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A Quantitative Comparison of all Commercially Motor Technologies

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Abstract

In this study we compare all commercially available electrical motors with different technology, including **BLDC**, **PMSM**, **SM**, **IM**, **Brushed DC motors**, **SynRM**, **SRM** and **Axial-Flux** motors. There are numerous suppliers that manufacture electric motors for different applications, however choosing a typical motor for a certain application is not so easy; particularly when customers are dealing with a pile of motor technologies. By comparing of different characteristics of the aforementioned motors, one can easily find which motor can fulfill the requirements subjected to constraints and objectives. These characteristics include size, nominal power, required voltage, nominal torque, number of poles, price and complexity of the motor. Thus, the main objective of this study is to give crystal clear information to customers to have the optimal choice subjected to their objectives and constraints.

Plagiarism Declaration

I understand that all my project work must be my own unaided work. If I make use of material from any other source, I must clearly identify it as such in any interviews, reports or examinations. I understand that my reports must be written unaided in my own words, apart from any quoted material, which I must identify clearly in the correct manner. I understand that the work, which I shall present for assessment, must be work carried out by myself only during the project period, which has not been previously prepared. Where any such previous work is made use of in the project, I shall make this clear in any interviews, reports or examinations. I understand that violation of these conditions may result in a mark of zero for the component or components of assessed work affected.

Parts of this work will be published as a conference paper.

Student number: s0185935

Signature: **Ali Aramesh**

January 2021

Acknowledgements

Firstly, I would like to express my appreciation and thanks to my supervisor, Dr. Stijn Derammelaere. It has been a great honor to work under his supervision as my internship project. Since I had another module entitled vehicle dynamics during the first year of JMDSAE with Dr. Derammelaere, I was quiet sure that I'm gonna see a different level of automotive engineering at the end of my internship project. Despite Covid-19 situation, regular meetings and his valuable advices helped me neither to get lost in the project nor lose any milestone.

I would also like to thank Dr. Jon Garcia-Barruetabeña for his valuable advices for preparing project plan and using management softaware for meeting the targets and milestones. It was really helpful.

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Chapter 1

Different parts of electric motor

1.1 Introduction

If we classify Electric motors, all of them will belong either to concentrated or distributed winding. Concentrated winding are split up in four categories which are brushless direct current motor (BLDCM), stepping motor(SM), Switched reluctance motor(SRM) and Brushed DC motor. Further BLDCM, Brushed DC motor and SM belong to permanent magnet category. On the other hand distributed winding motors contain permanent magnet synchronous machine(PMSM), Induction motor(IM) squirrel cage and Induction motor(IM) with wound rotor, Axial-flux motor and Synchronous reluctance motor (SynRM). In this work which is carried out as the internship project of the European program entitled "Joint Master's Degree in Sustainable Automotive Engineering" different motor technologies are compared quantitatively. The internship project took place in the University of Antwerp. The main objectives of this work contain a quantitative comparison of aforementioned motor technologies. In this study we focus within a range up to 3000 $[W]$. In chapter 2 an overview of motor technology and principle of operation of each technology are explained. In order to make it more comprehensive for the reader each technology followed by it's associated motor cross section. Chapter 3 contains the results of the quantitative comparison for all motor technology in terms of speed, torque, power, motor volume, price and rotor inertia and finally in chapter 4 we conclude and propose future work on different motor technology.

1.2 Project plan

Due to Covid-19 situation, the project was done in a telecommunication way. Meetings were held every two session via team Microsoft. After each meeting I would receive information in order to collect data which was needed for the goal of the project. Further I was given information about the motor technology in a format of PHD thesis which have been done by two other colleagues. During discussion in each meeting for evaluation of delivered job, I would receive some information for overcoming the problems. The meetings were taking place based on a regular way roughly every fourteen days. This work is done in a group; in following sections, complementary information will be provided for different subsets of project plan. Theses information include, time chart, tasks and milestones.

1.2.1 Methodology

Methodology of this work is based on collecting information about the motor characteristics which is released by associated suppliers under data sheets or catalogues. Collecting motor characteristics includes nominal speed $[rpm]$, nominal torque $[N.m]$, nominal power $[W]$, length and diameter of the motor $[mm]$, rotor inertia $[g.cm^2]$ and the price [€] of the motor. The main goal of the project is to give a quantitative comparison between motor technologies including BLDC, Synchronous machine, Switched reluctance machine, Brushed DC motor, permanent magnet synchronous machine, Axial-flux, Synchronous reluctance machine and Induction machine for both squirrel cage and wound rotor. In order to achieve this goal, methods are based on collecting information regarding motor technology. These information are collected from suppliers' websites, catalogues, data sheets and articles.

Quantitative analysis

By checking the website of the suppliers like Siemens, Beckhoff, servotechnica, Heng drive, ABB, etc, information released in their catalogues are extracted in a very readable **Excel** file. As it mentioned earlier these information are collected from the supplier websites as the source of the collected data.

1.2.2 Time chart

For this project like any other project a time chart is needed to layout the project tasks and time lines. Figure 1.1 shows Gantt chart lays out the project meetings and the decisions have been taken after each meeting and determining the milestones as well as future tasks in line with project objectives.

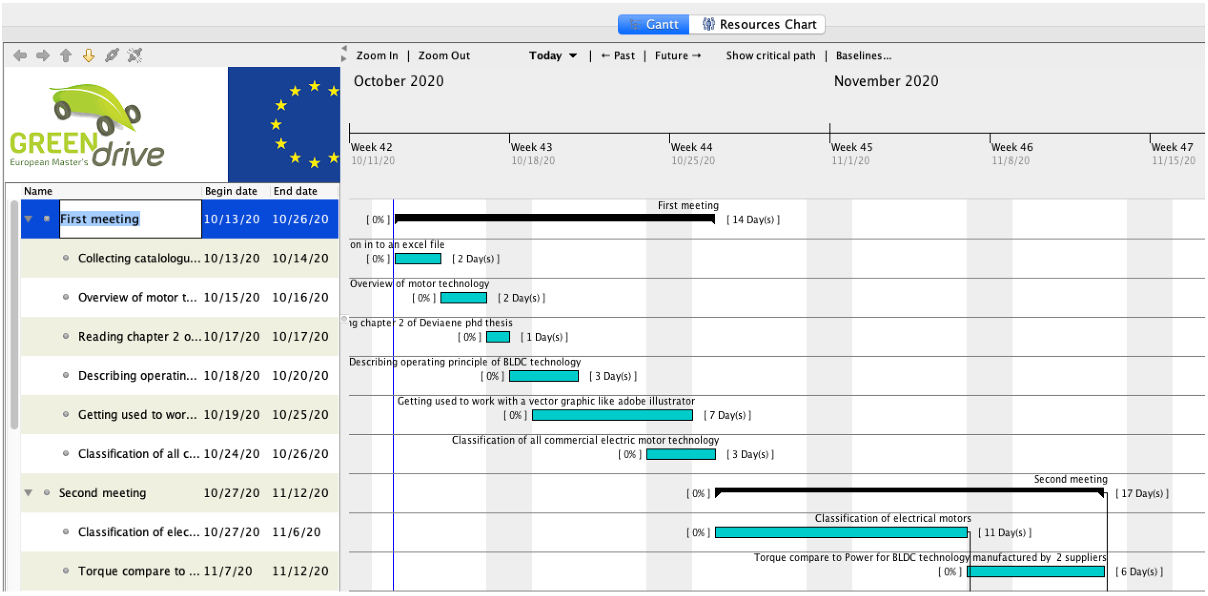


Figure 1.1: Tasks and timelines regarding first and second meeting

Writing the report is the most challenging and important part of the internship. Submitting a conference paper is another major task which was started from the beginning of the project. Figure 1.2 shows the start and due date of this task as well writing the internship report which are the most time consuming of the project.

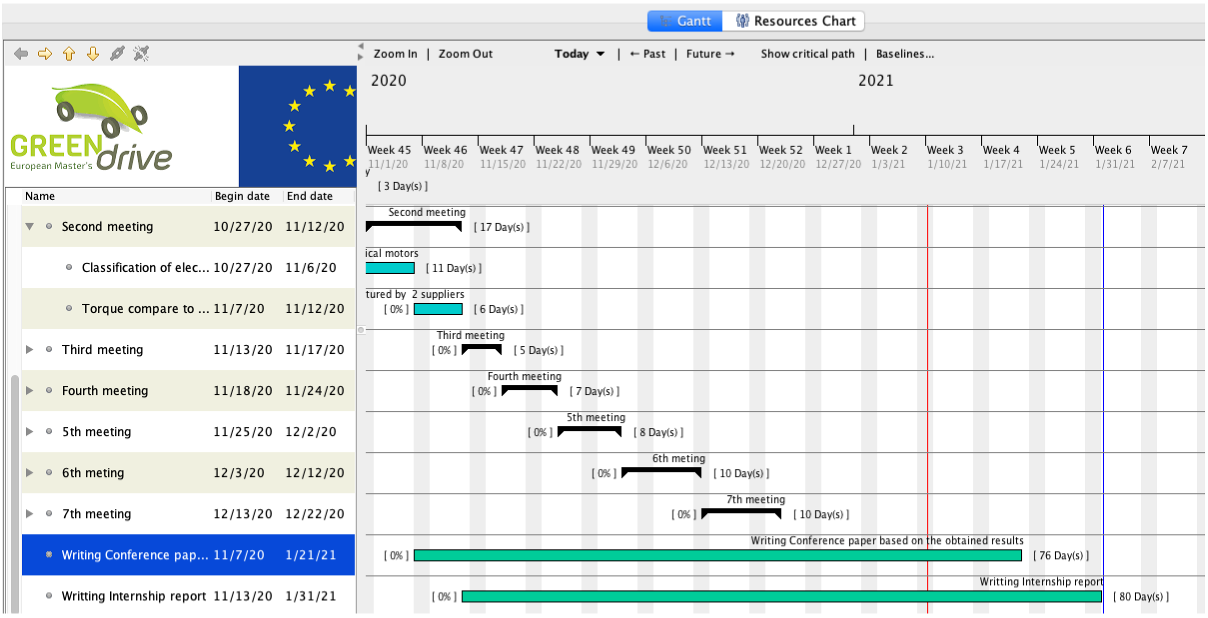


Figure 1.2: Internship report and conference paper as two major task and objective respectively and the associated timelines

1.2.3 Tasks

As the main goal of this project is to give a quantitative comparison between different motor technology the following tasks should be taken in to account. Although earlier a brief explanation was given regarding the tasks and objectives.

- Collecting data from catalogues, papers and suppliers' web page in a readable **Excel** file.
- Describing different motor technology with supporting graphics.
- Classification of electrical motors covering all commercially existing technologies
- Publication based on the obtained results.

