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Comparative Study and Design Optimization of a Dual-Mechanical-Port Electric Machine for Hybrid Electric Vehicle Applications

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# Abstract:

A new dual-mechanical-port (DMP) electric machine for hybrid electric vehicle applications, particularly in the power-split continuously variable transmission systems, is proposed in this paper. In order to comprehensively and quantitatively evaluate the pros and cons of the proposed machine, a comparative study of four DMP electric machines with different topologies is conducted. These four investigated DMP electric machines include a conventional DMP machine, a DMP machine with spoke-type permanent magnets, a DMP machine with reluctance rotor, and a DMP machine with open slots which is the proposed machine in this paper. Even though these four machines have similar topologies, they have different operating principles, which are demonstrated in detail. The comparison results indicate that the DMP machine with open slots outperforms the others in terms of torque/power density, efficiency, magnet utilization, etc. Accordingly, the DMP machine with open slots is selected for further investigation and optimization. A large-scale multi-objective optimization is carried out for this machine, where the differential evolution algorithm serves as a global search engine to target optimal performance. Finally, an optimal design is prototyped, and the experimental results are performed to verify the effectiveness of the analysis and simulation results in this paper.

# Nomenclature

|  |  |
| --- | --- |
|  | Amplitude of the fundamental air-gap flux density. |
|  | Amplitudes of the flux density of the harmonic order of . |
|  | Amplitudes of the flux density of the harmonic order of . |
|  | Predefined crossover probability. |
|  | Back-electromotive force (EMF) fundamental component amplitude of inner winding. |
|  | Back-EMF fundamental component amplitude of outer winding. |
|  | Positive real difference scale factor. |
|  | Gear ratio. |
|  | Inner stator tooth-arc width. |
|  | Inner stator yoke height. |
|  | Outer stator slot height. |
|  | Outer stator yoke height. |
|  | PM height. |
|  | Inner rotor tooth height. |
|  | Q-axis current. |
|  | Winding factor. |
|  | Speed of the inner rotor in r/min. |
|  | Speed of the outer rotor in r/min. |
|  | Number of series turns per phase. |
|  | Winding pole-pair number. |
|  | Flux modulator pole number. |
|  | PM pole-pair number of the inner rotor. |
|  | Pole-pair number of the inner winding. |
|  | PM pole-pair number of the outer rotor. |
|  | Pole-pair number of the outer winding. |
|  | Copper losses. |
|  | Core losses. |
|  | Power factor of the inner winding. |
|  | Power factor of the outer winding. |
|  | Output power. |
|  | PM eddy-current losses. |
|  | Number of the open slot teeth for the inner winding. |
|  | Cross-sectional area of each pole. |
|  | Average torques of the rotating rotor. |
|  | Average torques of the standstill rotor. |
|  | Output torque of the MGM portion. |
|  | Output torque of the PMSM portion. |
|  | Output torque of the Vernier machine portion. |
|  | Output torque of the inner rotor. |
|  | Initial value of . |
|  | Output torque of the outer rotor. |
|  | Initial value of . |
|  | Torque ripple of the inner rotor torque. |
|  | Torque ripple of the outer rotor torque. |
|  | Torque ripple of the rotating rotor. |
|  | Torque ripple of the standstill rotor. |
|  | Trail vector. |
|  | Parameter of the present population member. |
|  | Randomly selected presented population member, . |
|  | Inner tooth-arc width of the inner rotor. |
|  | Inner stator tooth-arc width. |
|  | Outer tooth-arc width of the inner rotor. |
|  | Outer stator tooth-arc width in degrees. |
|  | PM-arc width. |
|  | Efficiency. |

# SECTION I. Introduction

Compared to conventional internal combustion engine (ICE) vehicles, electric vehicles (EVs) and hybrid electric vehicles (HEVs) have been gaining more interest from the automotive industry and consumers, due to their superior vehicle performance, fuel economy, and reduced emissions [1], [2]. Due to the limitation of the current battery capacity, range anxiety is an inevitable issue for pure EVs. By contrast, HEVs have been recognized as the best compromise of conventional vehicles and pure EVs, which can offer better fuel efficiency, good driving performance, and longer distances/ranges [3].

The power-split continuously variable transmission (CVT) system plays a paramount/significantly important role in the success of modern HEVs, which transmits energy from input-port to output-port without conventional clutches or step ratio mechanical gears [4], [5]. Current commercial solutions for the CVT system in existing HEVs, *e.g.*, Toyota Prius, are based on a planetary mechanical gear which serves as the power-splitting device to distribute the kinetic power from an ICE and a single-shaft drive motor [6]. However, the planetary mechanical gear inevitably leads to bulkiness and heaviness, additional losses and hence reduced efficiency, noise and vibration, regular maintenance requirement, and high cost.

In order to solve the aforementioned issues associated with mechanical gears, several dual-mechanical-port (DMP) electric machines were developed and have attracted increasing attention [7], [8]. Compared to conventional electric machines, DMP machines integrate the function of the planetary mechanical gear and the drive motor, which makes them more suitable for direct-drive CVT systems in HEVs due to their inherently compact structure [9]. For example, a DMP switched reluctance machine is presented for HEVs in [10]. In this machine, the stator is located in the center, sandwiched by two reluctance rotors on the inside and outside, respectively. With a segmented rotor design, it allows flux path sharing of the stator back-iron between the interior and exterior parts, which reduces the size of the stator back-iron and hence improves the compactness of this machine. A DMP induction machine is also presented in the application of HEV powertrains in [11]. This machine consists of two free rotating rotors as the two mechanical ports, where the outer rotor is a squirrel-cage rotor while the inner rotor is a wound rotor. It was shown that this machine exhibits low cost, thermal robustness, and compact size. Furthermore, a hybrid permanent magnet (PM)-induction DMP machine is presented for HEV applications in [12], in which the PM rotor is sandwiched by the outer stator and the inner wound rotor. A similar hybrid PM-induction DMP machine is presented in [13], where the outer rotor consists of two-layer PMs. It was shown that this machine exhibits higher power density and higher efficiency than the above-mentioned counterpart in [11], and better robust outer-rotor structure than the counterpart in [12]. Building upon these aforementioned hybrid PM-induction designs, a new hybrid PM-induction DMP machine with hybrid excitation is presented in [14], [15], where the outer rotor is equipped with a single layer of PMs and a DC-field winding. With the regulation from the DC-field winding, the stator flux linkage can be flexibly changed while the flux linkage of the inner wound rotor is maintained. As a result, a desired flux linkage and torque on both the two rotors can be achieved for the multi-operation modes of HEVs. In addition, the DC-field winding provides an additional degree of freedom to minimize the losses of this machine. With the benefits of the high-energy PM material, these hybrid PM-induction DMP machines in [12]–[15] exhibit improved torque production capability, compared to the switched reluctance and induction counterparts in [10] and [11], respectively. Nevertheless, compared to conventional electric machines with a single air-gap structure, these machines still suffer from lower torque density, due to the enlarged magnetic reluctance caused by the dual air-gap structure.

