlapping speed areas of two design solutions lead to similar efficiencies in low speed area, while the efficiency is generally higher in medium speed area.

| Objective function value | Original scheme | Plan A2 | Plan B2 |
|--------------------------|----------------|--------|--------|
| UDC                      | 78.72          | 86.18  | 85.87  |
| EUDC                     | 86.11          | 88.18  | 88.37  |

**TABLE 9** Function value corresponding to objective function of two road conditions

|                                | Plan A2 | Plan B2 |
|--------------------------------|---------|---------|
| Stator outer diameter (mm)     | 204.49  | 206.2   |
| Stator inner diameter (mm)     | 147.43  | 148.67  |
| Tooth width (mm)               | 4.47    | 4.5     |
| Yoke height (mm)               | 7.04    | 7.1     |
| Air gap (mm)                   | 0.88    | 0.9     |
| Axial length (mm)              | 105.07  | 106.1   |
| Magnet width (mm)              | 27.71   | 28.46   |
| \(D1\) (mm)                    | 144.27  | 145.4   |
| \(O2\) (mm)                    | 34.44   | 34.98   |
| Motor weight (excluding casing) (kg) | 24.4    | 25.1    |
| PMs weight (kg)                | 1.50    | 1.57    |
| Copper weight (kg)             | 4.61    | 4.66    |
| Objective function of efficiency in urban road conditions | 84.73 | 84.65 |
| Objective function of efficiency in suburban road conditions | 87.95 | 88.04 |

**FIGURE 12** Motor efficiency comparison of optimised scheme

**TABLE 10** Optimisation design scheme
and high speed areas. Therefore, the efficiencies corresponding to plan A₁, A₂ and plan B₁, B₂ in optimisation of two different goals are close.

5 | CONCLUSION

This article presents an optimised design method for the EV drive motor based on road conditions. The optimisation process generally consists of the following parts. First, road conditions should be converted into speed, torque, and time used for motor, after which the components and weights of optimisation goal can be obtained. Second, the optimisation constraints are composed of loss limitation constraint, volume constraint, and geometrical feasibility. In combination with the optimisation algorithm, the motor optimisation based on NEDC road condition can be obtained. In the progress of optimisation, the calculation of electromagnetic performance is completed by the magnetic circuit method, and the accuracy of magnetic circuit calculation result is verified by comparison of large amount of experiments and calculation results.

This article studies two optimisations with different goals, one with efficiency as a single optimisation goal, and the other with efficiency and motor weight as combined optimisation goals. The purpose of combining various optimisation targets can be achieved through the adjustment of target weights. The optimised motor solution can be combined with actual application so as to achieve the purpose of efficient and material-saving design under all road conditions. Thus, it has significant and economic and social benefits in the large-scale motor production and utilisation sector.

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REFERENCES

1. Sarigiannidis, G., Beniakar, M.E., Kladas, A.G.: Fast adaptive evolutionary PM traction motor optimization based on electric vehicle drive cycle. IEEE Trans. Veh. Technol. 66(7), 5762–5774 (2017)

2. Lee, D., et al.: Efficiency improvement of IPMSG in the electric power generating system of a range-extended electric vehicle. IET Electr. Power Appl. 13, pp. 943–950 (2019)

3. Stipetic, S., et al.: Calculation of efficiency maps using a scalable saturated model of synchronous permanent magnet machines. IEEE Trans. Ind. Appl. 54(5), 4257–4267 (2018)

4. Wu, J., et al.: Optimisation design of a flux memory motor based on a new non-linear MC-DRN model. IET Electr. Power Appl. 13, 2035–2043 (2019)

5. Liu, L., et al.: Electromagnetic performance analysis and thermal research of an outer-rotor I-shaped flux-switching permanent-magnet motor with considering driving cycles. IEEE Electr. Power Appl. 13(12), 2052–2057 (2019)

6. Tian, L., et al.: Driving range parametric analysis of electric vehicles driven by interior permanent magnet motors considering driving cycles. CES Trans. Electr. Mach. Syst. 3(4), 377–381 (2019)

7. Zhu, X., et al.: Multimode optimization design methodology for a flux-controllable stator permanent magnet motor considering driving cycles. IEEE Trans. Ind. Electron. 65(7), 5353–5366 (2018)

8. Krasopoulos, C.T., Beniakar, M.E., Kladas, A.G.: Multicriteria PM motor design based on ANFIS evaluation of EV driving cycle efficiency. IEEE Trans. Ind. Appl. 54(4), 4257–4267 (2018)

9. Rahi-deh, A., Korakianitis, T.: Analytical magnetic field distribution of slotless brushless permanent magnet motors – Part I. Armature reaction field, inductance and rotor eddy current loss calculation. IET Electr. Power Appl. 6, pp. 628–638 (2012)

10. Tang, R.: Modern permanent magnet machines theory and design. Machine Press, Beijing, pp. 88–92 (2008) (in Chinese)

11. Deng, T., et al.: Advanced angle field weakening control strategy of permanent magnet synchronous motor. IEEE Trans. Veh. Technol. 68(4), 3424–3435 (2019)

12. Carraro, E., Morandin, M., Bianchi, N.: Traction PMSM motor optimization according to a given driving cycle. IEEE Trans. Ind. Appl. 52(1), 209–216 (2016)

13. Okamoto, Y., et al.: Material-density-based topology optimization with magnetic nonlinearity by means of stabilised sequential linear programming: SLPSTAB. IEEE Trans. Magn. 51(3), 1–4 (2015)

14. Zhu, X., et al.: Multi-objective optimisation of a permanent magnet flux-switching motor by combined parameter sensitivities analysis with non-linear varying-network magnetic circuit method. IET Electr. Power Appl. 13, 24–30 (2019)

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