



<b>Title</b>	<b>Comparison of outer-rotor permanent magnet machines for in-wheel drives</b>
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# Comparison of Outer-rotor Permanent Magnet Machines for In-wheel Drives

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**Abstract**—This paper quantitatively discuss and compare the emerging outer-rotor PM in-wheel motor drives, which can directly couple with the EV tire rim and remove the traditional mechanical transmission. These new types of in-wheel motor drives include the PM hybrid brushless (PMHB) type, PM memory brushless (PMMB) type, PM magnetic-geared (PMMG) type, and PM vernier brushless (PMVB) type. And all of them are able to produce the high torque output by their distinct features of flux control or flux modulation. Their configurations, in-wheel drive operation principles, and detailed operation performances are given to verify the validity of their in-wheel applications.

**Keywords**—Permanent magnet (PM) machine; PM hybrid machine; PM memory machine; magnetic-geared machine; PM vernier machine; flux control; flux modulation, in-wheel drive.

## I. INTRODUCTION

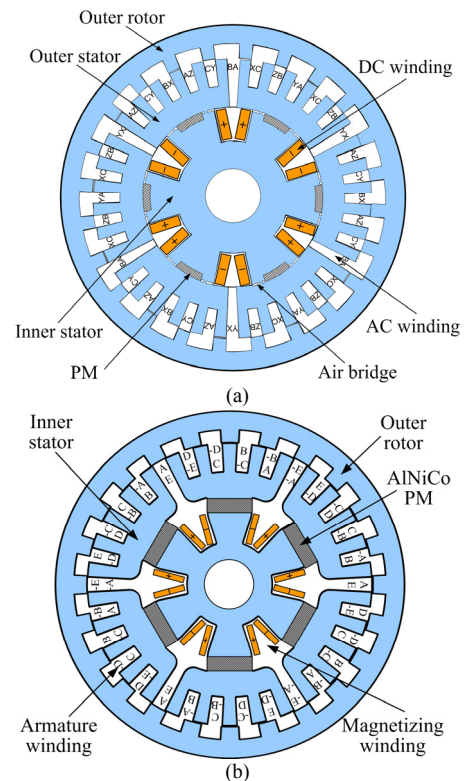
With more concerns on energy issue and environmental protection, electric vehicles (EVs) and their emerging technologies are paid much attention [1]-[11]. Different from the gasoline automobiles, the propulsion systems of EVs or hybrid EVs (HEVs) utilize the electric machines as the major or auxiliary power transmission devices [12]-[22]. In-wheel motor drives are regarded as one of the promised drive systems for EVs and HEVs since they have distinct merits of providing the electronic differential action [23]-[31].

Since the tire speed of EVs normally cover the range of 0~1000rpm, the in-wheel motors have to designed with the high speed geared types or the low speed gearless types [28]-[31]. If the low speed types are used for in-wheel motor drives, it achieves the advantages of gearless operation but suffers the drawbacks of bulky size & heavy weight for high torque output. If the high speed types are preferred, it removes the drawbacks of heavy weight & large size but suffers the gearing disadvantages of mechanical transmission loss, acoustic noise and regular lubrication. Thus, both types have their obvious shortcomings in practical application.

The purpose of this paper is to discuss the emerging PM machines for in-wheel motor drives, which inherently achieve the merit of the outer-rotor direct-drive topology and low-speed high-torque output. These emerging machines include four new PM types, namely the PM hybrid brushless (PMHB) machine, PM memory brushless (PMMB) machine, PM magnetic-geared

(PMMG) machine, and PM vernier brushless (PMVB) machine. Their characteristics and performances for in-wheel motor drives are discussed in detail. Both simulation and experimental results are given to verify the validity of the proposed motor drives.

Section II will discuss the configurations and characteristics of in-wheel motor drives. Section III will give the operation modes of in-wheel motor drives. Section IV will compare & discuss the characteristics of these in-wheel motor drives. In Section V, the simulation and experimental results will be given to demonstrate the different operation modes. Finally, a conclusion will be drawn.