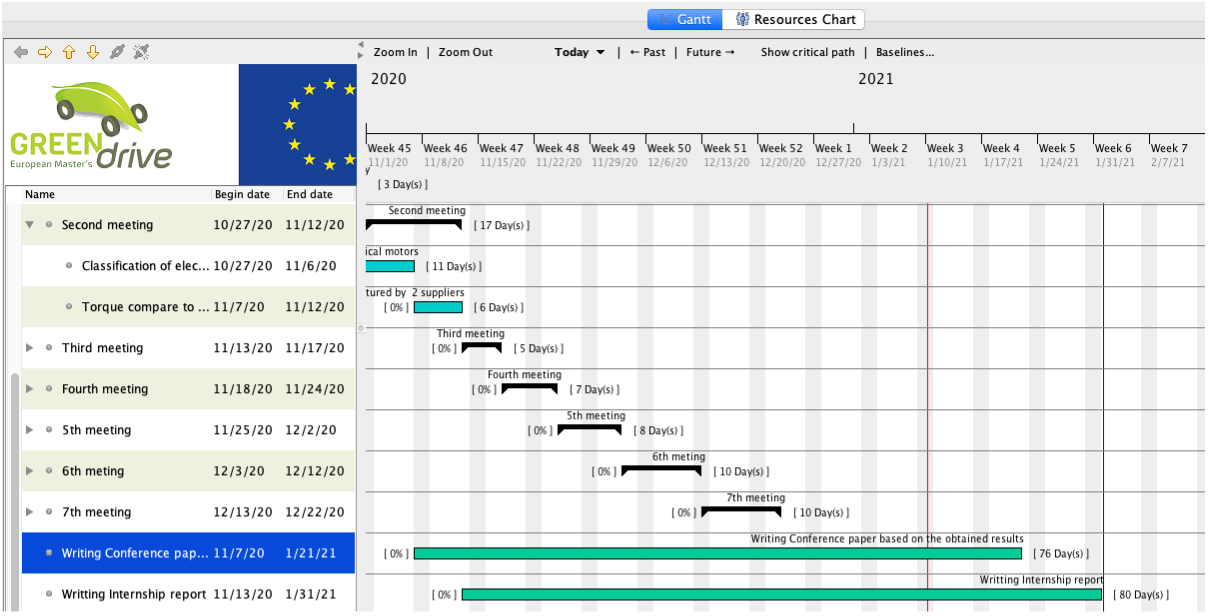


Figure 1.3: Internship report and conference paper as two major task and objective respectively and the associated timelines

1.2.4 Milestones

In this project the milestones are the tasks that should be delivered before next coming meeting. For measuring the goals of the project the project plan is included with the targets of each meeting with associated milestones; this helps to make sure that the project is in the right direction and in line with objectives. For instance figure 1.4 reflects the targets and milestones after fifth meeting which includes several tasks that are itemized as follows:

- Clear cross section of all considered motor technologies.
- Data collected in **Excel**.
- Comparison based on clear visualisation of the data.
- Publication

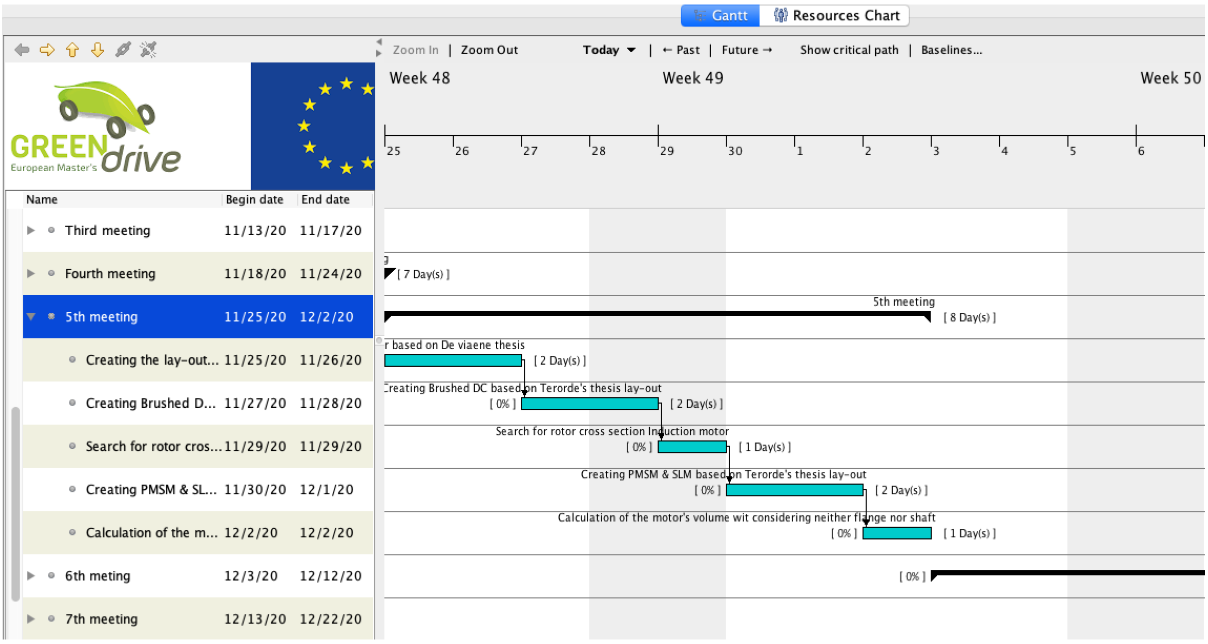


Figure 1.4: Targets and milestones after 5th meeting

1.2.5 Brief description of tasks and milestones

In this section a brief description of tasks and milestones are provided as one of the subsets of the project plan. The tasks' titles were itemized earlier, here the associated description are provided. Data related to each technology is collected by searching in supplier web-pages that manufacture elctric motors or some OEMs that provide e-mobility solutions as a sustainable and promising solution for reducing NOx and emission. Depending the level of professionalism of the suppliers they release data catalogues which helps us to collect needed information. This task is time consuming and sometimes doesn't lead to collecting suitable information necessarily. Motors principle of operations are described by illustration relevant motor technology; the motor technology cross section is designed with a graphic vector. In this work all motor technology are created with adobe illustrator which is a friendly user toolbox and has lots of flexibility and lets the users to create scientific cross sections of different technologies with details including coil winding in the rotor which is located in an extremely small place. In following chapters a zoom-in of small parts of the cross section are provided for those that haven't enough visibility. Figure 1.5 shows the visibility of field rotor winding after zooming-in a synchronous motor with cylindrical rotor.

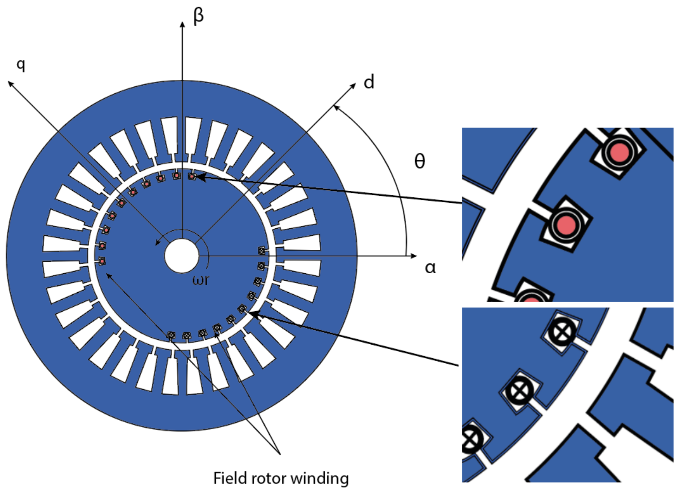


Figure 1.5: Visibility of field winding rotor winding created by adobe illustrator graphic vector

1.2.6 Meeting with supervisor

As milestones and targets of each meeting was based on each meeting, it was extremely helpful having regular meeting with Dr.Derammelaere who I was honoured to do my internship under his supervision. These meetings were held regularly roughly every twelve days. Further the possibility of communicating through Microsoft team chat page.

1.3 Technical part

From technical point of view this study provides a clear comparison that which motor technology suits typical application. For instance BLDC suited for high speed applications while PMSM provide higher torque density in compare with other technologies. Also Axial-flux technology is a optimal choice in terms of compactness and lightweight which is a major factor in e-mobility solutions, because motor is fixed on the chassis of the vehicle. Further stepper motors are a good option when cost is considered as a constraint thanks to their low price and free-maintenance. In following chapters the solutions will be plot and tabulated.

1.4 Soft skills

Despite of Covid-19 situation regular meeting were held regularly and after each meeting a meeting minutes was prepared. SWOT analysis, knowledge and skills gained during the first year of the program (Joint master's Degree in sustainable automotive engineering" and how they have been useful for completing the project will be explained in the following subsets associated with soft skills.

1.4.1 SWOT analysis

SWOT matrix is used in management and business. **SWOT** stands for Strengths, Weaknesses, Opportunities and Threads. In this section the whole internship advantage and disadvantages of point of view will be thoroughly analysed to distinguish this work with the other works that already have been done by the project manager.

STRENGTHS	WEAKNESSES
1. keep continuing to search for better data in catalogues released by more well-known suppliers 2. Obtaining good knowledge in electrical motor overview 3. Getting used to working with adobe illustrator by iterating a certain technology	1. Spending time on tasks that don't involve in the milestones of the project 2. Feeling stress before each milestone and meeting 3. Not so concentrated in whole working day 4. Perfection that sometimes leads to disappointment in case failure and loosing time

OPPORTUNITIES	THREATS
1. Opportunity to learn how to extract data from catalogues in suppliers' webpage faster than before 2. Improving search ability by optimising time. 3. Learning discipline and taking the job easier thanks to Dr. Derammelaere and this huge opportunity to work under his supervision.	1. Getting lost in a pile of data collected in an Excel sheet 2. Mixing some units regarding to certain quantity released by different suppliers 3. About to missing a milestone due to using gradient in stead of solid color for motor cross section

Also, In order to manage daily working hours **Somenka** plan template was used. Figure 1.6 shows the working daily hours.

12/10/20 till 18/10/20	total: 6h45	total:5h52	total:1h50	total:5h	total:9h25	total:7h35	total:7h30		AllInAll = 44h
19/10/20 till 25/10/20	8h38	11h15	9h10	9h16	8h35	3h26	7h27		AllinAll=57h47
26/10/20 till 01/11/20	9h53	8h28	Rest in peace Daddy	Rest in peace Daddy	1h42	3h11	3h05		AllinAll = 26h19
02/11/20 till 08/11/20	7h43	3h18	10h18	8h48	6h39	2h35	5h05		AllinAll = 44h26
09/11/20 till 15/11/20	8h51	7h19	3h04	5h26	5h55	6h25	7h10		AllinAll = 44h10
16/11/20 till 22/11/20	6h57	5h25	00:00:00	5h56	1h23	2h06	9h22		AllinAll = 33h09

Figure 1.6: Somenka template used for recording daily working hours

1.4.2 Gained knowledge linked to first year of JMDSAE

During the second trimester of first year some skills were gained; those skills were helpful especially in terms of soft skills like project plan and creating **Gantt chart**, which helped to make sure to achieve the targets and milestones.

1.4.3 Contribution of internship job tasks in to skills and knowledge base

Some of my skills and knowledge base improved thanks to the contribution of internship job tasks. For instance:

- I learned the classification of collecting data extracted from different suppliers
- I gained information on the graphic vector to illustrate different motor technology cross section.
- I gained analysing quantitatively through the comparison process and problem solving through the using of approximation for finding the stepper motor volume $[mm^3]$.

Further, during the internship i learned how to face with the issues and find a sustainable solution. Also, implementing the solution and consequently evaluating the effectiveness of the proposed solution. I learned how to manage the time and I feel this work significantly increased my soft skills by using management tools. If I want to excel at my job, search skills improvement as well as knowledge to use a graphic vector are the most important ones, however what I liked least was the virtual communication during the internship.

1.5 Different parts of an Electric Motor

In this study we compare the different technologies of concentrated and distributed winding including BLDC, Stepping motor (SM), Switched reluctance motor (SLM), Brushed DC motor, Permanent magnet synchronous machine (PMSM), Axial-flux,Synchronous reluctance motor (SynRM) and Induction motor (IM) for both round rotor and squirrel cage. There are numerous suppliers that manufacture electric motors for different applications, but choosing a typical motor for a certain application is not so easy, especially when customers are dealing with a pile of motor technologies. By comparing of different characteristics of aforementioned technologies, one can find easily which motor can fulfill the requirements subjected to constraints and objectives. These characteristics include volume $[m^3]$, nominal power $[W]$, nominal torque $[N.m]$, rotor inertia $[gm^2]$, price and complexity of the motor. Thus the main objective of this paper is to give crystal clear information to customers for having the optimal choice. More than 200 motors are chosen for this study. In this study an extend range of motor technologies from commercially view point are investigated. There are some major suppliers that manufacture motor technologies and most of the data are extracted from their catalogs.
By checking their data sheets a comparison between different motor technology specification will be possible.

All electrical motors are comprised of two major parts which are rotor and stator. Stator is the fixed part which can be placed inside or outside of the rotor depending the design. Rotor is the the dynamic part which has motion to convert electric energy to mechanical traction. There is a gap between a stator and rotor in order to prevent any contact between rotor and stator. any contact between these two major component can cause a major damage to the motor. In continue different parts of rotor and stator with schematic are explained.

As one step ahead before comparison of different motor technology, one should be able to answer the following questions:

- the components which motor composed of?
- where different parts of motor located and linked together?
- the alloy which is used to form the motor construction.

However in continue a brief explanation with a schematic of major parts of an electric motor are provided. The results of this work is published through an article in a conference as one of the objectives of the internship project.

1.5.1 Rotor

Rotor is the dynamic part of the motors; based on the design it can be located either exterior or interior of the motor.

Pole

Poles can be placed in rotor and stator. Figure 1.7 shows a particular type of a pole and it can be located inside or outside of a motor.

