UNIVERSITATEA TEHNICĂ
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HABILITATION THESIS

Electrical machines in electromechanical systems for sustainable development

Professor Claudia–Steluţa MARŢIŞ, PhD

Electrical Engineering Faculty

Technical University of Cluj-Napoca

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CONTENT

Acknowledgments

This research work has been carried out during the years 2002–2014 in the Electrical Machines and Drives Department of the Technical University of Cluj-Napoca, where I have been working as a teaching and research staff member.

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A. CONTEXT OF HABILITATION

In a dynamic society, in a continuous transformation and evolution, any professional sector needs a high-level, competent and motivated workforce. Being a member of academic staff of a university is one of the most complex professions, as in such a position you are always under the pressure of society challenges. At the same time, being an academic represents one of the most motivating profesion. It combines the talent to excite students' curiosity and to transfer the knowledge in a certain field, inducing to the young people the taste for knowledge and professional progress. The two words governing this profession are communication and creativity. Through communication one could relate with students, colleagues, and partners. Through creativity one can keep the freshness of the exposee and open new research horizons.

Growing up an academic is a complex process, due to the huge amount and diversity of the information to be acquired, but mostly to the high-level competences and skills to be developed. If one wants to be successful in gaining an academic position and then progressing in academia, it is important that one gains an understanding of the broader academic context in which she/he will be working. As academic one has to combine teaching and research and develop the capacity to transfer and integrate the new achieved knowledge in the course lectures. This asks for a high-level flexibility and open mind, keeping at the same time a reasonable receptivity and a critical reflection.

Personal and professional evolution of the academic is always sustained by the natural acquisition of new skills and competences. Management and mentoring activities are to be added to the teaching and research ones. As research project manager, the academic needs the capacity to manage human and material resources, and to use efficiently the existing infrastructures, in order to achieve the goals of the project. The coordination of the research team involves not only the distribution of the tasks and the evaluation of the progress, but also mentoring and guiding the young researchers (bachelor, master or PhD students).

Creating and developing a research team is not an easy task. It needs a continuous and persistent work on attracting more funds from different sources (national calls, European and international research oriented calls, research work for the industry, etc) and a very well defined recruiting and human resources developing strategy.

In this context, obtaining the habilitation in order to be able to supervise PhD theses is a natural step in the professional development of the candidate. This step will have an important impact on both the candidate teaching and research activity and on the teaching and research activitivies in the Electromechanical Systems Group and in the Department of Electrical machines and drives.

B. RESEARCH DIRECTIONS AND COMPETENCES

The research activity of the candidate is following the principles of Sustainable Development and the applications of Electrical Engineering in this field. Connected to the European research space, the candidate is oriented in two of the framework programme Horizon 2020 sections:

- Secure, Clean and Efficient Energy
  - Renewable energies based conversion systems (wind, water and sun energies based applications);
  - New energy efficient and low noise topologies and technologies for electromechanical converters for renewable energy based conversion systems;
  - Advanced tehnologies for electromechanical conversion system for smart grid integration.

- Smart, Green and Integrated Transport
  - Electric/hybrid vehicle propulsion systems (cars, buses, two and three wheels vehicles);
  - Enhancement of energy efficiency of electrical machines and drives for electrified auxiliairies in automotive;
  - Low-noise electrical machines and drives for automotive applications.

The competences developed by the candidate since PhD graduation can be grouped as follows:

1. ***Professional competences:***

- Advanced knowledge in electrical engineering in general and in electrical machines and drives in particular:
  - Optimal design;
  - Multi-physics modelling, simulation and testing;
  - Condition monitoring and diagnosis;
  - Component- and system-level evaluation of electromechanical systems.
- Advanced competences in research methods and techniques, work with different software packages for optimal design, modelling, analysis and testing od electrical and electromechanical systems;
- High capacity of identification, definition and solving of specific problem in electrical engineering in general and in electromechanical systems in particular.

2. ***Transversal competences:***

- Competences and abilities in human, material and financial resources management;
- Competences in using information and communication technologies;
- Project management competences.

C. RESEARCH ACTIVITIES AND RESULTS

Modern electromechanical technologies can help reducing the environmental impact of different economic sectors: industry, agriculture, energy, transport, etc. New electromechanical technology is constantly finding application in areas traditionally served by hydraulic and pneumatic systems and offers an efficient and cost-effective alternative to fluid power as it eliminates leaks, is quieter, requires less maintenance than older technologies and is more environmental friendly. Electromechanical systems have suffered important changes over the last years in terms of their size, weight and power consumption, delivering power only when is needed and spending a part of their cycle time at peak consumption compared to hydraulic and pneumatic systems.

Present work summarizes the research activity of the candidate after defending the PhD Thesis at the Technical University of Cluj-Napoca, confirmed by the Ministry of National Education, on the basis of Order no. 3951, dated 5th of June 2001. The research and teaching acitivities of the candidate after obtaining the PhD degree followed very closely the guidelines of the Sustainable Development politics, oriented on the benefits and interest of Electrical Engineering in this area. The main research directions of the candidate activity after 2001 are:

- Condition monitoring and diagnosis in electrical machines;
- Electrical machines and drives for automotive applications;
- Electrical machines and electromechanical systems for renewable energies based conversion systems.

Between 2001 and 2002, for seven months, the candidate worked as a postdoc researcher under the coordination of a well known experienced researcher, Professor Gerard A. Capolino from the University of Picardie Jules Verne, Amiens, France (UPJV). During this period she approached condition monitoring and diagnosis of electrical machines in general, and of induction machines in particular. The research activity in this field was extended after her return in Romania, working together with the former promoter of her thesis, Professor Karoly Biro, keeping also the contact with members of CREA Department at UPJV.The results of the research activity in this field will be presented in Chapter 2.

Since 2006 the candidate oriented her research activity towards two important research directions: automotive and renewable energies based applications. She continued the collaboration with her mentor, Professor Karoly Biro, but she also started to develop her own research projects. Most of the research subjects of professor Biro PhD students theses were proposed and followed by the candidate, working as a co-supervisor. The results of this activity are presented in Chapters 3 and 4.

2009 was an important moment in the professional career of the candidate, by obtaining the title of professor at the Technical University of Cluj-Napoca. This confirmed her experience for taking the next step: research group coordinator. Since then, the candidate applied and obtained research funds through several national and European calls.

The present work is organized in 5 chapters. Fisrt chapter reveals the contaxt of the research work and its approach. Chapter 2, 3 and 4 present the results of the of the reseach activities under the three mentioned research lines. The last chapter sinthetise the personal contribution of the candidate and defines the career development plan.

1. CONTEXT OF THE WORK

During the last decades there is a growing interest around the world in new electromechanical technologies designed to bring about improved management of resources and a better quality of life. This trend became more and more visible with the increasing concerns about the environmental quality, climate change and social equity, concerns that have converged to define an integrative approach: sustainable development (SD).

Since 1987, when World Commission on Environment and Development report, “Our common future” defined the concept of SD, efforts are being made systematically for the wise use of natural resources, minimum adverse impact and maximum positive impact on people and the environment. Also known as Brundtland report, the document was designed as "A global agenda for change", and included the “classic” definition of sustainable development: “development which meets the needs of the present without compromising the ability of future generations to meet their own needs”[1]. The concept acquired a greater international meaning and relevance with the United Nations Conference on Environment and Development in Rio de Janeiro, Brazil, in June 1992, that laid the foundations for the global institutionalization of SD. The document released at this summit, „Agenda 21” was adopted by representatives of 179 countries[2]. Its implementation was primarily the responsibility of governments, through national strategies, plans, policies and procedures. The involvement of international, regional and non-governmental organizations, as well as the broadest public participation, was encouraged.

Since the Brundtland report and the Rio Summit, the thinking and practice on sustainable development has evolved. The concept has been useful in framing approaches to development and growth, being accepted as a guiding principle and being integrated into the operations and governing mandate of many prominent international organizations.

Thus, in June 2001, the Goteborg European Council proposed a strategy for SD „which completes the Union's political commitment to economic and social renewal, adds a third, environmental dimension to the Lisbon strategy and establishes a new approach to policy making.” The SD Strategy of the European Union (EU SDS) set-up a framework for a long-term vision of sustainability and called for an integrated approach of sustainability as a multidimensional challenge: economic, environmental and social[3]. The priorities were thus defined as: combating climate change, ensuring sustainable transport, addressing threats to public health and managing natural resources more responsibly.

EU SDS was renewed in 2006 by “setting-out a single, coherent strategy on how the EU will more effectively live up to its long-standing commitment to meet the challenges of sustainable development.” The renewed EU SDS identified seven key challenges (see Table 1), the corresponding targets, operational objectives and actions, as well as the guiding

[1] ***, “Our Common Future”, Report of the World Commission on Environment and Development, Transmitted to the General Assembly as an Annex to document A/42/427 - Development and International Cooperation:Environment, United Nations 1987.
[2] ***, “Agenda 21”, document released by United Nations Conference on Environment & Development Rio de Janerio, Brazil, 3 to 14 June 1992.
[3] ***, "TOWARDS A SUSTAINABLE EUROPE”, Communication from the COMMISSION, Goteborg, 2001.

principles for their design and implementation[4]. Moreover, measuring progress towards SD was an integral part of the strategy and monitoring reports are to be produced every two years, based on EU set of SD indicators (EU SDIs). Four progress reports were delivered and they highlighted the fact that, despite considerable efforts to include action for SD in major EU policy areas, unsustainable trends persist and the EU still needs to intensify its efforts. Thus, the necessity of a new development framework arises.

A common new framework for SD was provided by the United Nations Conference on Sustainable Development (Rio+20) held in Rio de Janeiro in June 2012[5]. The Rio+20 outcome document, "The Future We Want", defines new horizons for SD and reaffirms the commitment to create a sustainable future for our planet, for both the present and future generations, by a balanced approach among economy development, environmental protection and social equity.

Table 1. Key challenges and their overall objectives as identified by the renewed EU SDS

Key challenge	Overall objective
Climate Change and clean energy	To limit climate change and its costs and negative effects to society and the environment
Sustainable transport	To ensure that our transport systems meet society's economic, social and environmental needs whilst minimising their undesirable impacts on the economy, society and the environment
Sustainable production and consumption	To promote sustainable consumption and production patterns
Better management of natural resources	To improve management and avoid overexploitation of natural resources, recognising the value of ecosystem services
Public health	To promote good public health on equal conditions and improve protection against health threats
Social inclusion, demography and migration	To create a socially inclusive society by taking into account solidarity between and within generations and to secure and increase the quality of life of citizens as a precondition for lasting individual well-being
Fighting global poverty	To actively promote sustainable development worldwide and ensure that the European Union's internal and external policies are consistent with global sustainable development and its international commitments

The document inspired the EU's strategy and actions for sustainable development and helped to further shape the EU Europe 2020 strategy as an effective tool for delivering on sustainable development. "Europe 2020-A strategy for smart, sustainable and inclusive growth" was launched by the European Commission launched a on 2010, March 3rd as a new 10-year economic strategy based on a higher coordination of national and European economic policy. The initiative wants to overcome the weaknesses of the Lisbon strategy and puts forward three mutually reinforcing priorities:

- Smart growth: developing an economy based on knowledge and innovation;
- Sustainable growth: promoting a more resource efficient, greener and more competitive economy;
- Inclusive growth: fostering a high-employment economy delivering social and territorial cohesion.

EU Europe 2020 Strategy objectives will be made operational through a range of key policies that are under preparation. The key policies will follow the recommendations of Rio+20 outcome document that provide a common framework for sustainable development,

[4] ***, "RENEWED EU SUSTAINABLE DEVELOPMENT STRATEGY", COUNCIL OF THE EUROPEAN UNION, Brussels, 2006.
[5] ***, Report of the United Nations Conference on Sustainable Development Rio de Janeiro, Brazil 20–22 June 2012.

where a balanced approach is sought among economy development, environmental protection and social equity.

Since more than 25 years, SD represents a part of our present and future. There is a continuous need to look forward towards sustainable technologies that could answer to our needs, without neglecting and compromising the needs of next generations. The development of sustainable technologies should target the energy supply sources and the energy consumers, either industrial, domestic or transport related.

It is generally accepted that two of the biggest challenges of our time, tightly linked to SD, are climate change and energy access and security.

There is growing interest in renewable energy around the world, as it offers the opportunity to contribute to a number of important sustainable development goals: energy access, energy security and climate change mitigation and the reduction of environmental impact of fossil-based energy systems[6]. Access to modern and affordable energy services is among the essential ingredients of economic development and requires a balanced energy portfolio sustained by the rapid recent growth in solar, wind, geothermal, biomass, wave energy, coupled with on-going technology improvements and cost reductions. Due to their dispersed nature and that of the resources they use, renewable energy sources will lead to intelligent energy management and to the decentralization of energy systems, playing a key role in increasing the energy security, while reducing or eliminating greenhouse gas emissions associated with energy use.

The integration of renewable energy generators has great impacts on the operation of the grid and calls for new grid infrastructure. Indeed, it is a main driver to develop the *smart grid* for infrastructure modernization. Smart grids are an evolving set of technologies, spanning the entire grid, from generation through transmission and distribution to various types of electricity consumers, as it can be noted in Figure 1.1. Some of these technologies are already found their maturity, while others require further development and demonstration.

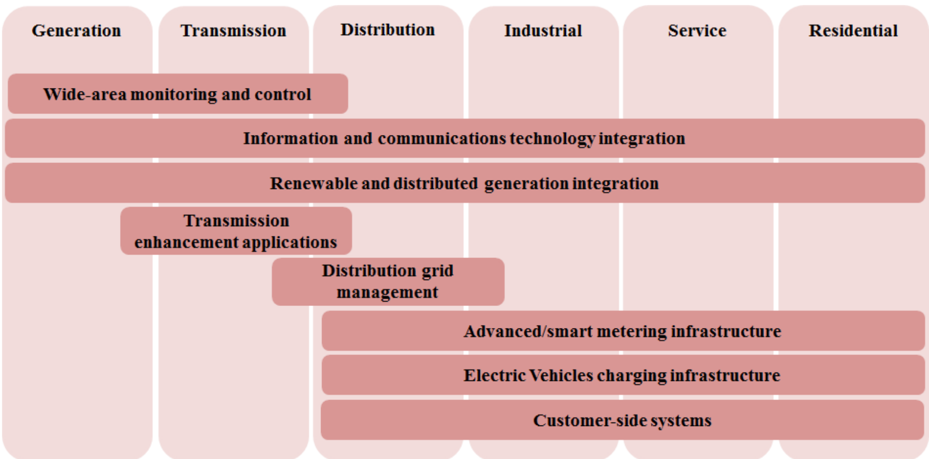

Fig. 1: Smart grid technologies

[6] Z. Chen, F. Blaabjerg, “Wind energy – the world’s fastest growing energy source”, IEEE Power Electronics Soc. Newsletter., vol. 18, 2006, pp. 15–19.

An important part of total energy use in the EU-27 in the last years is in buildings, residential and commercial, almost 30%, very close to the energy use in transport and more than in industry. In addition, the increasing number of households and shares of services in modern economies is expected to contribute to a rise of the energy demand in the near future. Small-scale distributed energy systems, with energy production and consumption usually tightly coupled, are emerging as a viable alternative. Using more than one energy sources, most often based on renewable energies or on high-efficiency fossil fuel-based technologies (combined heat and power) they are less dependent upon centralized energy supply, and, though, less sensitive to the uncertain availability of remote primary energy and transportation networks.

While the potential of renewable energy sources is enormous, the variable nature of their generation may pose integration challenges. Unlike the conventional sources of electric power, wind and solar power, for example, are not always available where and when needed. These renewable sources exhibit changing dynamics, nonlinearities, and uncertainties, challenges that require advanced control strategies for high-performance and reliable operation. Also, for the small-scale renewable technologies (SSRT) grid integration communication systems are crucial technologies, which enable the accommodation of distributed renewable sources and play a key role in monitoring, operating and protecting both generators and power systems.

Ambitious targets are established by EU's policies to surmount these problems and to promote energy from renewable sources, with a clear trajectory to 2050, with a focus on 2030, in order to provide the energy sector with the necessary investment stability and predictability as early as possible. Moreover, the continuous investment in R&D will add its contribution to ensure renewable energy technologies become competitive and ultimately market driven.

Although the European and national policies encourage householders, businesses and the public sector to consider installing small renewable technologies, such as small scale wind turbines (SWT), solar panels, micro-hydro power plants, the specific factors that drive the uptake of small scale grid-connected renewables are predominantly financial. Therefore, the high cost of the technology is the most important barrier to overcome. Renewable energy resources have also some problematic but often solvable technical and economic challenges, like being generally diffuse, not fully accessible, sometimes intermittent and regionally variable.

Thus, developing low-cost high performances solutions for small scale renewable technologies depends mainly on the type and performances of the drivetrain, including the mechanical transmission, the electrical generator and its related power electronics. For a simpler and lighter power plant the mechanical transmission can be eliminated and advanced technologies for the conversion system can be used. The direct-drive solution, for example, overcomes many disadvantages and brings a lower noise level, high overall efficiency and reliability, reduced weight and maintenance.

The automotive industry is one of Europe's key industrial sectors, since it is estimated to account for close to 8% of total manufacturing value added, almost 6% of total manufacturing employment (over 2 million employees), without considering the indirect employment (10-11 million persons) and it is one of the largest RTD investors in the EU. Any major disturbance to the automotive industry risks affecting the economic and social environment of Europe. For reducing the impact, the European Commission made the car industry a key focus of its recovery package, presented in November 2008.

The European Road Transport Research Advisory Council (ERTRAC), representing all sectors of the road transport industry, non-governmental organisations, Member States, and the European Commission, has developed a common vision, to identify research priorities and establish a Strategic Research Agenda for the next decades, and to stimulate its implementation[7]. Important European associations such as the European Association of Research and Technological Organizations (EARTO), the European Council for Automotive R&D (EUCAR), the European Association of Automotive Suppliers (CLEPA) and the European Automotive Research Partners Association (EARPA), have also defined major R&D priorities in automotive industry and road transport[8, 9, 10].

