Optimal design and control of electrical machines for more efficient energy conversion

Habilitation Thesis

Assoc. Prof. dr. ing. Tutelea Lucian Nicolae

Universitatea "Politehnica" din Timişoara
Facultatea de Inginerie Electrică

November 2014

Abstract

The habilitation thesis presents personal work and research results between August 1997 after Ph.D. thesis defended and November 2014. The title of my Ph. D thesis is "Polygonal stator flux control of the ac machines" and it was defended in July 1997 at University Politehnica Timişoara.

The habilitation thesis contains the following chapters: motivation, research directions, scientific and professional achievements, professional and academic development plan and the references chapter.

The motivation chapter briefly presents the research activities linked to the energy conversion, the cooperation with the other universities and the desire to continue the research and academic activities at superior level as a PhD supervisor in Electrical Engineering field.

In the second chapter, the main research directions such as: induction machine design, biaxial excited synchronous generator, permanent magnet machine, reluctance PM assisted motor, linear oscillatory motors, two rotors, single stator axial air-gap permanent magnet machine and complementary research directions such power electronics converters, are presented. For the each direction, only the main results are presented.

The "Scientific and professional achievements" are presenting in more details the activities from the main research direction.

The research direction on the induction machine design is reflected in five paragraphs. The induction machine design for flywheel energy storage project was developed during a post doc stay at Allborg University. A design of outer rotor induction machine software was produced and optimal flux control to reduce the losses at low load. A conference paper and a research report were published on this work. The induction machine and surface permanent magnet machine design for "in-wheel mounted drive for electric car" was developed during cooperation with the Allborg University as a guest research. Five conference papers and six research reports were published on this topic. Optimal design of induction machine was an important project for didactic but also for research purpose. One paper and a chapter in a book were published on this subject. Single phase two speeds induction and permanent magnet synchronous machine is a subject coming from home appliance industries. A two pole induction machine and four pole PM line start motors in the same machines was developed in order to have good efficiency at low power and low torque because this regime is most frequent in the compressor drive for house refrigerator. The project was developed in cooperation with Embraco, Brazilia. Two papers, first in ECCE conference and after substantial modification in IEEE transactions were published on this subject. The dual stator winding asynchronous (DSWA) generator is a new subject in cooperation with a team from Automatic Faculty, UPT in a PN-II-PT-PCCA grant. Five papers were already published on this topic.

The research on permanent magnet directions is reflected in the following chapters: optimal design of surface permanent magnet machine, internal permanent magnet machine but also in induction machine and surface permanent magnet machine design for in-wheel mounted drive for electric car. The optimal design software considering analytical models based on magnetic equivalent circuit, validated by finite element was developed for the surface permanent machine in two versions: with factionary tooth wound windings and for distributed winding. The torque pulsation reductions were also considered in this investigation. The brushless dc motor with permanent magnet for residential applications was also investigated in a national grant where I was director. Six papers were published on this topic. The internal permanent magnet machine was investigated from two points of view: cogging torque and torque pulsation reductions by pole tapered and possibility to use flux concentration and replace the rare earth

permanent magnets with ferrites which are low cost permanent magnet (even chipper than copper). Three papers were published on this topic.

The two rotors, one stator axial air-gap permanent magnet machine was another major research project in cooperation with Casino University, Italy. The main idea was to boost the hybrid vehicle development by some original contribution on electrical machines topology by combining the requested two machines in a single dual port machine. Seven papers and an invention patent in Italy were the project issues.

The bi-excited generator for automobiles (BEGA) research project has been focused on the efficiency of the automotive generators improvements by new generators topologies. We cooperate in this project with Aalborg University and Grundfos. I am coauthor at five papers on this subject.

The reluctance PM assisted motor was the subject with the highest research impact with more than 67 ISI citations. The starter/generator for mild hybrid vehicle was investigated at the beginning, with a prototype building. Finite element analyses, prototype test methodology with parameters estimation and two control strategies were developed. By optimal design, a full scale motor for hybrid or electrical vehicle power-train was designed with remarkable performances. We cooperate on the projects with this topic with Alborg University and Sauer Danfoss on the static power converter. Six papers (two in transactions) were published on this subject.

The linear oscillatory motor was the subject with the most published papers: eight papers from which three in the IEEE transactions and two invention brevets one of them in Germany. The flat and tubular oscillatory motor was investigates. The tubular topologies were investigated also in a national grant where I was director. We cooperate on this subject with Hanyang University, South Korea, Hilti from Germany, Casino University from Italy and Embraco, Brazil.

The powers electronics and control of the wind turbine generators are complementary subjects in a tight relation with electrical machines and energy conversion. Seven papers were published on these complementary research directions.

In the chapter “professional and the academic development plan” two future projects already started (with already 4 published papers) are described briefly with a short presentation of the main problems that will be solved. It is also presented the cooperation’s strategy with the futures PhD students and a strategy to attracting them through research results at the highest level.

The references list contains 198 papers or invention brevets where at 67 I am coauthor (at the 25 first author).

Rezumat

Teza de abilitare prezintă activitatea şi rezultatele de cercetare obținute, după susținerea tezei de doctorat, adică în perioada August 1997 până in prezent. Titlul tezei de doctorat a fost "Controlul poligonal al fluxului din stator în maşinile de curent alternative" şi a fost susținuta la Universitatea Politehnica Timişoara in iulie 1997.

Teza de abilitare conține următoarele capitole: motivație, direcții de cercetare, realizări științifice şi profesionale, planul de dezvoltare profesională şi academică şi în final capitolul de bibliografie.

Capitolul "motivația" prezintă pe scurt activitatea de cercetare legata de conversia energiei, cooperarea cu alte universități şi dorința exprimată de a continua cercetarea in domeniul ingineriei electrice la un nivel superior prin obținerea atestatului de abilitare.

Capitol al doilea prezintă principalele direcții de cercetare care sunt: proiectarea maşinilor asincrone, generatorul sincron bi-excitat pentru automobile (BEGA), maşina cu magneți permanenți, maşina cu reluctanță variabilă asistată cu magneți permanenți, oscilo-motoare liniare, maşina cu întrefier axial cu două rotoare şi un singur stator şi în final convertoare statice de putere ca direcție complementară de cercetare. Pentru fiecare din direcțiile de cercetare enumerate sunt prezentate principalele realizări.

Capitolul "Realizări ştiințifice şi profesionale" prezintă în detaliu activitățile desfăşurate in cadrul fiecărei direcții de cercetare şi principalele rezultate obținute.

Direcția de cercetare privind maşina de inducție este tratată in cinci paragrafe după cum urmează. Proiectarea maşini de inducție pentru a fi utilizată ca motor/generator intr-o aplicație de stocarea energiei în volanți de mare viteză, proiect desfăşurat in cadrul unui stagiu post doctorat la Universitatea din Aalborg unde s-a realizat codul MATLAB de proiectarea a unei maşini de inducție cu rotor exterior şi de asemenea strategia de control optimal al fluxului cu scopul de minimizarea pierderile la sarcini reduse. Rezultatele au fost publicate intr-un articol de conferința şi un raport de cercetarea. Proiectarea maşinii de inducție şi a maşinii sincrone cu magneți permanenți pentru o aplicație de vehicul electric cu motoarele plasate direct in cele patru roți a fost tema de cercetarea pe durata unui stagiu de cercetător invitat la Aalborg University rezultând patru articole în conferințe internaționale şi şase rapoarte de cercetare. Proiectarea optimală a maşinii de inducția a avut un dublu scop: didactic dar şi de cercetarea. Un articol de conferință şi capitolul dedicat proiectării optimale a maşinii de inducție din cartea „Electric Machines" au fost publicate. Motorul monofazat de inducție cu două viteze şi magneți permanenți este un subiect provenit din industria aparatelor electrocasnice prin colaborare cu firma Embraco din Brazilia. Ideea de bază este de a realiza o maşina electrică care funcționează ca maşină de inducție cu doi poli şi ca maşină sincrona cu magneți permanenți cu pornire directă de la rețea având patru poli, permițând un randament bun la sarcina redusa şi viteză redusă. Regimul de sarcina redusă este regimul normal de funcționare a compresoarelor de frigider şi de aceia se impunea ca în acest regim randamentul sa fie mare. Două articole, primul în volumul conferinței ECCE, şi după modificări importante republicat în revistă (IEEE transactions) sunt contribuțiile pe aceasta temă. Maşina de inducție cu două înfăşurări în stator în regim de generator este un subiect nou la care s-a lucrat în colaborare cu o echipă de la facultatea de automatică în cadrul unui grant de tip PN-II-PT-PCCA. Cinci articole au fost deja publicate pe acest subiect.

Direcția de cercetare a maşinilor cu magneți permanenți este reflectată în următoarele subcapitole: proiectarea optimală a maşinilor cu magneți permanenți de suprafață şi maşina sincronă cu magneți interiori. De asemenea în subcapitolul „proiectarea maşinii de inducție şi a maşinii sincrone cu magneți permanenți pentru o aplicație de vehicul electric cu motoarele plasate direct in cele patru roți", precum şi în subcapitolul „maşina de inducție şi sincronă cu magneți permanenți monofazată cu două viteze" există referiri la investigații detaliate asupra maşinilor cu magneți permanenți. In acest domeniu s-a realizat un program de proiectarea optimală utilizând un model analitic bazat pe metoda circuitelor magnetice echivalente şi validat prin metoda elementului finit. S-au luat în considerare maşinile electrice cu înfăşurări distribuite dar şi cele cu înfăşurări fracţionare concentrate. Maşina cu magneţi permanenţi de tip „BLCD” a fost cercetată şi în cadrul unui grant naţional de cercetare câştigat prin concurs ca director. De asemenea s-a investigat reducerea pulsaţilor de cuplu la aceste maşini. Şase articole au fost publicate pe acest subiect. Maşinile cu magneţi permanenţi interiori au fost cercetate prin prisma a două aspecte: reducerea pulsaţiilor de cuplu in gol şi in sarcină precum şi posibilitatea concentrări fluxului magnetic astfel încât să fie posibilă înlocuirea magneţilor permanenţi din pământuri rare cu magneţi permanenţi din ferită al căror preţ este mai mic chiar decât al cuprului. Trei articole la conferinţe au fost publicate pe acest subiect.

Maşina cu întrefier axial şi magneţi permanenţi cu două rotoare şi un singur stator a fost un subiect important de cercetare în colaborare cu Universitatea din Casino, Italia. Ideea de bază a fost să accelerăm dezvoltarea vehiculelor hibride prin contribuţii originale aduse asupra topologiei maşinilor electrice prin combinarea celor două maşini necesare in procesul de transfer de putere intr-o singură maşină electrică cu două porturi mecanice. Cercetarea in acest domeniu s-a materializat printr-un brevet de invenţie înregistrat in Italia si sase articole prezentate la conferinţe internaţionale.

Generatorul de automobil bi-excitat (BEGA) a fost un proiect de cercetare concentrat pe creşterea randamentului generatoarelor utilizate in domeniul automobilelor prin utilizarea unor topologii noi de generatoare auto. In cadru acestui proiect s-a colabora cu Universitatea din Alborg si firma Grundfos din Danemarca. Am fost coautor la cinci din articolele publicate pe acest subiect.

Maşina cu reluctanţă variabilă asistată cu magneţi permanenţi a fost subiectul cu cel mai mare impact asupra comunităţii ştiinţifice cu peste 67 de citări in articole indexate ISI. Pentru început a fost investigat un starter/alternator cu realizarea unui prototip de laborator. S-a realizat analiza cu element finit, elaborarea unei metodologii de determinare a parametrilor de circuit si două strategii de control. Utilizând proiectarea optimală s-a proiectat o maşină cu performanţe remarcabile pentru acţionarea unui vehicul hibrid sau electric. In cadrul acestui proiect s-a colaborat cu Universitatea din Aalborg si cu compania Sauer Danfoss pe partea de convertoare statice. Au fost publicate şase articole dintre care două in reviste (IEEE transactions).

Oscilo-motorul liniar a fost subiectul pe care s-au publicat cele mai multe articole: opt articole dintre care trei in reviste internaţionale (IEEE/IEE transactions) şi de asemenea s-au realizat două patente de invenţie. Au fost investigate atât topologii plane cât şi topologii tubulare. Investigarea unei topologii tubulare s-a realizat si in cadrul unui grant naţional câştigat prin competiţie ca director. De asemenea pe această temă s-a cooperat Hanyang University din Coreea de Sud, filiala Hilti din Germania, Universitatea din Casino, Italia şi compania Embraco din Brazilia.

Convertoarele statice de putere şi controlul generatoarelor eoliene sunt subiecte complementare in strânsă legătură cu maşinile electrice şi conversia energiei. Rezultatele cercetărilor in aceste domenii complementare au fost publicate in şapte articole.

In capitolul „Planul de dezvoltare profesională şi academică” au fost prezentate pe scurt două subiecte de viitor la care deja am început să lucrez având publicate deja 4 articole la conferinţe internaţionale. De asemenea s-a prezentat strategia de cooperare cu studenţii la doctorat şi atragerea acestora prin rezultate de cercetare la cel mai înalt nivel.

Lista bibliografică conţine 198 de articole sau brevete de invenţie dintre care la 67 sunt coautor, (la 25 prim autor).

Table of Contents

I Motivation

Since 1993, I have been devoted to teach and research activity at University “Politehnica” of Timisoara, where now I am associate professor with department of Electrical Engineering within Electrical and Power Engineering Faculty.

After I have defended my Phd. Thesis on “Polygonal control of the stator flux in ac drives” in July 1997 at University “Politehnica” of Timişoara, I have granted a three months post doc stage at Aalborg University, Denmark in the Danfoss Professor program where I carry out a research on the losses equivalence between artificial loading and shaft loading of induction machine [Tut 98]. The artificial loading allows testing the thermal design and cooling system of large induction machine even with vertical axes at rated current and rated losses without any shaft load, contributed this way to a better reliability with low cost equipment. I have got a second post doc stage at Aalborg University for 8 month working on the following three projects: “high speeds energy storage” [Tut 99], [Tut 00], “a generator system for a car”, [Bol 99b], [Bol 00], and “transients performances of power electronic devices” [Mun 00]. I was invited as a guest research for 9 month in 2000 at Aalborg University on project “Feasibility Study for Electric Drive System for Four Wheel Drive, in Wheel Mounting on Small, Battery Electric, Road Passenger Vehicle”. The research results were published in six research reports at Aalborg University and in four conference paper [Tut 01a, Tut 01b], [Tut 01c], [Tut 02] and the drives performances are still remarkable after 14 years despite of a huge progress in this field. I was involved in a project with BEEE-SPEED Timisoara and ABB Group Service Center AB, Corporate Research, Vasteras, Sweden, in 2002-2003, on modeling of the high speed (70 000rpm) surface permanent magnet generator based on finite element method (FEM) with experimental validation. In the mean time I have continued the investigations on the bi-excited generator for automobiles [Bol 02b], [Scr 04], [Scr 05] and on the PM assisted reluctance motor/generator for mild hybrid vehicle [Bol 02b], [Bol 04a], [Pit04] with remarkable technical results like 4.33N/cm^2 tangential force, wide constant power speed range with visibility impact of 37 ISI citation for a single paper [Bol 04a] and other 30 ISI citation on the machine control paper [Bol 06]. Recently I have work on optimal design of reluctance PM assisted motor considering nonlinear analytical model based on magnetic equivalent circuit [Tut 14b], in order to achieve the required high torque density, high efficiency PM-RSM drive required in hybrid vehicle applications. I have also investigated the two rotors, one stator axial air-gap permanent magnet machine [Bol 10a], [Tut 12b, Tut 12c, Tut 12d] in my concerns related to the hybrid vehicles. Recently in cooperation with prof. F. Marignetti from Casino University, Italy we patented the “Brushless electrical actuator with two independent rotors for hybrid electrical propulsion” solutions [Bol 14].

I have approached the linear oscillatory machine research field since 2004 [Bol 04b] and during a two mounts research stage at Hanyang University from South Korea, I have been developed a method to evaluate the linear oscillatory machine parameters and performances by experiments [Tut 05], [Tut 08]. The tubular multi-coil topology with multi-polar PM mover with radial plus axial PMs [Bol 12c] was investigated in comparison with the surface PM three phase brushless dc motor as a high performance, low cost drives for refrigerators compressor. This research was object of CNCSIS grants, 58GR/19.05.2006 topic 18 and 76GR/23. 05. 2007 topic 37. I have developed the first optimization design code in MATLAB for the tubular oscillatory machine mainly because of the solution novelty and due to the lack of clear design recommendations in the literature. The optimal design was exported to the three phase tooth wound brushless dc machines [Tut 07] that is still a special machine despite of its popularity in small power applications. The optimal design of electrical machine was further improved by considering the several random start points of Hooke Jeeves algorithm or by population evolutionary in genetic algorithm in order to increase the probability to get around to the global optimum. The optimal design was extended to induction machine [Tut 10a], and to the surface PM machines with distributed winding [Tut 10b]. The investigations of the linear oscillatory machine were oriented also to the electric valve actuator [Bol 07], [Bol 08b] for the thermal engine, including the dynamic model based on the FEM parameters. Open and close loop control [Aga 09], [Aga 10a] was also developed. After FEM analyses of several tubular PM oscillatory machines configuration, we find a geometric topology where the cogging force versus mover position is similar with mechanical spring elastic force and enough larger such that for a certain resonant frequency the mechanical springs are no necessary [Aga 13a]. I am coauthor at two invention patents on the oscillatory machine [Aga 10b], [Bol 12d], the second in Germany in cooperation with Hilti Company.

My concerns on renewable energy [Fat 06], [Ser 06] was enforced by my visiting researcher on renewable energy subject at Aalborg University in 2006 and a new seamless method to connect a PM standalone generator to the grid was developed [Fat 07a]. A high harmonics control method [Fat 07b] was developed in order to improve the renewable energy quality. I have continue the work in the renewable energy direction as a member in the PCCA 36/2012, PN-II-PT-PCCA-2011(lead by prof. O. Prostean, dean of the Faculty of Automatics and Computers, UPT), where I am responsible for the optimal design of the induction machine [Tut 13a, 13b, 14a, 14c, 14d] respectively brushless dc multiphase reluctance machine [Urs 13], [Aga 13b].

In my research activity, I have a good cooperation with the majority PhD students of academician prof. I. Boldea and prof. N. Muntean from the University Politehnica Timisoara, with PhD students from Technical University of Cluj-Napoca and also with PhD students from Hanyang University, South Korea.

My research directions seem to be much diversified but all of them are linked to the energy conversion and the research effort was focus to a better efficiency of energy conversion and to make available the advanced technologies for as many applications.

In the future I would like to continue the research on the energy conversion, that is a very important subject for the community, and I consider, that, the ability to be PhD supervisor will enforce my already rich research on this wide field and will open new horizons. Working with the PhD students will help me to improve my didactic activities by knowing better the students concerns.

II Research directions

1. Induction machine design

The induction machine is the most used motor in the industry applications and despite of more than 125 years when it was invented independently by Galileo Ferraris and Nicola Tesla in 1885, and in the short circuit rotor cage form by Mikhail Dolivo-Dobrovolsky, 1889, the research field on this most popular machine is still open mainly due to new applications (automotive, renewable energy conversion, energy storage, home appliance, and special design variable speed drives associate with power electronics), new materials and finally but not at the end the computer assisted design.

I have start my research on the induction machines design during a post doc stage at Aalborg University in 1999 when I have developed a MATLAB code to design a high speed induction machine with external rotor to drive a flywheel energy storage system [Tut 99], [Tut 00]. I have adapted the induction machine design with outer or inner rotor for electrical vehicle with in-wheel mounting drive. The flux optimization was used to reduce the electrical machine losses and with the regenerative braking we increase the vehicle autonomy up to 121km with 10kWh stored energy for a 600kg vehicle weight [Tut 01a], [Tut 01b], [Tut 02].

Later I have introduced optimal design of induction machine using a modified Hooke Jeeves algorithm in comparison with the genetic algorithm for automotive air-conditioning drive [Tut 10b].

I also have important research contribution on the efficiency improving of the single phase compressor motors for household refrigeration systems [Kaluf 12, Kaluf 14]. The present investigation shows a feasible way to create a 2-speed motor, without the need of an inverter, using a stator with two and four pole windings and a cage rotor with buried magnets (for four poles). The motor was designed to run synchronously at four poles (low speed 50 W, 84% efficiency) and asynchronously for two poles (high speed 100W, 60% efficiency).

The dual stator winding induction machines as wind power generator for micro grid applications are ones of ours most recent investigations on the inductions machine [Tut 13a, 13b, 14a, 14c, 14d].

2. Biaxial-Excited synchronous generator

The biaxial-excited synchronous generator for automobiles (BEGA), [Bol 00], [Bol 01a], was proposed as a new type of electrical generator with electromagnetic excitation in ‘d’ axes in order to control the voltage level at wide speed variation, respectively, a constant permanent magnet excitation in ‘q’ axes in order to compensate the armature reaction field. The main idea is to replace the existing Lundell generator, known for its small efficiency [Per 04] with a most efficient generator in condition of car electrification [Kas 96].

I have developed an analytical model of this new machine able to compute the external characteristics. After that during the post doc at Aalborg University in 1999, I have designed a new prototype of ‘BEGA’, by computer aided software developed in this scope. The BEGA prototype was used as technical base for several PhD. theses. Dr. Ing. S. Scridon developed the optimal design using Hooke Jeeves method implemented in Visual C language and proves by experiments the principle of biaxial-excited synchronous generator [Scr 04], [Scr 05]. Dr. Ing. V. Coroban expanded use in motoring proving a theoretical infinite speed range at constant power [Cor 09], and also applied the active flux control on this machine [Cor 11]. After 15 years the BEGA concept is still modern and probably it could be used in electrical or hybrid automobiles. Our research on this field has a good impact on the scientific community considering the 9 ISI citations on [Scr 05].

3. Permanent magnet machine

Nowadays, the permanent magnet machines are very important because it allows high density torque and at the same time it shows good efficiency.

I have investigate the outer rotor surface PM motor with 24 poles in the rotor and 27 factionary tooth wound coils, 3 phase in the stator for electrical vehicle in wheel mounting drive. The motor has good torque density and good efficiency at low speed [Tut 01c], but high core losses at high speed, especially at low torque are degraded the motor efficiency at high speed [Tut 02]. The surface PM motors characteristics are better used in the application that do not require a wide constant power speed range as compressors and pumps. Consequently we investigate the 6 tooth wound coil and respectively four rotor surface PM motor for refrigerators and air conditioning compressor. Optimal design Using Hooke Jeeves algorithm implemented in MATLAB with offline FEM validation was introduced in [Tut 07] and developed considering the cogging torque and torque pulsation reduction in [Gra 08], [Gra 11]. An automated manner to correct analytical model based on the online key FEM validation [Mun 12] is a further improvement of the optimal design algorithm. The single phase permanent magnet motor was studied in order to reduce further the costs of the small motors [Iep 08]. In our research [Iep 08], the gradual air-gap surface PM single phase synchronous motor was investigated by FEM, on a case study, in order to obtain a good compromise between starting torque, average torque and torque ripple. Then, based on a dynamic circuit model, the torque pulsations with trapezoidal current control is explored through digital simulations with about 80% (from average rated torque) initial self-starting torque. Internal PM rotor was also investigates with the objective to reduce the cogging torque and improve the motor reliability [Ile 05], [Sti 08, Sti 10] in a pretentious applications like steering by wire and recently in a flux concentration version with the objective to replace the expensive rare earth permanent magnets with ferrites [Isf 13a], [Isf 13b]. The impact of the optimal design of the surface PM machines counts 3 ISI citations on [Tut 07].

4. Reluctance PM assisted motor

The PM assisted high saliency synchronous machines [Jah 00], [Vag 00], have been progressively introduced in an effort to cut the initial system (drive) costs and maintaining good performance. The need of good efficiency in a very wide power-speed range of 6:1 in a hybrid electric vehicle can be accomplished by using the interior PM assisted reluctance synchronous machine [Lov 02].

In our research, [Bol 02b], [Bol 04a], [Bol 04c], the conceptual design and finite-element method analysis of a permanent-magnet-assisted reluctance synchronous motor/generator for mild hybrid vehicles was introduced. The main idea in this kind of machines is to use the reluctance torque while the PMs field are compensate the high current q axes armature reaction, usual at the rated current, and also to improve the motor saliency by pre-saturation of the magnetic bridge along the q axis. Contributions on the machines parameter identifications are presented in [Pit 04]. Sensor-less direct torque and flux control was developed for this machine [Bol 06] for a wide speed range and vector control based active flux concept with I-f starting in [Aga 10c].

Recently we developed the optimal design of reluctance PM assisted motor considering nonlinear analytical model based on magnetic equivalent circuit [Tut 14b], in order to achieve the required high torque density, high efficiency PM-RSM drive of 50/100 kW for 1350 rpm to 7000 rpm, for electrical or hybrid vehicle. The simulation results with FEM key validations shows the efficiencies above 92-93% for a 520 A peak phase current and a 40 kg active materials weight with only 2 kg of 1.1 T NdFeB magnets on the rotor. Our research in this field has an impressive impact in the scientific community, by considering the 37 ISI citations on [Bol 04a], others 30 ISI citations on [Bol 06] and 4 ISI citations on [Aga 10c].

5. Linear oscillatory-motors

The linear permanent magnet (PM) brushless oscillatory machines have gained momentum in the last years, in relation to Stirling engines, refrigerator compressors [Par 01], and hybrid electric vehicles (HEVs) [Cos 03], [Caw 01], marine wave renewable energy [Mue 03] and precision positioning [Liu 05], [Li 05], [Gut 05], [Shieh 06].

In our research we investigates the linear oscillatory motors with flat flux concentration PM mover [Bol 04b], tubular PM mover [Bol 12c], [Aga 13b] and stator flux reversal PM with two disks mover [Bol 07]. Comprehensive nonlinear model for transients and experiments on its validation are developed [Tut 05], [Tut 08]. A transverse flux, oscillatory machine to act a drilling hammer [Bol 12d] was patented in cooperation with Hilty Company.

A small power (25W) linear PM oscillatory motor for active cooling of the desktop computer, laptop or the like was investigated from topology to a general design model and an optimization design code, through FEM validations to the control dynamics model [Bol 12c]. Promising results such as: more than 74% efficiency for 60 grams total active material weight, 15 mm outer diameter at 270 Hz and ±3mm motion excursion, were obtained. A tubular multi-coil topology with multi-polar PM mover with radial plus axial PMs (Halbach array) was adopted. The optimal design based on Hooke-Jeeves method was implemented in Matlab code considering as objective function the sum of the power loss and mover weigh, each of them multiplied with a weighting factor. The optimization algorithm was applied to the initial design with the results of a 4% increasing in efficiency at about same total active material weight of 60 grams, for operation at resonance at 270Hz with the same total stator (primary) length (50mm). The final design validated FEM analyses. An approximate steady state and transients circuit model was introduced and applied to get the machine performance at steady state and then certify starting and open loop self-stabilization under load considering the actual thrust versus current and position, the emf versus position and cogging force versus position, as thy was obtained from 2D axis symmetric FEM. The nonlinear circuit model was implemented in Matlab Simulink and the starting process was analyzed considering gradual voltage open loop ramping and then close loop sinusoidal current control. The latter was proved to produce a remarkable starting time reduction (from 250ms to 100ms), while being also less dependent on machine parameters.

Further a new topology where the cogging force versus mover position is similar with mechanical spring elastic force was developed and for a certain resonant frequency the mechanical springs could be eliminate [Aga 13a]. New topology of linear oscillatory motor [Aga 10b] was developed in order to produce the highest trust and acceleration required to act the valves in the came-lees internal combustion engine. The magnetic normal force was used in order to achieve the required force density. The combination of the mechanical spring elastic force and permanent magnet cogging force by a clever design allows three static equilibrium positions as the both of the mover displacement and the middle position. The electrical energy (current in the coil) is used only to commutate the mover from one to other position. The optimal design with FEM validation and thermal constrain was used. The valve acceleration was the objective function [Bol 07], [Bol 08b]. Open-loop U/f and I/f dynamic circuit model rather successful validation was implemented [Aga 09a]. A sensor-less closed loop position control based on a FEM assisted estimator that uses two extra coils placed near the main coils gives better results [Aga 10a]. Our research on this field has a good impact on the scientific community with 18 citations on [Tut 08] and 2 citations on [Tut 05].

6. Two rotors, single stator axial air-gap permanent magnet machine

The research on the two rotors, one stator axial air-gap permanent magnet machine follows the idea to boost the hybrid vehicle development and to contribute with some original ideas to this burgeoning field. Usual the two electrical machines are required for HEVs power train, one of them connected to the internal combustion engine and another connected to the wheel drive. Therefore, the integration of both machines into an electromechanical set, in an attempt to improve the compactness [Zhe 07], [Cav 01] and the cost-effectiveness, is currently considered a challenging technology. Of particular interest is the so called "single-stator dual-rotor permanent-magnet machine" [Ham 09], [Tah 04].

I have study the "two rotors, single axial air-gap permanent-magnet machine" topologies and mathematical model with some 3D FEM validation [Bol 10a] (it has 4 ISI citations) in cooperation with a large team from UPT and from University of Cassino, and we proposed a new machine configuration [Bol 14]. Preliminary design and control of the two independents rotors by a single three phase inverter was developed through a two frequency technique [Bol 11]. The equivalent magnetic circuit's model validated by quasi 2D finite element and then optimal design [Tut 12c, Tut 12d] was the next step. The permanent magnet skewing was proposed and modeled in order to reduce the cogging torque and torque ripples [Tut 12c]. Based on the machines parameter and circuit model the machines features versus speed was analyzed.

Two machine topologies was studied, the first considering a single three phase ring winding, and the second topologies considers two pairs of three phase drum winding placed on the stator axial air gap surface. The second topologies were developed considering that the power required for the two electrical machines in HEV applications are usual in ration one to two. A four legs inverter with split capacitor was proposed with the delta connection of the three phase winding. It was demonstrated, through digital simulations, wide speed range control with compensated split capacitor-neutral voltage [Tut 12b]. The torque pulsations and power losses of the proposed method are reduced in comparison with those with a single 3 leg inverter where the two windings are considered in series. Both machines could be controlled independently over a wide speed and torque range.

7. Power electronics converters

The power converter research is complementary to the electrical machine research because the power converters have an important impact on the electrical machines performances when they are components of the same drives. The power converters are influence the electrical machine efficiency in two ways: by increasing the losses due to the high harmonics contents, but also the machine losses could be reduced by an intelligent control that is usually available only in drives with power converters. When we design an electrical machine with the scope to improve the efficiency we should consider also the power converter losses. I have studied the steady state and transients losses of the power electronic devices during a post doc stage at Aalborg University. We, prove experimentally that the power losses of the power converter could be computed separately after the current and voltage across to the converter devices was computed considering ideal circuit elements [Mun 00].

The power converters with reduced numbers of power devices have been studied as alternative of the classical power converter for the low cost applications. In this direction, a single transistor chopper and current source inverter with two low cost thyristors just turn on and off at fundamental frequency [Ili 06] was proposed for a single phase bifilar winding permanent magnet synchronous motor. The Z – source inverter [Pen 03a, Pen 03b], could be considered a low cost converter that produces any desired output AC voltage, even greater than the line supply voltage. We proposed a new PWM technique for the Z - source inverters in order to control the voltage boost and at the same time the output three phase voltage and frequency [Mun 07]. The four leg inverter [Tut 12b] proposed to drive the single-stator dual-rotor permanent-magnet machine, also, contributes to the low cost inverter development. An anti-parallel diodes leg was proposed in order to limit the overvoltage on the capacitors. The number of active semiconductor devices is still reduced in comparison with two full inverters. My research work on this complementary field also has impact on the scientific community with 5 ISI citations on [Mun 00] and one ISI citation on [Mun 07].

III Scientific and professional achievements

1. Induction machine design for flywheel energy storage

1.1 Introduction

The research work was focusing on the electrical machine design on motoring and generating able to charge or extract the kinetic energy of the flywheel. This application requires: very low losses in standby mode to minimize self-discharging, run at rated power through a wide range speed, good efficiency over all speed range, good power factor over all speed range, high speed machine. The outer rotor machines allow larger permissible tangential speed up to 800m/s [Vet 96], [And98] improving the energy storage density. Mechanical constrains: stress due to centrifugal force, elastic instabilities related to critical speed, rotor losses and rotor cooling condition have a decisive influence on high speed machine design [Wia 98].

