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Patent Landscape of Electric Machine Technologies for Electric Mobility

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Abstract

This paper examines the patent and publication landscape for automotive electric machines as key technology for electric mobility in a time frame from 2002 until 2012. For the analysis an indicator-based assessment of patent and publication information is carried out with the aim to identify all relevant research activities related to electric mobility over the last 10 years. While the analysis of patent applications serves as an important indicator for activities aiming to advance the state-of-the-art of technology development and is mainly driven by the industry, the analysis of peer-reviewed scientific publications serves as indication for basic and applied research, hence mainly driven by research institutions and universities. In this paper, a special focus lies on investigating research and development (R&D) activities related to Permanent Magnet Synchronous Machines (PSM), Induction Machines (IM), Switched Reluctance Machines (SRM) and Transverse Flux Machines (TFM). Thus, an extensive technology database was designed, covering detailed specifications of more than 3,100 peer-reviewed scientific publications and 59,000 patent applications in different world regions. Using text and data mining functionalities for this analysis, unique and sophisticated statements for technology development trends and research activities were identified. Results visualize the situation of Japan, USA, China, Europe, Germany and France in comparison based on the assessment of the respective patent markets on the one hand as well as technology driving and leading institutions on the other hand. Furthermore, this analysis will be accompanied by investigating how these technologies were used in existing prototype and series vehicles by automotive OEMs throughout the last 10 years, using DLR's unique vehicle concept database. The study shows that Japanese institutions are by far leading the technology development in selected areas, while China's patent market has gained significant importance since 2010.

Keywords: Battery Electric Vehicle, Powertrain, Electric Machine, Technology Assessment, Patent Analysis

1 Introduction

One of the main trends for current vehicle development is the further electrification of the automotive powertrain and by that the development of new or improved technologies in the field of electric mobility [1]. Key technologies for electrified vehicles include e.g. energy storage and energy converter devices like batteries, supercapacitors, fuel cell systems, range extenders, power electronics and electric machines [2].

Electrified vehicles like PHEVs (Plug-In Hybrid Electric Vehicles) or BEVs (Battery Electric Vehicles) make it possible to significantly reduce local emissions of greenhouse gases compared to conventionally powered vehicles and to increase the efficiency of energy usage. This allows OEMs to meet ambitious CO_2 reduction targets defined by politics, to avoid penalty fees and to account for changes in the awareness of customers concerning environmental issues. In order to gain competitive advantages and to realize supreme and innovative products in a global environment, all of the electric mobility key technologies are subject to strong investments in research and development (R&D) activities carried out by automotive OEMs, suppliers as well as research institutions and universities worldwide [3].

Beside the battery as most important and cost-intensive key technology of the electrified vehicle, also electric machines play an important role and the optimization and further improvement of the electric motors is one of the main goals of R&D activities in the field of electric mobility [4][5].

In the automotive industry, the most important electric machine type today is the Permanent Magnet Synchronous Machine, having a very good overall power density, degree of efficiency (90-95%) and can be integrated into the vehicle's powertrain with a relatively small, compact design [6]. Disadvantages arise in particular because of the high cost and limited access of rare earth materials (e.g., neodymium) used for the production of permanent magnets. Both are main drivers for R&D activities of externally excited electric motors like Induction Machines [7]. Induction machines have very good characteristics in terms of reliability, but disadvantages concerning power density, efficiency, volume/ weight and controllability. Induction Machines could in the future be an alternative primarily for small, robust and cheap cars. However, OEMs in the past used Induction Machines on the one hand in very small city vehicles like the Renault Twizy or Th!nk City for cost reasons, but on the other hand also in high-performance cars like the Tesla Roadster, the Model S or the Audi R8 e-tron concept vehicle [8].

Beside Synchronous Machines and Induction Machines, promising research is also carried out e.g. for Switched Reluctance Machines.

The reduction or substitution of rare earth materials in the electric machine, the development of alternative electric machine topologies as well as realizing a high integration of electric motor and power electronics is seen as key trend for current R&D activities [9]. Different technologies and solutions compete in a highly dynamic world market and it is uncertain which solution will prevail in the future 10].

However, detailed knowledge about R&D activities of leading institutions for automotive electric machines and its single components considering a wide timeframe is missing [11]. The aim of this paper is to identify the most relevant world regions for electric machines in terms of patent market importance on the one hand and technology leaders on the other hand in a global comparison and to derive trends in electric machine technology development by carrying out in-depth analysis of the international patent and publication landscape.

The patent analysis originally serves as an instrument for the strategic management of technologically driven companies and is used to investigate and evaluate activities in technology fields gauged as relevant for competition. As a tool to support planning and decision making, it helps in developing recommendations for a strategic management of technology and innovation [12]. To achieve this, the close correlation between monetary investments in R&D as an input factor and patent applications as an output factor is used. Patents by definition contain inventions which advance the state-of-the-art of single technologies and with economic interest could be applied in future products that allow for e.g. supreme performance characteristics [13].

Beside the use as a strategic planning tool, the patent analysis is also suitable to conduct technology- and trend-oriented competition analyses. Thus, patent information is used as an indicator to identify technology development trends as well as to evaluate the relative strength, the technological position and the competitiveness in comparison of institutions, countries and/or world regions.

