Optimized design and performance analysis of a magnetic-field modulated brushless dual-mechanical port motor with Halbach array permanent magnets

Ren He¹ and Junmin Li¹,²

Abstract
In order to develop an electrical continuously variable transmission (E-CVT) to replace mechanical power coupling equipment applied in series-parallel hybrid electric vehicle (HEV), this paper proposes a magnetic-field modulated brushless dual-mechanical port motor with Halbach array permanent magnets, which has a more compact structure. The operating characteristics are analyzed by the lever analogy. It is concluded that the motor can realize the speed and torque decoupling between the engine and the wheel, which meet multi-mode operation requirements for HEV. To realize the multi-objective design of torque output, torque ripple and usage amount of permanent magnets, an optimization scheme combined parameter sensitivity with response surface methodology is adopted. The trade-offs among the optimization objectives are considered, then the key structural parameters and its optimal values are efficiently determined. Based on a two-dimensional model, the electromagnetic performances are simulated and analyzed. The results show that, after the parameters optimization, the no-load back electromotive force (EMF) has better sinusoidal characteristic, and the torque ripples and cogging torque peaks of the motor have been significantly reduced. Furthermore, a prototype motor is tested. The experimental results are consistent with the simulation results, which demonstrates the validity of the proposed structure and parameter optimization method.

Keywords
series-parallel HEV, dual-mechanical port motor, magnetic-field modulated, Halbach array permanent magnet, multi-objective optimization, sensitivity, response surface methodology

Date received: 13 April 2020; accepted: 20 August 2020

Handling Editor: James Baldwin

Introduction
HEVs have the advantages of good driving performance, long driving distance, low pollution, low noise, and braking energy recovery, which are regarded as one of the ideal energy-saving and environmentally friendly vehicles at present, especially for series-parallel HEV. The power coupling system can reasonably distribute the power flow between multiple power sources of HEVs and realize multiple working modes to meet the needs of variable driving conditions, which plays an

¹School of Automotive and Traffic Engineering, Jiangsu University, Zhenjiang, China
²School of Mechanical Engineering, Anyang Institute of Technology, Anyang, China

Corresponding author:
Junmin Li, School of Automotive and Traffic Engineering, Jiangsu University, No. 301 Xuesfu Road, Zhenjiang, 212013, China.
Email: userljm704@163.com

Creative Commons CC BY: This article is distributed under the terms of the Creative Commons Attribution 4.0 License (https://creativecommons.org/licenses/by/4.0/) which permits any use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (https://us.sagepub.com/en-us/nam/open-access-at-sage).
important role in the development of entire vehicle. As is well known, some typical power coupling configurations of series-parallel HEV such as Prius THS, Chevy Volt, and Corun CHS use a planetary gear mechanism for power splitting. These power-coupling systems can independently control the speed and torque of internal combustion engine (ICE) with high efficiency, but which also bring some problems of vibration, noise and difficulty in maintenance. Hence, E-CVT was proposed more than ten years ago.

The E-CVT is also called as four-quadrant transducer (4QT) or dual-mechanical port (DMP) motor, which essentially belongs to the category of dual-rotor motor (DRM), and can realize the same function of the planetary gear mechanism, generator and motor in THS. Some scholars investigated parameters optimization design, thermal analysis, and magnetic coupling problem of the E-CVT. The results show that E-CVT has advantages of high power density, compact structure and easy control; and the hybrid powertrain based on E-CVT can reduce fuel consumption and CO2 emissions more than 30%. However, it also has some problems, such as magnetic coupling, extra power losses and poor reliability caused by the brushes and slip rings of inner rotor winding, and difficult to solve the overheating of inner rotor windings, which are largely attributed to the particular structure of DRM with brushes and slip rings. Therefore, to avoid these problems, it is necessary to develop brushless DRM.

Atallah et al. applied the magnetic-field modulated (MFM) principle to magnetic gears composed of two permanent magnet (PM) rotors with different pole pairs, which can transfer different speeds. Moreover, the motor integrated with magnetic gears has a feature of low speed and high torque, and it can be applied in electric vehicles. Thus, some brushless MFM-DMP permanent magnet motors used for HEVs were investigated. However, the torque regulating function of these motors is realized by an additional permanent magnet motor. The entire electrical power coupling system is longer in the longitudinal direction and has a large volume, which is not conducive to the lightweight of the vehicle.

