Electric Motors for Light Traction

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Abstract

Modern electric motors for road electric vehicles (automobiles, scooters, bicycles), light rail transit (street cars, trolley lines, subway trains), guided transit systems and elevators have been discussed. The paper aims at various types of rotary brushless motors, direct electromechanical drives and practical solutions to light traction systems. Modern permanent magnet (PM) motor technologies offer diversity of cutting-edge technology brushless motors, i.e., motors with one slot coil pitch windings, transverse flux motors, coreless disc type motors and PM assisted synchronous reluctance motors. There is a wide interest in liquid cooled traction motors and inverters as those apparatus minimize the volume of electromechanical drive systems and increase their power density. Frequently, the traction motor for road vehicles is integrated with a solid state converter. Light traction with linear motors has not been considered. Although induction motors are the most popular motors, PM brushless motors are more efficient, more compact, have better steady-state and dynamic performance at low speeds and are excellent motors for direct drive traction application.

Introduction

Light electric traction covers a wide variety of road vehicles with electric propulsion, e.g. hybrid buses, electric cars, scooters, etc., electric mass-transit passenger railways also called light rail transit (LRT), e.g., street cars (tramways), trolley lines, subway trains, etc., and guided transit systems as monorails, people movers and rubber tire wheel trains. LRTs can cater economically and effectively for passenger flows between 2000 and 20,000 passengers per hour. In modern electromechanical traction drives brushless electric motors are predominant. Brushless motors of cylindrical constructions are used in hybrid buses, electric cars, wheel-on-rail vehicles and guided transit systems, while disc type brushless motors are recommended for lighter vehicles as electric mini-cars, solar-powered cars, scooters and bicycles. Moreover, subway systems with tunnels of reduced cross section can also use linear induction motors (LIMs).

Performance characteristics and requirements

Characteristics of traction motors for electric vehicles are shown in Fig. 1. The constant torque and constant power region over wide speed range can be achieved through electronic control. Traction motors should meet the following requirements [9]:

– power rating: high instant power, high power density;
– torque – speed characteristics (Fig. 1): high torque at low speed for starting and climbing, high speed at low torque for cruising, wide speed range including constant torque region and constant power region, fast torque response;
– high efficiency over wide speed and torque ranges;
– high reliability and robustness under various operating conditions, e.g. at high and low temperature, rain, snow, vibration, etc.;
– low cost.

Electric motors of cylindrical construction

Induction, PM brushless and switched reluctance motors

The following brushless motors of cylindrical construction are used as modern traction motors:

– cage induction motor (IM);
– standard NdFeB PM brushless motor (PMBM) with NdFeB surface and interior type magnets [2, 3, 4, 5, 7, 10, 13, 16, 17, 18];
– PM brushless motor with short coil span (PMBMSCS) [1, 13, 16];
– hybrid synchronous motor (HSM) with both permanent magnets (PMs) and electromagnetic excitation [9];
– PM transverse flux motor (TFM) [13, 16];
– switched reluctance motor (SRM).

The rated power of electric motors for electric LRT is typically from 100 to 160 kW per axle and for rubber tire wheel trains from 70 to 110 kW per axle. The rated power of electric motors for hybrid busses is up to 75 kW per wheel (a brushless motor integrated with a transmission into a compact wheel motor unit) or 100 to 200 kW per vehicle (in the case of single hybrid propulsion unit). Passenger electric cars use motors typically rated from 30 to 75 kW. Fundamental advantages and drawbacks of the above motors are summarized in Table 1. Specifications of 75-kW brushless motors are compared in Table 2 [16].

DC brush type (commutator) motors are gradually replaced by more reliable and efficient brushless motors. Table 3 compares IMs and PMBMs with d.c. brush type motors.

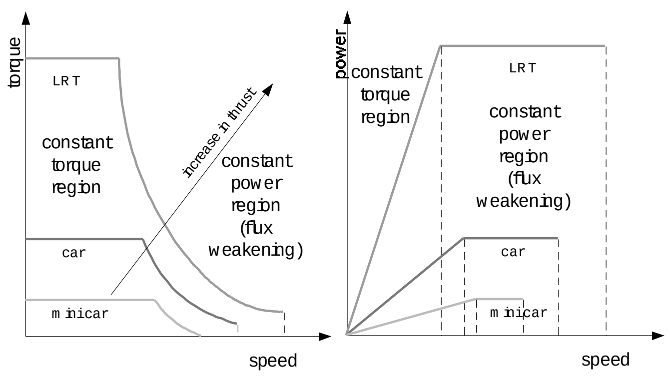


Fig. 1: Torque-speed and output power-speed characteristics of electronically controlled traction motors

Table 1. Fundamental advantages and disadvantages of brushless motors for light traction						
Type of motor	IM	PMBM	PMBMSCS	PM TFM	HSM	SRM
Advantages	Cost-effective motor	High power density, high efficiency			Field weakening	Simple and cost effective motor
		High power factor	Short end connections	No end connections		
Drawbacks	Small air gap, lower efficiency than that of PMBM	More expensive motor than IM and SRM	High sound power level, cost similar to PMBM	High torque ripple, low power factor	dc excitation winding, expensive motor	High torque ripple, high sound power level, small air gap

Table 2. Comparison of 75 kW brushless motors for electrical vehicles according to Voith Turbo GmbH & Co. KG, Heidenheim, Germany [16].						
Type of motor	IM	SRM	HSM	PMBM	PMBMSCS	TFM
Rotor	Internal Cu cage	Internal	External	Internal	Internal	External
Gear stages	1	2	1	1	1	1
Gear reduction ratio	6.22	12.44	6.22	6.22	6.22	6.22
Number of poles	2	6	20	24	40	44
Rated speed, rpm	940	1232	616	616	616	570
Rated frequency, Hz	49	82	103	123	205	209
Airgap, mm	1	1	2	2	3	1.2 to 2.0
Diameter, mm • Inner • Gap • Outer	 111 266 413	 56 278 400	 282 351 400	 313 341 410	 328 354 410	 90 354 366
Stack length, mm	276	200	243	229	255	124
Stack + end connections, mm	397	350	285	265	295	212
Material of stator stack	Laminations					Soft magnetic powder
Volume, 10^{-3} m^3	53.2	44.0	37.6	35.0	38.9	22.3
Mass of active parts, kg	272	147	106	79	71	73
PM mass, kg	-	-	2.7	4.7	7.0	11.5
Efficiency	0.900	0.930	0.932	0.941	0.949	0.976
Inverter power, kVA	396	984	254	361	385	455

Although, a cage IM is the most popular traction motor, this motor is not completely suitable for direct gearless electromechanical drives. The performance of IMs at low speeds is poor and the torque density (output torque-to-mass) is low. The best performance of direct electromechanical drives can be achieved with the aid of PMBMs, which are the highest efficiency, highest power density and highest torque density traction motors.

