Critical Review of Direct-Drive Electrical Machine Systems for Electric and Hybrid Electric Vehicles

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***Abstract*— With ever-increasing concern of fossil fuel storage and environmental pollution, transportation electrification has recently attracted extensive attention. In conventional propulsion systems, the engine is connected to the wheel through a clutch, reduction gearbox, and mechanical differential. The mechanical transmission inevitably results in power loss, noise, vibration, and additional maintenance. With elimination of the gearbox and transmission component, the direct-drive technique exhibits significant advantages of higher systematic efficiency, more flexible wheel control, and better passenger comfort. This paper aims to provide an overview of automobile direct-drive techniques and recent electrical machine developments for direct-drive propulsion systems. Benefits and limitations of various direct-drive machines are summarized and compared with typical industrial products. Finally, the opportunities, challenges, and future development trends are discussed in related to the research "hot spots".**

***Index Terms*—Electrical machine, electric vehicle, direct-drive, in-wheel motor, permanent magnet machine**

I. Introduction

ENERGY crises and and environmental pollution have attracted extensive attention in decades, and energy saving with emission reduction have been the global consensus for the 21st century [1]. Electrification brings an alternative solution for a variety of industrial applications, especially for the transportation automobile. With the rapid advancement of high-performance electric motor and power electronics, electric and hybrid electric vehicles (EV/HEVs) are investigated and developed as the substitution of conventional oil-fueled automobiles [2]. At the present time, the commercial battery electric and hybrid vehicles, e.g., Tesla Model S, Toyota Prius, BMW i3, have been widely accepted around the world [3], [4].

In the conventional gear-drive system in EV/HEV, the propulsion motor is connected to the wheels through a series of mechanical transmission components [5]. The mechanical transmission inevitably results in reduced efficiency, boosted weight, and increased maintenance cost. An alternative solution is to employ direct-drive system to eliminate the mechanical transmission components. In such case, more space is spared for battery and passenger accommodation, while better control flexibility can be realized with independent wheel control [6].

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The world's first direct-drive in-wheel motor for automobile was developed more than a century ago (i.e., in 1900 [7]), as shown in Fig. 1. The vehicle was driven by two direct-drive hub motors through lead acid battery installed in the curb. The hub motor concept was extended to four-wheel drive in the following generations to increase the propulsion power. However, the weight of lead acid battery was around 400kg while of hub motor drive was 272kg. The heavy motor significantly increased the unsprung mass and vehicle control difficulty, and the severe working condition raises challenge for motor safe operation [8]. In the following years, the EV with hub motor was defeated by oil-fueled combustion vehicle.

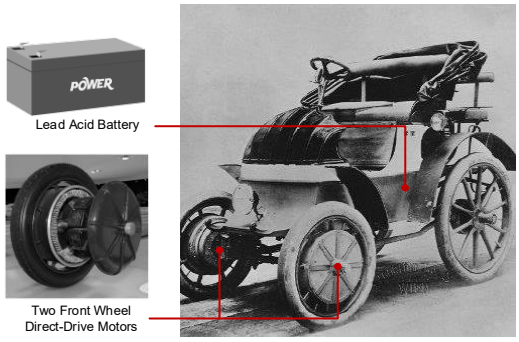


Fig. 1. The world's first direct-drive EV 'Lohner Porsche' developed by Dr. Ferdinand Porsche in 1900 [7], [8].

In the past century, the energy storage technique has been developed rapidly, and high-power density batteries have been employed for automobile applications [9]. Various direct-drive electric machines are also investigated [10], which provides higher power density with reduced unsprung weight. Therefore, the direct-drive machine systems have been re-considered for EV/HEVs recently [11]. With reference to typical gear-drive systems, this paper aims at providing a critical review on direct-drive techniques for electric propulsion and electric machine development trend for EV/HEV applications.

II. Vehicular Architecture

A. Gear-Drive System

The typical electric drive system for a commercial EV is shown in Fig. 2(a), and hybrid drive can be obtained by combining a combustion engine [12]. In the gear-drive system, the electrical motor is supplied by the battery package through a power controller. The electric motor operates at a relatively high speed for power boosting, and propulsion power is transmitted to the drive wheel through a reduction gearbox. To achieve different operating speeds of the drive wheels for vehicle turning, a mechanical differential is located between the drive wheels. The electrical components, including battery

package, power controller, drive motor, and mechanical transmission components, including reduction gearbox, mechanical differential, are all installed on-board.

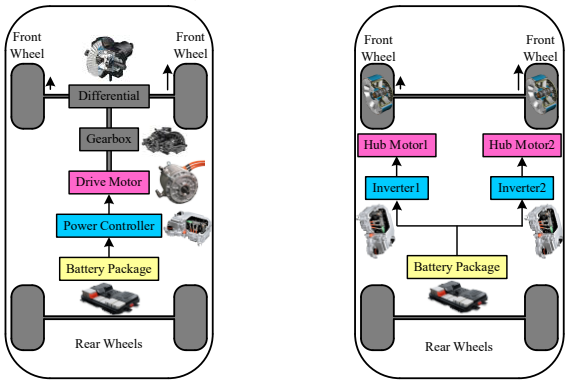


Fig. 2. Vehicular architectures. (a) Gear-drive system. (b) Direct-drive system.

Numerous electric machines have been comprehensively evaluated and compared for potential EV traction applications [13]. Two typical electric motors with gear-drive system for EV applications, i.e., induction machine (IM) for Tesla Model S [14]-[16] and permanent magnet synchronous machine (PMSM) for BMW i3 [17], [18] are listed in Table I. Both motors are equipped with distributed winding and inner rotors. The end-winding overhang of the distributed winding is long, resulting in an aspect ratio of outer diameter to axial length of about 1. With reduction gear ratio higher than 9:1, the motor is operating in high-speed of up to 15000rpm for power boosting. Both traction motors exhibit high torque and power to volume ratios up to 56Nm/L and 29kW/L using liquid cooling with current density of ~20A/mm^2. However, the mechanical gear volume increases with the transmission torque, resulting in bulky size of drive system. As can be observed in Table I, the active volume of reduction gear is around 1/4 of the propulsion motor. Accounting for the transmission gear, the systematic power density and efficiency can be around 20% and 3%, respectively, lower than the electric motor alone.