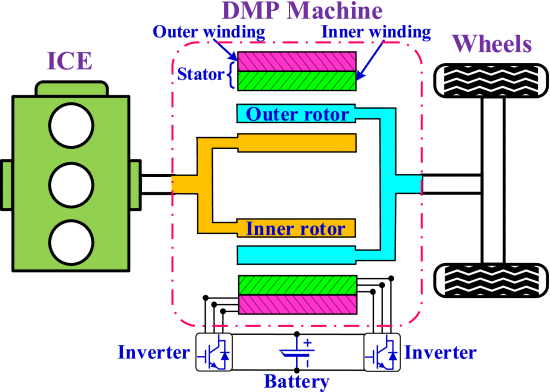
With the aim to further improve the torque density of DMP machines, a new breed of DMP machines are emerging, based on the recent development of the flux modulation theory [16], [17]. A DMP machine integrates a surface-mounted PM machine and a PM magnetic gear is presented in [18], [19]. In this machine, the PM magnetic gear consists of an outer PM rotor and an inner PM rotor. The outer PM rotor of the magnetic gear and the PM rotor of the surface-mounted PM machine share a same rotor. Based on the aforementioned structure, a DMP magnetically-geared machine is presented for vehicle applications in [20], which consists of a stator with windings, a modulating pole-pieces rotor, and a PM rotor. The modulating pole-pieces rotor works as the flux modulator to match the two magnetic fields from the stator and the PM rotor. It was shown this machine exhibits improved torque production capability. Furthermore, a DMP magnetically-geared machine with a sandwiched armature stator is presented in [21]. It consists of a surface-mounted PM rotor as the outer rotor and an interior PM rotor as the inner rotor, where the armature stator is sandwiched in-between the two rotors. The armature stator serves as not only the stator to accommodate the armature windings but also the flux modulator of the involved magnetic gear. It was shown that this machine can offer higher output torque than its integrated magnetic gear. Building upon the “flux-modulation” concept involved in Refs [16]–[21], several DMP magnetically-geared machines are presented in [22]–[24], in attempting to be used in the CVT systems of HEVs, which will be detailed in the following section of this paper.

A new DMP electric machine for the CVT-based HEV applications is proposed in this paper. In order to comprehensively and quantitatively evaluate the pros and cons of the proposed machine, a comparative study of four DMP electric machines with different topologies is conducted. These four investigated DMP electric machines include a conventional DMP machine, a DMP machine with spoke-type PMs, a DMP machine with reluctance rotor, and a DMP machine with open slots which is the proposed machine in this paper. Even though these topologies are similar, they have different operating principles. These four machines are investigated and compared in detail. The results indicate that the DMP machine with open slots outperforms the others in terms of torque/power density, efficiency, magnet utilization, *etc*. Accordingly, the DMP machine with open slots is selected for further investigation and optimization. A large-scale multi-objective optimization for this machine is carried out. Finally, an optimal design is prototyped, and the experimental results are performed to verify the effectiveness of the analysis and simulation results in this paper.

# SECTION II. Performance Comparison of DPM Machines

## A. DMP Electric Machines in CVT Systems of HEVs

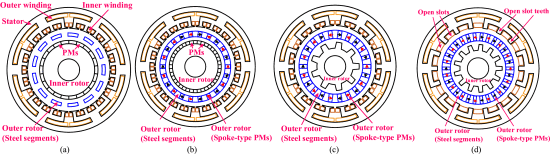
The schematic diagram of a DMP electric machine used in CVT systems of HEVs is shown in Fig. 1. As can be seen, the inner rotor and the outer rotor of the DMP machine work as the two mechanical ports, which are directly connected to the ICE and the wheels, respectively. The two rotors can rotate mechanically independent of each other so that the speed ratio between the two rotors can be varied in a continuously variable way, similar to the carrier and ring gears of the planetary gear set in conventional CVT systems. Hence, the ICE in this CVT system can always be operated at the highest efficiency speed, while the vehicle is allowed to run at any desired speeds. Through the DMP machine, the power from both the ICE and the battery splits according to the actual requirements of the HEV. More specifically, when the power supplied from the ICE is insufficient, *e.g.*, when the HEV is driven at startup or uphill where more power is needed, the DMP machine can work in motor mode to provide further support to drive the HEV. By contrast, when the power supplied from the ICE exceeds the required power, *e.g.*, when the HEV is driven at regenerative braking, idling time, or downhill, the DMP machine can work in generator mode to convert the redundant energy into electric energy which would be stored in the battery. This single DMP machine achieves the full functions of both the planetary mechanical gear and the drive motor in conventional HEV traction systems without the planetary mechanical gear set. As a result, the efficiency of the whole traction system would be improved, and the inevitable issues caused by the planetary mechanical gear in conventional CVT systems are eliminated.

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**Fig. 1.** Schematic diagram of a DMP machine in CVT systems of HEVs.

## B. DMP Electric Machines With Different Topologies

Four DMP electric machines with different topologies are compared and investigated, i.e., a conventional DMP machine (M-I), a DMP machine with spoke-type PMs (M-II), a DMP machine with reluctance rotor (M-III), and a DMP machine with open slots (M-IV), as shown in Fig. 2. It should be noted that the conventional DMP machine [see Fig. 2(a)] was originally presented in [22], the DMP machine with spoke-type PMs [see Fig. 2(b)] was originally presented in [23], the DMP machine with reluctance rotor [see Fig. 2(c)] was originally presented in [24], while the DMP machine with open slots [see Fig. 2(d)] is proposed in this paper.

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**Fig. 2.** Four investigated DMP machines. (a) Conventional DMP machine. (b) DMP machine with spoke-type PMs. (c) DMP machine with reluctance rotor. (d) DMP machine with open slots.