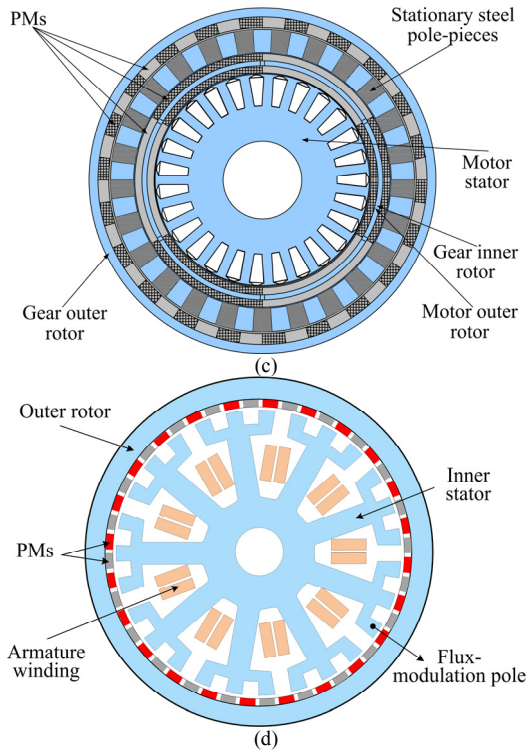


Figure 1. Proposed machine topologies. (a) PMHB type. (b) PMMB type. (c) PMMG type. (d) PMVB type.

## II. CONFIGURATIONS OF IN-WHEEL MOTOR DRIVES

### A. In-wheel Motor Topologies

Fig. 1 shows the proposed machine topologies, which indicate all of them having the outer rotors.

The PMHB machine has two kind of field excitations, namely PMs and DC field windings, which settle in the inner-layer stator. Its outer-layer stator accommodates with the AC windings, whereas its outer rotor only consists of iron steel. By controlling the DC field current, the airgap flux density can be strengthened and weakened. Moreover, by adding the auxiliary air-bridge between the two field excitations, the regulating capability of the airgap flux density can be further enhanced up to 9 times. The detailed configuration of this machine can be referred to [21].

The PMMB machine adopts the AlNiCo PM as the field excitation, which locate in the inner stator together with the magnetizing windings. The inner stator also accommodates the 5-phase AC windings, whereas the outer rotor has only iron-steel salient poles. Thus, by changing the magnetizing winding current, the excitation level of the AlNiCo PM can be regulated. And hence, the airgap flux density can be online tuning. The specification of this type of machine can be referred to [32].

The PMMG machine artfully integrates the PM synchronous motor together with the magnetic gear, which shares the same rotor. In this way, the outer rotor of the PM motor plays the role of the inner rotor of the magnetic gear. Hence, the torque and speed of the PM motor can be

effectively transmitted to the magnetic gear. So, the high-speed low-torque operation of the motor are changed to the low-speed high-torque operation of the magnetic gear output. The detail structure of this machine can be referred to [24].

The PMVB machine has the simple structure, which accommodates the AC winding in the inner stator and the PMs mounted in the outer rotor. By using the flux-modulation poles (FMPs), the high-speed rotating field of the armature winding can be modulated as the low-speed rotating PM field. Hence, the outer rotor can achieve the high-torque output at low speed operation. Its detailed configuration can be referred to [33].

Their similarities are summarized as follow.

- 1) Outer-rotor topologies are adopted. In this way, the outer rotor can directly couple with the EV tire rim.
- 2) Fractional-slot concentrated-winding (FSCW) structures are utilized for the AC armature windings. So, the FSCW structure can benefit these machines for short end winding turns, low cogging torque, high copper slot fill factor, uniform phase waveforms and so on[34].
- 3) Multi-pole structure is adopted, which can effectively reduce the cogging torque and increase the uniform pattern of phase waveforms.
- 4) The electromagnetic torque is dominated by the PM excited torque in normal operation cases. But the PMHB machine can generate the winding excited torque.