With ever increasing concerns on energy efficiency, energy diversification and environmental protection, the development of electric vehicle technology has taken on an accelerated pace. Internal combustion engine vehicles (ICEVs), in existence for over a hundred years and constantly being improved, need a major change to reduce fuel consumption and emissions. Electric vehicles (EVs) and hybrid EVs (HEVs) have been identified to be the most viable solution to fundamentally solve the problems associated with ICEVs.

For auxiliaries automotive applications, electrical actuation is a proven technology and offers benefits, including reliability, energy efficiency, and precise controllability. Enhancement of the vehicle performances and of the driving comfort, as well as the improvement of fuel economy and reduction of emissions are four important aspects that plead for introducing more decentralized electric drive systems in the vehicles[11, 12].

The automotive industry has a continuous high demand for electric drives. The field of actual automotive electric powered units spans a broad range including cooling fans, window and chair actuation, steering, braking, suspension, starter-alternator (integrated or belt driven), HVAC, propulsion for hybrid and full electric vehicles (HEV/EV). The further enhancement of high-performance automotive electric actuation requires energy-efficient, reliable, robust, low-cost electrical machines and highly integrated, energy-efficient power electronics and control modules. For achieving these requirements, the R&D activities should focus on the analysis and development of new topologies and concepts of electrical machines, taking into account the need for energy efficient drives, the harsh automotive environment (high temperature, vibrations, standards for the measurement of pass-by noise, etc.) and the availability of raw materials (in particular rare-earth materials for permanent magnets).

[7] ERTRAC Research Framework Steps to Implementation, European Road Transport Research Advisory Council, 2008, www.ertrac.org
[8] R&D Priorities for the Greening of Vehicles and Road Transport - A contribution by CLEPA and EUCAR to the European Green Car Initiative, EUCAR and CLEPA, 2009, www.eucar.be.
[9] European Roadmap Electrification of Road Transport, EPoSS, ERTRAC and SmartGrids, 2009, www.ertrac.org, http://www.smart-systems-integration.org.
[10] Further advances in automotive safety importance for European road transport research, EARPA, 2009, http://www.earpa.eu/.
[11] ***: "Challenges for a European market for electric vehicles", European Parliament, Directorate General for Internal Policies, Policy Department: Economic and Scientific Policy, 2010.
[12] ***: "Hybrid Electric Vehicle Components & Systems Importance for European Road Transport Research and FP7", EARPA Position Paper, January 2010.

In modern applications where both the environment and the specifications are placing more severe restrictions and demands on the EMD, it is becoming critical to consider the design at a system integration level, taking into account the multiple domains that are interconnected and influence each other. The electromagnetic, thermal, mechanical and vibro-acoustic design of the system must be considered simultaneously if the specifications are to be satisfied in the given environment. The four designs required for system integration are tightly interconnected and any change in one design will have consequences on the remaining three.

Therefore, there are many factors and constraints to be taken into account at the design stage of an EMD, especially for sustainable electromechanical systems for automotive an renewable energies based applications. Due to the complex, often contradictory requirements related to the different technologies and the diversity of potential solutions, modelling, simulation and testing tools and methods are needed for supporting the designer during the different phases of the development process. The three major challenges that should be considered and overcome by an appropriate design environment address **multi-domain**, **system integration** and **multi-level issues**.

Condition monitoring and diagnosis methods provide the knowledge and tools in order to detec, identify and isolate any possible fault at an early stage, avoiding an irreversible damage of a system. Moreover, fault tolerance is an important feature of sustainable systems, integrated in the early stage of conceptualization and design of every system.

2. CONDITION MONITORING AND DIAGNOSIS IN ELECTROMECHANICAL SYSTEMS

The history of monitoring and diagnosis is as old as the electromechanical systems (EMS) themselves. The manufacturers and users of EMS relied at the begining on simple protections such as over-current, over-voltage, earth-fault, etc. to ensure safe and reliable operation. As the electrical actuator is one of the critical components of the EMS, condition monitoring and diagnosis of electrical actuators in general and of electrical machines in particular became an important research and development subject for both industry and academia. Moreover, it is very important to diagnose faults at their very inception, as unscheduled actuator downtime can influence deadlines and cause financial losses.

Three-phase induction machines are widely used in industry and they are known as reliable and cheap component of a drive system. However, even if this electromechanical component is reliable, it can be submitted to external stresses coming from the system and degradation can occur even in the electrical and the mechanical parts of the induction machine itself. Due to the progress of signal processing techniques and related instruments, on-line monitoring has been used for electrical machines for which mechanical or electrical failures can be considered as a catastrophic event. Electrical fault detection in induction machines has been investigated largely for the last twenty years with success. However, the technology in this field is still in evolution and new instruments are under development. The fault classification for induction machines has been already presented in several publications[13]. If the interest is concentrated on electrical faults, it has to be related to the stator windings and to the rotor electrical configuration, considering only the squirrel cage

[13] S. Mandi, H. Toliyat, „*Condition monitoring and fault diagnosis of electrical machines – a review*", IAS Meeting, 1999.

structure that represents more than 99% of the induction machines manufacturing for the last ten years. Then, it is interesting to note that each electrical fault can have influence on both electrical and mechanical variables that can be measured around the induction machine[14].

The fault detection and identification methods usually involve several different types of fields of science and technology. They can be classified as: electromagnetic field monitoring, search coils, coils wound around motor shafts (axial flux related detection); temperature measurements; infrared recognition; radio frequency (RF) emissions monitoring; noise and vibration monitoring; chemical analysis; acoustic noise measurements; motor current signature analysis (MCSA); model, artificial intelligence and neural network based techniques. The most usually faults are: bearing problems, the stator or armature faults, the broken rotor bar and end ring faults of induction machines and the eccentricity related faults.

The research activity of the candidates in the field of electrical machines monitoring and diagnosis was performed at the beginning in the frame of a postdoctoral research stay at Universite Jules Verne Picardie, Amiens, France, between November 2001 and June 2002. The candidate worked together with Professor Humberto Henao, under the coordination of Professor Gerard A. Capolino. The main target of the research work during the mentioned period was the development of a model-based monitoring and diagnosis methods for induction machine electrical faults.

The consequences of inter-turn short circuits during motor operation are the reduction of the electromagnetic torque and damage of adjacent coils. Concerning the rotor bars faults, the effects are additional stator current frequencies and additional synchronous torques. This is the reason why these faults can be detected only by indirect measurements on the stator side or outside the machine[15].

Different methods have been proposed for stator and rotor fault detection. For example, the most well-known approaches for diagnosis of broken rotor bars in three-phase induction machines are based on the monitoring and processing of the stator currents to detect sidebands around the fundamental and other space harmonics present in the line current[16]. Methods based on measuring harmonics in motor torque, speed, and stray flux have also been developed. Circuit-oriented modeling approach can be envisaged in order to obtain an induction machine model from the distributed nature of machine windings on a conductor-by-conductor basis. The evaluation of unexpected behavior arising from model phenomena may be much realistic than clustered phase models. The use of circuit modeling allows time-domain investigations without having to implement transformation techniques. Then, the machine construction characteristics may be taken into account to introduce some physical particularities, as the distribution of the machine windings, the slot geometries and the squirrel-cage structure[17,18].

[14] G.A.Capolino, "A comprehensive analysis of the current status in low voltage induction motor diagnosis," Invited paper plenary session), Proceedings International Conference on Electrical Machines (ICEM'00), Espoo (Finland), August 2000, vol.2, pp.595-602.
[15] H. Henao, C. Demian, and G. A. Capolino, "*A frequency-domain detection of stator winding faults in induction machines using an external flux sensor*," *IEEE Trans. Ind. Applicat.*, vol. 39, pp. 1272–1279, Sept./Oct. 2003.
[16] A. Bellini *et al.*, "ENEL's experience with on-line diagnosis of large induction motors c age failures," in *Conf. Rec. IEEE-IAS Annu. Meeting*, vol. 1, Rome, Italy, Oct. 2000, pp. 492–498.
[17] C. Delmotte, H. Henao, G. Ekwe, P. Brochet, and G. A. Capolino, "Comparison of two modeling methods for induction machine study: Application to diagnosis," *COMPEL-Int. J. Comput. Math. Elect. Electron. Eng.*, vol. 22, no. 4, pp. 891–908, Oct. 2003.

A complete study of the induction machine allowing the determination of its harmonic characteristics generated in the line current was performed[19]. The method used to analyse the induction machine behaviour is based on the circuit-oriented approach. The developed model facilitates the estimation of frequencies and maximum values of the stator current harmonic components. Using the EMTP/ATP electrical network simulation package, the obtained circuit-oriented model is simulated in normal conditions at the rated load and the results are compared with theoretical results and experimental measurements.

Also a theoretical approach of the stray flux analysis in a three-phase squirrel-cage induction machine for stator and rotor electrical faults detection was carried out[20]. Initially, the stray flux is analyzed in a point outside the machine using the Biot-Savart law, taking into account the effect of the end-windings for the stator and the end-ring segments for the rotor squirrel-cage. The theoretical results are compared with experimental measurements on a healthy induction machine and on a faulty one under stator and rotor defects. The experimental tests have validated the analytical formula for the frequency of the harmonic components in the stray flux under stator and rotor electrical faults.

A complete analytical description of the rotor broken bars effects on the induction machine behavior, for diagnosis purposes was presented[21]. The stator current and the electromagnetic torque are important elements to study in order to define the behavior of the healthy induction machine and can provide a model-based approach of the rotor bars fault detection in induction machine. An experimental validation of the proposed analytical approach is provided.

The effect of space harmonics in the frequency components of stator and rotor currents under stator and rotor faults are analytically calculated in steady-state conditions. In order to validate the circuit-oriented approach, experimental measurements for an 11-kW 230-V/400-V 50-Hz four-pole induction machine in normal operating conditions and under winding short circuit are performed[22].

The research was extended on wound rotor IM. An analytical approach of the frequency response for the wound rotor induction machine as a possible method for fault diagnosis was proposed and analysed[23]. This approach is based on mmf, flux and emf computation for both healthy and faulty machines during any operating condition. The proposed technique is applied to study the effect of opening one phase either on stator or rotor sides. The computed harmonics of both stator and rotor currents are experimentally verified on a test-bed based on a small power wound rotor induction machine.

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[18] H. Henao, G. A. Capolino, and M. Poloujadoff, "A simulation methodology for induction machine diagnostics using the alternative transients program (EMTP/ATP)," in *Proc. Int. Symp. Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED'97)*, Carry-le-Rouet, France, Sept. 1997, pp. 185–190.

[19] Claudia Martis, H. Henao, G. A. Capolino, M. M. Radulescu: " *Harmonic characteristics of an induction machine connected to a distribution network*"- , The 28th Annual Conference of the IEEE Industrial Electronics Society Sevilla, Spain, CD-ROM, Paper SF - 006950, Nov.2002.

[20] H. Henao, Claudia Martis , G.A. Capolino: "*On the stray flux analysis for the detection of the three-phase induction machine faults*", Procedings of the 38th Annual IAS Meeting, October 2003, Salt Lake City, Utah USA, pp., 2003.

[21] Claudia Martis, B. Dobai, K. Biro: " *Analytical approach of the rotor broken bars effects on the induction machine behaviour*", ICIT'03 International Conference on Industrial Technology, ICIT'03 Maribor, on CD, RP3_06, ISSN 0-7803-7853-9, Slovenia December, 2003.

[22] H. Henao, Claudia Martis, G.A. Capolino: "*An equivalent internal circuit of the induction machine for advanced spectral analysis*", IEEE Transactions on Industry Applications, vol. 40, no. 3, pp. 726-734, may-june 2004.

[23] H.Henao, Claudia Martis , G.A. Gapolino: "*Analytical approach of the frequency response for the wound rotor induction machine for diagnosis purpose*", SDEMPED 2005, ISBN 0-7803-9123-X, pe CD, SD-5060, 2005.

The results of the research activity in the field of condition monitoring and diagnosis were presented in nine scientific articles published in international conferenecs proceedings and in scientific journals. Six of these articles are published in ISI and BDI indexed publications. All the six articles are cited by ISI and BDI indexed articles.

3. ELECTRIC GENERATORS FOR SMALL-SCALE RENEWABLE TEHNOLOGIES

There is growing interest in renewable energy around the world, as it offers the opportunity to contribute to a number of important sustainable development goals: energy access, energy security and climate change mitigation and the reduction of environmental impact of fossil-based energy systems. Access to modern and affordable energy services is among the essential ingredients of economic development and requires a balanced energy portfolio sustained by the rapid recent growth in solar, wind, geothermal, biomass, wave energy, coupled with on-going technology improvements and cost reductions. Due to their dispersed nature and that of the resources they use, renewable energy sources will lead to intelligent energy management and to the decentralization of energy systems, playing a key role in increasing the energy security, while reducing or eliminating greenhouse gas emissions associated with energy use.

The Directive 2009/28/EC on renewable energy, implemented by Member States by December 2010, sets ambitious targets for all Member States, such that the EU will reach a 20% share of energy from renewable sources by 2020 and a 10% share of renewable energy specifically in the transport sector. It also improves the legal framework for promoting renewable electricity, requires national action plans that establish pathways for the development of renewable energy sources, creates cooperation mechanisms to help achieve the targets cost effectively and establishes the sustainability criteria.

The EU Renewables Directive addresses two of the biggest challenges of our time: energy security and climate change. Moreover, recent trends, including increased electricity needs and advancements in grid management technologies are asking for a rethought of how the grid is upgraded and managed.

Electricity production, under the current centralized paradigm, is mainly linked to large generation facilities and then shipped through the transmission and distribution grids to the end consumers. Due to its higher level of integration, this type of energy supply system is vulnerable to disturbances, but apart this there are several issues reducing its attractiveness[24]. In the context of overcoming centralized energy supply systems disadvantages and taking into account the request for energy efficient and reliable energy production/supply systems one viable solution is to complement or even replace the existing paradigm with distributed generation where the electricity is produced next to its point of use.

Small-scale decentralized distributed generation systems (SSDDGS), using one or more renewable energy resources (fuel cells, photovoltaic cells, batteries, micro turbines, etc,) are highly flexible, allowing solutions to be tailored to local conditions and be installed much faster than a centralized system. Moreover they represent a possibility of getting to grips greenhouse emissions and reducing the contribution of the classical electricity system to climate change. SSDDGS can be integrated in micro-grids as small and flexible networks

[24] ***, "Research priorities for renewable energy technology by 2020 and beyond", *EUREC Agency Publication*, Belgium 2009.

having the ability to disconnect from the grid and operate independently under normal or abnormal conditions[25,26,27]. Although the European and national policies encourage householders, businesses and the public sector to consider installing small renewable technologies, such as small scale wind turbines (SWT) or solar panels, the specific factors that drive the uptake of domestic scale grid-connected renewables are predominantly financial. Therefore, the high cost of the technology is the most important barrier to overcome.

Developing a low-cost high performances solution for a SWT depends mainly on the type and performances of the drivetrain, including the gear-box, the electrical generator and its related power electronics. For a simpler and lighter wind power plant the gear can be eliminated and a low-speed generator can be used. The direct-drive solution overcomes many disadvantages and brings a lower noise level due to the low rotation speed, high overall efficiency and reliability, reduced weight and maintenance.

3.1. Advanced electromechanical technologies for small-scale wind applications

Different wind turbine concepts have been developed and built in order to maximize the energy harnessed, to minimize the cost and improve the power quality during the last decades[28,29]. Considering various types of existing wind generators and new generator topologies being developed for wind turbines, how to design and develop cost-effective generator topologies for wind turbines is an interesting issue, because each type has its strengths and weaknesses.

There is an intensive R&D work all over the world in this field. Different direct-drive and geared generator systems of the wind turbines have been discussed by a number of authors in a comparative manner trying to find the best solution for a specific power range. An important part of the R&D work was focused on drivetrain technologies for large on- and off-shore wind farms. Little work was done on the design and analysis of SWT technologies.

The definition of SWT is generally accepted to include any device up to a rated power of 50kW (typically 16m diameter). For domestic applications they are generally less than a few metres in diameter and generate 2-3 kW of power and they can be mounted on roof-tops or free-standing poles. They can be designed for both grid-connected and stand-alone operation, in conjunction with a power converter.

The SWT industry consists of more or less 250 companies, spread in 26 countries. The biggest part of these companies (more than a third) and the largest are located in USA. Some other important manufacturers are located in UK and Netherlands. Most of their SWT direct-driven concepts are mainly using a permanent magnet synchronous generator (PMSG) using high energy rare earth permanent magnets and a full-scale power electronic

[25] B. Kroposki, T. Basso, R. DeBlasio, “Microgrid standards and technologies,” *Proc. IEEE Power and Energy Society Annual Meeting*, 2008, pp. 1-4.
[26] G. Venkataramanan and C. Marnay,”A larger role for microgrids,” *IEEE Power and Energy Mag.* vol. 6, no. 3, pp. 78-82, 2008.
[27] H. Aki, “Independent hybrid renewable energy systems: example applications around the world”, *Proc. IEEE Power and Energy Society Annual Meeting,* 2010, pp. 1-4.
[28] D. Bang, H. Polinder, G. Shrestha, J.A. Ferreira, “Review of Generator Systems for Direct-Drive Wind Turbines”, EWEC 2008, Brussels.
[29] H. Polinder, D.J. Bang, H. Li, Z. Chen, „Concept report on generator topologies, mechanical & electromagnetic optimization”, report Project UpWind, Contract No.: 019945 (SES6), 2011.

converter for the grid connection, as they are considered to be more superior in terms of energy yield, reliability and maintenance problem[30,31,32,33].

The permanent magnet claw-pole synchronous generator (PMCPSG) for SWT was one important subject of the candidate work, as co-supervisor of the doctoral work of Florin Jurca. The research work on PMCPSG for SWT envisaged the design, analysis and optimization of the generator. Different topologies, different core and permanent magnet materials were considered and the performances of the generator were analysed. Between 2004 and 2009, the candidate was co-author of 30 scientific articles on PMCPCG. The articles were presented at national and international conferences and published in national and international indexed and non-indexed journals. Eight of these articles are included in cited ISI journals (1) and proceedings (7) and other 5 are included in cited BDI proceedings. Six articles are cited by articles included in ISI and BDI journals and proceedings.