1.2 Induction machine design

An open source, modular design code, was developed in MATLAB in a way that allow new modules adding in order to consider the tough requirements on electrical machines for flywheel energy storage applications. Classical knowledge of electrical machines, [Alg 70], [Ham 94] is combined to elaborate the computer design code. The maximum stress in the external rotor yoke [Liu 91] is used to check the mechanical constraint and if it exceeds the maximum admissible stress, the following actions are possible: decrease the rotor outer diameter and recalculate the electrical machine or retain the diameter and improve the mechanical strength of the rotor using an external retaining ring.

The electrical machine is running in a wide speed range in motoring and generator mode that means a large magnetic flux variation. The leakage flux become important in a deep flux weakening mode and based on [Ost 89] the equivalent magnetic circuit scheme, fig 1, is derived in order to compute the flux density and the equivalent electrical circuit parameter for every running regime considering the magnetic saturation. An iteratively numerical algorithm was developed in order to solve the nonlinear magnetic and electric circuit tight coupling equations.

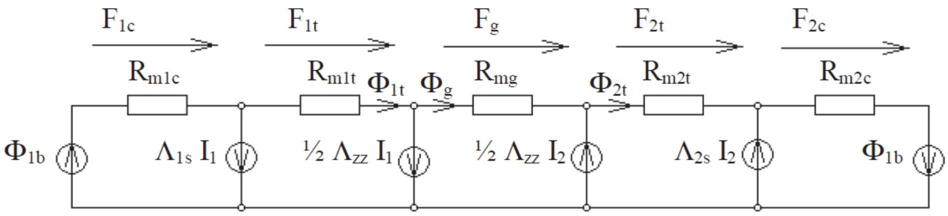

Fig. 1. Equivalent scheme of magnetic circuit [Tut 00].

The main specifications of the designed flywheel system are: utilizable energy 54MJ between 10,000 rpm and 20,000 rpm, charge and discharge at rated power 80kW, standard 3 phase load at 400V. The cross section of the induction machine is shown in Fig. 2 considering cylindrical respectively trapezoidal rotor bars. The developed software are computing and presents as a graphical results the machine performances: the electric power versus mechanical power, the efficiency and power factor versus output power [Tut 00] at base and at maximum speed. The flux density distribution, Fig. 3, shows a better utilization of iron on the rotor tooth for the trapezoidal slots, which also allows to reduce the outer diameter, and then for the same maximum tangential speed, the mechanical strength is reduced. At the base frequency, the maximum electromagnetic overload capacity is 409% of rated power in motor mode, and 500% of rated power in generator mode. At maximum speed (twice of base speed) the maximum electromagnetic load capacity is over 148% of rated power in motor mode and 160% or rated power in generator mode. From the machine performance characteristics, [Tut 00], was observed that the efficiency and power factor are poor at small load when constant voltage is used and consequently an optimal voltage versus load and frequency was proposed in order to improve the efficiency. The storage energy back-up time versus load is considerably improved by using the optimal voltage control, fig. 4.

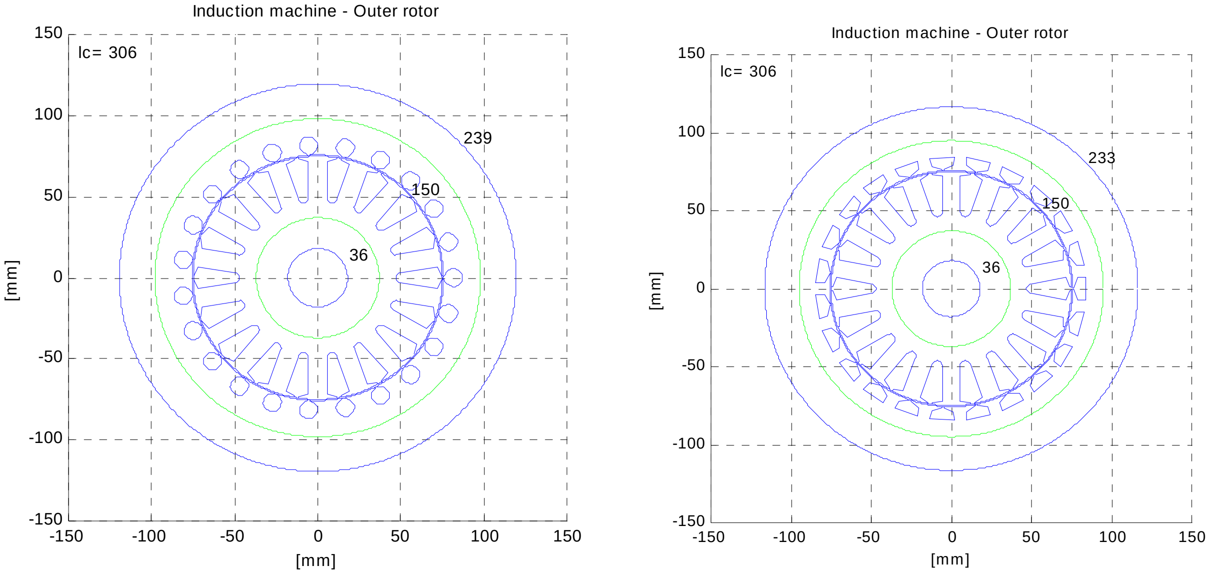

Fig. 2. Transversal sections of induction machine: a. shape of rotor slots as a circle, b. shape of rotor slots as a trapezoid.

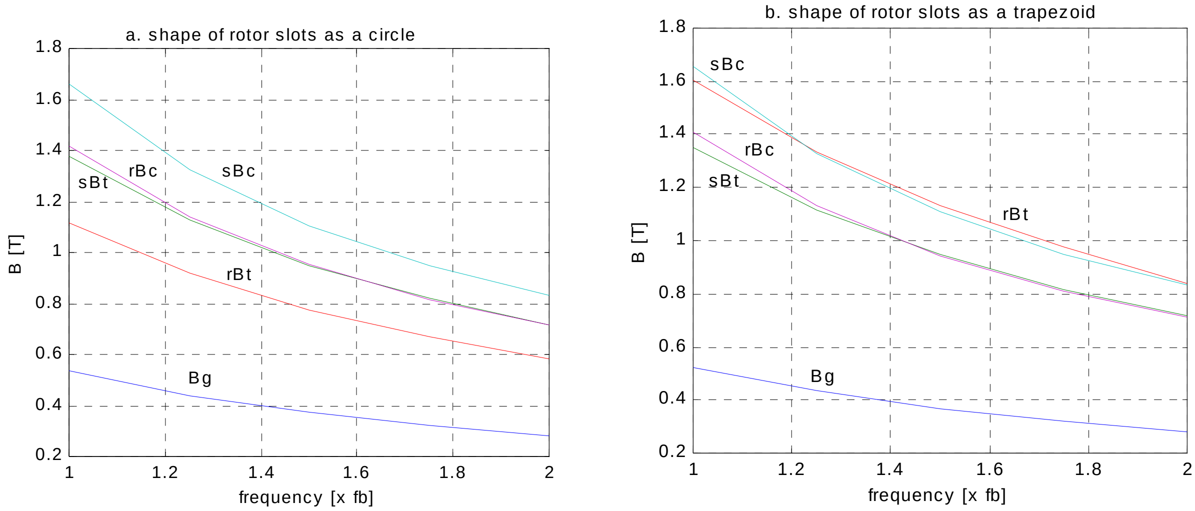

Fig. 3. Magnetic induction versus frequency (where: Bg air-gap maximum induction, sBc - stator core induction, Bt-stator tooth induction, rBc -rotor core induction, rBt-rotor tooth induction, base frequency fb=166.7Hz [Tut 00].

.

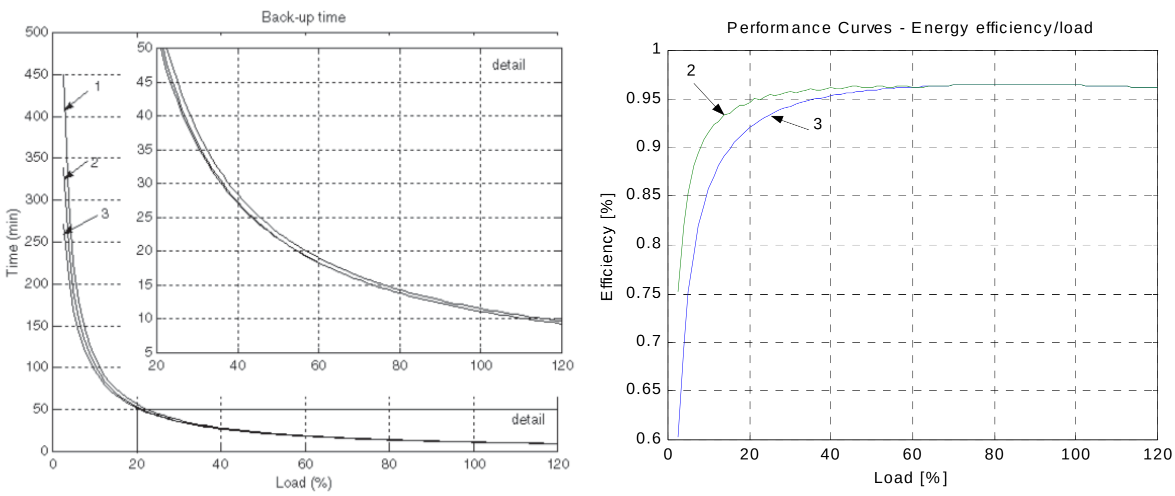

Fig. 4. Performances curves Back-up time and Energy efficiency versus load: 1.ideal generator, 2. optimal mode operation, 3. constant voltage operation [Tut 00].

The energy efficiency was computed for the generator regime as the ratio between the output electrical energy and mechanical energy when the flywheel speed decreases from maximum speed to base speed. The energy efficiency is 96.4% (at rated load) while the maximum efficiency, 96.5%, is reached at 85% of rated load. The efficiency decreases to 95.9% at 50% load and to 92.1% at 20% load. Optimized voltage operation improves the efficiency at light loads, 96.2% at 50% of rated load respectively 94.7% at 20% of rated load.

1.3 Conclusion

The research contributions are: a method to scale an induction machine for flywheel energy storage, the performance curves versus load at constant voltage and frequencies using a circuit model combined with a field model, a method to optimize the voltage versus load and frequency, back up time and energy efficiency computation; all embedded in the develop design software. The iron losses can be reduced using optimized voltage at medium and small load, increasing the backup time at low load. Very low mechanical loses are important to energy storage for a long time.

2. Induction machine and surface permanent magnet machine design for in-wheel mounted drive for electric car

2.1 Introduction

A high efficiency, low weight drive is necessary for electric vehicle, to offset the low density of electric energy storage in the battery [Bur 90] and make the electrical vehicle performance comparable to the internal combustion engine vehicle. The compact, in-wheel, direct drive [Car 96a, Car 96b] seems to be a good solution to increase the efficiency/weight ratio of the electrical vehicle but it requires low speed and high torque motors machine that usual are produced by permanent magnets machines [Car 96a, Car 96b, Car 94, Pro 96, Pat 97]. The permanent magnet machines are expensive and for some of them, the torque versus speed characteristics is quite far from the electric vehicle drive requirements [Pat 97, Pat 94].

2.2 Sizing the traction drives

A direct drive solution, DDS and a gear drive solution, GDS, were studied for a four motor, fig. 5, small city car driving with the main characteristics: length 2.5m, total weight 660kg, maximum payload 250kg and dynamic wind resistance coefficient C_w=0.3, and vehicle frontal area A_f=1.995 (m^2/s) [Tut 01a, Tut 01b]. The steady-state traction force of the vehicle, acceleration time and the top speed was used to compute the electrical motor design requirements [Tut 01b]. The steady-state traction force F_s as a sum of the rolling resistance, climbing force and drag resistance [Har 95], and then electrical motor request torque is computed and, fig. 6. The maximum speed and acceleration time depends on the traction power, fig. 7. The required rated torque of the motor is computed to drive in the worst-case condition, e.g. 40km/h on a 25% gradient, or 100km/h in a 10m/s head wind on a horizontal road. After reviewing the required torque, fig. 6, the rated torque for was selected to be 120 Nm. The maximum steady state vehicle speed on a horizontal road with zero wind speed depends only on the total available power and according to fig.10 a 20kW rated power is sufficient to drive the vehicle at 120km/h and also the acceleration time is acceptable.

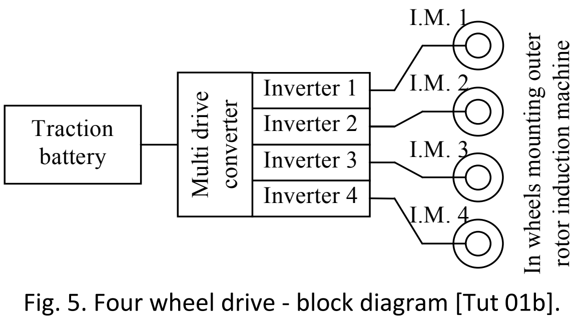

Fig. 5. Four wheel drive - block diagram [Tut 01b].

The direct drive induction/permanent magnet machine parameter are: Pn=5kW, rated torque 120Nm, and constant power speed range from 41.2 rad/s to 125 rad/s speed. The induction machine design software presented in [Tut 00] was further developed, [Tut 01a], to be able to design the outer and also the inner rotor induction machine for automotive application with the output data presented in Table 1. The outer rotor, surface permanent magnet machine with wound tooth factionary winding design is presented in [Tut 01c]. Cross section of induction machines and permanent magnet machine are shown in fig. 8.

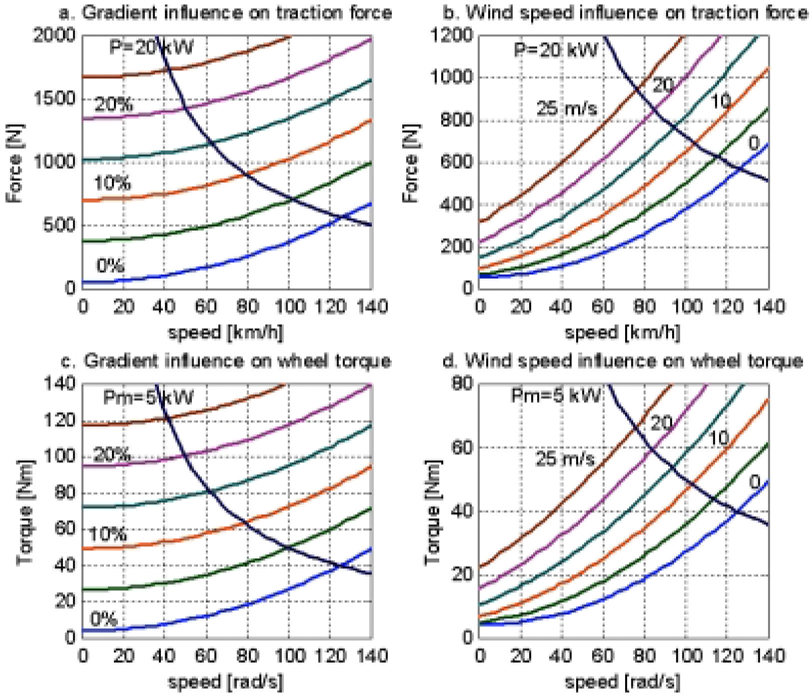

Fig. 6. Traction force and Motor torque versus speed [Tut 01b].

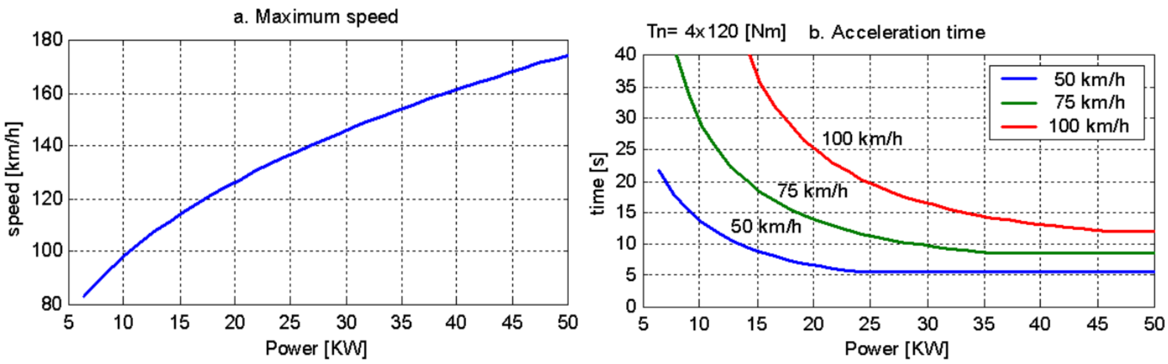

Fig. 7. Maximum speed and acceleration time versus total power [Tut 01b].

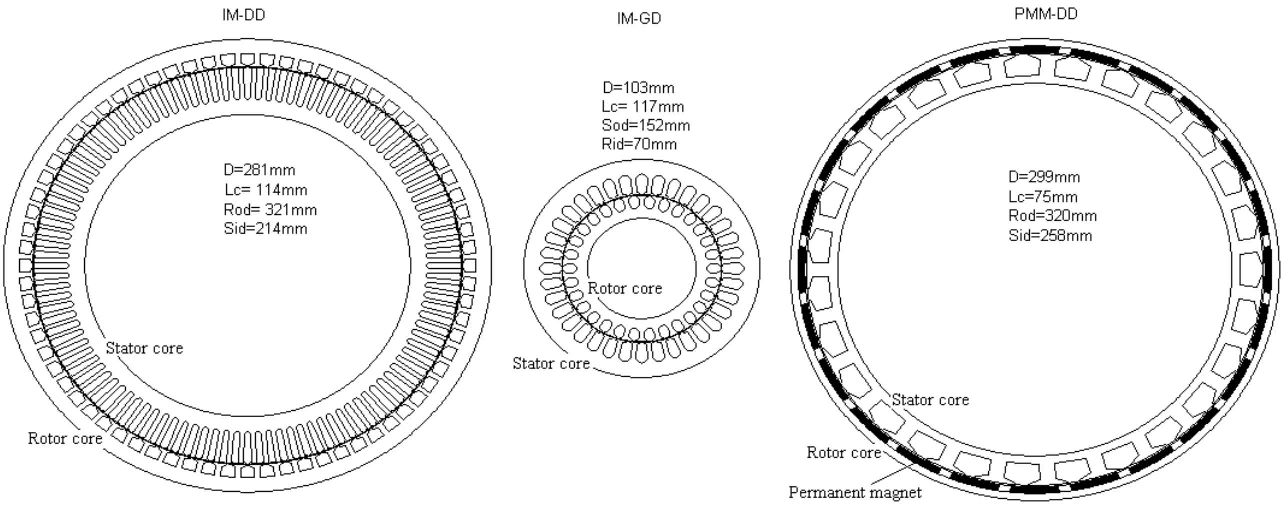

Fig. 8. Cross section of induction machine direct drive (IM-DD) respectively gear drive (IM-GD) and permanent magnet machine direct drive (PMM-DD [Tut 02].

Table 1. Motor and transmission parameters comparison.

Parameters	IM-DD	IM-GD	PMM	Units
Rated Power	5	5.5	5	KW
Rated synchronous speed	400	4000	597	Rpm
Rated line Voltage	200	200	190	V
Phase number	3	3	3	
Poles number	12	4	24	
Rated current	24.2	22.8	16.5	A
Rated frequency	40	133	119	Hz
Rated torque	119	13.1	80	Nm
Peak torque	283	37.1	240	Nm
Rated efficiency	79.3	89.3	92.5	%
Rated power factor	0.754	0.781	0.995	
Stator current density	4.69	6.63	5.6	A/m
Stator iron weight	12.56	3.85	5.75	Kg
Stator windings weight	9.33	2.71	3	Kg
Rotor Iron weight	10.99	2.35	2.89	Kg
Rotor cage or PM weight	6.24	1.96	1.94	Kg
Total motor weight	39.13	12.3	13.7	Kg
Transmission ratio	1	10	1	
Transmission Efficiency	100	90	100	%
Gear weight	0	4	0	Kg
Total Drive Weight	39.13	16.3	13.7	Kg

2.3 The control strategy

The optimal voltage (Optimal flux control) is used in order to improve the drive efficiency by minimize the motor and inverter total loss, [Bla 95, Bla 96, Mun 00]. The air-gap flux value is adjusted, based on search algorithm [Nei 96] in order to minimize the total losses. The energetic performances of the electrical vehicle provided with: direct drive (IM-DD), gear drive (IM-GD) induction machines or direct drive surface PM machines (PMM-DD), are compared at different speeds, fig. 9 [Tut 02]. The optimal and non-optimal (constant flux under base speed and constant voltage beyond) is presented for induction machines.

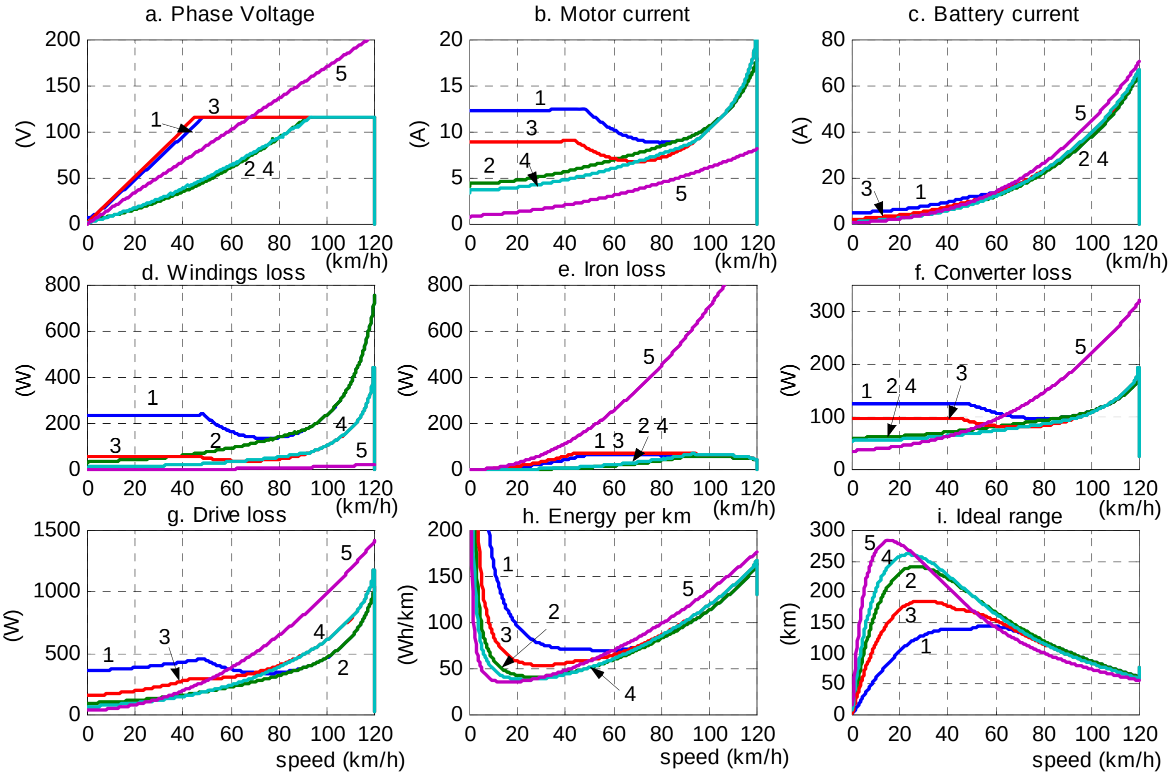

Fig. 9. Vehicle energetic performance versus vehicle speed: 1- IM-DD non optimal flux control, 2 -IM-DD optimal flux control, 3- IM-GD non optimal flux control, 4-IM-GD optimal flux control, 5-PMM-DD [Tut 02].

The energy used per km and the vehicle ideal range considering constant speed, fig 9.h and fig. 10.i show that PM motor is better at low speed. The electrical motor, power converter and total drive losses, (that include also the gear-box transmission losses for IM-GD) are presented in fig. 10 for IM-GD, IM-DD and PMM-DD considering non-optimized flux control (curves 1) and optimized flux control (curves 2) in an urban speed cycle condition. It could be noticed than in the urban cycle conditions the PMM-DD has better performance, followed by IM-GD and on the last place is IM-DD. Also it could be observed that the optimal flux control for IM is improving notably their performances. The losses waveforms in the extra urban speed cycle are presented in fig. 11.

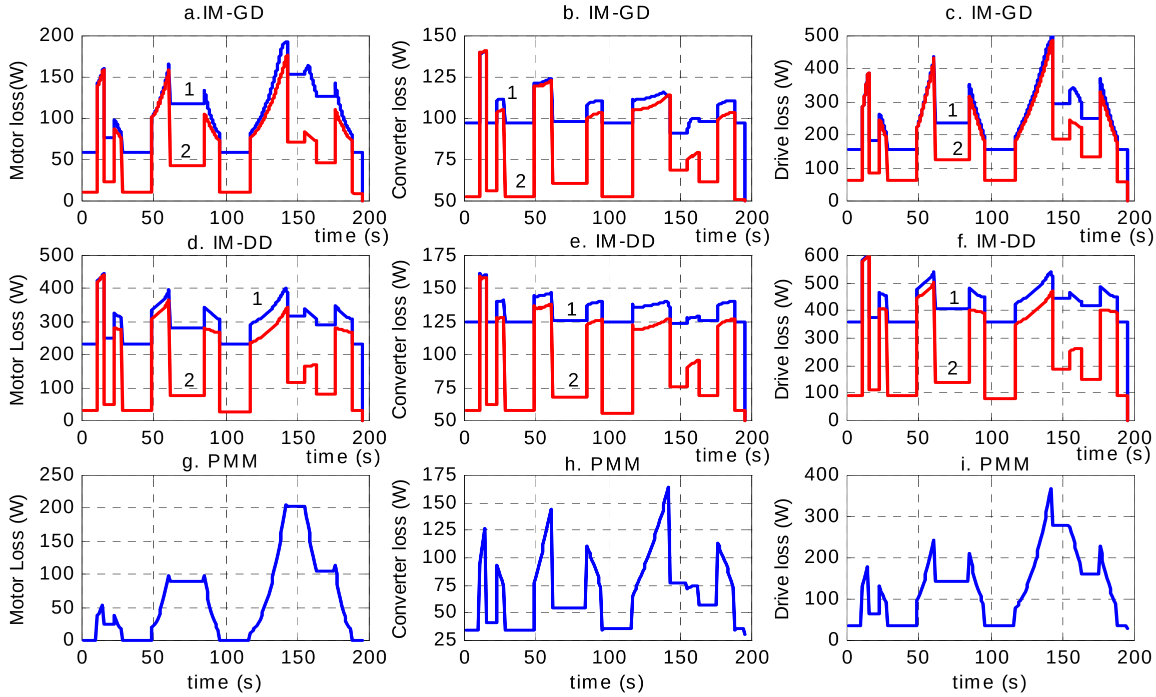

Fig. 10. Loss distribution for urban traffic conditions: 1 non-optimized flux, 2 optimized-flux control [Tut 02].

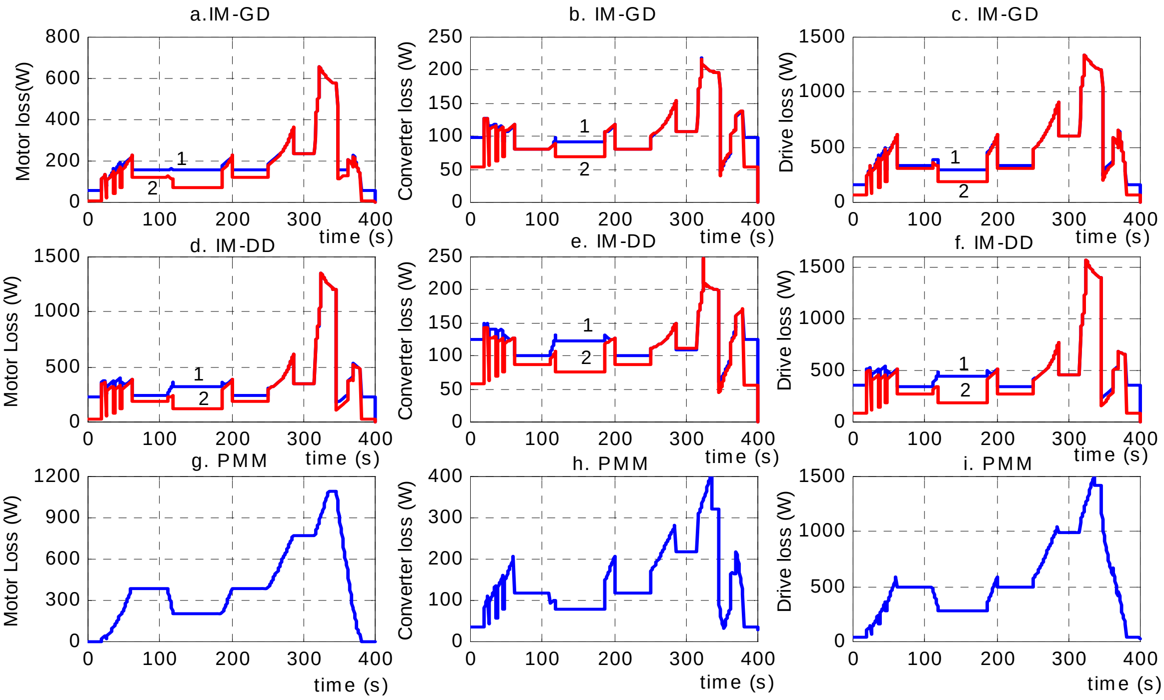

Fig. 11. Loss distribution for country traffic conditions: 1 non-optimized, 2 optimized-flux control [Tut 02].

It could be noticed than the IM-GD has the better performances in the extra-urban cycle conditions where the PMM-DD energetic performances are the worst. The optimal flux control improves the energetic performances of IM-GD and IM-DD especially in urban cycle conditions during low torque requirements.

A summary of the energetic performances is presented in Table 2, which shows that theoretical 188km electric vehicle autonomy is feasible with the PMM drive in urban cycle while IM-GD drive with optimized flux control could bring 121 km autonomy in combined drive cycle.

Table 2. Energy usage and vehicle estimated range.

	Urban		Extra Urban		Average	
	Energy (Wh/km)	Range (km)	Energy (Wh/km)	Range (km)	Energy (Wh/km)	Range (km)
IM-DD, constant flux	117.3	85.2	99.62	100.4	108.1	92
IM-DD, optimized flux	77.15	131.	93.08	107.4	86.91	115
IM-GD, constant flux	77.94	128.3	96.4	103.7	89.68	111
IM-GD, optimized flux	62.62	159.7	93.72	106.7	82.34	121
PMM	52.9	188	102	97	87.5	114

2.4 Conclusion

The induction machine design software developed during this research (guest researcher at Aalborg University 2000) is used as didactic support for electrical machine design with the student from the Electrical Engineering faculty of University Politehnica Timişoara since 2001. The research results are remarkable even today after 14 year despite to a huge progress in this field in the last year.

3. Optimal design of induction machines

3.1 Introduction

The results of several years' research on the optimal design of the induction machines are presented in the following rows [Tut 10b]. Large scale optimization is approached in order to optimize at the same time the main machines size [Mad 98] and local dimensions as stator slot dimensions [Kim 05] and rotor cage [Chi 98]. During this research two different classes of optimization algorithms represented by Hooke Jeeves method [Fai 01, Hoo 61] which is fast but rather converge to a local minimum and genetic algorithm [Wie 98, Hau 04] which has a better probability to find a global minimum with the price of large computation time was implemented in MATLAB code after several optimization methods [Rao 96, Ho 08a, Ho 08b, Seo 08] studies. Starting the Hooke Jeeves method with a large search step and then gradually reduce the step [Tut 07] could improve the algorithms ability to find a better solution than the nearest local optimum but there is no guaranty that it will be close to the global optimum. A modified version of the Hooke Jeeves algorithm that starts several times (50 times in our example) from random initial points is used to increase the probability to reach the global optimum with the prices of increasing also the computation time. The induction motor optimal design is usually a multi-criteria optimum problem where in this research all criteria are aggregated in to a single objective function using weighting coefficients. The local optimum placement in a two criteria plane (Pareto distribution) lets the designer choose the most feasible solution, which could be different from the best solution given by an algorithm that is based on rigid weighting coefficients.