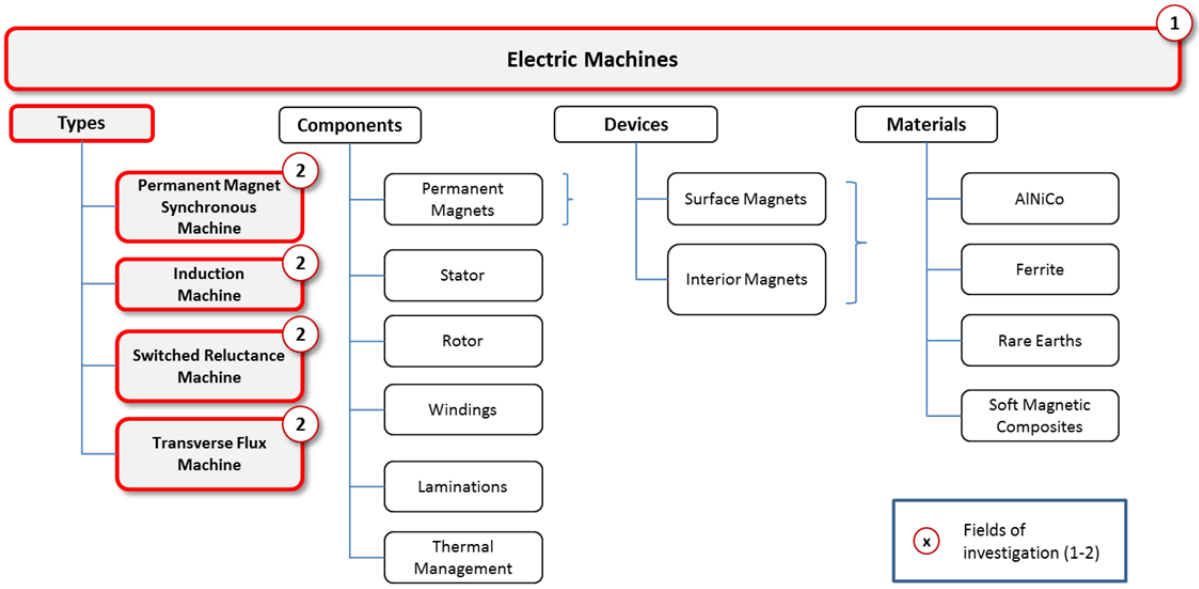

Figure 1: Fields of investigation in the scope of this study

In addition to patent applications, also peer-reviewed scientific publications can be interpreted as result of research activities and, therefore, serve as another indicator for investments in ongoing R&D [14]. In this paper, both methods will be used in combination to draw a holistic picture on research and development activities in the area of automotive electric machines. While publications mainly serve as a means for the documentation of basic or fundamental scientific achievements and, therefore, rather originate from research institutions and universities, patents focus more on the concrete use and economic utilization of an invention in e.g. innovative or improved products. Hence, patents are applied mainly by industrial companies.

2 Methodology and Scope

For the analysis in this paper, an indicator-based approach of technology assessment is carried out using patent and publication analyses in the field of automotive electric machines with the aim to identify all relevant research activities related to electric mobility over the years 2000-2012.

To achieve objective and scientifically relevant results in the context of this paper, the methodology follows a structured seven-step approach:

1. Identification and definition of relevant fields of investigation on electric machine system and component level.
2. Definition of the patent and publication search strategies by using IPC classes (International Patent Classification) and combining keywords where necessary.
3. Data acquisition in citation, abstract and patent databases (e.g. SCOPUS, Espacenet).
4. Structuring and harmonization of raw data, including relevant bibliometric indicators related to R&D (e.g. author/institution, title, abstract, year and geographical scope of application, citation) and the technology (e.g. technology field, component, parameter).
5. Design and buildup of technology databases containing patent and publication information.
6. Analysis of patent and publication (meta-) information (quantitative analysis).
7. Analysis of patent content by using text and data mining functionalities (qualitative analysis).

As to be seen in Figure 1, the scope of the study comprises different levels of investigation, whereas in this paper only the first level (“types”) will be of importance. Hence, patents and publications will be identified for electric machines as a complete system in the powertrain of electrified vehicles. Results will be shown for PSM, IM and SRM types.

For each field of investigation, the above-named steps were carried out, resulting in worldwide new and unique statements for the patent and

publication landscape in comparison of different world regions. The analysis covers six different geographical regions (China, Japan, USA and Europe with special focus on Germany and France). As a result, over 3,100 publications and 59,000 patents are analyzed in the context of this paper.

Futhermore, the DLR's Vehicle Concept Database was used with the aim to compare electric motors used in an early stage of vehicle development with those actually introduced into the market. The database comprises all electrified passenger cars presented at motor shows or introduced into the market over the years 2002-2012 in detail. Mild-HEV, Full-HEV, Plug-In HEV, Range-Extended Electric Vehicles (REEV) and BEV were considered for this analysis. Besides HEV, REEV and BEV in series production, it was the main goal to include concept cars, design studies and close-to-production prototype vehicles worldwide.

The Vehicle Concept Database comprises more than 215 parameters per vehicle. They are grouped into market-based parameters as well as technical parameters for different key technologies of electric mobility: Energy storage technologies (e.g. batteries), energy converter technologies (e.g. electric machines), power electronics, thermal management for electric machines and power electronics as well as lightweight design. Examples for market parameters include name of manufacturer, year of introduction, place of introduction (e.g. motor show), target market, target cost, vehicle segment and vehicle development stage, as well as general parameters concerning the vehicle concept itself like the degree of electrification, energy consumption per 100km in NEDC, CO_2 emissions per km, size in mm and weight in kg.

The technical parameters were identified and prioritized by literature research and carrying out interviews with experts in their respective technology field. A total of 55 technical parameters in the field of electric machines as key technology are covered. Prioritized parameters include for example the following:

- Technology (synchronous, induction, etc.)
- Installation site (gearbox, in-wheel, etc.)
- Effective power (kW)
- Power density (kW/kg)
- Nominal torque (Nm)

3 Results

Results of the patent and publication analysis will show international trends in R&D, leading institutions and their respective research networks as well as innovation dynamics over a wide timeframe for automotive electric machines (PSM, IM, SRM, TFM). Results of the DLR Vehicle Concept Database analysis will focus on the technology and the effective power of the electric machine in combination with the vehicle type and particularly the vehicle cross weight.

3.1 Patent and Publication Landscape for Automotive Electric Machines

For the analysis of the patent landscape in the area of „electric machines in the powertrain of electrified vehicles", a decided search strategy has been developed and applied at the patent database 'Espacenet' of the European Patent Office (EPO). For this, a total of 52 IPC classes (International Patent Classification) have been used (e.g., B60L, B60W, B60K) and combined with a keyword-based search strategy where necessary.

Altogether, more than 59,000 patents could be identified that were published in the world regions relevant for this evaluation: Japan (JP), USA (US), China (CN), Europe (EP), Germany (DE) and France (FR). The predominant majority of patents which refer to inventions in this technology field in the time frame from 2000 to 2012 were registered in Japan (40%), followed by the USA (22%) and China (14%). Patent applications in Europe and Germany have each a share of about 11% of the patent market. Only 1,303 patents (2%) were published on the French IP market ("intellectual property").