The development trend of power densities of high-speed traction motors (i.e., excluded gear) in gear-drive system is depicted in Fig. 3, with a sharp increasing power density demand can be observed [19]. At the recent presented gear-drive systems, the power density of electric motor alone can be approaching 9kW/kg. When the mechanical gear is included for consideration, the systematic power density can be around 7.2kW/kg. The demand of high-power density electric system provides critical requirement for motor design.

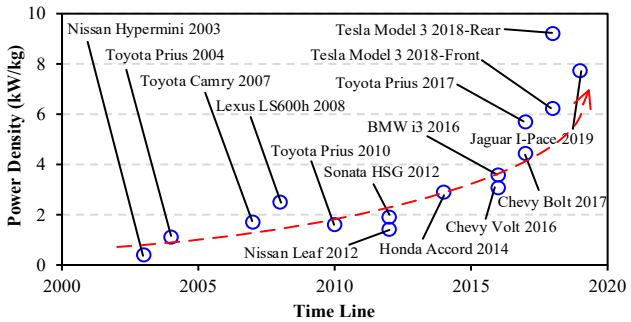
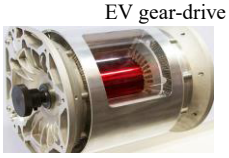
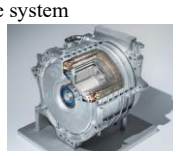


Fig. 3. Power density development trend of high-speed traction motor (i.e., excluded gear) in commercial gear-drive vehicles.

TABLE I
TWO TYPICAL GEAR-DRIVE ELECTRIC MOTORS FOR COMMERCIAL EV

	Tesla Model S	BMW i3
Application	EV gear-drive system	
Prototype photo		
Motor type	IM	PMSM
Winding type	Integer slot distributed winding	
Rotor type	Inner rotor	
Outer diameter	254mm	242.1mm
Stack length	152mm	132.3mm
Air-gap length	0.5mm	0.7mm
End-winding	~50mm	~32mm
Aspect ratio	1	1.2
Current density	20A/mm^2	18A/mm^2
Peak motor torque	430Nm	250Nm
Peak motor power	225kW	125kW
Maximum motor speed	15000rpm	11400rpm
Primary gear diameter	53.1mm/138.7mm	45.4mm/140mm
Secondary gear diameter	60.1mm/207.9mm	64.4mm/202.2mm
Primary gear width	36.5mm	21mm
Secondary gear width	45.4mm	28mm
Gear ratio	9.734:1	9.665:1
Active motor volume	7.7L	6.1L
Active gear volume	2.3L	1.3L
Peak motor efficiency	98%	94%
Peak motor plus gear efficiency	95%	91%
Peak motor torque/active motor volume	56Nm/L	41Nm/L
Peak motor power/active motor volume	29kW/L	21kW/L
Peak geared torque/active volume of motor plus gear	418Nm/L	325Nm/L
Peak geared power/active volume of motor plus gear	22kW/L	17kW/L
Cooling method	Liquid cooled	

*Data source: public references [14]-[18]

B. *Direct-Drive System*

The direct-drive system for the EV with front wheel drive is shown in schematic form in Fig. 2(b) [5]. Four-wheel drive can be achieved by adding another two hub-motors in the rear wheel, and hybrid drive can be achieved by attaching a combustion engine and generator. In a direct-drive system, mechanical transmission components between the electrical motor and drive wheels are not present, and the electric motor is integrated directly in the drive wheel. Each wheel motor is controlled by the different inverter individually under different operation speeds, and a conventional mechanical differential between the two drive wheels is eliminated. In some designs, the drive inverter can be further integrated with the hub motor for compact structure. Although the motor can be placed on the chassis with jack shafts to the wheels, additional mechanical transmission energy waste is produced.

Compared with conventional gear-drive, a direct-drive system eliminates the mechanical transmission. Therefore, drive-drive exhibits the advantages of higher system efficiency, less mechanical maintenance, and more space for on-board package. Furthermore, the inherently separate drive wheel

control provides more flexible control for different road conditions. However, since the propulsion motor is transferred to the wheel, the unsprung mass is increased, which is the main concern of direct drive system. Take the standard wheel R17 as an example, the vehicle operation speed of 80km/h demands the hub motor rotating at ~1000rpm, which is obviously smaller than that of gear-drive motor. To transmit similar power under much lower operation speed results in bucky motor size and challenges for the motor design. As a result, the direct-drive system has not been utilized for mass-produced commercial EV/HEV yet, and continuous investigations are required.

According to the above discussion, the key design requirements can be summarized as follows:

- *Compact Structure with High Aspect Ratio*: Since the direct-drive motor is installed inside the wheel, the motor size should fit the wheel. A high aspect ratio of outer diameter to axial length is preferred.
- *High Torque Density*: To transmit high power under a relatively low speed, high torque density is required for direct-drive motor.
- *High Efficiency at Low-Speed Region*: Since the direct-drive motor is coupled to wheel without reduction gear, the motor must have high efficiency at low speed.
- *Light Unsprung Mass*: Since the vehicle operation is strongly determined by unsprung mass, in-wheel direct-drive system should be designed with light weight.
- *High Fault tolerance*: To satisfy the harsh in-wheel operation, high fault tolerance is required. Therefore, the electric drive system with multi-phase or multi sub-systems is preferred.

III. Brushless Direct-drive Machines

A. Outer Rotor Permanent Magnet Synchronous Machine

With the rapid development of magnetic material, PMSMs are widely investigated to achieve properties of high torque density and high efficiency [20]. The outer rotor PMSM (OR-PMSM), as shown in Fig. 4(a), is a promising candidate for direct-drive application because it can directly couple its rotor to the wheel [21]. To fit the flat volume of an in-wheel installation, fractional slot concentrated winding is preferred. A high pole count enables thin iron yoke design, resulting in reduced volume and weight. The feasible stator/rotor pole combination for the modular stator structure are summarized in [22]. Concentrated windings, a consequence of partial pitch, are beneficial for high fault tolerance, easy manufacturing process, and high slot filling factor. Multi-phase design is another technique for high fault tolerance, and the fault tolerant capability has been validated in the five-phase OR-PMSM in [23]. Similarly, an OR-PMSM with a series of sub-motors is developed for Protean in [24]. Each sub-motor is controlled by a separate inverter and can operate independently even under single fault condition. Furthermore, the consequent pole is employed to reduce PM usage [25] and interior PM is investigated to incorporate the flux concentrating effect [26].