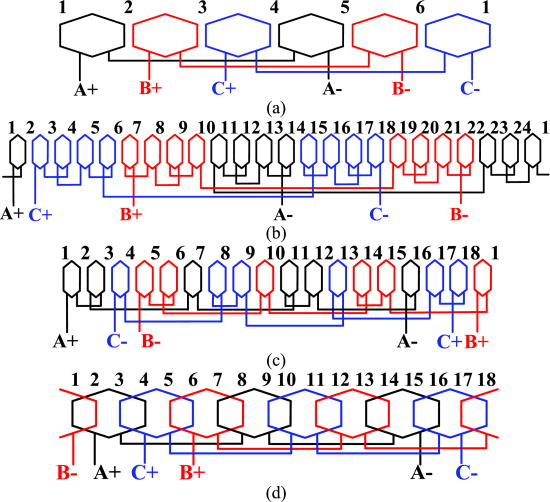
For a fair comparison, the four investigated machines share the same volume (outer diameter and stack length), electric loading for both the inner and outer windings, both outer and inner air-gap thicknesses, as well as PM content. The main parameters of the four machines are listed in Table I. The winding configurations of the four machines are shown in Fig. 3. It should be noted that these are laboratory-scaled machines. High power rating can be achieved if they are scaled-up and/or suitable cooling systems are applied.

* M-I: as can be seen from Fig. 2(a), there are two sets of windings in the stator for the conventional DMP machine, *i.e.*, outer winding and inner winding. The outer rotor consists of steel segments, while the inner rotor is a conventional surface-mounted PM rotor where the PMs are radially magnetized with alternative opposite polarity. The outer winding, the steel segments of the outer rotor, and the inner rotor, effectively form a magnetically-geared machine (MGM) portion, where the steel segments of the outer rotor work as the flux modulator. The flux modulator plays a role in matching the two magnetic flux fields from the stator and the inner rotor, which is the so-called “flux-modulation” phenomenon. Hence, the relationship of the outer winding pole-pair number, , the flux modulator pole number (steel segment number of the outer rotor), , and the PM pole-pair number of the inner rotor, , is governed by:

(1)

**TABLE I**Main Parameters of the Four Investigated Machines

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | M-I | M-II |  | M-III | M-IV |
| Stator outer diameter (mm) |  |  | 210 |  |  |
| Stator inner diameter (mm) |  |  | 130 |  |  |
| Stack length (mm) |  |  | 80 |  |  |
| Slot number for outer winding |  |  | 6 |  |  |
| Slot number for inner winding | 24 | 24 |  | 18 | 18 |
| Number of turns per phase (outer winding) |  |  | 68 |  |  |
| Number of turns per phase (inner winding) |  |  | 96 |  |  |
| Rated current (A) (outer winding) |  |  | 18 |  |  |
| Rated current (A) (inner winding) |  |  | 9 |  |  |
| Outer winding pole-pair number, |  |  | 2 |  |  |
| Inner winding pole-pair number, | 11 | 11 |  | 11 | 3 |
| Outer rotor steel segment number | 13 | 22 |  | 22 | 30 |
| Outer rotor PM pole-pair number, |  | 11 |  | 11 | 15 |
| Inner rotor PM pole-pair number, | 11 | 20 |  |  |  |
| Inner rotor salient tooth number |  |  |  | 9 | 13 |
| Outer air-gap height (mm) |  |  | 1 |  |  |
| Inner air-gap height (mm) |  |  | 1 |  |  |
| Inner diameter of inner rotor PMs (mm) | 97.44 | 96 |  |  |  |
| Height of inner rotor PMs (mm) | 8.28 | 4 |  |  |  |
| Inner diameter of outer rotor PMs (mm) |  | 107 |  | 97 | 97 |
| Height of outer rotor PMs (mm) |  | 10 |  | 15 | 15 |
| Width of the outer rotor PMs (mm) |  | 6.78 |  | 8.32 | 6.10 |
| PM volume (L) |  |  | 0.22 |  |  |
| PM material | N40UH (NdFeB, T, kA/m) |  |  |  |  |

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**Fig. 3.** Winding configuration. (a) Outer winding for the four investigated machines. (b) Inner winding of M-I and M-II. (c) Inner winding of M-III. (d) Inner winding of M-IV.

The inner winding and the inner rotor effectively form a regular permanent magnet synchronous machine (PMSM) portion. Hence, the relationship of the inner winding pole-pair number, , and the PM pole-pair number of the inner rotor, , is governed by:

(2)

* M-II: as can be seen from Fig. 2(b), differing from the conventional DMP machine, the outer rotor of this machine consists of both steel segments and spoke-type PMs which are circumferentially magnetized with alternative opposite polarity. The outer winding, the steel segments of the outer rotor, and the inner rotor, effectively form an MGM portion, where the steel segments of the outer rotor work as the flux modulator. Hence, the relationship of the outer winding pole-pair number, , the flux modulator pole number (steel segment number of the outer rotor), , which is equal to two times of the PM pole-pair number of the outer rotor, , *i.e.*, , and the PM pole-pair number of the inner rotor, , is governed by:

(3)

The inner winding and the outer rotor effectively form a regular PMSM portion. Hence, the relationship of the inner winding pole-pair number, , and the PM pole-pair number of the outer rotor, , is governed by:

(4)

* M-III: as can be seen from Fig. 2(c), the outer rotor of the DMP machine with reluctance rotor is similar to that of the DMP machine with spoke-type PMs [see Fig. 2(b)], while the inner rotor of this machine is a reluctance rotor. The outer winding, the PMs of the outer rotor, and the inner reluctance rotor, effectively form an MGM portion, where the inner reluctance rotor works as the flux modulator. Hence, the relationship of the outer winding pole-pair number, , the flux modulator pole number which is equal to the salient tooth number of the inner rotor, , and the PM pole-pair number of the outer rotor, , is governed by:

(5)

The inner winding and the outer rotor effectively form a regular PMSM portion. Hence, the relationship of the inner winding pole-pair number, , and the PM pole-pair number of the outer rotor, , is governed by:

(6)

* M-IV: as can be seen from Fig. 2(d), differing from the aforementioned three DMP machines which exhibit mono/single flux-modulation phenomenon within each other, the DMP machine with open slots exhibits “dual flux-modulation” phenomenon, which will be explained in detail in the following. The outer winding, the PMs of the outer rotor, and the inner reluctance rotor, effectively form an MGM portion, where the inner reluctance rotor works as the flux modulator. Hence, the relationship of the outer winding pole-pair number, , the flux modulator pole number which is equal to the salient tooth number of the inner rotor, , and the PM pole-pair number of the outer rotor, , is governed by:

(7)

It should be noted that differing from the aforementioned three DMP machines which have semi-closed slots for the inner winding, the DMP machine with open slots in Fig. 2(d) has open slots for the inner winding. The inner winding, the open slot teeth of the stator, and the PMs of the outer rotor, effectively form a Vernier machine portion, where the open slot teeth work as the flux modulator which is a static flux modulator and different from the rotating flux modulators mentioned-above. Hence, the relationship of the inner winding pole-pair number, , the static flux modulator pole number which is equal to the number of the open slot teeth for the inner winding, , and the PM pole-pair number of the outer rotor, , is governed by:

(8)

Hence, flux modulation phenomenon takes place in both the MGM portion and the Vernier machine portion of the proposed DMP machine with open slots. This is the so-called “dual flux-modulation” phenomenon.

