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A SURVEY ON PERMANENT MAGNET SYNCHRONOUS MACHINES: RECENT APPLICATIONS AND TRENDS

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Abstract

Nowadays, the development of technology for the design and manufacture of high-performance electro-motors and their use instead of current electric motors used in household, commercial and industrial sectors has been considered by engineers and industrial researchers. In recent years and especially in recent decades, Permanent magnet motors are preferred over direct-current and induction motors in many speed-varying industrial applications for low and medium power range, due to their inherent characteristics such as high energy density, high power, low inertia, low volume, and high power factor and efficiency. The inherent high efficiency of permanent magnet synchronous machines (PMSM) makes it an alternative to induction machines.

Keyword: Permanent Magnet, Synchronous Motor, Application

1. INTRODUCTION

In the PMSM, by creating a sinusoidal distribution for conductors at the stator surface, the airgap's flux density is closer to the sinus form [1]. By replacing the field's winding with a permanent magnet, the brushes, slip-rings, and copper losses could be removed from synchronous motor. The permanent magnet generates motors with permanent excitation. Fig. 1, shows two different ways in which permanent magnets are put into rotor [2, 3, 4].

The following figure shows the ratio of magnetic torque to reluctance torque in synchronous machines. Regarding the mechanism of torque producing, synchronous machines are divided into three distinct groups. The surface-PMSM (SPMSM), in which arc-shaped permanent magnets are embedded on the surface of cylindrical rotor (Fig. 2 a). Such machine is a complete PMSM which produces only magnetic torque. Synchronous reluctance machine (synRM) is a pure reluctance machine shown in Fig. 2. f. The inset SPMSM (Fig. 2. b) belongs to SPMSM category in terms of magnet arrangement, however it is a combined reluctance-magnetic motor because of its magnetic saliency. Interior PMSM (IPMSM) in which permanent magnets are buried inside the rotor (Fig. 2. c, d, and e) has magnetic saliency, so it is a hybrid reluctance-magnetic motor which can be considered as a PMSM motor regarding its reluctance torque (region II) or a synRM motor regarding its magnetic torque (region III) [5, 6].