3.2 The objective function and optimization variables [Tut 10b]

a) The objective function

Choosing the objective function is the first step of optimal design and it is very intricate in real applications which have to observe many contradictory requirements such as: reducing the initial cost, reducing the motor size and weight, improving the motor efficiency and power factor, reducing the torque pulsations and limit the components temperature to a feasible level. The multi-objective criterion should be aggregated somehow in a single objective function if the design objective is to embody a unique solution.

This could be a total cost function including penalty for unmet constrains. The objective function, C_t becomes:

$$C_t = C_i + C_E + C_a + C_p \tag{1}$$

Where C_i is the initial cost, C_E the cost of the lost energy, C_a is the additional cost that considers the impact of the machine size on the mechanical structure and finally C_p represents the penalty costs. The initial cost C_i, includes only active materials costs as the total manufacturing and selling costs depend tightly on the fabrication technology and cost management of the particular manufacturing technology which eventually may be approximated in relation to active material costs also:

$$C_i = m_{w1} p_{w1} + m_{w2} p_{w2} + m_{Fe\,u} p_{lam} \tag{2}$$

where p_{w1}, p_{w2} are the conductors material unity price for stator and rotor windings (usually cooper and aluminum) and p_{lam}, is the lamination unitary price say in USD (or EU)/kg, respectively m_{w1}, m_{w2} and m_{Feu}, are their weight. The manufacturing cost could also be evaluated using an artificial neuronal network [Ikeda 05] witch should be trained on a given production technology facilities.

The energy efficiency optimization is introduced by considering the energy loss during the expected run time of the machine. The cost of the losses energy C_E is:

$$C_E = P_N \left(1 - \frac{1}{\eta_N}\right) n_{hy} n_y p_E \tag{3}$$

Where n_{hy} is the annual operation equivalent hours, n_y operational years; p_E – energy cost (USD (EU)/ kWh). Very rarely, a motor operates all the time at rated power and speed; so we may introduce an ideal operation cycle characterized by probability α_i to operate at defined power loads P_i and efficiency η_i.

$$C_E = n_{hy} n_y p_E \sum_{i=1}^{n} \alpha_i P_i \left(1 - \frac{1}{\eta_i}\right) \tag{4}$$

The sum of probabilities, α_i to run at different loads should be equal by unity:

$$\sum_{i=1}^{n} \alpha_i = 1 \tag{5}$$

From many numerical examples, it was observed that, the energy loss cost is much larger than the initial cost. The optimization process is dominated by efficiency improvement rather than by initial cost reduction. Some motor manufacturers are not interested in energy losses cost once the efficiency is better than a minimum efficiency target η_{oi}. In this case the losses energy cost becomes a penalty function computed as in (6), and added to the objective function. Sometimes, when the target efficiency is not very large the penalty cost on the losses energy could vanish.

$$C_E = n_{hy} n_y p_E \sum_{i=1}^{n} \alpha_i p_i \tag{6}$$

$$p_i = \begin{cases} P_i \left(\dfrac{1}{\eta_{oi}} - \dfrac{1}{\eta_i}\right) & if \quad \eta_i < \eta_{oi} \\ 0 & if \quad \eta_i \geq \eta_{oi} \end{cases} \tag{7}$$

The additional cost C_a is considered to be in direct ratio with the total motor weight, m_t and a factor, p_m, which considers the machine weight impact on the mechanical structure cost.

$$C_a = p_m m_t \tag{8}$$

The penalty cost contains two terms: the over-temperature penalty cost C_{Temp} and the penalty for large starting current (for line start motors). The over-temperature penalty cost is computed considering that the surpassing of the maximum allowable winding temperature, leads to immature aging of the equipment. The penalty cost C_{Temp} may vary linearly or exponentially with over temperature and it could be computed as a sum of the stator, respectively, the rotor over-temperature. In this example it was computed as in (9):

$$C_{Temp} = \begin{cases} k_T (T - T_{\max}) C_i & if \quad T > T_{\max} \\ 0 & if \quad T \leq T_{\max} \end{cases} \tag{9}$$

The high starting current is important only for direct grid connection starts and it is computed in similar way, (10).

$$C_{Istart} = \begin{cases} k_{Istart}\left(\frac{I_{start}}{I_{1n}} - i_{s\_\max}\right)C_i & if \quad I_{start} > I_n \\ 0 & if \quad I_n \le I_{start} \end{cases} \qquad (10)$$

If the designed induction motor works only associated with power inverter, as in this example, a relative large starting current is chosen in a way that starting current penalty function remains zero (in this case i_{s_max}=8).

We may add penalty costs for any other technical constraints. For example, we may add a penalty for lower power factor, which is related to the converter kVA rating costs, also for the outer diameter or for machine axial length, etc.

b)The optimization variables [Tut 10b]

Sixteen optimization variables are used to control the machine main size dimensions as well the slots details. These 16 variables are grouped in a vector X_0.which is randomly initialized to be between minimum and maximum values X_{min}, X_{max}. The last element of the optimization vector is, in fact an index in a table that contains allowed numbers of rotor slots in correlation with numbers of poles and numbers of stator slots.

3.3 The modified Hooke Jeeves method [Tut 10b]

The Hooke Jeeves optimization algorithm, HJA, is a pattern search algorithm using two kinds of moves: exploratory moves (grid search) and then pattern moves, following the gradient, until movement in that direction does not produce smaller values of objective function, fig. 12.

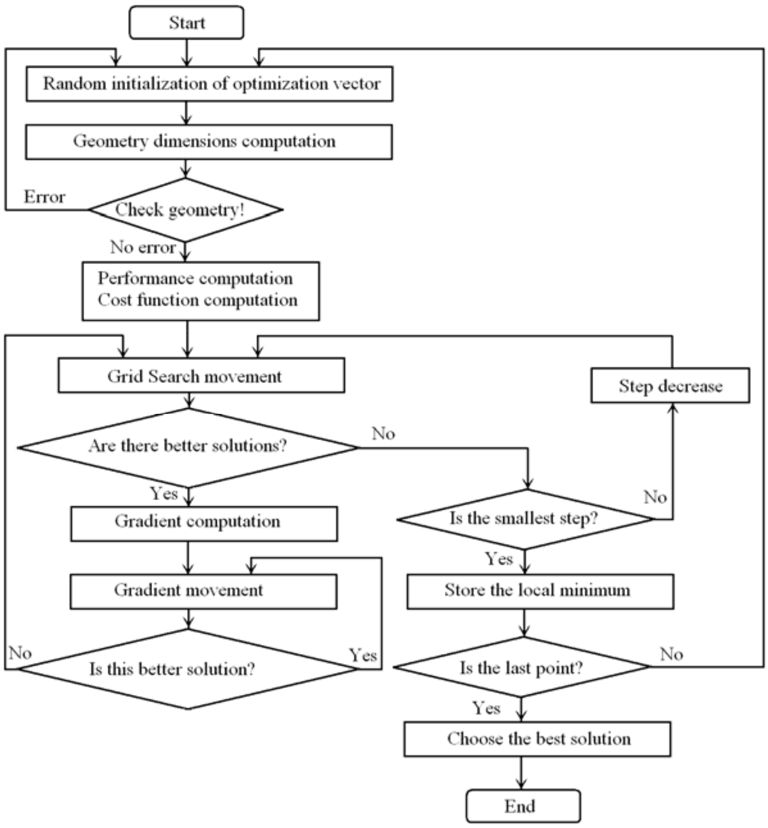

Fig. 12. Hooke Jeeves optimization – block diagram [Tut 10b].

The HJA optimization method needs an initial optimization vector to start with and then it is modified towards a new value in order to minimize the objective function. In general, the algorithm would catch a local optimum. Starting the algorithm from several random points will be eliminating these drawbacks danger of the requirement to provide a feasible initial point and the local optimum convergence.

$$X_0 = X_{\min} + (X_{\max} - X_{\min}) \cdot rand(16) \qquad (11)$$

Where *rand()* is a function that is generating a vector of 16 elements (in this case) random distributed between zero and unity.

Moreover, the initial vector generating loop should contain a counter to avoid an infinity loop if the process fails to find a feasible initial vector X_0 between its minimum, X_{min} and maximum values, X_{max}, after a finite number of successive trials.

The grid search movement starts with a large step and, when the algorithm fails to bring better motors, the search step is reduced gradually and the algorithm is restarted until the search step becomes smaller than a given value. It was noticed that a large initial search step (around 20% of the variable range) gives a better convergence to the global optimum, despite of the rough approximation of the numerical derivative for large step. Small values of initial search step often leads to a local minimum. The geometry dimensions and performance computation blocks are parts of general design and they are evaluated for every optimization vector produced by the optimization algorithm. If an error occurs during geometry computation or performance computation, the cost will be set two times larger than the initial cost and this way the unfeasible points will be automatically discarded by the algorithm. Finally, the features of the best motor and the evolution from initial vector to the best motor are presented.

3.4 The Genetic algorithm [Tut 10b]

The genetic algorithms, GA, consider a population of candidate solutions evolution under specific selection rules to a state that minimizes the cost function [Hau 04]. The genetic algorithms require a method to code the optimization variables, the objective function and a set of selection rules for the evolution of the population's members.

The optimization variables range was chosen as for HJA and the minimum variation step becomes the variable resolution, r_x, (in fact the same input file is used for HJA as well as for GA). Some of the optimization variables should be integer numbers (the number of slots per pole per phase, q_1, in our case, so its resolution is equal by unity). The binary (discrete) chromosome codification method is used here. The number of bits required for the genetic code for every variable, n_{bit}, is computed considering the number of distinct values for each variable, n_{vx}.

$$n_{vx}(i) = ceil\left(\frac{X_{\max}(i) - X_{\min}(i)}{r_x(i)}\right) \qquad (12)$$

$$n_{bit}(i) = 1 + floor(\log_2(n_{vx}(i))) \qquad (13)$$

Where "ceil" is the round function to nearest integer through plus infinity and "floor" is the round function through minus infinity. The genetic code, g_{xb} is an integer number between zero and n_{vx}. The optimization vector is computed from the genetic binary code:

$$\overline{X} = \overline{X}_{\min} + \overline{g}_{xb} \cdot \overline{r}_x \qquad (14)$$

The genetic code is generated randomly at the beginning through random generation of integer numbers and then through random mating of the chromosome. Consequently, a large number of electrical machines associated to the genetic are not viable. The procedure of the genetic code generation is repeated until the associated machines satisfy the minimum required condition.

The optimization design goal is to minimize the objective function, f(X), which, in the genetic algorithm language, means to maximize the fitness function f_r.(X) which is defined in (15) where p_s is the population size.

$$f_r(\overline{X}_i) = \frac{1}{f(\overline{X}_i)\sum_i^{ps}\frac{1}{f(\overline{X}_i)}} \qquad (15)$$

The offspring generations are produced by chromosome mating and crossover. After that a small part of chromosome is altered by mutation. The Monte-Carlo roulette selection method is used to select the mating chromosome. The genetic code is sorted in an ascending order of objective function and the rank of each code is computed (16), then random number, p, between zero and unity is generated. The member with smaller rank r_k, which is larger than the random number p is selected for mating. This way, a more adapted member has a large chance to become parent and to transmit the genetic information to the next generation. In order to avoid a rapid convergence to a local solution, the fitness function of the members which already become parents is divided by an exclusion factor, k_e in order to reduce temporarily the chance to become again parents in the next step. The member of old generation is ranked again and then the process to produce new members is continued until a new complete generation is produced. The proposed algorithm does not admit twins and, if an offspring is identical with any already existing member, it is discarded. A kind of elitism is also used and the best code is every time transferred without any alteration to the next generation. The new generation will take the place of the old generation and the algorithm is repeated until a specified number of generations are analyzed.

$$r_k = \sum_{i=1}^{k} f_r\left(\overline{X}_i\right) \qquad (16)$$

The induction machine design is based on the electrical machine design practice [Ham 94, Bol 10c, Bol 10d] and the Matlab induction machine design code is available on the [Bol 10c] attached CD.

3.5 Optimization results [Tut 10b]

The efficiency evolution considering the Hooke Jeeves and genetic algorithm, fig. 13, are increasing during the optimization process against to the machine weight increasing, fig. 14, which means that the initial cost are also increased, fig. 15. The total cost is monotonically decreasing, fig 21, for the both algorithm, (strict monotonically decreasing for HJA), despite that the initial cost is sometimes increasing because the lost energy cost is the dominant cost in this case. It could be noticed that parameters and machines dimensions have a smooth evolution in Hooke Jeeves algorithm while for the genetic algorithm they have rather randomly discontinuous evolutions.

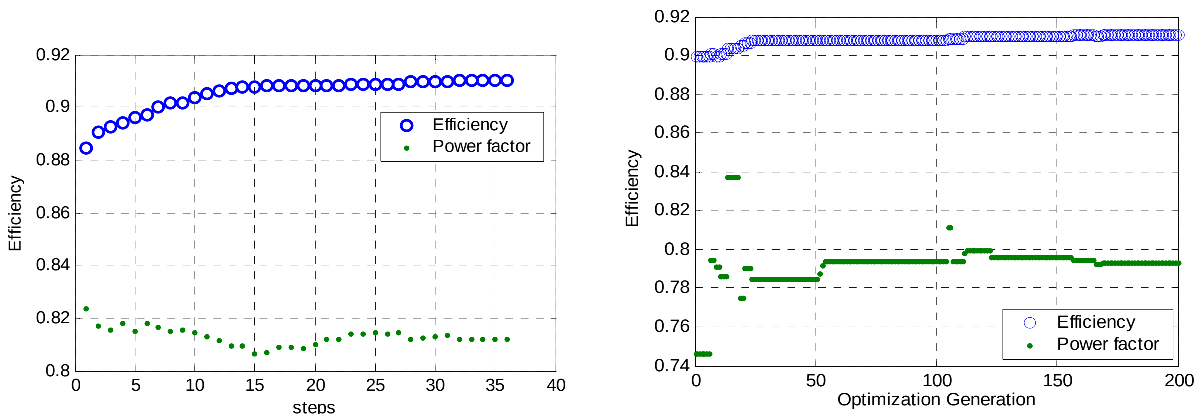

Fig. 13. Efficiency and power factor evolution: Hooke Jeeves (left) and genetic algorithm (right) [Tut 10b].

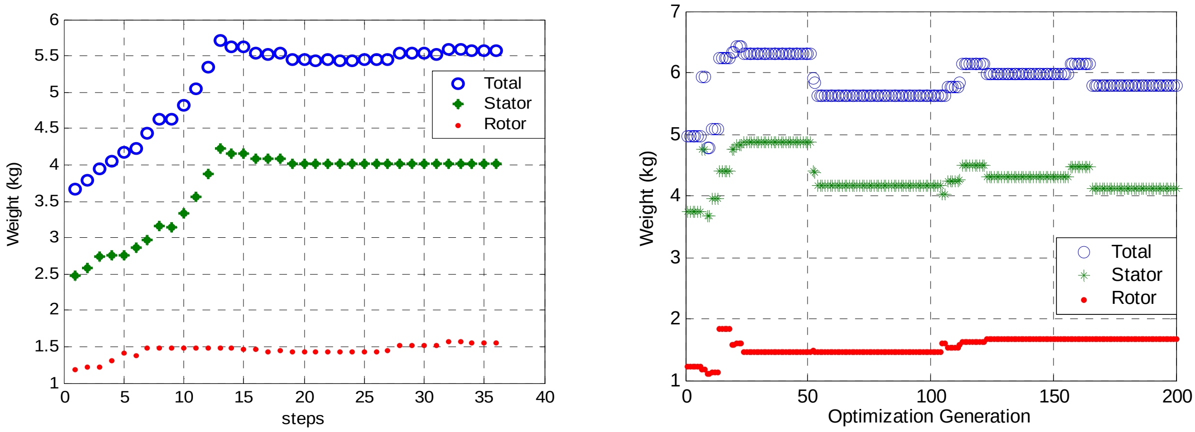

Fig. 14. Machines weight evolution: Hooke Jeeves (left) and genetic algorithm (right) [Tut 10b].

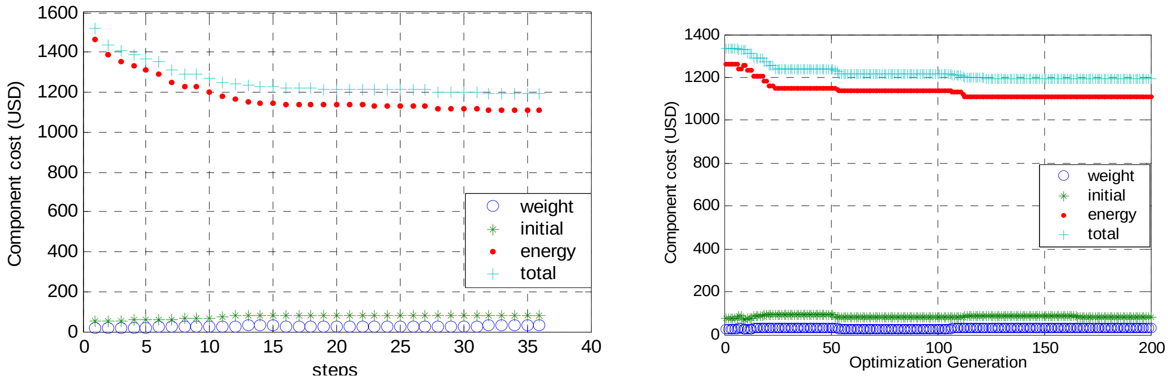

Fig. 15. Cost components evolution: Hooke Jeeves (left) and genetic algorithm (right) [Tut 10b**].**

The Pareto distribution of the local minimum in the multi objective function components coordinates; in our case efficiency versus machine weight is useful information for the decision engineer letting him to choose another good design that the computer indicate based only on the objective function minimum in the mathematical sense. For example for Hooke Jeeves optimization, the computer indicates that C_1 on fig. 16 is the best solution but a decision engineer could choose any solution along C_k curves (Pareto front).

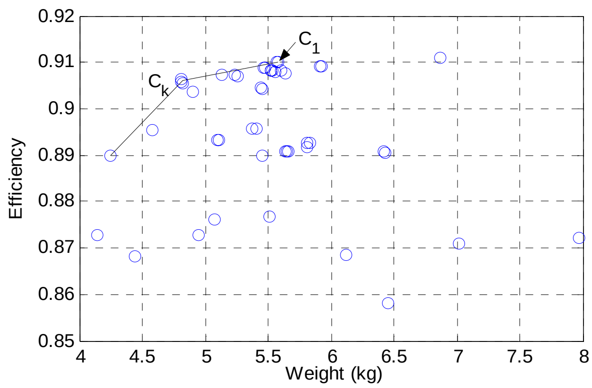

Fig. 16. Pareto distribution using Hooke Jeeves algorithm [Tut 10b].

For genetic algorithm two Pareto distributions could be presented, fig. 17, one from the best machine in each generation and other one based on the last generation that is considered most evaluated generation (they could merged in a single Pareto distributions). It is noticed from fig. 17 that, in its decision, an advised engineer could sacrifice about 1.5% efficiency to more than 40% the machine weight for a certain application.

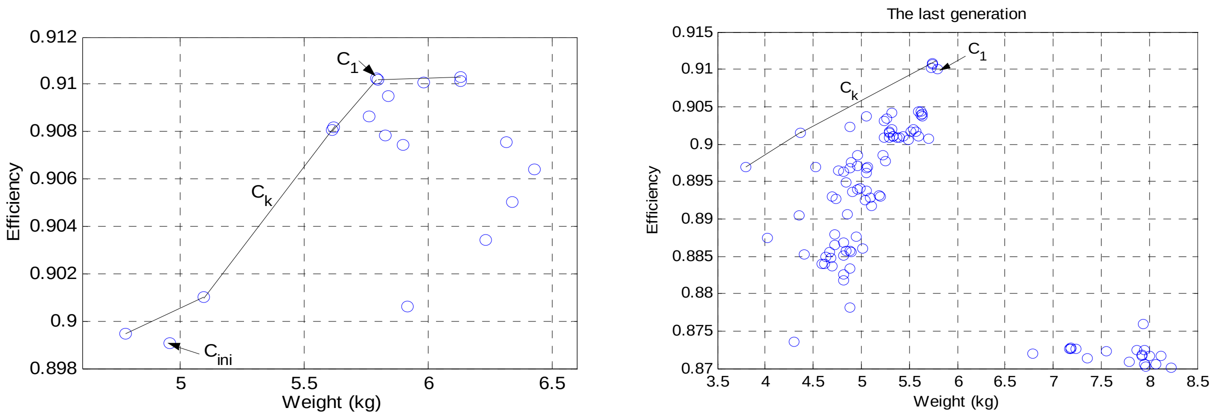

Fig. 17. Pareto distribution using genetic algorithm: the best motor in each generation (left), the last generation (right) [Tut 10b].

The optimization variables for the optimal solutions are shown in Table 3 while the main machines parameters and dimensions in Table 4.

Table 3. Optimization Variables for the best Motor [Tut 10b].

Variables	HJA	GA	Units	Observation
J_l	23.23	22.8	kA/m	linear electric loading
B_{ag}	0.61	0.63	T	air-gap flux density
B_{st}	1.67	1.64	T	stator teeth flux density
B_{sy}	1.44	1.46	T	stator yoke flux density
B_{rt}	2.1	2.14	T	rotor teeth flux density
B_{ry}	1.02	1.36	T	rotor yoke flux density
J_s	3.65	3.6	A/mm^2	stator current density
J_r	2.77	2.5	A/mm^2	rotor current density
h_{s4}	0.3	0.3	mm	tooth top height
s_{o1}	1	1.4	mm	stator slot opening
H_{r1}	0.5	0.8	mm	tooth top height
s_{o2}	1	1	mm	rotor slot opening
λ_c	0.5	0.4		machine shape factor $\lambda_c=l_c/\tau_p$
q_1	2	2		slot per pole per phase
y_1	0.83	0.83		coil span
r_{Slots}	20	20		Number of rotor slots

Table 4. Optimization Results Comparison [Tut 10b].

PARAMETERS	HJA	GA	UNITS	PARAMETERS	HJA	GA	UNITS
Dso (fig. 2)	144	149	mm	I1n (rated current)	58.75	60.2	A
Dsi (fig.2)	84.9	88.2	mm	Pcu (cooper losses)	96.4	93.6	W
Dri (fig.2)	22	23	mm	Pfe (iron losses)	120.3	123	W
Lc	37.2	34.4	mm	Rated efficiency	91.02	91.02	%
shOA (fig.3)	20.4	20.8	mm	Power factor	0.81	0.79	
hs1 (fig.3)	18.2	18.6	mm	Rs (stator resistance)	6.52	6.349	mΩ
hs3 (fig.3)	1.3	1.2	mm	Rr (rotor resistance)	3.954	3.342	mΩ
hsy (stator yoke height)	9.2	9.6	mm	Rfe (iron losses resist.)	7.43	7.25	Ω
wsp (stator teeth width)	4	4.4	mm	Lm0_sat	0.412	0.376	mH
N1 (turns per phase)	16	16	Turns	Lsl (stator leakage)	0.024	0.023	mH
rhOA (fig. 3)	18.5	22	mm	Lrl (Rotor leakage)	0.025	0.027	mH
wr1 (fig. 3)	7.8	7.9	mm	rJ (rotor inertia)	1.48e-3	1.71e-3	kg m^2
wr2 (fig.3)	3.8	2.8	mm	Ca (aux. weight cost)	27.85	28.95	USD
Rr1 (fig.3)	12.6	10.2	mm	Ci (active material cost)	80.94	82.83	USD
Rr2 (fig. 3)	3.9	4.2	mm	Ce (energy loss cost)	1110.00	1109.58	USD
Motor weight	5.57	5.79	kg	Ct (total cost)	1190.93	1192.41	USD
Simulation time	232.23	363.52	sec				

3.6 Conclusion

The main contribution on this research work are: developing an optimal design code for induction machine using two different algorithm: Hooke Jeeves and, respectively, genetic algorithms, which are compared in terms of performances and computation time effort in an exercise design of induction machine for air conditioning drives for automotive applications. Both methods use a global cost function that could be balanced, between initial active material cost or their total weight and motor efficiency, by choosing adequate weighting factors. The comparison is illustrated by a case study design (2.5kW, 9000rpm, 42Vdc) which essentially shows the Hooke Jeeves method with 50 random starting variables vectors needs 40% less computation time intensive for about the same final results. The HJA, starting from several random vectors and Pareto distribution of the local minimum in the multi objective function components coordinates is also a contribution of this work.

4. *Single phase two speeds induction and permanent magnet synchronous machine*

4.1 Introduction

The basic topology used by household refrigeration compressors is the single-phase induction motor whose theory and performance with now 85-87% efficiency for 2 poles at 100W, 50/60 Hz have been theoretically investigated for steady states [Mor29, Bol 10d, Bol 99a] with m.m.f. harmonics [Pop 07], synchronous torques [And 10] and thermal modeling [Bia 03] in the fore front. The line start three-phase permanent magnet synchronous motor with 87.3% efficiency at 600W is presented in [Kur 04] while for the single phase split capacitor motor the maximum efficiency is around 87% for a 1/5 horse power motor and it decreases to 80% for an 1/10 horse rated power motor [Rah 12]. The same value of 80% maximum efficiency (120W) is reported also in [Kur 10] considering a skewed rotor. The starting torque reduction and torque pulsations constitute the main problem of the line start PM motor and a torque computation model, considering the space harmonics, is presented in [Pop 06a] with the PM breaking torque [Kal 10] within layers theory for a surface PM canned rotor [San 09]. The improved rotor saliency is proposed in [Fan 09] in order to reduce the starting torque pulsations while the optimal design of line start PM motor, considering the efficiency and start torque as objective function, is approached in [Kim 09] where 4 rotor design variables are used while the balanced motor is followed in [Bae 11]. Starting the motor with 2 poles as induction motor and switching to 4 poles PM synchronous motor [Ali 10] is another technique to avoid PM breaking torque. The permanent magnet brushless-dc motor inverter feed drive [Wu 01] (variable speed), introduced rather recently in industry for small compressors, is highest in initial costs but also best in performance, with lowest total energy consumption for identical volume compressor but it requires a power electronics efficiency up to 95% and a motor efficiency above 90%. A high starting torque in refrigerator compressors is very important and in [Pop 06b] larger starting torque is reported using a start capacitor in comparison with variable frequency inverter feed motor.

4.2 Two speeds grid-connected hybrid motor drive

In an effort to keep costs down but also reduced energy consumption refrigerators we introduce [Kal 12, Kal 14] a novel 2 speeds grid-connected hybrid motor, fig.18. The 2 speed grid connected split phase induction motor is known [Wil 99], [Sas 71] but the proposed topology uses a separate split-phase stator winding, cage –PM – four pole rotor synchronous motor (PMSM operation mode) for low speeds and a single phase winding for 2 pole operations. To the best of my knowledge this combination of PM & cage rotor 4 pole PMSM and 2 pole induction rotor is new and thus it is not available in the literature. The specifications require around 84%efficiency at 50W output for 4 poles (low speed) synchronous motor operation and at least 60%efficiency in 2 pole operation at 100W output, with smooth transition from low to high speed under full load torque, and a rather simple motor connection switching solution.

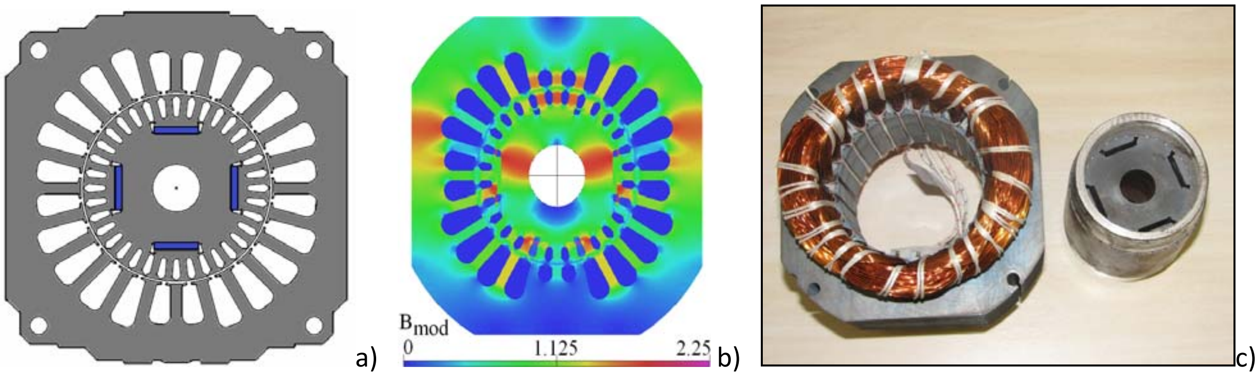

Fig. 18. Proposed geometry for a 2-4 poles motor: a) magnetic core cross section, b) flux density map for 2 pole operation, 1.3A peak current, c) prototype [Kal 14].

The measured efficiency on a dynamometer test bench, fig. 19, shows the contradictory influence of the permanent magnet length on the performances of the proposed motor in four respectively two poles operation mode. The four poles PM field does not exist in the two poles linkage flux, but it exists in the air-gap and magnetic core as space harmonic, fig. 20, and it increase the iron losses also in two poles operation mode.

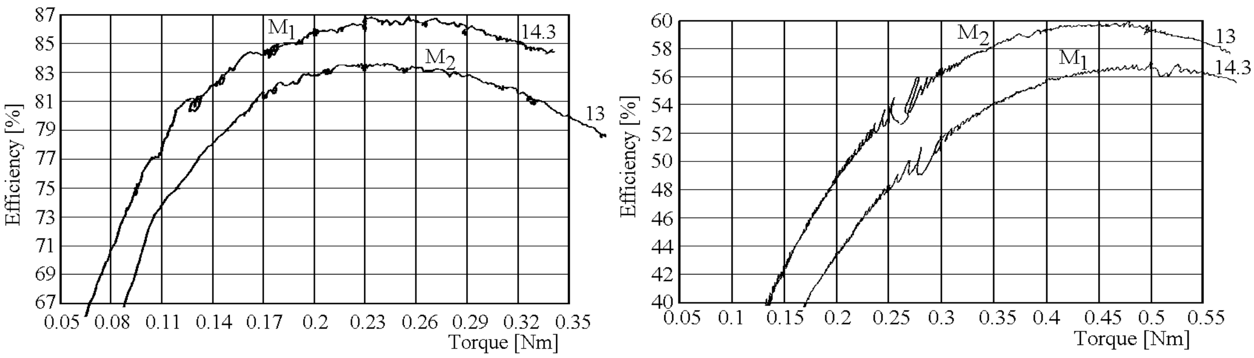

Fig. 19. Measured efficiency torque curves for 2p=4 a) and 2p=2 operation motors, b), and 13 mm M_2 and, respectively, 14.3mms, M_1, of PM per pole [Kal 14].

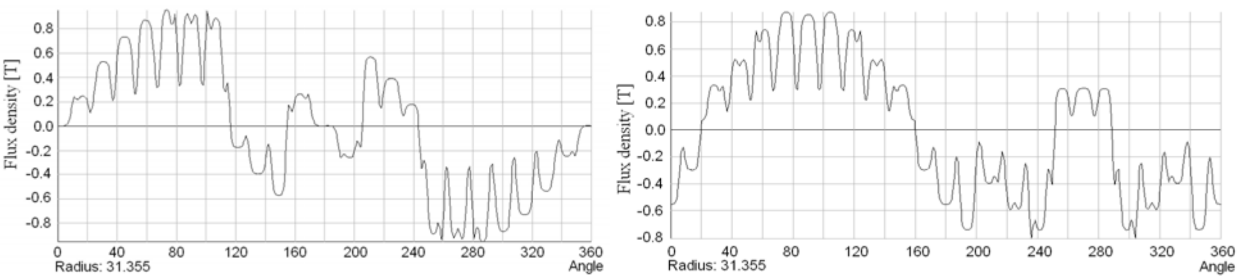

Fig. 20. Air gap flux density for 2 pole operation under load (Im2=1.3A – peak value) at two rotor position: zero respectively 45^0 PM pole angle – FEM analyses [Kal 14].