However, the fractional slot concentrated winding inevitably results in parasitic effect for PM machine due to the abundant magnetomotive force (MMF) harmonics [27]. The eddy current reduction and noise, vibration and harness (NVH) suppression for direct-drive OR-PMSM have been reported in [28] and [29].

B. Outer Rotor Induction Machine

Due to the sharp increased price of rare-earth material, there have been some attempts to develop non-PM machines for electric propulsion [30]. The outer rotor induction machine (OR-IM), as shown in Fig. 4(b), can be utilized for direct-drive systems [31]. The IM exhibits the benefits of lower production cost, high temperature duration, and better robustness [32]. However, power density, efficiency and power factor are both sacrificed compared with PMSM.

For in-wheel drive application, the main limitation of OR-IM is a relatively long end-coil distributed winding. It is possible to employ concentrated windings for IM, but torque density, efficiency and torque ripple are deteriorated [33]. The stator design with auxiliary slot and varying turns per coil is adopted to suppress the MMF spatial harmonics in [34], whereas the manufacturing process is complicated. To reduce the end-winding length and avoid the parasitic effect of the concentrated winding, the toroidal winding has been proposed for OR-IM in [35]. By locating half of the coil inside the inner stator, the machine volume becomes more compact. A shortcoming of the toroidal winding design can be observed as a waste of half winding and eddy current in the end packets, resulting in efficiency reduction for additional copper loss.

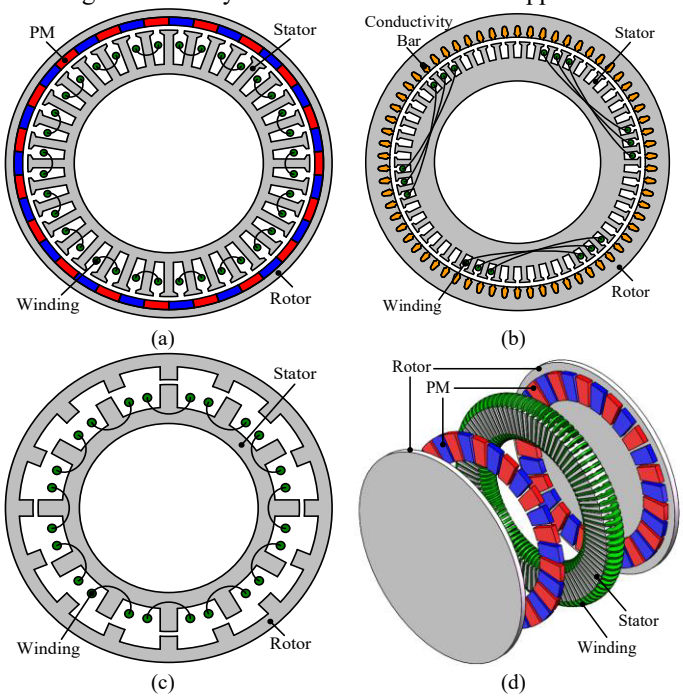


Fig. 4. Conventional brushless direct-drive machine configurations. (a) Outer rotor permanent magnet synchronous machine. (b) Outer rotor induction machine. (c) Outer rotor switched reluctance machine. (d) Axial flux permanent magnet synchronous machine.

C. Outer Rotor Switched Reluctance Machine

For non-PM design, an outer rotor switched reluctance machine (OR-SRM), as depicted in Fig. 4(c), is another possible solution. The OR-SRM has been systematically optimized for the direct-drive EV in [36]. It is revealed that the SRM exhibits the benefits of low cost, compact volume and

robust structure, whereas the torque density is still not comparable with PMSM.

To compensate the low torque of the SRM, some techniques have been adapted from machine topology improvement. In [37], the segmented OR-SRM with rotor pole number higher than stator pole number is investigated. With slightly lower torque density compared with PMSM, the OR-SRM provides a low-cost solution for direct-drive applications. Furthermore, a divided tooth design has been proposed to reduce magnetic saturation and ~50% improved torque density is achieved compared with conventional SRM [38]. The permanent magnets can be inserted in the stator slots to assist the torque production [39]. Although the torque density of PM-SRM is not comparable with the PMSM, its feature of high fault tolerance is inherited [40].

A disadvantage of OR-SRM for direct-drive application is the high pulsating torque, vibration, acoustic noise, and riding discomfort [41]. Multiphysics modelling is employed for SRM design considering NVH in [42]. Moreover, improved control methods are developed to suppress the NVH issues in SRM direct-drive system in [43].

D. Axial Flux Machine

Axial flux machine (AFM) is a proper design for in-wheel system due to the flat shape, compact structure, and high torque density, as depicted in Fig. 4(d). An early reported 25kW AF-PMSM in-wheel motor [44] can achieve rated torque density of 32Nm/L and peak torque density of 64Nm/L under water cooling, i.e., it is comparable with the radial flux PMSM. In [45] and [46], General Motors Co. has developed AF-PMSM for EV/HEV propulsion. The design accommodates a double rotor and sandwiches slotted stator with a toroidal winding. This motor can achieve peak torque density of 73Nm/L. To eliminate the slotting effect, YASA Co. has developed yokeless and segmented armature motors as alternative solution [47], [48]. As reported by YASA Co., its motor can achieve torque density of ~80Nm/L with peak efficiency of ~95% [49]. The yokeless design is beneficial to eliminate the slotting torque ripple and reduce the motor mass. However, the winding inductance is small because of increased air-gap length. As a result, flux-weakening is ineffective, and the motor is not fault tolerant.