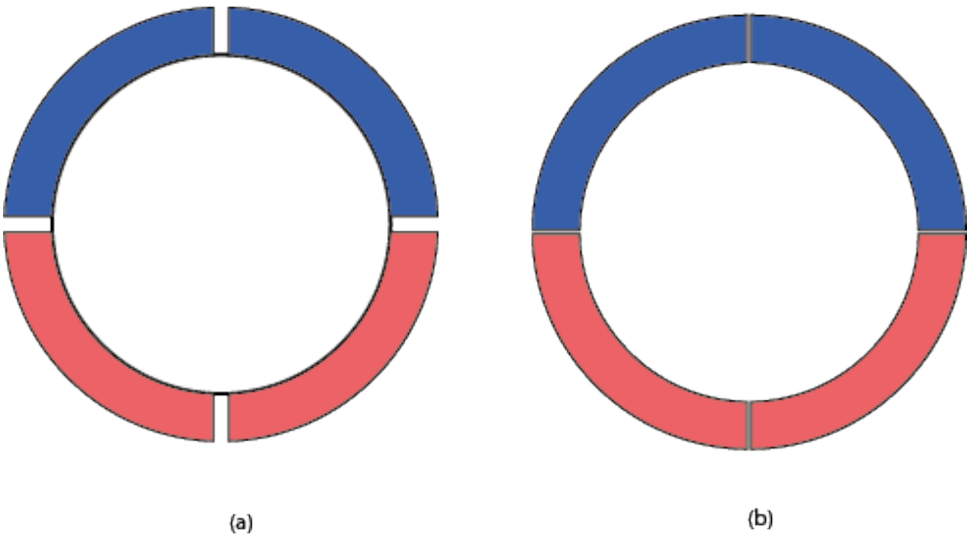


Figure 1.7: Surface mounted permanent magnet (a) and interior permanent magnet (b)

Magnet

One of the most important parts which is used in electric motor is magnet; they are used to put the rotor in motion.

1.5.2 Stator

Stator is the stationary part of the motor; rotor under operation align its poles with the stator and this generate the magnetic field which gives a rotation to the rotor.

Slot

Slots are located in the contour of the stator, where the windings are wrapped around them. figure 1.8 shows a cross section of a slot.

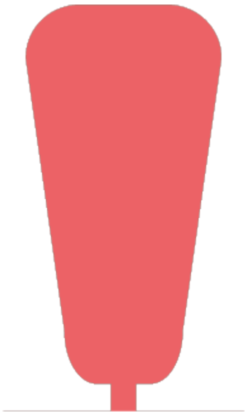


Figure 1.8: Cross section of of a slot type

Coil

There is an interaction between magnetic fields and electric currents in electric motors. Further electromagnetic coils are a part of electric motors.

Winding

By wrapping magnetic poles with wires windings are created, where these magnetic poles are feed by current. Infact this magnetic field converts the electric energy to mechanical energy, and this mechanical energy creates torque through the shaft and put the rotor in motion. By feeding stator winding with current a magnetic field is generated. Rotor is energized by current and consequently the electromagnetic force is induced and ultimately the rotor get into the motion and motor starts to rotates. Motor winding can be either stator- or rotor-winding. Figure 1.9 shows a cross section of a stator winding.

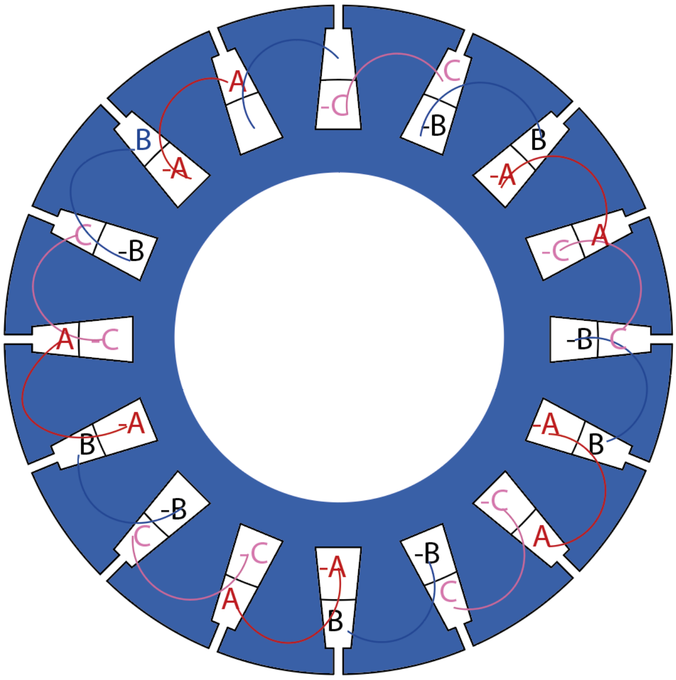


Figure 1.9: The Geometry of a stator winding surface

Chapter 2

Overview of electric motor technology

In previous chapter the structure of an electric motor was explained. The block diagram in figure 2.1 shows all technologies which are considered in this study. In continue each technology will be investigated by choosing two supplier for each of them. Nominal torque and nominal speed are compared to nominal power. Further a cross section of each technology is designed in *Abobe illustrator* to illustrate the different designs for different technology.

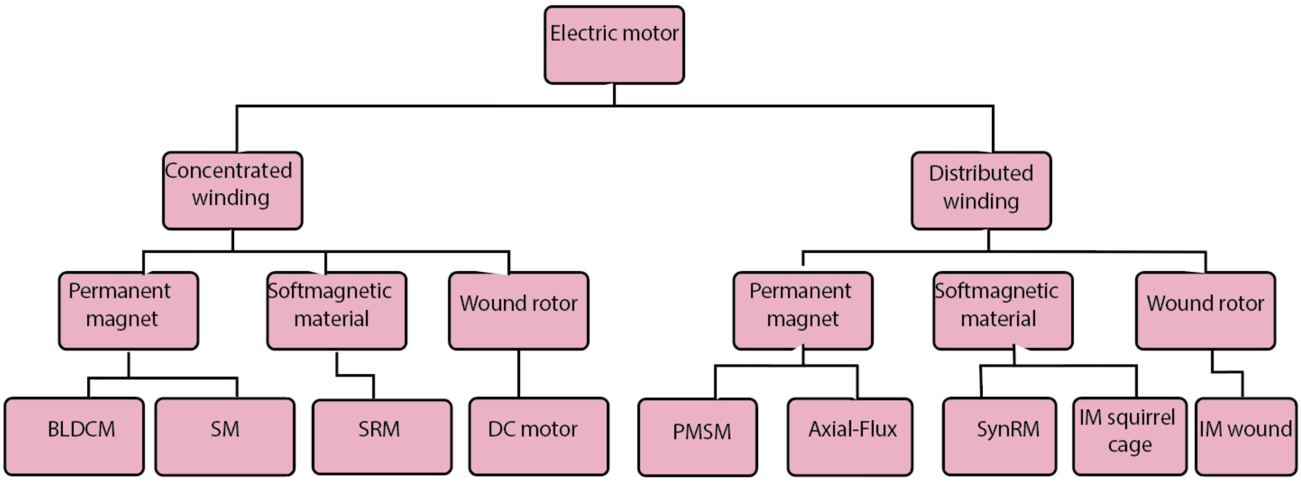


Figure 2.1: Classification of electrical motors covering the brushless dc motor(BLDC), stepping motor (SM), switched reluctance motor (SLM), dc motor, permanent magnet synchronous motor (PMSM), axial- flux motor, synchronous reluctance motor (SynRM), Induction motor (IM) for squirrel cage and wound rotor.

By classifying motor technology and investigating their operating principles one can simply find the optimal choice according to the dedicated requirements and constraints, however the study doesn't include motor design with scratch.

2.1 Concentrated winding

2.1.1 Brushless direct current motor(BLDCM)

Brushless permanent magnet direct current motors provide higher efficiency in compare with its brushed counterpart. The control of BLDC needs a change of phase between its coil to communicate with the phases of permanent magnet. In this technology Rotor becomes permanent magnet and Stator stands for coil winding which is called commutation. Based on magnet arrangement Rotor and Stator can have different pole pairs and different number of winding respectively. Unlike it's name, BLDC motor is an AC motor. With more pole pair, commutation occurs more frequently. During choosing the dimensions for Rotor and Stator it should be considered that gap between Rotor and Stator can lead to eddy currents and on the other hand rotor should rotate inside the stator without touching the interior surface of the Stator. Any contact between Rotor and Stator under operation can cause significant damage to the motor. There are two different designs of BLDC technology:

- In-runner
- Out-runner

In out-runner and in-runner rotor is located inside and outside of the motor respectively. The stator winding of BLDC is supplied by rectangular pulses and star connected, leading to trapezoidal back-EMF. Figure 2.2 shows a cross section of a brushless dc motor.

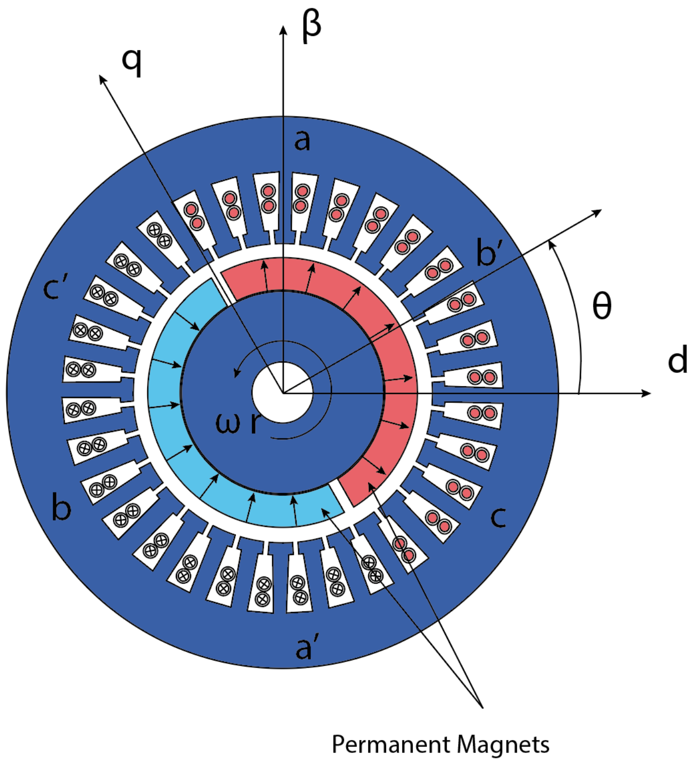
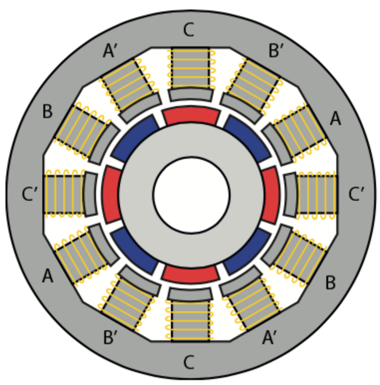
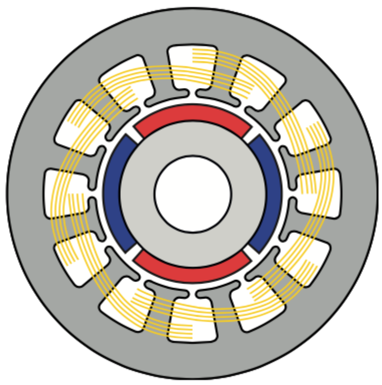


Figure 2.2: Cross section of a Brushless DC motor

The configuration of BLDC is similar to the permanent magnet synchronous motor. The major difference returns to the the winding configuration which are concentrated and distributed for BLDC and PMSM respectively. Figure 2.3 shows the difference between these two technology and how the windings are wrapped for both technology.



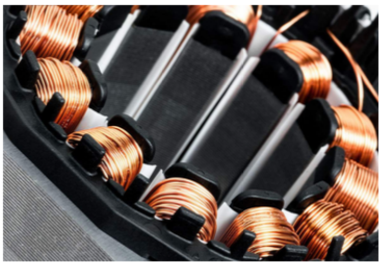
(a) BLDC with 12 slots and 8 poles



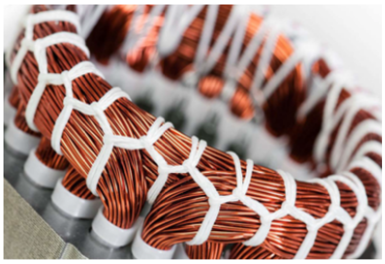
(b) PMSM without slot and 4 poles

Figure 2.3: Cross section of BLDC and PMSM
[1]

Figure 2.4 shows how the coils are wounded around one tooth and spanned several teeth for a concentrated and distributed winding respectively.