Their differences are concluded as follow.

- 1) Due to different design principles, these emerging outer-rotor in-wheel motors possess different operation features.
- 2) The PMHB type and the PMMB type can online change the magnetic field by the auxiliary DC windings, whereas the PMMG type and the PMVB type generate the magnetic field only by the PM excitation.
- 3) The PMHB type and the PMMG type are the stator-PM ones, whereas the other two are the rotor-PM types. Hence, the outer rotors of the first two types are more robust than the other twos in intermittent operation.
- 4) The PMMG type has three-layer airgap for electromechanical energy conversion. The other three have only one-layer airgap. Thus, the PMMG type is much more difficult for manufacturing than the others.
- 5) The EMF waveforms of the PMHB and PMMG ones are essentially trapezoidal, whereas the EMF waveforms of the other two are basically sinusoidal. So, the first two are suitable for the BLDC drive, while the other two are suitable for the BLAC drive.
- 6) The PMVB type is suitable for low-speed operation due to its vernier structure. The PMMG one can be fed with the high-speed rotating field of the armature winding current, and generate the low-speed rotating PM field. So, the PMMG type is also suitable to work at the speed of 600rpm. The PMHB and PMMB types have the flexible speed operation range due to their flux-control ability. Hence, their operation range is much wider than the other

twos. And they can not only cover the in-wheel speed range of 0~1000rpm, but also achieve the better performance than the other twos.

- 7) The amplitudes of the airgap flux density of the PMHB and PMMB types are lower than the other twos. It's due to the PM volume and double-salient structure. But the less PM volume leads to these two types possessing the higher cost-effectiveness than the later twos.
- 8) They have different ways to achieve the high torque output at low speed operation. The first two motor drives use the DC field or magnetizing current to strengthen & enlarge their magnetic field, whereas the later twos adopt the magnetic gear or flux-modulation pole to modulate their magnetic field distribution and obtain the gear effect.

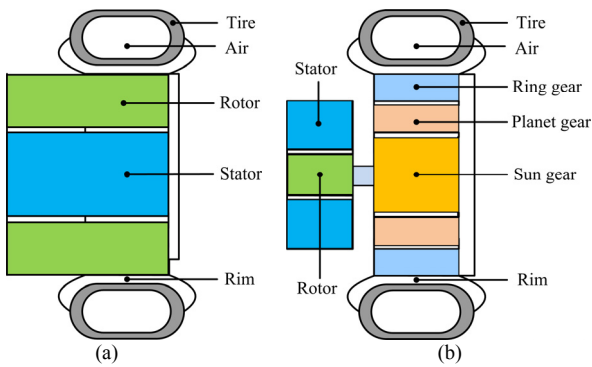


Figure 2. Schematic in-wheel motor drives. (a) Traditional low-speed gearless type. (b) Existing high-speed geared type.

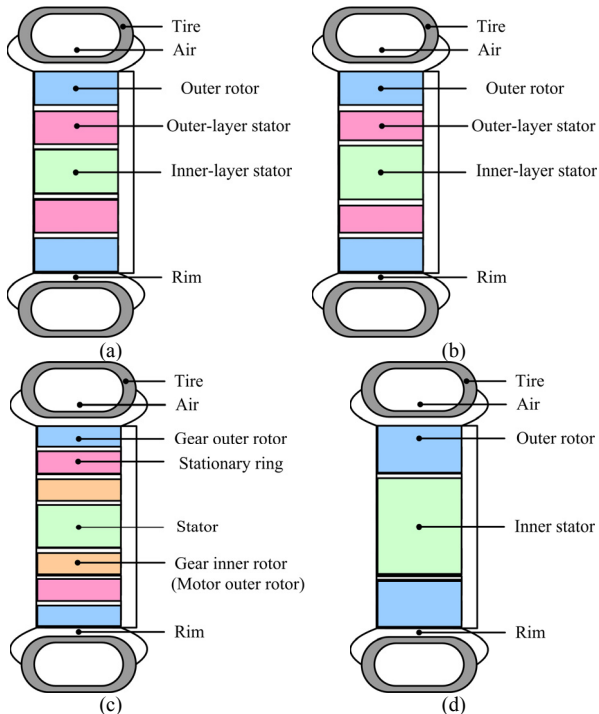


Figure 3. Proposed machine topologies. (a) PMHB type. (b) PMMB type. (c) PMMG type. (d) PMVB type.