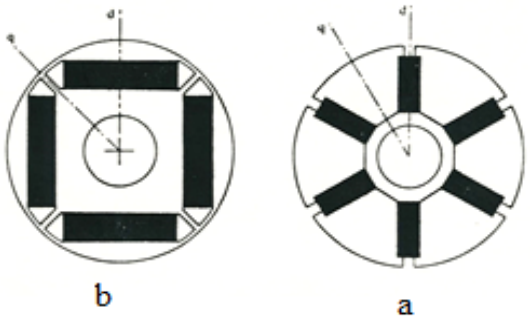

Fig. 1. PMSM WITH INTERIOR ROTOR MAGNET,a) RADIAL MAGNET, b) PERIPHERAL MAGNET

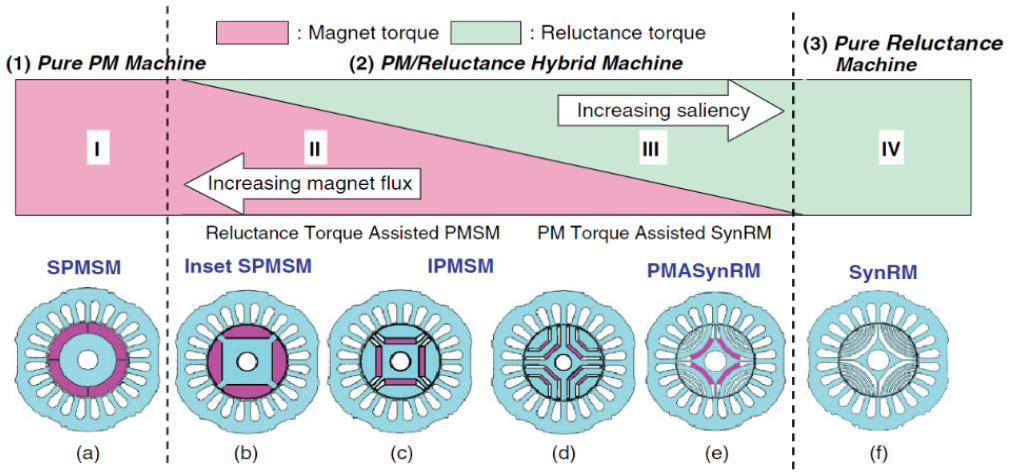

Fig. 2. THE CLASSIFICATION OF SYNCHRONOUS MACHINES IN TERMS OF THE MECHANISM OF TORQUE PRODUCTION

In order to increase the efficiency, stator structures could be investigated. The stator with concentrated windings and the space factor improvement with divided stator core can be used. Fig. 3, shows the IPMSM with concentrated windings [7, 8].

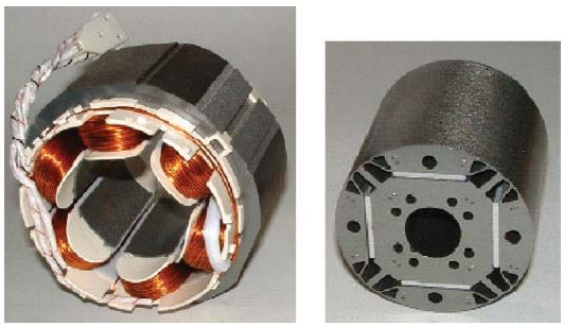

Fig. 3. THE IPMSM MOTOR WITH CONCENTRATED WINDINGS

Concentrated winding instead of distributed winding has been considered in many home applications recently. Distributed windings are commonly used in high power applications including electric vehicles (EV), combined electric vehicles (HEV), and traction motors.

2. THE APPLICATIONS OF PMSM

The application of the PMSM in factory automation, compressors, and vehicles has progressed dramatically with the development of magnetic materials with high coercivity that can withstand extreme temperatures and magnetic fields. Mass production of the PMSM for a compressor engine began in 1982. Since then, the cheap ferrite magnet was used in PMSM. The IPMSM with permanent NdFeB magnet was mass produced in 1996. The development of permanent magnet materials with high magnetic remnant flux density and magnetic coercivity is a matter of ongoing progress.

3. THE APPLICATION AS ELECTRIC VEHICLE

During the last decade, economic, functional and dimensional factors have caused an increasing attention to the study of electric motors in electric vehicles. It is anticipated that by the end of 2020 global demand for electric transport engines will increase from the current 4.5 million to 8 million. Japan is the largest manufacturer of traction engines with 58 percent of the world's total market. After Japan, the United States is the second largest producer with 19% of the world market. Europe and China are in the next positions. It is expected that China will produce 75KW EV motors. PMSMs are expected to have a major market share, while other motor technologies have less than 5% market share [9].

3.1. Favorable characteristics for a high-speed EV motor

The most suitable electric motor for EV traction should have high reliability, high efficiency, low size, weight, and cost, low temperature increase, error resistivity, high torque and power density. An EV engine should be capable of delivering high power and torque at low speeds for start, as well as high power with a high density at high speeds. The engine must also have a wide range of constant power at varying speed, as well as high torque in the constant torque region. In addition, high efficiency is required for wide ranges of speed and torque as well as for regenerating brake [10].