Considering the rare-earth material uncertainties, there are some efforts to develop non-rare-earth AF machines for in-wheel drive. An AF-SRM is developed for in-wheel EV, with purported higher torque density than its radial flux counterpart [50]. Furthermore, the inherent problem of high pulsating torque can be alleviated with the displacement of double-rotor structure [51].

E. Other Machines

Synchronous reluctance machines (SynRM) can be perceived as a special type of IPMSM with null PM flux linkage. The OR-SynRM exhibits similar torque density and lower torque ripple compared with OR-SRM, showing its potential to be a low-cost candidate for direct-drive applications [52], [53]. The main shortcoming of OR-SynRM is the bulky volume caused by the distributed winding, since such winding is preferred for reluctance torque production.

The transverse flux PM machine, with the synergies of radial, circumferential and axial fluxes, exhibits high torque density and is another candidate for direct-drive applications. In [54], the transverse flux PM machine is designed for in-wheel drive in comparison with PMSM. It can provide similar continuous torque density as a PMSM. However, its overload capability is limited, and power factor is too low due to severe flux leakage and magnetic saturation [55].

To further enhance the torque density, dual stator machines have been investigated by efficiently utilize the inner space. In [56], an ultra-high torque density dual-stator PMSM is presented with torque density of 120Nm/L and 19.6Nm/kg under armature current density of 19A/mm^2. Besides, the double stator concept has been utilized for SRM in [57], whose torque density can be improved 3 to 4 times compared with conventional single stator SRM. The main limitation for the dual-stator machine is assembling difficulty of double stator and cupped rotor, which restricts its potential for industrial production.

The dominant brushless direct-drive machines are compared in Table II, focusing on the potential utilization for EV/HEVs. Quantitative comparisons will be presented in the following.

TABLE II
COMPARISONS OF TYPICAL BRUSHLESS DIRECT-DRIVE MACHINES

	OR-PMSM	OR-IM	OR-SRM	AF-PMSM
Winding	Concentrated	Distributed or toroidal	Concentrated	Concentrated or toroidal
Volume	Compact	Bulky	Compact	Compact
Torque density	High	Medium	Low	High
Torque ripple	Low	Low	High	Low
Efficiency	High	Medium	Medium	High
Cost effectiveness	Low	Medium	High	Low
Fault tolerance	Low	Medium	High	Low

IV. EMERGING FIELD MODULATION DIRECT-DRIVE MACHINES

By incorporating the magnetic gearing effect in the electric motor, the transmission torque can be boosted through a pseudo gear [58]. As a result, the electric motor can output high torque directly with elimination of mechanical gear. With the utilization of field modulation effect, numerous novel electric machines have been developed for direct-drive applications over the past few decades [59].

A. Electric Machines with Magnetic Gear

In [60], magnetic gear is coupled with an electric machine, as shown in Fig. 5(a). The compound machine is consisted by PMSM (installed in inner part) and magnetic gear (installed in outer part), i.e., the outer rotor of PMSM is mounted with the inner rotor of magnetic gear. The outer rotor of magnetic gear can be connected with the wheel directly for electric propulsion. With the utilization of magnetic gear, the transmission torque can be enlarged. The main shortage of this design is the complicated structure, i.e., two rotary components, and three-layer airgaps.

To simplify the complicated structure, the inner high-speed rotor is replaced with a stationary armature structure, forming a compact magnetic geared machine (MGM) in [61]. An improved consequent-pole rotor design is depicted in Fig. 5(b) [62] to facilitate better PM utilization. The improved MGM is consisted of two stationary parts, one rotor, and double layer airgaps. In [63], it is shown that the torque density of the compound machine in Fig. 5(a) is significantly higher than that of the OR-PMSM, while the MGM in Fig. 5(b) exhibits similar torque density with the OR-PMSM.

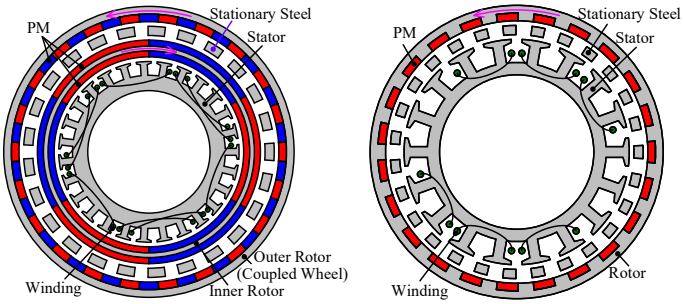


Fig. 5. Electric machines with magnetic gear. (a) Electric machine coupled with magnetic gear [60]. (b) Magnetic-geared machine [62].

B. *Flux Switching Permanent Magnet Machine*

The flux-switching PM machine (FSPMM) has been perceived as a promising candidate for electric propulsion due to its distinctive features of flux focusing and purported high torque density [64]. In [65], an OR-FSPMM has been developed for in-wheel drive, as shown in Fig. 6(a). The FSPMM inherently carries concentrated windings, resulting in compact structure. To enlarge the slot area, the OR-FSPMM with a wedge-shaped magnet and sandwiched magnet are presented in [66], [67]. Furthermore, to obtain high fault tolerance for in-wheel drive, the modular stator design and multi-phase design are adopted in [68], [69]. The main concern for FSPMM is the armature winding surrounded PM structure (see Fig. 6(b)), i.e., more effective thermal management is required considering high temperature demagnetization and overload operation.

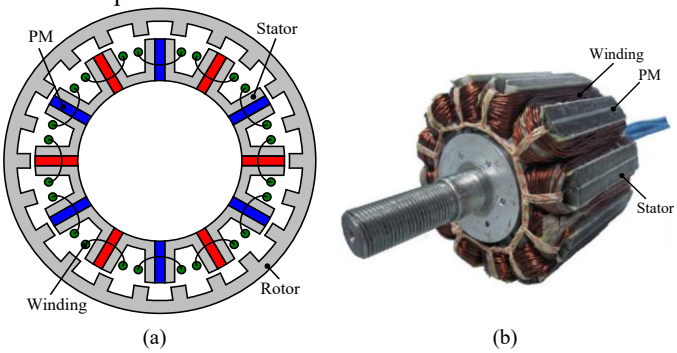


Fig. 6. Outer rotor flux switching PM machine [65]. (a) Machine configuration. (b) Constructed stator with armature winding surrounded magnets.