First step in the development of the PMCPSG is an analytical design process narrowing the design space to an acceptable solution, meeting required performance specifications. The analytical procedure includes the following topics: analysis of the specifications, selection of the topology and of the active and passive materials, dimensioning of the geometry, parameter and performance calculation, choice of the manufacturing technologies and costs prediction.

After the design is settled, the PMCPSG models can be extracted for further analysis and optimization. Numerical analysis using Finite Element Method (FEM) based software package allows a more comprehensive analysis of the performances of the structure that resulted from the analytical procedure. It gives more accurate results and it helps to improve the machine design and chose the proper objective function and variables for the optimization. An advanced optimization design process usually considers simultaneously the topology and materials optimization and then, if necessary, the shape and sizing optimization.

For design, analysis and development a claw-pole topology with Z_s stator slots and p claw-poles carried by two rotor steel plates was chosen. The selection of the proper combination between the number of the stator slots and rotor poles is based on: operational speed of the motor in the application, torque and power density aspects, cogging torque constraints, harmonic content and amplitude of the back-emf, torque quality, acoustic behavior, etc[34]. An axially magnetized permanent magnet (PM) mounted on the shaft, between the steel plates was considered. The slotted stator is equipped with a *m*-phase AC winding. A machine with 36 stator slots and 8 claw-poles is presented in Figure 2. A similar studied topology for a modular PMCPSG is presented in Figure 3.

[30] J.R. Bumby, N. Stannard, J Dominy, N. McLeod, "A Permanent Magnet Generator for Small Scale Wind and Water Turbines", Proceedings of the 2008 International Conference on Electrical Machines Paper ID 733.
[31] Y.S. Park, S.M. Jang, J.H. Choi, J.Y. Choi, D.J. You, "Characteristic Analysis on Axial Flux Permanent Magnet Synchronous Generator Considering Wind Turbine Characteristics According to Wind Speed for Small-Scale Power Application", IEEE TRANSACTIONS ON MAGNETICS, VOL. 48, NO. 11, NOVEMBER 2012.
[32] K. Sitapati, R. Krishnan, "Performance comparisons of radial and axial field, permanent-magnet, brushless machines," IEEE Trans. Indus. Appl., vol. 37, no. 5, pp. 1219–1225, Sep./Oct. 2011.
[33] M. Abarzadeh, H.M. Kojabadi, L. Chang, "Small Scale Wind Energy Conversion Systems", http://www.intechopen.com/books/wind-turbines/small-scale-wind-energy-conversion-systems
[34] G. Henneberger, I.A. Viorel, "Variable reluctance electrical machines", Shaker Verlag: Aachen; 2001.

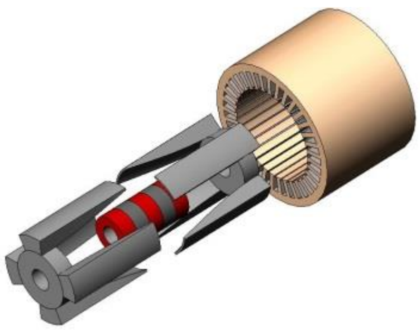


Fig. 2: 8-poles PMCPSGi.

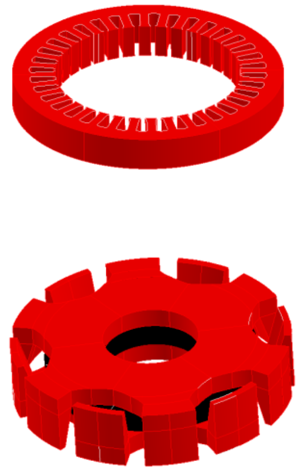
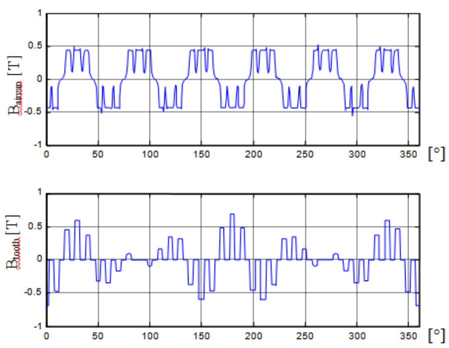


Fig. 3: Stator/rotor topology for a modular PMCPSG.

The magnetic flux density distribution affects the voltage waveform, and the losses, and hence the efficiency. The finite element method (FEM) is a simple, robust and efficient widely used method of obtaining a numerical approximate solution for a given mathematical model of the machine. Due to the complex three-dimensional structure of claw-poles, the magnetic field inside the claw-pole generator needs to be treated as a 3D problem, using Flux 3D software, considering the geometry details and non-linear magnetic properties of the materials[35,36,37,38]. The influence of different geometrical dimensions (stack length, pole length, pole width, etc), core material and permanent magnet material was analysed[39].



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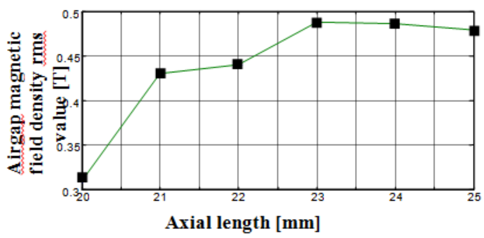


b

Fig. 4: Magnetic field distribution along the airgap and at tooth level (a) and its rms value as a funtion of a stack lenght of the machine (b).

[35] F. Jurca, Claudia Martis, I. Birou, K. Biro: "Analysis of a claw-pole synchronous machine for wind power conversion module", International conference on Electrical Machines, ICEM 2008, Vilamoura, Portugal 2008, on CD, E-ISBN : 978-1-4244-1736-0, Print ISBN: 978-1-4244-1735-2.
[36] Pyrho J, Jokinen T, Hrabocova V. Design of rotating electrical machines. John Wiley&Sons; 2008.
[37] Cioc I, Bichir N, Cristea N. Masini Electrice – Indrumar de proiectare, vol. II, Scrisul Romanesc Publishing House, 1981.
[38] F. Jurca, Claudia Martis, K. Biro: "Claw-pole generator analysis using flux 3D", SPEEDAM 2008 - International Symposium on Power Electronics, Electrical Drives, Automation and Motion, art. no. 4581153, pp. 1286-1291, 2008, E-ISBN : 978-1-4244-1664-6, Print ISBN: 978-1-4244-1663-9.
[39] F.Jurca, Claudia Martis, I. Birou, K. Biro: "Analysis of a claw pole synchronous machine for wind power conversion module", International Conference OPTIM 2008, Braşov, Romania, Print ISBN: 978-1-4244-1735-3, pg. 1-6.

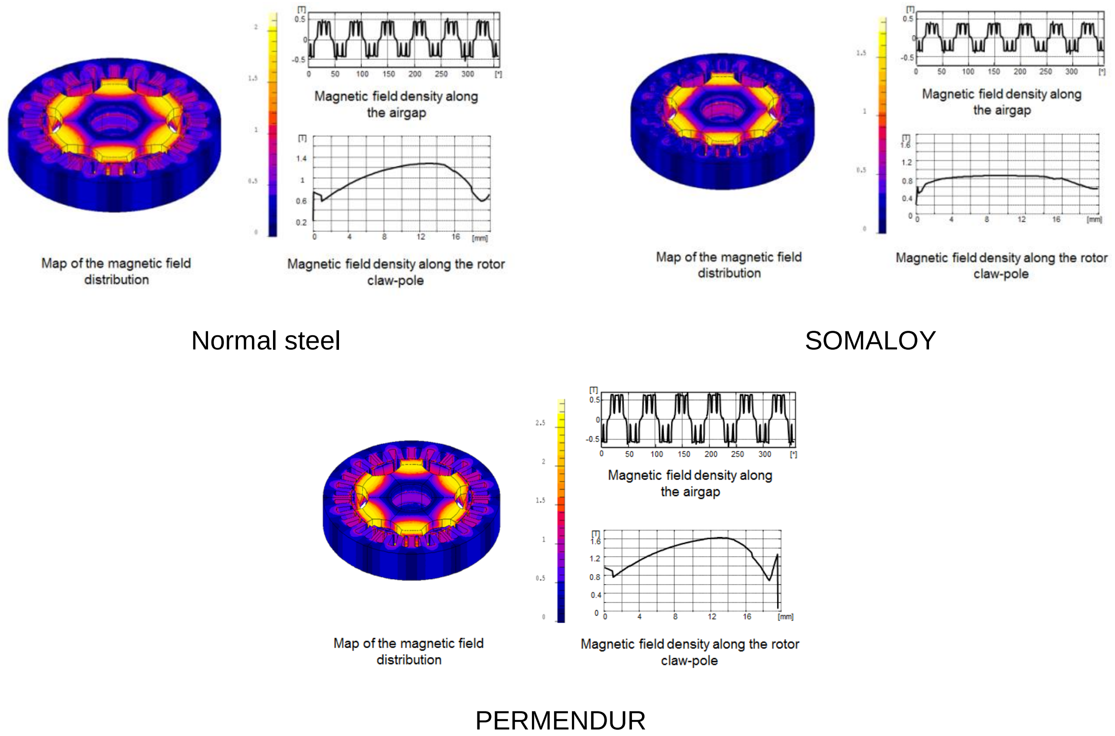


Fig. 5. Magnetic field density : map and distribution alog the airgap and claw-pole, respectively.

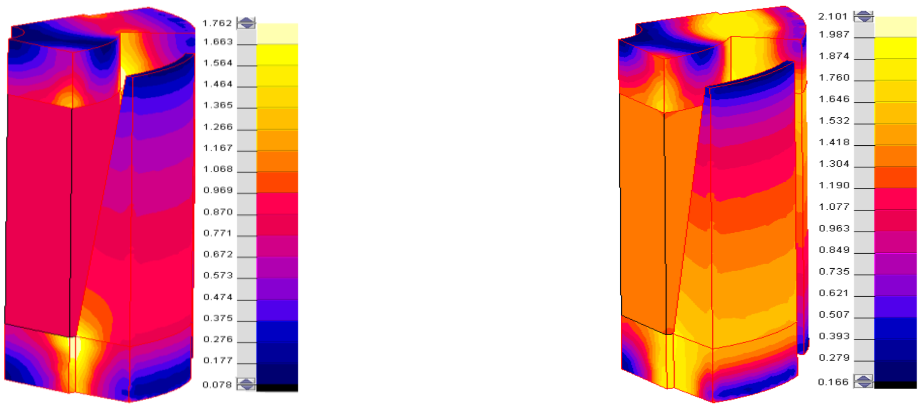
For high-performance or high frequency applications, the amorphous materials may replace the electrical steel. The core losses are lower due to material structure and due to material thickness, but a thin lamination increases the costs of manufacture and assembly. The saturation flux density level is around 1.8T, lower than that of the electrical steel (typically between 2...2.2T). Another solution could be represented by soft ferrites, but their saturation flux density level is only 0.35...0.5T. For applications requiring high flux density levels or high saturation flux density, Co-Fe alloys may be used. The highest saturation level corresponds to 2.34T (Permendur Fe49-Co49-2V). The complicated metallurgy of these alloys and the high price of cobalt represent important constraints and their use as a core material is restricted to some specific applications, for which the high material cost can be allowed[40]. For a PMCPSG module (Figure 9) the magnetic field density (in different section of the machine) for different rotor material is shown in Figure 5.

The overall performances of the PMCPSG are also linked to the type of the permanent magnets placed around the shaft[41] and to the geometry of the claw poles[42].

Several analysis were performed for the topology presented in Figure 2, with an ALNICO and a NdFeB magnet mounted on the shaft, respectively. The maps of the magnetic field

[40] F. Jurca, Claudia Martis, K. Biro: “Magnetic material influence on the performances of a claw-pole synchronous generator for wind systems”, International Conference and Exhibition on Power Electronics Intelligent Motion Power Quality, PCIM 2008, Nuremberg, Germany, on CD.
[41] F. Jurca, Claudia Martis, K. Biro: “Claw-pole generator analysis using flux 3D”, SPEEDAM 2008 - International Symposium on Power Electronics, Electrical Drives, Automation and Motion, art. no. 4581153, pp. 1286-1291, 2008, E-ISBN : 978-1-4244-1664-6, Print ISBN: 978-1-4244-1663-9.
[42] F. Jurca, C. Martis, K. Biro: “Claw-pole synchronous generator optimization topology” International Symposium on Electromagnetic Fields (ISEF), Arras 2009, pe CD, ISBN 978-2-84832-115-8.

density for the rotor claw-pole&steel plate (considering only one pole pair), at no-load, is given in Figure 6.



a b

Fig. 6: Magnetic field density map for one pole pair for the PMCPSG with ALNICO (a) and NdFeB (b).

As it can be noted, the magnetic field density value at the basis of the claw-pole, where the direction of the magnetic field path is changing, for the machine carrying NdFeB PMs is close to the saturation value. For avoiding the saturation, a shorter NdFeB PM should be used. Moreover, according to different studies on the claw pole machine, better performances can be obtained by using a specific shape for the claw-pole.

Thus, a complete design-analysis-optimization-testing procedure was developed[43]. An analytical pre-sizing algorithm was developed and implemented for different specifications. The main dimensions of the machine were computed, the windings were designed and the electromagnetic and electromechanical performances were analytically(magnetic equivalent circuit based analysis) and numerically (Finite Element analysis) evaluated. The magnetic equivalent circuit of the PMCPSG is presented in Figure 7.

An optimization procedure based on the analytical design procedure could be implemented and several variables (x_i) can be selected: rotor pole width at the base of the claw-pole (b_{pr1}), rotor pole width at the tip of the claw-pole (b_{pr2}), rotor pole tip height (h_{pr2}) and rotor pole length (l_{prt}) given by: $l_{prt}=l_{pr}+l_{t}$. In order to keep the topology, functional limits are set for each variable and specific constraints are set, together with a penalty coefficient for including them in the objective function.

The optimization of electric machines is a multivariable, nonlinear problem with constraints. As the objective functions cannot be expressed in a closed form, it is only possible to choose optimization methods which do not use derivatives of these objective functions. To treat problems with constraints is necessary to transform them in unconstrained ones. This can be done for example by embedding the constraints in the objective function. The so-called

[43] F. Jurca, Claudia Martis: "*Theoretical and experimental analysis of a three-phase permanent magnet claw-pole synchronous generator*", IET Electric Power Applications 2012, Vol. 6, Iss. 8, pp. 491–503.

direct search optimization methods fulfill these requirements. Hooke-Jeeves, one direct search method, was selected for the present application[44,45].

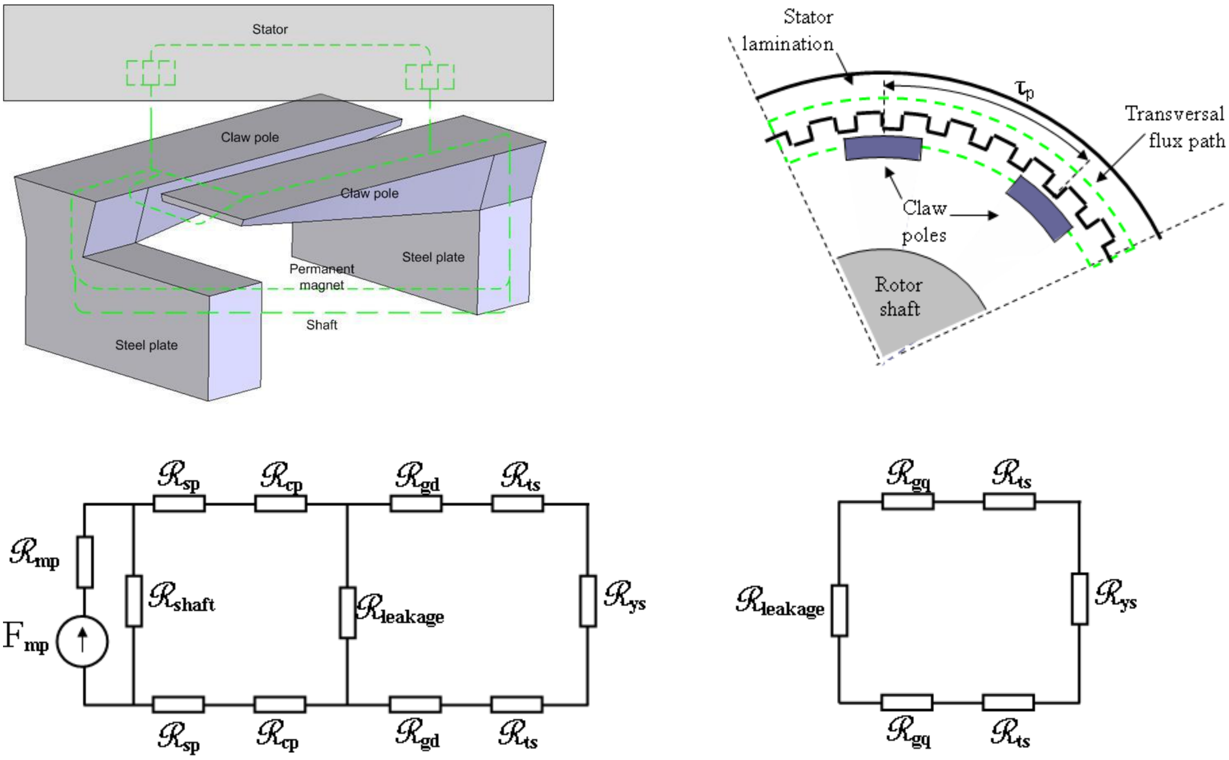


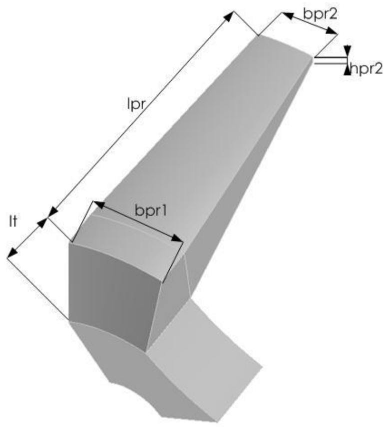
Fig. 7: d- and q-axis equivalent magnetic circuit and flux paths..