Based on the aforementioned operating principles of the four investigated machines, the rotor of the PMSM/Vernier machine portion should be the output shaft which will be connected to the wheels, while the other rotor should be the input shaft which will be connected to the ICE. More specifically, for M-I, the inner rotor should be the output shaft, while the outer rotor should be the input shaft. By contrast, for M-II, M-III, and M-IV, the outer rotor should be the output shaft, while the inner rotor should be the input shaft, see Fig. 1.

## C. Comparison of Magnetic Flux

The flux lines and flux density distribution of the four investigated machines under no-load condition are shown in Fig. 4. The flux density profiles at the center of the outer air-gap and the corresponding harmonic spectra are shown in Fig. 5. For better understanding of the operating principles of the four investigated machines, the following definitions are introduced:

1. For the PMSM portion, the output torque, , can be expressed as follows:

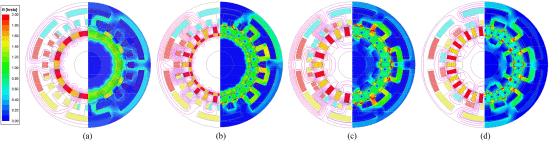
(9)

1. For the MGM portion, since the MGM can be regarded as a PMSM and a virtual gear with the gear ratio of , the output torque, , can be expressed as follows [25]:

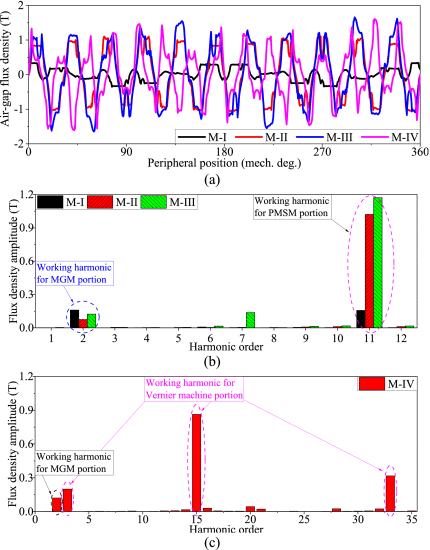
(10)

1. For the Vernier machine portion, the output torque, , can be expressed as follows [26]:

(11)

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**Fig. 4.** Flux lines and flux density distribution of the four investigated machines under no-load condition. (a) M-I. (b) M-II. (c) M-III. (d) M-IV.

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**Fig. 5.** Outer air-gap flux density. (a) Profiles. (b) Harmonic spectrum of M-I, M-II, and M-III. (c) Harmonic spectrum of M-IV.

Accordingly, the “effective flux density” can be defined as 1) for the PMSM portion is , 2) for the MGM portion is , and 3) for the Vernier machine portion is

,

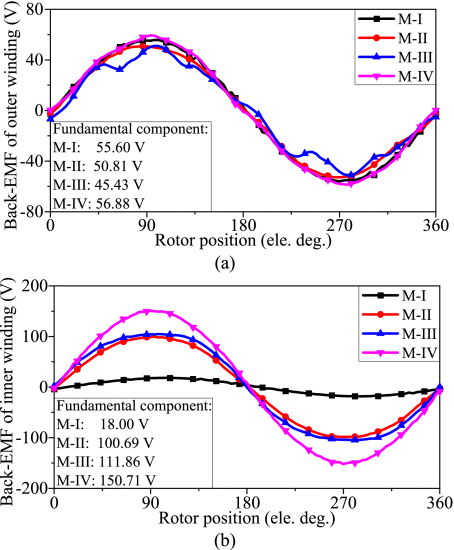
as shown in the boxes of ([9](https://ieeexplore.ieee.org/document/#deqn9))–([11](https://ieeexplore.ieee.org/document/#deqn11)). The flux density characteristics of the four investigated machines are listed in Table II. As can be seen, M-IV exhibits the highest effective flux density for the MGM portion and the Vernier machine portion. This is due to the fact that for the MGM portion, M-IV exhibits relatively high gear ratio and high amplitude of the working harmonic which is the 2nd harmonic component; for the PMSM/Vernier portion, there are three working harmonics for the Vernier portion of M-IV, while there is one single working harmonic for the counterpart PMSM portion of the other three candidates. As a result, M-IV is expected to exhibit higher output torque/power capability.

**TABLE II**Flux Density Characteristics of the Four Investigated Machines

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  |  | M-I | M-II | M-III | M-IV |
| MGM portion | Working harmonic | 2nd  (0.16 T) | 2nd  (0.08 T) | 2nd  (0.12 T) | 2nd  (0.12 T) |
|  | Gear ratio | 11/2 | 20/2 | 11/2 | 15/2 |
|  | Effective flux density | 0.88 T | 0.80 T | 0.66 T | 0.90 T |
| PMSM/Vernier portion | Working harmonic | 11th (0.16 T) | 11th (1.02 T) | 11th (1.17 T) | 3rd (0.20 T)  15th (0.86 T)  33rd (0.32 T) |
|  | Gear ratio | 1 | 1 | 1 | 5 for 3rd  1 for 15th  15/33 for 33rd |
|  | Effective flux density | 0.16 T | 1.02 T | 1.17 T | 1.71 T |

## D. Comparison of No-Load Back-Electromotive Force

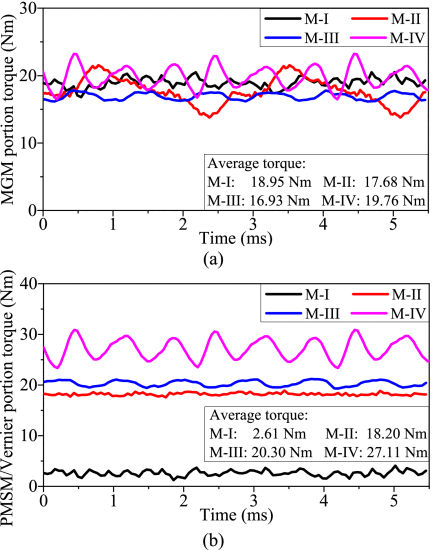
The no-load back-electromotive force (EMF) profiles of the four machines under the condition that the output shaft rotor (which is the inner rotor for M-I, while the outer rotor for M-II, M-III, and M-IV) is rotating at the speed of 1000 r/min, while the other rotor is at standstill, are shown in Fig. 6. The fundamental component amplitudes of the outer winding, , are 55.60 V, 50.81 V, 45.43 V, and 56.88 V for M-I, M-II, M-III, and M-IV, respectively. The fundamental component amplitudes of the inner winding, , are 18.00 V, 100.69 V, 111.86 V, and 150.71 V for M-I, M-II, M-III, and M-IV, respectively. As can be seen, M-IV exhibits the highest back-EMF fundamental components of both the outer winding and the inner winding.