### B. In-wheel Motor Drives

Fig. 2 shows the traditional and existing schematics of in-wheel motor drives, which includes the traditional low-speed gearless type and the existing high-speed geared type. It can be seen that the traditional low-speed type is able to directly couple with the wheel tire rim. But it has to be designed with the large stack length for achieving the high torque output at low-speed operation. On the other side, the existing high-speed geared type overcomes the former shortcomings of bulky size by adding the high-to-low speed planetary gear set. So, this type can be designed with the normal size for the high-speed high-torque output. However, this type is still too large and the planetary gear set needs regular maintenance, hence decreasing the transmission efficiency.

Fig. 3 is the proposed in-wheel motor drives, which all remove the mechanical transmission and is able to directly couple with the wheel tire rim. Thus, it can be seen that these in-wheel motor drives possess the merits of small size and weight, and eliminate the drawbacks due to the mechanical transmission. Also, their special design and operation principles make them readily produce the high torque output at the low speed. In addition, due to the appropriate size, these motor drives are suitable for the four-wheel drive EVs.

### III. OPERATION PRINCIPLE

Fig. 4 shows a four-wheel drive EV structure, which is equipped with the in-wheel motor drives by any kind of the proposed four motors. This drive system adopts the gearless type with the full electricity system. In this way, the EV can achieve the high efficiency of energy conversion and provide the extremely strong propelling power. In detail, the in-wheel motor drives play the role of electromechanical energy conversion. The control center takes responsibility of the coordinating control of in-wheel motors and the energy management. The power converters take the role of switching the electrical energy to the motors. The plug-in inverter is for EV charging with the normal 13A plug. Thus, the proposed types of in-wheel motor drives can work in the following operation modes [21], [31].

*Mode I:* This called starting mode functions to produce the launching torque and hence bring the EV into the normal operation condition.

*Mode II:* This called boosting mode functions to provide the auxiliary torque to propel the EV running, such as EV climbing the hill.

*Mode III:* This called charging mode functions to feed the energy back to the battery, such as EV running down the hill or braking.

*Mode IV:* This is called the steady mode, which implies the EV working in the cruising situation. Also, in this mode, the EV is able to realize the continuously variable transmission based on the motor drive control.



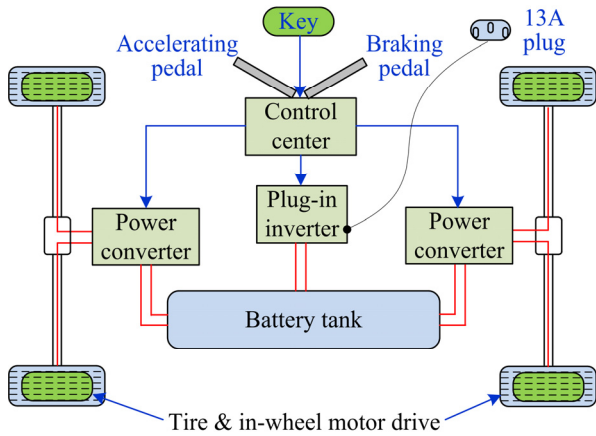


Figure 4. EV structure with proposed in-wheel motor drives.