In the Hooke-Jeeves method, a combination of exploratory moves and heuristic pattern moves is made iteratively. The exploratory search is done starting from an initial known point. The point is incremented in a coordinate direction by the specified step in that direction, and the objective function is evaluated. According to the result the move is accepted or not. The exploratory search is complete when all the n coordinate directions have been explored. For a successful search the new design point is called the current base point (X(k)). If the search fails, it will be repeated with a reduced step sizes. The pattern search is done in a single step in the direction given by the precedent and the actual point, and a new point is defined (X(k+1)), called temporary base point. Finding this point, a new exploratory search is initiated. If the search is successful, then the temporary base point is accepted as the new base point. If not, the base point is rejected and a new exploratory search is performed from the current base point. The procedure will continue till the exploratory search fails. Then it will be repeated with reduced step sizes and finally stops when the step sizes become sufficiently small.

Different objective functions are important for this kind of machine/application: maximum efficiency, maximum generated voltage, minimum cost. The efficiency and the generated voltage for no-load regime, were selected to build the multiobjective optimization function. The optimal geometry solution for the NdFeB claw-pole rotor is given in Figure 8a. The no-

[44] Kalyanmoy D. Optimization for engineering design: algorithms and examples. PHI Learning Pvt. Ltd; 2004.
[45] Rao S. Engineering Optimization. John Wiley & Sons; 1996.

load regime of the optimal machine topology, for the rated rotation speed was simulated. Figure 8b presents the maps of the magnetic flux density in the rotor core.



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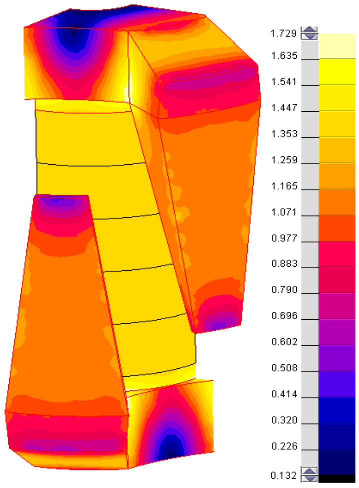


b

Fig. 8: Claw-pole optimal geometry (a), magnetic field density map for the rotor (b), respectively.

The optimized topology was built and tested, the results being presented in the PhD thesis of Florin Jurca[46].

During the last years, the PMSM market has to face the higher and higher price of the rare earth PMs provided mainly by Chinese industry. Thus it becomes inevitable, in the next future, the orientation to new and less expensive solutions, by maintaining, or even improving if possible, the level of performances, efficiency and reliability.

Therefore, by eliminating, reducing the volume or replacing the high energy PMs by low cost ferrite PMs, a decisive step towards a more cost effective and supply secure solution is taken. Several alternatives are to be taken into account. But among them, flux switching machine (FSM) seems to be the most suited candidates for SWT applications, especially for low wind speed locations.

The flux switching machine (FSM) concept it is not a new one and since 1950s [47,48] it was under continuous research and development all over the world. With all active parts accommodated by the stator and with a salient rotor similar to the one of switched reluctance machine (SRM), FSM has important advantages for motoring applications: high power density, simple and robust rotor, easy cooling, high speed and fault tolerance capabilities. The FSM can have various configurations (topologies). The major classification criteria are:

[46] Florin Jurca, "Generator cu poli gheară pentru microcentrale electrice", Teză de doctorat, Universitatea Tehnică din Cluj-Napoca, 2009.
[47] S. E. Rauch and L. J. Johnson, "Design principles of flux-switching alternators," AIEE Trans. 74III, pp.1261-1268, 1955.
[48] A.E. Laws, "An electromechanical transducer with permanent magnet polarization," Technical Note No.G.W.202, Royal Aircraft Establishment, Farnborough, UK, 1952.

excitation type; airgap flux orientation; stator core construction [49]. More information are to be given in Chapter 5.

3.2. Advanced electromechanical technologies for wave energy conversion systems

The ocean has an enormous energetic potential, capable of solving much of the present and future energy problems. Just by considering that 60% of the Earth's surface is covered by oceans and that water density is 800 times greater than air's it is obvious that the energy in the oceans is enormous. The coastal waters of Great Britain could provide 1 TWh daily, energy equal to the total electric consumption of the country[50]. Although the energy density is greater than that of other renewables and offers higher predictability, the ocean energy is not as attractive because it involves specific problems: deployment and maintenance cost are higher, energy must be transported to the shore, the devices must work in an aggressive environment and so on. Ocean energy can be divided into the energy of ocean waves, tides, salinity of ocean or temperature differences, numerous solutions for transforming these into usable energy being proposed[51]. Both linear and rotational electrical generators were used for the conversion of the wave energy into electrical one.

A direct-drive power take-off system for a WEC eliminates all the mechanical or hydraulic systems that are usually used to convert the wave motion into rotational motion compatible with conventional electrical generators, thus improving the reliability and efficiency of the system, a crucial aspect in the field of WEC. Linear generators can be incorporated in several ways in the wave energy absorber, but the working principle is the same: the stator, containing the coils, is fixed on the seabed or mounted on a high inertia device, making it relatively stationary, while the moving part is connected to a floating body that is moved up and down by the waves.

From the variety of linear generator structures, the ones using mobile coils are not considered, since they would imply reliability risks; the remaining structures can be divided into structures with moving iron of moving permanent magnets.

A study on the shears stress developed by various linear generator topologies pointed out that the Transverse Flux Machines (TFM) provide the highest force density in the air gap, but their complicated structures imply high manufacturing costs[52]. At the same time, because of their structure, only one- or two-sided structures have been reported, so high magnetic forces appear between the stator and the translator[53]. Another solution is the Vernier Hybrid Generator, with a simplified construction at the cost of lower shear stress values than the TFM[54]. It has a passive translator with teeth, while the stator is made of "C" shaped parts, which have both the coils and the PMs. The major drawback of such a structure is the high mover mass determining high inertia.

[49] Z.Q. Zhu, and J.T. Chen, "Advanced flux-switching permanent magnet brushless machines," (invited paper), IEEE Trans. Magnetics, vol.46, no.6, pp.1447-1453, 2010.

[50] Cruz J., editor Green Energy and Technology – Ocean Wave Energy, Current Status and Future Perspectives, Springer-Verlang Berlin Heidelberg, 2008.

[51] C. Miller – "A Brief History of Wave and Tidal Energy Experiments in San Francisco and Santa Cruz", http://www.outsidelands.org/wave-tidal.php

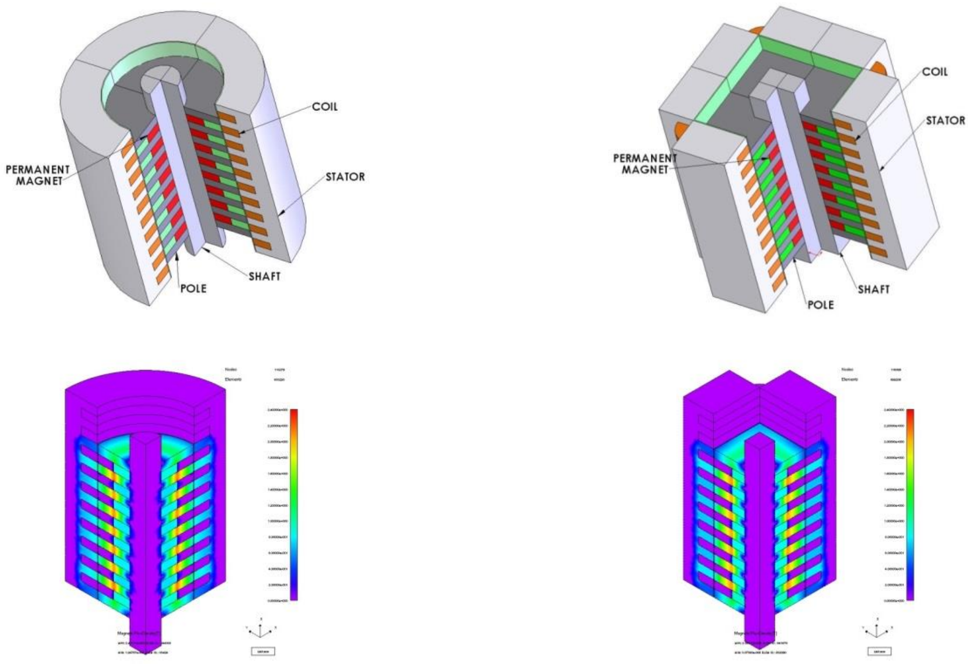
[52] Polinder H.; Mecrow B.C.; Jack A.G.; Dickinson P.G.; Mueller M.A. Conventional and TFPM linear generators for direct-drive wave energy conversion, IEEE Transactions on Energy Conversion, Volume 20, Issue 2. 260-267.

[53] N. J. Baker, and M. A. Mueller, "Design and Integration of Linear Generators into Direct Drive Wave Energy Converters'', Proceedings of Marine Renewable Energy Conference, Newcastle, March 2001 ISBN 1-902536-43-6.

[54] M.A. Mueller, J., N.J., P.R.M. Brooking – "Dynamic Modelling of a Linear Vernier Hybrid Permanent Magnet Machine Coupled to a Wave Energy Emulator Test Rig", Conference Record of the International Conference on Electrical Machines ICEM '2004, Cracow (Poland), on CD, 2004

Perhaps the simplest solution, although with lower shear stress values, is to use tubular permanent magnets mounted between iron pole pieces in sandwich type structure to form the moving part and ring shaped coils mounted on the stator. Such a structure would require the stator to be made of laminations to limit the magnetic losses that would appear in a solid stator. While in one or two sided structures the use of laminations is not a problem, in tubular topologies such a construction is problematic, because the laminations must be mounted parallel to the movement direction. Two solutions were investigated: completely eliminate the iron in the stator so the latter is made up of coils mounted on a nonmagnetic support resulting in a higher air gap, with negative influence on the generator performances or replace the tubular structure with a structure with more stators, varying from 2 to 8, mounted around the translator[55,56]. As the number of stators is higher, the approximation of the tubular structure is more accurate, but the manufacturing cost is higher.

Based on topologies reported in the literature and a rough pre-sizing procedure two configurations were considered[57]. First one corresponds to a tubular structure and it is given in Figure 9a. The second one, having similar envelope and identical permanent magnet volume, but with four-side structure is presented in Figure 9b. The axially magnetized PMs are mounted alternatively (i.e. so that adjacent magnet faces have opposite magnetic poles) between iron poles that guide the magnetic flux lines towards the air gap. Static and dynamic simulations were performed using JMAG Studio, a FEM based simulation software[58].



Tubular generator Four-side topology generator

Fig. 9: Cut-off section and Magnetic flux density distribution for the two considered topologies.

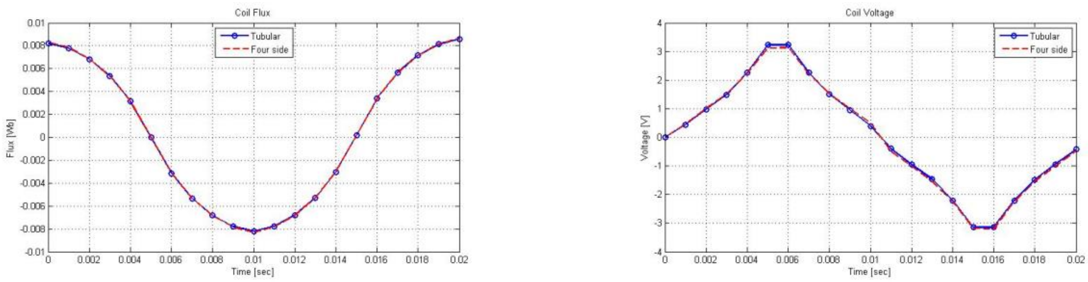
[55] Jonasson J.-P. Construction and Testing of an Air Cored Tubular Linear Generator , Master Thensis, Uppsala Universitet, Teknisk Fysik.

[56] Vermaak R.; Kamper M.J. Design of a novel air-cored permanent magnet linear generator for wave energy conversion, XIX International Conference on Electrical Machines (ICEM), 2010.

[57] C. Oprea, Claudia Martis, K. Biro, F. Jurca: "*Design and Testing of a Four-sided Permanent Magnet Linear Generator Prototype*", International Conference on Electrical Machines (ICEM), 2010 XIX, on the CD, 978-1-4244-4174-7.

[58] C. Oprea, Claudia Martis, F. Jurca, D. Fodorean, L. Szabo: "*Permanent magnet linear generator for renewable energy applications: Tubular vs. four-sided structures*", International Conference on Clean Electrical Power (ICCEP), 2011, ISBN: 978-1-4244-8929-9, Page(s): 588 – 592

Figure 10 shows the obtained flux and the induced voltage for one coil with almost identical results, even if the magnetic flux density repartitions in the two structures are different.



a b

Fig. 10. Coil flux (a) and electromotive force (b), of a stator coil, respectively.

Even if the electrical performances of the two studied structures are almost identical, some differences appear regarding the geometrical and efficiency aspects of the two generators. As expected, the coils of the four-side structure are 37.5% longer and the iron volume is 32.1% higher. Moreover, higher Joule and iron losses result. While the square section translator is heavier and could negatively influence the generator dynamics, from the electro-magnetic point of view there are negligible differences between the two translators. Taking into account the similar electrical performances of the two structures and the manufacturing difficulties of a tubular stator made of laminations, a four-side linear generator structure was chosen for further study.

Based on application-oriented input specifications the main geometric dimensions of the generator were determined, considering the technological and material constrains (availability of PM dimensions and types, winding capabilities, etc.). Once the design is settled, an optimization procedure is required, in order to reach the optimal solution. To this purpose, a sub-optimal design tool was developed using Labview, based on Magnetic Equivalent Circuit (MEC) analysis and implemented for a similar generator dedicated to free-piston in automotive application[59].

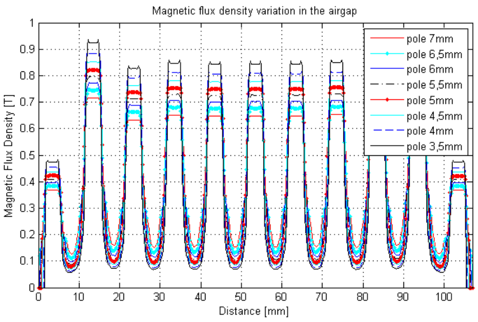
As part of the sub-optimal design process the effect of translator pole shape on the magnetic forces and generated voltages was considered. The translator pole has a square section with a square hole in the middle that allows mounting on the shaft.

Eight cases were considered, with the pole width towards the air gap varying from 7 mm to 2.5 mm in 0.5 mm steps and for each case the magnetic flux density repartition and induced voltages were analysed. The air gap magnetic flux density, electromotive force and the topology of the rotor pole are given in Figure 11.

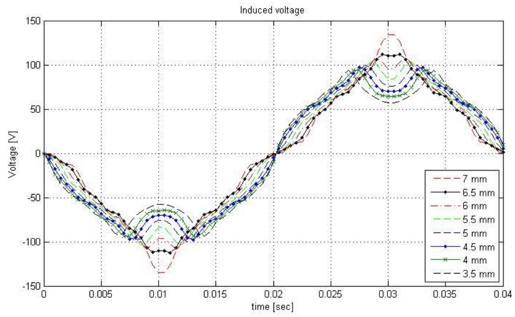
One of the common problems in PM machines is the large forces between the stator and the mover. Several solutions were proposed to reduce the cogging force. A radical solution is to eliminate the magnetic circuit of the stator and using an air-cored structure, as presented above, but the cogging force can be also reduced by skewing the stator teeth, translator poles or of the permanent magnets, depending on the electrical machine structure. In the

[59] C. Oprea, L. Szabó, Claudia Martis: "*Linear Permanent Magnet electric generator for free piston engine applications*", ICEM 2012, 0689-ff-007706.pdf, IEEE Catalog Number: CFP1290B-USB, ISBN: 978-1-4673-0141-1.

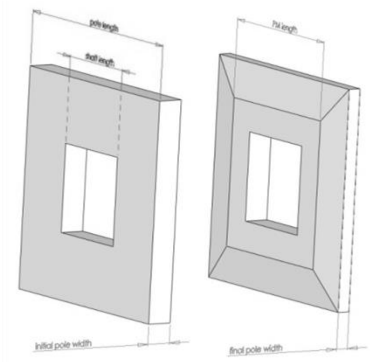
case of the four-side PM linear generator skewing could be obtained by mounting the stator lamination unaligned (that would require the coils to have a three-dimensional shape) or by building the translator poles like in Figure 12a.



a



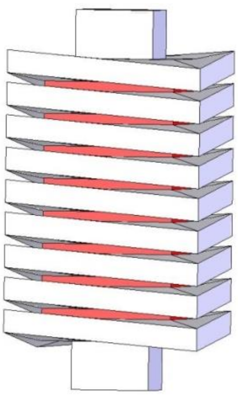
b



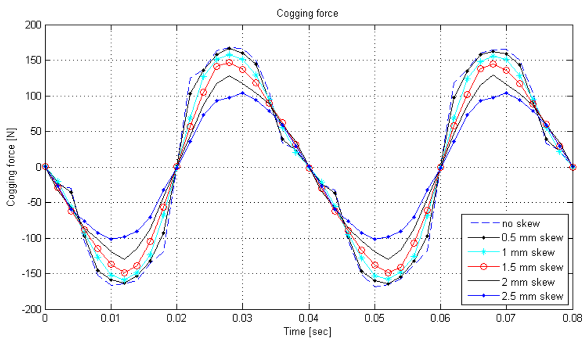
c

Fig. 11: Airgap magnetic flux density (a), electromotive force (b), and the topology of the magnetic pole before and after the sub-optimal analysis (c).