As shown in Figure 2, the Japanese (orange) and US-American (light blue) IP-markets show a relatively constant and similar increase in patent numbers from 2000 on until the year 2012. The relevance of the Chinese market (purple) increased continuously and overtook Europe (red) and Germany (green) in 2009, taking the 3rd place. This development culminates in the fact that the USA for the first time is pushed from 2nd to 3rd place in 2012.

In direct comparison of the patent situation in 2000 and 2010, an increase in total numbers of about 580% (1,211 to 6,965) can be registered. In particular, Japan with a leading position already in 2000 was able to even increase the gap in total numbers, although loses market share of applied patents of about 13% within the following ten years, reaching a total of 42% in 2010.

The German IP market gained importance for international patentees and the market share of 6% in 2000 increased to 10% in 2010. The pure number of patent applications in Germany grew about a factor of ten, two times stronger compared to Japan within this period of time.

By far the most dynamic development is, however, to be observed in China. Here, the market share could be increased from 2.6% to 14.7% within the last 10 years. The absolute number of applied patents at the same time reached 1,024 in 2010, the third best figure behind the USA and Japan. Even more remarkable dynamics can be identified from this point in time on: Within the following 2 years, China was able to increase the share of patents published on the own IP market from 16.8% to nearly 27%, while at the same time the share of Japan decreased from 24% in 2010 to 17% in 2012. The USA was able to raise its share again slightly after losses until 2010 and reached the leading position in 2012 with 32% share.

The analysis of patent application numbers over time aims at identifying activities and dynamics in comparison of different world regions to finally evaluate the relevance of the respective IP markets for international patentees. For the derivation of statements in terms of the technology position of different world regions, however, it is necessary to identify the main drivers of technology development and leading institutions within the technology field. This will be indicated in the following ranking for technology leaders in the area of automotive electric machine systems.

Because the explanatory power of statements derived from pure patent numbers is limited, for the following ranking patents that protect the same content in different world regions or are assigned to the same patent family will be ignored. Thus, multiple countings of similar inventions will be avoided and the ranking of the TOP institutions will be based only on patents with relevant content that really advance the state of the art of the technology.

In the ranking of technologically leading institutions in a global comparison, Asian enterprises hold nine positions within the TOP10, as Table 1 shows. In particular, it is Japanese

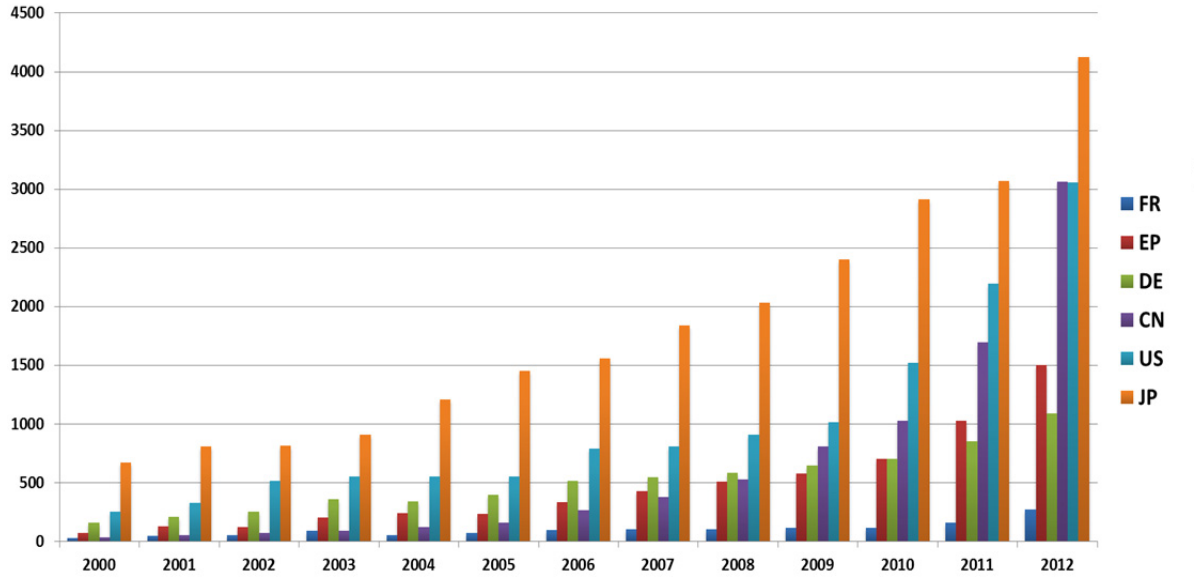

Figure 2: Number of patent applications in the field of "electric machines" by world region, 2000-2012

institutions that by far are most important drivers of technology development for automotive power electronics. They are leading with a total number of 19,695 inventions, with only Toyota (Motors & Jidosha) altogether being responsible for 9,776 inventions.

Table 1: Leading institutions in the field of automotive electric machine systems

Rank	Institution	No. of inventions	Country
1	TOYOTA MOTOR	7.789	
2	HONDA MOTOR	3.073	
3	NISSAN MOTOR	2.835	
4	TOYOTA JIDOSHA	1.987	
5	HYUNDAI MOTOR	1.255	
6	MITSUBISHI JIDOSHA KOGYO	1.055	
7	GM GLOBAL TECH OPERATIONS	833	
8	DENSO	829	
9	AISIN AW	722	
10	HITACHI	685	
11	ROBERT BOSCH	679	
12	FORD GLOBAL TECH	655	
13	DAIMLER	637	
14	KIA MOTORS	427	
15	PEUGEOT CITROEN AUTOMOB	411	
16	ZF FRIEDRICHSHAFEN	399	
17	MAZDA MOTOR	367	
18	RENAULT	357	
19	TOSHIBA	353	
20	BAYERISCHE MOTOREN WERKE	347	

In comparison to that, German OEMs hold only 984 inventions and are ranked with Daimler (incl. DaimlerChrysler) on position 13 and BMW on 20. Best-placed German enterprise is a tier 1 supplier on position 11 with 679 inventions: the Robert Bosch GmbH.