(a) Concentrated winding



(b) Distributed winding

Figure 2.4: Coils are (a) wounded around each tooth and (b) spanned several teeth [1]

The back electromotive force (EMF) induced in BLDC has a trapezoidal shape. And this back-EMF is represented by the equation 2.1

$$e = k_e \omega_m F(\theta_e) \tag{2.1}$$

where e, k_e, ω_m, θ_e and F_{θ_e} are described as follows:

$$e = back - EMF$$

$$k_e = back - EMF constant$$

$$\omega_m = \textit{mechanical rotational speed [rad/s]}$$

$$\theta_e = \textit{electrical position [rad]}$$

$$F_{\theta_e} = \textit{back-EMF shape}$$

As it can be understood the position of the rotor depends on the stantaneous value of the back-EMF. Figure 2.5 illustrates the ideal back-EMF hall sensor which indicates the commutation moments for the square-wave current as a function of electrical angle and ultimately controlling of a three-phase brushless DC motor.

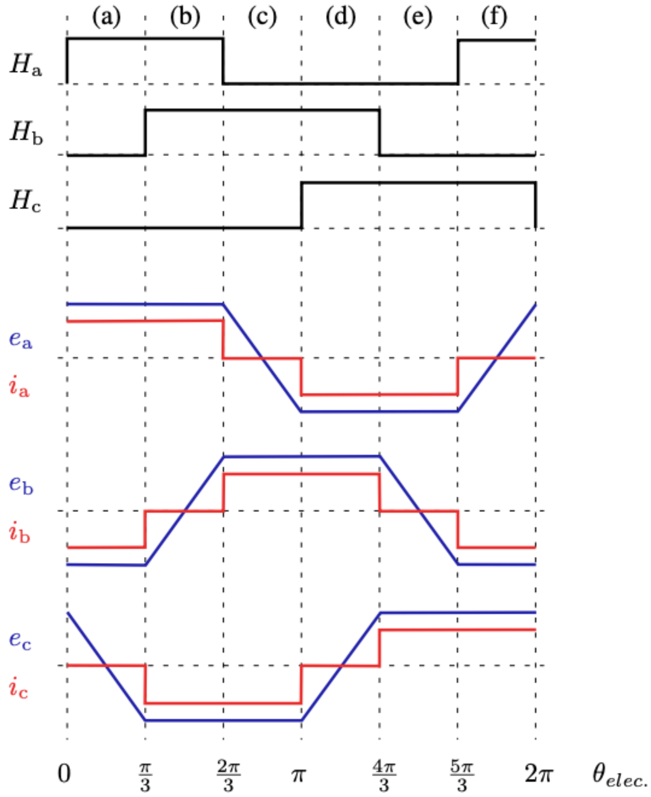


Figure 2.5: Back-EMF Hall sensor signal for controling a three-phase BLDC motor [1]

Figure 2.6 shows the feedback of Hall sensor.

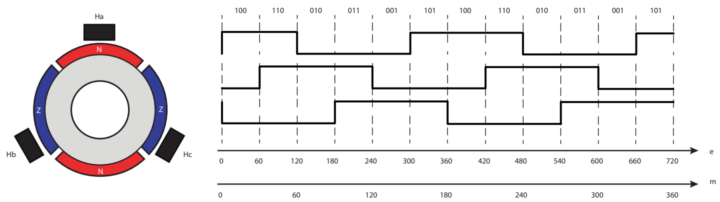


Figure 2.6: Feedback of the Hall sensor [1]

For BLDC technology two suppliers including GEMS and Dunkermotoren are chosen. Speed range, torque range, power range, volume range and rotor inertia range are tabulated.

BLDC topology					
Supplier	Speed range(rpm)	Torque range(Nm)	Power range (W)	Volume range (m^3)	Rotor inertia ($g.cm^2$)
GEMS	800 - 7000	0.113 - 9.7	35 - 3000	$(4,53-143)*10^{-5}$	48 - 9000
Dunkermotoren	3110 - 10500	0.02 - 2.78	31 - 3000	$(0,87-158,3)*10^{-5}$	15 - 1890

The number of motors and corresponding price are provided in the following table.

BLDC motor topology		
Supplier	Number of Motors	Price(Euro)
GEMS	23	N
Dunkermotoren	23	N

Operating principle of BLDC motor in a 6-steps of perceivable way

Figure 2.9 illustrates a surface of a BLDC machine comprised of 12 stator slots and 8 rotor poles. The design of fractional slot pole will cause a decrease in cogging torque. BLDC has a Trapezoidal back-EMF and is controlled by trapezoidal control. Forgoing figure shows a BLDC with a four pair-pole, thus commutation occurs each 15°. Stator comprised of 12 coils (slot), accordingly 12 phases are needed. Two phase of three phases are excited while the third one is off. One electrical period will be completed after a six commutations which leads to a 90°mechanical rotation. Electrical and mechanical rotation are proportional with the number of rotor poles which is given in the equation 2.2

$$\theta_e = p.\theta_m \tag{2.2}$$

where p is the number of rotor pole pairs. Rotor positioning can be measured by either embedding the hall sensors in to the stator or installing encoders which is roughly expensive. Figure 2.7 shows the block diagram of a position control of a servomotor.

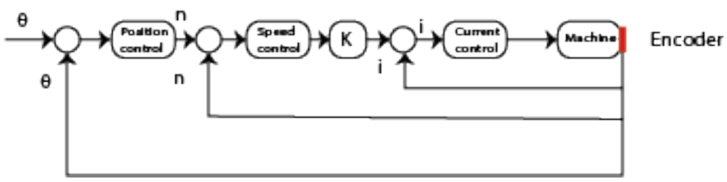


Figure 2.7: Block diagram of a position control of an electric motor

Although embedding Hall sensors is a cheaper solution and requires less maintenance, but any misalignment can lead to an inaccurate rotor positioning due to error generation. Figure 2.8 shows a feedback of Hall sensor embedded in to a BLDC stator and relation between electrical and mechanical angular position.

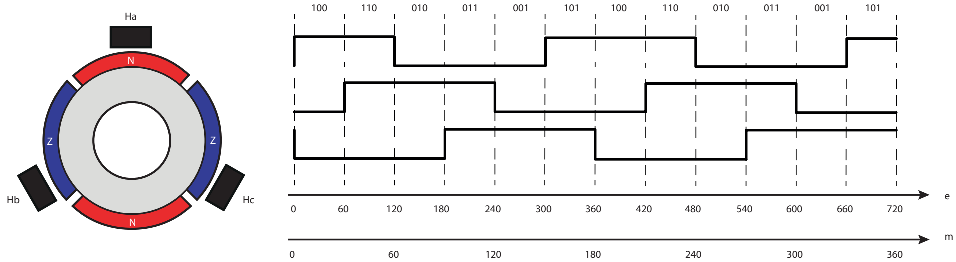


Figure 2.8: Hall sensor as a function of electrical and mechanical angular position of a BLDC at position $H_a = 1$, $H_a = 0$ and $H_a = 0$
[1]

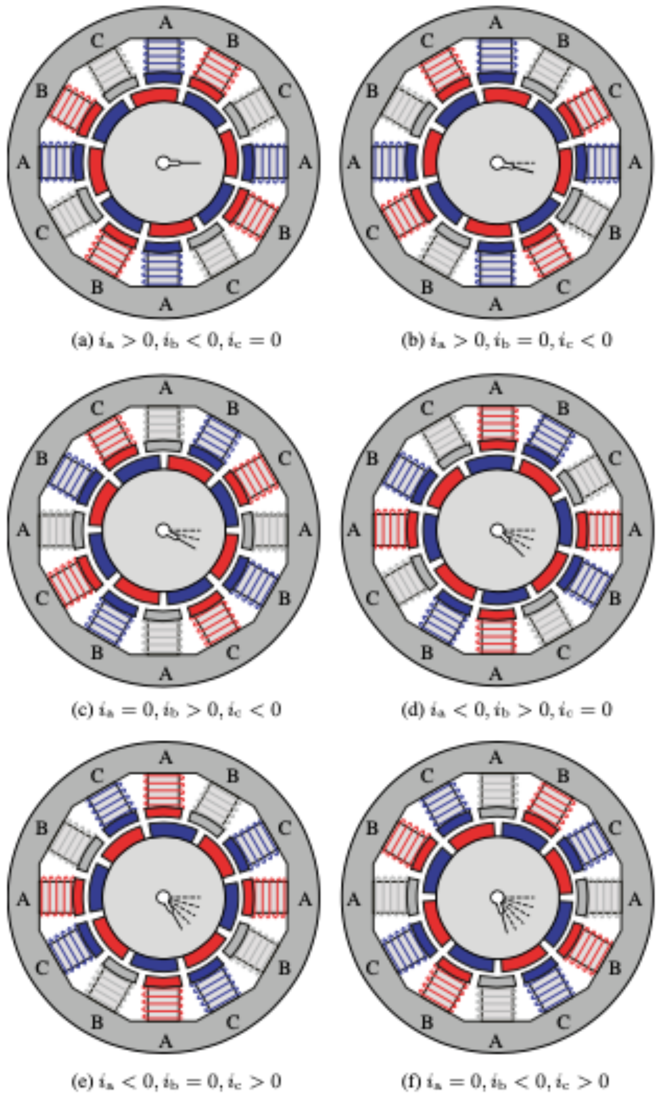


Figure 2.9: Operating principle of a BLDC motor with 12 slot and 8 pole.
[1]

Principle operation with Square-wave currents

In order to reduce the cost due to the use of Hall sensors, back-EMF can be extracted by coil voltage which is measured by position sensorless techniques. Thus back-EMF should be measured while current and its derivative are zero. meaning that in equation 2.3:

$$v = R.i + L.\frac{di}{dt} + e \tag{2.3}$$

voltage will be equal to induced electromotive force. Figure 2.10 shows the zero-crossing detection of the electromotive force for determining the commutations.

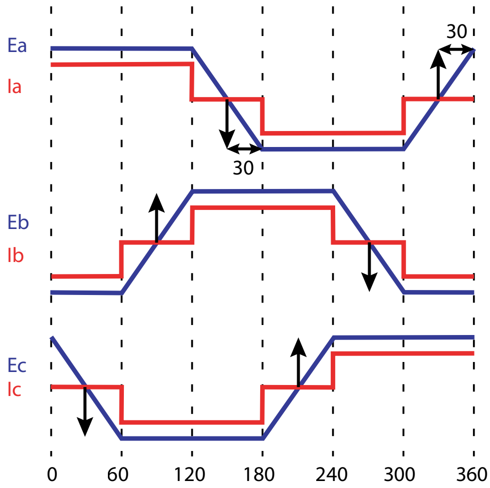


Figure 2.10: Zero-crossing detection of the back-EMF to determine the commutation moments [1]

Figure 2.11 shows 3 times of phase A, B and C. Theses three phases represent the current which goes through the coils. Indeed rotor align itself with the stator magnetic field. In this case each 15°.

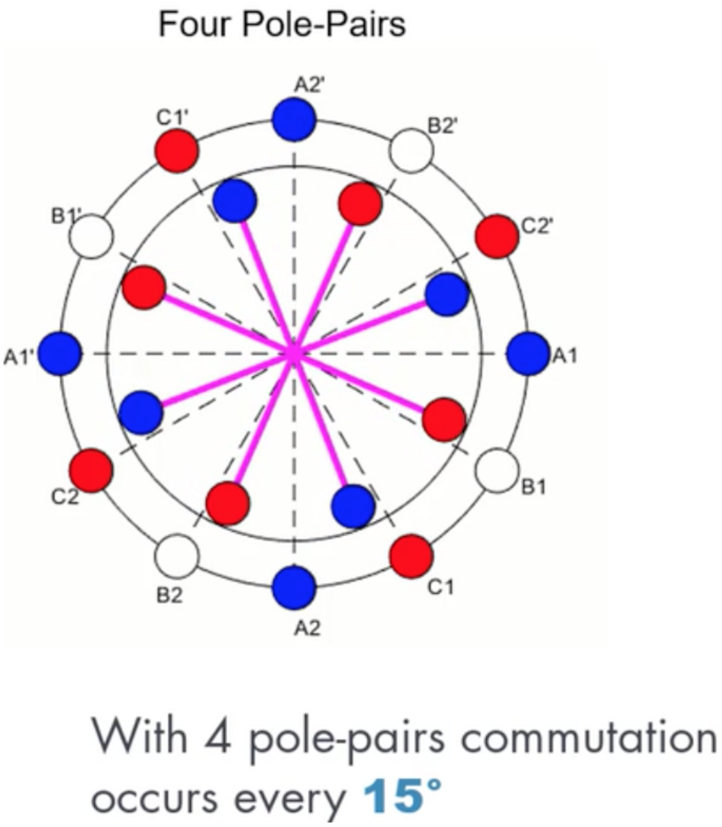


Figure 2.11: BLDC with four pole-pair
[5]

Indeed stator magnetic field is generated when 15[°] is completed and each two coils align together.