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**Fig. 6.** No-load back-EMF profiles. (a) Outer winding. (b) Inner winding.

## E. Comparison of Torque Characteristics

The MGM portion torque profiles of the four machines with only outer winding excitation are shown in Fig. 7(a). As can be seen, the average output torque results are 18.95 Nm, 17.68 Nm, 16.93 Nm, and 19.76 Nm for M-I, M-II, M-III, and M-IV, respectively. The PMSM/Vernier portion torque profiles with only inner winding excitation are shown in Fig. 7(b). As can be seen, the average output torque results are 2.61 Nm, 18.20 Nm, 20.30 Nm, and 27.11 Nm for M-I, M-II, M-III, and M-IV, respectively. As can be observed, M-IV exhibits the highest average output torque for both the MGM portion and the PMSM/Vernier portion.

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**Fig. 7.** (a) MGM portion torque with only outer winding excitation. (b) PMSM/Vernier portion torque with only inner winding excitation.

## F. Results Discussion

The key performance metrics of the four investigated machines are compared and listed in Table III, where  and  are the average torques with both the outer and inner winding excitations of the rotating rotor (inner rotor for M-I, outer rotor for M-II, M-III, and M-IV) and the standstill rotor, respectively.

**TABLE III**Performance Comparison of the Four Investigated Machines

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | M-I | M-II | M-III | M-IV |
| Output shaft rotor speed (r/min) | 1000 | 1000 | 1000 | 1000 |
| Input shaft rotor speed (r/min) | 0 | 0 | 0 | 0 |
| Frequency of outer winding (Hz) | 183.33 | 366.67 | 183.33 | 250 |
| Frequency of inner winding (Hz) | 183.33 | 183.33 | 183.33 | 250 |
| (both windings) (Nm) | 21.89 | 34.74 | 36.05 | 46.31 |
| (%) | 14.72% | 22.48% | 6.70% | 1 3.41% |
| (both windings) (Nm) | -22.83 | -16.10 | -12.78 | -17.23 |
| (%) | 20.26% | 9.37% | 3.08% | 3.76% |
|  | 0.40 | 0.21 | 0.49 | 0.42 |
|  | 0.92 | 0.99 | 0.99 | 0.98 |
| Output power (kW) | 2.29 | 3.64 | 3.77 | 4.85 |
| Core losses (W) | 125.00 | 286.42 | 164.47 | 160.37 |
| Copper losses (W) | 156.01 | 156.01 | 156.01 | 156.01 |
| PM eddy-current losses (W) | 35.68 | 51.19 | 18.39 | 40.55 |
| Efficiency | 87.86% | 88.05% | 91.76% | 93.14% |
| Torque density (Nm/L) | 16.14 | 18.35 | 17.63 | 22.94 |
| Power density (kW/L) | 0.83 | 1.31 | 1.36 | 1.75 |
| PM utilization (Nm/L) | 203.27 | 231.09 | 221.95 | 288.82 |

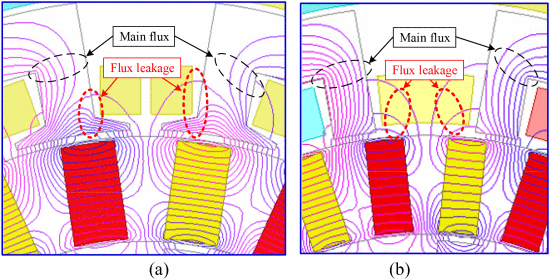
As can be seen from the aforementioned results, even though the MGM portion outputs of M-I including the back-EMF and the output torque is relatively high [higher than those of M-II and M-III, see Figs. 6(a) and 7(a)], the PMSM portion outputs of M-I are very low [see Figs. 6(b) and 7(b)].

This is due to the fact that for the PMSM portion of M-I, the PMs are too far away from the stator [see Figs. 2(a) and 4(a)]. Hence, the equivalent air-gap thickness is very large, and the magnetic reluctance is very high.

Compared to M-I, the PMSM portion outputs of M-II are significantly improved [see Figs. 6(b) and 7(b)]. This is due to the fact that by inserting the spoke-type PMs into the outer rotor, the magnetic reluctance of the PMSM portion is significantly reduced. Moreover, the spoke-type PMs exhibit flux-focusing effects, which further improves the PMSM portion outputs. The MGM portion outputs of M-II are slightly lower than those of M-I, even though these two machines have similar structure for the MGM portion. This is due to the fact that compared to M-I, the PM excitation of M-II for the MGM portion is reduced.

The MGM portion outputs of M-III are slightly lower than those of M-II [see Figs. 6(a) and 7(a)], due to the fact that the flux modulator of M-III is moved from the outer rotor to the inner rotor, which is farther away from the armature winding, *i.e.*, the outer winding, and hence, the flux modulation effect is reduced. However, the power factor of the outer winding is improved (see Table III), which may be due to the fact that the flux leakage is reduced. The PMSM portion outputs of M-III are higher than those of M-II [see Figs. 6(b) and 7(b)] due to the increased PM excitation for the PMSM portion. Moreover, the reluctance inner rotor of M-III is more suitable for a robust design of electric machines used for HEVs.

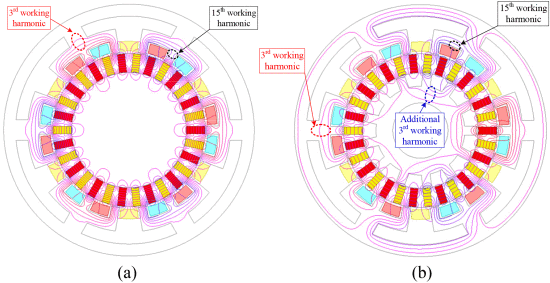
The MGM portion outputs of M-IV are higher than those of M-III [see Figs. 6(a) and 7(a)], even though these two machines have similar structure for the MGM portion. This is due to the fact that M-IV has higher gear ratio than M-III, *i.e.*, 7.5 for M-IV vs. 5.5 for M-III (see Table II). Another potential reason is that compared to M-III, the slot opening flux leakage of M-IV is reduced due to the open slot structure, as shown in Fig. 8. The PMSM/Vernier portion outputs of M-IV are significantly improved compared to the other three candidates. This is due to the fact that this portion of M-IV works in a Vernier machine manner which acts as a regular PMSM plus a virtual reduction gear, and more working harmonics are involved in energy conversion (see Table II), while this portion of the other three machines work as a regular PMSM.