4. REVIEW OF EV PRODUCTS

A large number of commercially available EVs are fed either with PMSM or induction machines, and most of them are axial flux type. Depending on the size and design of the vehicle, their maximum power is between 45kW and 400kW. The HEV has a motor between 15 kW and 110 kW, depending on the design and the hybrid level of the device. These engines generally produce, at least, a torque between 180 and 450 Nm, with a maximum speed of between 4500 and 13500 rpm.
Nissan uses its 80kV PMSM engine in its all-electric car called the Leaf, with a torque of 280 Nm and a constant power of up to 10390 rpm [11]. The machine has 48 slots, 8 poles where the stator's exterior diameter, the interior diameter of rotor, and the motor length are 199 mm, 130 mm, and 151 mm, respectively. The Mitsubishi i-MiEV has a 47-kW PMSM engine with a torque of 180 Nm [12]. The Chevy Volt hybrid electric vehicle has a PMSM motor of 110 kW, 9,500 RPM, and 12 Poles, as well as a PMSM 55 kW, 6000 RPM, 16 poles generator which can produce a torque of 370 and 200 Nm, respectively. Both types of machines are IPMSM that lead to agility of the rotor and improvement of torque density [13]. The hybrid Toyota Prius has several versions, each of which has IPMSM machines of varying power. Toyota is continually improving the performance of traction cars with an output power of 50kW and 60kW in their 2004 and 2010 versions. The rated torque and speed of these models are 400Nm and 207 Nm, 6000 rpm and 13500 rpm, respectively. Honda and Hyundai hybrid cars focus on both surface and interior PM machines. Honda has produced a high efficiency PMSM with pancake-shaped interior magnets with a power output of 15.5 kW for the Civic hybrid car [11, 14, 15].
In general, the PMSM machine has been used globally for hybrid and electric vehicles:

BYD e6, Citroen C-Zero, Ford Escape Hybrid, Ford Fusion Hybrid, Honda Accord Plug-in, Mitsubishi i-MiEV, Nissan Leaf, Peugeot iOn, Toyota Prius, Volvo C30, Fiat 500e.

For example, the two companies, Siemens and Volvo, produced the second generation Volvo C30 electric motor with IVETEC MRS 7701 Siemens engine (Fig. 4)

Fig. 4. THE IVETEC MRS 7701 ENGINE FOR VOLVO C30.

The Bosch Company has also built the SMG 180/120 engine with the power of 80kW for the Fiat 500e.

5. APPLICATION AS TRACTION MOTOR

In the Fig. 5, a roadmap for the technology of traction motors extracted from the roadmap for replacing critical raw materials in the EU by 2020, has been provided [16].

4.1. The prototype manufactured by Toshiba for electric train

Since 1990, Toshiba has begun manufacturing PMSM engines for railway cars. PMSM advantages such as energy saving, noise reduction, less and easier maintenance, and etc. are approved with customer service pilot tests. PMSM systems have been used to mass production of trains and metro systems, and in this way they are introduced to the global market. The Toshiba Roadmap for developing railway systems with PMSM is shown in Fig. 6.
The Tokyo Metro Company has been equipped with Toshiba's PMSM system since 2007, and its economic exploitation has begun. Japan Freight Railway Company is also equipped with hybrid locomotives and a mass production system is under construction.

6. PMSM APPLICATION IN THE ELEVATOR OF HIGH-RISE BUILDINGS

Nowadays, different elevator technologies are put in service in high-rise buildings. In 1995 KONE introduced PMSM technology in the low rise volume market with its revolutionary MonoSpace. The small EcoDisc machine allowed the complete elimination of the machine room, as it fitted in the hoist way. Gearless EcoDisc (Fig. 7) technology reduces the energy consumption by some 50 to 60% compared to conventional geared and hydraulic installations.

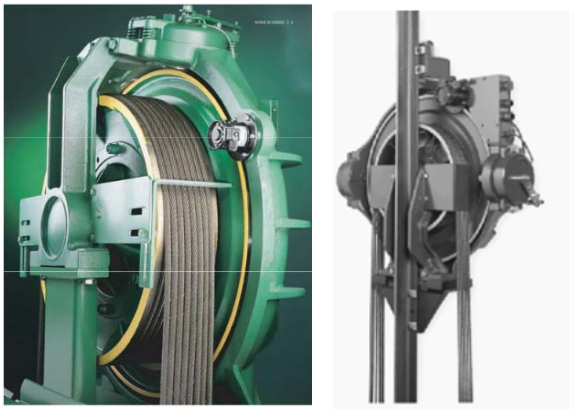

Fig. 7. ECODISC [10]

KONE has now made gearless Permanent Magnet Synchronous Motor (PMSM) technology economically feasible throughout the complete load speed range. From the smallest and slowest elevator required up to the biggest and fastest. PMSM motors are extremely efficient reducing energy consumption to an absolute minimum [17,18].