The dynamics model and simulations considering the transitions between four and two poles operation mode was developed in Matlab Simulink based on the transient's equations of the induction and synchronous machine with a switch and capacitor bank model and it was used to study and size the motors parameters in order to have a good drive start-ability [Kal 12, Kal 14].

4.3 Conclusion

The present investigation shows a feasible way to create a 2-speed motor, without the need of an inverter, using a stator with two and four pole windings and a cage rotor with buried magnets (four poles). The motor was designed to run synchronously at 4 poles (low speed 50 W, 84% efficiency) and asynchronously for 2 poles (high speed 100W, 60%efficiency). Moreover, rather comprehensive models for steady state and transients accounting for various losses and for magnetic saturation have been developed to optimally design the machine according to specifications. Four percent efficiency rise by optimal design methodology for low speed operation in comparison with the experienced standard analytical design was obtained and considered satisfactory. The theoretical effort was satisfactorily verified in part by 2-D FEM inquiries and in full scale industrial experiments. Although this motor can be a good option for the applications where the 2/1 ratio speed variation can generate benefits. The attractiveness of this solution can vary with the cost of the materials (mainly magnets and starting devices) and must be ultimately evaluated, case by case, by the motor designer.

5. Dual stator winding asynchronous (DSWA) generator

5.1 Introduction

Induction generators have been employed to operate as wind turbine generators and small hydroelectric generators coupled to the grid or in isolated power systems [Ban 03], due to the practical advantages related to low maintenance cost, better transient performance, ability to operate without dc power supply for field excitation, good overload protection ability and brushless construction. The major drawbacks of traditional induction generator systems [Jab 90] are related to reactive power regulation and poor output voltage performance under the load and speed variations. Grid connected induction generator with small parallel power converter [Che 13] which controls the synchronization process or with a series full power converter [Mul 94] that allow also energy storage in the dc battery are operate at fixed frequency that means almost constant shaft speed. A full power converter with bidirectional power flow [Che 14] allows wide speed variation but the power converter cost is still too large for many applications. The wound induction machine allow to control the output power using low cost converter by controlling only the power transferred trough the rotor [Chi 08], [Pan 03]. A configuration with two wound rotor induction machines could be used to avoid the slip ring and brushes [Nou 11], but especially in low speed applications the weight and cost of two machines is too large. The double stator windings machine introduced by T.F. Barton since 1927 and developed by Ph. Alger [Alg 30], consists in two similar but separate three-phase stator wound windings with the same number of poles. Both stators are fed with the same frequency and the rotor is a standard squirrel cage. Dual stator winding induction generator with a converter connected to the control winding is used to supplies ac loads with reduced harmonic distortion [Bu 12, Ojo 00] or d.c. loads by adding a diode rectifier on the load side [Wan 05, Yon 09].

5.2 The DSWA generator

The first contribution to this field is the parameters and performance comparisons obtained by optimal design, introduced also by the author, considering the influence of number of poles, Table 5, [Tut 13a].

Table 5. Comparative study of standard induction generator on poles number, 3kW, 25rpm [Tut 13a]

Poles number		8	12	16	18	20	24
Base frequency	Hz	15	24	32.5	36.5	40.5	49
Active materials cost	USD	512.8	425.1	399.1	398.8	384.7	403.3
Objective function (total cost)		1478.8	1385.3	1355.8	1367.7	1399.7	1431.2
Efficiency		84.83	84.9	84.95	84.79	84.18	84.01
Power factor		0.81	0.75	0.73	0.72	0.7	0.69
Weight active materials weight	kg	88.8	68	58.4	55.4	51.8	48.8
Optimization time	s	10	23.8	12.8	8.9	6.8	10.2
Air-gap	mm	0.35	0.35	0.35	0.35	0.35	0.35
Rated current	A	5.61	6.05	6.19	6.31	6.54	6.56
Outer stator diameter	mm	386	409	484	519	533	594
Inner stator diameter	mm	286.3	319.6	393.9	433.4	450.1	519.7
Length of stator laminations pack		139.3	107.1	72.0	65.1	60.2	55.3
Air-gap flux density	T	0.85	0.85	0.83	0.81	0.81	0.73
Specific solenation	kA/m	16.22	15.31	15.94	15.0	14.45	13.07

The 16 poles generator is considered the optimum because in this case the machine has the maximum efficiency, while the active material cost is also near its minimum and the power factor (which influences the power convertor cost) is not too large.

According to our study [Tut 13a] the double stator winding induction generator could reduce the inverter (active rectifier) KVA with 43% to 28% in case of 8 poles, respectively, 24 poles, when the inverter is placed on the excitation winding. The full power rectifier and the dc-dc boost converter required in this case are reducing drastically the advantages of this scheme. The converter KVA reductions are smaller, 19% to 30.6%, when the inverter is placed on main windings. In this case the converter power reduction is higher for a large number of poles where the converter for standard induction machine is also larger due to smaller power factor. The method does not require other power electronics but it requires a capacitor battery on the excitation windings.

Our research proves mathematically that the DSWA efficiency is smaller than a single winding induction machine in the same size by around 5% due to bad utilization of stator windings. The efficiency could be recovered by over-sizing the DSWA with 10%-6.5% (8 -24 poles) in diameter which means 29% to 37.8% in the generator weight and about 32%-35% in the active material costs. Economic benefits will be obtained when the full power inverter price is larger than the generator price with more than 50%, which is the case for small power machines.

5.3 The dynamic saturated model

Another important contribution is the dynamic saturated model implemented in flux rotating frame coordinate [Tut 13b] with the transients and steady state magnetization inductance approximation by a rational function.

$$L_M = L_{M0} \frac{1 + a i_0^{n-1}}{1 + b_1 \cdot i_0^{n-1} + b_2 \cdot i_0^n} \tag{17}$$

Where L_{M0} is initial value of magnetization inductance and a, b_1 and b_2 are strict positive constants. The polynomial degree, n, is chose as small as it is possible and still has enough function curvature variation. The meanings of the proposed function coefficient are: L_{M0} – is the inductance around zero current, $\frac{1}{\sqrt[n]{b_2}}$ the bending current point, the $L_{Mo}\frac{a}{b_2}$ ratio represent the saturated flux (maximum value) and finally b_1 controls the maximum of the inductances curve (for enough larger value of the b_1 there is no maximum) and guard positive transients inductance.

An algorithm to compute the coefficient from the finite element, experimental results or even from analytical model considering nonlinear magnetic equivalent circuit was developed based on the optimization theory with acceptable approximation error as it is shown in fig 21.

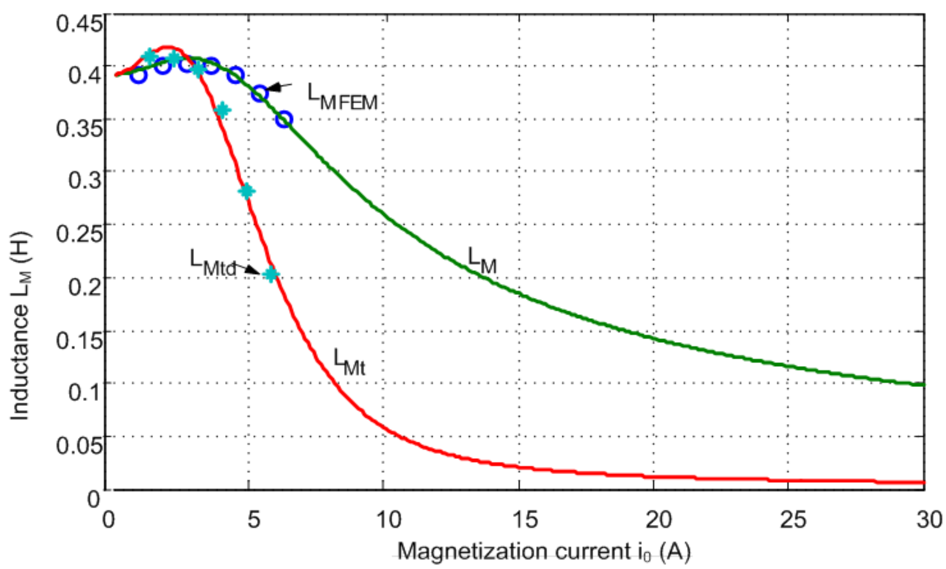

Fig. 21. Fig. Magnetization inductances inductance approximation [Tut 13b].

The saturated model of DSWA was implemented in Matlab Simulink by vector approaches, fig. 22, keeping the apparent simplicity of the induction machine model.

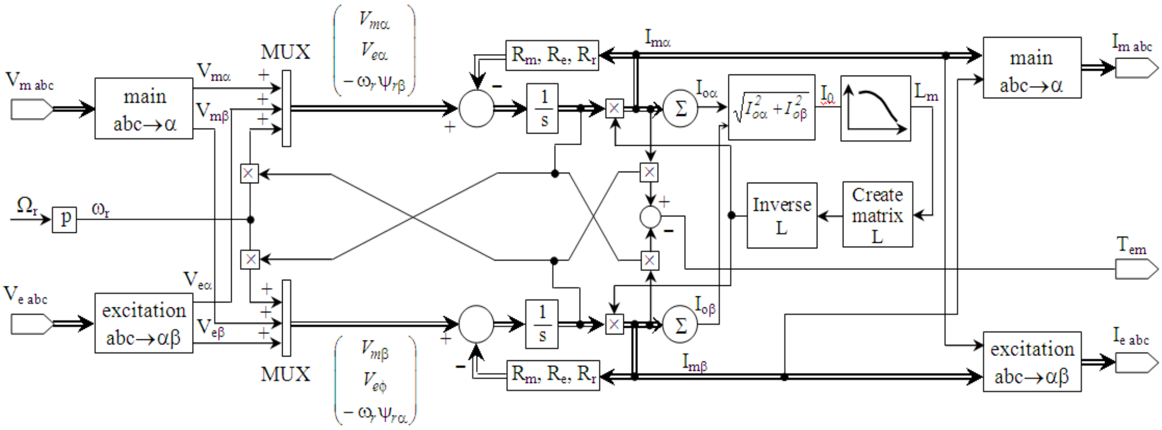

Fig. 22. Dynamic saturate DSWA block diagram [Tut 14e].

The stator inductances matrix, L (18), is built around to the link nonlinear inductances L_m (17) which is added to the stator leakage inductances assumed to be constant. It could be noticed from DSWA block diagram, fig. 22, that inverse of L matrix is computed online at each time step.

$$L = \begin{pmatrix} L_m + L_{\sigma m} + L_{me} & L_m + L_{me} & L_m \\ L_m + L_{me} & L_m + L_{me} + L_{\sigma e} & L_m \\ L_m & L_m & L_m + L_{\sigma r} \end{pmatrix} \qquad (18)$$

The simulations results, considering the turbine aerodynamic model [Hei 98], prove the self-exciting ability, without any control intervention (degraded mode) of the DSWA with the price of large transient electromagnetic torque and overvoltage, fig. 23, over a constant load (rated) impedance, constant (rated) wind speed and the generator initial speed 10rad/s.

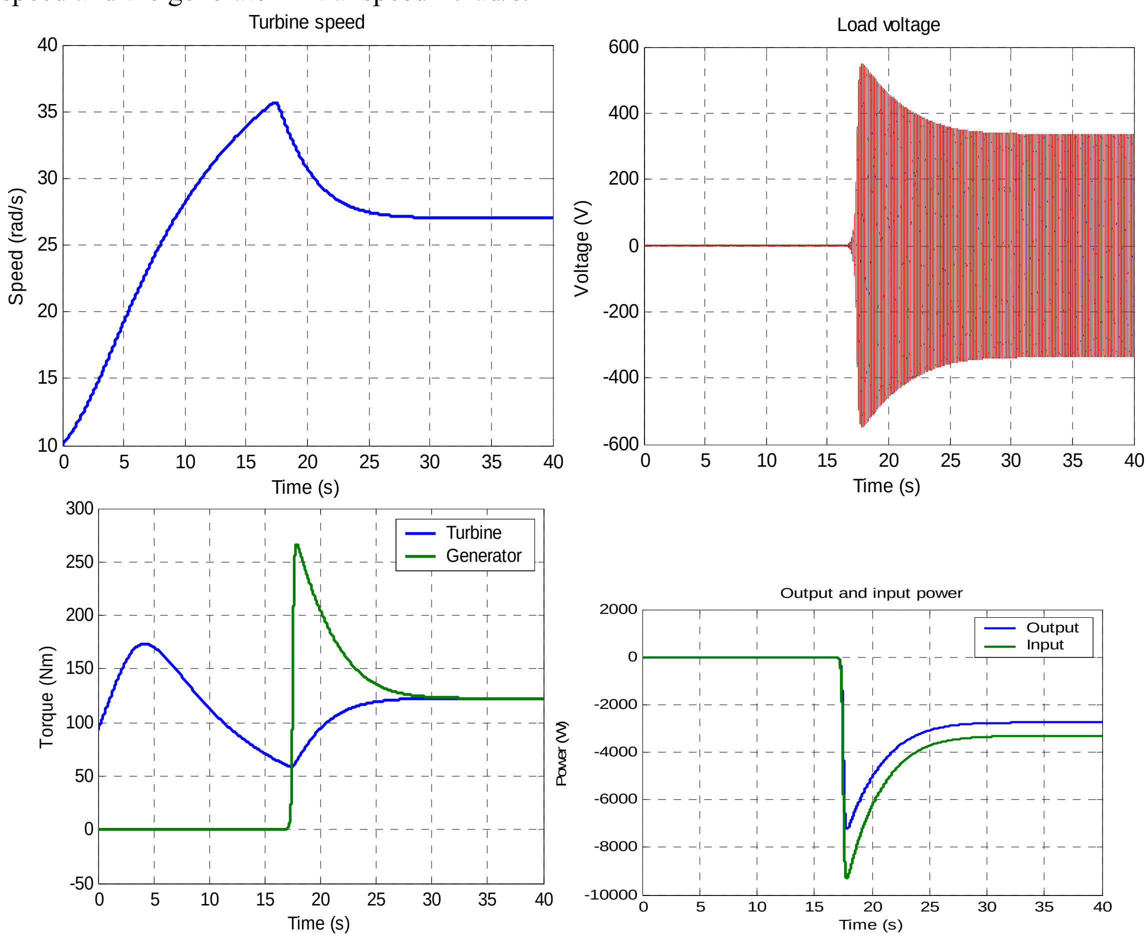

Fig. 23. Auto-excitation process and nominal load at high wind speed (8 m/s) [Tut 14e].

The system transients stress is significantly reduced when the power converter is used, [Tut 14e], even with a simple feed-forward main voltage control and a test wind speed profile simulating a gust.

5.4 Active and reactive power in both winding – the new control strategy

Considering our conclusion from [Tut 13a] we proposed a better utilization of the DSWA [Tut 14c] by using the both winding for active and reactive power exchange as in proposed scheme shown in fig 24a.

In contrast to other dual stator winding cage-rotor induction generator systems the one presented here uses a (40-50) % power rating PWM converter in the main winding to deliver both active and some reactive power in a controlled manner acting alone at low speeds. At high speeds the (33-50) % power rating auxiliary winding with parallel terminal capacitors and diode rectifier produce additional (40-50) % more active power. A wide speed range brushless generator with a (40-50) % PWM converter was thus obtained, with self starting capability. We adapted the proposed scheeme from fig. 24a, considering the rapid prototyping concept with the equipment already existent in the lab and the test setup, shown in fig. 24b was implemented in order to prove, experimentaly, the new control strategy.

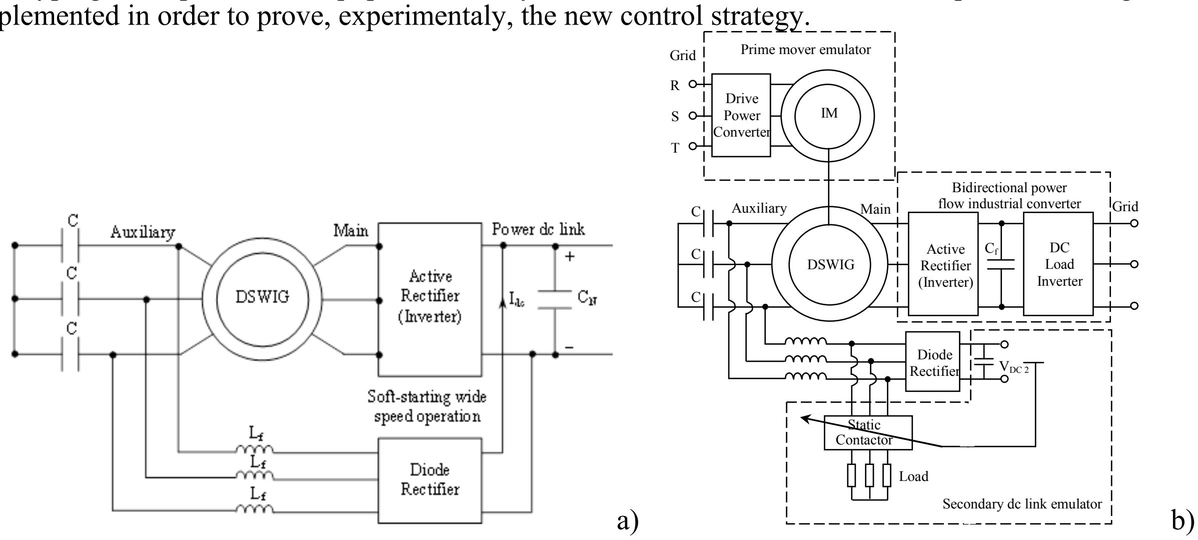

Fig. 24. Proposed scheme and test setup [Tut 14c].

The experimental results shown that our proposed scheme could extract all power available from a wind turbine for a large speed range, fig. 33a while fig. 33b prove that the our emulator of dc constant voltage bus is able to keep the dc voltage constant with an acceptable error.

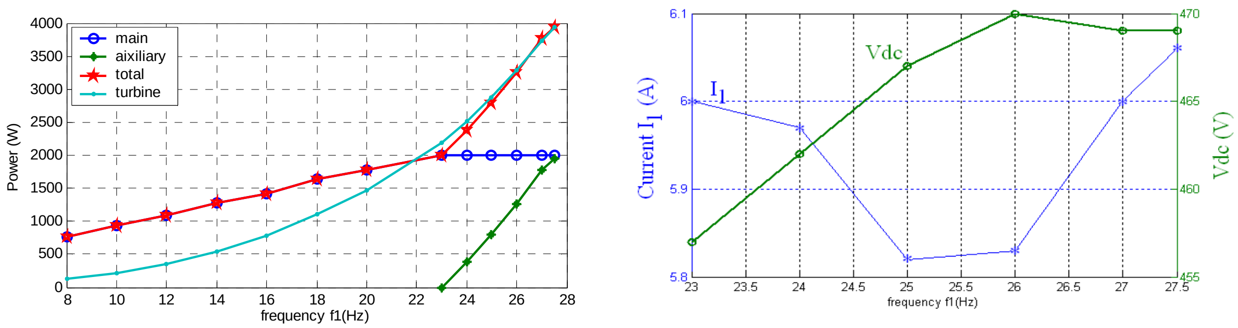

Fig. 25. Experimental results [Tut 14c].

5.5 Parameters identification

Another important contribution of our research on DSWA is the parameter identification of a dual three phase's stator winding induction machine using genetic optimal algorithm [Tut 14a]. The estimated parameter are: the voltage ratio between main and auxiliary winding, the main winding resistance and leakage reactance, the cage rotor resistance and reactance, the coupling leakage reactance between main and auxiliary winding, the magnetization non saturated reactance, equivalent iron loss resistance and mechanical losses including their variation with speed. The parameter are calculated from standard no load and short circuit test performed on both stator winding, by minimization the sum of squared errors between measured and computed currents, active power and reactive power in several points and it is different from the [Riv 12] methods, that require a power converter, speed sensor and mechanical coupling of two electrical machines. It is also different from the genetic algorithm proposed by [Rai 02] that identifies the induction machine parameter from no load start transients.

The estimation is performed by using an equivalent circuit scheme of the DSWA and simple standard test without requiring mechanical coupling of two machines or a mechanical sensor. The model uses constant parameters as they are required in practical applications. The linkage inductance variation with the magnetization current could be added further using no load test points at larger voltage. During the parameter identification the machine speed is also estimate at each no-load test point. If the speed variation range is small then the mechanical losses distribution in Columbian friction, viscous friction and fan friction is poor on the component distribution but the total mechanical losses (sum of the components) has a good precision. One of the our proposed method is the measurement error rejection in general and for leakage inductances that slightly depend on the current in the real machines, the computed values could be considered the best constant values approximation.

5.6 Conclusion

The DSWA generator could be used as a low cost solution in wind or hydro renewable energy conversion, especially in applications where two electrical output ports are required. Our research has important contributions on sizing the generator, dynamic saturated model which is mandatory for self-excitation study, new more efficient control strategy and parameters identifications.

6. The Biaxial-Excited synchronous generator

6.1 Introduction

The strong tendency of car electrification [Kas 96] and efficiency limits of the claw-pole rotor generators, besides assisting claw-pole rotors with PMs [Hen 94] are the main reason to find new solutions for the car generators. Hybrid excitation with hetero-polar coil in d axis plus high energy PMs also in d axes [Syv 96] or the excitation coil on the stator producing homo-polar excitation [Miz 94] have cumbersome rotor configuration and large PM fringing flux. Switched-mode rectifier, instead of the diode rectifier, at full power rating has been shown to produce 70% efficiency in a Rice–Lundell generator at 50 V dc [Per 04].

6.2 The biaxial-excited synchronous generator

The biaxial-excited synchronous generator for automobiles (BEGA), [Bol 00], [Bol 01a], was proposed as a new type of electrical generator with electromagnetic excitation in 'd' axes in order to control the voltage level at wide speed variation, respectively, a constant permanent magnet excitation in q axes in order to compensate the armature reaction field, fig. 26.

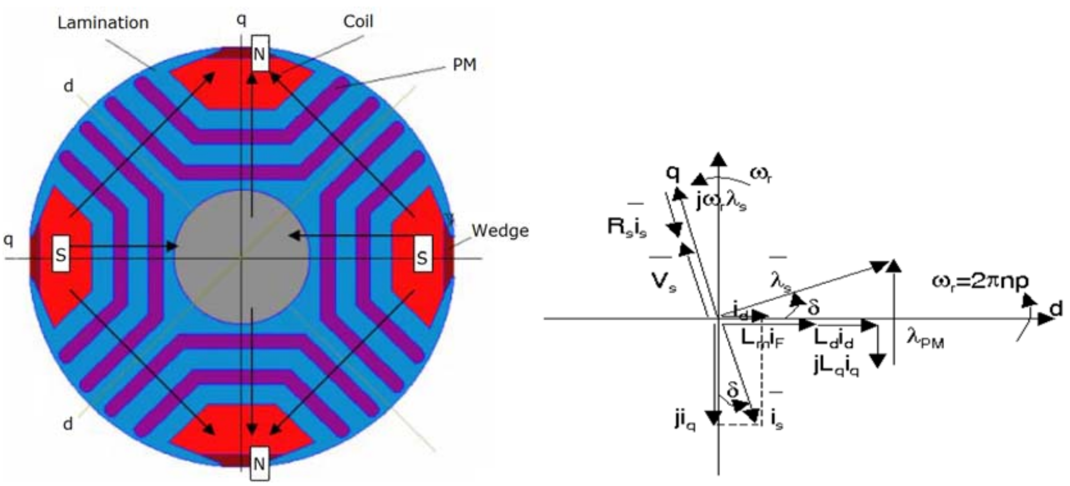

Fig. 26. The BEGA rotor and phasor diagram at unity power factor [Scr 05].

A design methodology was developed and based of the design software implemented in Matlab, a new prototype, fig. 27, was built with the support of Aalborg University and Grundfos Denmark.

Sample test results, fig. 39 shows larger output power obtained with positive field current which means that in this case the armature reactions is compensate be the q axes PMs.

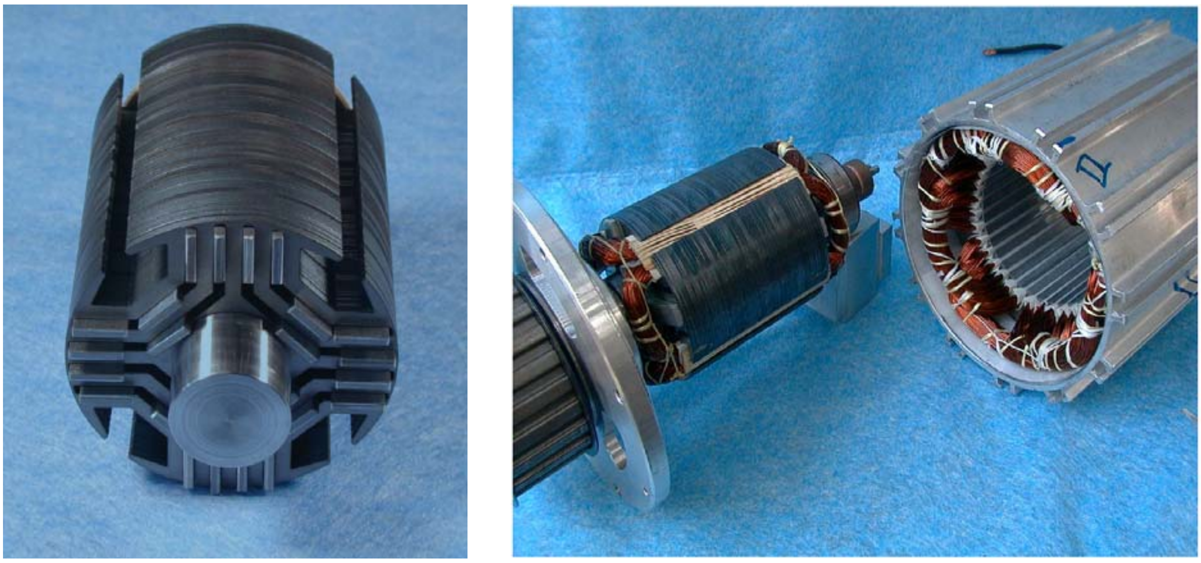

Fig. 27. Details of the BEGA prototype [Scr 05].

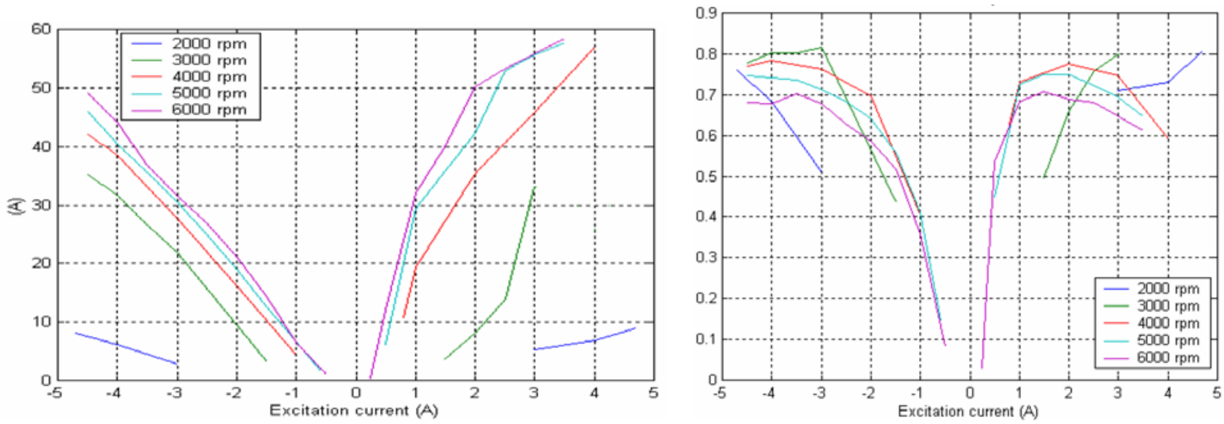

Fig. 28. Load test: d.c. load current vs. field current (left), efficiency vs. the field current [Scr 05].

6.3 Conclusion

The BEGA was proposed as a new electric generator topology. A general design methodology and optimal design software was developed. Two prototypes one at UPT and other one in cooperation with Alborg University were build and tested successful [Bol 02a], [Scr 04]. The control of this new machine in the motor regime was developed ahead by Dr. Ing. S. Scridon, Dr. Ing. V. Coroban and Dr. Ing. C. Paicu in their Ph. D thesis. Theoretical infinite constant power speed range was demonstrated [Cor 09, Cor 11]. After 15 years the concept is still modern and probably it could be used in electrical or hybrid automobiles.

7. Optimal design of surface permanent magnet machine

7.1 Introduction

The large number of optimization variables as well the multi-objective of the optimization design and their nonlinearities and discontinuities make this task difficult [Wen 06]. Some approaches are considering stochastically methods to model the real problem [Lei 09] through analytical functions. Others are using stochastically method to find good and poor correlations between some variables and same objectives [Son 07] and then select only the variables that have sufficient effect on machine performance. Another similar approach is to use artificial intelligence principles for robust identification of the complex machine model [Ark 07]. A large category of optimization methods are based on biological metaphor as a polymorphism of the life evolutionary principle as they occur in the ant colony optimization algorithm [Ho 08a], particle swarm optimization, [Ho 08b], territorial dispute between groups [Ho 08c] and different kinds of genetic algorithms [Hau 04]. The optimization methods are looking generally for the global optimum but from manufacturing reasons the found optimum should be also robust in terms of small variations of optimization variables [Ho 08d].

7.2 Surface permanent magnet machine - Hooke Jeeves and genetic algorithm optimal design comparisons

The analytical model based on the equivalent magnetic circuit considering magnetic saturation is used to evaluate the permanent magnet machines performances. The objective function is the global cost function that could be balanced, between initial active material cost, active material weight or the machine efficiency, by choosing adequate weighting factors [Tut 10a].

A comparison between Hooke Jeeves [Hoo 61], [Rao 96] and genetic algorithm optimization methods are investigated on the surface permanent magnet synchronous motors with distributed winding optimal design [Tut 10a].

A case study of optimal design for a three phase, four poles automotive application motor (air condition compressor drives) with the rated power, Pn=2.5kW, rated phase voltage, Vfn=28V (rms) and 6000rpm is used to compare the optimization methods. The design motors parameters are shown in table 6 where HJ1 means the optimum found by Hooke Jeeves method when the initial point is in the middle of each variable range, while HJ2 means the best optimum when the algorithm was started 50 times, by random initial variable vectors. The GA1 and GA2 are the optimal solutions find by genetic algorithm (stochastic algorithm) that is producing slightly different solutions at each run.

Table 6. Optimization results comparison [Tut 10a]

PARAMETERS	HJ1	HJ2	GA1	GA2	PARAMETERS	HJ1	HJ2	GA1	GA2
sDo (mm)	119.0	116.0	132.0	126	B_{ry} (T)	1.75	1.85	2.08	1.72
sDi (mm)	66.0	66.0	73.0	72	J_s (A/mm^2)	6.73	4.51	4.20	5.80
h_{s4} (mm)	1.1	0.5	0.7	0.5	λ_c	1.4	2.0	1.3	1
s_o (mm)	4.0	5.0	5.4	5.7	q1	2.00	2.00	2.00	2.
h_{sOA} (mm)	14.4	0.1	14.1	13.6	y1	0.83	0.83	0.83	0.83
h_{s1} (mm)	12.6	12.3	12.7	12.5	λPM	0.68	0.85	0.98	0.87
h_{sy} (mm)	12.1	11.1	15.4	13.4	PM Weight (kg)	0.146	0.191	0.191	0.174
w_{st} (mm)	4.4	12.7	4.1	3.7	Motor Weight (kg)	4.735	6.229	6.219	4.530
N1	24	3.3	24	28	I_q (A)	35.09	34.66	35.86	34.9
rDi (mm)	47.0	49.0	55.0	50	P_{cu} (W)	73.01	59.52	67.85	76
hPM (mm)	2.0	1.4	1.5	2.1	P_{fe} (W)	104.36	95.13	78.33	94
δ (mm)	1.45	0.90	0.70	1.15	efficiency	92.94	93.73	94.03	93.19
J_l (A/mm)	24.89	16.49	16.60	23.6	C_i (USD)	81.6	108.9	105.9	80.0
B_{ag0} (T)	0.65	0.68	0.76	0.72	C_e (USD)	284.8	250.7	238.0	273.8
B_{st} (T)	1.26	1.78	1.75	1.85	C_t (USD)	366.4	359.6	343.9	353.8
B_{sy} (T)	0.90	0.90	0.90	0.98	sim_time (s)	3.94	97.31	250.3	247.7

When the optimization variable vector is large (12 in this case) neither Hooke Jeeves algorithm nor genetic algorithm can find firmly the global optimum but however they find a notably better than initial solution. The genetic algorithm tends to find a better solution than Hooke Jeeves algorithm but requires notably (2.5 times) more computation effort. Large values of the initial variation step could improve the HJ chance to find solutions close to global optimum. The use of HJ algorithm is recommended also when we would search an optimum solution starting from a known initial solution [Tut 10a].