The main purpose of this paper is to develop an E-CVT with a smaller volume applied in series-parallel HEV. According to the MFM principle, the rotating permanent magnetic field of inner PM rotor in magnetic gears is substituted with the rotating magnetic field generated by the armature windings of inner stator. The modulation ring rotor and the outer PM rotor are considered as two independent rotors. Furthermore, the Halbach array is adopted in the arrangement of inner and outer PMs of outer rotor. Then, a novel MFM brushless DMP motor with Halbach array PMs (HMFM-BDMPM) is proposed in this paper. In fact, the HMFM-BDMPM is a four-port motor, which includes two mechanical ports and two electrical ports. Due to the integrated structure and complicated energy conversion, it is difficult to understand the power transmission relationship and determine optimal structure parameters. Therefore, this paper presents a graphical method to analyze the speed and torque relationships of the HMFM-BDMPM, and a multi-objective optimization method based on the combination of sensitivity analysis and response surface methodology to optimize structure parameters.

This paper is organized as follows: Section 2 introduces the structure and working principle of the HMFM-BDMPM, and the operating characteristics are analyzed by the lever analogy in Section 3. The structure parameters are optimized by the multi-objective optimization method in Section 4. Based on a two-dimensional finite element model, the electromagnetic performances before and after the optimization are compared in Section 5. Section 6 verifies the validity of proposed structural scheme and simulation results by experiments. The conclusion and future research are presented in the final section.

**Structure and principle of the HMFM-BDMPM**

The HMFM-BDMPM is integrated by an inner magnetic-field modulated PM motor (IMFM-PMM) and an outer PM synchronous motor (OPMSM) sharing the outer rotor, as shown in Figure 1. To reduce the speed adjustment range of the inner stator magnetic field, a planetary gear mechanism was laid out between the ICE and the HMFM-BDMPM. The IMFM-PMM is similar to modulated magnetic gear, and consists of the inner stator, the modulation ring rotor and the inner PM of outer rotor. There are a certain amount of magnetic conduction blocks and non-magnetic conduction blocks arranged alternately in the modulation ring rotor, as shown in Figure 2. The OPMSM is composed of the outer stator and the outer PM of outer rotor. The ICE is connected to the sun gear, the planet carrier

![Figure 1. Hybrid drivetrain based on the HMFM-BDMPM.](image-url)
is connected to the modulation ring rotor, the gear ring is fixed, and the outer rotor is connected to the final drive of vehicle.

Under the action of the modulation ring rotor, the magnetic fields in the inner and middle air-gap change remarkably. The modulated magnetic fields will generate, which can further realize the energy conversion in the IMFM-PMM. To avoid the influence of magnetic coupling, the inner and outer PMs of outer rotor were arranged in Halbach array. The reason is that the Halbach array has a characteristic of magnetic self-shielding, which can effectively shield the magnetic field on one side and strengthen the magnetic field on the other side. It has a more sinusoidal air-gap magnetic field than the conventional structure, and shows high torque density, low torque ripple and little core loss. Since the speed of modulation ring rotor and outer rotor can be controlled independently by adjusting the speed of inner stator magnetic field, the IMFM-PMM can decouple the ICE speed and the wheel speed. However, the torques transmitted by these two rotors in the IMFM-PMM are proportionate, so the OPMSM is used to decouple the ICE torque and the wheel torque. Hence, the HMFM-BDMPM can realize that the speed and torque of the ICE are completely independent of the wheels, which can be applied in series-parallel HEV like THS.

Because the OPMSM can be regarded as a traditional PM motor, the IMFM-PMM has a complex structure with two mechanical ports and one electrical port, so the speed and torque relationships of various parts are more complicated. In the next section, the lever analogy is mainly adopted to analyze the operating characteristics of the IMFM-PMM.

### Characteristics analyses of the HMFM-BDMPM

The lever analogy is a method to simplify the motion of planetary gear set by equating to a lever model. It is mostly used in the design of automatic transmissions. In recent years, several scholars have also applied it to the transmission scheme design of E-CVT for series-parallel HEV.21,22

In order to explain the operating characteristics of the IMFM-PMM, the following assumptions are made:

- The pole pairs number of inner stator magnetic field and inner PM field of outer rotor are \( p_{si} \) and \( p_{ro-PMi} \), respectively, and the number of magnetic conduction blocks is \( N_{rm} \).
- The speeds of inner stator magnetic field, modulation ring rotor, and inner PM field of outer rotor are \( n_{si} \), \( n_{rm} \) and \( n_{ro} \), respectively.
- The electromagnetic torques acting on inner stator magnetic field, modulation ring rotor, and inner PM field of outer rotor are \( T_{si} \), \( T_{rm} \) and \( T_{ro-PMi} \), respectively.