TABLE I. PARAMETERS OF PROTOTYPES

Item	PMHB type	PMMB type	PMMG type	PMVB type
Number of phase	3	5	3	3
No. of rotor poles	24	24	44	48
No. of stator poles	36	30	27	27
No. of PM poles	6	6	6	48
Number of AC winding slots	36	30	27	9
Number of AC winding turns	46	60	27	80
Number of DC winding slots	6	6	-	-
Number of DC winding turns	150	250	-	-
Rotor outside & inside diameter	270.0mm 221.2mm	270.0mm 221.2mm	194.0mm 172.0mm	240.0mm 203.2mm
Stator outside & inside diameter	220.0mm 40.0mm	220.0mm 36mm	120.0mm 44.0mm	202.0mm 40.0mm
Outer airgap length	0.6mm	0.6mm	1.0mm	0.6mm
Stack length	80.0mm	80.0mm	40.0mm	60.0mm
PM material	NdFeB	AlNiCo	NdFeB	NdFeB

TABLE II. PERFORMANCES OF PROTOTYPES

Item	PMHB type	PMMB type	PMMG type	PMVB type
Rated power	2kW	0.95kW	2kW	2.2kW
Speed range	0~4000rpm	0~2000rpm	0~1000rpm	0~1000rpm
Rated torque	20Nm	15Nm	30Nm	35Nm
Rated current	6A	5A	18.5A	11A
Torque boost	Flux control	Flux control	Gear effect	Gear effect

#### IV. MACHINE CHARACTERISTICS

The prototype parameters and basic performances of these in-wheel motor drives are given in Table I and Table II.

Since these machines have two type of PM materials, namely NdFeB PM and AlNiCo PM, Fig. 5 shows the operation principles of these two kind of PMs. It can be seen that the operation point of the NdFeB PM can retrieve back to the original point after demagnetizing. But the operation point of the AlNiCo PM moves to the different position after demagnetizing due to its nonlinear feature.

Fig. 6 is the airgap flux density distributions of these in-wheel motor drives under no-load condition. It can be seen that both PMHB and PMMB types can achieve flux control ability by field windings or magnetizing windings. But the PMHB type has much wider regulating range of airgap flux density than the PMMB type. Also, Fig. 6(c) and Fig. 6(d) demonstrate that the high frequency of the inner armature winding field is effectively modulated to the low frequency of the outer rotor PM field. So, it verifies that both these two machines have the gear effect with the magnetic gear structure or the vernier structure. But it can be observed that the PMVB type with one-layer airgap is much simpler than the PMMG type with three-layer airgaps for achieving the gear effect. Generally, all these machines possess the high flux density by full excitation, which indicates their torque ability for serving the EV drive.

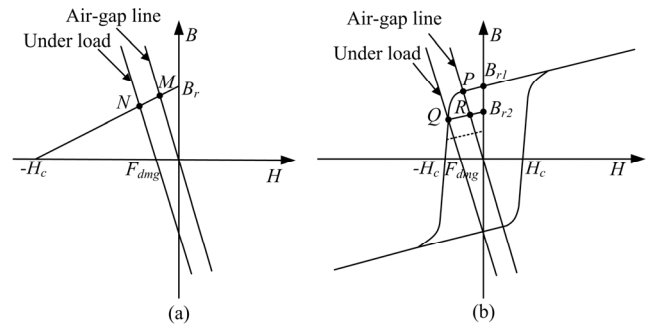


Figure 5. Operation principle of PMs. (a) NdFeB PM. (b) AlNiCo PM.