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**Fig. 8.** Zoom-in flux lines. (a) M-III. (b) M-IV.

It should be noted that Vernier PM machines typically suffer from a low power factor [27], [28]. Moreover, as mentioned in Refs. [29] and [30], there are crucial issues for conventional Vernier PM machines using spoke-type PM structure, due to the oscillation of the rotor magnetomotive force. As a result, the output torque capability will be significantly reduced. However, the Vernier machine portion of M-IV exhibits a very high-power factor of 0.98 (see Table III), and the output torque of the Vernier machine portion is very high. This phenomenon can be explained as follows:

* The flux lines of the Vernier machine portion of M-IV without and with the inner rotor are shown in Fig. 9. As can be seen from Fig. 9(a), the low-order working harmonic of the machine without the inner rotor, *i.e.*,  (harmonic), travels through 2 PM pieces and bypass 1 PM piece, or travels through 4 PM pieces and bypass 1 PM piece. Hence, the magnetic reluctance of this magnetic path is very high, which reduces the flux modulation effect and the output torque capability. By contrast, as can be seen from Fig. 9(b), besides the aforementioned magnetic path for the 3rd working harmonic, there is an additional magnetic path which travels through 2 PM pieces via the inner rotor core (see the flux lines marked by the blue dotted line). As a result, the flux modulation effect and the output torque capability are improved.

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**Fig. 9.** Flux lines of the Vernier portion. (a) Without inner rotor. (b) With inner rotor.

* The back-EMF and output torque profiles of the Vernier machine portion of M-IV without and with the inner rotor, are shown in Fig. 10. As can be seen, the back-EMF and the output torque of the Vernier machine portion with the inner rotor are significantly improved, compared to those without the inner rotor. More specifically, the fundamental component of the back-EMF is improved by 23.93% from 121.61 V to 150.71 V, and the output torque is improved by 25.10% from 21.67 Nm to 27.11 Nm. These results are in consistent with the theoretical analysis mentioned-above.



Fig. 10. Vernier portion outputs. (a) Back-EMF. (b) Output torque.

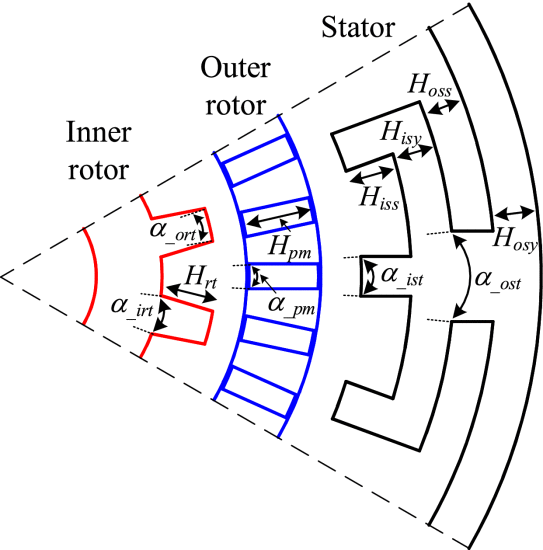
Accordingly, it can be concluded that the inner rotor of M-IV artfully works as not only the additional flux guide/bridge to carry the low-order working harmonic of the Vernier machine portion, but also the flux modulator of the MGM portion.

Overall, compared to the other three candidates, M-IV exhibits the highest torque/power density (improved by more than 25% compared to the other three candidates, which is a significant improvement), highest efficiency, highest PM utilization, acceptable power factors in both the outer winding and the inner winding. Hence, M-IV is more suitable for the HEV applications. Accordingly, M-IV is selected for further optimization and investigation. It should be noted that even though compared to M-I and M-II, the power factors of the MGM portion of M-III and M-IV are improved, all the power factors of the MGM portion of the four investigated machines are still relatively low (see Table III). This is due to the fact that MGMs with higher gear ratios suffer from higher flux leakage and lower flux density in the air-gap excited by the PMs, and hence higher synchronous reactance and lower power factors [31], [32].

# SECTION III. Multi-Objective Optimization

## A. Parametric Model

The parametric geometry model of the proposed machine, *i.e.*, the DMP machine with open slots, is shown in Fig. 11. As can be seen, there are 11 independent design variables involved in the multi-objective optimization, including the outer stator yoke height, , the outer stator slot height, , the outer stator tooth-arc width in degrees, , the inner stator yoke height, , the inner stator slot height, , the inner stator tooth-arc width, , the PM height, , the PM-arc width, , the inner rotor tooth height, , the outer tooth-arc width of the inner rotor, , and the inner tooth-arc width of the inner rotor, .

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**Fig. 11.** Parametric model for the proposed machine.

## B. Optimization Fitness Function

The large-scale multi-objective optimization of the proposed machine design is carried out by pursuing the three following objectives simultaneously:

1. Maximization of the outer rotor torque and the inner torque given by the expression as follows:

(12)

1. Maximization of the efficiency, , given as follows:

(13)

1. Maximization of the outer winding power factor, .

Meanwhile, two constraints are incorporated in the optimization fitness function with the following goals:

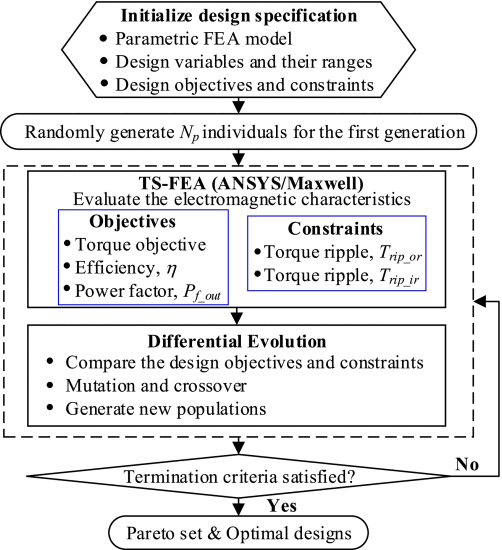
1. Restrain the outer rotor torque ripple, ;
2. Restrain the inner rotor torque ripple, .