### Speed relationship of the IMFM-PMM

According to the MFM principle, the relationship of \( p_{si} \), \( N_{rm} \) and \( p_{ro-PMi} \) is expressed as:

\[
N_{rm} = p_{si} + p_{ro-PMi} \tag{1}
\]

The relationship of \( n_{si} \), \( n_{rm} \) and \( n_{ro} \) is expressed as:

\[
n_{si} = \frac{p_{ro-PMi}n_{ro} - N_{rm}n_{rm}}{p_{ro-PMi} - N_{rm}} \tag{2}
\]

Combining equations (1) and (2), the following equation can be obtained:

\[
\frac{n_{si} - n_{rm}}{n_{ro} - n_{rm}} = -\frac{p_{ro-PMi}}{p_{si}} \tag{3}
\]

Assuming \( \lambda = -\frac{p_{ro-PMi}}{p_{si}} \), equation (3) can be further expressed as:

\[
n_{si} - n_{rm} = -\lambda(n_{ro} - n_{rm}) \tag{4}
\]

The lever analogy is adopted to illustrate the relationship of \( n_{si} \), \( n_{rm} \) and \( n_{ro} \), as shown in Figure 3. Point A, B and C represent inner stator, modulation ring rotor and inner PMs of outer rotor, respectively, which are in a line. Assume that the distance between point A and B is \( \lambda \), and the distance between point B and C is 1. The line segment perpendicular to line ABC represents the value and direction of speed. In addition, the length of line segment represents speed value, and the speed direction is specified as follows: it is positive above line ABC, on the contrary, it is negative.

Thus, \( n_{si} \), \( n_{rm} \) and \( n_{ro} \) can be expressed by line segment \( \overline{AD} \), \( \overline{BE} \) and \( \overline{CF} \), respectively. The slopes of line DE and EF can be expressed as:
Combining equations (4) and (5), it can be obtained:

\[
k_{DE} = \frac{n_{si} - n_{rm}}{\lambda} \quad k_{EF} = \frac{n_{rm} - n_{ro}}{1}
\] (5)

Combining equations (4) and (5), it can be obtained:

\[
k_{DE} = k_{EF}
\] (6)

It shows that point D, E, and F are also in a line. That is, the speeds of inner stator magnetic field, modulation ring rotor and inner PMs of outer rotor are always collinear, which accord with the relationship of lever. While any two speeds of those are given, the value and direction of the third speed is easy to determine. Therefore, for the IMFM-PMM, when the speed of outer rotor caused by the wheel load changes, the speed of modulation ring rotor can be kept constant by adjusting the speed of inner stator magnetic field. Thus, it can maintain ICE working in high fuel efficiency zone.

**Torque relationship analysis of the IMFM-PMM**

Based on the MFM principle, this section will analyze torque relationships and energy transformation among three ports. Firstly, the positive directions of speed, torque and power are given as follows:

- The positive direction of both the speeds and the torques of inner stator magnetic field, modulation ring rotor and inner PMs of outer rotor are specified to be counterclockwise.
- The power output from the port is positive. Conversely, the power input the port is negative.

The electrical power \(P_{si}\) at inner stator port is expressed as:

\[
P_{si} = 2\pi T_{si}n_{si}/60
\] (7)

![Figure 3. Diagram of collinear speed.](image)

![Figure 4. Diagram of lever-balancing torque.](image)

Note that the positive electrical power means that the IMFM-PMM works as a generator, and the negative electrical power means that the IMFM-PMM works as a motor.