A compact power train can be designed at minimum costs if a special stator PMBM, the so called PMBMSCS is coupled to the engine crank shaft [1]. In a PMBMSCS the stator winding coil span is almost equal to one tooth pitch instead of one pole pitch (Fig. 2). Such a winding is similar to the salient pole winding. Owing to very short end connections, the winding losses are reduced that results in the increased motor efficiency in comparison with a standard PMBM [16]. Short end connections also reduce the axial motor length and allow for designing a flat, pancake type motor. The stator stack can be divided into arc-shaped modules, one module per tooth pitch, as shown in Fig. 2 (18 modules). Ferrous powder materials, e.g., Accucore (TSC Ferrite Int., U.S.A.) or Somaloy™500 (Höganäs, Sweden) can simplify the stator assembly and reduce the cost. The rotor can either be with surface or interior sintered NdFeB PMs. The rotor surface magnets shown in Fig. 2 are of bread loaf shape [13].

The TFM can develop higher torque density than a similar PMBM. TFMs can be designed either as double-sided or single sided motors (Fig. 3). Although, this topology is still not mature, it is expected that only single sided TFMs with internal rotors (Fig. 3b) are the candidates for mass production. As the number of poles increases, the power factor increases too, and the current, outer diameter and mass decrease. Advantages of TFMs include [13]:

Table 3. Comparison of brushless and brush type motors.			
Type of motor	IM	PMBM	d.c brush type motor
Peak efficiency, %	92 to 95	92 to 97	85 to 89
Efficiency at 10% load, %	73 to 82	83 to 94	80 to 87
Maximum speed, rpm	9,000 to 15,000	4,000 to 10,000	4,000 to 6,000
Cost per output power, U.S.$.kW	90 to 100	130 to 170	130 to 200
Relative cost of solid state controller to dc brush type motor	6 to 8	3 to 5	1

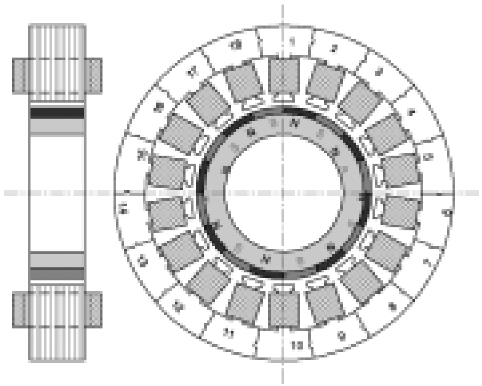


Fig. 2: PMBMSCS: stator winding with one slot coil pitch. The stator core is divided into one tooth pitch segments (one segment per coil)

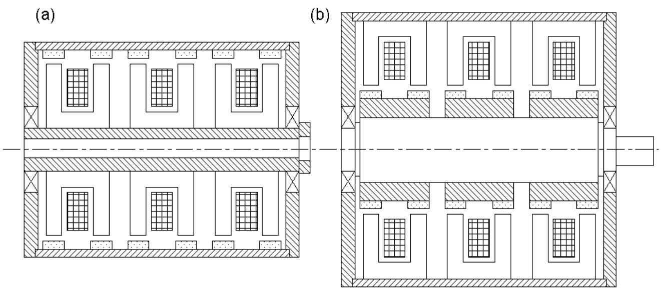


Fig. 3: Three-phase TFM consisting of 3 single-phase units with: (a) internal stator, (b) external stator

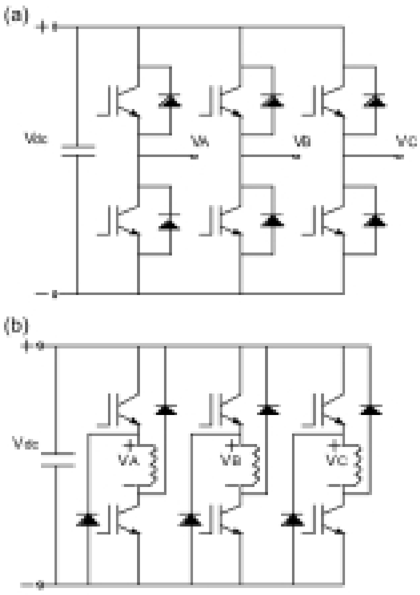


Fig. 4. Comparison of solid state converters for three-phase motors: (a) IM (inverter), (b) SRM

(a) less winding and ferromagnetic core materials for the same torque than in standard PMBMs, (b) simple stator winding consisting of a single ring-shaped coil per phase with no end connections, (c) the more the poles, the higher the torque density and power factor, (d) a three-phase motor can be made of three (or multiple of three) identical single-phase units, (e) standard three-phase voltage-fed inverter can be used. On the other hand, careful attention must be given to [13]: (a) 3D stator core - to avoid a large number of components, it is necessary to use radial laminations, sintered powders (Accucore, Somaloy™) or hybrid magnetic circuits (laminations and sintered powders), (b) the motor outer diameter is smaller in the so called "reversed design", i.e., with external PM rotor and internal stator, (c) as each stator pole faces the rotor pole and the number of stator and rotor pole pairs is the same, special measures must be taken to minimize the cogging torque. Traction TFMs for electric buses are manufactured by Voith Turbo GmbH, Germany.

The efficiency of a SRM can be a little higher than that of its IM counterpart of the same rating. The most important advantages of SRMs are: (a) simple construction (only laminations and stator coils); (b) no rotor PMs, no rotor windings; (c) the best performance-to-cost ratio; (d) short end connections as in PMBMSCS; (e) high efficiency over wide speed range; (f) fault tolerance better than that of PMBM; (g) higher torque-to-current ratio as compared with IMs; (h) inherently well suited motor for traction applications.

Although there is abundance of publications and patents on SRMs, this technology is still not mature for practical applications in commercial traction systems. Major drawback include: (a) high torque pulsation (over 20 %); (b) high acoustic noise (about 80 dB at full load and low speeds); (c) lower shear stress than that in PMBMs; (d) lower efficiency that that of PMBMS; (e) small air gap (0.4 to 0.7 mm); (f) standard parts cannot be used; (g) standard power electronics converters cannot be used (Fig. 4); (h) limited number of manufacturers; (i) "reluctance" to apply SRMs in industry.

The HSM is designed as a brushless motor. One of possible constructions is shown in Fig. 5 [9]. The excitation system consists of PMs mounted on the rotor and stationary internal d.c. winding which is used to boost the starting torque and weaken the field at higher speeds (Fig. 1).

