DESIGN OF ELECTRIC MACHINES:
Axial Flux Machines
Electric Energy Group in FIGURES

- 20 university researchers involved (9 of them doctors)
- 15 PhD students
- 10 granted full time students
- 10 granted part time students

Long term cooperation with more than 6 leader companies such as: Orona, Ingeteam, Trainelec, ModragonComponentes, Ormazabal, Ikelan.

More than 160 undergraduate and postgraduate students as well as more than 35 professionals from the industry currently studying the following degrees:

- Master in Power Electronics and Energy
- Automatics and Industrial Electronics Engineer
- Master in Electric Energy
- Graduate in Industrial Electronics
- Customized advanced courses in power electronics and drives

Editorial Board

Dr. Gonzalo Abad, coordinator of the master in power electronics and energy and the degree in automatics and industrial electronics engineer.

Dr. Javier Poza, coordinator of drives for traction and electric energy generation applications research line.

Dr. Jon Andoni Barrena, coordinator of power electronic systems for electric energy control research line.

Mr. Jose Maria Canales, coordinator of the energy storage systems research line.

Dr. Igor Baraia, coordinator of the master in electric energy.

Dr. Gaizka Almandoz, coordinator of the electrical machines and control area.

Mr. Aritz Milikua, coordinator of the electronics area.

Mr. Ander Dominguez-Macaya, Magazine Administrator.
Overview of Axial Flux Machines. 

Author: Aritz Egea

1. Background

Investigations in the field of electrical machines have included a wide variety of matters and concepts. The design, the control, or thermal aspects are some examples of commonly studied issues. From the first DC machines to the current leading induction machines, there is no doubt that high level of technological development has been achieved.

Permanent magnet synchronous machines have gained much interest in recent years. The search for more efficient and eco-friendly machines makes this an interesting field of research. Development of new materials and concepts as well as new needs and applications have placed permanent magnet (PM) machines in a prominent position.

The inherent features of PMs, such as high efficiency, high compactness and wide operation speed range, make these machines suitable for direct drive applications. In direct drive applications, the shaft of the machine is directly coupled to the shaft of the application, thus avoiding the gearbox, which leads to more efficient and compact solutions. The high power of current magnet materials may decrease the size of the machine in comparison with the classic induction machines. Furthermore, PM machines have a magnetized motor, so that the consumption of electrical energy is decreased. These machines are able to work at low speed, which is very interesting for direct drive low speed applications; however, high speeds are also reachable, giving the PM machine a wide speed range. However, the capability of flux weakening is not as good as in induction machines.

Depending on the direction of the flux through the air gap, PM machines are divided in three main groups: radial, transversal, and axial flux machines (Figure 1-1).

Mondragon University (MU) has been researching topics in electrical machines for years, in both industrial projects and PhD theses. Some of these theses were related to radial flux permanent magnet machines for elevation applications. One of the latest PhD thesis is focused on the design of axial flux machines.

Figure 1-1: Permanent magnet synchronous machines a) radial b) axial and c) transversal [1]
2. History of the Axial Machine

From the beginning, human beings have developed systems to take advantage of the power in nature. For example, after the invention of steam and combustion machines, in 1831 Faraday built the first disc generator, which is shown in Figure 1-2-a. This device is considered the first electric generator in history; furthermore, it was based on the axial flux concept. In 1889, Tesla also patented a machine that used the axial flux principle (Figure 1-2-b). However, after the first patent of a radial flux machine in 1937, the axial flux machine was displaced and almost forgotten.

The main reasons, among others, for this neglect were the large attraction forces between the rotor and stator, manufacturing difficulties, and the high cost. Nevertheless, the interest in axial flux machines has increased in recent years because of new materials and manufacturing technologies. Hence, the need for new applications has become a boost for axial flux machines.

Figure 1-2: First machines reported in history [8]: a) disc generator built by Faraday and b) electromagnetic machine with a disc rotor built by Tesla

Figure 1-3: Diagram of axial machine topologies
3. Topologies of Axial Flux Machines

One of the most interesting aspects of axial flux machines is the wide range of topologies they offer. These different options may fit several applications. In [9] a deep study of the different topologies of axial flux machines is done.

As shown in Figure 1-3, axial flux machines are divided into three main groups: single-side machines (Figure 1-4), double side machines (Figure 1-5 and Figure 1-6) and multistage machines (Figure 1-7). In addition, a variety of configurations can be carried out within each group. This constructive flexibility makes axial machines suitable for different applications and optimizable for the specific requirements of each application.