The USA is represented by GM (833) and Ford (655) on rank 7 and 12, Tesla Motors all in all holds 122 patents (22 inventions) in the area of electric machines for electrified vehicles. Best-placed Chinese enterprises are Chery Automobile and BYD with 117 and 81 inventions, followed by the Tsinghua University in Peking with 55 inventions.

When considering patents that refer to technological advances for different types of electric machine topologies, altogether 1,518 patents throughout the relevant world regions could be identified. Thereof, the Permanent Magnet Synchronous Machine has the largest share of 84%, followed by the Induction Machine (11%) and the Switched Reluctance Machine (8%). The Transverse Flux Machine has a share of less than 1%.

The technological focus of the different world regions is quite similar, as Figure 3 shows. The Synchronous Machine has dominant shares between 74% (CN) and 83% (JP), only France seems to be quite less focused on this type of electric motor with only 58% share. R&D activities for the Induction Machine follows on rank two in all countries except of France with an average share of 10%. It is noteworthy that China in comparison to the other world regions is more concentrated on technologies related to the Induction machine with an overall share of 18%. The Switched Reluctance Machine holds shares between 7% (DE) and 24% (FR). Patents related to the Transverse Flux Machine in the powertrain of electrified vehicles can in substantial extent only be identified in Germany and Europe.

The analysis of scientifically reviewed publications draws a slightly different picture. Although a strong research focus can also be identified for all world regions on the Permanent Magnet Synchronous Machine, the shares for all other machine types are generally higher. In comparison to patents, results in scientific publications rather represent basic or fundamental research and, thus, are mainly driven by universities and research institutes. The contents here are stronger based on theoretical principles or aim at solving basic problems concerning the feasibility of new technologies. Accordingly, R&D

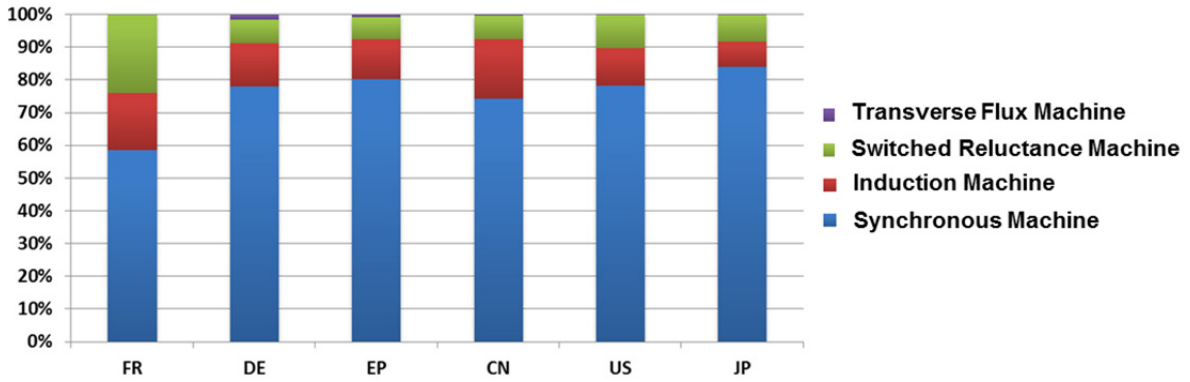

Figure 3: Share of patents for electric machine types by world region

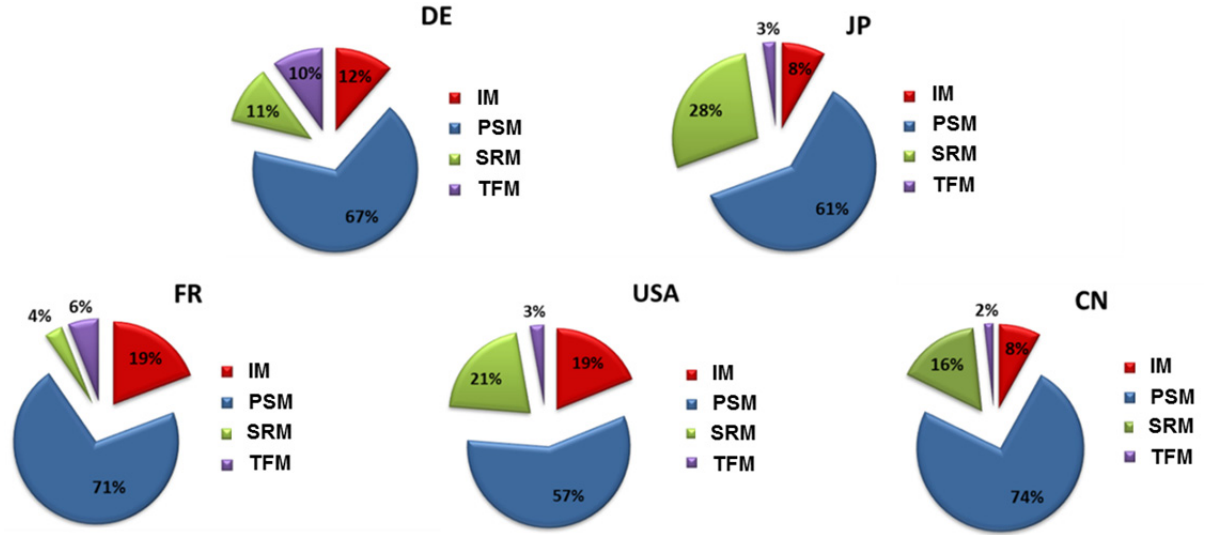

Figure 4: Share of publications for electric machine types by world region

activities described in scientific studies do not concentrate as much on market-oriented application as patents do and are further away from commercial use.

As to be seen in Figure 4, the shares of alternative electric machine types are higher in comparison to the patent analysis. In Germany, for example, the publication share for PSM is approximately 10% lower than the patent share while the shares of IM, SRM and TFM are significantly higher. A total of 932 scientific publications with focus on different machine types have been assessed.

3.2 Patent and Publication Landscape for PSM Technologies

In the ranking of leading patentees for PSM technologies in a worldwide comparison, Asian institutions again are main drivers of the technological development and take 15 positions in the TOP20 (Table 2). Japanese companies are by far leading with a total number of 606 inventions that were applied for patent protection and by that, dominating the Asian region. The only Asian company not headquartered in Japan is Hyundai as South Korean (SK) enterprise on rank 19 with 7 inventions. Japanese OEMs, however, seem to be main driver for development of PSM technologies with Honda (114 inventions), Toyota (altogether 172), Nissan (39) and Mitsubishi (27) as leading institutions.