## C. Differential Evolution Optimization Algorithm

As a metaheuristic optimizer, the differential evolution (DE) optimization algorithm attempts to find a global maximum/minimum by iteratively improving a population of candidate designs until the convergence criteria are satisfied [33]. Differing from other derivative-free population-based evolutionary algorithms, *e.g.*, genetic algorithm, particle swarm optimization, *etc.*, the DE algorithm utilizes a weighted difference between candidate designs to facilitate the improvement of future generations, which has been shown to outperform other stochastic optimization algorithms in terms of the rapidity of convergence, as well as the diversity and high definition of the resulting Pareto fronts [34]. The most basic form of the DE algorithm is the mutation and crossover ideas, *i.e.*, the parameter of a new trail member, , is updated by adding the weighted difference between two population vectors to a third vector, which is expressed as follows:

(14)

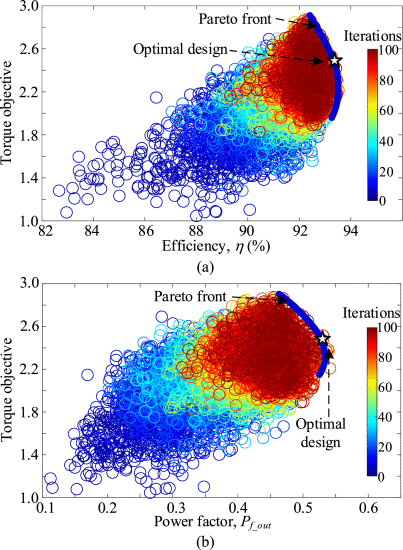
The overall optimization procedure is shown in Fig. 12.

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**Fig. 12.** Flowchart of the automated optimization procedure.

## D. Optimization Results

A total of 10000 designs are explored with 100 iterations and 100 designs per generation. The scatter plot of the objectives from feasible designs is shown in Fig. 13. As can be seen, conflicts exist between these three objectives. As the iteration/generation number increases (from blue color to red color), the candidates converge onto the Pareto front. This result indicates that the DE algorithm works effectively for the fulfillment of multiple objectives. An optimal design marked with a black star in Fig. 13 is selected from the Pareto front based on the best compromise between these three objectives.

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**Fig. 13.** Optimization results. (a) Torque objective vs. efficiency. (b) Torque objective vs. power factor of outer winding.

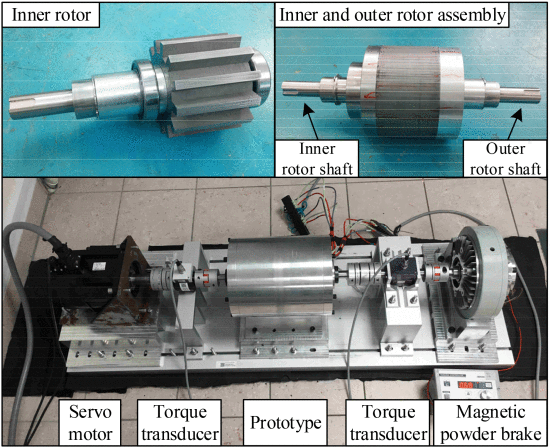
The main parameters of the optimal design as well as the initial design are listed in Table IV.

**TABLE IV**Parameters and Performance of the Optimal Design

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Parameter | Initial design | Optimal design | Parameter | Initial design | Optimal design |
| (mm ) | 11.5 | 9.0 | (mm ) | 10.0 | 8.0 |
|  | 10.0° | 11.4° | (mm ) | 9.5 | 8.3 |
| (mm ) | 10.0 | 9.7 |  | 10.0 ° | 6.3 ° |
| (mm) | 10.0 | 15.0 |  | 6.0 ° | 5.74 ° |
| (mm ) | 15.0 | 13.0 |  | 13.0 ° | 9.0 ° |
|  | 18.0 ° | 14.0 ° | - |  | - |
| Electromagnetic performance |  |  |  |  |  |
| (V) | 58.93 | 58.31 | (V) | 96.01 | 162.83 |
| (Nm) | 36.27 | 48.93 | (%) | 20.68 | 13.53 |
| (Nm) | -17.26 | -17.66 | (%) | 9.26 | 6.44 |
|  | 0.32 | 0.53 |  | 0.97 | 0.97 |
| Output power (kW) | 3.80 | 5.12 | Efficiency, (%) | 91.85 | 93.24 |
| Torque density (Nm/L0 | 19.32 | 24.04 | Power density (kW/L) | 1.37 | 1.85 |

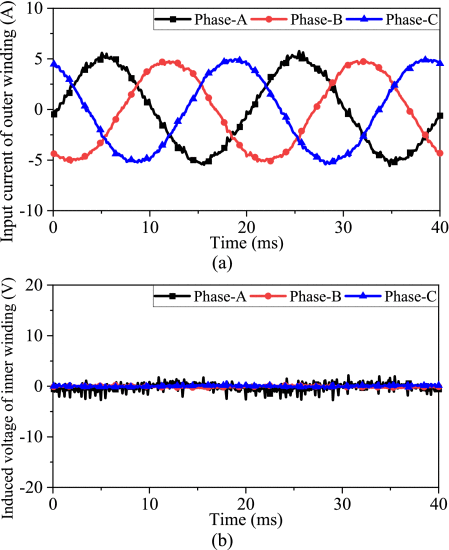
# SECTION IV. Experimental Validation

The optimal design selected from the previous section is prototyped. The prototype and experimental setup are shown in Fig. 14.

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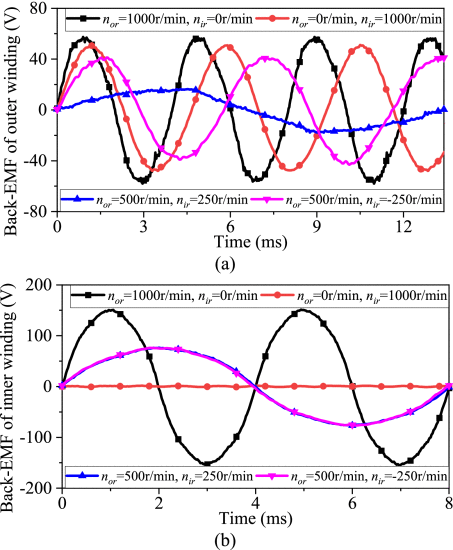
**Fig. 14.** Prototype and experimental setup.

Since there are two sets of windings in the prototype, *i.e.*, the outer winding and the inner winding, validation of the decoupling of the two sets of windings is of paramount importance. When both rotors are at standstill and the outer winding (MGM portion) is excited with 50 Hz, 5 A alternating current, the measured induced voltages of the inner winding (Vernier machine portion) are shown in Fig. 15. As can be seen, when the outer winding is excited, the induced voltages of the inner winding remain almost zero. This result indicates that the mutual inductance between the two sets of windings is negligible, and the two sets of windings are decoupled. This is due to the fact that the pole-pair combination of the prototype meets the requirement/criterion for the decoupling design of two sets of windings as mentioned in Refs. [23] and [35].

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**Fig. 15.** Decoupling validation. (a) Input current of outer winding. (b) Induced voltage of inner winding.