Control of BLDC motor with Hall sensors

There are three types control for BLDC motors. Sinusoidal, field oriented and sensorless control. [7]

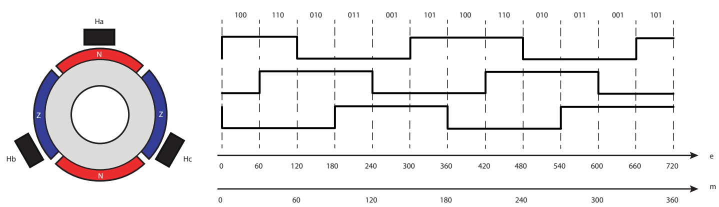


Figure 2.12: Feedback of the Hall sensor
[1]

2.1.2 Brushed DC motors

Brushed DC motors consist of stator and rotor, the stationary and fixed part respectively. The electromagnetic coils create the stator field. The electromagnetic coils can be in series or parallel.

The rotor is connected to an isolated copper which is called commutator. The current passes through the commutator and carbon brushes. This is why this technology is called Brushed DC motor.

Figure 2.13 shows a cross section of a brushed DC motor. DC brushed are used in many applications because of their high speed and lower price in compare with their Brushless counterparts.

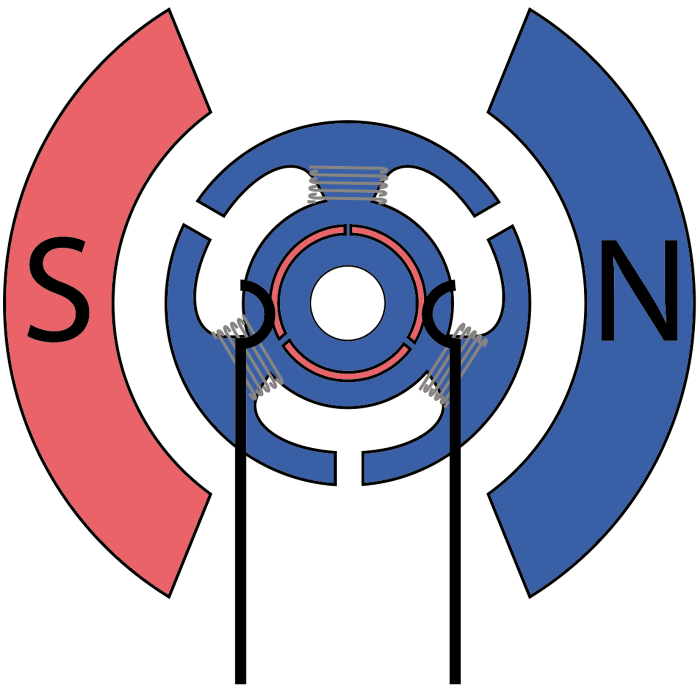


Figure 2.13: Cross section of a brushed DC motor

Two suppliers including **Dunkermotoren** and **Sunrise Motor** are chosen for this technology. Information regarding torque, speed, power, volume and rotor inertia are tabulated as below.

Brushed DC motor topology					
Supplier	Speed range(rpm)	Torque range(Nm)	Power range (W)	Volume range (m^3)	Rotor inertia ($g.cm^2$)
Dunker	2500 - 3750	0.01 - 0.63	3.65 - 796	$(1.9 - 49.5) * 10^{-5}$	11 - 3200
Sunrise	800 - 4800	0.33 - 2.6	16,6 - 1082	$(3.2 - 119.2) * 10^{-5}$	N

A total number of 69 motors are considered for brushed dc motor technology.

Brushed DC motor topology		
Supplier	Number of Motors	Price(Euro)
DunkerMotoren	45	N
Sunrise Motor	24	N

2.1.3 Stepping motor(SM)

Stepping motor is another technology of existing motor technology. Suppliers provide stepping motors in three design topology which are mentioned as follows:

- permanent magnet stepping motor
- variable reluctance stepping motor
- Hybrid stepping motor

So as most of the principles of Hybrid stepping motors are valid for the other two designs, Hybrid stepping motor are considered as the representative of stepping motor technology. In figure 2.14 the two-phase hybrid stepping motor is depicted. The number of steps for this motor is given by :

$$n_{steps} = 2 * n_{rotor\ teeth} * n_{phases} \tag{2.4}$$

Meaning that for a 50 pole pairs, the number of steps will be 200 of 1.8°for a complete revolution. In figure 2.14, the schematic of a two-phase hybrid stepping motor is illustrated.

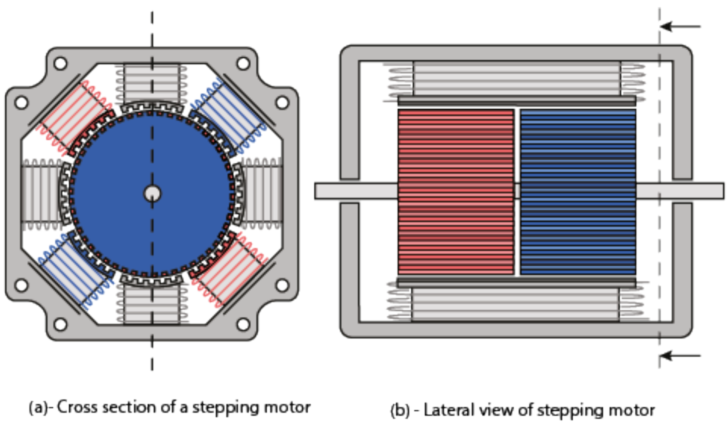


Figure 2.14: Two-phase hybrid stepping motor with 50 rotor teeth per north and south stack [1]

In Stepping motors (SM), finding power is not so easy, thus by an approximation the power in SM can be obtained. Formula 2.5 provides a good approximation for obtaining the power in stepping motors according to torque compared to power in this technology.

$$P = \frac{2}{3} * T_{nom} * n_{nom} * \frac{2 * pi}{60} \tag{2.5}$$

Where $T[N.m]$ and $n[rpm]$ are nominal torque and nominal speed respectively. Two supplier including **Nanotec** and **FESTO** are considered for this technology. Speed, torque, power, volume and rotor inertia are tabulated as bellow.

Stepping motor(SM) topology					
Supplier	Speed range(rpm)	Torque range(Nm)	Power range (W)	Volume range (m^3)	Rotor inertia ($g.cm^2$)
Nanotec	133 - 7058	0.018 - 11.7	2.4 - 207.7	$(0.3134 - 27.21) * 10^{-5}$	0.0002 - 0.55
FESTO	430 - 6000	0.09 - 9.3	38.0 - 1789	$(1,8 - 57.9) * 10^{-5}$	18 - 3000

A total number of 24 motors are considered for this technology.

Stepping motor(SM) topology		
Supplier	Number of Motors	Price(Euro)
Nanotec	17.0	87 - 445.27
FESTO motor	8	N

Stepper motors are not a good choice for high speed application, but in terms of nominal torque [Nm] and power density they are good options.They are packed and provide maximum torque based on their volume. [2]

2.1.3.1 Principle operation for open-loop control in stepping motors

Figure 2.15 illustrates the operating principle of a hybrid stepping motor while it is energized with positive and negative current.

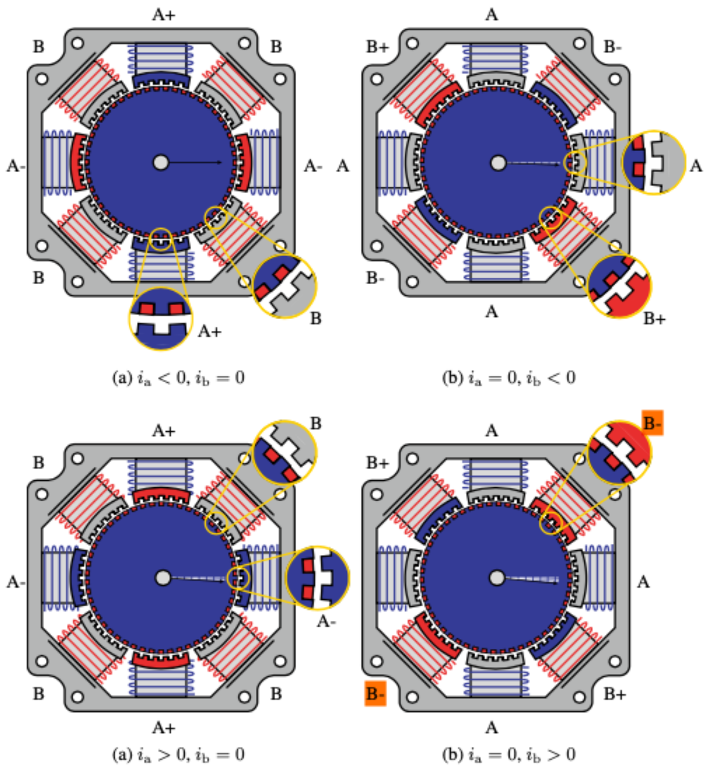


Figure 2.15: Principle operation of SM energized with positive and negative current [1]

2.1.3.2 Current wave-form

Current waveform in stepping motors are provided with different steps. In following sub steps Full-step, Half-step and Micro-step waveform are investigated with associated current waveform figures.

2.1.3.2.a Full-step

Figure 2.16 shows the current full-step waveform. The stator windings are energized with current and magnetic field are created; due to magnetic field the opposite pole of the rotor tooth is attracted.

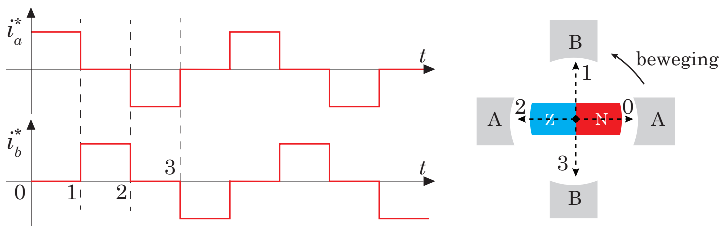


Figure 2.16: Current waveforms full-step [1]

If the two stator windings are energized at the same time, the maximum torque will be obtained as its illustrated in the figure 2.17

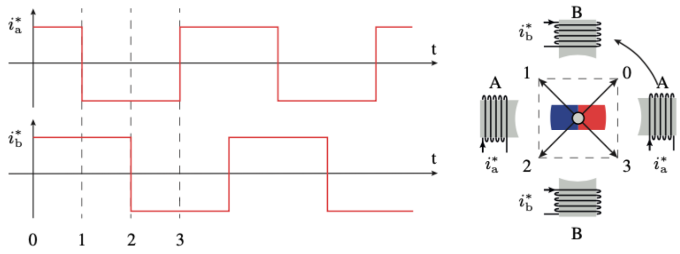


Figure 2.17: Current waveform Full-step, two stator winding energized simultaneously [1]

2.1.3.2.b Half-step

If the step sizes are divided by two the entitled half-step is obtained as shown in figure 2.18. Likewise in full-step the principle is the same and rotor will align itself with the energized phase.

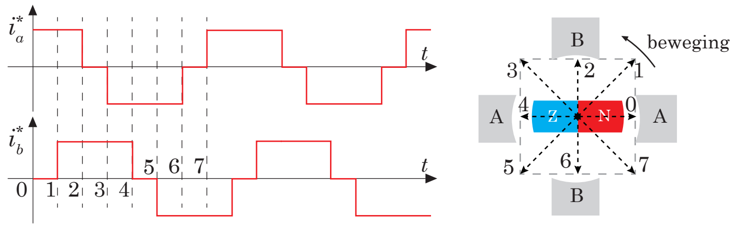


Figure 2.18: Current waveforms Half-step [1]

2.1.3.2.c Micro-step

If full-step waveform divided by four, micro-step is obtained which makes it possible for obtaining small step angles and consequently smoother rotor motion. figure 2.19 shows the micro-step which looks more sine form for better resolution. This control divides a full-step as much as 256 times. This can significantly increase the resolution.