C. *Vernier Permanent Magnet Machine*

By incorporating a field modulator in stator teeth, the vernier PM machine (VPMM) is highly promising for direct-drive application due to high torque density and simple structure [70]. Conventional VPMM carries a high gear ratio with low armature pole count and large slot number, and distributed winding is adopted [71]. To reduce the end-winding length, the auxiliary modulation pole is introduced in stator tooth [72] (see Fig. 7(a)). The dual-PM concept is employed in flux modulation pole in [73] to enhance the torque density. Furthermore, a multi-phase design with fault tolerant tooth is employed in [74] to mitigate the electromagnetic coupling of adjacent phases.

VPMM suffers from the inherent problems of significant flux leakage and low power factor (see Fig. 7(b)). The optimization of power factor for the VPMM considering driving cycle is presented in [75]. However, the power factor after optimization is still quite low (i.e., ~0.6), resulting in increased burden for inverter and power supply.

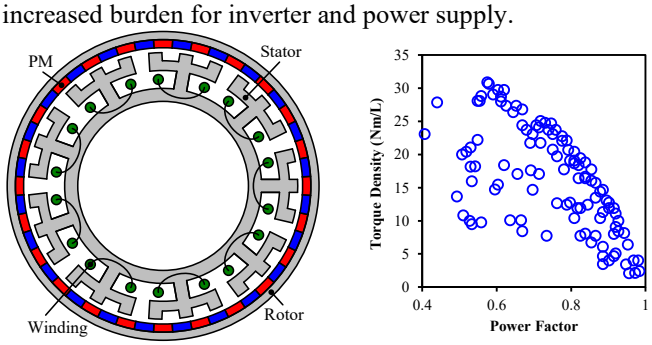


Fig. 7. VPMM [72]. (a) Machine configuration. (b) Power factor versus torque capability during optimization.

D. *Less/Non-PM Field Modulation Machine*

Considering the high cost of rare-earth magnets, there are some attempts to develop less/non-PM field modulation machine to improve cost effectiveness [76], [77]. In [78], a hybrid-excited machine (HEM) with the synergies of PM and field winding is developed, as shown in Fig. 8(a). The field winding excitation compensates the reduced PM flux linkage, and the regulation of field excitation facilitates variable speed operating. To totally eliminate permanent magnets, the wound-field machine (WFM) is developed in [76], as depicted in Fig. 8(b). Although the material cost is reduced compared with a PM machine, its torque density is substantially lower. With the introduction of an additional field winding, the main limitations of HEM and WFM are increased field winding copper loss and reduced machine efficiency.

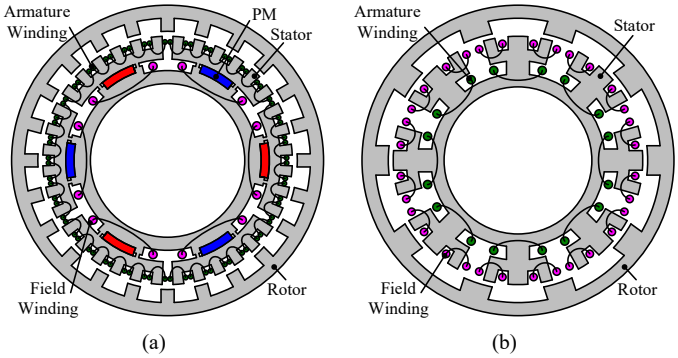


Fig. 8. Less/non-PM field modulation machines. (a) HEM [78]. (b) WFM [76].

To conclude, these field modulation machines are compared in Table III, focusing on the potential utilization for EV/HEVs. Quantitative comparisons will be presented in the following.

TABLE III
COMPARISONS OF FIELD MODULATED DIRECT-DRIVE MACHINES

	MGM	FSPMM	VPMM	HEM/WFM

Winding	Distributed	Concentrated	Distributed /Concentrated	Concentrated
Construction	Bulky	Compact	Medium	Medium
Torque density	High	Medium	High	Low
Efficiency	High	Medium	High	Low
Cost effectiveness	Low	Low	Low	High
Fault tolerance	Low	Medium	Medium	Medium

V. State of Art of Direct-drive Electric Machines

A. Industrial State of Art

Over the past years, some industrial companies have developed a series of products for in-wheel direct-drive applications. Table IV provides a summary of various industrial motors developed for in-wheel direct-drive EV/HEVs. Some conclusions can be obtained from the parametric comparisons.

TABLE IV
Comparisons of Typical Direct-drive In-Wheel Motor Products

Parameter	Protean [79]	Mitsubishi [80]	Elaphe [81]
Product Series	Pd18	Lancer Evolution MIEV	L1500
Prototype photo			
Motor type	OR-PMSM	OR-PMSM	OR-PMSM
Outer diameter	433mm	445mm	464mm
Axial length	125mm	134mm	142.2mm
Aspect ratio	3.5	3.3	3.3
Volume	18.4L	20.8L	24.0L
Continuous torque	650Nm	-	650Nm
Continuous power	60kW	-	77kW
Peak torque	1250Nm	518Nm	1500Nm
Peak power	80kW	50kW	110kW
Maximum speed	1600rpm	1500rpm	1480rpm
Continuous power/volume	3.3kW/L	-	3.2kW/L
Peak power/volume	4.3kW/L	2.4kW/L	4.6kW/L
Peak efficiency	93%	-	-
Motor Mass	36kg	-	34.8kg
Cooling Method	Liquid	-	Liquid
Parameter	**Printed Motor Works [82]**	**General Motors [46], [47]**	**YASA Motors [49]**
Product Series	XR32-13	-	YASA-750
Prototype photo			
Motor type	OR-PMSM	AF-PMSM	AF-PMSM
Outer diameter	324.5mm	340mm	368mm
Axial length	130mm	75mm	98mm
Aspect ratio	2.5	4.5	3.8
Volume	10.8L	6.8L	10.4L
Continuous torque	300Nm	200Nm	400Nm
Continuous power	5.87kW	16kW	70kW
Peak torque	577Nm	500Nm	790Nm
Peak power	42kW	25kW	200kW
Maximum speed	2000rpm	1200rpm	3250rpm
Continuous power/volume	0.5kW/L	2.4kW/L	6.7kW/L
Peak efficiency	-	90%	95%
Peak power/volume	3.9kW/L	3.8kW/L	19.2kW/L
Motor Mass	32.35kg	34kg	37kg
Cooling Method	Liquid	Liquid	Liquid