The mechanical power \(P_{rm}\) and \(P_{ro-PMi}\) at the port of modulation ring rotor and inner PMs of outer rotor are respectively expressed as:

\[
P_{rm} = 2\pi T_{rm}n_{rm}/60
\] (8)

\[
P_{ro-PMi} = 2\pi T_{ro-PMi}n_{ro}/60
\] (9)

When all losses are ignored, the IMFM-PMM keeps to the law of energy conservation. Therefore, the sum of both the powers and the torques of three ports should be zero, respectively.

\[
2\pi(T_{si}n_{si} + T_{rm}n_{rm} + T_{ro-PMi}n_{ro})/60 = 0
\] (10)

\[
T_{si} + T_{rm} + T_{ro-PMi} = 0
\] (11)

Combining equations (10) and (11), it can be obtained:

\[
\frac{T_{ro-PMi}}{T_{si}} = \frac{n_{si} - n_{rm}}{n_{ro} - n_{rm}}
\] (12)

According to equations (4) and (12), it can be obtained:

\[
\frac{T_{ro-PMi}}{T_{si}} = \lambda
\] (13)

Substituting equation (13) into equation (11), it can be obtained:

\[
T_{si} = -\frac{1}{\lambda + 1} T_{rm}
\] (14)

\[
T_{ro-PMi} = -\frac{\lambda}{\lambda + 1} T_{rm}
\] (15)

In equations (14) and (15), the negative sign indicates the reverse direction of two torques. The relationships of \(T_{si}, T_{rm}\) and \(T_{ro-PMi}\) can also be illustrated by the lever analogy, as shown in Figure 4. Point A, B, C and the distances between them have the same
definitions as previously mentioned. The difference is that the line segment perpendicular to line ABC represents the value and direction of torque, and the length of line segment represents torque value. The torque direction is specified as follows: it is positive above line ABC, otherwise it is negative.

If the torques acting on point A, B, and C are equivalent to the forces, it is easily found that the sum of the torques acting on A, B, and C equals zero. Meanwhile, when any one of point A, B, and C is selected as a pivot point, the algebraic sum of the product of the torque and the corresponding force arm for the other two points also equals zero.

For instance, if point A is selected as pivot point, the following torque equilibrium equation can be obtained:

\[ T_{ro-PMi} \cdot (\lambda + 1) - T_{rm} \cdot \lambda = 0 \]  \hspace{1cm} (16)

Similarly, if point B and C are selected as pivot points, respectively, the torque equilibrium equations can be obtained as follows:

\[ T_{ro-PMi} \cdot 1 - T_{si} \cdot \lambda = 0 \]  \hspace{1cm} (17)

\[ T_{rm} \cdot 1 - T_{si} \cdot (\lambda + 1) = 0 \]  \hspace{1cm} (18)

Note that, the algebraic values of \( T_{si} \), \( T_{rm} \) and \( T_{ro-PMi} \) are considered in equations (16)–(18). Compared equations (12)–(15) with equations (16)–(18), it can be seen that two sets of equations are consistent. Thus, when any torque acting on inner stator, modulation ring rotor and inner PMs of outer rotor is given, it is easy to determine the torque value and direction of the others. Besides, it shows that the torque directions of inner stator and inner PMs of outer rotor are always the same, which are opposite to that of modulation ring rotor.

From the above analysis, we can draw a conclusion that the IMFM-PMM can realize speed decoupling, but it cannot decouple torque among three ports.

**Torque decoupling analysis of the OPMSM**

When the armature windings of both the inner stator and the outer stator are connected to three-phase current, the outer rotor bears modulation torque \( T_{ro-PMi} \) generated by the IMFM-PMM under the action of modulation ring rotor. Meanwhile, it also bears electromagnetic torque \( T_{so} \) generated by the OPMSM under the influence of outer stator magnetic field. Then the two torques are superimposed and transmitted to final drive. Assume the output torque of the HMFM-BDMPM is \( T_{op} \), the relationships of \( T_{ro-PMi} \), \( T_{so} \) and \( T_{op} \) can be expressed as:

\[ T_{so} + T_{ro-PMi} = T_{op} \]  \hspace{1cm} (19)

Note that, in this case, the speeds of outer stator magnetic field, inner PMs of outer rotor and the HMFM-BDMPM output are the same as \( n_{ro} \). Because the windings currents of inner stator and outer stator can be controlled independently, the electromagnetic torque generated by the OPMSM can be regulated freely to meet the load torque changes of the wheel. Thus, the output torque of ICE can be kept constant, which maintains ICE working with a high fuel-efficient.