In Table 1, mass-produced PMSM manufacturers and their product specifications for use in elevators are presented.

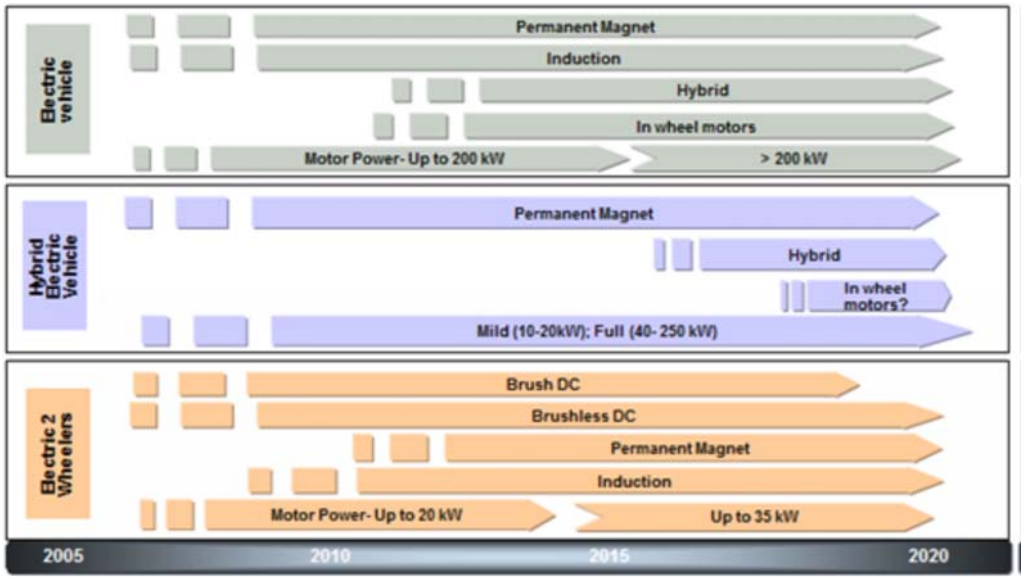

Fig. 5. TRACTION MOTOR TECHNOLOGY ROADMAP TILL 2020

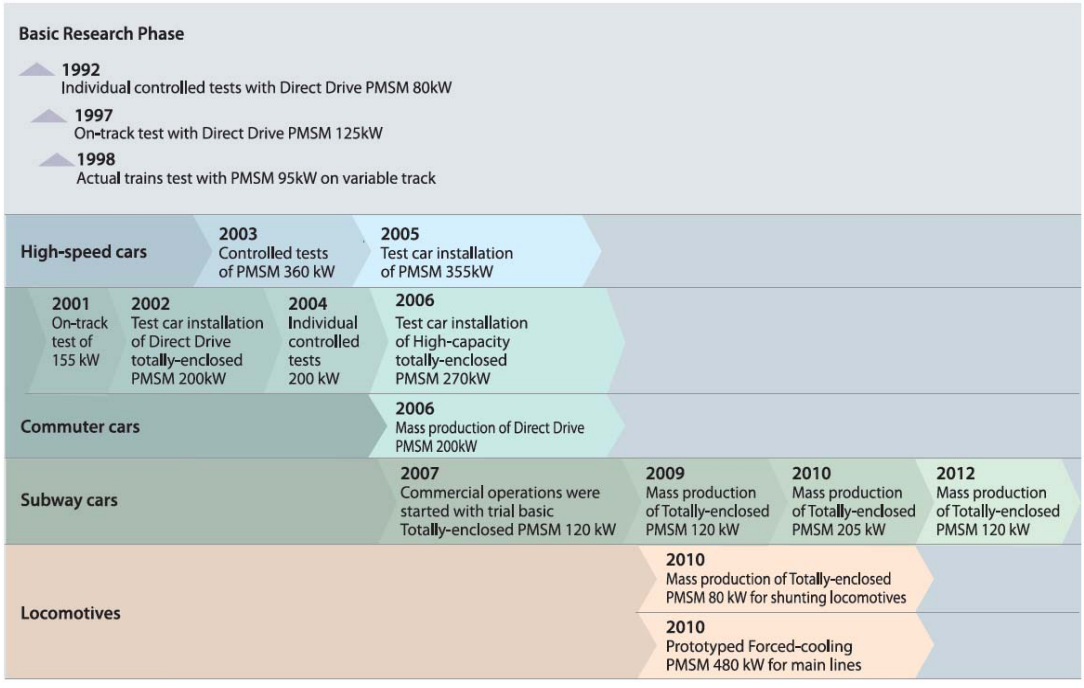

Fig. 6. TOSHIBA ROADMAP FOR DEVELOPING RAILWAY SYSTEMS WITH PMSM

TABLE. 1. PMSM MANUFACTURERS FOR ELEVATORAPPLICATION

company	country	Motor's commercial name	specifications	reference
Bharat Bijlee	India	GreenStar	230 volt 5-20 passengers 0.5-1.5 m/s	*https://www.bharatbijlee.com*
YASKAWA	japan	L1000A	16 passengers	*https://www.yaskawa.com*
EL+MO	India	-	18 and 24 poles	www.elmomc.com
Shenyang Bluelight	china	WYT-L	AC380V 320kg～1050kg 0.5m/s～2.0m/s 20 poles 2.44/1.22A	*en.sylg.cn*
Shenyang Bluelight	china	WYT-H	AC380V 1600kg 3m/s～8m/s 30 poles	*en.sylg.cn*
Toshiba	japan	SPACEL-Ⅲ	8-26 passengers 630-2000 Kg 1-2 m/s for 1050 Kg 6 KW compared to 7.5 KW conventional elevators	*www.toshiba.com*
Suzhou Dazen Electromechanical Technology Co.	china	-	380V 0.5-3m/s 450-1600kg 5-70A	*www.dazenelevator.com/*
Imperial Electric	England	400-500-LS-800 Series	1,250 to 8,000 lbs. 100 to 1,400 fpm (feet per minute).	*www.imperialelectric.com*
Lafert	italy	LIFT	driving torque range 140 to 900Nm for payload 240 to 1600kg	www.lafert.com/
WELLIFT	china	V8	400kg - 1600kg 0.5m/S - 4.0m/S 1000-10000 $	*www.wellift.com*

7. SERVOMOTOR APPLICATION OF PMSM

The PMSM is utilized in various control applications in industry, such as roller or conveyor belt in automatic cutting machines, spaghetti making machine, offset press system, frames and panels coverage system, and etc. (Fig. 8). The main reasons for this application are low maintenance, synchronization of the axes, stable speed without vibration, small drive size, high controllability, and etc.

Bonfigioli and Mitsubishi are the most prominent companies in this field. Bonfigioli has been manufacturing PMSM since 1976, claiming it is ideal for automatic machines for applications requiring highest standards in terms of dynamics, precision, robustness, durability, and long trouble-free operation. Bonfigioli has been manufacturing PMSM since 1976, claiming it is ideal for automatic machines for applications with high dynamic requirements, particularly suited to typical applications in plastic and metal machining, packaging, food and beverage processing, winding and textile industries.