Staring from the initial translator pole shape, with a uniform width of 7 mm, six cases were considered with the pole corners skewed with up to 2.5 mm in 0.5 mm steps. The cogging force is presented in Figure 12b, showing a 61.8 % reduction for a 2.5 mm skew compared with the initial case. In the same time the generated voltage is 25% smaller in the last studied case.



a

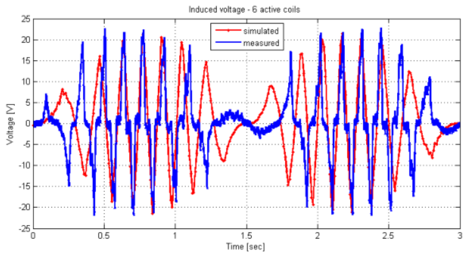


b

Fig. 18. The skwed translator (a) and the cogging torque variation for different skew angles (b).

Based on the results presented above the four-side PM linear generator was built and tested. To improve the performance of the generator the translator pole shape was modified according to the results presented above; however, the skewing could not be achieved with the available technology. Linear generators can be built with a translator longer than the translator, so that the coils are active throughout the entire cycle, or with a longer stator. A prototype was built, with 29 slots and 21 poles, meaning that at least 8 coils were inactive. The inactive coils will act as additional load when the generator is working in load regime, causing an important voltage drop. A solution for this is to disconnect these coils using predictive control techniques, and thus maximizing the power transfer from the generator[60]. The test bench and the electromotive force, simulated and measured, are given in Figure 13.

a



b

Figura 13: Standul experimental (a) şi tensiunea indusă, simulate şi măsurată experimental (b).

The research work was presented in 4 scientific articles (2 published in ISI proceedings and 1 in BDI proceeding) and a PhD thesis (author Claudiu Oprea under the supervision of professor Biro Karoly). The work was continued by Dr. Claudiu Oprea in the frame of a postdoctoral fellowship under the scientific coordination of the candidate. Two ISI indexed scientific articles were published.

4. ELECTRICAL ACTUATORS FOR GREEN AND ENERGY-EFFICIENT VEHICLES

The automotive industry has a continuous high demand for electric drives. The field of actual automotive electric powered units spans a broad range including cooling fans, window and chair actuation, steering, braking, suspension, starter-alternator (integrated or belt driven), HVAC, propulsion for hybrid and full electric vehicles (HEV/EV). The further enhancement of high-performance automotive electric actuation requires energy-efficient, reliable, robust, low-cost electrical machines and highly integrated, energy-efficient power electronics and control modules. For achieving these requirements, the R&D activities should focus on the analysis and development of new topologies and concepts of electrical machines, taking into account the need for energy efficient drives, the harsh automotive environment (high temperature, vibrations, standards for the measurement of pass-by noise, etc.) and the availability of raw materials (in particular rare-earth materials for permanent magnets).

[60] Vermaak R.; Kamper M.J. Experimental Evaluation and Predictive Control of an Air-Cored Linear Generator for Direct-Drive Wave Energy Converters, IEEE Transactions on Industry Applications, Volume 48, No 6, Nov.-Dec. 2012, 1817-1826.

Moreover, the integration of electric powered units in vehicles represents an important challenge due to strict and specific noise-vibration-harshness (NVH) and electromagnetic interferences (EMI) requirements.

Several machine types are adopted or under serious consideration for automotive applications [61, 62]. The automotive industry uses a large number of DC brushed permanent magnet motors, which can vary from a few in an inexpensive car to about 100 in a luxury car. They have been preferred as electrical actuator for pumps, fans, windows, steering systems, anti-lock braking devices. The limitations of this type of motor mainly regarding the wear of brushed and the lower power density make them improper for some actual high performance applications[63, 64, 65].

To date, PMSM are widely accepted as the most potential candidate for the considered applications, capable of competing with IMs. They are adopted, due to their advantages by a large part of the well-known automakers (from Europe, USA and Asia) for both propulsion (EV, HEV or FCEV) and small power automotive applications (as steering, assisted or powered, and electromechanical brake) systems[66,67,68]. Its major disadvantages are the high cost of rare-earth magnets, as these materials are expected to become less available in the future and the additional current component required for field weakening, whereby higher stator losses occur and the efficiency decreases at high speeds. A large amount of research work was done and an impressive number of scientific papers, reports and PhD theses were published on the design, development and control of PMSM drives, for automotive applications. Even if PMSM technology seems to be a mature one, there are still challenges to be overcome. They are related mainly to the electromagnetic, thermal and vibro-acoustic design of PMSM drives, especially for the ones working at high speeds.

SRMs have a very simple construction, with concentrated windings mounted on the stator teeth and no windings nor magnets on the rotor. These machines are thus cheap and highly robust, with low rotor inertia and good efficiency in a wide speed range. The absence of (high-energy) PM material (e.g. NdFeB and SmCo) is likely to become a major advantage of SRMs. The cooling of these machines is relatively simple as the rotor is "cold" (only some iron losses in the laminations). Because of the physical and magnetic isolation of the phases, SRMs are inherently fault tolerant. However, they also have some important drawbacks: their power density is normally lower than the one of PMSMs, and their magnetic characteristics are highly nonlinear with respect to both current and position, which

[61] M. Zeraoulia, s.a.: "Electric Motor Drive Selection Issues for HEV Propulsion Systems: A Comparative Study", IEEE Trans.on Vehicular Technology, vol. 55, no. 6, 2006.

[62] T. Finken, s.a.: "Comparison and design of different electrical machine types regarding their applicability in hybrid electrical vehicles", Proc. ICEM 2008.

[63] H. Kohmann, M. Kreuzer, W. Roeder: " Electrical machine i.e. direct current motor, for use in steering drive device of motor vehicle, has coils and coil sections connected with each other in electrical series connection, and coil group formed from coil sections", Patent DE20081004297520081020, BROSE FAHRZEUGTEILE GMBH, 2008.

[64] R. Hessdoerfer, H. Kirchner, R. Hessdoerfer: "Method for producing a rotor of a commutator motor, a commutator motor, and anti-lock braking device", Patent DE20081004224220080922, BROSE FAHRZEUGTEILE GMBH, 2008.

[65] M. Kreuzer, W. Roeder: "Commutator motor for use in anti-lock braking device of motor vehicle, has stator provided with stator poles, and armature rotor provided with armature teeth, which are arranged with rotor grooves lying at periphery of armature rotor", Patent DE20081004166420080828, BROSE FAHRZEUGTEILE GMBH, 2008.

[66] W. Aimeng, J. Yihua, W.L. Soong: "Comparison of Five Topologies for an Interior Permanent-Magnet Machine for a Hybrid Electric Vehicle", IEEE Trans. on Magnetics, Vol. 47, 2011.

[67] R.G. Shriwastava, M.B. Diagavane: "Electric power steering with Permanent magnet synchronous motor drives used in automotive application", Proc.ICEES, 2011.

[68] A.Omekanda, s.a.: "Switched reluctance and permanent magnet brushless motors in highly dynamic situations: a comparison in the context of electric brakes", IEEE Industry Applications Magazine, Vol. 15, 2009.

complicates the control and is the cause of torque ripple and acoustic noise. Moreover, the inverter is also more complex, involving more switching elements. Power density and noise reduction are thus important design aspects for SRMs. Its advantages were however taken into account in considering it as a solution for steering and electromechanical brake system[69] and for some experimental propulsion systems[70], but, for winning the competition against IM and PMSM as potential electrical actuator for automotive applications, there is more research work to be done in order to overcome the disadvantages linked to the vibro-acoustic behaviour and high torque ripple content.

There are several comparative studies approaching the selection of the most appropriate electric-propulsion system for either EV or HEV, but none of them are taking into account the potential of **VRSM**. Malan[71] shows that VRSM drive has almost all the advantages of the SRM drive or even more. In the literature, VRSM is not mentioned either as a possible solution for the electrical actuation of steering or electromechanical brake systems either. VRSM's performances strongly depend on the saliency ratio[72, 73], but increasing the saliency ratio complicates the rotor construction and drastically increases the motor cost. Interesting results concerning the influence of the saliency ratio on the VRSM steady-state performances, mainly on power factor and efficiency and the effect of rotor dimensions on d- and q- axis inductances in the case of a VRSM with flux barrier rotor are given[74]. Compared to IM the VRSM's larger torque density comes from the absence of rotor cage and related losses. Different dynamic behavior is expected for VRSM due to the specific relationships between currents and fluxes. Some peculiarities exhibited by the VRSMs' vector control, different from other a.c. machines like IM are also discussed. Most of the literature on VRSM drives has concentrated mainly on the design and control of the machine with the goal of improving control, efficiency and torque production, drive flexibility and cost. However, the design and development of a VRSM for electric-propulsion purposes needs more comprehensive studies concerning its implementation as a propulsion motor, as well as its thermal and vibro-acoustic behavior. The analysis of the interdependencies between VRSM design and control strategy with noise and vibration needs deeper research works, especially in the context of a multi-physics approach.

Optimal design, modelling, analysis and testing of electrical actuators for automotive applications represent the main research topic of the candidate work during the last 8 years. The research work was focused at the beginning on small power electrical machines auxiliairies in vehicles (steering and braking systems), then it was extended on electrical machines for electric/hybrid vehicles propulsion.

4.1. Electrical actuators for steering systems

Since 2006, the candidate research work was focused on electrical machines for automotive applications. In the frame of a national research project, two PMSM topologies were studied.

[69] *H. Klode, s.a.: "The Potential of Switched Reluctance Motor Technology for Electro-Mechanical Brake Applications", SAE Technical Paper Series, 2006.*
[70] *A.G. Hofmann, K.A. Kasper, R.W. De Doncker: "High-speed switched reluctance drives: A promising alternative to power electric vehicles", Proc. ICPE & ECCE, 2011.*
[71] *J. Malan, M.J. Kamper: "Performance of a Hybrid Electric Vehicle Using Reluctance Synchronous Machine Technology", IEEE Trans. on Industry Applications, vol. 37, no. 5, 2001.*
[72] *I.A., Viorel, s.a.: "Reluctance synchronous machine with a particular cage less segmental rotor" Proc.of ICEM 2002.*
[73] *I.A. Viorel, s.a.: "The segmented rotor reluctance synchronous motor saliency ratio calculation", Proc. of ELEKTRO 2006.*
[74] *W. Hanguang, L. Qiuhua, Y. Linjuan, "An investigation of the synchronous reluctance motors", Proc.of ICEMs' 2001, China.*

The main requirements governing the design, analysis and development of the electrical actuator were low torque ripple and and fault tolerance.

There are several different configurations of brushless motors which use rotating permanent magnets and stationary phase coils. The proposed configuration is presented in Figure 14. The machine has 12 stator slots, 10 buried permanent magnets (NdFeB) on the rotor, and concentrated windings on the stator poles[75,76]. The machine was designed for 400 W rated power, 500 rpm rated speed and 2000 rpm maximum speed. The chosen combination of slot- and pole-numbers fits with both a three-phase machine. However, the necessity of developing fault-tolerant applications oriented the analysis on a six-phase winding connection on the same machine topology. Taking into acount the cost constraints, for the experimental model the stator of an IM was used[77].

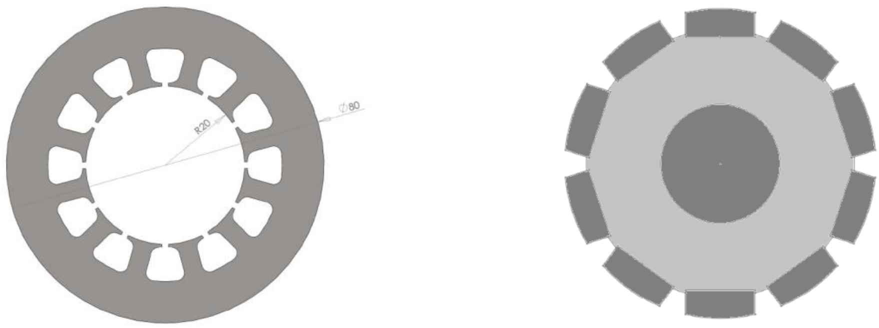


Fig. 14: Stator lamination and rotor cross-section of the 12/10 PMSM for electrical-power assisted steering (EPAS) systems.

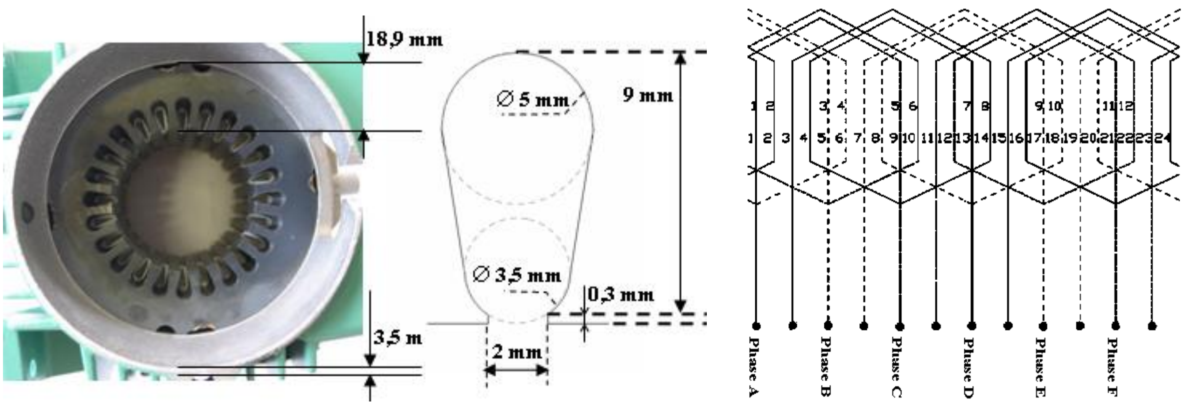


Fig. 15: Stator topology and winding configuration of the two poles PMSM for EPAS systems.

75 C. Oprea, Claudia Martis, K. Biro: "*Six-Phase Brushless DC Motor for Fault Tolerant Electric Power Steering Systems",* ACEMP'07 and ELECTROMOTION'07 Joint meeting, 10-12 September 2007 Bodrum Turkey

76 C. Oprea, Claudia Martis: "Finite element analysis of a brushless dc actuator for fault tolerance electric power steering systems" , ISEF 2007 - XIII International Symposium on Electromagnetic Fields in Mechatronics, Electrical and Electronic Engineering, Prague, Czech Republic, September 13-15, 2007

77 C.Oprea, Claudia Martis: "*Fault tolerant permanent magnet synchronous machine for electric power steering systems"*, International Symposium on Power Electronics, Electrical Drives, Automation and Motion SPEEDAM 2008, pp. 256-261, 2008, E-ISBN: 978-1-4244-1664-6, Print ISBN: 978-1-4244-1663-9.

One of the problems of automotive industry today is the ever-increasing electrical power demands that are stretching the capabilities of present on-board power supplies. Today's luxury class vehicle draws 1200W to 1500W of steady state power from electrical system and has about 2.5km of wire and a number of 350 connectors and nearly 1500 cut leads. The steady state electrical power needed in the future is estimated to be in range of 3000W to 7000W. This power could be met efficiently using higher voltages. Other reason for going to higher supply potential are connected to the wire diameters being too big for keeping losses down and to the connectors having problems handling the current. While the total power demand will grow, a transition from 12 to 42 DC voltage will be necessary.

In this contaxt and taking advantage of the collaboration with researchers of Ecole Superieure d'Ingenieurs en Electronique and Electrotechnique, Amiens, France, a six-phase PMSM with gear box for EPAS (90 W, 3000rpm, 42V DC) was proposed, analyzed and developed. The research work was developed in the frame of a PhD thesis, by Arthur Mathyas, under the supervision of professor Biro Karoly and with the collaboration of the candidate. Figure 15 presents the stator core (taken form an IM) and the winding configuration.

In the design of the rotor structure with permanent magnets, the objectives to be reached are the reduction of the size of the magnets to decrease the cost of the machine. The design of the rotor structure has not to be complex; an easiness of the manufacturing process must be kept in mind for a future industrial application. There are many construction possibilities of the rotor, to install the magnets on the rotor, which can be divided into two categories: the surface-magnet motors and the interior-magnet motors. Therefore 3 topologies were analyzed and their performances compared to the ones of an IM built for the same purpose[78].

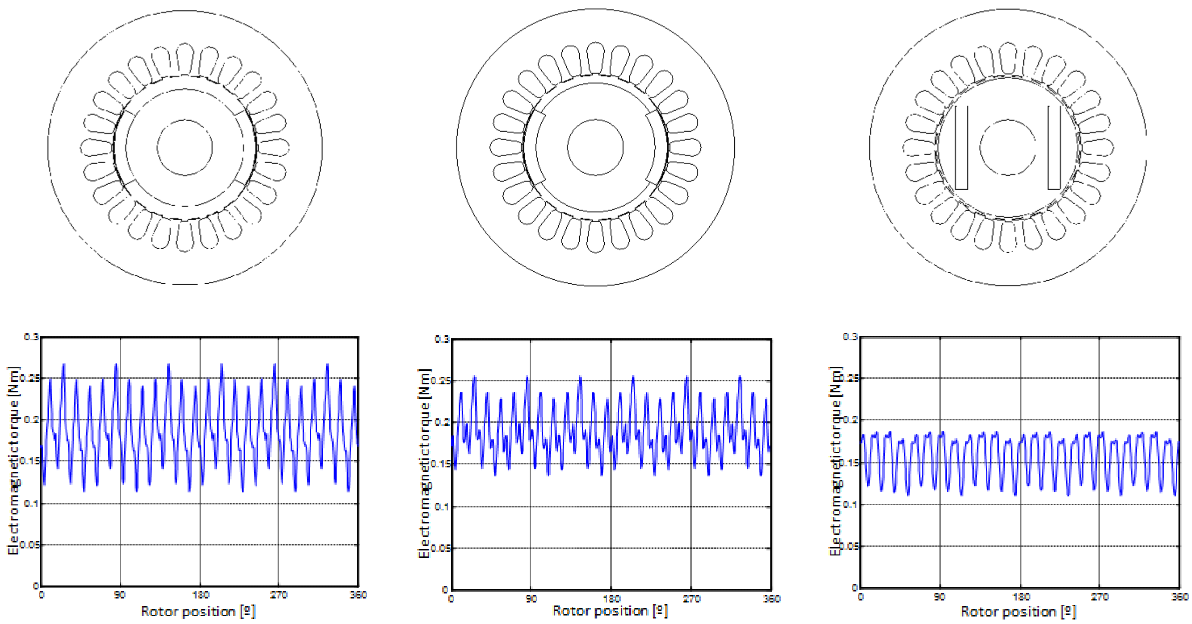


Fig. 16: The influence of rotor PMs location on the electromagnetic torque.