No German OEM is to be found in this ranking. The strongest companies in this technology field from Germany seem to be the tier-1 supplier Siemens AG and Robert Bosch GmbH on rank 17 and 20. Best-placed German OEMs are Volkswagen (4 inventions), BMW (3) and Daimler (2). Porsche and Audi each have one invention in their portfolio. The United States of America are represented by GM (27) and Ford (13). Best-placed Chinese institutions are Tongji University, United Electronci Automotive Systems und Chongqing Tsingshan Industries with each 2 inventions.

Table 2: Leading institutions in the field of PSM technologies

Rank	Institution	No. of inventions	Country
1	HONDA MOTOR	114	
2	TOYOTA MOTOR	113	
3	HITACHI	80	
4	TOYOTA JIDOSHA	50	
5	DENSO	46	
6	NISSAN MOTOR	39	
7	AISIN AW	33	
8	TOSHIBA	30	
9	MITSUBISHI DENKI	27	
10	GM GLOBAL TECH OPS	27	
11	YAMAHA MOTOR	18	
12	FUJI ELECTRIC	18	
13	MATSUSHITA ELECTRIC IND	14	
14	FORD GLOBAL TECH	13	
15	TOYOTA CENTRAL R & D LABS	9	
16	MITSUBA	8	
17	SIEMENS	8	
18	MEIDENSHA	7	
19	HYUNDAI MOTOR	7	
20	BOSCH	7	

When expanding the patent search strategy for PSM technologies to include not only inventions relevant for electric machines in the automotive sector and in the context of electrified vehicles, but for all possible application fields of semiconductor technologies like aerospace, energy or robotics, the

picture of leading institutions in this technology field changes, as seen in Table 3.

Table 3: Leading institutions in the field of PSM technologies with expanded search scope [a]

Rank	Institution	No. of inventions	Country
1	MATSUSHITA ELECTRIC IND	1.437	
2	MITSUBISHI DENKI	1.281	
3	DENSO	967	
4	HITACHI	832	
5	TOSHIBA	728	
6	TOYOTA MOTOR	619	
7	HONDA MOTOR	581	
8	ROBERT BOSCH	495	
9	NISSAN MOTOR	489	
10	NIPPON DENSAN	480	
11	LG ELECTRONICS	472	
12	SANYO ELECTRIC	431	
13	SIEMENS	418	
14	DAIKIN IND	375	
15	YASKAWA ELECTRIC	371	
16	PANASONIC	361	
17	JTEKT	330	
18	ASMO	293	
19	SAMSUNG ELECTRONICS	279	
20	MITSUBA	270	

[a] not limited to automotive inventions

Matsushita Electric Industrial (or Panasonic) leaps from rank 13 to the top position with 1,437 inventions related to PSM technologies, followed by the Japanese OEM Mitsubishi which can improve its position from 9 to the second most important technology driver. Also Toyota and Honda – leaders for patent applications with direct relation to electrified passenger cars – are still represented within the TOP10 of all patentees worldwide, ranked 6th and 7th. On position 8 and best-placed German enterprise is the Robert Bosch GmbH with 495 inventions. Siemens AG takes rank 13 with 418 inventions.

Altogether, a dominance of Asian institutions can also be identified when expanding the scope of the patent analysis. However, the share of R&D activities for Japanese institutions decreases slightly in favor of South Korea, decreasing from 91% to approx. 83%, still dominating the technology development.

3.3 Patent and Publication Landscape for IM Technologies

More than 5,300 patents related to Induction Machine technologies could be identified considering a time frame from 2000 to 2012 and expanded search scope, while only 220 exist when regarding patents limited to electrified vehicles. This corresponds to a share of electric mobility driven R&D of only 4%.

Leading in terms of absolute numbers is the Chinese market for intellectual property (1,600 patents), meaning that international patentees seem to consider the Chinese market as most relevant for this technology. On 2nd and 3rd place following are the patent markets of the USA (1,100) and Japan (1,000). In particular from 2008 on, China was able to strengthen its position, reaching a share of applied patents on its own market 53% in 2012, compared to only 11% in the year 2000. The USA and in particular Japan lose significance (7% and 19%) within the same period of time and reach a total of only 16% and 11% market share in 2012.

About 730 patents for Induction Machines were applied on the German IP market in this time frame. Also here, the development of applied patents is reducing strongly compared to China. While the output of patents on the German IP-market could be increased by over 160%, Germany loses, nevertheless, a total of 14% of market share and decreases from 21% to only approx. 7%.

In the analysis of leading institutions and main drivers of technology development in the field of Induction Machine technologies (see Table 4), Japanese institutions take eight positions out of the TOP20, having a total of 405 inventions in their portfolios. It is noteworthy that a Japanese OEM is even to be found in this ranking with expanded search scope (Mitsubishi, position 3, 112 inventions). Toyota is ranked on place 20 with 15 inventions, Honda (11) is positioned on place 41.

Best-placed German enterprise and at the same time leading the whole ranking is Siemens with a total of 136 inventions (349 patents) in its portfolio, followed by Bosch with 37 inventions (163 patents) on position 10. SEW Eurodrive is rankd on 13 with 26 inventions (51 patents). German OEMs in this technology field are represented by Daimler (16 inventions), Volkswagen and BMW (each 3) and Porsche (1).

The USA is represented by GE (44), GM (27) and Emerson Electric (22). Best-placed Chinese enterprises are Chongqing Machinery (45) and Thongda Motors (36 inventions). Furthermore, Yongji Xinshisu Electric (17) and Jiangso University (16) are positioned within the TOP20 for Induction Machines. China in international comparison to e.g. the field of PSM technologies seems to be very active in the field of Induction Machines not only considering the importance of

the patent market, but also driving the technology development.