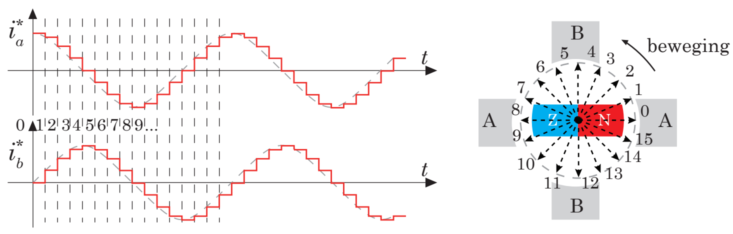


Figure 2.19: Current waveforms micro-step [1]

In stepping motor, step per revolution is obtained by:

$$\frac{step}{revolution} = \frac{360°}{stepangle} \tag{2.6}$$

meaning that for a stepper motor with a step angle of 1,8°, step per revolution is $\frac{360°}{1,8°} = 200$. For stepping motor calculation like maximum speed, equation 2.7 is provided:

$$Max\ speed = \frac{V}{2LI_{max} * spr} \tag{2.7}$$

Where:

$$V = applied\ voltage$$

$$I_{max} = maximum\ current$$

$$L = stepper\ motor\ inductance$$

$$spr = steps\ per\ revolution$$

One of the reasons that in stepper motors high torque and speed can't be obtained simultaneously is that, when the speed is high the winding doesn't have sufficient time to reach its rated value. Formula 2.8 determines the time constant, that takes for a current flowing through a winding, to reach to 63% of the rated value.

$$\tau_e = \frac{L}{R} \tag{2.8}$$

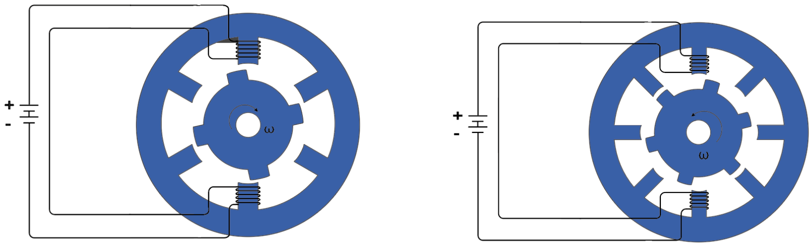
Where, $L[mH]$ and $R[Ohm]$ are inductance and resistance respectively. Low cost maintenance and high torque at the start of the motor make Stepper motor interesting for commercial applications. Holding torque is obtained by the multiplication of torque constant and current through the stator winding.

$$T = K_t i \tag{2.9}$$

Where K_t and i are torque constant and current through the stator winding respectively. Thanks to precise positioning, there is no need of feedback or encoder in stepper motor. Position of the rotor can be determined by counting the steps.

2.1.4 Switched reluctance motor(SRM)

The switched reluctance motor(SRM) seems to be interesting for several applications thanks to its simple structure, cost and reliability. SLMs have not any winding and magnet in their rotors[3]. SRMs are suited for the applications with high speed and torque with high efficiency. Figure 2.20 shows SRM for three and four phases.



(a) 4/6 topology of a SRM (b) 6/8 topology of a SRM

Figure 2.20: Cross section of a 6/4 and 8/6 switched reluctance machine

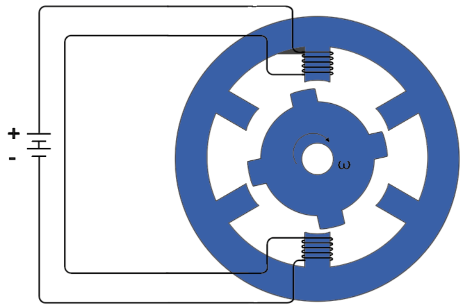


Figure 2.21: a cross section of a 4/6 three phase SRM technology

Two suppliers including **Rocky mountain Motor** and **Found Motor** are considered for this technology. Speed, torque, power and volume are tabulated as below for this technology.

Switched reluctance motor topology					
Supplier	Speed range(rpm)	Torque range(Nm)	Power range (W)	Volume range (m^3)	Rotor inertia (gm^2)
Rocky Motor	14000 - 15000	1,3 - 10,7	448 - 3000	$(1,33-3,1)*10^{-3}$	N
Found Motor	3500 - 5600	2.0 - 8,2	1200 - 3000	N	N

A total number of twelve are chosen for this technology.

SSwitched reluctance motor topology		
Supplier	Number of Motors	Price(Euro)
Rocky Mountain	6	N
Found Motor	6	N

2.1.4.1 Operating principle of switched reluctance motor

Reluctance motors are classified in three groups including switched reluctance motors (SRM), variable reluctance synchronous motors (VRSM) and DC excited flux switching machines (DCEFSM). SR motors are simple and robust and they don't have any permanent magnets. Further high speed and low cost are the other advantages of this technology. Besides of these advantages control, electronics and torque ripple are the main drawbacks of this technology.

2.2 Distributed winding

2.2.1 Permanent magnet synchronous machine(PMSM)

In permanent magnet synchronous motors magnets can be located either inside or outside of the rotor. Figure 2.22 illustrates the schematic of a rotor and stator of a PMSM motor.

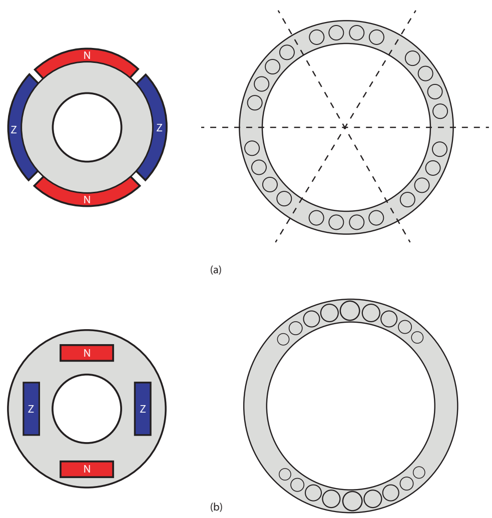


Figure 2.22: Rotor and stator of a PMSM
[1]

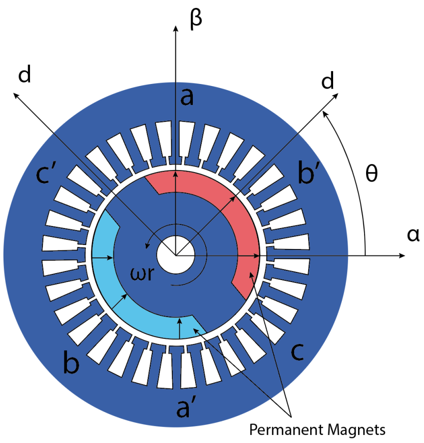
Two suppliers including **Beckhoff** and **ABB** are considered for this technology.

Permanent magnet synchronous motor (PMSM) topology					
Supplier	Speed range(rpm)	Torque range(Nm)	Power range (W)	Volume range (m^3)	Rotor inertia (gm^2)
Beckhoff	1400 - 8052	0.18 - 18.5	150 - 2910	$(6.85 - 302.5) * 10^{-5}$	29 - 57100
ABB	900 - 3600	0.99 - 23.7	373 - 2237	$(1.5 - 4, 45) * 10^{-3}$	2350 - 161050

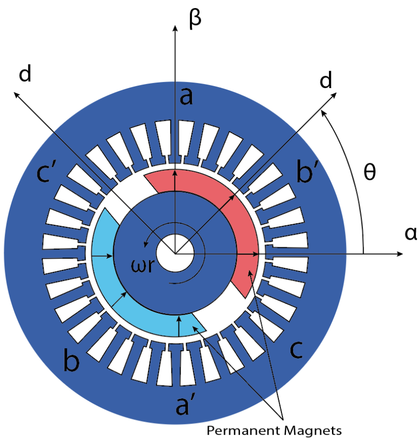
A total number of 39 motors are considered for this technology.

PMSM technology		
Supplier	Number of Motors	Price(Euro)
Beckhoff	32	N
ABB	7	N

Figure 2.23 shows Two different designs of a PMSM. The magnets can be located inside or outside of the rotor as it mentioned earlier.



(a) PMSM inset



(b) PMSM mounted

Figure 2.23: Cross sectional of 2-pole inset and mounted PMSM

Figure 2.24 shows how windings are located in the rotor. The north and South poles are depicted with different colors.

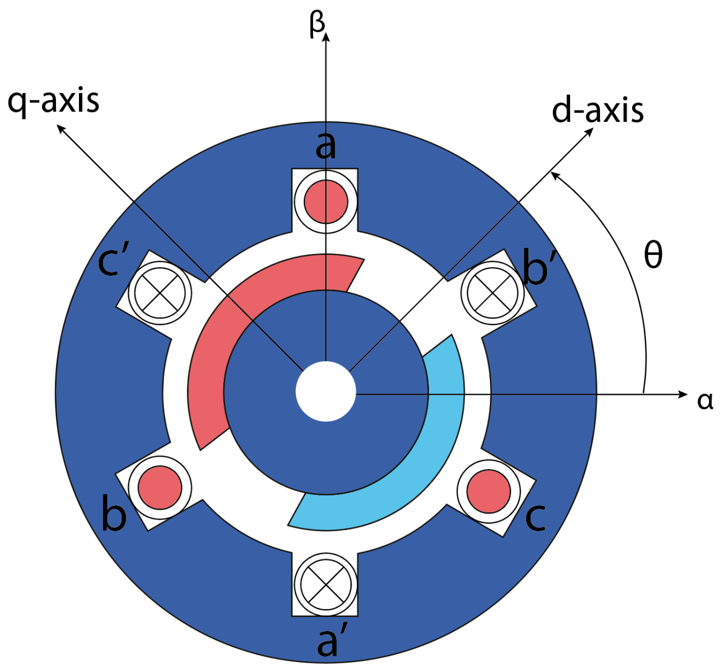


Figure 2.24: Cross section of a permanent magnet synchronous motor, three phases, one pole-pairs

Depending to rotor shape, motor design can be distinguished for the same technology. Figures 2.25 and 2.26 illustrate a cross section for a salient pole and cylindrical rotor.

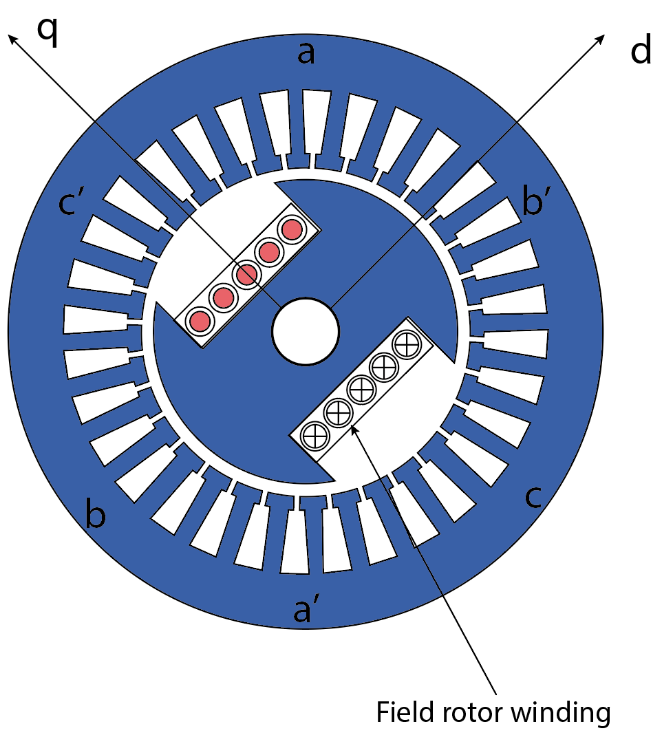


Figure 2.25: Cross section of synchronous machine with salient pole

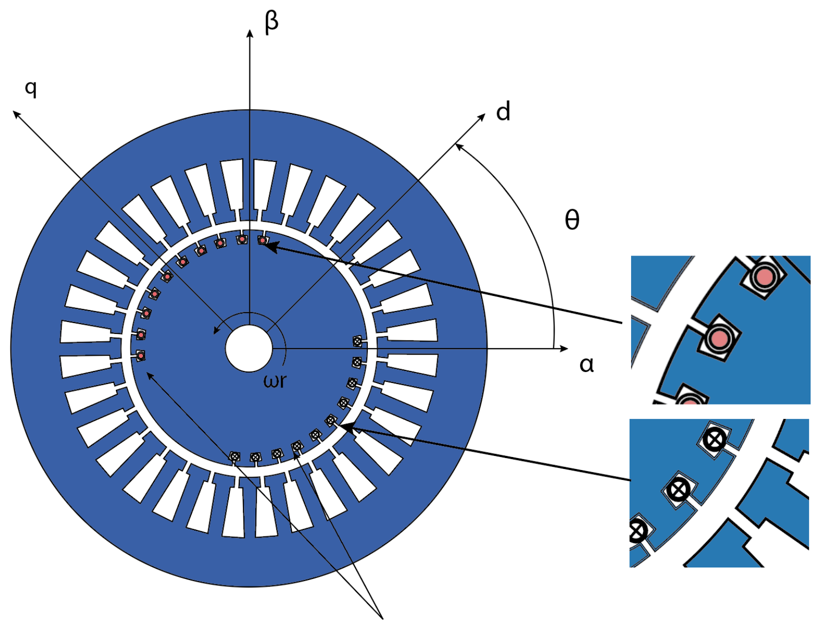


Figure 2.26: Cross section of Synchronous machine with cylindrical rotor

2.2.2 Induction motor(IM)

There are two types of rotor construction in Induction machines.