Synchronous reluctance motors with PMs

An example of new developments in traction motors is the PM assisted synchronous reluctance motor [2]. This is an interior type PM motor with several flux barriers per pole. PMs are placed in each air barrier (longitudinal slot), as shown in Fig. 6. The air barriers are of different thickness to improve the air gap flux density distribution. With respect to a reluctance machine, ferromagnetic ribs are saturated by the PM excitation flux. With a suitable choice of the PM flux, the power factor increases. As a result, the PM assisted reluctance motor requires a lower current than an equivalent synchronous reluctance motor to develop the same torque. The motor exhibits a high saliency ratio and consequently the

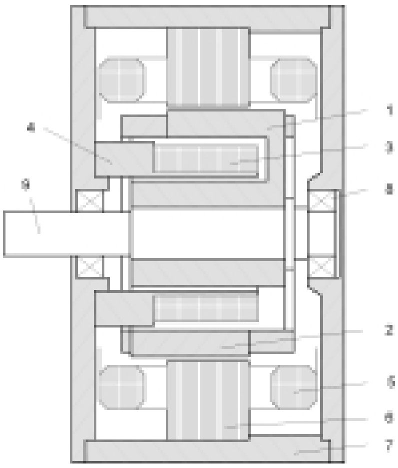


Fig. 5: Construction of PM HSM: 1 – North pole, 2 – South pole, 3 – d.c. field winding, 4 – field winding holder, 5 – stator winding, 6 – stator core, 7 – frame, 8 – bearing, 9 – shaft [9]

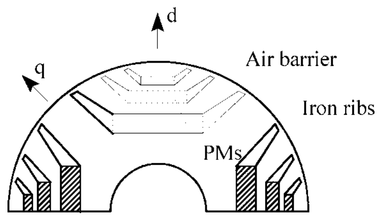


Fig. 6: PM assisted synchronous reluctance motor

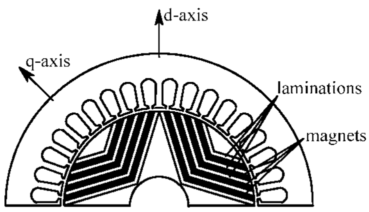


Fig. 7: Axially-laminated IPM motor

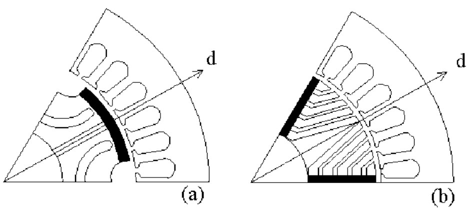


Fig. 8: One-pole segment of NSPM motor with (a) surface PMs (b) buried PMs.

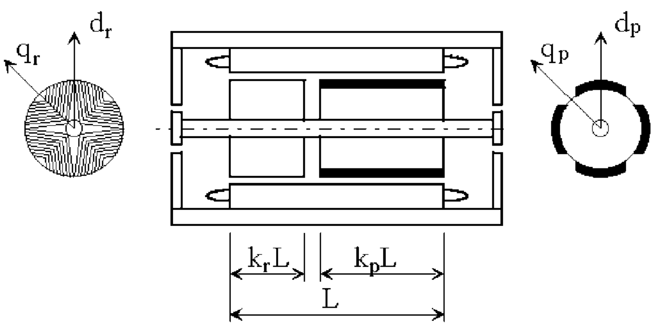


Fig. 9: Brushless motor with a two-part rotor

required volume of PMs is small. Low energy and low-cost magnets can be used, such as plastic ferrites or plastic-bonded NdFeB magnets.

The axially laminated reluctance motor assisted by PMs is shown in Fig. 7. Rotors of these machines consist of plastic ferrite magnet layers between axial laminations. Since the axially laminated rotor is characterised by a very high saliency ratio, low energy magnets can be used. In addition, the high equivalent non-magnetic air gap protects PMs against demagnetisation. The drawback is the high cost of manufacturing.

The normal saliency PM (NSPM) rotors [2] are obtained by making flux-barriers in buried PM rotor cores to limit the *q*-axis flux, without obstructing the *d*-axis flux. The effect of the barriers is to obtain higher *d*-axis than *q*-axis inductance, i.e. $L_d > L_q$. One of possible configurations is the segmented PM motor, shown in Fig. 8. It can be obtained from a surface PM rotor (Fig.8a), or from a buried PM rotor (Fig. 8b). Flux barriers are designed along the *d*-axis, so that the PM flux-linkage and the *d*-axis inductance remain practically the same, while the *q*-axis inductance is reduced.

Unlike other topologies of PM motors, the brushless motor with two-part rotor (Fig. 8) allows for an independent choice of the *d* and *q*-axis permeances [2, 7, 8, 21]. Therefore, the two-part rotor offers excellent flexibility in motor design, making it easier to obtain the motor parameters that can meet the required performance. Fig. 9 shows a two-part rotor with a surface mounted PM unit and a reluctance unit. The reluctance unit has the *d*-axis d_r aligned with the magnet axis d_p of the PM unit. A large difference between the two axis inductances can be obtained by implementing an axially-laminated rotor in the reluctance unit.

Disc type (axial flux) PM brushless motors

The design of disc type PMBMs is complicated by the presence of double-sided air gap, high attractive axial forces, and mechanical integrity of the rotor-shaft joint. However, these motors are suitable for smaller electrical vehicles, because they can easily be integrated with wheels (Fig. 10) or other components of the electromechanical drive system [14,19,20]. Low-speed disc type PMBMs are also well suited to gearless elevators (Ecodisk™ motor, Kone, Hyvinkää, Finland) [15]. The following constructions can be used for electrical vehicles [13]:

– double-sided motor with internal PM disc rotor;
– double-sided motor with one internal stator and twin PM rotor;
– single sided motor;
– ironless double-sided motor;

Since the first three topologies are widely discussed in literature, e.g., [13], only the ironless double-sided disc motor (Fig. 11) will shortly be described. This motor has neither the armature nor rotor core. The internal stator consists of full-pitch or short-pitch coils wound from insulated wires. Coils are arranged in overlapping layers like petals around the center of a flower and embedded in a plastic of very high mechanical integrity. The twin non-magnetic rotor discs have cavities of the same shape as PMs. Magnets arranged in Halbach array are inserted in these cavities and glued to the rotor discs. Ironless motors have very high efficiency (no core losses), do not produce any torque ripple at zero current state and are lightweight motors. The drawback is larger amount of PM materials as compared with PMBMs with ferromagnetic cores.