Table 4: Leading institutions in the field of IM technologies with expanded search scope [a]

Rank	Institution	No. of inventions	Country
1	SIEMENS	136	
2	LG ELECTRONICS	113	
3	MITSUBISHI DENKI	112	
4	HITACHI	81	
5	FUJITSU GEN	57	
6	MATSUSHITA ELECTRIC IND	49	
7	CHONGQING MACHINERY	45	
8	GEN ELECTRIC	44	
9	TOSHIBA	42	
10	ROBERT BOSCH	37	
11	ZHONGDA MOTORS	36	
12	GM GLOBAL TECH OPERATIONS	27	
13	SEW-EURODRIVE	26	
14	YASKAWA ELECTRIC	24	
15	DENSO	22	
16	EMERSON ELECTRIC	22	
17	FANUC	18	
18	YONGJI XINSHISU ELECTRIC	17	
19	JIANGSU UNIV	16	
20	TOYOTA	15	

[a] not limited to automotive inventions

3.4 Patent and Publication Landscape for SRM Technologies

In the area of Switched Reluctance Machines connected to electrified vehicles, altogether 162 patents could be identified, so that a clear trend over time cannot be derived. The Japanese IP-market takes up about 37% of all applied patents, followed by the USA (30%), Europe (12%), Germany (9%) and China (8%).

When expanding the scope of the patent analysis, more than 4,700 patents could be found regarding technologies for Switched Reluctance Machines. Within the time frame from 2000 to 2012, constantly high efforts can be recognized in Japan as well as in the USA. All in all, Japan is leading with approx. 1,600 applied patents, followed by the USA with approx. 1,200 and China with approx. 800. The Chinese patent market gained significant importance from 2004 on, taking the leading position in 2012.
The Japanese market, on the other hand, lost a total of 24% market share throughout the years and reached only 20% in 2012, while China could increase the output by a factor 30. Starting from a market share of only two percent in the year 2000, it reached 27% within a decade and even 42% until 2012. The US IP-market stayed on a relatively constant level with a share of between 22% and 29%. In Germany, however, a steady decline of patent applications is recognizable from 2006 on. While the German IP market in 2000 possessed approx. 12% of the market share, only 3.6% remained in the year 2012.

The leading institution in this technology field is headquartered in South Korea: LG Electronics with 224 inventions (394 patents). On the second position follows Switched Reluctant Drives (Great Britain, 106 inventions), the third position takes Denso (Japan).

Table 5: Leading institutions in the field of SRM technologies with expanded search scope [a]

Rank	Institution	No. of inventions	Country
1	LG ELECTRONICS	224	
2	SWITCHED RELUCTANCE DR	106	
3	DENSO	110	
4	SAMSUNG ELECTRONICS	94	
5	TOYOTA MOTOR	93	
6	TOSHIBA	86	
7	MITSUBISHI DENKI	81	
8	MATSUSHITA ELECTRIC IND	74	
9	HITACHI	72	
10	AISIN SEIKI	69	
11	NISSAN MOTOR	68	
12	JAPAN SERVO	60	
13	EMERSON ELECTRIC	57	
14	FUJITSU GEN	53	
15	MITSUBA	44	
16	DAIKIN IND	38	
17	ROBERT BOSCH	38	
18	NANJING UNIV	35	
19	DANA	30	
20	OKUMA	28	

[a] not limited to automotive inventions

Japanese institutions hold 60% of the relevant patents within this analysis and still are main technology driver, however, they do not seem to be as dominant as e.g. with PSM technologies. It still is remarkable that even with expanded search scope, Japanese OEMs are to be found in the TOP ranking. Toyota (incl. Toyota Central R&D) is ranked 5th with 93 inventions, Mitsubishi on position 7 (81) and Nissan (68) on position 11, as Table 5 shows. Emerson Electric is the best-placed US-American enterprise, the Robert Bosch GmbH on rank 17 leads the technology development from a German perspective. China is represented with the Nanjing University Aeronautics & Astronautics (35 inventions).

3.5 Patent and Publication Landscape for TFM Technologies

In the special field of patent applications for Transverse Flux Machines connected to the

powertrain of electrified passenger cars, only 13 patents altogether could be identified. Germany is leading with 6 patents published in 1996, 1998 and 2001. Actual research activities can only be recognized on the Japanese, US-American and European patent market, each having one patent application in the year 2012. Voith AG, Toshiba and Daimler are responsible for these activities.

Again, the scope of the patent analysis will be expanded in the following so that a total of 390 patents can be evaluated throughout the years 2000 to 2012. The IP-markets in the USA and Germany seem to be most important here with 104 and 102 patents applied, followed by Europe (85), China (51), Japan (41) and France (4). Analyzing the patent landscape in detail, it can be seen that R&D activities in Germany mainly concentrate on the years 2000 to 2004, while in the following years the USA and – from 2011 on – China became relevant. In 2012, the Chinese patent market even reached the first position in terms of importance for international patentees.

German institutions lead the ranking for Transverse Flux Machines with altogether 11 positions out of the TOP20. The first position is hold by Voith AG (27 inventions, 86 patents), followed by Robert Bosch GmbH (19 inventions, 69 patents) and the Harbin Institute of Technology headquartered in China. On position 5 and 7 two German OEMs can be identified, having 9 and 7 inventions in their technology portfolio. German enterprises are responsible for 52% of all patent activities related to TFM technologies. Considering Japanese R&D activities, only one company could be identified within this ranking: Minebea K.K. on position 19 with 2 inventions. North American enterprises are Motor Excellence, LLC (position 6), Hamilton Sundstrand (respectively United Technologies Corp.) on position 8, Otis Corp. on 10 as well as Eocycle Technologies headquartered in Canada on rank 20.

3.6 DLR's Vehicle Concept Database

In addition to the analysis of patents and publications, technological trends can also be observed on the vehicle system level. As it can be seen in Figure 5, the number of electrified vehicles introduced to the market or presented as prototype or concept cars increased significantly since 2003. In particular the number of BEV boosted from 2008 until 2011, while the number of HEV remained on a constant level.