**Structural parameters optimization of the HMFM-BDMPM**

**Initial parameters design**

From the structural form, the HMFM-BDMPM can be regarded as a cascade connection of the IMFM-PMM and the OPMSM in radial space. The power equation is expressed as:

\[ D^2l_{af} = \frac{6.1K_E P_N}{\alpha_p K_B K_d B_d A n_e \eta \cos \phi} \]  \hspace{1cm} (20)

Where \( D_s \) is armature diameter, \( l_{af} \) is active length of armature core, \( P_N \) is rated output power, \( K_E \) is ratio of induced electromotive force to terminal voltage at rated load, \( \alpha_p \) is pole-arc coefficient, \( K_B \) is waveform coefficient of air-gap magnetic field, \( K_d \) is winding coefficient, \( B_d \) is air-gap magnetic flux density, \( A \) is line load, \( n_e \) is rotated speed, \( \eta \) is motor efficiency, and \( \cos \phi \) is power factor.

It is noted that, for the IMFM-PMM, \( n_e \) is rated speed of inner stator armature magnetic field, which is calculated according to equation (2). However, for the OPMSM, \( n_e \) is rated speed of outer PMs of outer rotor.

Learning from previous design experiences, the stator pole-slot ratio of both the IMFM-PMM and the OPMSM is adopted as 10/9. Considering the effect on output torque of the motor, we select matching relationship between the number of magnetic conduction blocks and the pole pairs number of inner PM field of outer motor as 22/17. The magnet per pole number of inner and outer Halbach PMs of outer rotor is set at 2 and 3, respectively.

Whereupon, once the output power and rated speed of the IMFM-PMM and the OPMSM are determined, the initial values of main design variables can be calculated according to equation (20), as listed in Table 1.

**Parameters optimization**

Due to the complex structure and many parameters of the HMFM-BDMPM, the optimization procedure is a heavy workload by the method of traditional single objective optimization or independent parameter optimization. Besides, the global optimal solution can not
be obtained, and it is difficult to meet multiple optimization objectives simultaneously. Thus, this paper adopts an optimization design scheme with the combination of multi-objective sensitivity and response surface methodology. Firstly, parameters that have a greater impact on the optimization objectives can be screened out by sensitivity analysis. Then, by the combination of response surface methodology and multi-objective optimization algorithm, the optimal values of sensitive parameters are furtherly determined.

According to equation (20), when $P_{N_i}$, $n_e$ and $i_e$ are given, $D_s$ is a certain value. Therefore, the structural parameters of modulation ring rotor, and inner and outer PMs of outer rotor are selected as design variables. The parameterized geometry model is built as shown in Figure 5.

### Optimization objectives

Considering the application characteristics and cost requirement of the HMFM-BDMPM, this paper selects output torque, torque ripple, and usage amount of PMs (expressed by area) as optimization objectives. Among the three objectives, the output torque is more important to meet power demand of the vehicle firstly, and its weight coefficient is set at 0.6. The torque ripple and usage amount of PMs can be considered to have a lower equal importance, and their weight coefficients are set at 0.2, respectively.

The functions of three optimization objectives are expressed as:

- Output torque: max (avg (Torque))
- Torque ripple: min (pk2pk (Torque)/avgabs (Torque))
- Usage amount of PMs: min (sum (MagnetArea))

Assume that $k_{rip}$ denote the ratio of pk2pk (Torque) to avgabs (Torque), the expression can be written as:

$$k_{rip} = \frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{avg}}} \quad (21)$$

Where, $T_{\text{max}}$ and $T_{\text{min}}$ refers to the highest value and the lowest value of the output electromagnetic torque for the IMFM-PMM and the OPMSM in a cycle, respectively; and $T_{\text{avg}}$ is the average value for them.

- Usage amount of PMs: min (sum (MagnetArea))

The comprehensive objective function is constructed as:

$$F(x) = m_1f_1(x) + m_2f_2(x) + m_3f_3(x) \quad (22)$$

Where $f_1(x)$, $f_2(x)$, and $f_3(x)$ are sub-optimization objective function, $m_1$, $m_2$, and $m_3$ are weight coefficients of the corresponding sub-optimization objective.
Parameter sensitivity analysis. Sensitivity refers to the influence of input variables of the system on output variables. The variables with a relatively low sensitivity can be ignored, thus the input parameters that have a greater impact on the optimization objective can be screened out, which reduces the number of input variables and achieve efficient optimization design of the system.23

According to the original values (Table 1) and the parameterized model (Figure 5), $d_m$, $W_m$, $d_{pmi}$, $d_{pmo}$, and $W_{pmo}$ are selected as optimization variables in the sensitivity analysis.