Water cooled traction motors

Water cooled electric motors (Fig. 12) and inverters (Fig. 13) minimize the volume of electromechanical drive systems and increase

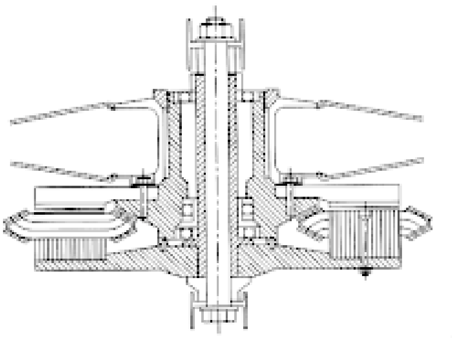


Fig. 10: Disc-rotor motor fitted to spoked wheel of an electric car [19]

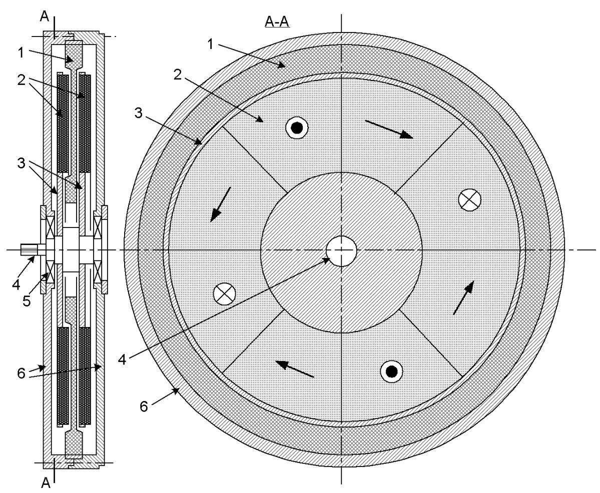
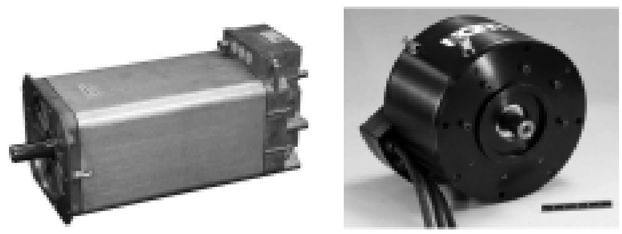
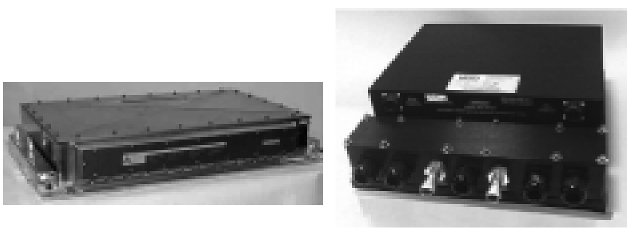


Fig. 11. Ironless double-sided PM brushless motor of disc type: 1 – stator winding, 2 – PMs, 3 – rotor, 4 – shaft, 5 – bearing, 6 – frame [13].



(a) (b)

Fig. 12: Water-cooled motors for electric and hybrid buses manufactured by (a) Siemens, Germany,(b) UQM Technologies, U.S.A



(a) (b)

Fig. 13: Water cooled inverters manufactured by (a) Siemens, Germany, (b) UQM Technologies, U.S.A

their power density. Table 4 shows specification of induction and PM synchronous machines for electric vehicles (EVs) manufactured by Siemens, Germany, which can operate both as motors and generators. Table 5 shows motor-generators of similar applications manufactured by UQM Technologies, Frederick, CO, U.S.A. Motors shown in Table 4 and Fig. 12a are fed from liqiud cooled dual inverters (two machines per one inverter, 10 kHz switching frequency). Motors shown in Table 5 and Fig. 12b are fed from liquid cooled IGBT PWM inverters with switching frequency of 20 kHz.

Control

The control system is responsible for governing the operation of the electric motor driven vehicle. The control system receives inputs from the operator, feedback signals from the motor controller and the motor, and also feedback signals from other systems within the vehicle. The speed at which the control system must receive data from other systems, process the data in an algorithm and output a response to the given conditions must be accomplished in milliseconds. This requires the control system to have a microprocessor. For example, if the temperature of the windings of the motor gets too hot, the control system can limit the output of the motor by feeding a signal back to the microprocessor.

In battery operated EVs the controller is the device which operates between the batteries and the motor to control speed and acceleration. The controller transforms the battery's d.c. current into a.c. for the IM or PMBM or simply regulates current flow for d.c. motors. The controller can also reverse the field coils of the motor so that when in a braking mode, the motor becomes a generator and energy is put back into the batteries. This is known as regenerative braking and over the course of a single charge can return as high as 10% or more of the energy consumed by the drive system to the batteries.

The type of control depends on the motor and drive requirements. In PMBMs, the drive can be operated at higher speed than the rated speed of the motor by reducing the excitation flux to maintain a constant voltage and constant power (Fig. 1). The magnetic flux in the d-axis is weakened by injecting a negative (demagnetising) component of the d-axis current.

The analysis of the flux weakening (FW) region can be performed using the circle diagram plotted in the $i_q - i_d$ coordinate system [18, 21]. The current limit (rated current locus) is represented by the circle, the voltage limit (rated voltage loci) by ellipses, and the constant torque loci (τ) by hyperbolas, as plotted in Fig. 14. Operation at base speed corresponds to the point B. The base speed is the speed at which the voltage reaches its nominal value and separates the constant torque region and FW region. The FW operation is achieved by imposing a proper demagnetising *d*-axis current to keep the current and voltage within their limits at any speed. The drive works at rated current with operating speed $\omega = 2$ or $\omega = 4$, indicated by points R and S, at torque t = 0,613 and t = 0,202 respectively.

Electromechanical drive systems

LRTs and guided transit systems

Modern LRTs and guided transit systems use inverter-fed cage IMs (Table 6). Dc commutator motors are used in older systems, e.g., Sapporo (Japan) rubber tire wheel subway trains (lines opened in 1976). Some urban trains, e.g. , Sky Train in Vancouver (Canada), subway Toei Line No. 12 in Tokyo (Japan), subway Line No. 7 in Osaka (Japan), and advanced LRT in Kuala Lumpur (Malaysia), use LIMs. There are 2 LIMs (100 to 120 kW) per car.

Table 4: Liquid cooled electric motors and generators manufactured by Siemens, Germany

Type	AC Induction Machines		PM Synchronous Machines		
Cooling Media:	water/glycol mixture				
Rated voltage dc, V:	650				
Rated power, kW	67	85	85 kW at 2500 rpm	120 kW at 4000 rpm	200 kW at 7200 rpm
Rated torque, Nm	160	220	320	320	600
Max. torque, Nm	360	450	450	450	1200
Rated current, A	124	142	170	170	265
Max. speed, rpm	10,000	9,000	4,000	4,000	8,000 rpm
Mass, kg	90	120	120	120	200
Power density, kW/kg	0.74	0.71	0.71	1.0	1.0
Dimensions LxWxH, mm	425x245x245	510x245x245	560x245x245	560x245x245	not specified
Ambient temperature °C	– 30 °C to 70 °C				
Degree of Protection:	IP 65 / 9k				

Table 5: Liquid cooled electric motors for EVs and HEVs manufactured by UQM Technologies, Frederick, CO,U.S.A.