[78] A.Matyas, G. Aroquiadassou, A. Mpanda-Mabwe, Claudia Martis, K. Biro: "*Torque ripple analysis of a 42V fault tolerant six-phase permanent magnet synchronous machine*", IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society, on the CD, ISBN: 978-1-4244-5225-5.

A harmonic content analysis and the average value computation were done. Table 2 presents the spectral components, the average value of the developed electromagnetic torque (Tem) for the same value of stator current and the amplitude of the cogging torque (TCog). It can be noticed that for the PMSM6, the internal surface magnet topology is a good candidate for the given application instead of IM6. Its higher electromagnetic torque spectral contents, compared to the IM6, could be reduced with a suitable control strategy.

Tabel 2. Comparative analysis of the performances of the three topologies presented in Figure 22 and an IM with the same envelope answering to the same requirements.

Topology	Electromagnetic torque spectral components – magnitude [Nm]					Electromagnetic torque average value [Nm]
	0Hz	300 Hz	600Hz	900 Hz	1200 Hz	
PMSM I	0.37	0.012	0.004	0.004	0.049	0.1855
PMSM II	0.38	0.012	0.003	0.004	0.033	0.1895
PMSM III	0.31	0.0045	0.0025	0.0015	0.0032	0.1574
IM	0.35	0.0014	0.001	-	-	0.17

Finally, an experimental model, with demi-burried PMs was chosen (Figure 17). Due to cost constraints, the PMs were built using 6 paralelipipedical general purpose PMs.

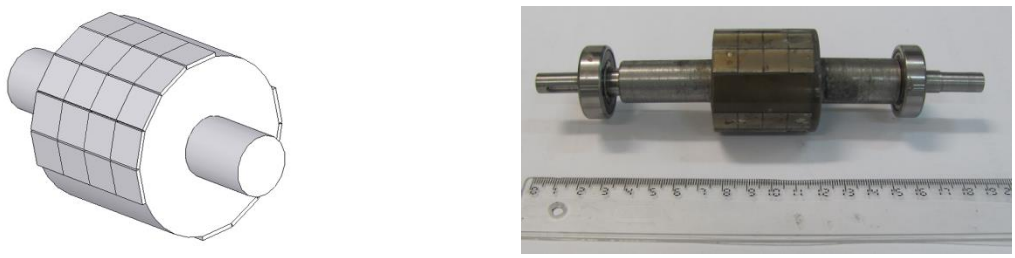


Fig. 17: The rotor of the PMSM, the CAD representation and the experimental model.

An experimental evaluation of the performances was carried out with some of the results presented below.

The experimental power factor and current are slightly different comparing to the theoretical ones, as it can be noted from Figure 18. The efficiency and torque are closer to the ones theoretically computed. According to the overall experimental performances evaluation, the machine answered to the design requirements. Further different control strategies were implemented on the test-bench for evaluating the dynamic performances of the machine

The high power density permanent magnets are extremely sensitive to the temperature increase, the stability temperature limit being well down to 120°C. That is an inconvenient to be taken into consideration since in the automotive applications the ambient temperature limits are between -40°C to 125°C and even more. The PMSM also raises concerns about failure modes and, without an adequate design and control, can produce quite important cogging torques.

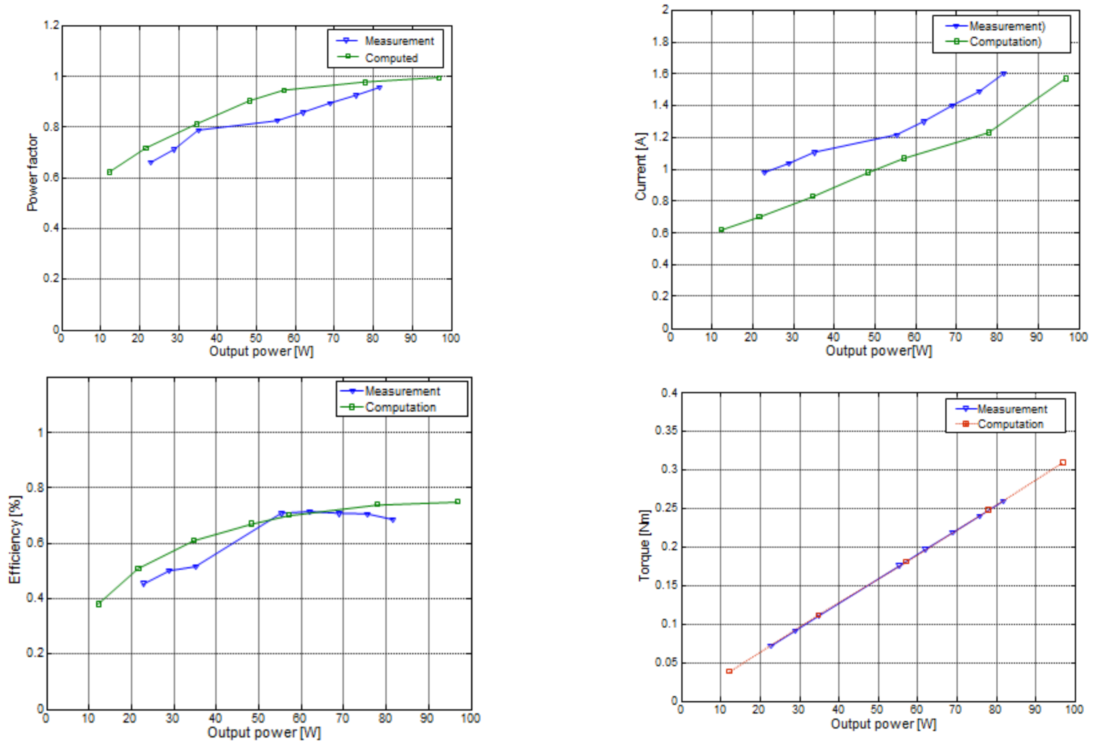


Fig. 18: Validation of the theoretical approach through experimental measurements.

SRMs are not yet commonly used but have undeniable advantages for automotive applications when compared to more classical machine types. SRMs have simple topology and they are easy to construct. The absence of permanent magnets gives an excellent high-temperature performance and high reliability. Also, SR machines can survive a single-phase failure and keep on moving, which adds a highly desirable level of redundancy to the application. Whether it is possible to benefit from these qualities depends on how well the SR disadvantages can be addressed or at least sufficiently mitigated. The evaluation of the SRM potential as automotive electric actuator for an electric power assisted steering (EPAS) system was performed. SRM performances are strongly dependent on its control, so that the development of an efficient, reliable, fault tolerant system implies both optimal design of the electrical machine and optimal control strategy development.

The selection of the proper topology for a specific application is the most difficult problem to be solved during the design process. As the implementation of an optimization design procedure is very difficult for topology selection, the experience-based procedure represents even today the most used method.

Five SRM topologies for an EPAS application were analysed. Different number of phases and different combination of stator and rotor pole number were considered, keeping the same main dimensions (outer and inner stator diameter, airgap length, stack length, stator pole height, stator yoke width, rotor pole height) and the same winding per phase (number of turns and wire diameter).

A preliminary sizing of the machine was carried on, giving the initial geometric data. The key dimensions were calculated and the winding will be dimensioned. A numerical-based performances analysis was performed for each case. The comparison of the results could give the best solution for the SRM topology, suited for further analysis and development of a SRM drive for EPAS applications.

The developed electromagnetic torque vs. rotor position (given in electrical degrees) is depicted in Figure 19, and Table 3 presents the average value and the ripple given by each analyzed topology.

Table 3. Average and Ripple Values for the considered topologies

	5-phase	**4-phase**		**3-phase**	
	10/8	8/6	8/10	6/4	6/8
Average torque [Nm]	5.97	6.86	4.77	2.81	4.64
Ripple [Nm]	2.17	4.49	1.57	6.4	3.4

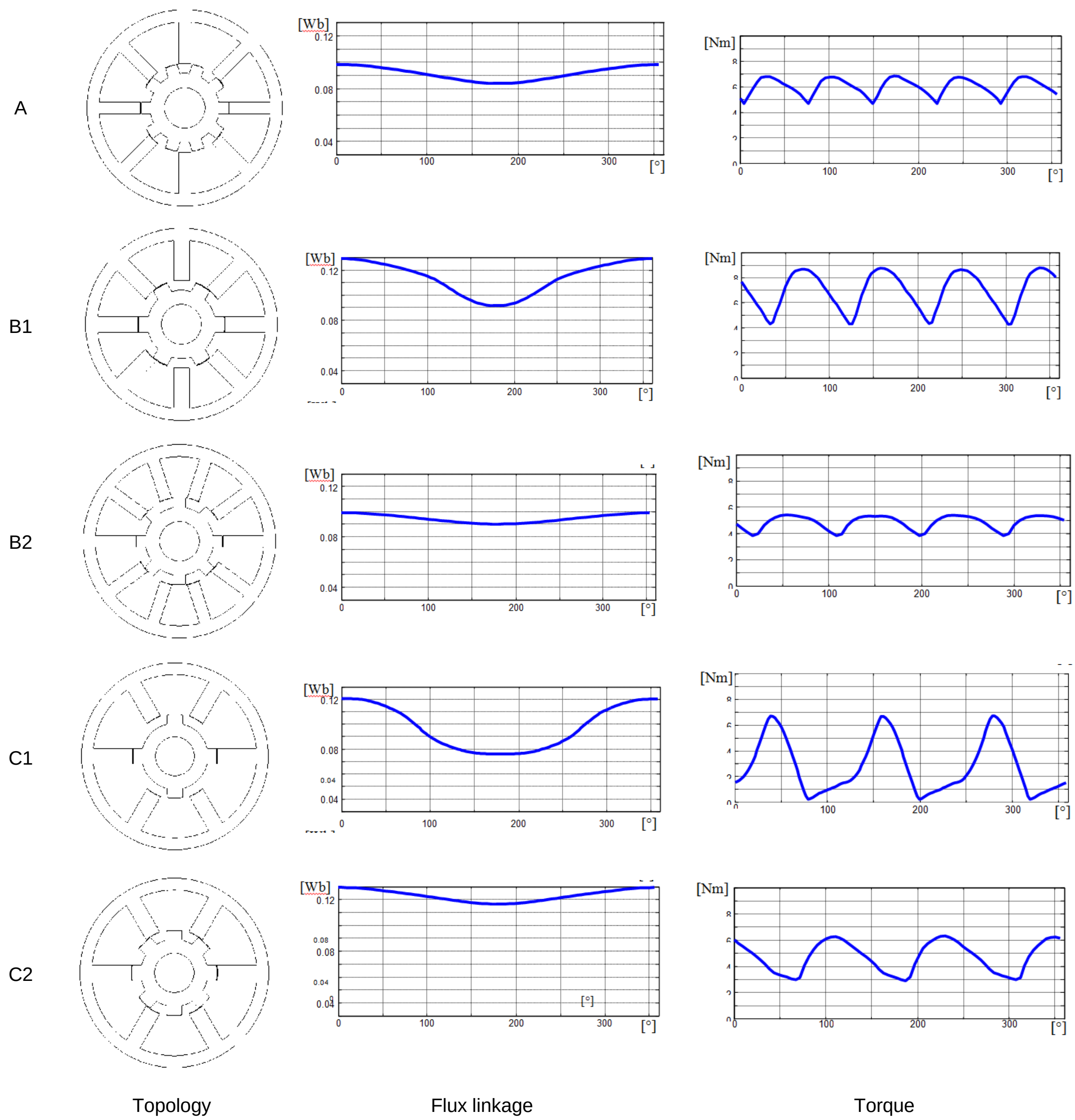


Fig. 19: The SRM topologies, flux linkage and electromagnetic torque.

Analyzing the results of the work, the best solutions for a SRM for an EPAS system seem to be A and B1 topologies. The main disadvantages of the first one are the high value of the slot fill factor and the higher number of needed converter phase units that will increase the complexity of the control and the overall cost of the drive. The second topology's main disadvantage consists of the higher level of torque ripple. This problem could be though solved using a proper control technique, including a torque ripple strategy.

Moreover a multiphysic approach, integrating an optimal design, modelling and analysis for electromagnetic, thermal, vibro-acoustic and control aspects is required. Therefore the actual research work of the candidate is focused on developing and integrating tools for multiphysic and multi-level design, analysis and testing of electrical machines and their drives for automotive applications.

4.2. Electrical actuators for electromechanical braking systems

Although currently most number of vehicles in the roads is equipped with hydraulic braking system, a development study conducted by Frost & Sullivan predicts that in the closed future the auto industry will start to replace more and more hydraulic braking system with brake by wire systems [84]. The need for faster brake responding, better fuel economy, simplified system assembly, easy maintenance, more environmentally friendly and improved safety design has resulted in new Electro-Mechanical Braking (EMB) System. Working as a parking brake, EMB supports the functions of the conventional handbrake. Replacing the conventional hydraulic braking system with an advanced EMB not only reduces the weight of vehicles, but also has the potential for a large number of new features. In October 2001, Mercedes Benz E-class and SL models are introducing the world's first production electronic brake by wire technology in Mercedes-Benz SL500 (also used in Toyota Estima). Bosch, Continental Teves, Delphi, TRW and other OEM supplier companies have all developed next generation brake-by-wire systems for potential use on future vehicles. These companies have already invested millions of dollars in research and development for this area of study.

For replacing completely the hydraulic system in order to transmit the commands through the wire, the braking force is generated directly at each wheel by high-performance electric motors controlled by an ECU (Electronic Control Unit), and executed by signals from an electronic pedal module which includes 4 intelligent braking actuators[79].

SRM and PMSM are considered to be two reliable electric actuation solutions for EMBs. The PMSM advantages in terms of high torque density, low torque ripples, low weight are important strengths for implementing it as an electrical actuator for EMB systems. SRM fault tolerance potential, as well as its advantages in terms of temperature, recommends it also for this kind of applications.

A study focused on both SRM and PMSM, evaluated each machine dynamic behavior, in all four quadrants torque-speed operating regions, for an EMB application[80,81]. The analysis concluded that a 20% longer SRM provided overall similar dynamic performance, but only if

[79] X-by-Wire, New Technology for 42V Bus Automobile of the Future, Nathan Ray Trevett, April 2002

[80] A.M. Omekanda, B. Lequesne, H. Klode, S. Gopalakrishnan, I. Husain:" Switched reluctance and permanent magnet brushless motors in highly dynamic situations: A comparison in the context of electric brakes", Industry Applications Conference, 2006. 41st IAS Annual Meeting. Conference Record of the 2006 IEEE (Volume:3)

[81] A.M. Omekanda, B. Lequesne, H. Klode, S. Gopalakrishnan, I. Husain: "SRM and PMSM A comparison in the context of electric brakes", INDUSTRY APPLICATIONS MAGAZINE _ JULY /AUG 2009.

the SRM is fitted with a speed limit. Thus a method to choose such a speed limit was developed, and the software algorithm implementation was found to be simple and successful. The EMB force control problem has been approached in several articles[82,83,84]. One of the key issue in the design and implementation of EMB system is represented by the estimation of frictional and clamping forces. Therefore, different clamp-force estimation and calibration methods and tools were proposed and analyzed.

As a major issue in automotives is being represented by the need for improved fuel efficiency and much more flexibility concerning latest technologies used in X-By-Wire's, the current 14 V bus has become insufficient. Therefore, car manufactures has come to the conclusion that the solution is to increase the voltage and implement a new 42 V bus in the system. Some aspects have to be considered during the design of the brake by wire drive systems: reliability, performance, thermal and acoustic behavior, energy efficiency and cost.

For a typically wheel braking torque between 1000 and 2000 Nm, a 300 kW rated power PMSM was proposed. Its base speed, 1000 rpm, is chosen in such a way that it can operate in a large speed range. The machine should be able to work up to 3 times its base speed; therefore it will be designed for flux weakening capabilities. In order to produce 300 W of power at 1000 rpm the machine should produce a torque of 2.86 Nm. The research work was carried out in the framework of the PhD thesis of Raluca trifa, under the supervision of prof. Biro Karoly and with the collaboration of the candidate. The results were presented in six scientific articles, presented at international conferneces and/or published in scientific journals (one ISI indexed and one BDI indexed).

Apart from these requirements, several aspects should be taken into account. The machine should fit in a given volume (outer diameter less than 86 mm and stack length less than 120 mm), operate in harsh conditions (temperature between -40º and +125º) and have a low manufacturing cost. Moreover, the system has to be fault-tolerant and fail-operational until a safe state (e.g. vehicle stands) will be reached. In order to reach the fail-operational requirements an additional effort for redundancy in the control components, sensors, software, power supply, and the communication system is mandatory. Summarizing, the design requirements for the PMSM are given in Table 4.

Table 4. EMB actuation design requirements.