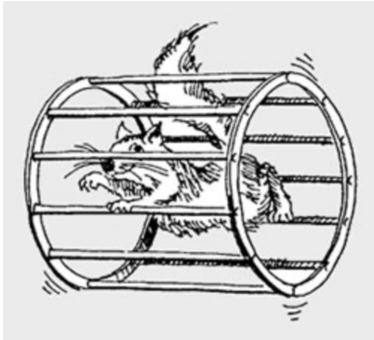
- Squirrel cage rotor
- Wound-rotor

Both designs will be explained with associated cross in separate parts.

2.2.2.a Squirrel cage rotor

Induction motor squirrel cage is used to convert electrical energy to mechanical motion. It is low cost and due to not having brushes the maintenance is cheape in compare with BLDC motors.

(a) Rotor and stator EMF interaction.



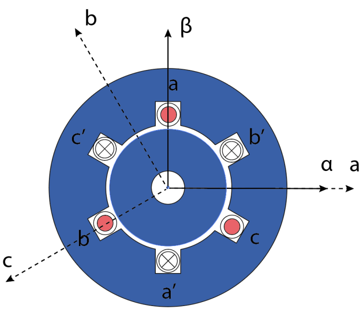
(b) Squirrel cage!

Figure 2.27: Squirrel cage induction motor [8]

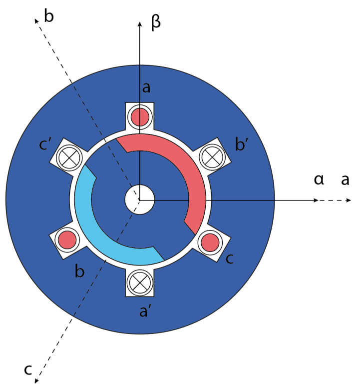
Among the differences between induction motor and synchronous machine, the basic one is that the IM unlike the synchronous machine is an asynchronous machine.

2.2.2.b Wound rotor

In Wound rotor induction motor, rotor has three winding likewise stator winding; the windings which are located in slots are connected to slip rings and by rotating the rotor they rotate accordingly, while brushes stay stationary. As it stated earlier the interaction of magnetic field in rotor and stator trigger the torque and cause the rotor to rotate. There are two kinds of induction motors which are three and single phase. The single phase is powered by a single phase AC power and is used in small applications due to size and power constraints. Single phase induction motors are used in household applications like washing machine, refrigerator, pumps and etc. figure 2.28 shows Induction motor with and without permanent magnets.



(a) Cross section of an Induction motor



(b) Induction motor with PM located inside the rotor

Figure 2.28: Induction motor with and without permanent magnets

In an electric motor there are two magnetic field which generated by rotor and stator. While stator magnetic field is rotating, the idea is that rotor align its magnetic field with the stator magnetic field. The three phase set of currents in the stator have equal amplitude with a phase difference of 120°. These currents flow in the stator winding and generate the magnetic field. Among proposed configuration for rotor winding, four rotor winding is the most complete which are denoted by f, d_1, q_1 and q_2, where f stands for field winding, q_2 stands for eddy currents in rotor and d_1 and q_1 represent dampers.

Further, housing of the motor protect the motor from dust, water and humidity. depending on the environment and application two housing are provided by different suppliers.

- Aluminum housing
- Cast-Iron housing

While Aluminum housing is lighter, cast-iron guarantee more robustness. Figure 2.29 illustrates an induction motor with a wound-rotor.

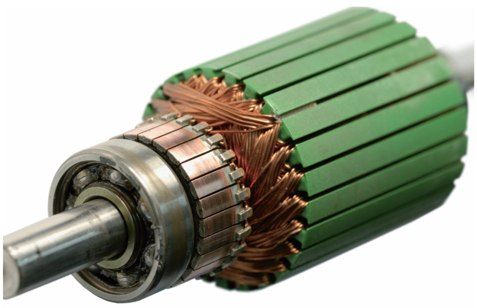


Figure 2.29: Induction motor wound-rotor
[9]

Two suppliers including **OMEC** and **MT motori electrici** are chosen for induction motor.

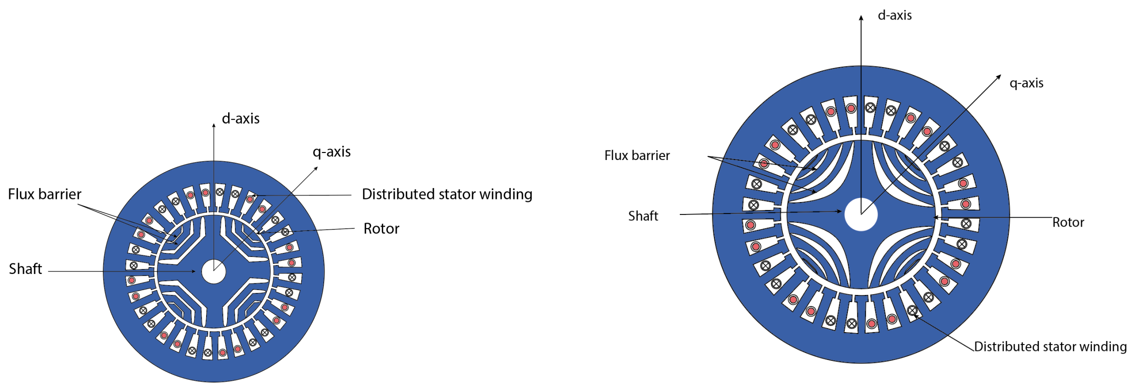
Induction motor(IM) topology					
Supplier	Speed range(rpm)	Torque range(Nm)	Power range (W)	Volume range (m^3)	Rotor inertia ($g.cm^2$)
OMEC	693 - 1430	0,42 - 40,2	60 - 3000	$(5,7-47,3)*10^{-4}$	1000 - 382800
MT motori electrici	1340 - 1450	0,65 - 19,8	90 - 3000	$(6,3-40,6)*10^{-4}$	N

A total number of 46 motors are considered for this technology.

Induction motor technology		
Supplier	Number of Motors	Price(Euro)
GAMAK	23	N
MT motori electrici	13	N

2.2.3 Synchronous reluctance motor(SynRM)

Synchronous reluctance motors can be used in any condition. due to the size and weight of this technology, it is more often used in big scale applications. Suppliers try to cut the electricity bill and increase efficiency by changing the design of the motor. Some of these designs contains the arc shape of the flux-barrier of the rotor and installing high quality magnet inside the flux barrier to cut the cogging torque. Figure 2.30 illustrate two different flux barrier design of a synchronous reluctance motor.



(a) Linear flux barrier design (b) Arc flux barrier design

Figure 2.30: Two different designs of SynRM motor

Further figure 2.31 a salient pole rotor for a synchronous reluctance motor.

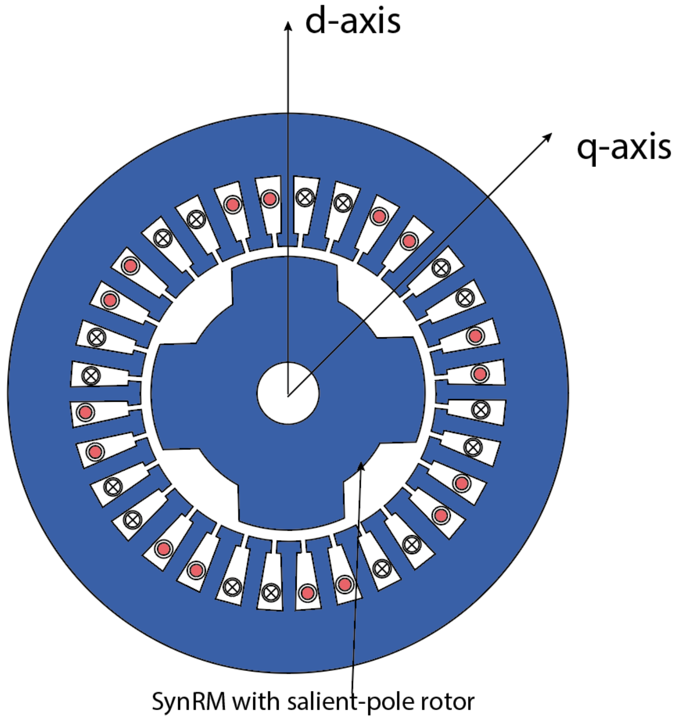


Figure 2.31: SynRM salient pole rotor

Two suppliers including **Siemens** and **SICEMOTORI** are chosen for this technology. Speed, torque, power, volume of the motor and rotor inertia are tabulated as below.

Synchronous reluctance motor(SynRM) topology					
Supplier	Speed range(rpm)	Torque range(Nm)	Power range (W)	Volume range (m^3)	Rotor inertia ($g.cm^2$)
Siemens	615 - 725	1,4 - 40	90 - 3000	$(8,9-148,8)*10^{-4}$	7700 - 370000
SICEMOTORI	1400 - 1500	3,5 - 19,1	550 - 3000	$(1,2-4,06)*10^{-3}$	750000 - 2900000

A total number of 17 motors are considered for this technology.

SynRM motor technology		
Supplier	Number of Motors	Price(Euro)
Siemens, 8-ole, Iron-cast	11	N
SICEMOTORI	6	N

2.2.4 Radial-flux Machine

The methodology of the radial-fluux density is as the same of the induction machine.

2.2.5 Axial-flux machine

Some difficulties including iron-loss, cogging torque, eddy current in PM, copper loss, torque ripple make the axial-flux machine more complex in compare with radial-flux.

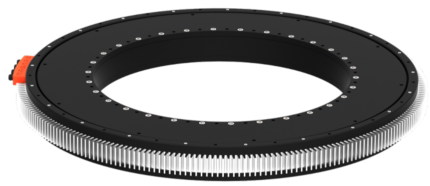
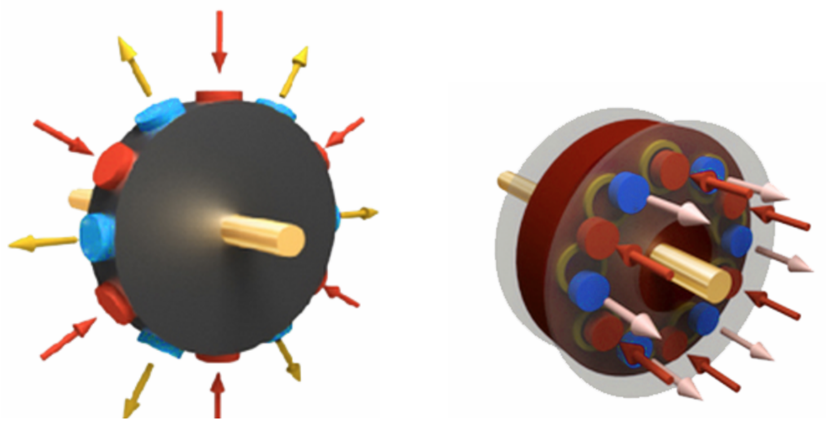


Figure 2.32: Axial-flux PM electric machine
[4]

Since the windings are buried between the rotor disks, it will cause a cooling challenge. Figure 2.33 shows how flux is produced in both topology.