Type	HighTor 35	Caliber EV53	PowerPhase100
Cooling Media:	50.50 water-glycol mixture		
Rated voltage dc, V:	250 to 400		
Rated continuous power, kW	23.5	30	55
Peak power, kW	35	53	100
Rated continuous torque, Nm	150		200
Peak torque, Nm	380	240	550
Max. speed, rpm	4500	8000	4400
Maximum efficiency, %	90	94	90
Mass, kg	40		86
Power density, kW/kg	0.59	0.75	0.64
Diameter, mm	280		372
Length, mm	216		362

PMBMs are recommended for direct (gearless) electromechanical LRT drives. The most important advantages of LRTs with gearless electromechanical drives over geared drives are [13]: (a) the gravity center of the bogie is lowered, (b) the wheel diameter is reduced as motors are removed from the trolleys and gearboxes are eliminated, (c) it is easy to design a steerable bogie for negotiating sharp curves, (d) gearless electromechanical drives require a limited maintenance (no oil), (e) the noise is reduced. Fig. 15 shows a PMBM wheel of a street car [6] and Fig. 16 shows a PMBM for light traction developed by RTRI, Kokobunji, Japan [17]. A modern three-phase induction motor for LRTs is shown in Fig. 17. A typical low-level floor LRT (tramway) is shown in Fig. 18.

Hybrid electric vehicles

Hybrid electric vehicles (HEVs) are now at the forefront of transportation technology development. HEVs combine the internal combustion engine of a conventional vehicle with the electric motor of an EV, resulting in twice the fuel economy of conventional vehicles. The electric motor is usually located between the combustion engine and clutch. One end of the rotor shaft of the electric motor is bolted to the combustion engine crankshaft, while the opposite end can be bolted to the flywheel or gearbox via clutch. The electric motor serves a number of functions, i.e.:

– assisting in vehicle propulsion when needed, allowing the use of a smaller internal combustion engine;
– operating as a generator, allowing excess energy (during braking) to be used to recharge the battery;
– replacing the conventional alternator, providing energy that

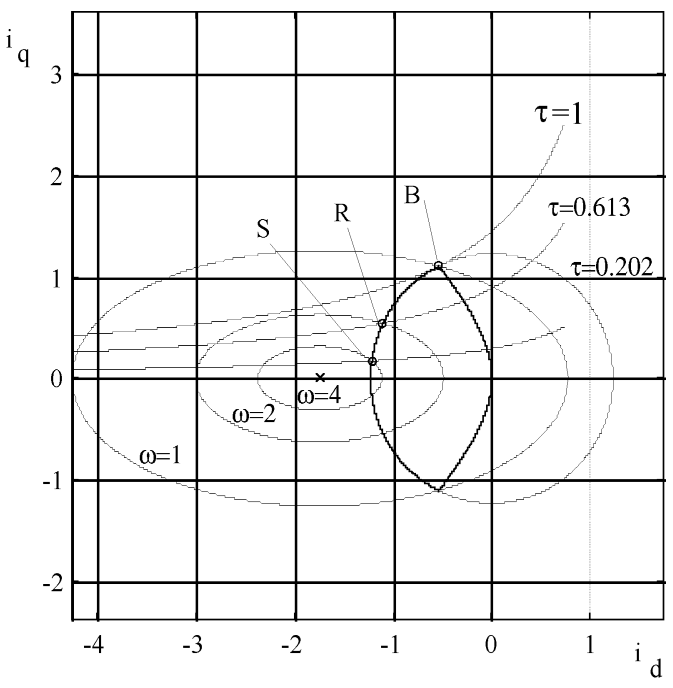


Fig. 14: Circle diagram for analysis of the flux weakening (FW) region

Table 6 :Examples of applications of three-phase induction motor to LRTs (Elin EBG Traction GmbH, Vienna, Austria)

Application	Design	Motor type	Technical data
Vienna Metro type U11	Axle driven. Helical gear-box with quill shaft and cardan coupling	3-phase induction motor MCF-425 V06 Z9Z Water jacket cooling	125 kW, S2-1h 1230 rpm nom. 3846 rpm max 3×470 V
Low-floor tram Ulf	Suspended single wheel drive with a standing motor-gearbox unit	3-phase induction motor MCF-420 Z04 Z9Z-9 Water jacket cooling	80 kW S2 60 kW S1 4300 rpm max. 3×380 V
Tram Rome	Axle driven. Helical gear-box with quill shaft and driving flange	3-phase induction motor MCF-022 U04 Z9Z Air-cooling	120 kW, S1 2285 rpm nom. 4280 rpm max. 3×425 V
Tram Cityrunner Linz	Axle driven. Bevel helical gearbox	3-phase induction motor MCF-022 U04 Z9Z Air-cooling	100 kW, S1 1680 rpm nom. 5000 rpm max. 3×371 V
LRT Badner Bahn	Axle driven. Helical gear-box with quill shaft and driving flange	3-phase induction motor MCF-020 Z04 Z9B-9 Water jacket cooling	105 kW 2369 rpm nom. 5135 rpm max. 3×597 V
Tram Lodz refurbishment	Axle driven	3-phase induction motor MCF-018 S06.9 Air-cooling	61 kW, S1 1634 rpm nom. 4435 rpm max. 3×387 V
Motorcoach class 4090	Axle driven. Two-stage helical gear-box with hollow shaft and driving flange	3-phase induction motor DAM 80 Water jacket cooling	68/80 kW 1340 rpm nom 4520 rpm max. 3×500 V

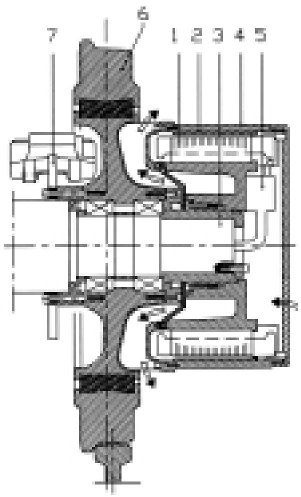


Fig. 15: Gearless motorwheel for a street car with PMBM: 1 – stator, 2 – external rotor with PMs, 3 – axle of the wheel, 4 – rotor enclosure, 5 – terminal board, 6 – rim of the wheel 7 – brake [6]

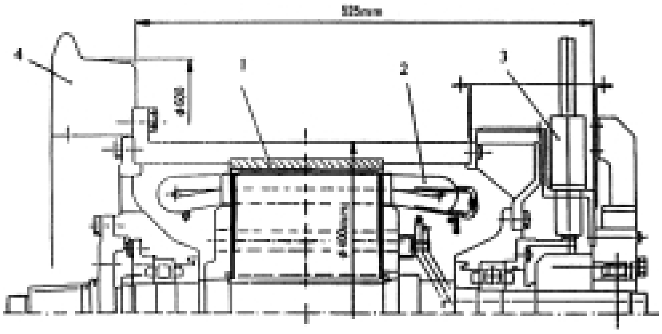


Fig. 16: PMBM rated at 80 kW for light electric train developed by RTRI, Kokubunji, Japan: 1 – surface PMs, 2 - internal stator 3 – position sensors, 4 – wheel [17]

Fig. 17: Modern three-phase IM manufactured by Elin EBG Traction GmbH

Fig. 18: Low-level floor LRT manufactured by LRT Bombardier Transportation

ultimately feeds the conventional low voltage, e.g., 12 V electrical system;
– starting the internal combustion engine very quickly and quietly that allows the internal combustion engine to be turned off when not needed, without any delay in restarting on demand.
– damping crankshaft speed variations, leading to smoother idle.