7.3 Conclusions

The main contribution of this work is the surface permanent magnet optimal design code development using two different algorithms: Hooke Jeeves and, respectively, genetic algorithms with their advantages and disadvantages that was pointed above. The developed design code is powerful tools that will help us in the future research to produce a tight machine design according to the applications requirements as low cost, high efficiency, low weight including also other constraints.

8. *Internal permanent magnet machine*

8. 1 Introduction

Investigation of the interior permanent magnet synchronous motor with eight poles in the rotor and non-uniform (6+6) stator slots and concentrated windings fed with trapezoidal currents [Ile 05], was done in order to maximize the pole flux, and minimize the cogging [Sti 08]. The PM separation from the rotor core at high speeds due to centrifugal force can be avoided since the PM are inserted in the interior of rotor core [Bia 03] and the cost of the IPMSM is reduced in comparison with surface mounted permanent magnets [Cro 02], due to the simple shape of permanent magnets. Moreover, the rotor pole face designed using several notches, could reduce the cogging torque and reluctance torque pulsations [Kan 07].

8.2 Ferrites flux concentration topology versus NdFeB without flux concentration topology

A comparative study of two PMSM, one containing surface NdFeB PMS and the other interior spoke-displaced Ferrite PMs, fig. 29, [Isf 13a], [Isf 13b] was done in order to find new solution as a reaction to the rare earth permanent magnet crises.

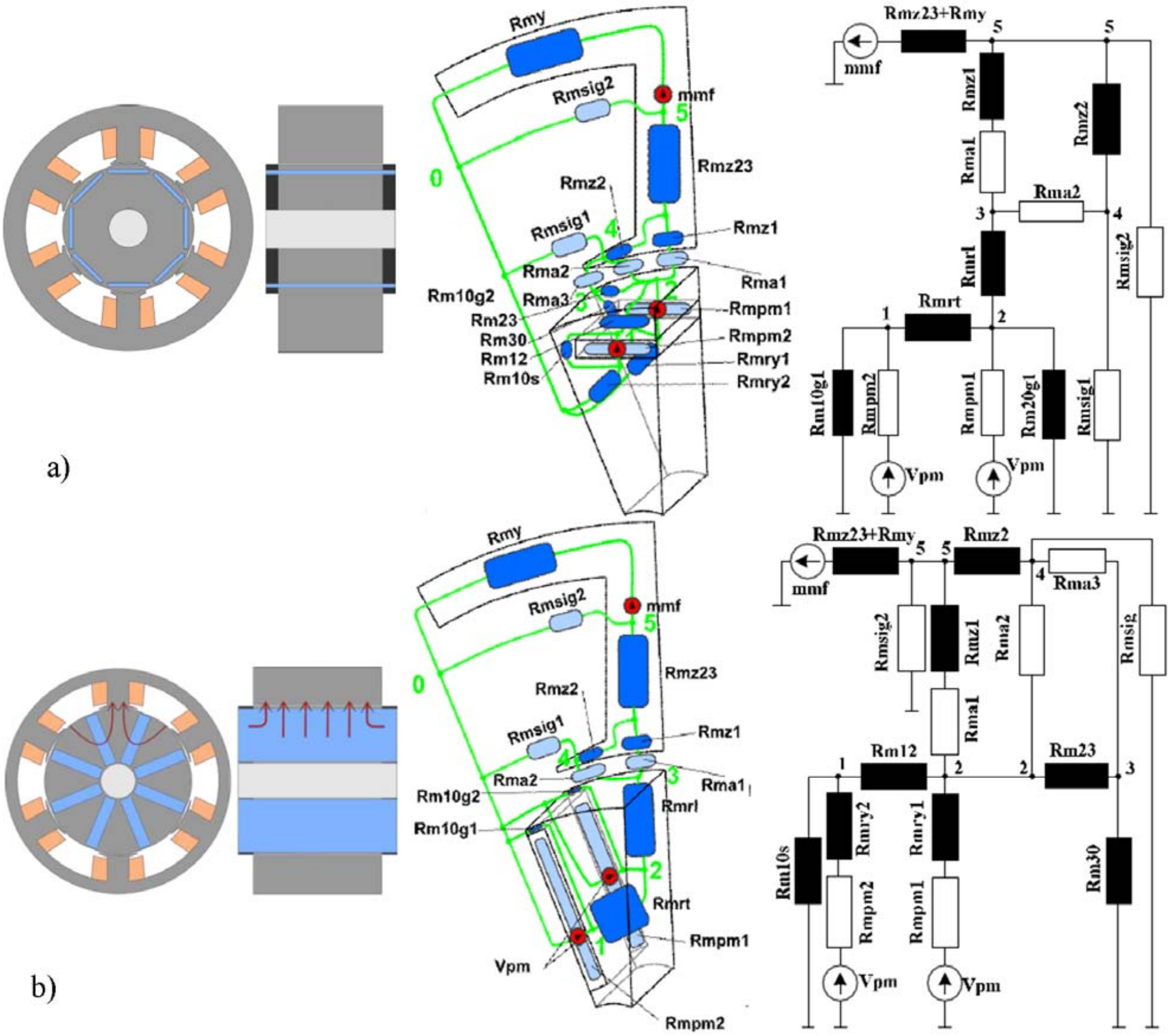

Fig. 29. Comparative of 6 slot/8 pole synchronous motor topologies and equivalent circuit model
a) NdFeB IPM rotor, b) Ferrite IPM rotor [Isf 13b].

FEM embedded optimal design methodologies are introduced with case studies at 120W, 500W, 1000W, 2000W, 4500rpm, 290 (380) VDC. For both comparative machines the 6 slot/8 poles configuration has been adopted, based on economic and manufacturing considerations. The six slot stator accommodates a concentrated, double layer winding with non-overlapped coils. The torque pulsations with sinusoidal current control are reduced by shaping the air-gap and by two segmental skewing [Sti 10].

In order to achieve the same performances, double flux concentration for the ferrite PM rotor is used, fig. 29 b. The spoke PM allows radial flux concentration and a prolonged rotor with respect to the stator stack length allows axial flux concentration [Sil 05]. The analysis covered an optimal design methodology [Bol 10c] using the 3D magnetic equivalent circuit model and online embedded finite element. Vector current control simulation for a step load at rated torque proves the effectiveness of the results. Four case studies have been considered within the power range of 100W-2000W. The results show that the same high efficiency can be achieved with Ferrite magnets at the same or even smaller material cost. The "price" is paid though, in larger mass and inertia. However, in applications where this does not constitute a drawback, such as pumps, compressors, home appliances etc. the proposed Ferrite IPMSM represents a good alternative [Isf 13a].

A case study for the automotive a.c. compressor, with an average power of 2kW at 6000 rpm, was also investigated [Isf 13b]. High energy (NdFeB) PMSM with surface and interior PM rotors have been tried for the purpose, for a motor efficiency above 93 - 94% which, for a PWM converter efficiency of 96%, would meet the typical 90% drive efficiency automotive requirements.

8.3 Conclusions

Our research main contributions include: a quasi 3D magnetic circuit nonlinear model of IPMSM with NdFeB (one piece/pole) and of a dual PM flux concentration spoke-Ferrite-IPM rotor 6 slot/8 pole SM; an optimal analytical design methodology with embedded 2D FEM to verify the average torque production automatically, FEM inquiries to obtain, by tapered air-gap and 2-shifted-segments-rotor, a reasonable cogging torque and a pretty sinusoidal emf such that to yield less than 5% total full torque pulsations for sinusoidal (vector) current control. About the same 95% machine efficiency is obtained with both NdFeB and Ferrite IPM at 2kW, 6 krpm, 42Vdc, but with a 33% reduction in active material cost for a 30% heavier machine in the case of Ferrite PM rotor.

9. Two rotors, one stator axial air-gap permanent magnet machine

9.1 Introduction

Hybrid electric vehicles (HEV) are considered the way of the future for automobiles [Cha 08], to reduce energy consumption and air pollution [Cha 01], [Gao 06]. The energy density of gasoline is for more than what the electrical battery could offer [Ehs 97] than the HEV is a viable solution for urban and extra urban transportation. The basic characteristics of an electric drive for EVs [Zhu 07],[Ter 97] are: high torque density and power density, very wide speed range, covering low-speed crawling and high-speed cruising, high efficiency over wide torque and speed ranges, wide constant-power operating capability, high torque capability for electric launch and hill climbing, high intermittent overload capability for overtaking, high reliability and robustness, low acoustic noise and reasonable cost. The electric drive for HEVs needs additional [Ehs 05]: high-efficiency generation and good voltage regulation over wide-speed range. The electric propulsion corroboration with the thermal engine (ICE) that is let to operate close to the sweet point (torque and speed for maximum efficiency or minimum emission) independent to the vehicle speed [Mil 06] is the key problem of HEV.

Axial Flux Permanent Magnet (AFPM) Machines first appeared in the technical literature in mid-70. Today, among the most prominent appliances are fans, elevators, ships, vehicles and airplane propulsion [Mar 99], [Pro 97]. Therefore, the integration of both machines into an electromechanical set, in an attempt to improve the compactness [Zhe 07], [Cav 01] and the cost-effectiveness, is currently considered a challenging technology. Of particular interest is the so called "single-stator dual-rotor permanent-magnet machine" [Ham 09], [Tah 04].

9.2 Proposed topologies

The two rotor one stator axial air-gap permanent magnet machine is a drive system to produce dual, independent, electromechanical torque output using an axial-air-gap machine with a single stator and winding and two different PM rotors, fig. 30, [Bol 10a].

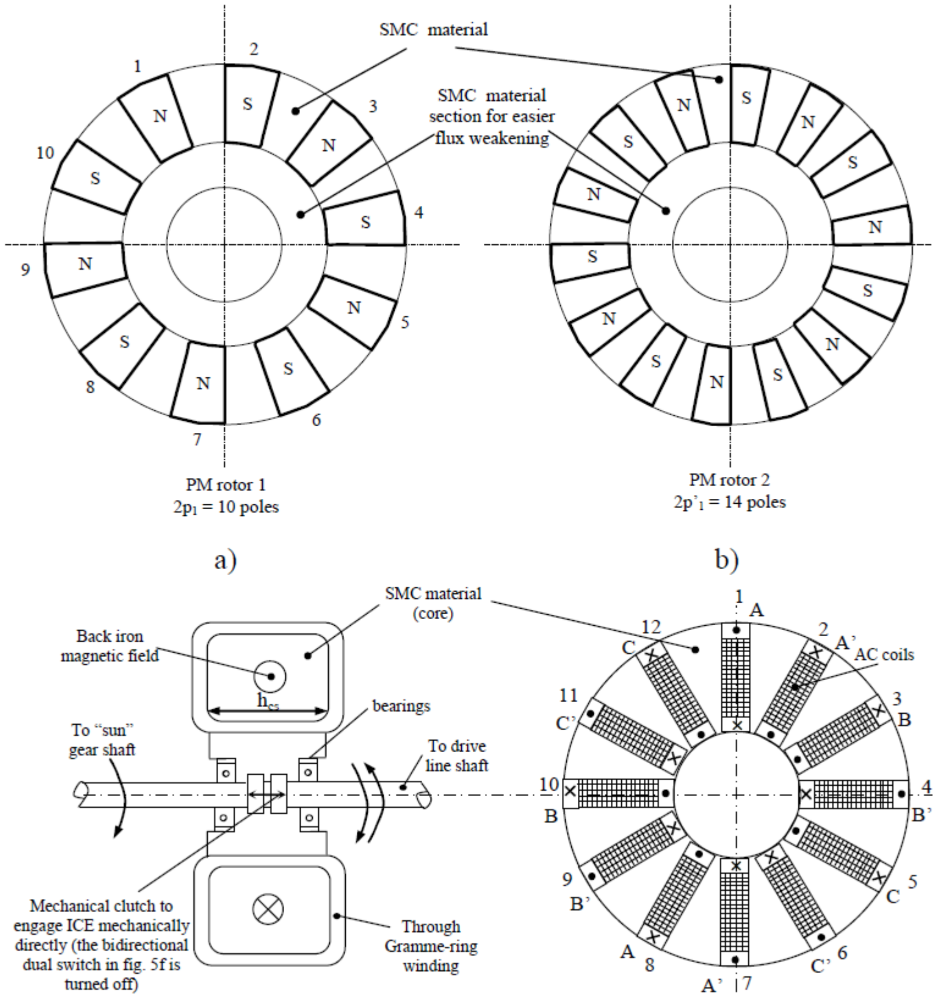

Fig. 30. Dual PM rotor (10 poles/14 poles) axial air-gap single stator (12slots), proposed typical topology [Bol 10a].

The same stator winding with only 12 coils appear as a factionary winding with different number of slots per pole per phase: q = 0.40 for the 10 poles side, and q = 0.29 for the 14 poles side. The double layer winding layouts is considered through two matrices as in [Ost 89] that contains all the information of the winding arrangement in the stator slots [Gie 04]. The concentrated windings make it possible to significantly increase the machine inductance in order to reduce the negative d axis current in flux weakening [Cro 02]. Rare earth magnets, e.g. Neodymium Iron Boron (NdFeB), were used, to keep the high efficiency and high torque density [Qu 03], despite of PM rather high price.

9.3 Dual rotor single stator and single three phase inverter

The vector control of the dual rotor single stator with a single winding has been developed, [Tut 11a], fig. 31, for a single three phase inverter that produces three phase output voltage with two frequencies components; the torque current for each rotor is controlled through the stator current that passes the two serial windings. The machine, coupled with the thermal engine (ICE), can operate as starter for short time at engine start-up and as generator, when the rotational speed is established by the thermal engine's regulator. The other machine can operate as motor in wide speed range (both inferior and superior to the generator's), but also in generator regime with power recovery at braking.

By simulation, it is shown that the power transfer through both rotors could be well controlled when their speeds difference is larger and also when their electrical speeds is equal when the power transfer between generator and motor being made directly and only the difference are passing the inverter. The zone where the rotors electrical speeds difference is smaller could be passed in the transitory regime without important torque oscillations and speed. It is found also that passing from one operation regime into another (motor-generator or reverse) is made rapidly and easier**.**

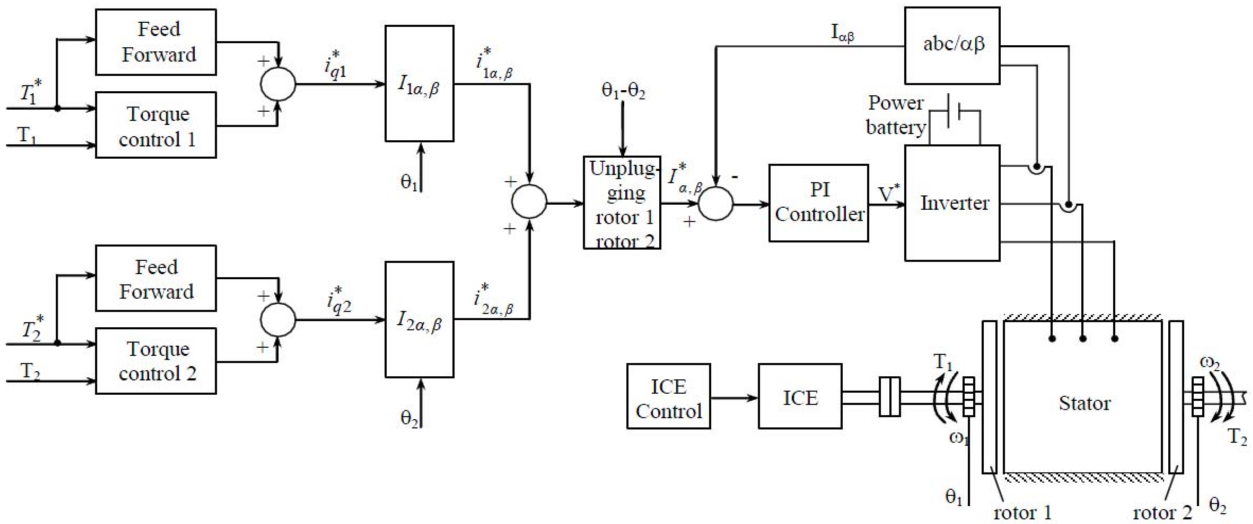

Fig. 31. The proposed dual vector control strategy [Tut 11a].

9.4 Four legs inverter

In last years, some research efforts have been directed to develop a new family of power converters with reduced costs and losses. A known proposed solution was the three-phase voltage-source inverter (VSI) with only two inverter legs but despite of reduced number of the active elements the main shortcomings of this topology are: decreased voltage gain and thereby increased current rating for the devices at the same output power, increased stress in both power devices and electric machine and large variations of the voltage across the two DC-link capacitors [Bla 99].

We, [Tut 12b], proposed four legs inverter, fig. 32, to supply the dual rotor PMSM, single stator core with two twin windings in Δ connection to maintain the phase voltage at same level as in 3 leg inverters. Moreover we proposed to add the diodes D_1, D_2 leg in parallel with the capacitors C_1 and C_2 as it is shown in fig. 47, in order to limit the overvoltage on the capacitors C_1 and C_2.

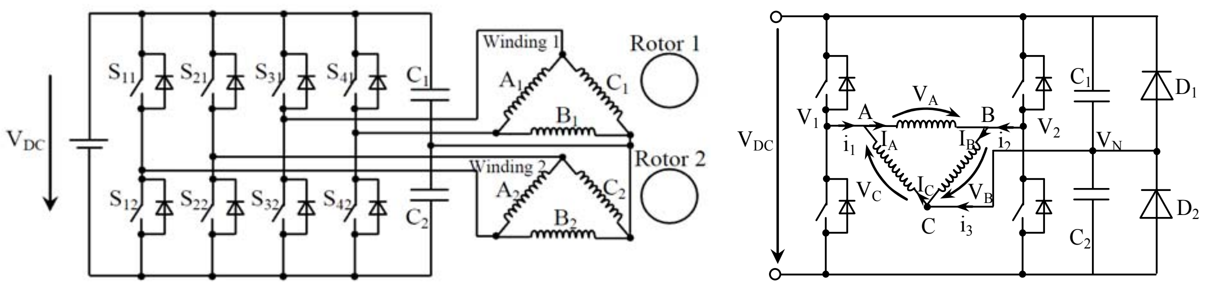

Fig. 32. Proposed single stator dual rotor PMSM drive-system with two distinct stator windings and four legs inverter, the circuit of one machine [Tut 12b].

The four leg inverter that drives the two rotors should result in additional reliability and compactness through at the cost of addition kVA rating. The A and B phases of both machines are connected to dedicated legs whereas C phase of both machines is connected to the neutral point of the two-split capacitors. The standard PWM technique in three-phase voltage source inverters is not directly applicable because only two phases may be modulated. So, a dedicated PWM strategy that reduces the capacitor middle point voltage pulsations is introduced and "tested" through extensive digital results.

The inverter model and phase voltage in stator orthogonal coordinate V_α, V_β, was derived considering the Δ connection and the capacitor passive leg:

$$\begin{pmatrix} V_\alpha \\ V_\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \frac{3}{2} & -\frac{3}{2} & 0 \\ \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & -\sqrt{3} \end{pmatrix} \cdot \begin{pmatrix} V_1 \\ V_2 \\ V_N \end{pmatrix} \quad (19)$$

$$\frac{dV_N}{dt} = -\frac{i_3}{C_1 + C_2} \tag{20}$$

The converter model, fig. 33, is based on the linear equations (19-20) plus a saturation (limitation) block. The block diagram from fig. 33 is not considering the diode D, D2 in parallel with the split capacitor. When the diode are added, also the null voltage are limited between zero and dc voltage.

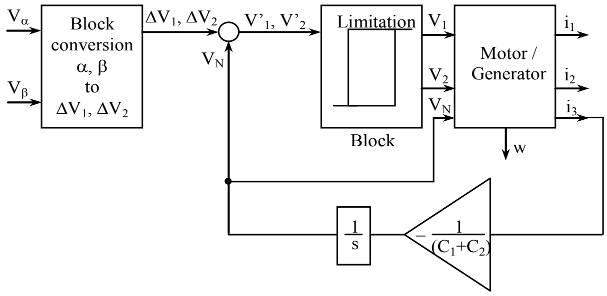

Fig. 33. Inverter and machine block diagram [Tut 12b].

The output voltages are defined by the gating signals of the two leg switches and by the two DC-link voltages (V_1 and V_2). In this way it is further possible to take into account the influence of the variations of the voltage across the two DC-link capacitors (C_1 and C_2). On the principle of feedback linearization the control voltages, V_1 and V_2 were computed, (21), based on V_α, V_β given by vector control and measured value of V_N.

$$\begin{pmatrix} V_1 \\ V_2 \end{pmatrix} = \frac{1}{\sqrt{6}} \begin{pmatrix} 1 & \sqrt{3} \\ -1 & \sqrt{3} \end{pmatrix} \cdot \begin{pmatrix} V_\alpha \\ V_\beta \end{pmatrix} + \begin{pmatrix} 1 \\ 1 \end{pmatrix} \cdot V_N \tag{21}$$

A PI controller on the error between capacitor middle point voltage and its reference (half dc voltage value), is generating a references of unbalanced current compensation. A single PI controller is used but the output limitation is different for the two machines. The unbalanced current compensation is transformed in the rotor frame and then it is added only to the d axis current reference. In this way, the compensation current influence on the torque is reduced for surface PM machines (no saliency). The vector control block for one of the motor and V_N voltage control is shown in fig. 34. Sample transients results are shown in fig. 50 where the M1 connected to the thermal engine (smaller inertia) is starting first and then the M2 which connected to the vehicle power train (larger inertia) is starting [Tut 12b].

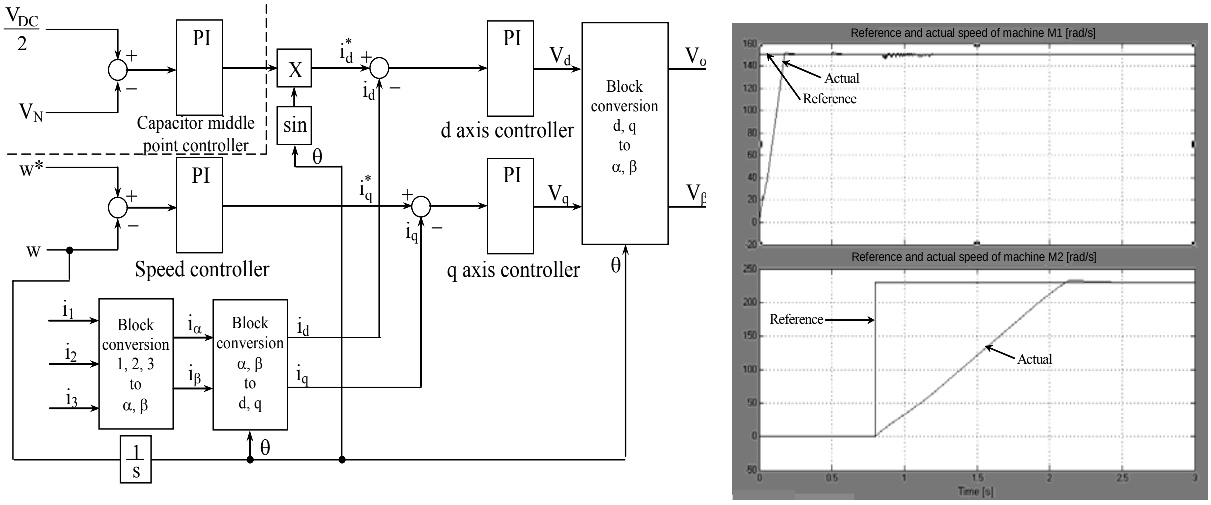

Fig. 34. The proposed vector control and simulations results [Tut 12b].

9.5 Optimal design single stator dual rotor surface PMs machine [Tut 12d]

Three-dimensional exploded view of PMSM single stator core, dual rotors and twin windings is presented in fig. 35, while the associate equivalent magnetic circuit for one pole is presented in fig. 36. The key design equations and design procedure of the Single Stator Dual Rotor PMSM by the equivalent magnetic circuit method is presented considering a skewed PM angle effects on machine performance [Tut 12c]. The optimal design using Hooke Jeeves algorithm is discussed in [Tut 12d]. The proposed analytical model was validated by quasi 3D FEM (also proposed here) with an accuracy of 8-10% for torque, and 13 % for inductances. The errors could be further reduced by a more complex analytical model. The rotor permanent magnet details are presented in fig. 35 where R_c is the radius of a fictive cylinder where the machine is cut and expanded in an equivalent linear machine used for quasi 3D FEM analyses, fig. 37.

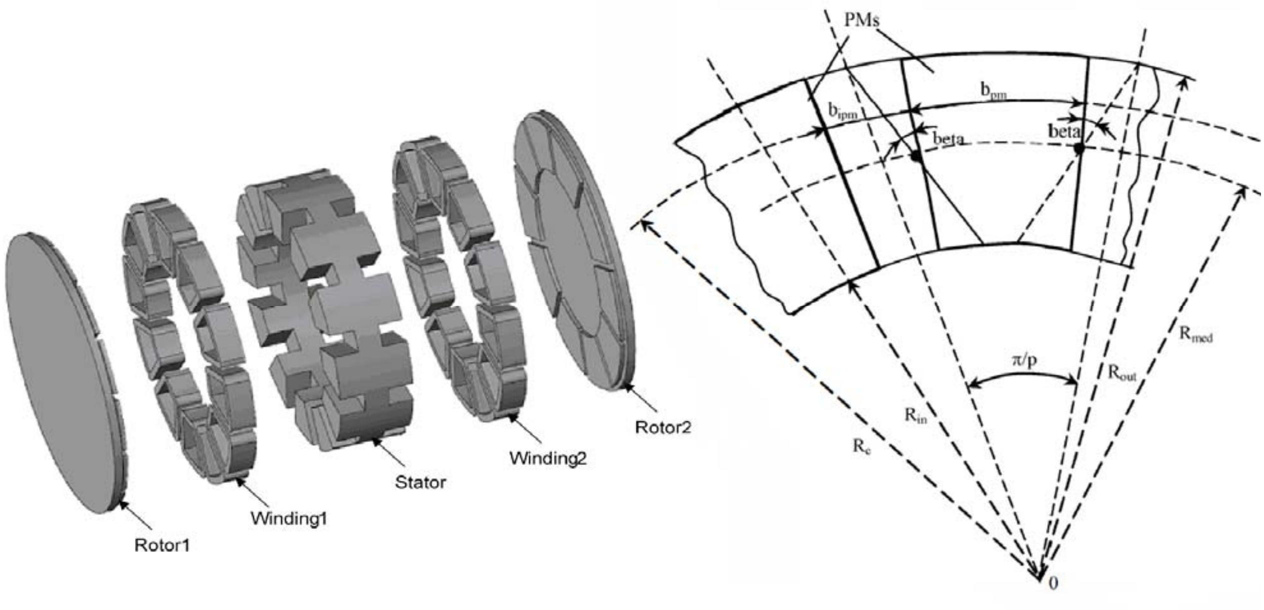

Fig. 35. Three-dimensional exploded view of single stator and dual rotors PMSM [Tut 12d] and skewed PMs [Tut 12c].

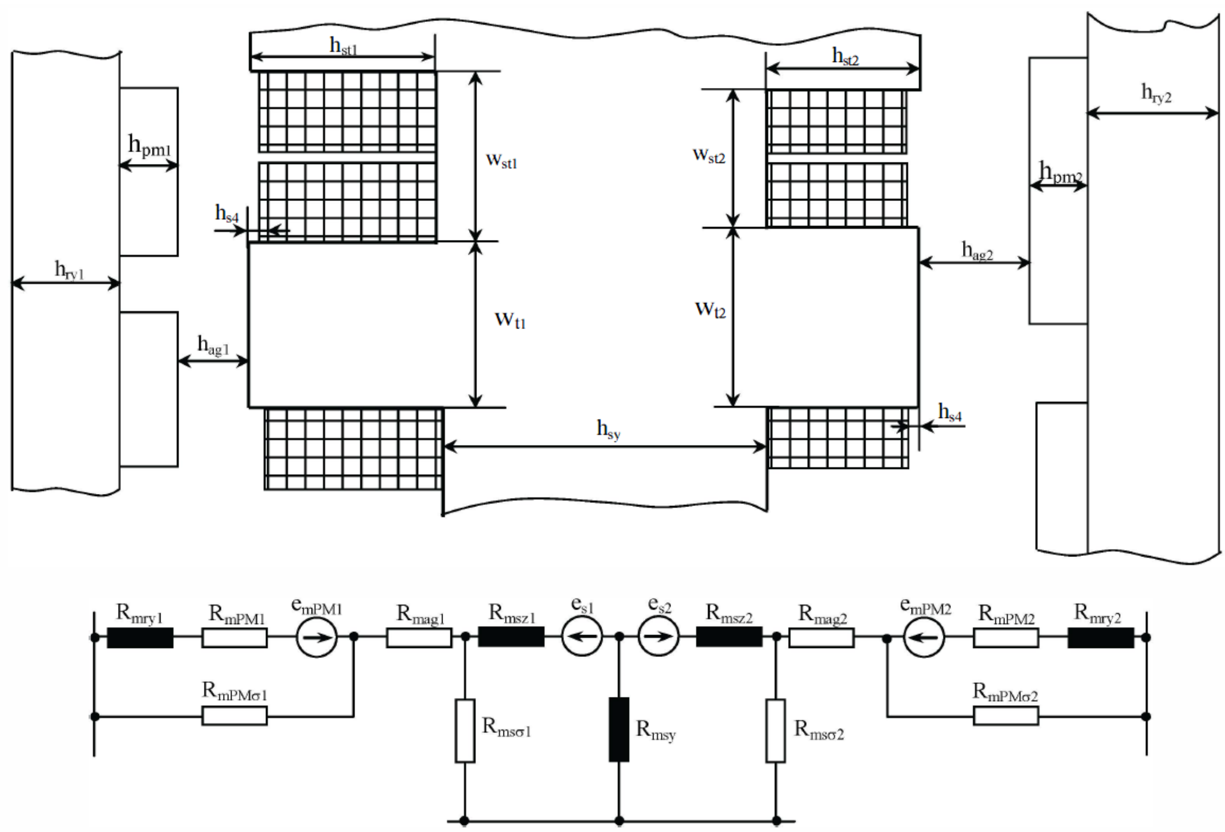

Fig. 36. The equivalent magnetic circuit for one pole at R, radius (between R_{in} and R_{out}) [Tut 12c].

An assembly of two machines (generator 55 kW and motor 110 kW) for a hybrid electric vehicle at 6000 rpm, with outer diameter 394 mm, axial length of 188 mm and active materials mass 133kg and was optimal designed. The machines parameters were computed in FEM considering 3 layer and Simpson's rule was applied to compute the average value.