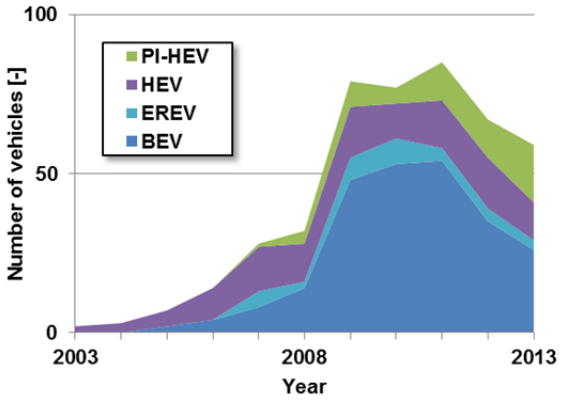

Figure 5: Number of new electrified vehicles presented as prototype/concept cars or introduced into the market pear year

The most important technology concerning the excitation of electric machines is the permanently excited machine, as it can be seen in Figure 6. Only very few vehicles have been equipped with externally excited machines throughout the years. Thus, a trend towards alternative electric machine technologies is not visible so far.

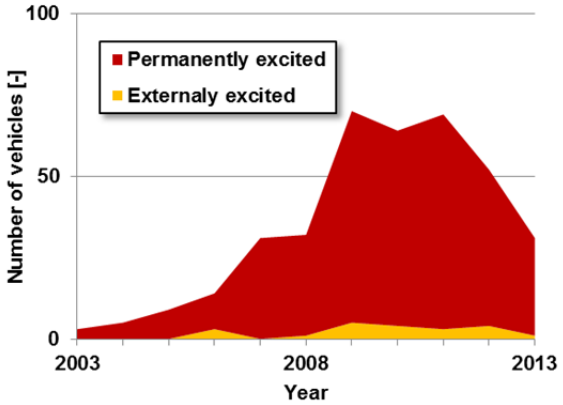

Figure 6: Number of vehicles using different excitation technologies per year

Considering those concept vehicles equipped with alternative, externally excited machines, mainly Battery Electric Vehicles have been used (Figure 7). More than 95% of the Hybrids (PHEV, HEV and REEV) had permanently excited electric machines in their drivetrain installed. But even for BEV, the share of permanently excited machines reached almost 90%.

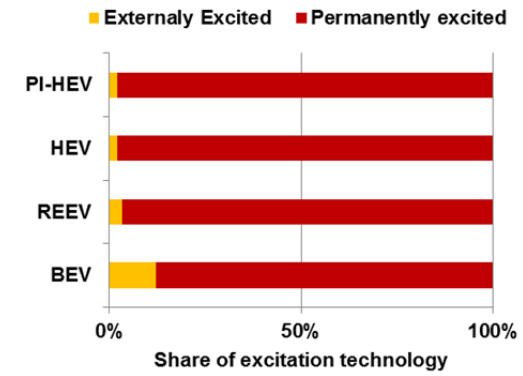

Figure 7: Share of excitation technology per electrification concept

More in detail, the installed power varies from vehicle to vehicle as shown in Figure 8. Categorizing the vehicle concepts by their electrification concept, it can be seen that the installed power per cross weight increases by raising the electrification from HEV to BEV. Regarding the mean of installed power per cross weight, BEVs reach 8.8 kW/100kg, PHEVs 4.9 kW/100kg and HEVs 3.8 kW/100kg.

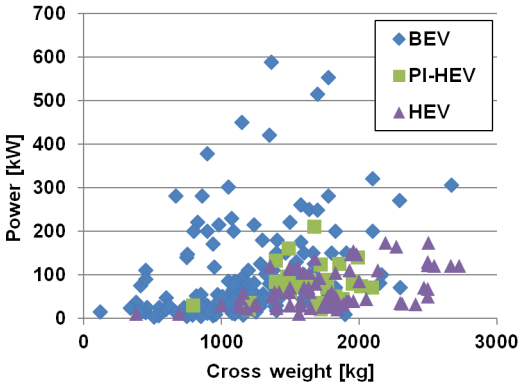

Figure 8: Installed maximum power of electric machine plotted against the vehicle cross weight per electrification concept

4 Summary and Conclusion

In the following section, the 'technological basis' of the analyzed world regions in the field of automotive electric machines will be illustrated. This will summarize all of the conducted analyses above and by contrasting will highlight the patent landscape in terms of market and technology development over time in a portfolio chart.

The „growth of the patent market" on the y-axis shows the increase in the respective countries Japan, USA, China, Germany and France in comparison to applied patents for a period of 10 years. The focus of the illustration lies on 2007 (with base year 2002) and in 2012 (with base year 2007). The „share of the patent market" on the x-axis indicates how much percent of the patents were announced in the respective country to protect the intellectual property there. By that, it accordingly serves as an indicator for the importance of the respective country for internationally active patentees and their inventions. The size of the land flags indicates, furthermore, how strong the respective country itself is involved in the technology development, measured in the percentaged share of globally applied patents of institutions headquartered in the respective country in the years 2007 and 2012 („technology share"). All together, the chart illustrates the situation and the dynamics of the market as well as the technology in combination.

As Figure 9 illustrates, Japanese companies are leading the technological position in the field of automotive electric machines by far and were responsible for the development of about 64% of all patents in the year 2007 and still 54% in 2012. Also the Japanese patent market seems to be the most important one in international comparison, leading with about 32% share in 2012. However, the Japanese patent market lost large amounts of share (19 percentage points) within the last five years. The dynamics of the patent market growth increased slightly in the same time period, with about 220% growth rate to be identified for 2012 (on the basis of 2007).

The United States of America were able to increase their market share by about five points compared to 2007 to reach 27% in the year 2012. At the same time, the growth rate of applied patents on the US-American IP-market rose from 160% in 1007 to 370% in 2012. US-based institutions over the last 10 years were responsible for a very constant amount of inventions to drive automotive electric machine technology development with shares between 15% and 16%. By that, US-American institutions lay behind Japanese ones and on the same level as German institutions in 2012.

Although having a virtually constant situation in terms of technology share in the USA, the importance and growth of the US-American patent market could be increased – in particular in comparison to the Japanese market.