- PMSM machines have been dominant candidates for in-wheel direct-drive application, because it can meet the high output torque (i.e., 500~1500Nm) and high efficiency requirements.
- Outer rotor and axial flux structures are promising due to the requirement of in-wheel installation with large aspect ratio of outer diameter to axial length.
- The maximum speed is generally around 1200rpm~2000rpm for high-speed cruise, while the rated speed is even lower.
- Due to low-speed operation, the maximum efficiency of direct-drive motor is around 90% to 95%, i.e., slightly lower than that of the high-speed motors in gear-drive systems. However, the direct-drive system can provide comparable or even higher efficiency than the conventional gear-drive system, when the loss of transmission gear is considered.
- Liquid cooling is generally adopted for high current density and high output power requirements.
- Around twice overload peak output capability is required for the vehicle startup and climbing period.
- Motor weight is about ~35kg. It increases the unsprung mass and is still the main shortage of in-wheel direct-drive topology.
- The power to volume ratio of direct-drive motor is generally 3~5kW/L. Yasa motor exhibits highest power density of 19kW/L, whereas the commercial road EV in-wheel drive can hardly achieve the top operation speed of 3250rpm.

B. Comparison of Different Machines

To fairly evaluate the performance and potential application of various electric machines for in-wheel direct-drive applications, the torque and power densities of existing machines are compared in Fig. 9. According to the published information in Table I, the systematic power density of gear-drive system can be around 18kW/L under the peak current density of 20A/mm^2. The design target of the direct-drive motor to obtain a similar output capability is set as continuous power density of 9kW/L, assuming twice overload capability. Under the regular operation speed of ~1000rpm for EV/HEV in-wheel drive, the continuous torque density should be approaching 85Nm/L.

As can be observed from Fig. 9(a), the torque densities and power densities of OR- and AF-PMSMs in published literatures are 15~35Nm/L and 0.5~4kW/L. The relatively high torque/power densities benefit from the utilization of high magnetic strength rare-earth material. For the non-PM machine, the OR-IM and OR-SRM obviously exhibit lower torque density. The torque density of OR-IM is around 5~15Nm/L, and that of OR-SRM is 5~20Nm/L. The field modulation machines in general exhibit higher torque densities (see Fig. 9(b)) and are very promising for the direct-drive application. The dual-rotor MGM exhibits the highest torque density of ~87Nm/L whereas the construction is complicated with triple layers air-gap. The torque density of integrated MGM is around 20~50Nm/L, whereas the double layer air-gap structure is still more complex than other conventional machines. The torque density of OR-FSPMM is around 10~25Nm/L, which cannot achieve the design target. The OR-VPMM exhibits torque density around 5~50Nm/L, i.e., higher than that of conventional PMSMs. There are some

developments of non/less-PM field modulation machine to cope with rare-earth material crisis. However, the torque density of the WFM is around 5~20Nm/L, i.e., similar with SRM but lower than PMSM.

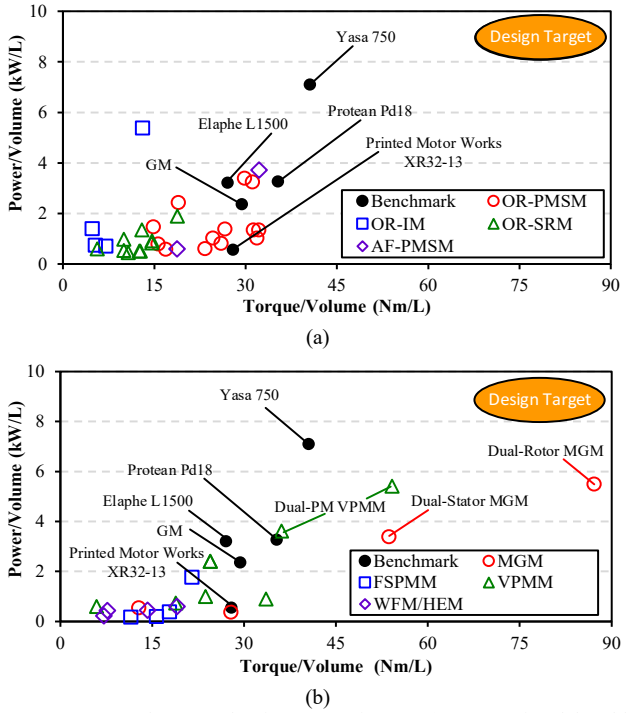


Fig. 9. Torque and power density comparisons. (a) Conventional brushless machines [20]-[49]. (b) Emerging field modulation machines [60]-[78].

As can be concluded from Fig. 9, the torque and power densities of present direct-drive motors are not able to fulfill the design target for EV/HEV applications yet. Further development of direct-drive electric motors is needed to meet the ever-increasing propulsion power requirement.

VI. Development Trend

Although the direct-drive systems for EV/HEV can eliminate the mechanical transmissions, the major challenges are the large unsprung mass, harsh in-wheel operation condition, and limited electric braking performance. Up to date, there are still no commercial mass-production vehicles equipping with the direct-drive motor. Over the past decades, numerous efforts have been done for academic research and industrial development. The major opportunities and development trends are summarized in this section.

A. High Power and Light Weight Motor

According to Fig. 3, the power density of conventional gear-drive traction motor (excluded reduction gear) is approaching 9kW/kg [19]. Accounting for the transmission gear, the power density of the gear-drive motor system can be around 7.2kW/kg. The peak power densities (i.e., power/mass) of recent direct-drive motor products are shown in Fig. 10, where only very few industrial developed direct-drive motors can fulfill comparable power density with conventional gear-drive traction system. Another most challenging concern for direct-drive in-wheel system is the significant unsprung mass, which increases difficulty for vehicle operations [83]. The direct-drive motor is coupled with wheel directly and operates under a relatively low speed. Therefore, high power and light weight have been the main development objective for direct-drive in-wheel systems. Further improvement of power density in the direct-drive motor not only can fulfill the EV/HEV requirement, but also solve the unsprung mass concern.