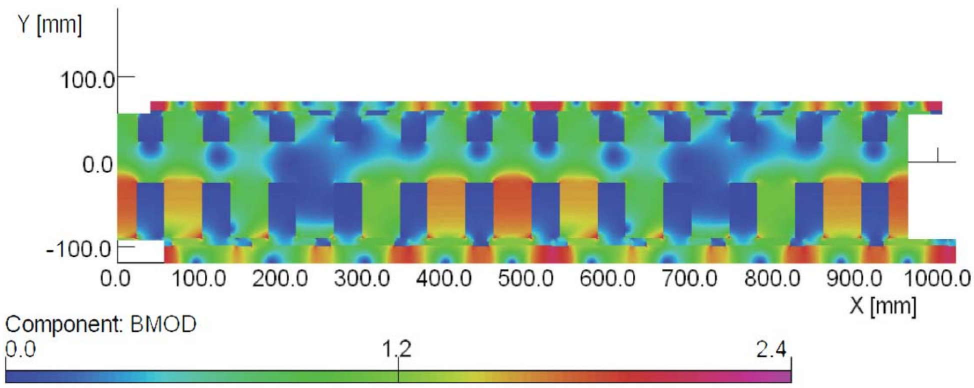

Fig. 37. The flux density distribution at full load [Tut 12c].

Based on the electrical circuit model the maximum available torque versus speed for both machines (rotors) is presented in fig. 38 in comparison with the constant power torque. It could be notice that for both rotors the maximum available torque is larger than required constant power torque. The d,q currents components versus speed are also presented in fig. 38.

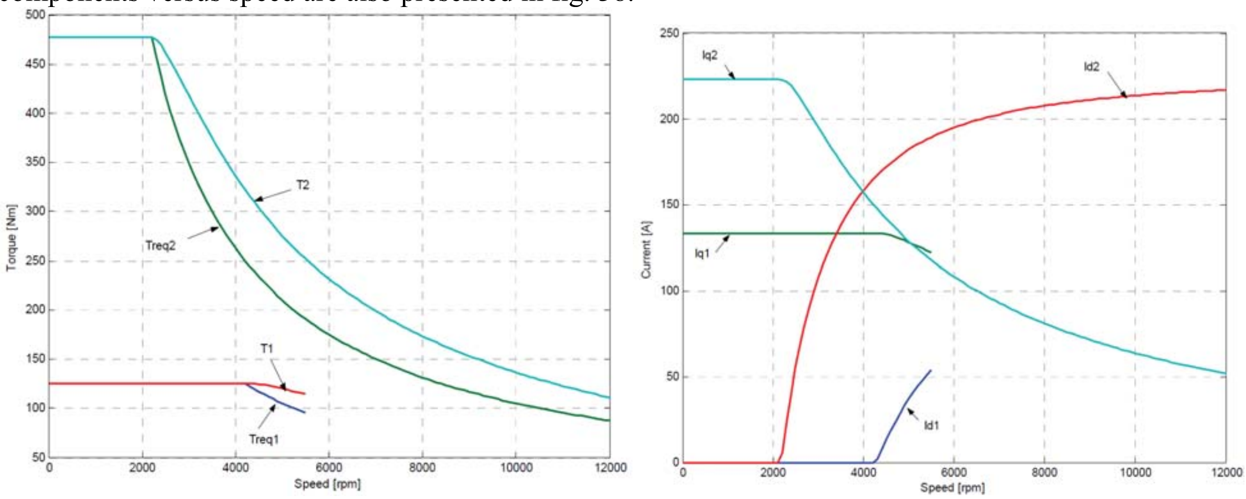

Fig. 38. Mechanical characteristics [Tut 12d]

9.6 Conclusion

The study of dual port axial air-gap electrical machine has been performed by means of following steps: two rotors single stator axial air-gap topologies; equivalent circuit model; optimal design; 3D-FEM analyses; quasi 3D FEM analysis in order to reduce the simulation time but also to use the advanced 2D FEM facilities as time stepping and external circuit; a control method using a single inverter being able to operate both rotors as motor and as generator in a wide speed range, in the same sense or in different senses by a using the two frequencies technique; a control method by using a four leg inverter.

Two machine topologies was studied, the first considering a single three phase ring winding, fig. 30 and the second topologies considering two pairs of three phase drum winding placed on the stator axial air gap surface, fig. 35. The second topologies were developed considering that the power required for electrical machines in HEV applications are usual in ration one to two. A four legs inverter with split capacitor was proposed with the delta connection of the three phase winding. It was demonstrated, through digital simulations, wide speed range control with compensated split capacitor-neutral voltage active compensation It is possible to run one machine at low speed using the current compensation through the both inverters. The model shows the increasing of machines RMS currents, compared with two symmetrical inverters (with 3 legs, each). An anti-parallel diodes leg was proposed in order to limit the overvoltage on the capacitors. The torque pulsations and power losses of the proposed method are reduced in comparison with those with a single 3 leg inverter where the two windings are considered in series. Both machines could be controlled independently over a wide speed and torque range. The number of active semiconductor devices is still reduced in comparison with two full inverters. In future investigations the use of a split battery system is intended, in order to further reduce the capacitors size in the inverters. Finally we concludes that the dual rotor, single stator axial air-gap could be a viable solution for HEV power train.

10. *Reluctance PM assisted motor*

10. 1 Introduction

The mild hybrid from Toyota makes use of a 42-V battery and a claw-pole generator/motor [Ter 03] and produces about 20%–25% fuel saving in town driving while the extra equipment cost is around $1000. The need for a good efficiency in a very wide power-speed range of 6:1 in a hybrid electric vehicle can be accomplished by using reluctance PM assisted motor when it operates at high flux densities [Com 03].

10.2 Starter generator for mild hybrid vehicle

The conceptual design and finite-element method analysis of a permanent-magnet-assisted reluctance synchronous motor/generator for mild hybrid vehicles where a large constant power speed range (6:1) is required and machine volume, converter peak kVA, and battery size are the main constraints was introduced in [Bol 02b], [Bol 04a], [Bol 04c]. During launch-assist, the storage system must deliver high power to the ISG system. The cross section on the PM-RSM machine and the prototype on the test rig are shown in fig. 39 while the maximum torque, dc current and efficiency versus speed are shown in fig. 40.

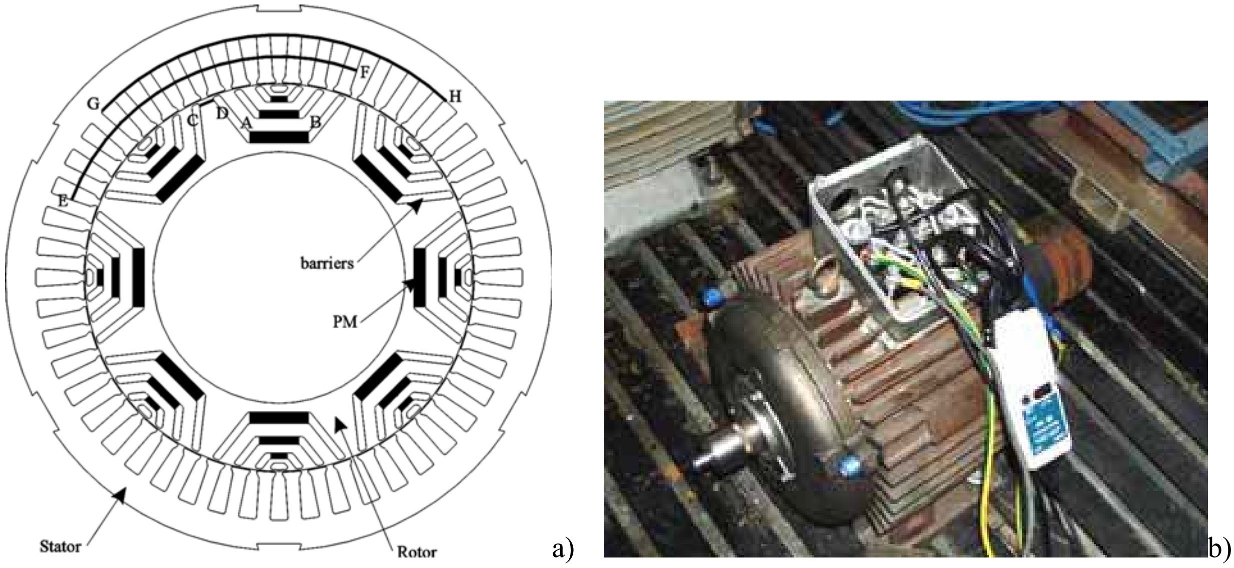

Fig. 39. PM-RSM machine: a) core cross section [Bol 04a], b) the prototype on the test rig [Pit 04].

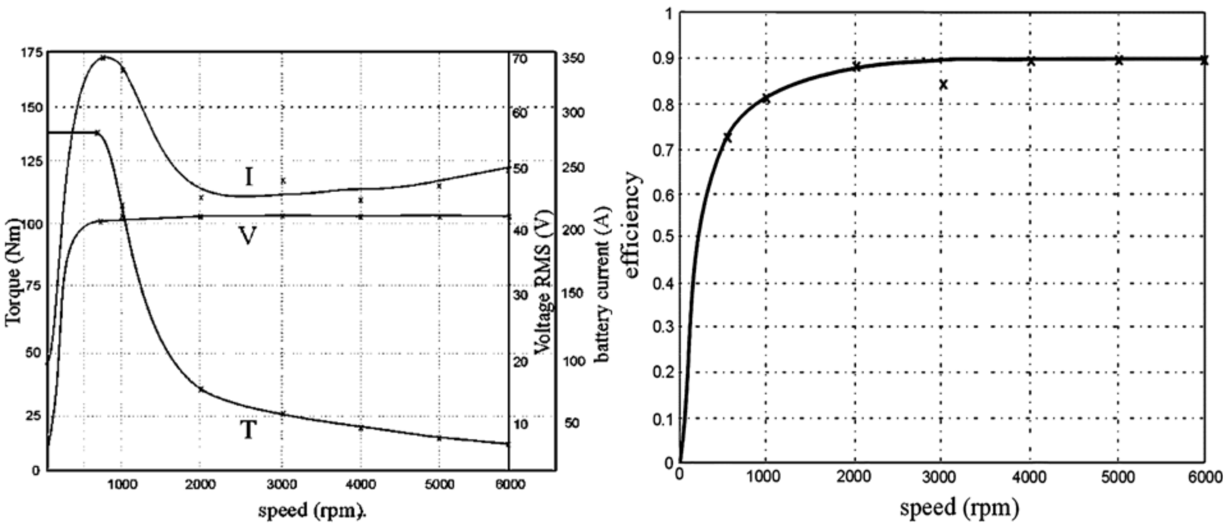

Fig. 40. Peak torque, voltage rms, battery current and efficiency (FEM—corrected analytical model) [Bol 04a].

Careful flux-barrier and permanent-magnet sizing, high magnetic saturation, and current density are the main requirements for maximum torque production with constraint volume. A specific tangential force density of 4.33 N/cm^2 is obtained. Rated (continuous) power-battery limited is 2.5 kW at 42 V dc, from 1000 to 6000 r/min. The peak torque of 140 N m is obtained at 202 A (rms/phase) and can be secured up to 500 r/min. Peak power is still 7.85 kW at 6000 r/min at 42 V dc with an efficiency of 90%.

10.3 Circuit parameter computation

The parameters cannot be determined by IEC Standard recommendations, therefore in our research [Pit 04] a combination of methods is proposed. Based on the d – q model steady [Bol 96a] and vector diagram the internal angle expression is derived [Pit 04]:

$$\delta = \arctan 2(a_1, b_1) \pm \arccos\left(\frac{V_{PM}}{\sqrt{a_1^2 + b_1^2}}\right)$$
$$a_1 = -V_{e1} - X_q I_s \sin(\varphi_1) \quad (22)$$
$$b_1 = X_q I_s \cos(\varphi_1)$$

The cross saturation also influence the inductances and then the L_d inductances depends on I_d and also to I_q. Considering a constant L_q inductance measured, from standstill or from short-circuit, the I_d and I_q current was computed from measured phase current in the load test and then the L_d versus I_d was computed, fig 41.

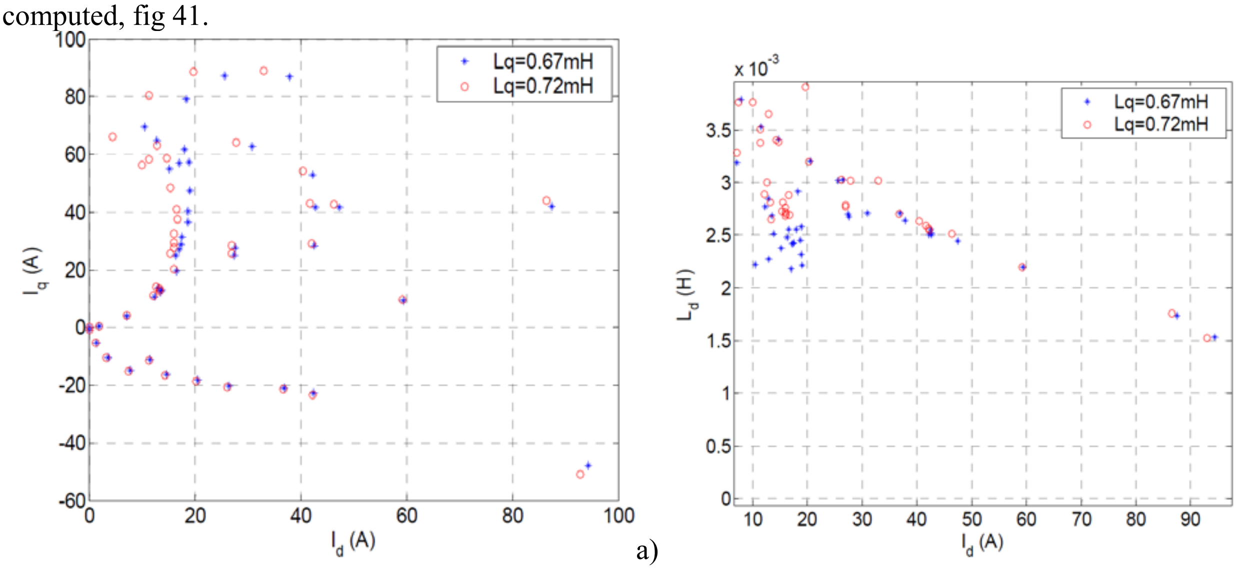

Fig. 41. Determination of I_q (a), L_d (b) and δ_v (c) from on load ac tests – for both L_q calculated from standstill (L_q = 0.72 mH) and from no load + short-circuit (L_q = 0.67 mH), [Pit 04].

10.4 Power train for (hybrid) electric vehicle (HEV/EV)

The aim of this research [Tut 14b] is to introduce – by general analytical nonlinear and then optimal design with vector control a hybrid electric and electric vehicles (HEV/EV) electric propulsion system for 50/100 kW, 1350–7000 rpm (600 Nm peak torque/40 kg) at above 91% overall efficiency 300 Vdc battery for a peak phase current of 520 A. In the 50 kW continuous, with a 100 kW peak (short duty), the 60 Nm/liter in Toyota’s fourth generation of Prius (IPMSM with sintered V shape NdFeB magnets) at efficiencies above 92% for a wide speed range (3/1 or more) has not been matched. But lower cost solutions came close, to 75% of torque density (45 Nm/liter) at 2-4% less efficiency; however, in general, with higher speed electric machines and thus higher gear ratio transmission (the SRM [Kiy 12] is a notable exception). As the Ferrite PM assisted RelSyn machine systems pose strong problems of PM demagnetization, the induction machines cannot provide sufficient wide constant peak power range (say at 173%) current, SRM [Kiy 12] require a higher peak kVA inverter rating (and cost) and the dc excited synchronous machine requires an additional excitation converter and brush-type energy transmission to rotor.

After searching quite a few alternative electric machines the low weight (40 kg) NdFeB (1.1T) PM–Reluctance synchronous machine with vector control was enveloped in detail. Finite element validation of flux density, torque, inductances and non-reconfigurable vector control for the entire peak torque (power) very challenging envelope substantiate a moderate cost high performance HEV (EV) drive. Optimal design considering the machine cross sections from fig. 42 and nonlinear analytical model based on magnetic equivalent circuit fig. 43 is used to achieve the design requirements. The motor current I_m, and its components on 'd axes', Id, and 'q axes', I_q, versus speed at the maximum available torque, peak power (100kW), and rated power (50kW) are shown in fig. 44. The efficiency and power factor at peak power and rated power versus speed are also shown in fig. 44.

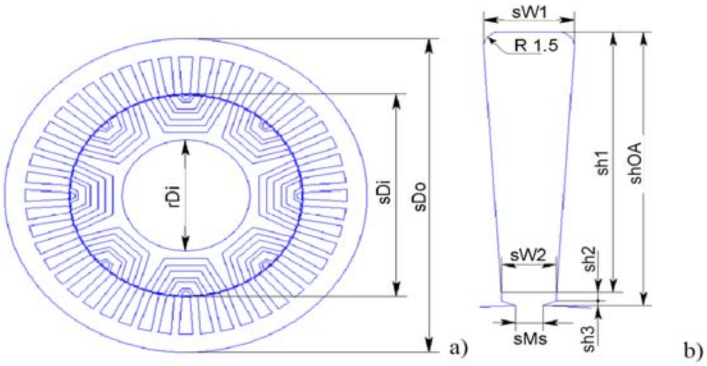

Fig. 42. a) Cross section of IPMSM; b) stator slot [Tut 14b].

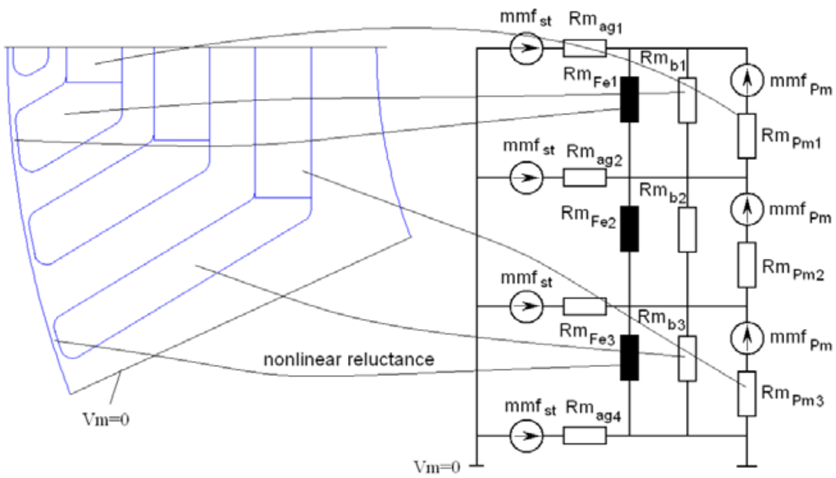

Fig. 43. q axis equivalent magnetic circuit [Tut 14b].

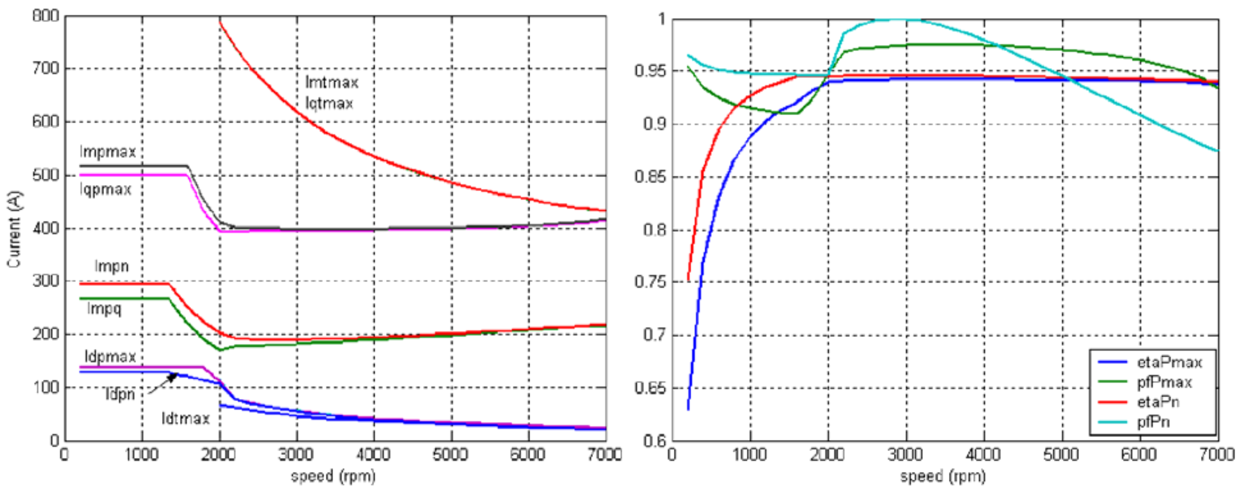

Fig. 44. Current/speed curves family and Efficiency and power factor for optimal cycle cost [Tut 14b].

A high torque density, high efficiency PM-RSM drive of 50/100 kW for 1350 rpm – 7000 rpm, 300 Vdc for efficiencies above 92-93% for the optimally designed solution for a 520 A peak phase current and a 40 kg active materials weight (out of which only 2 kg of 1.1 T NdFeB magnets) are required.

10.5 Conclusion

Our research on PM-RSM starts with design and prototyping of a starter-generator for mild hybrid vehicle. Vector control strategy was implemented for this machine and also the parameter estimations from no load respectively load test. Analytical model considering equivalent magnetic circuit was elaborate and validate by finite element analyses. A full scale machine for hybrid/electrical vehicle was designed with the remarkable performance in sense or torque density, efficiency, and wide speed control. It should be pointed few major advantages of PM-RSM in comparison with the PMM: good efficiency at high speed because it does not require high d axes negative current for field weakening, does not require special over voltage protection system and finally less PM quantity means cost reduction and less sensitivity on the market PM price fluctuation.

11. Linear oscillatory-motors

11.1 Introduction

The linear permanent magnet (PM) brushless oscillatory machines [Bol 01c] have gained momentum in the last decade, in relation to Stirling engines, refrigerator compressors [Par 01], and hybrid electric vehicles (HEVs) [Cos 03], [Caw 01], marine wave renewable energy [Mue 03] and precision positioning [Liu 05], [Li 05], [Gut 05], [Shieh 06]. Among the existing versions of the linear PM oscillo-machines those with PM-mover [Rou 88], coil mover [Bol 96b], [Bol 96c], [Bol 97], iron mover [Bol 97], [Caw 01] are predominant.

11.2 Flat linear oscillatory motors

A novel linear flux reversal PM oscilo-machine with effective flux concentration, made of two longitudinal lamination stator cores which accommodate four identical coils, fig. 45, which may be connected in series or in parallel to a single phase power grid, was proposed [Bol 04b]. The PM mower is also made of longitudinal laminations with flux barrier filled with permanent magnets of alternating polarity, fig. 45a. A flat surface, allows for permanent magnet flux concentration (FCPM) and the machine core is easy to manufacture from laminations, fig 46. Our research focuses on designing a PM mover with flux concentration [Bol 04] and also to the development of a comprehensive nonlinear model for transients and on its validation [Tut 05], [Tut 08].

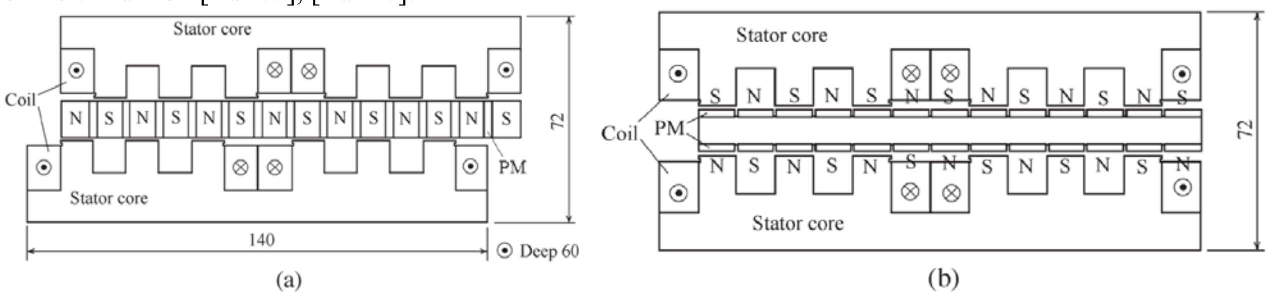

Fig. 45. Prototype configuration. a) Linear oscillatory machine with internal PM mover, b) SPM mover. [Tut 08].

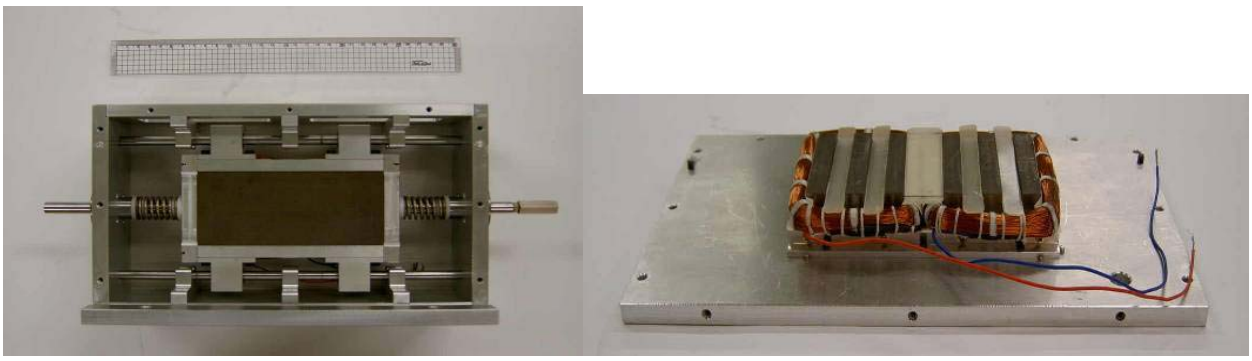

Fig. 46 Mover with one side stator assembly and stator with coils [Bol 04].

In what follows, such a set of static and dynamic tests and the test arrangement, fig. 47, are introduced and applied to a linear flux reversal PM brushless machine with surface PM and an interior PM mover with flux concentration, respectively

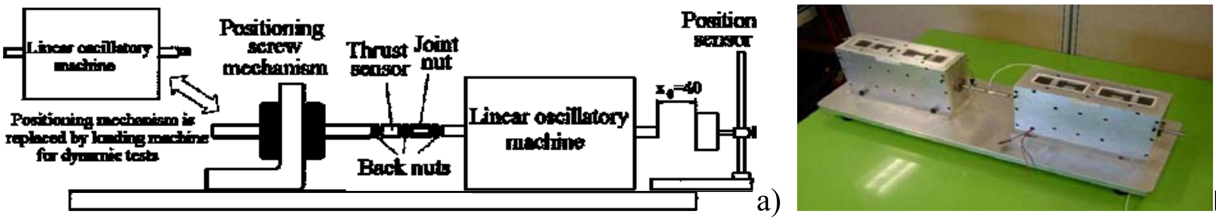

Fig. 47 a) Static test: mechanical setup [Tut 05], b) The two prototypes - back to back prototype [Bol 04].

The test results are compared with the FEM results, fig. 48. The test inductances differ from the fem computed inductances at small currents because the fem does not consider the first inflexion point on the magnetization curve. The geometric dimensions influence on the thrust is analyzed by FEM after it was validated on the existing prototype, [Tut 08], in order to improve the performances of linear oscillatory machine. The oscillatory motor thrust was increase more than three times, fig. 49 by reducing the air-gap from 1 to 0.4 mm, increasing the PM height from 2 to 3 mm and the stator core back from 10 to 15 mm.

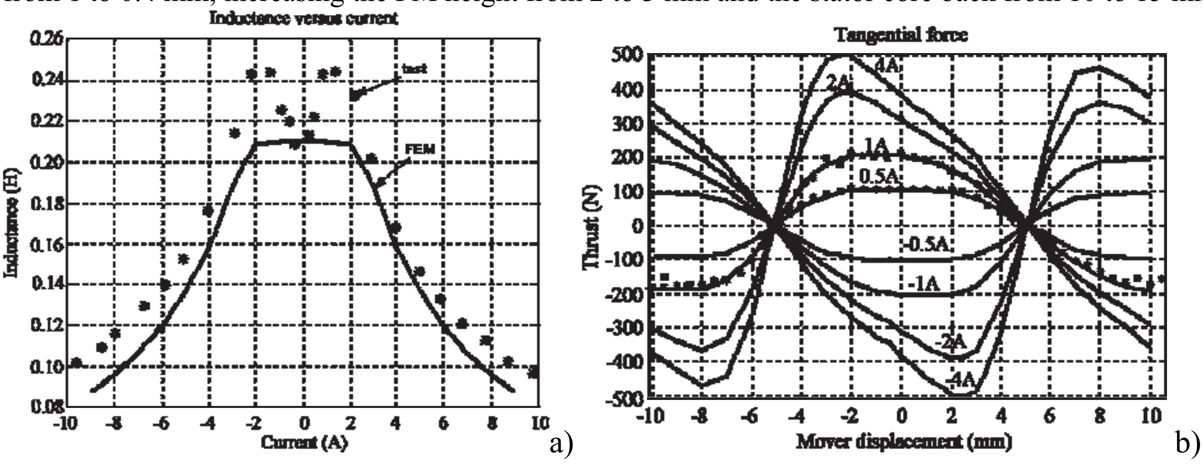

Fig. 48. Standstill test versus FEM analysis: a) inductance versus current, b) Thrust versus mover position and coil current; solid line—FEM, ∗—standstill test [Tut 08].

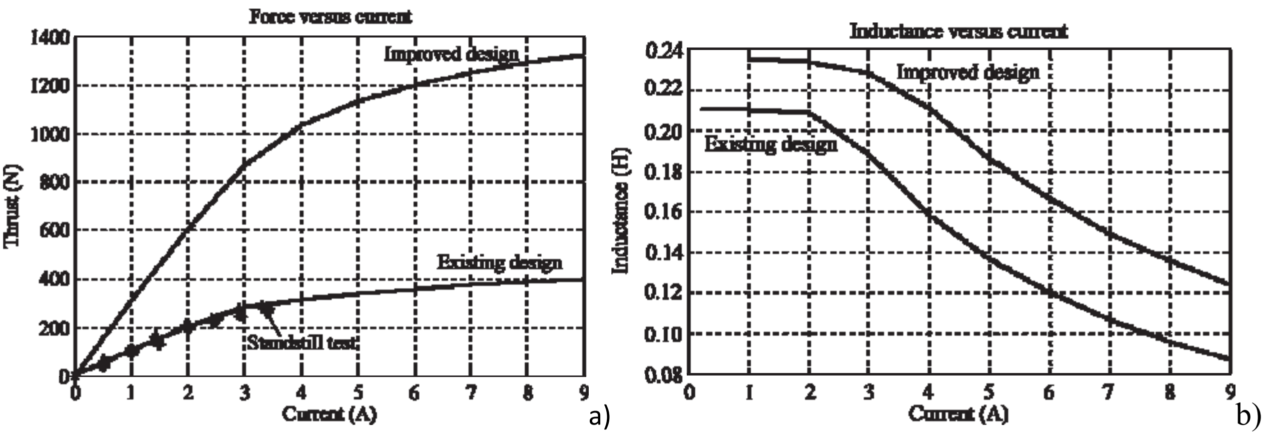

Fig. 49. Performances comparisons between existing and improved design: a) Thrust for existing and improved design; solid line—FEM, ∗—standstill test, two parallel path, b) Inductance for existing and improved design based on FEM at zero mover displacement and two parallel paths [Tut 08].

The efficiency depends on the output power but also it has a strong dependency on the frequency, fig. 50 and it reaches its maximum at mechanical resonant frequency while the output power reaches the maximum values at the electromechanical resonant frequencies [Tut 08]. The existing of two resonant frequencies could be noticed following the current and speed phase lag related to the voltage, fig. 50.