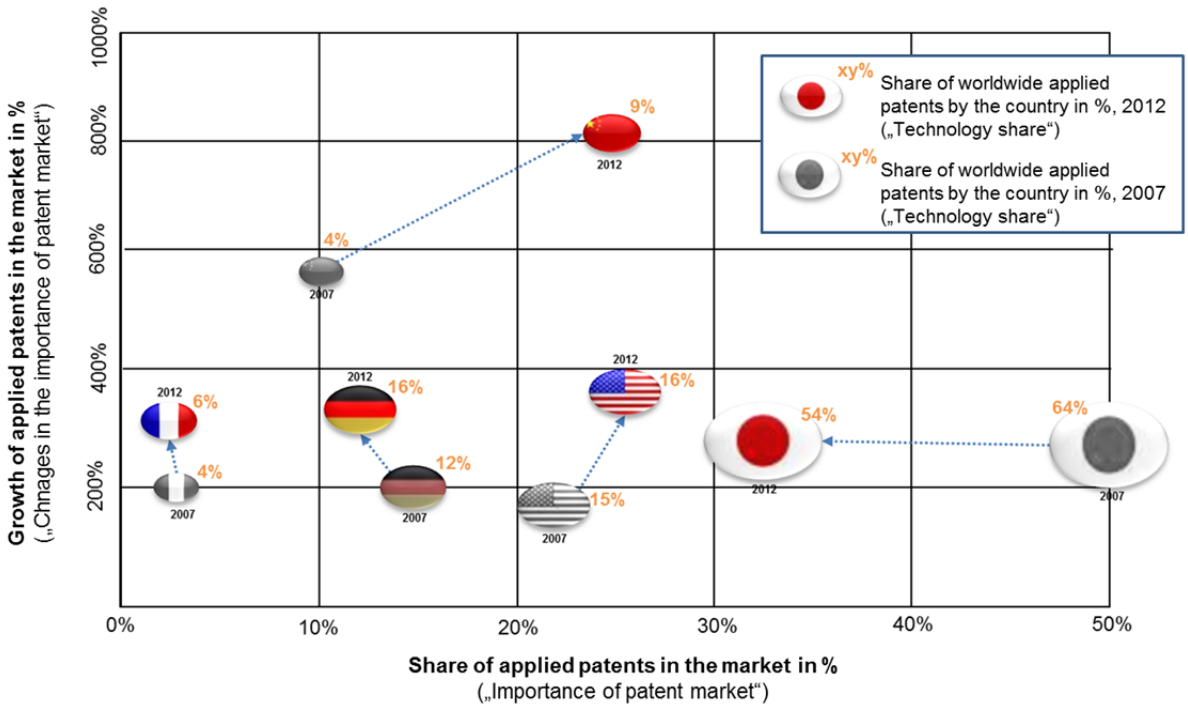

Figure 9: Technological basis for automotive electric machines by world region

German companies could raise the technology share from 12% in 2007 to more than 16% in 2012 and by that reached the same level as US-based companies as second most important driver of automotive electric machine development. However, the relevance of the German IP market decreased for international patentees within this period of time, so that only about 13% of all patents were applied on the German market, a decline by approx. three percentage points. The market growth gained dynamics and reached 340% growth rate in 2012, while in comparison of the years 2002 and 2007 only approx. 200% of growth could be achieved.

France within the scope of this investigation plays a minor role in terms of market importance as well as technology share. While French enterprises could slightly increase their share in technological development (4% in 2007; 6% in 2012), the meaning of the French market in terms of market share within this period decreased from 3% to only 2% in 2012. At the same time, the growth rate of at the French IP market applied patents could be increased to reach 320% in 2012 (with base year 2007), starting at 200% in 2007 (with base year 2002).

Very remarkable is the situation in China in comparison of the years 2007 and 2012: The Chinese patent market reached more than 26% of share in 2012 and by that, takes the second position in terms of importance for international patentees behind Japan. Within the years 2007 to 2012, about 16 points market share could be won accordingly. Besides, the dynamics of the market growth increased constantly and claimed more than 810% in 2012 in comparison to 530% in the base year 2007. The share in terms of technological development in the area of automotive electric machines could also be increased significantly, reaching 9% in 2012 compared to only 4% in 2007. China by that takes the fourth position behind Japan (54%) and Germany/ USA (each 16%).

Acknowledgments

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References

[1] KPMG International, *Global Automotive Executive Survey,* 2014.

[2] Federal Ministry of Education and Research (BMBF), *Electric Mobility – Rethinking the Car*, Bonn, 2013

[3] T. Wiesenthal, G. Leduc, P. Cazzola, W. Schade, J. Köhler, *Mapping Innovation in the European Transport Sector*, Luxembourg, 2011

[4] Nationale Plattform Elektromobilität (NPE), *Fortschrittsbericht der Nationalen Plattform Elektromobilität (Dritter Bericht)*, Bonn, 2012

[5] U.S. Department of Energy (DoE), Vehicle Technologies Office, *Annual Merit Review*, 2013

[6] B. Bose, Power electronics and motor drives: advances and trends. ISBN 978-0-12-088405-6, London, Elsevier Inc., 2010

[7] T. Wallington et. Al., *Sustainable Mobility: Lithium, Rare Earth Elements, and Electric Vehicles,* Lecture Notes in Electrical Engineering, ISSN 1876-1100, 191(2013), 155-166

[8] B. Frieske, M. Klötzke, F. Mauser, *Trends in Vehicle Concept and Key Technology Development for Hybrid and Battery Electric Vehicles*, EVS27, Barcelona, 2013

[9] B. Frieske, M. Klötzke, H. Hüging, T. Koska, STROM - *Ergebnisse der Forschungsreise Japan (Key Technologies for Electric Mobility - Research Results Japan)*, 2013

[10] H.E. Friedrich, B. Frieske, *Trends in der Fahrzeugtechnik vor dem Hintergrund politischer Vorgaben und erwarteter Marktentwicklung (Trends in Automotive Engineering Considering Policy Guidelines and Market Development)*, Deutsches Zentrum für Luft- und Raumfahrt, Sindelfingen, 2012

[11] Büro für Technikfolgen-Abschätzung beim Deutschen Bundestag (TAB), *Konzepte der Elektromobilität und deren Bedeutung für Wirtschaft, Gesellschaft und Umwel*t (Concepts of Electric Mobility and their Meaning for Economy, Society and Environment), 2012

[12] S. Chang, *Using patent analysis to establish technological position: Two different strategic approaches,* 2012

[13] J. Pienkos, *The Patent Guidebook,* 2004

[14] R. Ruegg, G. Jordan, *Overview of Evaluation Methods for R&D Programs*, 2007

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