8. MAJOR CONTRIBUTORS IN PMSM INDUSTRY

Japan's MEIDENSHA Company produces PMSM products with the specifications mentioned in Fig. 9, which are categorized depending on their application.

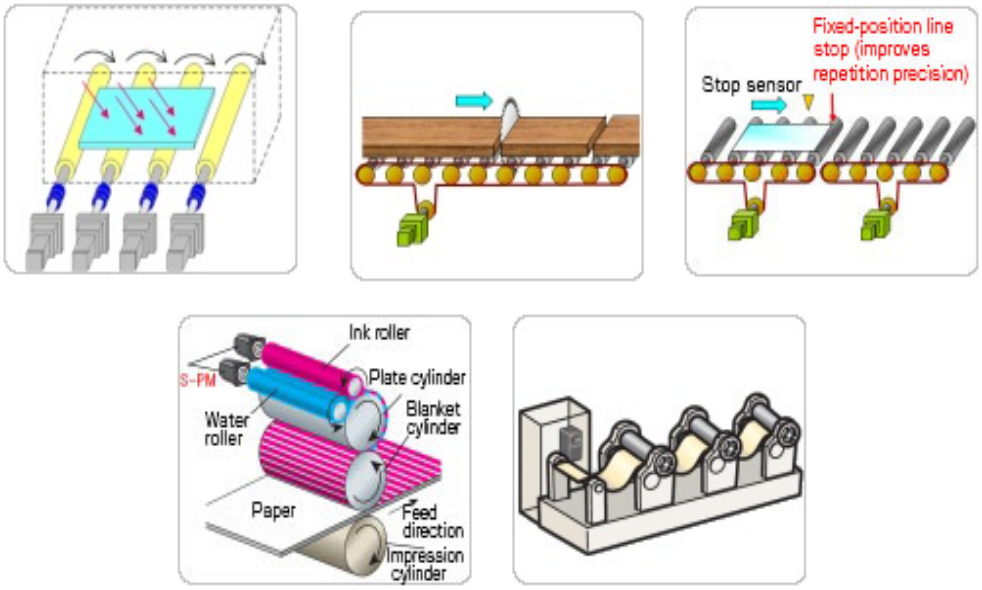

Fig. 8. THE APPLICATIONS OF PMSM IN CONTROL PROCESSES

Category	voltage	Output (kw)
		0 1 10 100 1000 10000
PM servo motor	200V/ 400V Series	3.7 — 400
Self-starting PM type motor	200V/ 400V Series/td>	0.6 — 15
Energy saving PM motor	200V/ 400V Series	11 — 400
Sensor less PM motor		
PM Motors for Elevator	200V/ 400V Series	2.1 — 18

Fig. 9. MEIDENSHA'S PRODUCTS

The American Parker Hannifin Company, with its many branches in Europe, America and Asia, has produced a PMSM machine called GVM (Global Vehicle Motor) (Fig. 10) for transportation systems, drives and electrohydraulic pumps [19].

Johnson Electric Holdings Ltd. manufactures various versions of rotary and linear PMSMs.

For the PMSM, there is an application as a ceiling fan in very low power ranges. Some versions of this fans (Fig. 11) manufactured by Chinese OPTIMAL and SHENGQI companies are available in the Iranian market.

Fig. 10. PMSM MACHINES PRODUCED BY PARKER HANNIFIN

An Overview Of The largest PMSM Manufacturers' Products Hhave Been Provided In Table 2.