As in radial flux machines, in axial flux machines the winding may be either concentrated or distributed. In the case of concentrated windings, coils are wound around teeth (Figure 1-4), whereas in the case of distributed windings, coils surround more than one tooth. Furthermore, in some machine configurations it is possible to have a toroidal winding. In this case, the coils are wound in the stator, which results in a toroidal shape (Figure 1-6-b).

I. Single Side

This is the simplest topology in the axial flux machines range. This kind of machine consists of a single stator and a single rotor, as shown in Figure 1-4. The stator core may be either slotted (Figure 1-4-a) or slotless (Figure 1-4-b).

![Figure 1-4: Single side machine: a) slotted stator and b) slotless stator](image)

In this configuration, the attraction force exerted by the magnets between the rotor and the stator may be a drawback. The axle and the bearings must withstand this force, so they have to be properly dimensioned.
II. Double Side

Double side machines consist of three elements in two possible configurations:

- Double Stator – Single Rotor: The interior rotor is placed between two stators.
- Single Stator – Double rotor: The interior stator is placed between two rotors.

1) Interior Rotor Axial Flux Machines

In these kinds of machines, an interior rotor is placed between two stators, as shown in Figure 1-5. One of the interesting advantages of this configuration is that the core of the rotor shown in Figure 1-5-a can be avoided to obtain a coreless rotor as shown in Figure 1-5-b. The magnets have to be held in a non-ferromagnetic material to create the rotor structure. In this way, a lighter machine is obtained. It has to be noted that because the rotor is between the two stators and in the case when the distance from the rotor to each stator is equal, the attraction forces are equilibrated, avoiding possible stress in mechanical parts.

![Figure 1-5](image)

*Figure 1-5: Interior rotor machines: a) with ferromagnetic core in the rotor and b) coreless rotor*

Similar to single side machines, the stators can be either slotted or slotless. The electrical connection between the two stators may in series or parallel, taking into account that the characteristics of the machine depend on this connection: that is, higher voltage in a series connection and higher current in a parallel connection.

2) Interior Stator Axial Flux Machines

In this topology, the magnets are usually mounted in a ferromagnetic material to facilitate the magnetic flux flow between adjacent magnets.

There is a wide range of possibilities for the configuration of the stators in these machines. On the one hand, in the configuration known as north-north (N-N), magnets with opposite magnetization direction are placed in front of each other, as shown in Figure 1-6-a-b.
In this configuration, the path of magnet flux is closed along the stator yoke so that the stator core is needed. The winding may be placed surrounding the teeth, as shown in Figure 1-6-a. This figure shows a slotted stator with concentrated one layer winding. However, a toroidal winding with a slotless stator would be also possible, as shown in Figure 1-6-b. The main disadvantage of slotless machines is that the coils take place in the air gap, which increases the effective air gap length.

Another possible configuration is the north-south (N-S) machine. In this case, magnets with the same magnetization direction are placed in front of each other. The magnetic flux passes through the air gap and is then closed through the rotor yoke. Because the path followed by the flux does not use the stator yoke, this part could be avoided, leading to a lighter stator core consisting only of ferromagnetic teeth, as shown in Figure 1-6-c. Moreover, it could even be possible to avoid the whole stator core and place the coils in the air gap as shown in Figure 1-6-d. However, the N-S configuration is not feasible with toroidal windings because both side forces would cancel each other, resulting in a null overall torque.

![a) Interior slotted stator N-N machine with lap winding, b) Interior slotless stator N-N machine toroidal winding, c) Interior ferromagnetic core stator N-S machine, and b) Interior coreless stator N-S machine](image)
III. Multistage

This topology could be defined more accurately as a concept than a type of machine. The idea is to place stators and rotors alternately to obtain a machine with as much sides or stages as desired in order to fulfill the application’s requirements. This configuration offers a quite interesting possibility: modularity. Figure 1-7 shows a multistage axial machine with two stators and three rotors. The connection between the winding of different stages could be done in either series or parallel. Furthermore, a connection/disconnection of stages could be done depending on the temporary requirements of the application. This connection may allow fault tolerance as the machine can keep working even if any of the stages is damaged or disconnected.

![Multistage axial flux machine with two stators and three rotors](image)

*Figure 1-7: Multistage axial flux machine with two stators and three rotors*

4. Suitable Applications for Axial Flux Machines

Throughout history, induction machines have been the most frequently used topologies in common industries. However, in recent years, because of ecological thinking and the rise low-speed applications, permanent magnet synchronous machines have become more popular. Furthermore, the development of new applications, such as electrical vehicles and renewable energy has pushed the development of high-performance, direct-drive electrical machines. The improvement in fabrication techniques and the appearance of new materials have had an important part in this development.