Rated power	P_N	300W
Rated speed	n_N	1000 rot/min
Phase number	m	3
Frequency	f	33.33Hz
DC voltage	U_a	42 V c.c.
Power factor	$\cos\varphi$	0,9
Efficiency	η_N	0.7

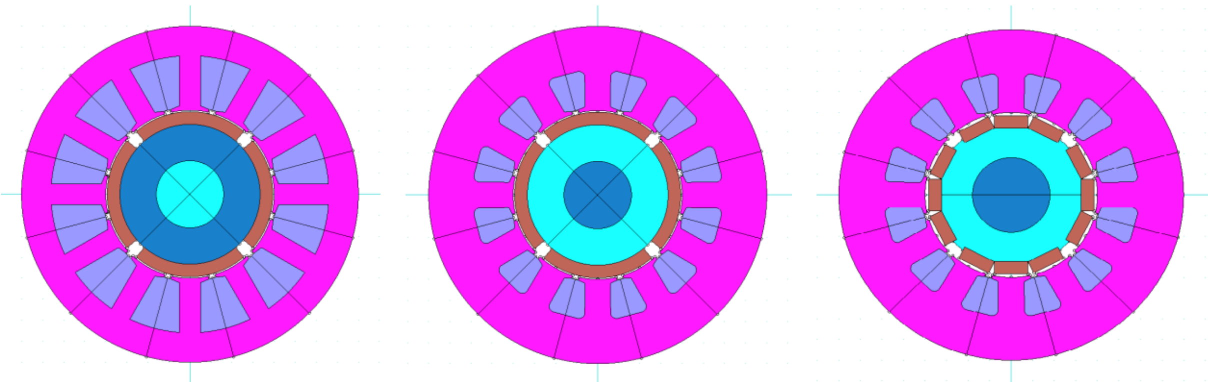
[82] C. Line, C. Manzie, M.C. Good:" Electromechanical Brake Modeling and Control:From PI to MPC", IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY, VOL. 16, NO. 3, MAY 2008

[83] C. Jo, S. Hwang, H. Kim:" Clamping-Force Control for Electromechanical Brake", IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, VOL. 59, NO. 7, SEPTEMBER 2010.

[84] Z. Zhou, C. Mi, G. Zhang: " Integrated control of electromechanical braking and regenerative braking in plug-in hybrid electric vehicles", Int. J. Vehicle Design, Vol. 58, Nos. 2/3/4, 2012

The selection of the proper topology is a very challenging task and it has to deal with choosing the proper combination of the number of stator slots and the number of rotor magnetic poles. As for this specific application a low manufacturing cost is an important aspect, already existing laminations and permanent magnets were used. Several lamination topologies are available; therefore a rough estimation of the stator inner diameter is necessary[85,86].

The final cross-sections of the designed (PMSM_1) and existing (PMSM_2) 12/4 stator PMSM are given in Figure 20 (a) and (b). Since the acquisition of a new permanent magnet always involves additional cost, rectangular prismatic field magnets of sintered neodymium iron boron (NdFeB) material from the range of already existing magnets were adapted to meet the requirements of the desired application. This may necessitate a few minor changes to be made in the assembly, but considering the cost constraints, it is worthwhile to do so. Each arc-shaped permanents magnet in Figure 20 (a) and (b), respectively, is replaced by three rectangular prismatic ones as it can be noted in Figure 20 (c) (PMSM_3) [87].



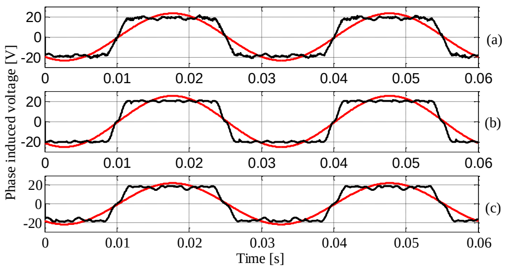
a b c

Fig. 20: Studied topologies.

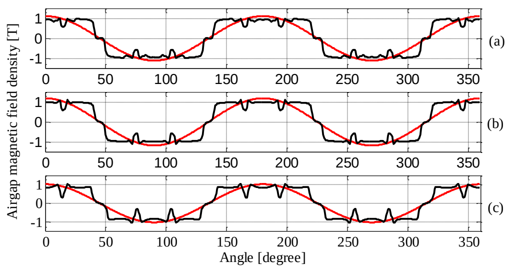
The evaluation of the steady state performances of an electrical machine is based on the analysis of the electrical and magnetic characteristics which describe the relationship between the main electric and magnetic quantities of the machine. Such characteristics describe not only any operating condition but also provide a mean to compute some important parameters of the machine needed to build the equivalent circuit model for dynamic performances analysis. Moreover, for a complete evaluation, thermal and structural analysis should be considered.

Computer simulation using the finite element technique is very useful for achieving this objective. The simulation work has been carried out using JMAG software package, taking advantage of its integrative approach of both electromagnetic and thermal analysis.

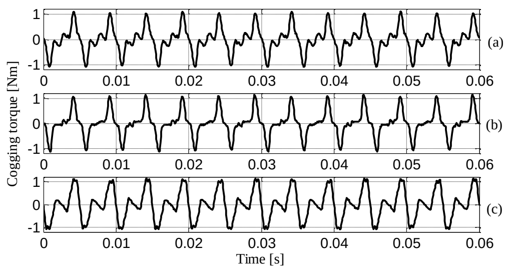
[85] R. Trifa, Claudia Martis, K. Biro, F. Surdu: "*PMSM Design for brake by wire technology in automotives*", Journal of Computer Science and Control Systems, Vol 3. Nr. 1 2010, ISSN 1844-6043, pp. 237-241.
[86] R. Trifa, Claudia Martis, K. Biro, F. Surdu: "*Design Optimization of a Permanent Magnet in a Synchronous Motor for Brake-By-Wire Technology in Automotives*", Journal of Electrical and Electronics Engineering, Vol. 4, Issue 1, ISSN 18446035, 2011.
[87] R.Trifa, Claudia Martiş, K. Biro: "*Design and Analysis of a Permanent Synchronous Machine for Automotive Electromechanical Braking System*", PRZEGLĄD ELEKTROTECHNICZNY (Electrical Review) Vol 2012, No 7b.



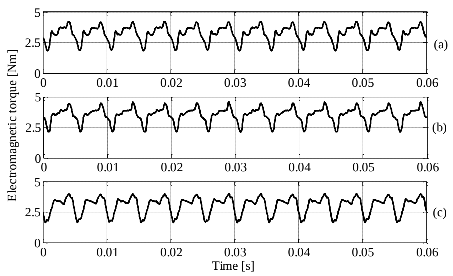
Airgap magnetic field density distribution



Electromotive force



Cogging torque



Electromagnetic torque

Fig. 21: Comparative analysis of the three considered topologies.

Tabel 6. Comparative results of the three considered topologies

Topology	B_{1max} [T]	B_{av} [T]	E_{1max} [V]	E_{rms} [V]	T_{av} [Nm]	t_r [%]	t_c [%]
PMSM_1	1.1123	0.8464	26.76	19.73	3.23	73.93	68.36
PMSM_2	1.1852	0.8962	28.77	21.24	3.51	69.49	65.27
PMSM_3	1.0348	0.8357	26.38	19.37	3.06	76.99	72.41

The performance prediction and the analysis of electric machines depend to a large extent on the accurate evaluation of the air gap field. Therefore, both no-load and load electromagnetic analyses were carried out. The objective of the electromagnetic analysis is two-fold: (i) evaluating the steady-state performances and (ii) computing the losses and thus preparing the inputs for the thermal analysis. Moreover, a thermal analysis was performed in order to visualize the temperature distribution and its evolution in different parts of the machine.

Figure 21 shows the airgap magnetic field density and phase induced voltage, as well as their fundamentals for each of the considered topology. The cogging and electromagnetic torque for sinusoidal source is also presented. An analysis of the harmonic content of the magnetic field density revealed the dominat componets. A synthese of the results is given in Table 6. PMSM_3 has high torque ripple and cogging torque factors, therefore a torque ripple minimization strategy combined with a cogging torque compensation technique are necessary in order the machine be suitable for EMB applications.

A detailed modelling and analysis of the last topologie was performed. Electromagnetic and thermal analysis at the motor level was carried out. As the focus is on the electrical machine behavior analysis, an appropriate simple model for the electro-mechanical brake application is developed. Since the motor provides a torque input which, in turn, induces the clamp force, the current and the clamp force are correlated. Moreover, the characteristic of the

EMB caliper can be defined as a pseudo-static relationship between the rotor position and the induced clamp force[88]. A clamping force profile is imposed and the simulation is carried out using Matlab-Simulink environment. The profile of the clamping force corresponds to a typical brake scenario: brakes apply, brake release and direction reversal[89].

4.3. Electrical machines for EV/HEV propulsion

HEVs/EVs are a strategic automotive industry focus due to the growing emphasis on air and noise pollution, both by consumers and governmental instances. These vehicles rely on advanced electronically-controlled systems working together across a wide range of operating conditions to ensure efficient performance, safety as well as reliability. They combine components from the traditional internal combustion engine powertrain with new electronic drivetrain components such as an electric motor/generator, power converters, battery pack, and associated controllers and sensors. Safe and reliable vehicle operation depends on the successful integration and verification of all these drivetrain components, requiring multi-disciplinary research.

There is a wide range of development activities to integrate an electrical motor into a car powertrain, either as an additional motor for micro, mild and full hybrid vehicle, or as a unique source of power for pure electrical vehicle.

According to several reviews of the state of the art on the electrical machines for HEVs/EVs propulsion systems there are four machines types applied: DC machine, IM, PMSM and SRM. Each machine has advantages and disadvantages which make them interesting in different vehicle concepts.

The interest on DC machine decreased during the last decades as it has a moderate power density, a small efficiency and reliability. Squirrel-cage IM offers a higher power density, higher efficiency and reliability when compared to the DC machine. However, the removal of the rotor heat asks for additional issues and it has to be taken into account the relatively low efficiency at high speed due to the rotor losses, when compared to PMSM.

Reluctance motors, due to their high power density at low cost, represent an ideal solution for many applications, including HEVs/EVs. However, there are two important drawbacks that have to be overcome in order to be comparable to IMs and/or PMSMs: high torque ripple at low speeds and an important acoustic noise.

The recent developments in power electronics technology and materials have made SRM an attractive candidate for HEVs/EVs applications. Construction wise the rotor of SRMs is very simple and robust (absence of windings and permanent magnets) and this also applies to some extent to the stator (small number of coils on salient poles). As a result SRMs are cheap and robust, and very suitable for high-speed applications as well as for harsh environment applications. However, when comparing to PMSM or IM, it is important to take into account the power converter and control in the context of a given vehicle system and its control strategy.

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[88] C. Jo, S. Hwang, H. Kim:" Clamping-Force Control for Electromechanical Brake", IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, VOL. 59, NO. 7, SEPTEMBER 2010.

[89] Raluca Trifa, „Motorul sincron cu magneţi permanenţi pentru frânarea electromecanică la automobile", Teză de doctorat, Universitatea tehnică din Cluj-Napoca, 2012.

The list of the SRM technology advantages can be summarized as: low cost, low weight, high efficiency, and high reliability. The absence of permanent magnets gives an excellent high-temperature performance. Also, SRMs have proven their fault-tolerance, which adds a highly desirable level of redundancy to the application.

The design and analysis of different topologies of SRM for vehicle propulsion, as well as different optimization and control strategies were approached by the candidate as a co-supervisor of the work of two PhD students (Adrian Pop and Vlad Petrus). Their work was performed under a joint PhD program with Universite Libre de Bruxelles, the two promotors of the theses being professor Vasile Iancu from the Technical University of Cluj-Napoca and professor Johan Gyselinck from Universite Libre de Bruxelles.

The design and analysis of different SRM topologies for traction applications was performed[90]. A preliminary sizing for getting the initial geometric data of the machine was carried out. Average developed electromagnetic torque, torque ripple content, losses and weight were the comparison criteria. The goal of the comparative analysis was to arrive to the best topology in terms of electromagnetic torque, torque ripple content and losses for a SRM suitable for EV propulsion.

FEM-based and measurement-based procedures for the characterisation and modelling of the SRM's torque model have been implemented [119, 120]. Scripting routines that allow a rapid modiffication of the geometry (number of phases, number of poles, geometrical dimensions, pole shape, etc.) have been created, allowing the study of the influence of the geometry on the torque production in SRMs[91].

Using the 2D FE electromagnetic model embedded in a multiphysics design optimisation routine having as objective function the torque density, multiple constraints were considered in two different cases regarding the initial design. In the first case a new SRM was designed based on a (analytical) pre-sizing routine starting from the requirements of an EM used for EV propulsion. In the second case an existing SRM, already implemented in full EV propulsion was considered. Depending on the objective scenario, gains of up to 25% were reported in terms of average torque, without the need for changing neither the cooling circuit, nor the deterioration of NVH properties (second mode shape eigen-frequency used as indicator) in both cases[92,93,94,95].

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[90] V. Petrus, A. C. Pop, Claudia Martis, J. Gyselinck, V. Iancu: "*Design and comparison of different Switched Reluctance Machine topologies for electric vehicle propulsion*", International Conference on Electrical Machines (ICEM), 2010 XIX, on the CD, 978-1-4244-4174-7.

[91] V. Petrus, A. C. Pop, Claudia Martis, V. Iancu: "*A 5-phase SRM for Electric Vehicle Propulsion*", Journal of Computer Science and Control Systems, Vol 3. Nr. 1 2010, ISSN 1844-6043, pp.177-183.

[92] A.C. Pop, V. Petrus, Claudia Martis, V. Iancu, J. Gyselinck: "*On the firing angles control of 8/6 Switched Reluctance Machine*", Journal of Electrical and Electronics Engineering, Vol. 4, Issue 1, ISSN 18446035, 2011.

[93] A.C. Pop, V. Petrus, Claudia Martis, J. Gyselinck: "*Parameter Identification and 2D FE Modeling of Existing Switched Reluctance Motors*", International Conference EVER 2011, Monaco, 2011.

[94] A.C. Pop, V. Petrus, J. Gyselinck, Claudia Martis, V. Iancu: "*Finite Element Based Multiphysics Optimal Design of Switched Reluctance Motors Used in Electric Vehicles Propulsion*", Journal of Computer Science and Control Systems, Vol. 5, Issue 1, ISSN 1844-6043, 2012.

[95] A.C. Pop, V. Petrus, Claudia Martis, V. Iancu, J. Gyselinck: " *Comparative study of different torque sharing functions for losses minimization in switched reluctance motors used in electric vehicles propulsion*", 13th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM 2012), RF-002852, IEEE Catalog Number: CFP1222D-PRT, ISBN: 978-1-4673-1650-

A torque control and its optimisations in order to improve the efficiency and torque ripple over the entire speed range in both motoring and generating modes was performed[96,97,98,99]. Significant improvements were reported both in terms of losses reduction (up to 50% reduction in copper losses) as well as an augmentation of the region from the torque-speed plane, with smooth torque production capability (up to 30%). In order to improve the convergence performance, a smooth model has been developed, which in addition, allowed for the separation of the two causes of ripple. Optimal firing angle control was implemented for speeds higher than 1000 rpm and the optimal firing angles were computed for different objective functions as well as different ICs for the optimisation routine. For the generating operation, only the peak-to-peak torque ripple was considered for minimization. The optimal control methods were successfully implemented and both simulation-wise and experimental-wise on a four-phase, 30kW peak power, SRM supplied via an asymmetric H bridge converter having a DC machine as a load.

The results of the research work were presented in 13 scientific papers, 9 of them in BDI proceedings and journals.

Permanent Magnet Induction machine (PMIM) is a new comer for the direct driven HEV powertrain applications. PMIM is a combination between the classical squirrel-cage IM and the PMSM. The PMIM has the potential to be the optimal machine: it has the capability to work both as a motor and generator for HEVs propulsion or electric energy generation, combining the advantages of the IM (little maintenance) with those of the PMSM (high torque, good efficiency). A PMIM topology was designed and analysed in the frame of a PhD thesis, by Anamaria Gazdac. The PhD student was also enroled in a joint PhD program together with Universite Picardie Jules Verne and Ecole Superieure d'Ingenieurs en Electronique and Electrotechnique, Amiens, France.

The PMIM, also called hybrid asynchronous machine, consists of one stator and two rotors (Figure 22 a). The stator is a conventional induction machine stator, equipped with a 3-phase winding. The inner squirrel cage rotor is the equivalent of the rotor from the induction machine. The second rotor, freely rotating, is a steel tube, which has mounted on both his inner and outer surface permanent magnets (PM rotor). The role of this second rotor is to provide an additional flux to the machine, so the demand for magnetizing current and reactive power can be diminished, when working as a generator, but it will also generate an increase of the torque, when working as a motor.

A preliminary investigation of the PMIM performances, in order to compare its behavior to an IM and a PMSM, respectively was performed[100]. After an analytical design procedure, each machine was modeled and simulated, for the load regime, using FEM-based software. For

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[96] V. Petrus, A.C. Pop, Claudia Martis, V. Iancu, J. Gyselinck: "*Comparative study of different current control techniques for a 4-phase 8/6 switched reluctance machine*", Journal of Electrical and Electronics Engineering, Volume 4, Issue 1, 2011, Pages 173-178.

[97] V. Petrus, A. C. Pop, C. S. Martis, V. Iancu, J. Gyselinck: "*Direct Torque Control of a 4-Phase Switched Reluctance Machine*", Joint ACEMP and Electromotion Conference, Istanbul, 2011.

[98] V. Petrus, A. C. Pop, Claudia Martis, V. Iancu, J. Gyselinck: "*Direct instantaneous torque control of SRMs versus current profiling – comparison regarding torque ripple and copper losses*", 13th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM 2012), RF-002771, IEEE Catalog Number: CFP1222D-PRT, ISBN: 978-1-4673-1650-7.

[99] V. Petrus, A.C. Pop, J. Gyselinck, Claudia Martis, V. Iancu: " *Average torque control of an 8/6 Switched Reluctance Machine for Electric Vehicle Traction*", Journal of Computer Science and Control Systems, Vol. 5, Issue 1, ISSN 1844-6043, 2012.

[100] A.M.Gazdac, A.Mpanda Mabwe, Claudia Martis, F.Betin, K.Biro: " *Analytical design algorithm and FEM analysis of the dual-rotor Permanent Magnet Induction Machine*", ICEM 2012, 1183-ff-002194.pdf, IEEE Catalog Number: CFP1290B-USB, ISBN: 978-1-4673-0141-1.

the same stator topology, the PMIM seems to be superior in terms of average electromagnetic torque and copper losses.