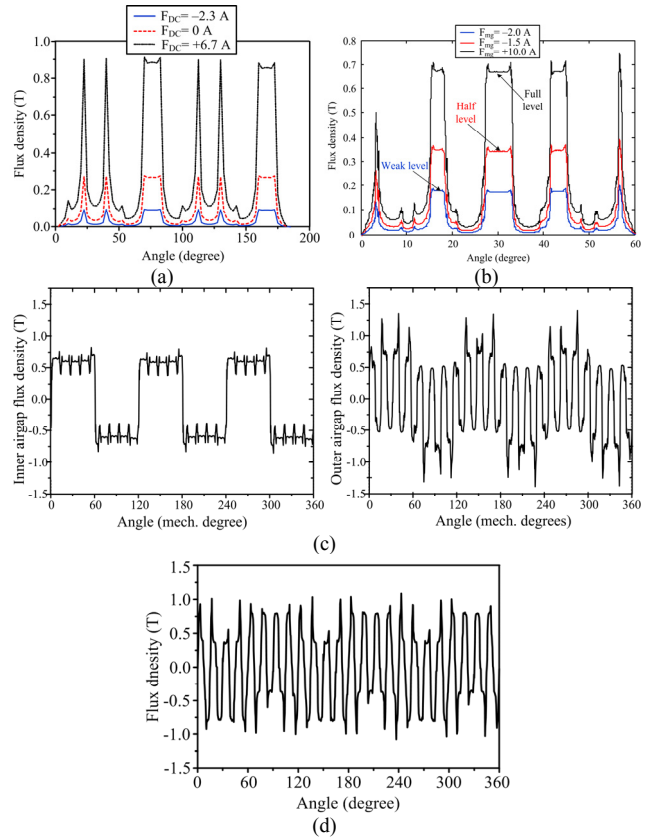


Figure 6. Airgap flux density. (a) PMHB type. (b) PMMB type. (c) PMMG type. (d) PMVB type.

## V. PERFORMANCE COMPARISON

The comparison performances of these in-wheel motor drives are discussed and analyzed according to their four operation modes. All the simulation results are calculated by the finite-element-method; also, the measured results are obtained based on the prototype testing [21],[24],[32],[33].

First, the starting and boosting performances are evaluated and shown in Fig. 7. It can be seen that all these in-wheel motor drives can effectively start the EV under the rated current. It means that with multi-time of rated currents, the starting torque will be strong enough for EV cranking. In addition, the theoretically boosting torque is also given in Fig. 7(d), which also demonstrates the torque ability

Second, the charging performances are compared as shown in Fig. 8. It can be found that the PMHB and PMMB ones can maintain the output voltage as constant by flux control. But the other two have no this capability. The PMMG type has the trapezoidal EMF waveform whereas the PMVB type has the sinusoidal one.

Third, their torque performances are discussed and compared as shown in Fig. 9. It can be observed that the PMHB type can online boost the torque to meet the desired sudden load. Also, with the similar function of the magnetic field strengthening, the PMMB type is able to produce the high torque output. In addition, the PMMG and PMVB types can readily obtain the high electromagnetic torque under the low speed with their gear effects. Thus, based on the flux strengthening function or the gear effect, all these machines can achieve the desired torque output.

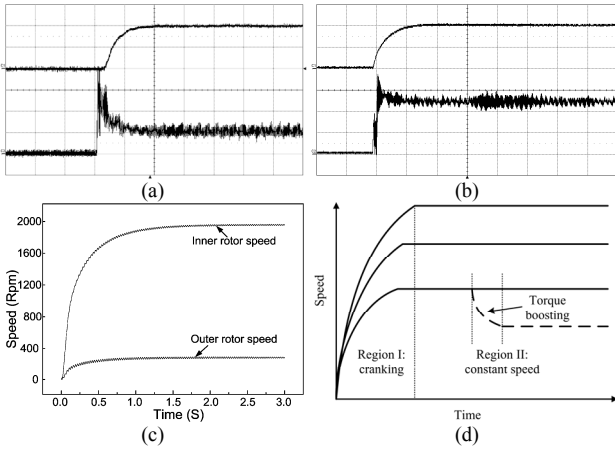


Figure 7. Starting & boosting performances. (a) PMHB type (measured: 200rpm/div, 10Nm/div, 1s/div). (b) PMMB type (measured: 200rpm/div, 2Nm/div, 1s/div). (c) PMMG type. (d) PMVB type.