Up to this writing, PMSMs have been dominant for the direct-drive products considering the high torque density and compact structure. Although various field modulation machines have been presented, (see Fig. 9), industrial application is limited due to complicated mechanical structure and low power factor. Further performance improvements of these field modulation machines are expected for practical EV/HEV applications. Apart from novel machine structure investigation, another technical route is to develop advanced magnetic material. Neodymium iron boron (NdFeB), invented in the 1980s [84], has been perceived as a promising magnet due to the high remanence and intrinsic coercivity. Slight improvement has been further achieved with advanced microscopic techniques for energy product enhancement and high temperature stability duration in recent decades [85]. The torque/power density of PM machines can be improved with development of stronger magnetic material in the future.

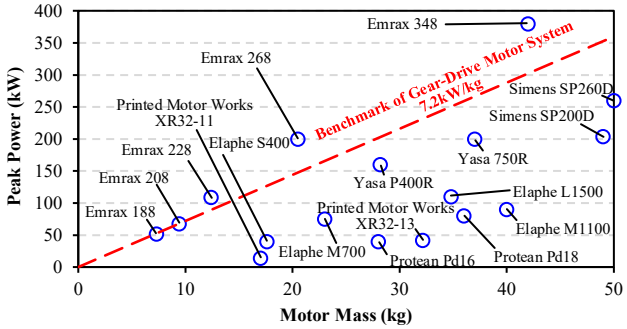


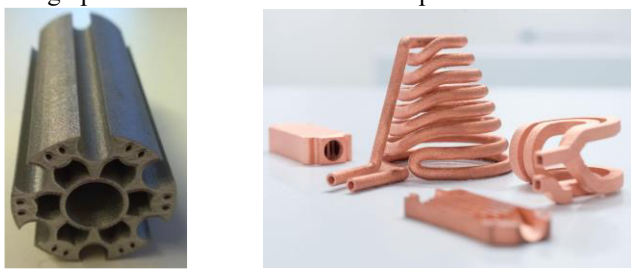
Fig. 10. Peak power densities of latest direct-drive motor products.

B. Additive Manufacturing

Additive manufacturing denotes to fabricating component through depositing materials in layers, and it is also known as 3D printing technique. Different from conventional casting and rolling processes, additive manufacturing facilitates more flexible material composition and manufactured shape and is attractive for electric machine fabrication [86].

The steel lamination with up to 6.5% silicon content is beneficial to increase the magnetic permeability and electrical resistance [87]. However, considering compound steel with high silicon content is brittle and impractical for rolling, conventional iron steel with a silicon content of 3.5% or less is generally used. With the utilization of additive manufacturing, steel cores with the silicon content of 6.5% have been fabricated and tested [88]. Furthermore, additive manufacturing enables flexible and complicated structure fabrication. In [89], a shaped salient rotor core is printed for SRM, as depicted in Fig. 11(a). Novel high performance electric machine with complicated mechanical structure can be fabricated with assistance of additive manufacturing. In [90], various shapes of conductor and winding are manufactured, as shown in Fig. 11 (b). The printed conductor and cooling jacket permit high slot fill factor and better thermal conduction. To conclude, additive

manufacturing is able to synthesize high performance magnetic material for conventional machine and facilitate manufacturing novel high performance machine with complicated structure.



(a) (b)

Fig. 11. Electric machine components with additive manufacturing. (a) Printed magnetic iron core [89]. (b) Printed conductor and winding [90].

C. Thermal Management

Increasing electrical loading is an effective technique to enhance high torque density for electrical machine. However, a direct-drive motor is sealed inside the wheel, where it is difficult to remove heat under heavy load situations. The in-wheel motor is located beside the brake disc and the thermal condition can be severe at frequent start-stop conditions. Therefore, the in-wheel motor requires efficient cooling system to ensure durability and high-power output.

Air-cooling is structurally simple, and it has been developed for the in-wheel EV drive in [91]. The housing with cooling grooves is designed and optimized to improve the heat exchange effectiveness. To enhance the heat dissipation for higher power output, oil-cooling system is employed for in-wheel motor in [92]. Apart from air- and oil-cooling, the water/coolant-cooling through water jacket has been widely utilized for on-board operation. In [93], different water jacket configurations have been investigated to improve the heat dissipation effectiveness. The cooling system for Protean in-wheel direct-drive motor is discussed in [94], as depicted in Fig. 12. An axial cooling jacket is attached to the inner stator for heat exchange in the stack direction. Additional radial cooling jacket along orthogonal direction is designed considering the end-winding is local hotspot. In the prospective heat dissipation system, better thermal conductivity coolant, local heat dissipation for hotspot and more efficient cooling channel/path should be further developed.

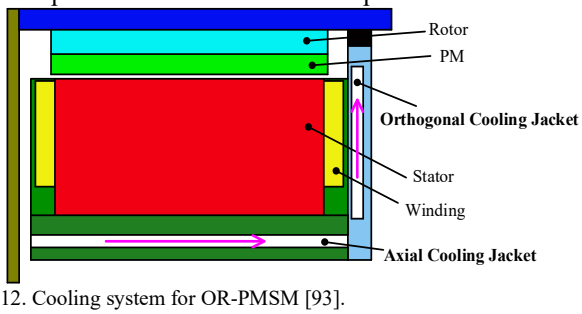


Fig. 12. Cooling system for OR-PMSM [93].

D. Less/Non-Rare-Earth PM Alternative

The in-wheel motor equipping with a rare-earth magnet is promising due to the high torque density and high efficiency. However, the recent sharp increase of rare-earth material price appeals for development of electric motors with free of rare-earth magnet. In [95], it is reported that U.S. Department of Energy targets development of next-generation traction motors with no rare-earth material. Meanwhile, the New Energy and Industrial Technology Development Organization, a public management organization in Japan, has also started variety of free-rare-earth or half-rare-earth motor projects [96].