The measured back-EMF profiles with different outer rotor and inner rotor speeds are shown in Fig. 16. The simulated and measured results are listed in Table V. As can be seen, the frequency and the amplitude of the outer winding back-EMF are affected by both the outer and inner rotor speeds, while those of the inner winding back-EMF are only affected by the outer rotor speed. These results are consistent with the theoretical analysis in Section II. Moreover, the simulated and measured results are in very good agreement.

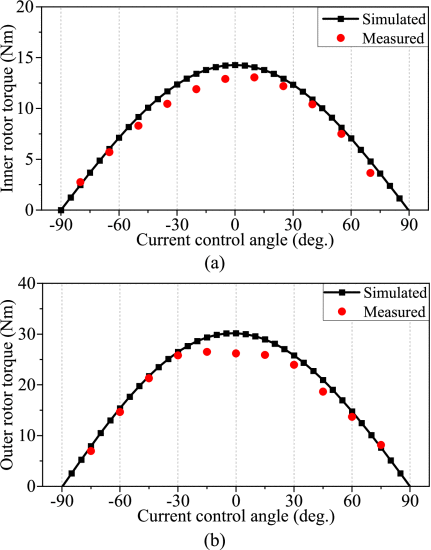
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**Fig. 16.** Measured back-EMF. (a) Outer winding. (b) Inner winding.

**TABLE V**Simulated and Measured Back-EMF Results of the Prototype

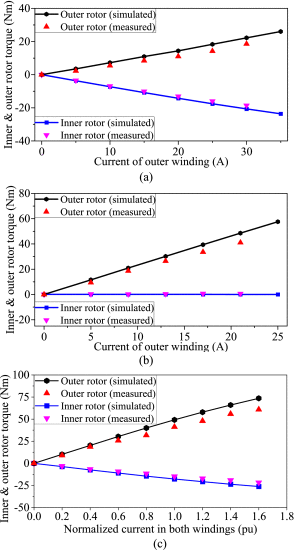
|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Cases | Winding | Frequency (Hz) |  | Amplitude (V) |  |
|  |  | Simulated | Measured | Simulated | Measured |
|  | outer  inner | 250.00  250.00 | 251.26  250.00 | 58.31  162.81 | 56.99  156.30 |
|  | outer  inner | 216.67  - | 215.52  - | 50.35  0.06 | 48.83  0.32 |
|  | outer  inner | 70.83  125.00 | 72.63  125.00 | 16.56  81.46 | 16.13  78.41 |
|  | outer  inner | 179 .1 7  125.00 | 173.6 1  125.62 | 41.67  81.44 | 39.65  78.19 |

The inner rotor torque versus current control angle with only outer winding excitation where the current amplitude is 20 A is shown in Fig. 17(a), while the outer rotor torque versus current control angle with only inner winding excitation where the current amplitude is 13 A is shown in Fig. 17(b). As can be seen, the maximum torque is achieved near a current control angle equal to zero electrical degree for both the inner and outer rotor torques. This result indicates that the reluctance torques of both the MGM portion and the Vernier machine portion are negligible, and therefore,  (d-axis current) = 0 control method is valid for both the MGM portion and the Vernier machine portion.

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**Fig. 17.** (a) Inner rotor torque vs. current control angle. (b) Outer rotor torque vs. current control angle.

The simulated and measured torques versus the input currents are shown in Fig. 18. As can be seen from Fig. 18(a), when only the outer winding is excited, this machine works as a magnetically-geared machine. More specifically, both the outer and inner rotor torques are proportional to the outer winding current. Meanwhile, the outer rotor torque and the inner rotor torque maintain a stationary ratio, *i.e.*, . By contrast, as can be seen from Fig. 18(b), when the only inner winding is excited, this machine works as a Vernier PM machine. More specifically, the outer rotor torque is proportional to the inner winding current, while the inner rotor torque maintains to be zero. It should be noted that in Fig. 18(c), the currents are normalized with respect to the base/rated values of 18 A and 9 A for the outer winding and the inner winding, respectively. As can be seen, when both sets of windings are excited, this machine works an integrated machine which combines both a magnetically-geared machine and a Vernier PM machine. Moreover, the simulated and measured torques are in acceptable agreement.



**Fig. 18.** (a) Output torque vs. outer winding current. (b) Output torque vs. inner winding current. (c) Output torque vs. both winding currents.

# SECTION V. Conclusion

A new DMP electric machine for the CVT-based HEV applications is proposed in this paper. In order to comprehensively and quantitatively evaluate the pros and cons of the proposed machine, a comparative study of four DMP electric machines with different topologies is conducted. These four investigated DMP electric machines include a conventional DMP machine (M-I), a DMP machine with spoke-type PMs (M-II), a DMP machine with reluctance rotor (M-III), and a DMP machine with open slots which is the proposed machine in this paper (M-IV). It was revealed that even though these machines have similar topologies, they have different operating principles. Moreover, the performance metrics of these four machines evolve and progressively go forward from M-I to M-II to M-III to M-IV. More specifically, compared to the conventional machine (M-I), the torque density of M-II is improved by using spoke-type PMs in the outer rotor. Compared to M-II, the outer winding power factor, the efficiency, and the power density of M-III are improved by using a reluctance inner rotor. Differing from the other three machines, M-IV works in an artful manner, *i.e.*, this machine works as an integrated machine which combines both a magnetically-geared machine and a Vernier PM machine. Due to the “dual flux-modulation” phenomenon involved in this machine, M-IV exhibits significantly improved torque/power density and efficiency. Then, a large-scale multi-objective optimization of the proposed machine (M-IV) was carried out using the metaheuristic differential evolution optimization algorithm. An optimal design was obtained for prototyping from the Pareto fronts. The experimental results verified the effectiveness of the analysis and simulation results in this paper. The proposed DMP machine is suitable for HEV applications, particularly in the power-split continuously variable transmission systems, which allows the ICE to be always operated close to the sweet point (torque and speed for maximum efficiency or minimum emission) indifferent to the vehicle speed.

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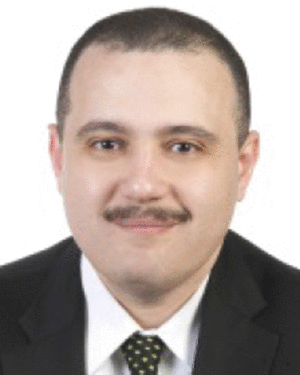
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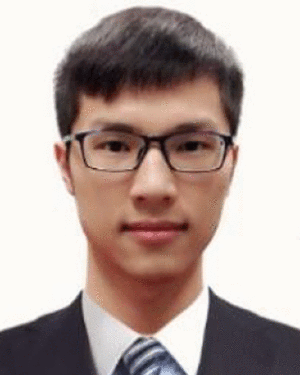
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