In some of these applications, axial flux machines might be a good choice because of their disk shape, multi stage capability, and characteristic high torque density. These features make axial flux machines a real alternative to classical radial flux machines. In that sense, it is possible to find companies that commercialize axial machines.

Nowadays the majority of applications share the same requirements: high efficiency, saving of space, and economic feasibility, among other characteristics. The role of the electrical machine is of paramount importance in application in general.
Axial flux machines may be used in any kind of application. However, three applications may be the most relevant due to the numbers of documents and amount of research a review of the literature reveals in the search for information about axial flux machines: wind power, electric vehicles, and elevation.

**Figure 1-8: a) EU power capacity 2011 [15] and b) Kestrel e150 wind turbine**

### I. Wind Power

Because it is highly developed and efficient, wind power has become the leading actor among renewable energies. In fact, in some European countries, such as Denmark, Spain, and Portugal, wind power is among the main energy sources (The European Wind Energy Association [EWEA] report 2011). According to the EWEA report, wind power has increased from 2% of the total power capacity in 2000 to 10% in 2011 [15]. Historically the induction machine was widely used in wind turbines, but in recent years the use of permanent magnet synchronous machines has increased [16]. The main reason is that by avoiding mechanical coupling and reducing the size of the machine, the system becomes lighter, more efficient, and maintenance free. Most machines used in wind turbines are radial flux machines, but several researches[17–21]have proposed axial machines. There are also commercial solutions, such as those proposed by Kestrel Wind Turbines Ltd. This company offers a range of axial machines between 600W and 3KW.

### II. Electrical Traction

Among applications of electrical traction, the electrical vehicle stands out. Hybrid vehicles, which combine a combustion engine with an electrical motor, as well as fully electric vehicles, are a fact nowadays, and there are commercial models on the market. It seems that in the future, the trend will be to develop electrical vehicles with in-wheel machines based on the concepts shown in Figure 1-9. This will lead to a very sensitive and precise driving.

However, an axial flux machine has not been used in any known commercial electrical vehicle although several researches have focused on this application[22–28]. For
example, [22] built an in-wheel axial machine prototype for a solar vehicle (Figure 1-10-a). In [28], an axial machine for an hybrid vehicle was presented (Figure 1-10-b). Furthermore, studies have applied flux weakening to axial flux machines, which is an interesting vehicle application. For example, Lipo et al. reviewed different weakening options reported in the literature for both radial and axial machines [27]. In [28], an example of flux weakening used a mechanical system that adjusted the shifting of the two series-connected windings in the stators.

Figure 1-9: a) Traction system concept for an electrical vehicle by Volvo and b) Built-in wheel by Siemens (Radial flux)

Figure 1-10: In-wheel axial flux machine a) solar vehicle [22] and b) hybrid car [28]
Another potential sector that may benefit by the characteristics of the axial flux machine is the elevation industry. In 1992, the Kone Corporation in Finland was a pioneer of launching elevators with a gearless machine. Subsequently, direct-drive technology was developed quickly and most companies have implemented it in their products, choosing the radial flux machine and placing it in different positions.

Figure 1-11 shows how the machine room is avoided by using direct drive technology and consequently saving space and money. Despite these important improvements, some extra space is needed to house the machine. Due to the shape of axial machines, which are flat and wide, they are a good option for saving space. The machine can be integrated with the rails of the elevator as is done in the KoneMonoSpace\textsuperscript{TM} concept, as shown in Figure 1-12. Furthermore, the high torque density of the axial flux machine may reduce their size.

III. Elevation

Figure 1-12: MonoSpace\textsuperscript{TM} elevator by Kone: a) traction system and b) EcoDisc\textsuperscript{TM} machine
Kone currently uses single side axial machines (MonoSpace™) for common buildings and interior rotor machines (Alta™) for skyscrapers, where higher torque and speed are needed. Both machines are shown in Figure 1-13. One of the main differences between these machines is that while the MonoSpace™ machine is integrated with the rails, the Alta™ is placed on the top of the lift shaft.

The literature search yielded only one study[31] in which the axial machine was applied to elevation. In this work, SIMINOR Ascenseurs and a researcher at the University of Rome jointly developed two twin prototypes for a direct-drive elevator system without a machine room. The machines were rated at 5 kW and 95 rpm.