Hybrid electric buses

A hybrid electric bus with low floor may have electric motors integrated in each of its four driven wheels (Fig. 19). The propulsion system components included in the hybrid transit bus are brushless motors (IM, PMBM, SRM or TFM) to supply or accept power from the wheels, power electronics converters, a battery for energy storage, and the auxiliary power unit consisting of a diesel engine, alternator, rectifier and associated control. Specification of electric buses including hybrid buses are given in Table 7 Batteries for hybrid electric buses are usually flooded lead acid (PbA), nickel-cadmium (NiCd) and nickel hydrate (NiMH) batteries.

Hybrid electric gasoline cars

The electric motor, e.g., PMBM assists the gasoline engine in the low speed range by utilizing the high torque of electric motor, as shown in Fig. 20. The PMBM can increase the overall torque by over 50% [1]. Currently manufactured hybrid electric gasoline cars (Fig. 21) are equipped either with IMs or PMBMs. In most applications, the rated power of electric motors is from 10 to 75 kW (Table 8). From cost minimization point of view, application of sintered NdFeB PM motors is economically justified not only for small electric cars and scooters, but also for larger HEVs, including buses. PMBMs, PMBMSCSs, and PM TFMs are the highest efficiency motors. Frequently, the electric motor is integrated with power electronics converter (Fig. 22).

Solar-powered racing electric cars employ two disc type ironless motors (Fig. 11) mounted on (or in) the rear wheels, similar to Fig. 10. To win the race, a car needs to convert the maximum amount of solar energy, and use this energy well [14, 19, 20]. The

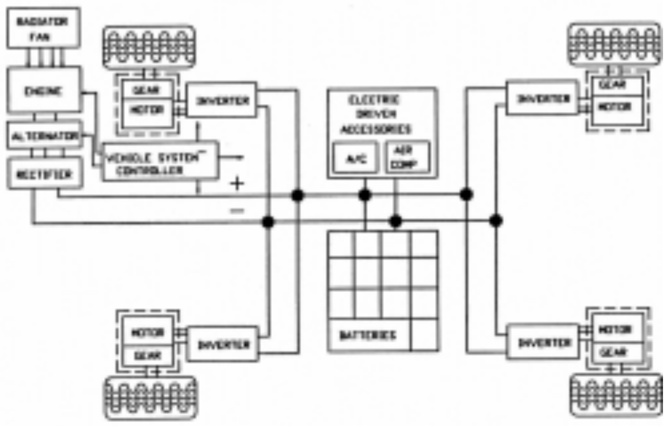


Fig. 19: Hybrid bus drive system with a.c. motors and reduction gears integrated into each of its four driven wheels [13]

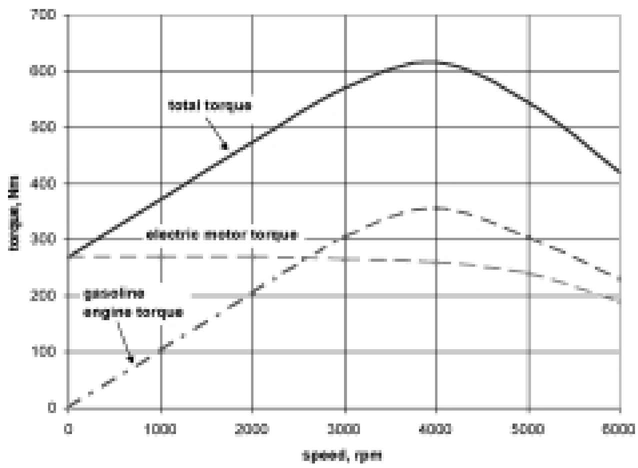


Fig. 20. Torque-speed characteristics of an electric motor and gasoline engine. The electric motor assists the gasoline engine at low speeds.

Table 7: Fuel cell, electric and hybrid electric buses

Make	Curb mass kg	Number of passengers	Combustion engine	Electric motor	Battery	Range km	Maximum speed km/h	Manufacturer
Nova Fuel Cell		47	N/A	a.c. ind. 170 kW	PbA	560+	88	Nova Bus www.novabus.com
ZEbus Ballard Fuel Cell		70	N/A	PM brushless 186 kW	PbA	250	120	Ballard PS www.ballard.com
AVS-22 electric	6580	22	N/A	a.c. ind. 140 kW	PbA	70 to 105		AVS www.avs.com
Trolley/Shuttle electric	6580	19 to 22	N/A	a.c. ind	PbA/NiCd	80 to 160	64	Ebus www.ebus.com
EVF22 electric	5450	22	N/A	a.c. ind	PbA 350 Ah	95	72	EVI-USA www.evi-usa.com
30C-LF CNG hybrid	8500	26	2500 cc Ford CNG	2x48 kW				NABI www.nabiusa.com
D40i hybrid		44	3700 cc 6 cylinders	2x75 kW	PbA		95	New Flyer www.newflyer.com
RTS hybrid	13,620	47	Diesel	a.c. ind. 170 kW	PbA	560	84	Nova Bus www.novabus.com
30’-40’ ThunderVolt hybrid		22	5900 cc Diesel	Siemens a.c. ind. 2x85 kW	PbA, NiMH, Li-Polymer	240 to 480	105 to 120	ISE Research Corporation www.isecorp.com
Orion VII hybrid		42	5900 cc Diesel	a.c. ind. 186 kW	PbA		100	Orions Bus Ind. www.orion.com

Table 8: Hybrid electric gasoline cars

Make	Mass kg	Number of passengers	Combustion engine	Electric motor	Battery	Range km	Max. Speed km/h
Nissan Tino	1500	5	4 -cylinder	75kW PMBM	Li-Ion	1145	180
Honda Insight	840	2	3-cylinder 50 kW	10kW PMBM	NiMH		
Honda Civic	1240	4	4-cylinder	63kW PMBM	NiMH		
Toyota Prius	1255	5	4-cylinder 52 kW	33kW PMBM	NiMH	965	160
Ford Escape	1425	4 to 5	4-cylinder 95 kW	65kW PMBM	NiMH	720 to 885	

Table 9: PMBM for eCycle hybrid motorcycle manufactured by ECycle Incorporated, Reading, PA, U.S.A.