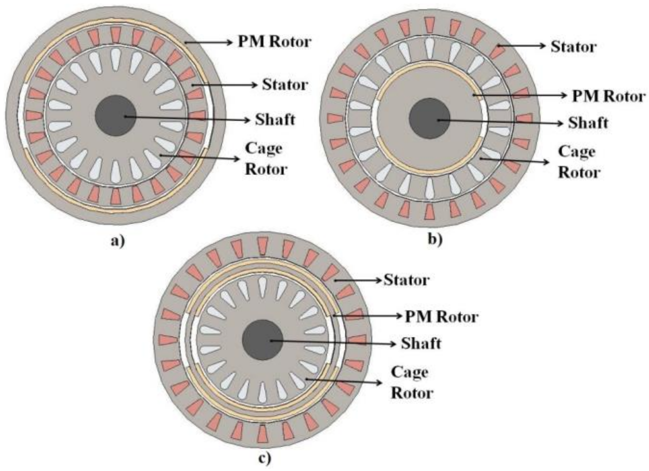
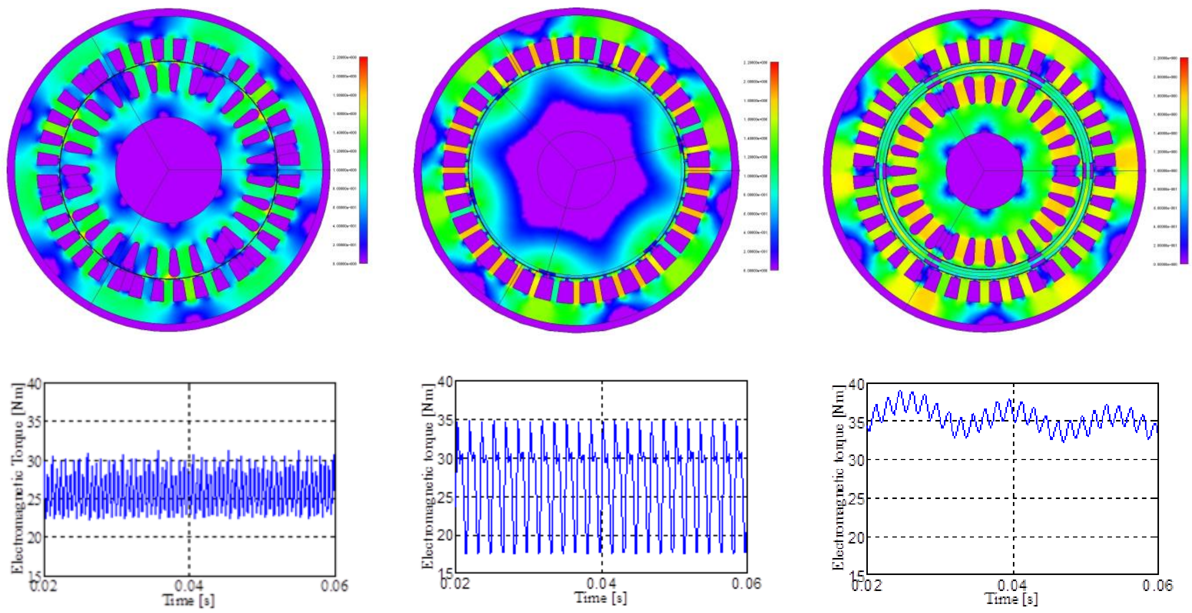


Fig. 22: PMIM topologies.

Figure 23 presents the developed electromagnetic torque and the map of the magnetic field distribution in the cross section of each machine, for sinusoidal feeding current. It can be noticed that the torque produced by the PMIM shows a great improvement in comparison to that produced by the IM and the PMSM.



IM PMSM PMIM

Fig. 23: Magnetic filed map and electromagnetic torque of the three considered machines.

Different PMs location, as well as different geometrical dimensions and materials were considered in order to perfom a comparative analysis and evaluate the influence on the machine performances[101,102, 103]. As the results of the evaluation were considered promising,

[101] A.M. Gazdac, Claudia Martis, A.Mpanda Mabwe, K. Biro: "*Analysis of the material influence on the performance of the dual-rotor permanent magnet induction machine*", 13th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM 2012), RF-002372, IEEE Catalog Number: CFP1222D-PRT, ISBN: 978-1-4673-1650-7.

after PhD graduation the researcher is now enrolled as a postdoc researcher at Ecole Superieure d'Ingenieurs en Electronique and Electrotechnique, Amiens, France and continues the exploration of the machine, also under experimental tests.

4.4. Multi-physics and multi-level analisys of the electrical machines and drives for automotive applications

The research work on this direction started in 2012 with a national research project (ALNEMAD) with the candidate as director and having as partners the Politehnica University Bucharest and LMS Romania SRL Brasov. The research activities are under going and they open the collaboration in the frame of 4 European projects under FP7 framework (3 under Marie Curie Actions and 1 under Cooperation). The candidate is coordinator of two of them and responsible on the Technical University of Cluj-Napoca side for the other 2.

The world of vehicle acoustics is quickly adapting to the new needs of these vehicles. The vibro-acoustic signature of the modern cars in general is quite different from vehicles equipped with traditional engine-driven or electro-hydraulic powered auxiliaries. The current generation of cars and especially HEV/EV poses a potentially different concern in that they are too quiet and therefore pose a threat to pedestrians when the vehicles are traveling at idle or low speeds. On the other hand, in situations where the combustion engine is turned off or there is no combustion engine anymore, other noise sources, like electric powered units, can become dominant and annoying. Missing the covering sound and the mechanical power of the combustion engine in several operating conditions of the vehicle, more and more electric powered units are getting relevant for the sound.

Concurrently, placing a high number of electrical and electronic systems into a limited space raises the problem of keeping the EMI of these systems from interfering with each other through radiated and conducted emissions. The electric powered units and related power electronics can cause broadband emissions which could impair the control systems normal modes of operation. If not properly controlled, the interference can cause malfunction of the control electronics performing many safety and communication relevant functions. Safety assurance asks for a detailed analysis of risk, including that of exposure to EMI. Risk mitigation is required for all identified EMI risk that could have an adverse effect on safety.

Therefore, in the context of this new vehicle design paradigm, it becomes critical to understand and manage the interaction between different fields of physics (electromagnetism, thermal, mechanics, acoustics) for the design and development of electrical machines and drives (EMDs) for automotive applications, where both the environment and the specifications are placing more severe restrictions and demands. Moreover, the multi-physics approach should be extended from component- to system-level taking into account the multiple domains that are interconnected and influence each other. The electromagnetic, thermal, mechanical and vibro-acoustic design of the system must be considered simultaneously if the specifications are to be satisfied in the given environment and under specific NVH and EMI requirements. The four designs required for system

[102] A.M. Gazdac, Claudia Martis, A. Mpanda, K. Biro, G. Aroquiadassou, R. Trifa: "*Theoretical Study and Comparative Analysis of a Permanent Magnet Induction Machine*", Proceedings of International Conference ISEF 2011, on CD, 2011.
[103] A.M.Gazdac, A.Mpanda Mabwe, Claudia Martis, F.Betin, K.Biro: "*Investigation on the Thermal Behavior of the dual-rotor Permanent Magnet Induction Machine*", 38th Annual Conference on IEEE Industrial Electronics Society (IECON 2012) Book Series: IEEE Industrial Electronics Society Pages: 1858-1863, 2012.

integration are tightly interconnected and any change in one design will have consequences on the remaining three.

The existing design, modelling and testing platform (DeMoTEST), set-up by UTCN and LMS, will be used for carrying out the optimal design and analysis of the electrical machines under study considering the coupled electromagnetic and vibro-acoustic approach. DeMoTEST (Figure 24) is an open-architecture platform providing multi-physics and different levels approach for the design, modelling and testing of EMDs for automotive applications. The platform provides both component-level modelling and analysis and system-level performances evaluation of EMDs.

At component-level, following the specifications (inputs and constraints), for the given machine type, fast analytical design tool is applied for comparing the different options and arriving at a first design. It will also be able to perform optimizations to minimize geometrical dimensions according to different objective functions (output power, efficiency, average torque, etc.) and to deliver sufficiently accurate models for system electromagnetic design task.

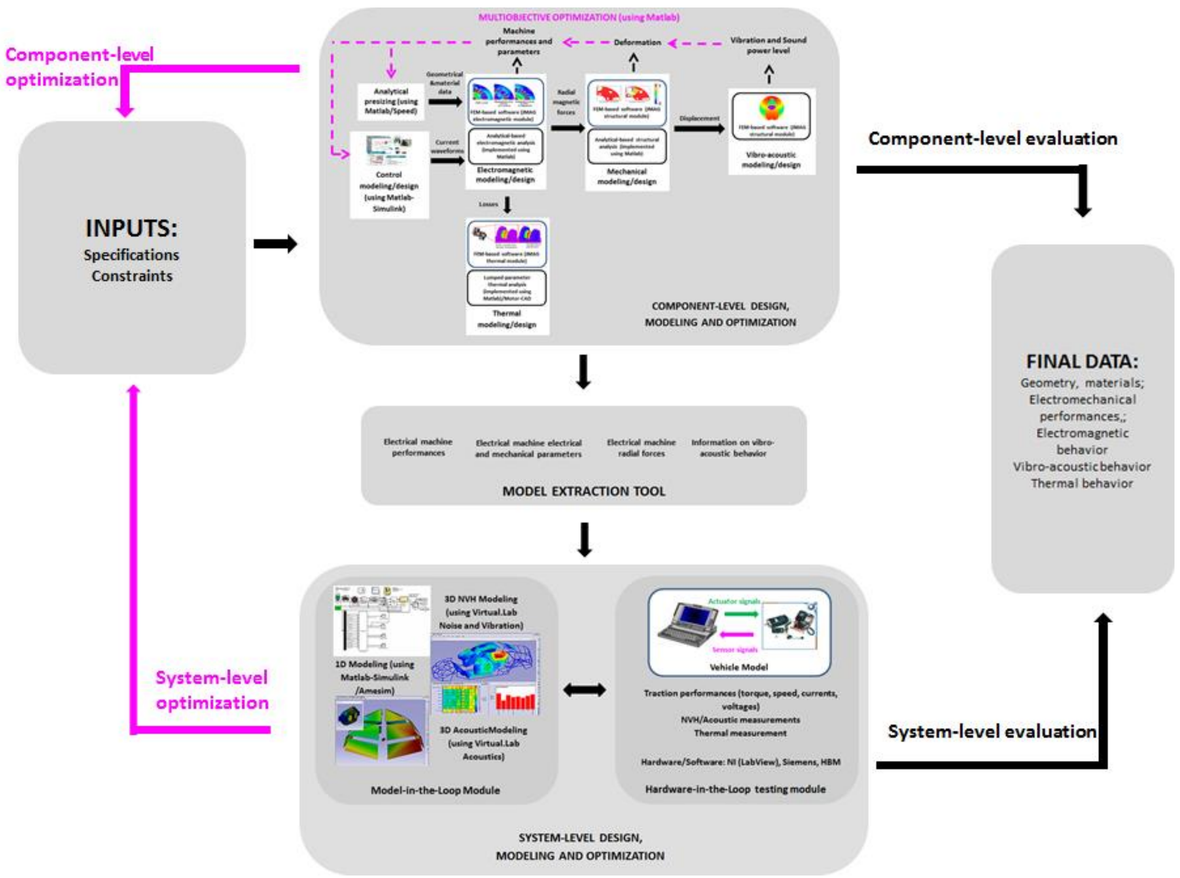


Fig. 24: DeMoTEST Platform

After the design is settled, models will be extracted for being implemented in the Electromagnetic design module. Thus, in this second stage, either a numerical or analytical method will be used for refining the magnetic design. For the study of the control strategy impact on the performances of the electrical drive, a field-circuit coupled approach will be implemented. Therefore, the electromagnetic design module will be coupled via a circuit model with the Control design module and the transient behaviour of the drive will be analysed. Using this procedure, the geometry, the materials and the windings may be adjusted to satisfy the specifications and minimize (or maximize) some objective function, at the electromagnetic design level.

Based on the results of the electromagnetic design, in terms of exciting force and using the structural solver of the Mechanical design module the calculation of the periodic, mechanical deformation of the electrical machines will be performed. The deformation of the machine will be represented by the displacement of the individual nodes of the mechanical model. The structural modules will also provide the vibrations, centrifugal force, contact and sound pressure. For the acoustic simulation, the mechanical deformation is transformed to the velocity of the nodes. The sound pressure and sound particle velocity will be evaluated on predetermined points or surfaces, so acoustic power and sound intensity of the machine will be calculated using the Vibro-acoustic design module. The results are available for discrete frequencies. The influence of the different machine geometrical, electrical or mechanical parameters on the vibro-acoustic behaviour can be analysed.

Rigorous performance evaluation at the system-level has to be made during component development and before its implementation on the final system. In the traditional development of automotive components offline simulations (Model-in-the-Loop - MiL) are used within the system specification phase to estimate the potentials of possible parameter sets. This results in a tuning of components (e.g., in terms of power and torque rating) and a rough guideline for the various control loops. In addition to pure computer simulation, Hardware-in-the-Loop (HiL) simulation replaces some simulation models by one or several real components. The rest of the system and processes are simulated in real-time, which typically requires a parallel computing environment with adequate input-output capability for signals of adequate bandwidth. HiL technology enables a qualitatively new approach to develop and/or to test vehicle electrical components, as, through HiL, a highly realistic simulation of the component in an operational virtual environment is achieved.

Since now, the research activities focused on the component-level module, with the development and implementation of the analytical tools for design and analysis (electromagnetic and vibroacoustic). In parallel work is done in collaboration with both national and European partners for the development of MiL and HiL modules. The results of the research activities so far are published in scientific articles in BDI journals and proceedings[104,105,106,107,108,109,110].

[104] T. Rusu, O. Birte, L. Szabo, Claudia Martis: "*Script Controlled Modeling of Low Noise Permanent Magnet Synchronous Machines by using JMAG Designer*", Journal of Computer Science and Control Systems - Vol. 6, Nr. 1, 2013.

[105] A.T. Filip, R.P. Hangiu, Claudia Martis, K.A. Biro: "*Analytical Model for Predicting Displacements in Permanent Magnet Synchronous Machine*", The 8th International Symposium on Advanced Topics in Electrical Engineering, May 23-25, 2013.

[106] R.P. Hangiu, A.T. Filip, Claudia Martis, K.A. Biro: "*Permanent magnet synchronous machines for integrated starter alternator Applications*", Miskolc - XXVII. microCAD International Scientific Conference, 2013.

[107] A.T. Filip, R.P. Hangiu, Claudia Martis, K.A. Biro: "*Radial Force and Modal Shapes Calculation in Permanent Magnet Synchronous Machines*", Journal of Computer Science and Control Systems - Vol. 6, Nr. 1, 2013. EBSCO

[108] F. Nicolae Jurca, R.P. Hangiu, C. Martis: "*Design and Performance Analysis of an Integrated Starter-Alternator for Hybrid Electric Vehicles*", Advanced Engineering Forum (Volumes 8 – 9), pg. 453-460, 2013,

[109] O. Birte, T. Rusu, L. Szabo, Claudia Martis: "*Script Controlled Model of a Synchronous Reluctance Machine for Rapid Design Optimization*", Journal of Computer Science and Control Systems - Vol. 6, Nr. 1, 2013. EBSCO

[110] R.P. Hangiu, A.T. Filip, Claudia Martis, K.A. Biro: "*Analysis of the Operating Modes of an Integrated Starter Alternator for Automotive Applications*", Journal of Computer Science and Control Systems - Vol. 6, Nr. 1, 2013. EBSCO

5. CONCLUSIONS

The research and development work of the candidate during her professional evolution is a very rich and dynamic one. The results can be summarized as follows:

- 4 textbooks
- 125 scientific articles presented and national and international conferenecs and published in scientific journals, from which :
  - 23 in ISI Thomson-Reuters indexed journals and/or proceedings;
  - 42 in BDI indexed journals and/or proceedings;
  - 21 cited by other articles in ISI Thomson-Reuters indexed journals and/or proceedings (78 citations) and in BDI indexed journals and/or proceedings (120 citations).
- 7 national grants as director/responsable ;
- 4 FP7 European projects as coordinator (2) and as Technical University of Cluj-Napoca responsible (2);
- Research team member of 12 national projects and 7 international projects.

The activity of the candidate as collaborator or as co-supervisor of PhD students work has to be mentioned. This activity is important in demonstrating that the candidate is prepared for obtaining the habilitation and enrolling her own PhD students to supervise.

D. CAREER DEVELOPMENT PLAN

Sustainable Development was and remains the main leading concept of the candidate teaching and research activity, before and after obtaining the habilitation. The research activity of the candidate in the future will always follow the European research priorities, keeping the connections with the main actors in this field: European Commission, industrial actors (private companies, as present and future partners), academic and research actors (universities and research institutes).

The short-term (2 years) career objectives can be grouped as follows:

- Enrollement of at least 3 PhD students per year;
- Extending the Electromechanical Systems group and attracting a higher number of students to follow the Specialization in Electromechanics at the Faculty of Electrical Engineering of the Technical University of Cluj-Napoca;
- Preparing, as coordinator, of at least two proposals for calls in the frame of Horizon 2020;
- Participation as one of the main partners to the preparation of at least two proposals for calls in the frame of Horizon 2020;
- Development of a high-level equipped laboratory for Model-in-the-Loop and Hardware-in-the-Loop simulation and testing of electrical machines and drives for automotive applications.

The long-term (5 years) career objectives envisage:

- To be an active actor to the modernization of the teaching and research activities in our group and to higher connect them to the ones in European universities and companies;
- Increasing the number of participation of our university as coordinator/partner in national, European and other international research and teaching programs;
- Increasing the attractiveness of the research activity in our university by better promoting our work and by increasing the number of research projects;
- Extending the collaboration with the industry;
- Creating a spin-off company for engineering services in the field of electromechanical systems for energy, automotive and industrial applications.