5. References


Patxi Madina Hernández’s PhD Thesis defense

Mondragon 1st February 2012, 11:00 pm, the PhD student Mr. Patxi Madina Hernández from the Polytechnic School of Mondragon University defended her doctoral thesis at the assembly hall of Mondragon Unibertsitatea. The title of the thesis: “Metodología de diseño de motores síncronos de imanes permanentes para aplicaciones ferroviarias” and his supervisors are: Josu Galarza, Javier Poza, obtaining CUM LAUDE grade.

Fretting is the main deterioration reason in metallic cables, which leads to a reduction in the components' lives. The wire interweave structure makes it very complex and expensive for an experimental study. In order to reduce this disadvantage and widen our knowledge over this phenomenon, this thesis has developed a finite element model for the prediction of wear trace and crack initiation for small diameter wires subjected to fretting wear.

A rail orientated permanent magnet machines design development methodology has been developed, an induction motor dominated sector, which is having every year more efficient and compact machines. Permanent magnet machines are suitable for size reduction and efficiency increase.

Court of the thesis:

-Dr. Mr. José Germán Giménez Ortiz (Universidad de Navarra)
-Dr. Mr. José Ignacio del Hoyo Figueras (EHU-UPV)
-Dr. Mr. Miguel Martinez de Iturralde Maiza (CEIT, Universidad de Navarra)
-Dr. Mr. Txomin Nieva Fatela (CAF Power & Automation)
-Dr. Mr. Gaizka Ugalde Rosillo (Mondragon Unibertsitatea)
Mikel Oyarbide Urquizu’s PhD Thesis defense

Mondragon 26th March 2013, 11:00 pm, the PhD student Mr. Mikel Oyarbide Urquizu from the Polytechnic School of Mondragon University defended his doctoral thesis on the Auditorium of the Polo Garaia. The title of the thesis: Development and Implementation of SoC and SoH Estimators for Lithium Based Energy Storage Systems and his supervisor is: Ander Etxeberria, getting CUM LAUDE grade.

Currently, Lithium ion batteries are, by their nature, the best choice of all electrochemical systems for energy storage. However, its use may be dangerous, and, according to latest researches, its duration is entirely related to the conditions in which they are used. Thus, this research is the development of algorithms implementable via online to estimate the state of charge (SoC) and state of health (SoH) of these batteries, so that they can later improve their conditions of use and prolong its life.

Court of the thesis:
- Dr. Mr. Jean Michel Vinassa (Université Bordeaux)
- Dr. Mr. Oscar Miguel Crespo (CIDETEC Foundation)
- Dr. Mr. Ander Goikoetxea Arana (Mondragon Unibertsitatea)
- Dr. Mr. Igor Cantero Uribe-Echeberria (CEGASA)
- Dr. Mr. Jon Andoni Barrena Bruña (Mondragon Unibertsitatea)
The President of Uruguay, José Mujica, visited the University of Mondragon

The president of Uruguay, José Mujica, went to the Corporative Center of MONDRAGON, where he was welcomed by the President of the General Council of the Corporation, Txema Gisasola. The visit was part of an official trip in which the Uruguayan President was exploring new business possibilities for his country.

Visit to Mondragon

The Uruguayan President showed from the beginning a willingness to come to the village to visit MONDRAGON Corporation. Indeed, one of the main interests of José Mujica was to know in detail aspects linked to the field of training, the role played by education in the development of Cooperative Experience and training programs currently offered by Mondragon.

During his visit he proceeded to the signing of a framework agreement on cooperation between the Ministry of Industry, Energy and Mining of Uruguay and the MONDRAGON Corporation, whose main purpose is the exchange of programs and experiences designed to promote Uruguayan cooperative system.

He visited the Electronics department facilities where he was shown various kinds of electronic devices, mostly related to the actual POPBL (Project/Problem Based Learning) students of the master were doing.
The University of Mondragon and the IUT

The past 6 February, MGEP lecturers, Jose Mº Canales, Ander Goikoetxea and Fernando Garramiola traveled to Châteauroux invited by the IUT de l’Indre (Université d’Orléans). During the visit, the International Relationship Department and the Academics from the IUT were presented the uniqueness of the University, the Cooperativism and the Mondragon Group. Afterwards, the academic offer was shown, the POPBL (Problem/Project Based Learning) model and the International Exchange offer.

The next day a talk was given to 60 students from the IUT, in which the University of Mondragon and some semester projects from both undergraduate and postgraduate of the Energy and Power Electronics Master were introduced. Some of the projects were the wire guided robot, the automation of a greenhouse and the control of a wind turbine.

This visit reinforced the relation between MGEP and the IUT from l’indre.