The parameter sensitivity analysis results of the IMFM-PMM and the OPMSM are shown in Figure 6(a) and (b), respectively. As can be seen, the parameters that have the greatest impact on the three-optimization objectives of the OPMSM are $d_{pmo}$ and $W_{pmo}$. For the IMFM-PMM, the parameters that have a main impact on output torque and torque ripple are $W_m$ and $d_{pmi}$. Besides, $d_{pmo}$ and $W_{pmo}$ also have a certain effect on torque ripple, and $d_{pmi}$ has the greatest impact on usage amount of PMs. After comprehensive consideration, the key parameters of the IMFM-PMM are determined as $W_m$ and $d_{pmi}$, and those of the OPMSM are $d_{pmo}$ and $W_{pmo}$.

Response surface analysis. Response surface indicates the relationship between output variables and a set of input variables. When there are fewer input variables in the objective function, the response surface methodology can be used to quickly find optimal solution of the system.24

Based on the key parameters of the IMFM-PMM and the OPMSM determined previously, the response surface methodology was used to obtain the relationships between optimization objectives and each parameter.

Figure 7(a) shows the response of the optimization objectives of the IMFM-PMM to $W_m$ and $d_{pmi}$. The absolute value of average output torque increases first and then decreases with the increase of $W_m$, which reaches to the maximum at $W_m = 8.5^\circ$. Meanwhile, it increases as $d_{pmi}$, but the growth rate becomes slower after $d_{pmi} = 6$ mm. The torque ripple decreases first and then increases with the increase of $W_m$ and $d_{pmi}$, which reaches to the minimum at $W_m = 8.5^\circ$ and $d_{pmi} = 7.5$ mm, respectively. The usage amount of PMs increases linearly as $d_{pmi}$. Therefore, the value of $d_{pmi}$ should be 6 mm to 7.5 mm, and the value of $W_m$ should be about 8.5$^\circ$.

Figure 7(b) shows the response of the optimization objectives of the OPMSM to $d_{pmo}$ and $W_{pmo}$. The average output torque increases as $d_{pmo}$, but the growth rate becomes slower after $d_{pmo} = 5.5$ mm. Meanwhile, it increases linearly as $W_{pmo}$ approximately. The torque ripple increases first and then decreases with the increase of $W_{pmo}$, which reaches to the maximum at $W_{pmo} = 10.5^\circ$. The usage amount of PMs increases with the increase of $d_{pmo}$ and $W_{pmo}$. Therefore, $W_{pmo}$ should be a higher value in the constraint range, and the value of $d_{pmo}$ should be about 5.5 mm.

Furthermore, after the trade-offs among the three objectives were fully considered, the feasible design points of the IMFM-PMM and the OPMSM were obtained by the multi-objective genetic optimization algorithm, as shown in Figure 8(a) and (b), respectively. At the same time, three candidate design schemes with high satisfaction were screened out. The optimal values of key parameters were finally determined as listed in Table 2.

Evaluation of electromagnetic performances

Based on the optimized parameters, a two-dimensional finite element model was built. Some electromagnetic performances of the HMFM-BDMPM were simulated before and after parameter optimization.

No-load back EMF

Figure 9(a) and (b) show the comparisons of A-phase no-load back EMF waveforms of the IMFM-PMM
the optimized parameters can bring a better sinusoidal wave of back EMF for the OPMSM. The back EMF waves of the IMFM-PMM have good sinusoidal characteristic before and after the optimization.

### Output torque and torque ripple

Figure 10(a) and (b) show output torque and torque ripple comparisons of the IMFM-PMM and the OPMSM before and after parameter optimization, respectively. As can be seen, the average output torques have a little changes, which accord with theoretical calculated values. However, the torque ripple reduces significantly after the optimization. The torque ripple coefficient of the OPMSM reduces from 0.152 to 0.103, and that of the IMFM-PMM reduces from 0.151 to

and the OPMSM before and after parameter optimization, respectively. Compared with initial parameters,
In addition, as seen in Figure 10(a), when the inner stator winding is separately excited \((f = 125\ \text{Hz})\) and \(n_{rm}\) is set at 0, \(n_{ro}\) is obtained as \(-441.2\ \text{r/min}\) by equation (2). The simulation result shows that the torques subjected by the inner stator, modulation ring rotor and outer rotor are \(-12.92\ \text{N}\cdot\text{m}, 56.6\ \text{N}\cdot\text{m}, \) and \(-43.78\ \text{N}\cdot\text{m},\) respectively, which meet the torque relationship of equation (11). So the correctness of the foregoing theoretical analysis was verified.