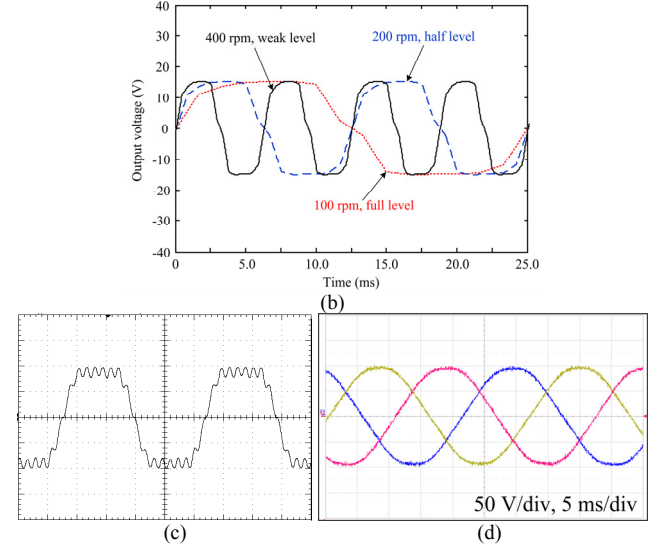
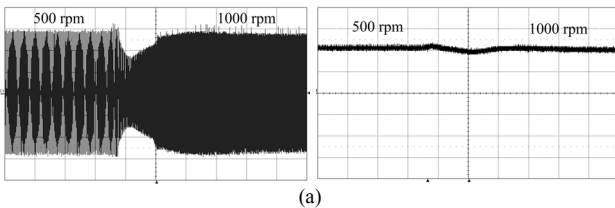


Figure 8. Charging performances. (a) PMHB type (measured phase output voltage: 50V/div, 200ms/div; measured rectified voltage: 100V/div, 200ms/div). (b) PMMB type (simulated). (c) PMMG type (measured voltage: 25V/div, 1ms/div). (d) PMVB type (measured voltage).

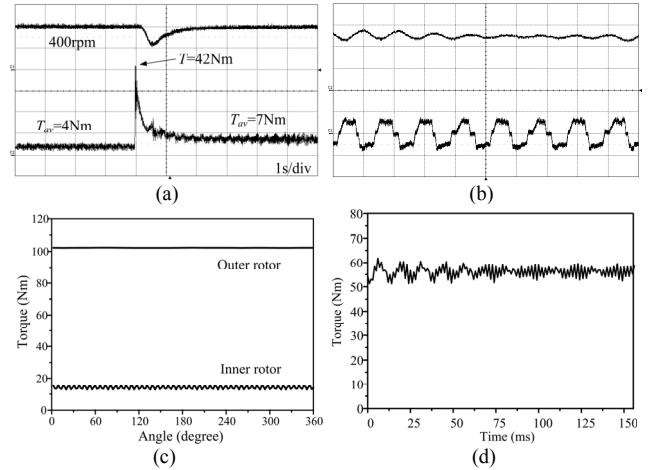


Figure 9. Torque performances. (a) PMHB type (measured speed & torque). (b) PMMB type (measured torque & current under 400rpm: 2Nm/div, 2A/div, 5ms/div). (c) PMMG type (simulated). (d) PMVB type (simulated).

## VI. CONCLUSION

In this paper, four types of emerging in-wheel motor drives are compared and discussed. The comparison results can be concluded as follow.

- (1) All these motor drives are able to achieve the high torque for the EV launching & boosting.
- (2) They possess the high torque output based on their distinct merits of flux control & flux modulation.
- (3) They cover the speed range of 0~1000rpm for the EV direct-drive operation.
- (4) The PMHB type takes the advantage of flux control by online-regulating the DC field winding. The PMMB type achieves the similar flux control by the memory feature of

AlNiCo PMs. So, the PMMB type has the higher efficiency than the PMHB one. The PMMG type uses the magnetic gear to enlarge the output torque. And the PMVB type adopts the flux-modulation pole to obtain the gear effect. Thus, the PMVB one is much simpler than the PMMG type

#### ACKNOWLEDGMENT

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