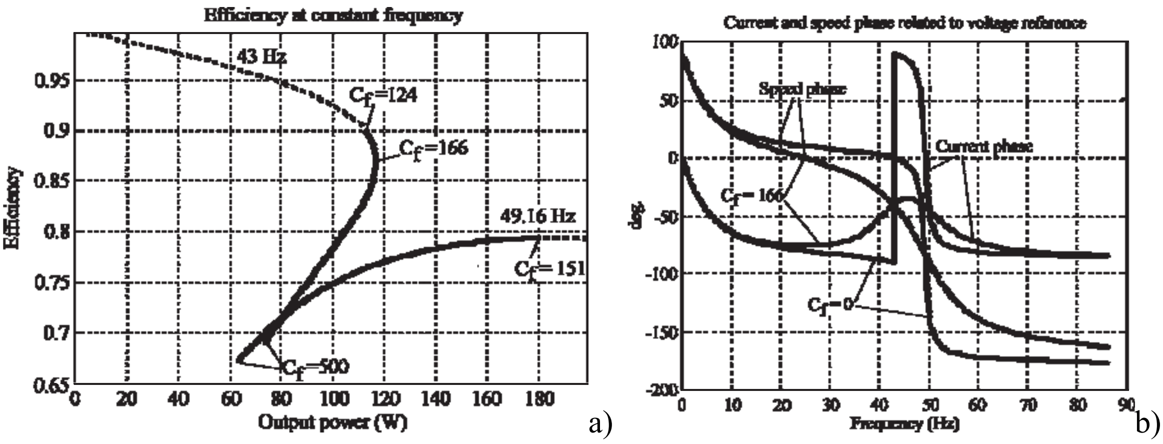

Fig. 50. Oscillatory motors – nonlinear behavior: a) Efficiency versus output power at two relative closed frequencies, b) Current and speed phase lag related to the voltage; c_f – the load equivalent friction coefficient [Tut 08].

A nonlinear dynamic model considering the cogging force, Columbian friction and thrust dependency on the position was elaborated and implemented in Matlab-Simulink, fig. 51. Mover free oscillation test are used to find the mechanical resonance frequency. The simulations results are in good agreement with the test results, fig. 52.

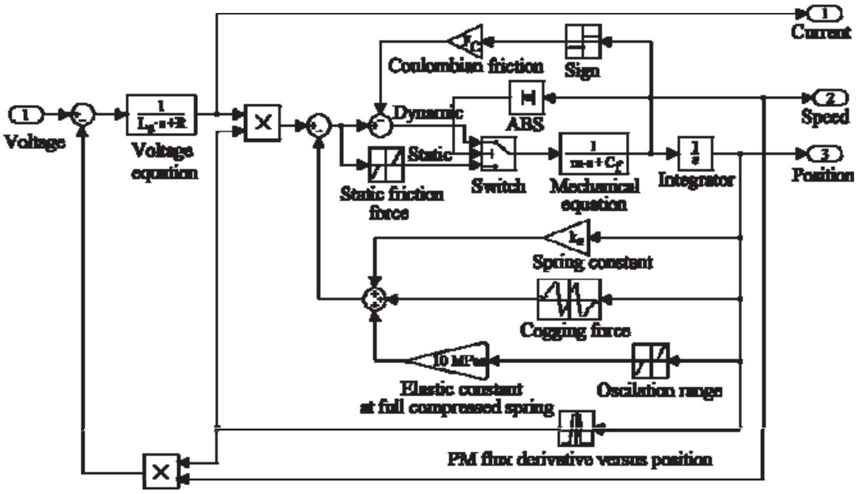

Fig. 51. Block diagram of the oscilatory machine nonlinear model [Tut 08]

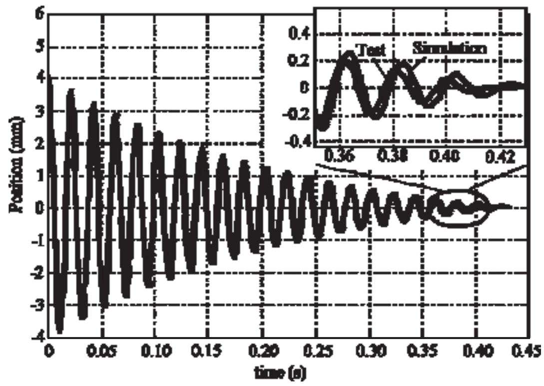

Fig. 52. Free oscillation test and simulation for coupled machines

1.3 Tubular linear oscillatory motors

Several tubular PM oscillatory machines were studied, three of them already published: inner mover and outer stator with radial air-gap, fig. 53, [Bol 12c], valve actuator which has an axial variable air-gap and use the normal electromagnetic force [Bol 07, Bol 08, Aga 10], and the spring-less oscillatory motor, fig. 54, [Aga13a] which is a particular case of a more general topology with a lighter mover placed between two concentrically stators. The tubular oscillatory motors were proposed to drive the reciprocation compressor for the refrigerators, eliminating in this way the crank rod mechanism. Digital simulations show that linear oscillatory machine could start in less than 0.1s without the complications met for a single phase motor.

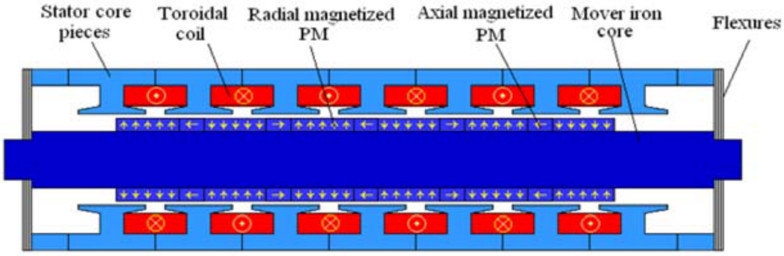

Fig. 53. Small power tubular PM oscillatory motor [Bol 12c].

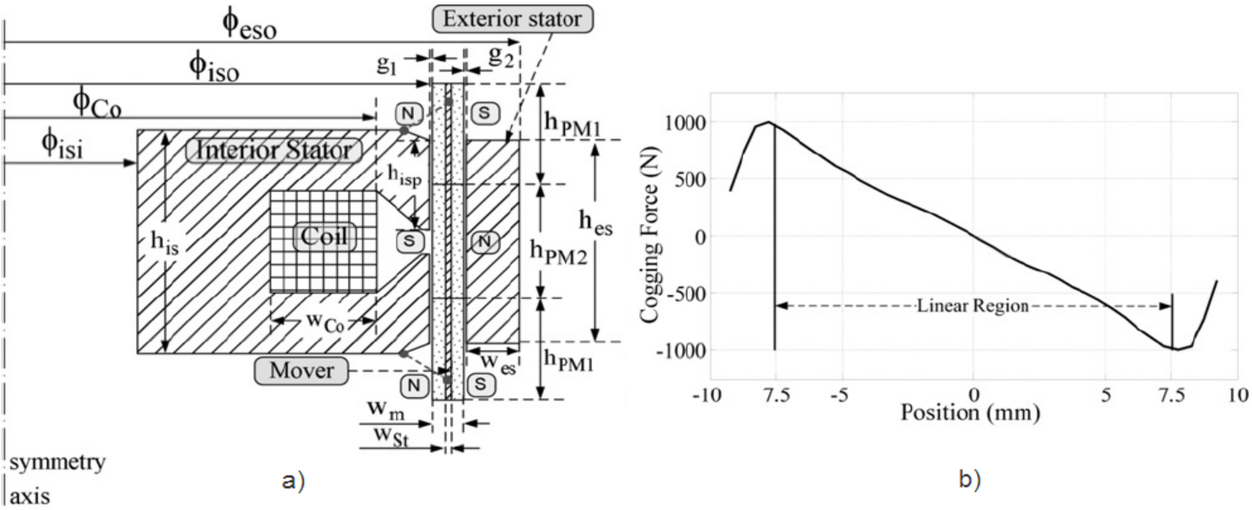

Fig. 54. Spring-less oscillatory motor: a) geometry, b) cogging force versus mover position [Aga 13a].

11.4 Conclusion

Linear actuators research is a long time research concerning a better efficiency of the home appliance actuators or automotive application actuators. Flat oscillatory machines were designed and a set of tests was proposed in order to indentify the oscillatory machines parameters [Tut 05, Tut 08]. Also the dynamic model and control strategies were developed. PM flux concentration mover was analyzed by finite element and was patented, [Bol 12c], in cooperation with Hilti. The tubular oscillatory machine was also researched and several topologies was developed and then analytical models using equivalent magnetic circuit was developed for each topology and based on this the optimal design was performed for each topologies. The analytical models are validated by finite element analyses. The behavior of the oscillatory motor in an open loop was analyzed based on the dynamic models and then closed loop control was proposed. At large magnitude oscillations, (close to the maximum available magnitude) the oscillatory motors tend to be unstable especially at low load and when they are running at resonance frequency where the efficiency reaches its maximum. Our research proves by extensive digital simulations but also by pole locus in complex plane that the close loop control is stable. Senseless positions close loop control was developed for the valve actuator. Our research study the oscillatory motor fed by a single phase converter where the close loop control is used but also line start motors at 50 or 60 Hz where a nonlinear harness spring is stabilizing the oscillations even at low load.

IV Professional and academic development plan

Energy conversions will remain the main problem of the mankind and only energy resource diversification with a better efficiency of energy conversion could bring a sustainable development of the humanity. The high standard of living is based on the electrical energy applications. More than 99% of the electrical energy is produced by electrical machines, according to [US 14]. Moreover 60-70% of the electrical energy is used by electrical machines [Vuk 13, page 10]. Considering my research background and the energy conversion as one of the most important problem nowadays, I will continue to orientate my future research on the energy conversion by electrical machine with all aspects: optimal design, electrical machine topology diversification, electrical machine control and power electronics associate with the electrical machines. Under this general research theme I will orientate my neat future research on the following particular directions: electrical machines for power train in electrical or hybrid vehicles considering the dc excited synchronous machines as an alternative to permanent magnet machines, electrical generators for renewable energy and electrical motors for home appliances.

The hybrid and electrical vehicle request a high torque density, high efficiency electrical machines with a large constant power speed range. Rare earth permanent magnets are used in order to get high torque density and high efficiency electrical machines but there are several drawbacks of the PMs motor in automotive power train applications: difficulties to reach the required wide speed range; the d axis current is large at high speed and then the efficiency is small at high speed due to large copper and additional iron losses; it required a fast response overvoltage protection; the PMs motor features are changed notably when it operate in a wide temperature range; the cost of the rare earth PMs are large and unpredictable.

I have started to work at two different solutions that could satisfy the tough technical request of the electric dives for the hybrid or electric vehicles: brushless dc multiphase reluctance machine (BLDC-MRM), respectively dc excited synchronous machine with contactless excitation system. The BLDC-MRM was introduced by Professor H. Weh [Weh 86] and already I have participated to a BLDC-MRM prototyping during my work on the engineer diploma in 1988-1989. The test results considering all six phase in a series connections was published in 1990 [Bol 90]. After the [Law 94] no more significant paper was published until now when the study was resumed in the Ph. D thesis of D. Ursu [Urs 14a], [Bol 12], [Aga 13], [Urs 13], [Urs 14b]. I have planned to continue the research in this direction and expect the following results:

- improve the circuit model including the computation of the commutating voltage, that will be included in the objective function as a constrain, also a better torque accuracy in comparison with the finite element method;
- develop a better model of rotor iron losses;
- reducing the number of current sensors and eliminate the motion sensor;
- optimize the control for motoring and breaking generator in order to reduce the machine losses and keep a good torque response;
- direct comparison between brushless dc mode (trapezoidal current considering excitation phase an torque phase) and synchronous reluctance mode (sinusoidal current – dq control) on the same six phase machine;
- develop a mechanism to detect a phase fault (interrupted phase) in machine or in converter and adjust the control to run in fault tolerant mode (with one or more phases interrupted in different position);
- design a prototype for electrical vehicle considering all requirements for this applications.

The d.c. excited synchronous machine is also a potential solution for the hybrid and electrical vehicle. The excited power transferred through the slip-rings and brushes is the main drawbacks of the dc excited synchronous machine but it could be eliminated using a rotary transformer and inverter contactless system. I have already submitted a proposal project, PN-II-PT-PCCA-2013-4-1776, on this topic and despite that it did not get governmental finance, I have improved it and I will continue the research on this direction. The research on this direction will be focus on system with low volume, low cost and high performance rotary transformers controlled by power electronics able to control the power flow within the rotors of small or large electric machine by means of contactless power transfer. I believe that proposed solution, with rotary transformer, will be better, than existing brush or brushless solutions that are shortly enumerated:

- Slip rings and brushes, that is considered to have reduced reliability and also it decreasing the insulation capacity due to the graphite powder, and higher maintenance cost.
- Exciter machine that consist in an inversed synchronous machine provided with a diode rectifier on the rotor side. In variable speed the exciter machine becomes prohibitive large in order to cover small speeds and the solution cannot be applied at zero speed.
- Exciter machine that consist in doubly fed induction machine provided with a diode rectifier on the rotor side. At small speed it becomes expensive and has smaller efficiency than a rotary transformer.

The rotary transformer and the inverter have in this case a power of 1-3% of the power of the synchronous machine and for low power transferred between rotor winding and stator, a rotary single phase transformer may be used, powered in the stator by a frequency inverter at around 300÷1200 Hz.

With the contactless power transfer solution, the excited synchronous machine could be used where it was possible to use only PM solution. Moreover, the rotary transformer solution may be also applied for the claw-pole synchronous machine [Tut 12a], [Bol 05], and biaxial excited synchronous machine [Cor 11]. This way, a wide range constant power may be obtained, with excitation field weakening, and the losses will be reduced at high speed [Bol 10c], because field weakening is naturally obtain by reducing the excitation current and not by applying a high demagnetization current in the d axis, like in the PM machines. The over voltages protection, mandatory to use on wide speed range PM machines, is not necessary for dc excited machines.

The research activities and expected results on this topic are: - Development of a design methodology for innovative single phase and three phase small and large power rotary transformers; - The optimal design, using at least one of the following methods: Hooke Jeeves, Genetic algorithm, Particle Swarm Optimization, considering the losses model (copper, iron and mechanical losses) and the maximum admissible over-temperature as constrain; - The finite element analysis (FEA) of the rotary transformers (electrical parameter validation, iron losses, cooling model; - The development of new constructive solutions for rotary transformers, considering magnetic powder and laminations. Identifying and analyzing the constructive solutions in order to reduce / eliminate the rotary transformer vibration and noise, and improve the power factor and efficiency; - Developing a laboratory model, in order to evaluate their performance, particularly: the efficiency gains with respect to existent solutions on the market.

The scientific goals are to develop advanced knowledge on contactless power transfer and to develop innovative, cost-competitive, and environmentally acceptable rotary transformer and fabrication technologies.

On the home appliance research direction, a major research and development effort is made on improving the efficiency of the home appliances equipment because the consumption energy in small power equipment becomes more and more important with increasing of living standards worldwide. On this research direction, I will continue research on the already started subjects: IPM-SM with flux concentration, [Isf 13a] and stator ferrite PM single phase motor [Isf 14]. On the IPM-SM with flux concentration, our team in cooperation with the Embraco, Brazil will continue the research, building and testing new prototypes. The expected contributions are: 3D flux concentration for ferrite permanent magnet which permit similar performance with the more expensive NdFeB; magnetic barrier form shape to protect the PMs against demagnetization phenomena during the overload, new methods for uniform PM magnetization, and also new contributions in the control. On the stator ferrite PM single phase doubly saliency small motor the research will be continued by designing a prototype with a good self-starting capability. The expected results are a low cost high efficiency variable speed motor with the contribution on improving the motor start-ability by rotor and stator pole shape, a better analytical model using the equivalent magnetic circuit validated by finite element, optimal design, developing the dynamic model and the control strategies.

The proposed research will contribute to the Community's societal objectives to address climate change by reducing the level of CO_2 emissions from electric energy production industry and from transportation which is a mast according to the Decision 601/2012/EC of the European. Furthermore, improvements in air quality expected as the results of the proposed research implementation will contribute to health of European citizens' improvement. The proposed research directions and the expected results are correlated with the European Community directives and also with the national economic interests and then I hope to attract national and European grants in order to put in the practice the innovative ideas.

The proposed research work will be enforced if I become a PhD supervisor. The PhD students will help me to carry out the proposed research but more than this, they will spread out the research results and they will implement the new knowledge in the real life. The PhD students will brings new ideas and theirs points of view on the today's burning issues.

The research results and especial the cooperation with the PhD students will help me to understand the younger's problems on realm of science and will help me to improve my didactic activity.

On the other hand, I believe that the good research results, with impact in the local and global economy will attract new enthusiastic younger researcher on this promising research field despite to the actual PhD student's shortage.

V References

[Aga 09a] S.C. Agarlita, I. Boldea, F. Marignetti, L. Tutelea, "Linear Permanent-Magnet Valve Actuator - The Dynamic Model: Digital Simulations, Open-Loop U/f and I/f Operation and Position Estimation Performance, with Experiments", *Proc of 8th ELECTROMOTION* 2009, pp. 320-324.

[Aga 10a] S.C. Agarlita, I. Boldea, F. Marignetti, L.N. Tutelea, "Position Sensor less Control of a Linear Interior Permanent Magnet Oscillatory Machine, with Experiments", *Proc. of 12th OPTIM 2010*, PTS I-IV, 2010, pp. 689-695.

[Aga 10b] S. C. Agarlita, I.G. Boldea, L.N. Tutelea, "Electromagnetic device for actuation of valves of heat engine comprises pre-polarized electromagnet, fixed magnetic cores, internal core and external core", Patent Number: RO125407-A2, 2010.

[Aga 10c] S.C. Agarlita, M. Fatu, L.N.Tutelea, F. Blaabjerg, I. Boldea, "I-f Starting and Active Flux Based Sensorless Vector Control of Reluctance Synchronous Motors, with Experiments", *Proc. of the 12th OPTIM*, PTS I-IV, 337-342.

[Aga 13a] S.C. Agarlita, L.N. Tutelea, I.Boldea, "Modelling and control of a springless resonant linear permanent magnet oscillomotor", *IET Electric Power Applic.*, 2013, pp. 150-158.

[Aga 13b] S. Agarlita, D. Ursu, L. Tutelea, I. Boldea, B. Fahimi, "BLDC multiphase reluctance machines: A revival attempt with 2D FEM investigation and standstill tests", *Energy Conversion Congress and Exposition (ECCE)*, 2013 IEEE, pp. 1850-1857.

[Alg 30] P. L. Alger, E. H. Freiburghouse, and D. D. Chase, "Double windings for turbine alternators," *AIEE Trans*., vol. 49, pp. 226–244, Jan. 1930.

[Alg 70] P. L. Alger, "Induction Machines The Behaviour and Uses", Gordon and Breach Publishers, 1970.

[Ali 10] A.D. Aliabad, M. Mirsalim, N.F. Ershad, "Line-Start Permanent-Magnet Motors: Significant Improvements in Starting Torque, Synchronization, and Steady-State Performanc", *IEEE Trans.,* Vol. Mag-46, no. 12, 2010, pp. 4066-4072.

[And 10] P. S. Andersen, D.G. Dorell, N. C. Weihrouch, P.K. Hansen, "Synchronous torques in split phase induction motors", *IEEE Trans*. Vol. IA-46, no.1 2010, pp. 227-231.

[And 98] S. IB Andersen, "Designed of modular flywheel system". *EESAT'98,*1998 Chester (UK).

[Ark 07] A.A. Arkadan1; A.A.Hanbali, N.Al-Aawar, "Design Optimization of ALA Rotor SynRM Drives Using T-AI-EM Environment", *IEEE Trans. On Magnetics*, Vol. 43, No. 4, April 2007, pp. 1645-1648.

[Bae 11] S.-W. Baek, B-T.Kim, B-I. Kwon, "Practical optimum design based on magnetic balance for a single phase line start PM motor", *IEEE Trans.*, Vol. MAG-47, no.11, 2011, pp 3008-3011.

[Ban 03] Bansal, R.C., Bhatti, T.S., and Kothari, D.P., "Bibliography on the Application of Induction Generators in Nonconventional Energy Systems",*IEEE Transaction on Energy Conversion*, vol. 18, no. 3, Sep. 2003, pp. 433-439.

[Bia 03] N. Bianchi, S. Bolognani, F. Tonel, "Thermal analysis of a run-capacitor single-phase induction motor", *IEEE Trans.* IA-39, no. 2, 2003, pp.457-465.

[Bla 95] Blaabjerg, F.; Jaeger, U.; Munk-Nielsen, S., "Power losses in PWM-VSI inverter using NPT or PT IGBT device", *IEEE Trans. on PE* Vol. 10, No. 3, May 1995, pp. 358 –367.

[Bla 96] Blaabjerg, F.; Pedersen, J.K.; Sigurjonsson, S.; Elkjaer, A., "An extended model of power losses in hard-switched IGBT-inverters", *IAS'96*, Vol. 3 , pp. 1454 –1463.

[Bla 99] F. Blaabjerg, D.O. Neacsu, J.K. Pedersen, "Adaptive SVM to Compensate DC-Link Voltage Ripple for Four-Switch Three-Phase Voltage-Source Inverters", *IEEE Trans. on Power Electronics*, vol. 14, no. 4,1999, pp. 743-752..

[Bol 00] I.Boldea, S. Scridon, L. Tutelea: "BEGA – a biaxialexcitation generator for automobiles" *in Proceedings of the 7th International Conference OPTIM 2000*, Brasov, May 10-11 2000, pp.345-352.

[Bol 01a] I. Boldea, S. Scridon, L. Tutelea, "BEGA – A biaxial excitation generator for automobiles", *JEE* vol. 1, no. 1/2001 paper 8, pp/ 50-57.

[Bol 01c] Boldea, S ANasar „ Linear electro devices" book Taylor and Francis publ. 2001.

[Bol 02a] I. Boldea, E.A. Ritchie, F. Blaabjerg, S. Scridon, L. Tutelea, "Characterization of biaxial, excitation generator for automobiles, *Proc of 8th International Conference on Optimization of Electrical and Electronic Equipments*, 2002, pp. 371-376.

[Bol 02b] I. Boldea, L. Tutelea, C.I. Pitic, "PM – assisted Reluctance Synchronous Motor / Generator", *Proc. of 8th International Conference on OPTIM 2002*, vol II, Brasov May 20-21 2002 vol. 2, pp. 383-388.

[Bol 04a] I. Boldea, L. Tutelea, C. I. Pitic, "PM-Assisted Reluctance Synchronous Motor/Generator (PM-RSM) for Mild Hybrid, Vehicles: Electromagnetic Design", *IEEE Trans. on IA*, VOL. 40, NO. 2, 2004, pp.492-498.

[Bol 04b] I.Boldea, M.Topor, J. Lee, L. Tutelea, "Linear flux PM oscilo machine with effective flux concentration", *OPTIM 2004*, Vol.2, pp. 371-376.

[Bol 04c] I. Boldea, "Starter/alternator systems for hybrid electric vehicles and their control: A review," in *Proc. ICEM'04*, Je Ju Island, Korea, 2004.

[Bol 05] I. Boldea and S.A. Nasar, "Electric Drives", 2nd Edition, New York: CRC Press, Taylor & Francis, 2005, chapter 14.

[Bol 06] I. Boldea, C. I. Pitic, C. Lascu, Gh. D. Andreescu, L. Tutelea, F. Blaabjerg, P. Sandholdt, "DTFC-SVM Motion-Sensorless Control of a PM-Assisted Reluctance Synchronous Machine as Starter-Alternator for Hybrid Electric Vehicles", *IEEE Trans. on PE*, Vol. 21, No. 3, 2006, pp. 711-719.

[Bol 07] I. Boldea, S. Agarlita, L. Tutelra, F. Marignetti, "Novel linear PM valve actuator: FE design and dynamic model", *Proc of LDIA 2007*, Lille.
[Bol 08b] I. Boldea, S.C. Agarlita, F. Marignetti, L. Tutelea, "Electromagnetic, thermal and mechanical design of a linear PM valve actuator laboratory model", *Proc. of the 11th OPTIM 2008*,Vol. II A and B, pp.259-264.
[Bol 10a] Boldea I., Topor M., Marignetti F., Deaconu S. I., and Tutelea L. N., "A Novel, Single Stator Dual PM Rotor, Synchronous Machine: topology, circuit model, controlled dynamics simulation and 3D FEM Analysis of Torque Production", *12th OPTIM 2010*, Brasov, pp. 343-351
[Bol 10c] Boldea I, Tutelea L.N., "Electric Machines– Steady State, Transients and Design with MATLAB", CRC Press, 2010,.
[Bol 10d] I. Boldea, S. A. Nasar, "Induction Machines Design Handbook", second edition, book, CRC Press Florida 2010.
[Bol 11] I. Boldea, L.N. Tutelea, S.I. Deaconu, F. Marignetti, "Dual rotor single stator brushless PMSM motor/generator system for full HEVs", *ECAI 2011*, 2011, Pitesti, pp. 95-102.
[Bol 12a] I. Boldea, L.N. Tutelea, D. Ursu, "BLDC Multiphase Reluctance Machines for Wide Range Applications: a revival attempt", *15th EPE/PEMC*, Novi-Sad, 2012, pp. LS1b.1-1 - LS1b.1-6.
[Bol 12c] I. Boldea, L.N. Tutelea, S.C. Agarlita, C. Pompermaier, I.H. Setter, "25 W linear PM oscillo-motor (PM-LOM): general and optimal design, with FEM validation and controlled dynamics", *Proc. of ICEM 2012*, pp. 2726-2732.
[Bol 12d] I. Boldea, L. Tutelea, B. Sander, A. Binder, "Linear motor for e.g. drilling hammer, has rotor comprising two magnets and movably supported between two cores and two air gaps in filled manner, where two air gaps comprise plane that comprises rotor movement axis", Patent Number: DE102011077241-A1, 2012.
[Bol 14] I. Boldea, S. Deaconu, F. Marignetti, L. Tutelea, "Brushless electrical actuator with two independent rotors for hybrid electrical propulsion", Patent Number: IT1409332-B, 2014-Q06615 [65].
[Bol 90] I.Boldea, G. Papusoiu, S.A. Nasar, Z.Fu, "A novel series connected switched reluctance motor", *Proc. of ICEM 1990*, Part 3, pp. 1212-1217.
[Bol 96a] I. Boldea, "Reluctance Synchronous Machines and Drives", London, U.K.: Oxford Univ. Press, 1996.
[Bol 96b] Ion.Boldea, S. A. Nasar, B Pensweick, B Ross, R Olan „ New linear reciprocating machine with stationary permanent magnets" Record of IEEE IAS 1996,Vol 2, pp. 825- 829.
[Bol 96c] Boldea S. A. Nasar „US patent" No. 5, 564, 596.
[Bol 97] Boldea, C. Wang, B Yang, S. A Nasar „Linear actuators and generators,, book, Cambridge University press, 1997.
[Bol 99a] I.Boldea, T. Dumitrescu, S.A. Nasar, "Unified analysis of 1-phase ac. motors having capacitors in the auxiliary winding", *IEEE Trans.* Vol. EC-14, no. 3, 1999, pp. 577-585.
[Bol 99b] I. Boldea, "Automotive electric generator systems. A review," in *Proc.of ELECTROMOTION'99*, vol. 1, Patras, Greece, 1999, pp. 7–19.
[Bu 12] Bu, F., Huang, W., Hu, Y., Shi, J., and Shi, K., "A Stand-Alone Dual Stator-Winding Induction Generator Variable Frequency AC Power System," *IEEE Transaction on Power Electronics*, vol. 27, no. 1, Jan. 2012, pp. 10-13.
[Bur 90] Burke A.F., "Electric Vehicle Propulsion And Battery Technology 1975-1995", *Proceedings of IECEC-90*, vol. 6, pp. 119 –135.
[Car96a] F. Caricchi, F. Crescimbini, O. Honorati, A. Di Napoli, E. Santini E, "Compact wheel direct drive for Evs", *IEEE Industry Applications Magazine,* vol. 2, Nov.-Dec. 1996 , pp.25 –32.
[Car 96b] F. Caricchi, F. Crescimbini, A. Di Napoli, M. Marcheggiani, "Prototype of electric vehicle drive with twin water-cooled wheel direct drive motors", *Proceedings of PESC '96*, pp. 1926 -1932 vol.2.
[Car94] Caricchi, F.; Crescimbini, F.; Fedeli, E.; Noioa, G. "Design and construction of a wheel-directly-coupled axial-flux PM motor prototype for Evs", *Record of IAS,* 1994, pp. 254-261 vol.1.
[Cav 01] Cavagnino, A., Lazzari, M., Profumo, F., Tenconi, A., 2001. „A Comparison Between the Axial flux and the Radial-flux Structures for PM Synchronous Motors," *Proc. of 36th IAS*, pp. 1611-1618.
[Caw 01] W. Cawthorne, P. Famoury, and N. Clark, "Integrated design of linear alternator/engine system for HEV auxiliary power unit," *Conf. Record IEEE-IEMDC*,2001, pp. 267–274.
[Cha 01] C. C. Chan and K. T. Chau, "Modern Electric Vehicle Technology", Oxford, U.K.: Oxford Univ. Press, 2001
[Cha 08]K.T. Chau, C.C. Chan, C. Liu, "Overview of PM brushless drives for electric and hybrid electric vehicles", *IEEE Tran. on IE*, vol. 55, no. 6, June 2008, pp. 2246-2257.
[Che 13] Chen, W.L., and Xie, C.Z., "Active Voltage and Frequency Regulator Design for a Wind-Driven Induction Generator to Alleviate Transient Impacts on Power Grid," *IEEE Trans. Ind. Electron.*, vol. 60, no. 8, Aug. 2013, pp. 3165-3175.
[Che 14] H.S.Che, E. Levi, M. Jones, M.J. Duran, W.P. Hew, N. Rahim, "Operation of a Six-Phase Induction Machine Using Series-Connected Machine-Side Converters," *IEEE Trans. on Ind. Electron.*, vol. 61, no. 1, 2014, pp. 164-176.
[Chi 08] ChittiBabu, B., Mohanty, K.B., and Poongothai, C., "Performance of Double-Output Induction Generator for Wind Energy Conversion Systems", *Emerging Trends in Engineering and Technology*, July 2008, Nagpur, Maharashtra, India, ISBN 978-0-7695-3267-7, pp. 933-938.
[Chi 98] A. Chiba, T. Fukao, "Optimal design of rotor circuits in induction type bearingless motors", *IEEE Trans. on Magnetics*, Vol. 34, No. 4, 1998 pp. 2108 – 2110.
[Com 03] M.Comanescu, A. Keyhani, M. Dai, "Design and analysis of 42-V Permanent-Magnet Generator for Automotive Applications", *IEEE Trans. on EC*, Vol. 18, No.1, March 2003, pp. 107 - 112.
[Cor 09] V. Coroban-Schramel, "BEGA - as a Starter/Generator with Vector Control", PhD Thesis, UPT, Timisoara, 2009
[Cor 11] V. Coroban-Schramel, I. Boldea, G.D. Andreescu, F. Blaabjerg, "Active-Flux-Based Motion-Sensorless Vector Control of Biaxial Excitation Generator/Motor for Automobiles", *IEEE Trans. IA* vol. 47, no. 2, 2011, pp. 812-619.
[Cos 03] A. Cosic, J. Lindback,W. M. Arshald, M. leksell, P. Thelin, and E. Nordlund, "Aplication of a free-piston generator in a series hybrid vehicle," *Proc. of LDIA 2003*, Birmingham, U.K.
[Cro 02] J. Cros and Ph. Viarouge, "Synthesis of high performance PM motors with concentrated windings", *IEEE Transactions on energy conversion*, Vol. 17, No. 2, June 2002, pp. 248-253.
[Ehs 05] M. Ehsani, Y. Gao, S. E. Gay, and A. Emadi, "Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design", Boca Raton, FL: CRC Press, 2005.
[Ehs 97] M. Ehsani, K. M. Rahman, and H. A. Toliyat, "Propulsion system design of electric and hybrid vehicles," *IEEE Trans. Ind. Electron.*, vol. 44, no. 1, pp. 19–27, Feb. 1997
[Fai 01] JawadFaiza and Mohammad B. B. Sharifianb, "Optimal design of three phase induction motors and their comparison with a typical industrial motor", *Computers& Electrical Engineering*, Vol. 27, No. 2, 2001, pp. 133-144
[Fan 09] L. Fang; B.H. Lee, J.-Pyo Hong; H. Nam, "Rotor saliency improved structural design for cost reduction in single-phase line-start permanent magnet motor", *Record of IEEE ICCE 2009*, pp. 139-146.
[Fat 06] M. Fatu, I. Boldea, C. Lascu, L. Tutelea, G.D. Andreescu, "Motion sensorless variable speed PMSG control at power grid", *Proc. of the 10th OPTIM*, VOL III, pp. 9-16.
[Fat 07a] Marius Fatu, Lucian Tutelea, Ion Boldea, Remus Teodorescu, "Novel motion sensorless control of standalone permanent magnet synchronous generator (PMSG): harmonics and negative sequence voltage compensation under nonlinear load", *Proc. of EPE 2007*.
[Fat 07b] Marius Fatu, L. Tutelea, R. Teodorescu, F.Blaabjerg, I.Boldea, "Motion Sensorless Bidirectional PWM Converter Control with Seamless Switching from Power Grid to Stand Alone and Back", *PESC 2007*, pp. 1239-1244;.
[Gao 06] Gao Y. and Ehsani M., "A Torque and Speed Coupling Hybrid Drive train-Architecture, Control and Simulation", *IEEE Transaction on Power Electronics*, vol. 21, no. 3, May, pp. 741-748, 2006
[Gie 04] Gieras, J. F., Wang, R-J., Kamper, M. J., 2004. „Axial-flux Permanent Magnet Machines," *Dordrecht: Kluwer Academic Publishers*, p. 340.
[Gra 08] V. Grădinaru, L. Tutelea, I. Boldea, "25 kW, 15 krpm, 6/4 PMSM: Optimal Design", *Proc of OPTIM*, 2008, VOL I, pp. 249- 256.