	MG13	MG18	MG24	MG30	MG36	MG48	MG62	MG93	MG120
Torque constant, Nm/A	0.13	0.18	0.24	0.30	0.36	0.48	0.62	0.93	1.2
EMF constant, V/krpm	13.5	19.0	25.5	31.8	38.3	51.5	65	97	25
Inductance, μH	33	68	132	202	290	500	900	2000	3500
Resistance, Ω	0.024	0.070	0.074	0.11	0.154	0.29	0.44	1.0	1.7
Max. continuous current, A	100	60	57	47	40	29	24	11	6

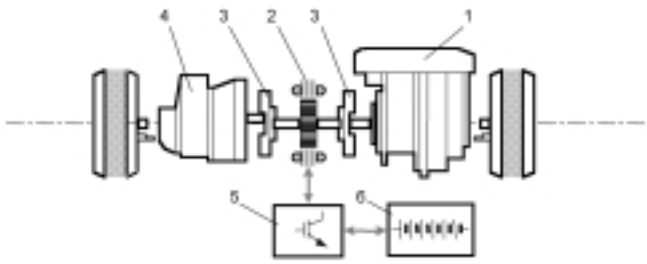
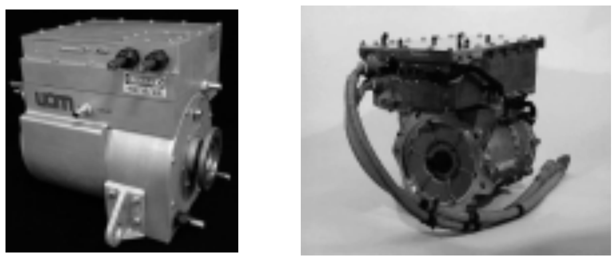


Fig. 21. Hybrid electric gasoline car: 1 – gasoline combustion engine, 2 – integrated motor-generator, 3 – cranking clutch, 4 – gearbox, 5 – inverter, 6 – battery.



(a) (b)

Fig. 22: Liquid cooled integrated PM brushless motor-inverter systems: (a) INTETS‘ manufactured by UQM Technologies, Frederick, CO, U.S.A (b) Hitachi, Japan.

motor must meet two basical requirements: very low mass and very high efficiency. For example, specifications of discs motors with Halbach array of PMs (40 poles) used in Aurora cars (Australia) are as follows: mass of frameless motor 7.7 kg, rated speed 1060 rpm, rated torque 16.2 Nm, maximum continuous torque 39 Nm at 1060 rpm, efficiency 98.2% [20].

Hybrid electric motorcycles

The hybrid electric motorcycle (Fig. 23 a) uses the MG24 PMBM with a special housing in its drive train. This is a 3-phase, motor rated at 5 kW continuous and 15 kW peak power (Table 9). In the hybrid motorcycle, the motor sees up to $120V_{dc}$ with a peak current of 70 A. The stator is made from electrical steel laminations and wound with insulated copper wire. The rotor is made from a one-piece, precision machined, steel casting and has twelve NdFeB PMs (service temperature up to 180°C) mounted on its circumference (Fig. 23 b). The magnets are retained with a stainless steel band and the rotor is balanced prior to assembly. Speeds up to 10,000rpm are possible at the appropriate voltage. The motor/generator is greater than 94% efficient under some circumstances.

Electric vehicles

EVs do not have any combustion engine. The propulsion system consists solely of electrical motor fed from a battery. Battery is charged from power utility system, when the vehicle is not used, usually at nightime. Table 10 shows specifications of electric cars. The most promising near-term replacement for the PbA battery appears to be NiMH battery. Specific energy of a NiMH battery is about double that of a PbA battery.

Electric scooters

In electric scooters brush type d.c. motors, SRMs and PMBMs have been used so far. In most cases, geared electric motors drive the rear wheel with the aid of belt or chain gear.

The best scooter on European market is Peugeot Scoot Elec (Fig. 24) powered by a 16-V 2,8-kW peak power, 2100 rpm dc separately excited brush type motor (Fig. 24 b). Peugeot Scoot Elec uses three NiCd batteries (Fig. 24 c). A full charge takes five hours. The battery is at 95 % capacity within two hours and will absorb enough energy to cover around 5 km after just ten minutes. Typical maximum range is 45 km at 50 km/h speed.

The Lectra scooter manufactured by EMB, Sebastopol, CA, U.S.A., uses geared SRM with peak torque 10.8 Nm (54.2 Nm after reduction) and maximum speed 15, 800 rpm.

The Lepton scooter (Fig 25 a) made in Italy uses a PMBM with embedded PMs (Fig. 25 b). The maximum output power is 2.0 kW and continuous power 1.0 kW. The capacity of a 48-V PbA battery is 38 Ah and recharge time 6 h. The top speed is 40 km/h and a)

b)

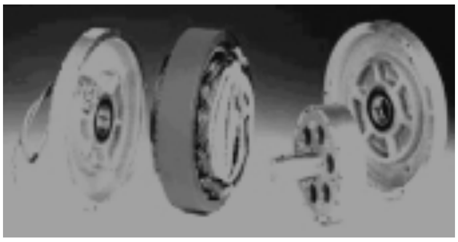


Fig. 23: a) Hybrid electric motorcycle manufactured by eCycle Incorporated, Reading, PA, U.S.A; b) MG PMBM for eCycle hybrid electric motorcycle

a)

b)

c)

d)

Fig. 24: Peugeot electric scooter and electromechanical drive components (a) Peugeot electric scooter; (b) d.c. brush type motor; (c) NdCd batteries, (d) driving gear.

Table 10: Specifications of electric cars

Make and model	Battery type	Motor kW	Speed power km/h	Driving range, km	Payload kg	Charging system
Honda EV Plus, 1999	NiMH	49	130+	95 to 130	320	Conductive
DymlerChrysler Electric Minivan, 1999	NiMH	75	130	130 to 145	360	Conductive
Ford Ranger EV pickup track, 1999	PbA NiMH	67	120	80 to 130	295 to 565	Conductive
GM Chevrolet S10 pickup track, 1998	PbA NiMH	85	110	65 to 130	360 to 430	Inductive
Nissan Altra EV 1998/2000	Lithium-ion	62	120	130 to 160	370	Inductive
Solectria Force 1999	NiCd/NiMH	42	105	135 to 160	350 to 410	Conductive
Toyota RAV4-EV, 1999	NiMH	50	125	200	355	Inductive

range up to 32 km. One of the fundamental parameters which determine the goodness of the motor is the amount of absorbed current: its peak value should be limited not to damage the battery and to obtain a convenient discharge curve of the battery[3].