Gaizka Almandoz, Gaizka Ugalde, Javier Poza and Ana Julia Escalada wrote a chapter (8th) of the book “MATLAB, a fundamental tool for scientific computing and engineering applications – Volume 2”

This excellent book represents the second part of three-volumes regarding MATLAB- based applications in almost every branch of science. The present textbook contains a collection of 13 exceptional articles. In particular, the book consists of three sections, the first one is devoted to electronic engineering and computer science, the second is devoted to MATLAB/SIMULINK as a tool for engineering applications, the third one is about Telecommunication and communication systems and the last one discusses MATLAB toolboxes.
Dr. Arturo Mediano’s lecture at the University of Mondragon

The lecture about “EMI/EMC: Electromagnetic Interference in Electronic Systems” was given by Dr. Arturo Mediano last May at the University of Mondragon and lasted 4 hours. The problem of EMI and EMC were first introduced together with a process of design thinking about EMI issues. He then explained how to test EMC, legislation and the importance of that design in high frequency electronics.

Dr. Arturo Mediano’s brief biography

Arturo Medium is Doctor (1997) Industrial Engineer (1990) from the University of Zaragoza, Spain. He is member of the Power Electronics and Microelectronics (MPSG) of the Engineering Research of University Institute of Aragon, University of Zaragoza. He has a solid experience collaboration with industry especially in training and consulting in RF design and design / troubleshooting in Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC). He has given dozens of courses and seminars for industries and institutions in the fields of RF / EMI / EMC in Spain, USA, Switzerland, France, UK, Netherlands and Italy.
WORKSHOP: New Trends on Design and Control of Electrical Machines

The workshop that took place in Polo Garaia had the main objective of giving an insight into technological trends in design and control of electrical machines. New application requirements concerning to cost, size and efficiency, are leading to new challenges for engineers that research on design and control of electrical machines. Due to that, and even though the long-standing market place of industrial electrical machines, they are still key components for modern systems using, producing and transforming electricity. Nowadays they are associated with innovation and they are under major focus in both industry and academia.

Zi-Qiang Zhu, Professor at the University of Sheffield (UK), gave a presentation over viewing technological trends in electrical machines, with particular reference to new and novel machine topologies on permanent magnet (PM) machines and switched/synchronous reluctance machines, including: Novel PM machine topologies, Hybrid excited PM machines which uniquely integrate PM technology into induction machines, switched and synchronous reluctance machines and wound field machines, Variable flux machines and Magnetless machines.

Phil H. Mellor, Professor at the University of Bristol (UK), talked about lumped parameter methods employed in the steady state and transient thermal modeling of high specific output electrical machines. New developments in lumped networks were presented alongside improved models.
for loss calculation. The effectiveness of the method was illustrated through test results and analyses of example electrical machine prototypes designed for electric vehicle and more electric aircraft applications.

Fernando Briz, Professor at the University of Oviedo, talked about the elimination of rotor position/velocity sensors (and cabling) in AC drives, which has long been desired and the methods developed to achieve this goal, commonly referred to as sensorless control. Among the expected benefits of sensorless control are cost and size reduction, as well as increased robustness. Sensorless control techniques for AC machines that rely on the fundamental excitation are capable of providing high performance control in the medium- to high-speed range, but fail in the very low-speed range and/or for position control. Sensorless methods based on tracking the position of saliencies (asymmetries), measure the response of the machine when high-frequency excitation, which is superimposed to the fundamental excitation used for torque production, is applied. These methods have the capability of providing position/speed control in the low-speed range, including zero speed. This presentation is a review of the saliency tracking based methods that have been proposed for the rotor position/speed sensorless control of AC drives.
Master in Power Electronics and Energy

Information:
http://www.mondragon.edu/meep

Professional master in Electric Energy

Information:
Electric Energy Group:

Dr. Gonzalo Abad
Mr. Ibon Ajuria
Dr. Gaizka Almandoz
Mr. Jon Aranguren
Dr. Igor Baraia
Mr. Antonio Barbero
Dr. Jon Andoni Barrena
Mr. José María Canales
Dr. Ander Etxeberria
Mr. Fernando Garramiola
Mr. David Garrido
Dr. Ander Goikoetxea
Mrs. Aitziber Gorostiza
Mr. Aritz Milikua
Dr. Javier Poza
Dr. Gaizka Ugalde
Mr. Josu Fernández
Dr. Aritz Egea
Dr. Patxi Madina

www.mondragon.edu/enele

Loramendi 4, Apdo.23
20500 Mondragón
Gipuzkoa, Spain
Tel. +34 943 79 47 00
Fax +34 943 73 94 10