[Gra 11] V. Gradinaru, L. Tutelea, I. Boldea, “Hybrid analytical/FEM optimization design of SPMSM for refrigerator compressor loads”, *Proc. of Electromotion Joint Conference (ACEMP)*, 2011 International Aegean Conference on, Istanbul, 2011, pp. 657 – 662.
[Gut 05] H. M. Gutierrez and P. I. Ro, “Magnetic servo levitation by sliding-mode control of no affine systems with algebraic input invariability,” *IEEE Trans. Ind. Electron.*, vol. 52, no. 5, pp. 1449–1455, Oct. 2005.
[Ham 09] Hamadou G. B., Masmoudi As., Abdennadher I., and Masmoudi Ah., “Design of a Single-Stator Dual-Rotor Permanent-Magnet Machine”, *IEEE Trans. on Magnetics*, vol. 45, No. 1, January, 2009, pp. 127-132
[Ham 94] Essam S. Hamdi, “Design of small electrical Machines”, John Wily & Sons 1994.
[Har 95] A. Harson, P.H. Mellor, D. Howe, “Design considerations for induction machines for electric vehicle drives”, *Electrical Machines and Drives*, 1995. pp.16 –20.
[Hau 04] Randy L.Haupt, Sue Ellen Haupt, “Practical Genetic Algorithms –second edition”, John Wiley & Sons, New Jersy, 2004.
[Hei 98] Siegfried Heier, "Grid Integration of Wind Energy Conversion Systems," John Wiley & Sons Ltd, 1998, ISBN 0-471-97143-X
[Hen 94] G. Henneberger, “Improvement of the output performance of the claw-pole alternators by additional permanent magnets,” *Proc. of ICEM’94*, Paris, France, 1994
[Ho 08a] Siu-Lau Ho, ShiyouYang, “A Computationally Efficient Vector Optimizer Using Ant Colony Optimizations Algorithm for Multobjective Designs”, *IEEE Trans on Magnetics*, Vol. 44, No. 6, June 2008, pp. 1034-1037.
[Ho 08b] S.L.Ho, Shiyou Yang, and Guangzheng Ni, “Incorporating A Priori Preferences in a Vector PSO Algorithmto Find Arbitrary Fractions of the Pareto Front of Multiobjective Design Problems”, *IEEE Trans. on Magnetics*, Vol. 44, No.6, 2008, pp.1038-1041.
[Ho 08c] Jang-Ho Seo, Chang-Hwan Im, Sang-YeopKwak, Cheol-Gyun Lee, Hyun-Kyo Jung , “An Improved Particle Swarm Optimization Algorithm Mimicking Territorial Dispute Between Groups for Multimodal Function Optimization Problems”, *IEEE Trans. On Magnetics*, Vol. 44, No.6, June 2008, 1046-1049.
[Ho 08d] S.L.Ho, Shiyou Yang, Guangzheng Ni, K.W.E.Cheng, “An Efficient Tabu Search Algorithm for Robust Solutions of Electromagnetic Design Problems”, *IEEE Trans. On Magnetics*, Vol. 44, No.6, June 2008, pp. 1042-1045.
[Hoo 61] R.Hooke, T.A.Jeeves, “Direct search solution of numerical and statistical problems”, *Journal of ACM*, Vol. 8, No. 2, pp212-229, 1961.
[Iep 08] L.I. Iepture, L. Tutelea, I. Boldea, “FEM analysis and control of a tapered airgap single phase PMSM”, *Proc. of 11thOPTIM*, 2008, Vol I, pp. 241-248.
[Ile 05] D. Iles-Klumpner, “Automotive Permanent Magnet Brushless Actuation Technologies”, PHD Thesis, Dept. Elect. Eng., Polytechnic University of Timisoara, 2005.
[Ili 06] G. Iliescu, L. Tutelea, I. Boldea, “Performance of a Single-Phase Self-Starting PM Brushless Motor Fed by a Chopper-Controlled Current-Source Thyristor Inverter”, *OPTIM 2006*.
[Isf 13a] A.S. Isfanuti, M. Baba, L. Tutelea, A. Moldovan, I. Boldea, “Surface NdFeB versus Ferrite IPM motor drive for low power (100W to 2000W) applications: FEM embedded optimal design with full step torque response validation in sensorless vector control”, *39th IECON, Vienna 2013*, pp. 3177-3182.
[Isf 13b] A. Isfanuti, L. Tutelea, S. Agarlita, I. Boldea, “NdFeB Versus Ferite IPM Motor For Automotive A.C. Comprssor Electric Driving: Modeling and FEM-Embeded Optimal Design”, *Journal of electrical engineering*, vol. 13 no. 3 / 2013, pp. 263-270.
[Isf 14] A.S. Isfanuti, L.N. Tutelea, F.J.H. Kalluf, I. Boldea, “A novel design of stator Ferrite PM single phase doubly salient small motor: FEM characterization and controlled dynamics”, *OPTIM 2014*, pp. 284-290.
[Jab 90] Jabri, A.K.A., and Alolah, A.I., “Limits on the performance of the three-phase self-excited induction generators,” *IEEE Tran.on Energy Conversion*, vol. 5, no. 2, Jun. 1990, pp. 350–356
[Jah 00] Jahns, T.M., “Component rating requirements for wide constant power operation of interior PM synchronous machine drives”, *Industry Applications Conference*, 2000. Conference Record of the 2000 IEEE Vol. 3, 8-12 Oct. 2000, pp. 1697 – 1704.
[Kal 10] F.J.H.Kalluf, C. Pompermaier, M. V. Ferreira da Luz, N. Sadowski, “Braking torque analysis of the single phase line-start permanent magnet synchronous motor”, *Record of ICEM-2010*, Roma Italy.
[Kal 12] F. Kalluf, A. Espindola, L. Tutelea, I. Boldea, “2/4 POLES split phase capacitor motor for small compressors: a comprehensive characterization”, *Procof ECCE*, 2012, pp. 158-165.
[Kal 14] F.J.H. Kalluf, L.N. Tutelea, I. Boldea, A. Espindola, “2/4-POLE Split-Phase Capacitor Motor for Small Compressors: A Comprehensive Motor Characterization”, *IEEE Trans. on IA*, 2014, Vol. 50, No.1, pp. 356-363.
[Kan 07] G.-H. Kang, Y.-D.Son, and G.-T. Kim, “A Novel Cogging Torque Reduction Method for Interior Type Permanent Magnet Motor”, *IAS*, Sept. 2007, pp. 199-125.
[Kas 96] G. Kassakian, H. C. Wolf, J. M. Miller, C. J. Hurton, “Automotive electrical systems circa 2005,” *IEEE Spectr.*, vol. 33, pp. 22–27, Aug. 1996.
[Kim 05] Jae-Woo Kim, Byung-Taek Kim, Byung Il Kwon, “Optimal stator slot design of inverter-fed induction motor in consideration of harmonic losses”, *IEEE Trans. on Magnetics*, Vol. 41, No. 5, 2005, pp. 2012 – 2015.
[Kiy 12] K. Kiyota, A. Chiba, “Design of switched reluctance motor competitive to 60kW IPMSM in third generation HEV”, *IEEE Trans.*, vol. IA-48, no.6, 2012, pp. 2303 – 2309;
[Kur 04] K. Kurihara, M.A. Rahman, “High-efficiency line-start interior permanent-magnet synchronous motors”, *IEEE Trans. on IA*, vol. 40, no. 3, 2004, pp. 789-796.
[Kur 10] K. Kurihara, T. Kubota, M. Hori, “Steady-State and Transient Performance Analysis for a Single-Phase Capacitor-Run Permanent-Magnet Motor With Skewed Rotor Slots”, *IEEE Trans. on IE*, vol. 57, no. 1, 2010, pp. 44-51.
[Law 94] J.D. Law, A. Chertok, T.A. Lipo, “Design and performance of field regulated reluctance machine”, *IEEE Trans. On Industry Applications*, IA-30, No. 5, 1994, pp. 1185-1192.
[Lei 09] Gang Lei_, K. R. Shao_, YouguangGuo_, Jianguo Zhu_, and J. D. Lavers, “Improved Sequential Optimization Method for High Dimensional Electromagnetic Device Optimization”, *IEEE Trans. On Magnetics*, Vol. 45, No. 10, October 2009, pp. 3993-3996.
[Li 05] X. Li, R. Du, B. Denkena, and J. Imiela, “Tool breakage monitoring using motor current signals for machine tools with linear motors,” *IEEE Trans. Ind. Electron.*, vol. 52, no. 5, pp. 1403–1408, Oct. 2005.
[Liu 05] Z. Z. Liu, F. L. Luo, and M. A. Rahman, “Robust and precision motion control system of linear-motor direct drive for high-speed X–Y table positioning mechanism,” *IEEE Trans. Ind. Electron.*, vol. 52, no. 5, pp. 1357–1363, Oct. 2005.
[Liu 91] P. Liutard, P. Brissonneau, Ch. Chillet, A. Foggia, “Preliminary Investigations in High Speed Electrical Machine Design”, *International conference on the evolution and modern aspect of synchronous machine*, part 3, Zurich 1991, pp. 840-844.
[Lov 02] E.C. Lovelace et all, “Design and experimental verification of a direct-drive interior PM synchronous machine using a saturable lumped-parameter model”, 2002, *Record of the 37th IAS Annual Meeting. Conference*, Vol. 4, 13 – 18 Oct.2002, pp: 2486 - 2492.
[Mad 98] G. Madescu, I. Boldea, T.J.E. Miller, “The optimal lamination approach to induction, machine design global optimization”, *IEEE Trans. IA*, Vol. 34 No.3, 1998,422-428.
[Mar 99] MarignettiF., and Scarano M., “An Axial-flux PM Motor Wheel”, *Proc. Electromotion ’99*, July, 1999, Patras, Greece, pp. 1-6.
[Mil 06] J. M. Miller, “Hybrid electric vehicle propulsion system architectures of the e-CVT type,” *IEEE Trans. PE*, vol. 21, no. 3, 2006, pp.756–767.
[Miz 94] Mizuno, Takyuki, C. O. Kabushiki, and K. Meidensha, “Hybrid excitation type permanent magnet synchronous motor,” European Patent Application 941056335, Dec. 4, 1994.
[Mor 29] W.J. Morril, “The revolving – field theory of the capacitor motor, *Trans. AIEG,* April, 1929, pp. 614-637.

[Mue 03] M. A. Mueller, N. J. Baker, P. R. M. Brooking, and J. Xiang, "Low speed linear electrical generators for renewable energy applications," *Proc. of 4th LDIA 2003*, Birminghan, U.K, pp. 29–32.
[Mul 94] Muljadi, E., and Lipo, T.A., "Series compensated PWM inverter with battery supply applied to an isolated induction generator," *IEEE Tran.on Industry Applications*, vol. 30, no. 4, Jul./Aug. 1994, pp. 1073–1082.
[Mun00] Munk-Nielsen S, Tutelea L.N., Jæger U., "Simulation with Ideal Switch Models Combined with Measured Loss Data Provides a Good Estimate of Power Loss", *IAS 2000*, CD-ROM Paper 67.04.pdf.
[Mun 07] N. Muntean, L. Tutelea, I. Boldea, "A Modified Carrier – Based PWM Modulation Technique in Z - Source Inverters", *Proceedings of ACEMP*, 2007, pp. 174-180
[Mun 12] A. Munteanu, I. Boldea, L. Tutelea, "Novel hybrid design methodology for a surface permanent magnet synchronous motor", *SPEEDAM, 2012*, pp. 603 – 608.
[Nei 96] P. Neittaanmarki, M.Rudnicki, A. Savini, "Inverse Problems and Optimal Design in electricity and magnetism", Clarendon Press Oxford 1996, ISBN 0-19-859383-X
[Nou 11] Nouali, S., and Ouali, A.,"Multi-Layer neural network for sensorless MPPT control for Wind Energy Conversion System using Doubly Fed Twin Stator Induction Generator", *Systems Signal and Devices, 8th International Conference on, 2011*, Sousse, ISBN 978-1-4577-0413-0, pp. 7.
[Ojo 00] O. Ojo, I. E. Davidson, "PWM-VSI inverter-assisted stand-alone dual stator winding induction generator", *IEEE Trans. on IA*, Vol. 36, No. 6, 2000, pp. 1604-1611
[Ost 89] V.Ostovic, "Dynamics of Saturated Electric Machines", Springer-Verlag, 1989.
[Pan 03] Panda, D., and Lipo, T.A., "Reduced switch count double converter fed wound rotor induction machine drive for wind energy application", *Electric Machines and Drives Conference*, June 2003, vol.3, ISBN 0-7803-7817-2, pp. 1924-1931.
[Par 01] K. Park, E. P. Hong, and K. H. Lee, "Development of a linear motor for compressors of household refrigerators," in *Proc. Rec. LDIA*, 2001,
[Pat 94] D. Patterson, R.Spee, "The design and development of an axial flux permanent magnet brushless DC motor for wheel drive in a solar powered vehicle", *IAS '94,* vol. 1, pp. 188 -195.
[Pat97] Patterson, D.J. "High efficiency permanent magnet drive systems for electric vehicles", *IECON 97*, Vol. 2, pp.391-396.
[Pen 03a] F. Z. Peng " Z-Source Inverter", *IEEE Trans. Ind. Appl.*, vol. 39, March-April 2003, pp. 504-510.
[Pen 03b] F. Z. Peng, X. Yuan, X. Fang and Z. Qian "Z-Source Inverter for Adjustable Speed Drives", *IEEE Trans. Power Electr.* Letters, vol. 1,No. 2, June 2003, pp. 33-35.
[Per 04] D. J. Perreault and V. Caliskan, "Automotive power generation and control, *IEEE Trans. on PE*, vol. 19, no. 3,2004, pp. 618–630.
[Pit 04] C.I. Pitic, L. Tutelea, I. Boldea, F. Blaabjerg, "The PM-assisted reluctance synchronous starter/generator (PM-RSM): Generator experimental characterization", *Proc of 9th International Conference OPTIM*, 2004, pp. 275-282.
[Pit 04] C.I. Pitic, L. Tutelea, I. Boldea, F. Blaabjerg, "The PM-assisted reluctance synchronous starter/generator (PM-RSM): Generator experimental characterization", *Proc. of the 9th OPTIM*, 2004, pp.275-282.
[Pop 06a] M. Popescu, T.J.E. Miller. Mc. Gilp, F.J. Kallut, C. da Silva, L. von Dokonal, "Effect of winding harmonics on the asynchronous torque of a single phase line start PM motor", *IEEE Trans. IA-42*, No. 4, 2006, pp.1014-1023.
[Pop 06b] M. Popescu, T. J. E. Miller, M. I. McGilp, G.Strappazzon, N. Trivillin, R. Santarossa, "Torque Behavior of One-Phase Permanent-Magnet AC Motor", *IEEE Trans.* Vol. EC-21, No 1, 2006, pp. 19-26.
[Pop 07] M. Popescu, C. Rasmussen, T.J.E. Miller, Mc. Gilp, "Effect of mmf harmonics on a single-phase induction motor performance – a unified approach", *Record of IEEE IAS 2007*.
[Pro 96] F. Profumo, Z. Zheng,A. Tenconi, A. "Axial flux machines drives: a new viable solution for electric cars",*IECON'96*, vol.1 pp. 34 -40.
[Pro 97] Profumo F., Zhang Z., and Tenconi A., "Axial flux machine drives, a new viable solution for electric cars", *IEEE Trans. IE*, vol. 44, No. 1, 1997, pp. 39-45
[Qu 03] R. Qu, T.A. Lipo, "Dual-Rotor, Radial Flux Toroidally-Wound, Permanent-Magnet Machines, *IEEE Trans. on IA*, vol. 39, no. 6, 2003, pp. 1665-1673
[Rah 12] M.A. Rahman, A.M. Osheiba, K. Kurihara, M.A. Jabbar, H. W. Ping, K. Wang, H.M. Zubayer, "Advances on Single-Phase Line-Start High Efficiency Interior Permanent Magnet Motors", *IEEE Trans. on IE*, vol. 59, no.3, 2012, pp.1333-1345.
[Rai 02] A.Raie, V. Raschtchi, "Accurate identification of parameters, in winding function model of induction motor, using genetic algorithm", *SICE Proc. 2002* Aug. 5-7, Osaka, pp. 2430-2434.
[Rao 96] Singiresu S. Rao, "Engineering Optimization: Theory and Practice, 3rd Edition", John Wiley & Sons, 1996.
[Riv 12] J. A. Riveros, A. G. Yepes, F. Barrero, J. Doval-Gandoy, B. Bogado, O. Lopez, M. Jones, E. Levi, "Parameter Identification of Multiphase Induction Machines With Distributed Windings—Part 2:Time-Domain Techniques", *IEEE Trans. EC*, Vol. 27, N4. 4, Dec. 2012, pp. 1067-1077.
[Rou88] O. Roubiček, Z. Pejšek, O. Podzimek, „Progress in the development of electric linear drives intend ended for technological applications" *EMAS, 1988*, vol. 14, no. 2, pp 73-81.
[San 09] E.Peralta-Sanchez, A.C. Smith, "Line-Start Permanent-Magnet Machines Using a Canned Rotor", *IEEE Trans. on IA*, vol. 45, no. 3, 2009, pp. 903-910.
[Sas 71] V. V. Sastry, P. S. Rao, P.V. Rao, "Improved Tow-Speed single-Winding Single-Phase Induction Motors", *IEEE Trans*., Vol. PAS-90, No.3 , 1971, pp.1355-1366.
[Scr 04] S. Scridon, I. Boldea, L. Tutelea, F. Blabjerg, E. Ritchie, "BEGA – A biaxial excitation generator for automobiles comprehensive characterization and test results", *IAS 2004*, vol. , pp. 1682-1690.
[Scr 05] S. Scridon, I. Boldea, L. Tutelea, F. Blabjerg, E. Ritchie, "BEGA – A biaxial excitation generator for automobiles comprehensive characterization and test results", *IEEE IA*, vol. 4, no. 4, pp. 935-944.
[Seo 08] J.H.Seo, C.H.Im, S.Y.Kwak, C. G. Lee, H. K. Jung, "An Improved Particle Swarm Optimization Algorithm Mimicking Territorial Dispute Between Groups for Multimodal Function Optimization Problems", *IEEE Trans on Magnetics*, Vol. 44, No. 6, June 2008, pp. 1046-1049.
[Ser 06] I. Serban G.D. Andreescu, L. Tutelea, C. Lascu, I. Boldea, Frede Blaabjerg, "New State Observers and Sensorless Control of Wound Rotor Induction Generator (WRIG) at Power Grid with Experimental Characterization", Proc. of 32nd IECON 2006, Paris, 2006.
[Shi 06] H. J. Shieh, F. J. Lin, P. K. Huang, and L. T. Teng, "Adaptive displacement control with hysteresis modeling for piezoactuated positioning mechanism," *IEEE Trans. Ind. Electron.*, vol. 53, no. 3, pp. 905–914, Jun. 2006.
[Sil 05] V.C. Silva, S.I. Nabeta, M.A.M Afonso, J.R. Cardoso, "Axial flux concentration technique applied to the design of permanent magnet motors: theoretical aspects and their numerical and experimental validation", *Proc. of EMDC*, 2005 pp.1988-1994.
[Son 07] ShimpeiSonoda,Yasuhito Takahashi, Kenji Kawagishi,Naoki Nishida, and Shinji Wakao, "Application of Stepwise Multiple Regression to Design Optimization of Electric Machine", *IEEE Trans. On Magnetics*, Vol. 43, No. 4, April 2007, pp. 1609-1612
[Sti 08] A. Stirban, L. Tutelea, D. Iles-Klumpner, I. Boldea, "FEM analysis of concentrated coils nonuniform slot (6+6/8) IPMSM fed with trapezoidal current", *Proc. of 11thOPTIM*, 2008. Vol I, pp, 45-52.
[Sti 10] A. Stirban, "Low cogging torque PMSM drives with rectangular current control", Ph.D. dissertation, Dept. Elect. Eng., Polytechnic University of Timisoara, 2010.
[Syv 96] C. D. Syverson, "Hybrid alternator with voltage regulator," U.S. Patent 5 502 368, Mar. 26, 1996.
[Tah 04] Tahri Y., Sahbi M., Masmoudi A., and Elantably A., "A new electromechanical concept for hybrid power trains", *Int. J. Appl. Electromagn. Mech.*, vol. 19, no. 1-4, 2004, pp. 625-629

[Ter 03]T. Teratani, K. Kuramochi, H. Nakao, T. Tachibana, K. Yagi, and S. Abou, "Development of toyota hybrid system (THS-M) with 42V powernet," in *Proc. IEMDC*, vol. 1, Madison, 2003, pp. 3–10.
[Ter 97] M. Terashima, T. Ashikaga, T. Mizuno, K. Natori, N. Fujiwara, and M. Yada, "Novel motors and controllers for high-performance electric vehicle with four in-wheel motors," *IEEE Trans. Ind. Electron.*, vol. 44, no. 1, pp. 28–38, Feb. 1997.
[Tut 00] L. Tutelea, E. Ritchie, I. Boldea, "Design of induction machine with external rotor for flywheel", *Proceedings of NORPIE*, 13-16 June 2000, Aalborg, Denmark, ISBN 87-89179-29-3, pp. 251-256.
[Tut 01a] L.Tutelea, E.Ritchie, I. Boldea, "Induction machine design with and without mechanical transmission for electrical vehicle drives", *4th ELECTROMOTION'01*, Bologna, 2001, pp. 275-280.
[Tut 01b] L.N. Tutelea, E. Ritchie, "Modelling and Simulation of Four Wheel Drive System for Electric Vehicle Using Induction Machine",*Proc. of EPE '01*. Graz, Austria.
[Tut 01c] L. Tutelea, E. Ftitchie, I. Boldea, "Permanent Magnet in-wheel Synchronous Motor for Electric Vehicle", *ICEMS 2001*, pp. 831-834.
[Tut 02] L.Tutelea, E.Ritchie, I. Boldea, "Comparative Performance of Induction and Synchronous Permanent Magnet Machine for Electric Vehicle Drives", *Proc of OPTIM 2002*, Brasov, pp.
[Tut 05] L. Tutelea, M. C. Kim, Y.-D. Chun, T. H. Kim, S.-B.Lim, J. S. Ahn, J. Lee, I. Boldea, "A Set of Experiments to More Fully Characterize Linear PM Oscillatory Machines", *IEEE Trans.On Magnetics*, Vol. 41, No. 10, 2005, pp. 4009-4011.
[Tut 07] L. Tutelea, I. Boldea, "Optimal Design of Residential Brushless d.c. Permanent Magnet Motors with FEM Validation", *Proceedings of ACEMP*, 2007, pp. 435-439.
[Tut 08] L. N. Tutelea, M. C. Kim, M. Topor, J. Lee, I. Boldea, "Linear Permanent Magnet Oscillatory Machine: Comprehensive Modeling for Transients with Validation by Experiments", *IEEE IE*, Vol. 55, N0. 2, 2008, pp. 493-500.
[Tut 10a] L. Tutelea, I. Boldea, "Surface Permanent Magnet Synchronous Motor Optimization Design: Hooke Jeeves Method Versus Genetic Algorithms", *Proc of IEEE ISIE 2010*, pp. 1504-1509.
[Tut 10b] L. Tutelea, I. Boldea, "Induction Motor Electromagnetic Design Optimization: Hooke Jeeves Method Versus Genetic Algorithms", *Proc of. OPTIM 2010*, PTS I-IV, 2010, pp. 485-492.
[Tut 11a] L.N. Tutelea, S.I. Deaconu, I. Boldea, F. Marignetti, G.N. Popa, "Design and Control of a Single Stator Dual PM Rotors Axial Synchronous Machine for Hybrid Electric Vehicles, *EPE 2011*, Birminghan, UK, 10 pp. 1-10.pp. 283–286.
[Tut 11b] L.N. Tutelea, S.I. Deaconu, I. Boldea, F. Marignetti, G.N. Popa, "Quasi-3D FEM Analysis of an Single Stator dual PM Rotors Axial Electric Vehicles", *Electrimacs 2011*, 2011, Cergy-Pontoise, France.
[Tut 12a] L. Tutelea, D. Ursu, I. Boldea, "IPM claw pole alternator system for more vehicle breaking energy recuperation", www.jee.ro, JEE Vol. 12, no. 4, 2012.
[Tut 12b] L.N. Tutelea, I. Boldea, S.I. Deaconu, "The Single Stator Dual Rotor PMSM for HEV: Two Windings and 4 Leg Inverter Control", *15thEPE/PEMC*, Novi-Sad, 2012, pp. DS3a.1-1- DS3a.1-6.
[Tut 12c] L.N. Tutelea, S.I. Deaconu, I. Boldea, "Design and FEM validation for an axial Single Stator Dual Rotor PMSM", IECON 2012-*38th Annual Conference on IEEE Industrial Electronics Society*, Montreal, 2012, pp. 2929 – 2935.
[Tut 12d] L.N. Tutelea, I.Boldea, S.I. Deaconu, "Optimal design of dual rotor single stator PMSM drive for automobiles", Rec. of *IEVC 2012*, pp.1-8.
[Tut 13a] L.N. Tutelea, S.I. Deaconu,N. Budisan, I. Boldea, "Double stator winding induction generator for wind and hydro applications: 2D-FEM analysis and optimal design", *Proc. of 15yh EPE 2013*, Lille 2013, pp. 1-10.
[Tut 13b] L.N. Tutelea, S.I. Deaconu, I. Boldea, N. Budisan, "Design, Control and 2D-FEM Validation for an Double Stator Winding Induction Generator", *Proc of. 39th IECON 2013*, Vienna, pp. 2732-2737.
[Tut 14a] L.N. Tutelea, I. Boldea, S. I. Deaconu, "Parameter optimal identification of dual three phase stator winding induction machine", *Proc. of OPTIM 2014*, pp. 231-238.
[Tut 14b] L. Tutelea, A. Popa Moldovan; I. Boldea, "50/100 kW, 1350–7000 rpm (600 Nm peak torque, 40 kg) PM assisted Reluctance synchronous machine: Optimal design with FEM validation and vector control", *Proc. of OPTIM, 2014*, pp. 276-283.
[Tut 14c] L. N. Tutelea, I. Boldea, N. Muntean, S. I. Deaconu, "Modeling and Performance of Novel Scheme Dual Winding Cage Rotor Variable Speed Induction Generator with dc Link Power Delivery", *Proc. of ECCE 2014*.
[Tut 14d] L. N. Tutelea, S. I. Deaconu, G. N. Popa, "Reduced Cost Low Speed Wind or Hydro Energy Conversion System with Twin Stator Windings Induction Generator", *Proc. of 16th PEMC* , Antalya, Turkey, 2014, pp. 404-411.
[Tut 14e] L. N. Tutelea, S. I. Deaconu,, I. Boldea, "Optimal Design of DC Excited Synchronous Generator for Large Direct Drive Wind Turbine", *Intermag*, Dresda 2014, pp. EP04.
[Tut 98] L. Tutelea, I. Boldea, E.A. Ritchie, P. Sandholdt, F. Blaabjerg, "Thermal testing for inverter-fed induction machines using mixed frequency method", *Proceedings of ICEM'98*, Istanbul,Turkey, 1998,pp. 248-253.
[Tut 99] L.N. Tutelea, E.A. Ritchie, "Electric Drive Systems for Uninterruptible Power Supply, using Flywheel Energy Store: Feasibility Study and Preliminary Design Exercise", Aalborg Universitetsforlag, I14 98 S 0095, 1999.
[Urs 13] D. Ursu, L. Tutelea, I. Boldea, "Proposal with 2D FEM analysis of a six phase, 12 poles, 3kW, 200 rpm BLDC multiphase reluctance machine wind generator", *Power Electronics and Applications (EPE)*, 2013 15th European Conference on, Lille 2013, pp. 1-9.
[Urs 14a] D. Ursu, "Brushless DC Multiphase Reluctance Machines and Drives", Ph.D thesis, Politehnica Timisoara University, Timisoara 2014.
[Urs 14b] D. Ursu, P. Shamsi, B. Fahimi, I. Boldea, "5 phase BLDC-MRM: Design, Control, FEA and Steady-State Operation Experiments", *OPTIM Brasov, 2014*, pp. 354-361.
[US 14] U.S. Energy Information Administration / Monthly Energy Review September 2014.
[Vag 00] A. Vagati et al., "Comparisons of ac motor based drives for electric vehicle applications" *Record of IEEE IAS 2000*, pp. 1460 – 1463.
[Vet 96] W.Vetter, A. Colotti, K. Reichert, "A new motor/generator for flywheel applications", *ICEM'96 Vigo*, Spain, vol. II, pp.348-352.
[Vuk 13] S.N. Vukosavic, "Electrical Machines", Springer, New York 2013.
[Wan 05] Wang, D., Ma, W., Xiao, F., Zhang, B., Liu, D., and Hu, A.,"A Novel Stand-Alone Dual Stator-Winding Induction Generator With Static Excitation Regulation", *IEEE Trans. on EC*, vol. 20, no. 4, December 2005, pp. 826-835.
[Weh 86 a] R. Mayer, H. Mosebach, U. Schroder, H. Weh, "Inverter-fed multiphase reluctance machine with reduced armature reaction and improved power density", *Proc. of ICEM 1986*, Munchen, Part 3, pp. 1138-1141
[Wen 06] Wen Ouyang; Zarko, D. Lipo, T.A., "Permanent Magnet Machine Design Practice and Optimization", *Record of 41th IAS 2006,* Vol. 4, pp.1905 – 1911.
[Wia 98] Albert Wiart, "Motors for high-power, high-speed electrical drives", *2nd ELROMA-82*, 1998, pp. 30-37.
[Wie 98] J.P. Wieczorek, O. Gol, Z. Michalewicz, "An evolutionary algorithm for the optimal design of induction motors", *Magnetics, IEEE Trans. on* Vol. 34, No. 6, 1998 pp. 3882 – 3887.
[Wil 99] S. Williamson, A. C. Smith, "A Unified Approach to the Analysis of Single-Phase Induction Motors", *IEEE Trans.* Vol. IA-35, No. 4, 1999, pp. 837-843.
[Wu 01] Z. Wu; J. Wang; J. Ying; J. Zeng, "Sensorless brushless DC motor drive for air-conditioner compressor", *Record of IEEE-ICEMS 2001*, vol. 2, pp. 968-971.
[Yon 09] Yong Li, Yuwen Hu, Wenxin Huang, Lingshun Liu, and Yong Zhang, "The Capacity Optimization for the Static Excitation Controller of the Dual-Stator-Winding Induction Generator Operating in a Wide Speed Range", *IEEE Trans. on IE*, Vol. 56, No. 2, 2009, pp.530-54.
[Zhe 07] Zheng, P. Liu, R. Thelin, P. Nordlund, E. Sadarangani, C., "Research on the Parameters and Performances of a 4QT Prototype Machine Used for HEV," *IEEE Tras.on Magnetics*, Jan. 2007 Vol. 43 No. 1, pp: 443–446.