Numerous less/non-PM machines, including IM, SRM, SynRM and WFM have been investigated for direct-drive systems. However, the torque densities of these non-PM machines are not comparable with PMSM, as shown in Fig. 8. Utilization of non-rare-earth magnet, e.g., ferrite, AlNiCo, suffers from potential demagnetization under heavy load [97]. Therefore, development of high torque density electrical machines with less/non-rare-earth magnet remains to be challenging for potential substitution of PMSM for direct-drive in-wheel systems.

E. Integrated Motor Drive

The integration of an electric machine with an inverter can eliminate connecting cables, separate housing, and hence achieving higher power/torque density. The recent development of wide bandgap devices has improved the power density and temperature tolerance duration of power electronics. Therefore, the integrated motor drive system is highly promising for automobiles with strict requirements of electric drive volume, mass and efficiency [98].

The integrated motor drive technique has been utilized for in-wheel system by Protean in [99], and the exploded view of key components are shown in Fig. 13. To obtain high fault tolerance, the Protean in-wheel system is designed with four sub-motors and four sub-inverters. For the in-wheel drive system, the package of cabling to the motor is challenging since the cables have to survive from repeated bending and articulation with suspension and steering movement. If the inverter is packaged on the vehicle, 12 shielded phase cables are required to drive the in-wheel motor. By integrating the electric drives with motor, only 2 DC cables are demanded for power supply. With the elimination of connecting cable between motor and inverter, higher efficiency can be featured for the integrated motor drives. Nevertheless, some concerns are listed for the development of integrated motor drives. Since the drive circuits are sealed inside the wheel, the power electronics should survive from harsh on-road environments, including high/low temperature, dirt, water and vibration. Furthermore, the electromagnetic compatibility of power electronics should be examined due to long-term exposure to magnetic field of electric machine.

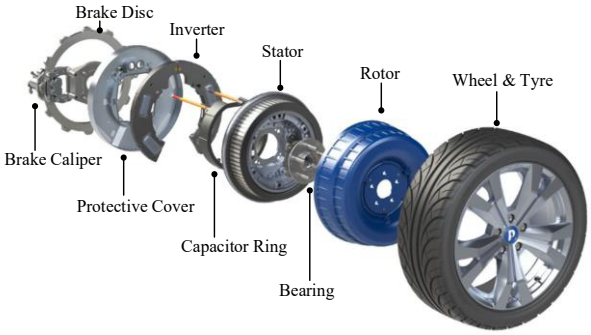


Fig. 13. Integrated motor drive system [79].

F. Electric Drive System Optimization

An electric drive system consisting of electrical machine, drive circuit and controller are key components for in-wheel direct-drive applications. In [100], the electric drive system is optimized under multi-level methods for systematic performance improvement. The robust design of an electric drive system is conducted under multi-level methods accounting for manufacturing uncertainties and tolerances [101]. Compared with the single level design of machine and drive, the systematic optimization avoids the local convergence and obtains global optimal design for whole electric system.

Different from conventional fixed speed motor, the direct-drive motor for EV/HEV is operating under variable speeds, i.e., its working conditions are more complicated [102]. In [103], the optimization of a direct-drive PMSM for race car application is conducted considering the operation under driving cycle. Apart from rated parametric design, the flexible working conditions, including low-speed and field-weakening regions are evaluated for the Pareto-optimal design. Furthermore, the equipment of in-wheel motor provides higher flexibility for vehicle control regarding different road conditions. In [104], the four in-wheel motor independent control utilizing motor driving and braking torque distribution is presented to enhance the vehicle stability. The propulsion torque of each in-wheel motor is assigned through the optimal torque distribution algorithm under the coordinative analysis. Therefore, the optimization of electric direct-drive system should be conducted under multi-level of motor topology and parametric design, inverter drive circuit design, controller hardware and algorithm design, as depicted in Fig. 14.

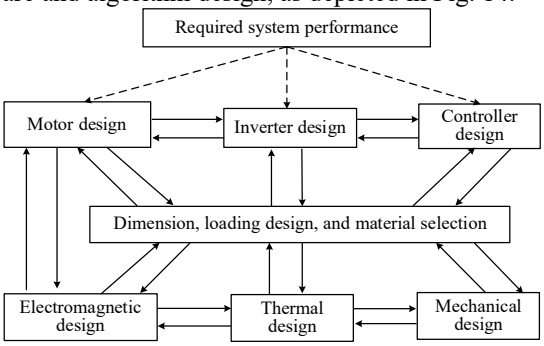


Fig. 14. Design optimization of electric drive system [100].

VII. Conclusion

Adoption of wheel motors for electric cars will require development of motors that exhibit high torque and power to mass ratio and that can tolerate the very difficult conditions (thermal isolation, vibration) in the wheel. Compared with the conventional gear-drive system, the direct-drive system eliminates the mechanical transmission components and exhibits lower vibration and noise, less maintenance cost, higher transmission efficiency, and more flexible vehicle wheel control.

Because of the high torque density and compact structure, the OR- and AF-PMSMs with fractional slot concentrated winding are attractive for direct-drive systems. As non-PM substitutions, the OR-SRM and OR-IM have been perceived as cost-effective candidates whereas their torque densities are sacrificed. The emerging field modulation machines possess satisfactory torque density with the utilization of magnetic gearing effect. However, the machine structure is complicated and power factor is relatively low, hence restricting the practical industrial applications.

In the continuous investigation of direct-drive machine system for EV/HEV, electric machines with higher power densities are highly demanded to satisfy the output requirement and reduce the unsprung mass. Additive manufacturing can be employed for high performance machine fabrication with advanced material. Efficient thermal management system is required for overload capability and high peak output. Considering the rare-earth material crisis, development of less/non-PM machines should be conducted as alternatives. Furthermore, the integrated motor drive can achieve more compact system volume and the systematic optimization should be established for electrical system performance improvement.

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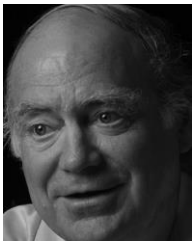

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