Fig. 11. PMSM APPLICATION AS A CEILING FAN

TABLE. 2. THE PRODUCTS OF TOP PMSM MANUFACTURERS

company	country	Product's specifications	application	reference
MITSUBISHI	japan	0.1-2.2 KW 3000 rpm	as roller or conveyor belt in automatic cutting machines, spaghetti making machine, offset press system, frames and panels coverage system, and etc.	*http://www.*mitsubishielectric.com/fa/products*/drv/gear/pmerit/spm_right_angle/index.html*
HITACHI	japan	11 KW	-	*Hitachi.com*
VEM motors	germany	0.09-471 KW 0.6-7500 Nm 500, 750, 1000, 1500, and 3000 rpm	-	*https://www.vemgroup.com/fileadmin/content/pdf/Download/Kataloge/Kataloge/pm_en.pdf*
ABB	china	1120 kW at 220 r/min 25 - 1600 kW at 300 r/min 38 - 2240 kW at 430 r/min 57 - 2500 kW at 600 r/min Torque range: 1000 to 50 000 Nm	Water/air cooling	*new.abb.com*
SIEMENS AG	Germany	Air cooling : rated power 150-1181 KW Rated torque : 7200-14100 Nm Speed: 200/300/400/500/600/800 rpm Water cooling: Rated power: 196-2073 KW Rated torque: 9375-41000 Nm Speed: 200/300/400/500/600/800 rpm	Paper, steel, and plastic industry	*w3app.siemens.com* *cache.industry.siemens.com*
YASKAWA Motor Corporation	japan	200 V: 2.2kW to 110Kw (for 1,750min-1) 400V: 2.2kW to 630kW (for 1,750min-1)	-	*https://www.yaskawa.com*
Emerson Industrial Automation	USA	3-350 KW 1500-5500 rpm 315-500 KW 1500-3600 rpm	pump ،vehicle ،control process	*https://www.emerson.com/en-us/automation-solutions*

company	country	Product's specifications	application	reference
MEIDENSHA	japan	0.6-9 KW 600-20000 rpm	servomotor	*http://www.meidensha.com*
CONTINENTAL	Germany	60 to 120 kW	Electric vehicles	*www.continental-corporation.com/en/press/press-releases/2015-06-29-emotor-102102*
Allied Motion Technologies	USA	Not available	servomotor	*https://www.alliedmotion.com*
Baumüller	Germany	Water cooling : 80 kW, 200 kW, 140 kW, 40 kW Torque: Min.: 165 Nm Max.: 588 Nm Rotational speed: Min.: 3,000 rpm Max.: 6,000 rpm	-	*http://www.directindustry.com/prod/baumueller/product-9305-1827506.html*
Baldor Electric Co. Inc.	USA	1,2, and 3 hp 1800 rpm	-	*www.Baldor.com*
Mclennan	England	24, 110, and 220 V 32,62, and 265 mA 10 Ncm 250 rpm	servomotor	*https://www.mclennan.co.uk*
Franklin Electric	USA	4-37 KW	pump	*http://franklinwater.eu*
Nidec (Leory Somer)	USA	3-350 KW 1500-5500 rpm 315-500 KW 1500-3600 rpm	-	*http://acim.nidec.com/motors/leroy-somer/products/permanent-magnet-synchronous-motors*
Regal Beloit Corp.	USA	0.56-15 KW 600-3600 rpm	-	*https://www.regalbeloit.com/Brands/Marathon-Motors/Products/NovaMAX-EC-Permanent-Magnet-Motor*
Rockwell Automation	USA	10HP to 400HP	Electric pumps for oil industry, available to operate into liquids	*https://www.arcweb.com/blog/rockwell-automations-artificial-lift-solution-helps-operators-thrive-challenging-times*
Toshiba	japan	80, 120, 145, 190, 205, and 220 KW	Train traction system	*www.toshiba.co.jp*
WEG	sweden	1200, 1800 and 3600 rpm 5 up to 250 kW	-	*www.weg.net*
ARADEX	germany	500,700, and 900 KW at 1500 rpm 9.5, 15, 22, and 29 KW at 3000 rpm	Traction drives	*www.aradex.de*

9. SUMMARY AND CONCLUSION

The most prominent manufactured PMSMs studied in various researches and their application were investigated. The main producers around the world of this type of machines were also presented. Undoubtedly, other products have been fabricated and presented in literature, and some other retailers are active in this area, which were not addressed in this manuscript.

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