Electric bicycles

Electric bicycles are ideal for commuting or adventure cycling. Electric motors assist on long rides, hills or just short rests. Electric bicycles use direct electromechanical drives, PMBMs with pulse width modulated controllers, and have built-in free-wheeling, so when a rider is just pedaling, there is no drive-train lag. PMBMs are usually rated at 150 to 300 W and fed from 24 to 42 V battery. The speed of electric bicycles is up to 25 km/h and the range is about 20 km. Electric bicycles with hub motor are shown in Fig. 26.

The design of a front wheel mounted PMBM with external rotor is shown in Fig. 27. Powder magnetic materials and ferrite PMs offer a low cost brushless motor. The stator winding pole pitch is equal to one slot pitch (PMBMSCS, see also Fig. 2). Larger (1kW, 30 Nm) PMBM for electric bicycles or tricycles is shown in Fig. 28. The motor efficiency: 87 to 95%, diameter 190 mm, thickness 76 mm and mass 5.4 kg.

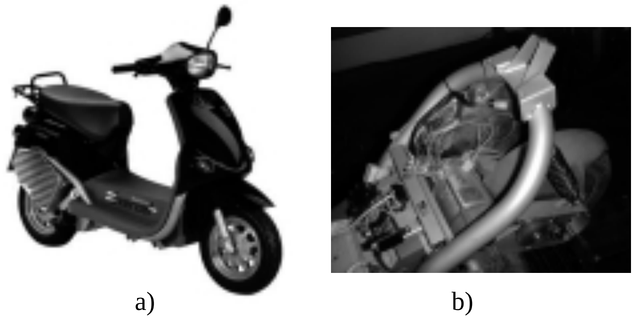
Gearless elevator propulsion system

Modern elevators use gearless propulsion systems. The concept of gearless electromechanical drive for elevators was first introduced in 1992 by Kone Corporation in Hyvinkää, Finland [15]. With the aid of a disc type low speed compact PMBM Ecodisk™, the penthouse machinery room can be replaced by a space-saving direct electromechanical drive. In comparison with a low speed axial flux cage IM of similar diameter, the PMBM has much shorter stator stack, double the efficiency and three times higher power factor. Specifications of Kone PMBMs of disc construction are shown in Table 11.

Fig. 29 a shows a single-sided disc PMBM for hoist applications. In the case of elevators, the disc-type motor is installed between the guide rails of the car and the hoistway wall [10,15]. Fig. 29 b shows the propulsion system of the Kone gearless elevator. A similar elevator motor and propulsion system as Ecodisk™ has recently been developed by Mitsubishi Electric, Japan.

Conclusions

A growing interest in road EVs, LRTs and guided transit systems stimulates research efforts oriented towards innovative solutions



a) b)

Fig. 25: a) Lepton electric scooter; b) PMBM and driving mechanism of Lepton scooter

(a) (b)

Fig. 26: Electric bicycles with (a) front hub motor; (b) rear hub motor

Table 11: Specifications of single-sided PM disc brushless motors for gearless elevators manufactured by Kone, Hyvinkää, Finland

Specifications	MX05	MX06	MX10	MX18
Rated output power, kW	2.8	3.7	6.7	46.0
Rated torque, Nm	240	360	800	1800
Rated speed, rpm	113	96	80	235
Rated current, A	7.7	10	18	138
Efficiency	0.83	0.85	0.86	0.92
Power factor	0.9	0.9	0.91	0.92
Cooling	natural	natural	natural	forced
Diameter of sheave, m	0.34	0.40	0.48	0.65
Elevator load, kg	480	630	1000	1800
Elevator speed, m/s	1	1	1	4
Location	hoistway	hoistway	hoistway	machine room

to electromechanical traction drives and new types of electric motors.

NdFeB PMBMs including PMBMSCS and TFMs are the highest power density and efficiency traction motors. The only drawback from manufacturing point of view is their higher cost as compared with IMs.

SRMs and TFMs have a potential to compete with standard PMBMs and PMBMSCS. On the other hand, the SRM and TFM technology is still not mature.

Industrial production of PMs, after declining worldwide in 2001, is now growing again. In connection with high demand on EVs, this is a symptom that traction motor sector will become soon the most dynamic sector in the motion control industry.

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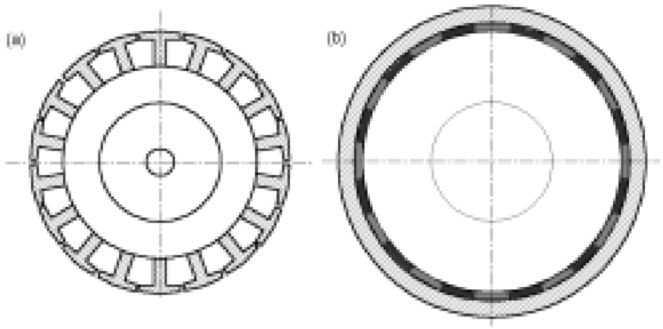
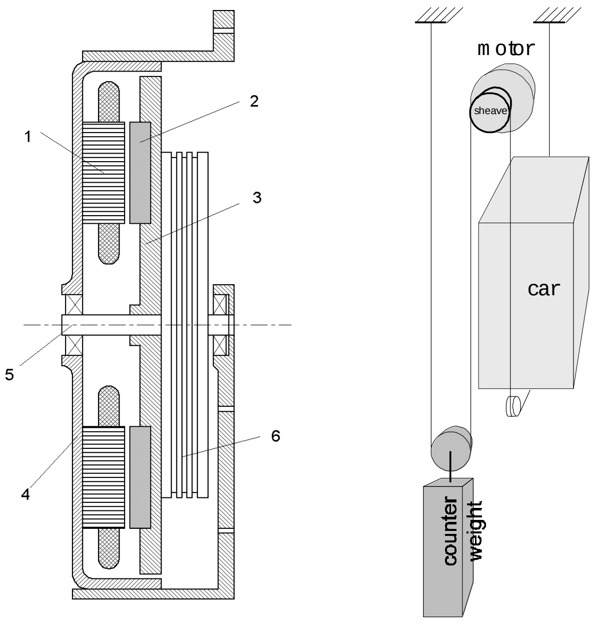


Fig. 27: PMBP for electric bike: (a) stator; (b) external rotor (Höganäs AB, Sweden)

Fig. 28: 1-kW, 470-rpm, 30-Nm PMBM for electric bicycle manufactured by Electric Bike System, Inc., Camarillo, CA, U.S.A.



a) b)

Fig. 29: a) Single sided disc PMBM for hoist applications: 1- stator, 2 - PM, 3 - rotor, 4 - frame, 5 - shaft, 6 – sheave; b) Propulsion system of Kone MonoSpace™ elevator

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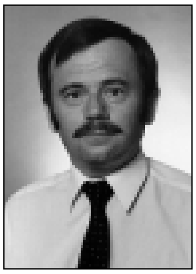

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