Cogging torque

Figure 11(a) and (b) show cogging torque comparisons of the IMFM-PMM and the OPMSM before and after parameter optimization, respectively. Compared with those of initial parameters, the cogging torque peaks of both motors have been significantly reduced after the optimization. For the OPMSM, the cogging torque peak decreases from \(2.11\ \text{N}\cdot\text{m}\) to \(0.51\ \text{N}\cdot\text{m}\), and it decreases from \(2.05\ \text{N}\cdot\text{m}\) to \(0.61\ \text{N}\cdot\text{m}\) for the IMFM-PMM.

In summary, it is concluded that the electromagnetic performances of the HMFM-BDMPM have been well improved after the parameter optimization. With ensuring that the output torque meets power requirements, both the torque ripple and the cogging torque have been significantly reduced, which can effectively reduce the vibration and noise of the motor.

Experimental validations

In order to verify the rationality of the HMFM-BDMPM structural scheme and the validity of the parameter optimization method, a prototype motor was manufactured. Figure 12 shows the schematic of test system. The IMFM-PMM and the OPMSM are driven by a frequency converter. The positions of modulation ring rotor and outer rotor are obtained from an optical encoder. The loads of the IMFM-PMM and the OPMSM are built by using the electrical dynamometer to offer various load demands. The test bench for the HMFM-BDMPM is shown in Figure 13. The operating characteristics of the IMFM-PMM and the OPMSM were tested.

Figure 14(a) and (b) show the test and simulation results of A-phase no-load back EMF of the IMFM-PMM and the OPMSM, respectively. It can be seen that the variation trends of measured back EMF
waveforms are basically in agreement with the parameter optimized simulation results aforementioned in Figure 9(a) and (b), which have a slight decrease in the peak, but they also exhibit the characteristics of sinusoid.

The average torques and torque ripples of the IMFM-PMM and the OPMSM at various currents are depicted in Figure 15(a) and (b), respectively, which indicate that the test results are largely accorded with the simulation results. Besides, it can be seen that the relationships between the output torque and current are approximately linear. However, there are some small differences between the measured and simulation waveforms, which mainly result from the defects of manufacturing and assembling, limitation of testing conditions and measurement errors. Overall, the test results can reveal the validity of the proposed structural scheme and optimization method for the HMFM-BDMPM.

Conclusions
In this paper, a new magnetic-field modulated brushless DMP motor with Halbach array permanent magnets and synthesizing multi-objective optimization method are proposed and investigated. By the lever analogy and the law of energy conservation, the operating
characteristic analyses indicate that the HMFM-BDMPM can decouple the speed and torque between the ICE and the wheel to meet multi-mode operation requirements for series-parallel HEV, which can be taken as a potential alternative of planetary gear power coupling equipment. With the combination of multi-objective sensitivity analysis and response surface methodology, the tradeoff design among the optimization objectives of output torque, torque ripple, and usage amount of PMs is achieved efficiently. The simulation results of electromagnetic performances of the motor before and after the parameters optimization show that, after the optimization, the no-load back EMF has better sinusoidal characteristic; the torque ripples of the IMFM-PMM and the OPMSM have reduced by 54.3% and 32.2%, respectively; and the cogging torque peaks of the IMFM-PMM and the OPMSM have reduced by 70.2% and 75.8%, respectively. Meanwhile, the speed-regulating function of the IMFM-PMM is verified. The experimental results agree generally with the simulation results, which indicate that the proposed structure scheme and parameter optimization method are feasible.

In the future, the further research on thermal analysis and driving performance under different operating conditions should be carried on to lay the foundation for practical application of the motor in vehicle.

Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was founded by the National Natural Science Foundation of China (Grant No. 51875258).

ORCID iD
Junmin Li https://orcid.org/0000-0003-4713-5466

References
1. Kim H, Wi J, Yoo J, et al. A study on the fuel economy potential of parallel and power split type hybrid electric vehicles. Energies 2018; 11: 2103.
2. Zhang XW, Li CT, Kum D, et al. Prius + and Volt-: configuration analysis of power-split hybrid vehicles with a single planetary gear. IEEE Trans Veh Technol 2012; 61: 3544–3552.
3. Liu J and Peng H. Modeling and control of a power-split hybrid vehicle. IEEE Trans Control Syst Technol 2008; 16: 1242–1251.
4. Zhao Z, Jiang L, Wang C, et al. Engine start-up optimal control for a compound power-split hybrid powertrain. Mech Syst Signal Pr 2019; 120: 365–377.
5. Syed FU, Kuang ML and Ying H. Active damping wheel-torque control system to reduce driveline oscillations in a power-split hybrid electric vehicle. IEEE Trans Veh Technol 2009; 58: 4769–4785.
6. Hoeijmakers MJ and Rondel M. The electrical variable transmission in a city bus. In: 2004 IEEE 35th annual power electronics specialists conference, Aachen, Germany, 20–25 June 2004, pp.2773–2778. IEEE.
7. Zheng P, Liu R, Thelin P, et al. Research on the parameters and performances of a 4QT prototype machine used for HEV. IEEE Trans Magn 2007; 43: 443–446.
8. Xu LY. Dual-mechanical-port electric machines-concept and application of a new electric machine to hybrid electrical vehicles. IEEE Ind Appl Mag 2009; 15: 44–51.
9. Pisek P, Stumberger B, Marcic T, et al. Design analysis and experimental validation of a double rotor synchronous PM machine used for HEV. IEEE Trans Magn 2013; 49: 152–155.
10. Mo L, Quan L, Zhu X, et al. Comparison and analysis of flux-switching permanent-magnet double-rotor machine with 4QT used for HEV. IEEE Trans Magn 2014; 50: 1–4.
11. Xiang Z, Zhu X, Quan L, et al. Multilevel design optimization and operation of a brushless double mechanical port flux-switching permanent-magnet motor. IEEE Trans Ind Electron 2016; 63: 6042–6054.
12. Zhu X, Shu Z, Quan L, et al. Multi-objective optimization of an outer-rotor V-shaped permanent magnet flux switching motor based on multi-level design method. *IEEE Trans Magn* 2016; 52: 1–8.

13. Sun X and Cheng M. Thermal analysis and cooling system design of dual mechanical port machine for wind power application. *IEEE Trans Ind Electron* 2013; 60: 1724–1733.

14. Bai J, Liu Y, Sui Y, et al. Investigation of the cooling and thermal-measuring system of a compound-structure permanent-magnet synchronous machine. *Energies* 2014; 7: 1393–1426.

15. Zheng P, Liu R, Wu Q, et al. Magnetic coupling analysis of four-quadrant transducer used for hybrid electric vehicles. *IEEE Trans Magn* 2007; 43: 2597–2599.

16. Yeh YH, Hsieh MF and Dorrell DG. Different arrangements for dual-rotor dual-output radial-flux motors. *IEEE Trans Ind Appl* 2012; 48: 612–622.

17. Atallah K, Wang JB, Calverley SD, et al. Design and operation of a magnetic continuously variable transmission. *IEEE Trans Ind Appl* 2012; 48: 1288–1295.

18. Fan Y, Zhang L, Huang J, et al. Design, analysis, and sensorless control of a self-decelerating permanent-magnet in-wheel motor. *IEEE Trans Ind Electron* 2014; 61: 5788–5797.

19. Bai J, Zheng P, Yu B, et al. Investigation of a magnetic-field modulated brushless double-rotor machine with the same polarity of PM rotor. *IEEE Trans Magn* 2015; 51: 1–4.

20. Sun L, Cheng M, Wen H, et al. Motion control and performance evaluation of a magnetic-g geared dual-rotor motor in hybrid powertrain. *IEEE Trans Ind Electron* 2017; 64: 1863–1872.

21. Bai J, Zheng P, Tong C, et al. Characteristic analysis and verification of the magnetic-field-modulated brushless double-rotor machine. *IEEE Trans Ind Electron* 2015; 62: 4023–4033.

22. Zhang Y, Ma X, Yin C, et al. Development and simulation of a type of four-shaft ECVT for a hybrid electric vehicle. *Energies* 2016; 9: 141.

23. Jahanbakhshi R and Keshavarzi R. Intelligent classifier approach for prediction and sensitivity analysis of differential pipe sticking: a comparative study. *ASME J Energy Resour Technol* 2016; 138: 052904.

24. Hasanien HM, Abd Rabou A and Sakr S. Design optimization of transverse flux linear motor for weight reduction and performance improvement using response surface methodology and genetic algorithms. *IEEE Trans Energy Convers* 2010; 25: 598–605.