(a) Flux is produced radially along the contour of the rotor

(b) Flux is produced axially along the axis of the rotor

Figure 2.33: Flux produced in both technology of radial- and axial-flux
[4]

There are two designs for stator; slotted or slotless, the slotted design is a complex technology for axial-flux, thus slotless design is more handy for motor manufacturer [10]. Axial-flux motors provide high power density and high efficiency.

In order to give a clear image of axial-flux motor this technology is compared with radial-flux motor technology which is used in BMW i3 motor depicted in figure 2.34.

(a) BMW i3 Motor

(b) Magnax AXF290

Figure 2.34: Two motor technology for e-mobility manufactured by (a) BMW and (b) Magnax [6]

The characteristics of both motor technology are tabulated in the following table.

Comparison of radial -flux PM motor and yokeless axial-flux PM motor		
Supplier	BMW i3 Motor	Magnax AXF290
Technology	Radial flux	Axial flux
Diameter(mm)	300	290
Weight(kg)	46	25
Peak Power(kW)	125	≥ 400
Peak Torque(Nm)	250	≥ 510

In Axial-flux motors what makes this technology distinguished in compare to to the other motor technologies is that, magnetic fields are created axially, which is located parallel with shaft. In axial-flux motors cogging torque is significantly reduced. Further this technology is ironless and makes this technology lighter. Thanks to generating higher torque, Axial-flux motors are used in e-mobility although before they have been using more in stationary applications.

Chapter 3

Quantitative comparison

In previous chapter the motors topology, principle of operation and their corresponding advantages and disadvantages were investigated. More than 200 machines were chosen to give a quantitative comparison between different technologies. This comparison is considered based on the properties like speed, torque, power, volume and rotor inertia.

3.1 Speed

By comparing the nominal speed of different electric motor technology electric motor to rated power, the figure 3.1 is obtained.

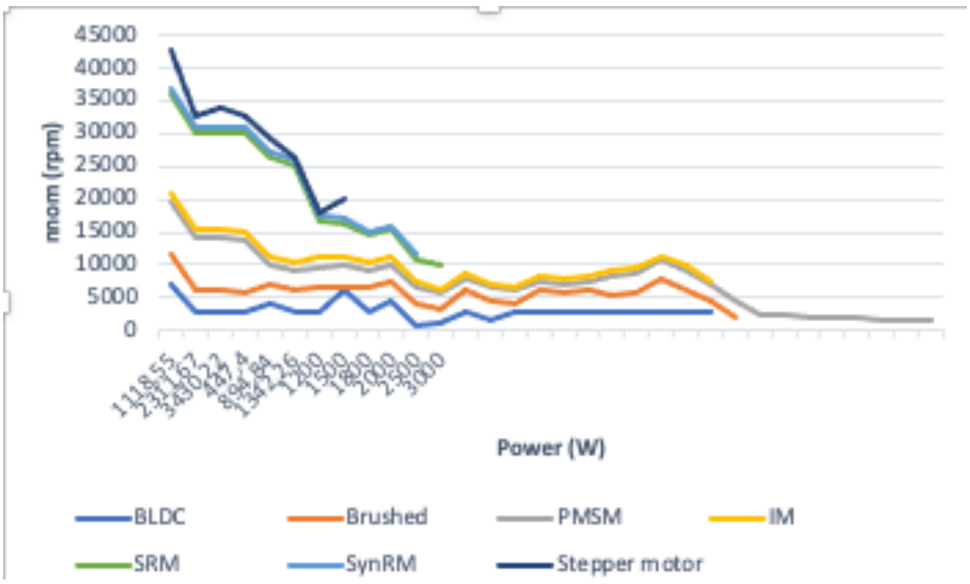


Figure 3.1: Nominal speed compared to power

3.2 Torque

By comparing nominal torque to nominal power figure 3.2 is obtained.

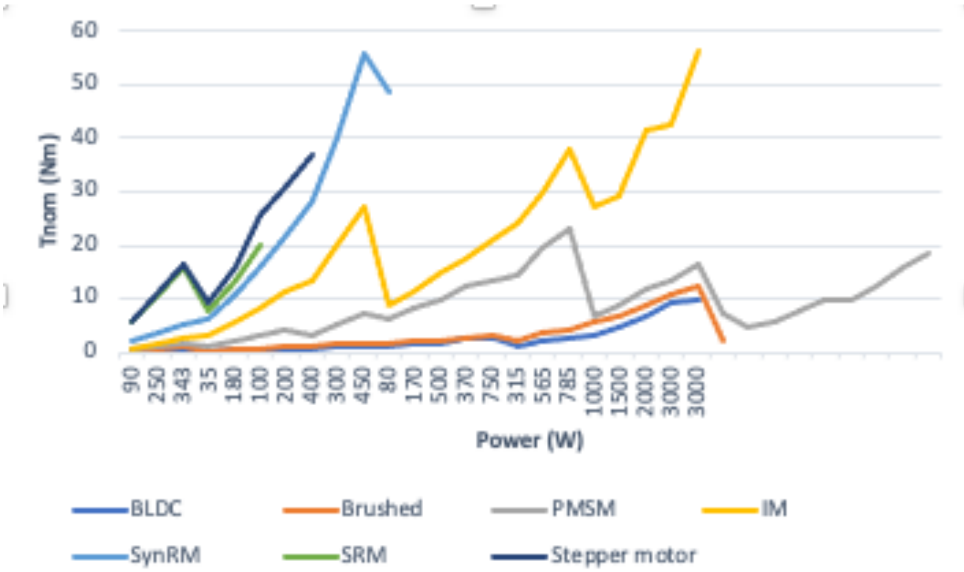


Figure 3.2: Rated torque compared to power

While comparing nominal torque to volume leads to figure 3.3.

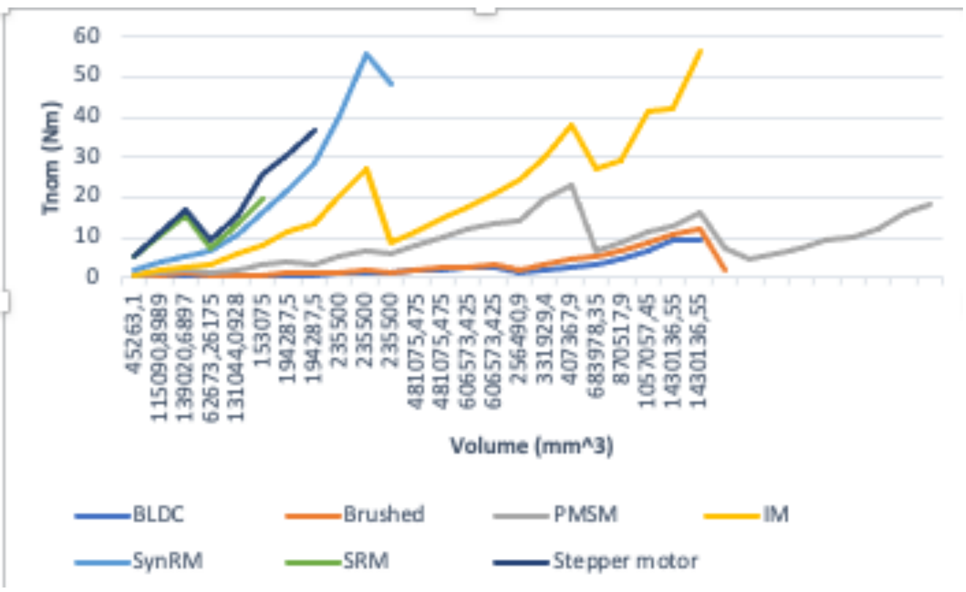
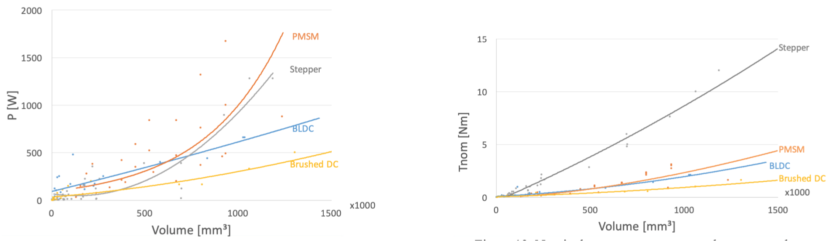


Figure 3.3: Nominal torque compared to power



(a) Motor power compared to volume

(b) Nominal motor torque compared to volume

Figure 3.4: Stepper motor performance in compare with other motors

3.3 Power density

By depicting power to volume figure 3.5 is obtained. This comparison gives the optimal solution to the customers when size is a constraint.

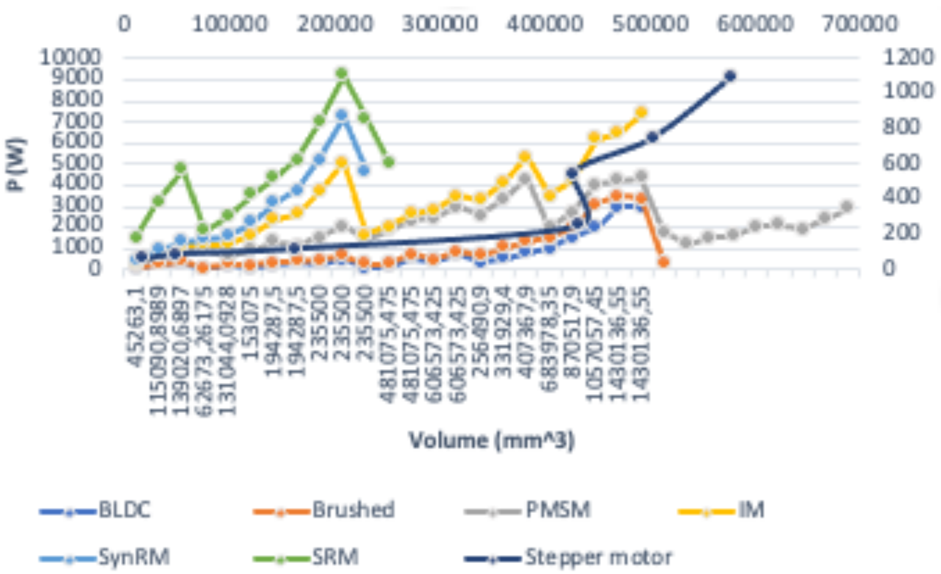


Figure 3.5: Power compared to volume

3.4 Acceleration and overload capacity

By dividing the motor maximum torque (Nm) to rotor inertia ($g.cm^2$), maximum accelerating $\alpha_{max}[rad/s^2]$ is obtained which is an interest for dynamic applications [2]. Figure 3.6 shows maximum acceleration compared to power.

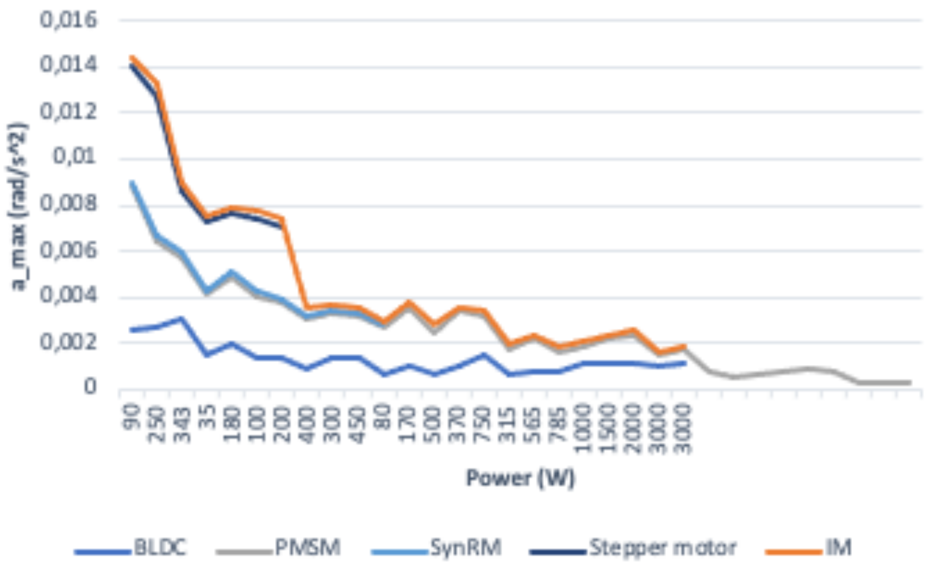


Figure 3.6: Maximum acceleration compared to power

Chapter 4

Conclusion and proposed technology for future job

In this work different motor technology were compared quantitatively. Two supplier were chosen for each technology and based on each motor characteristics, different plot were illustrated to show which technology better suits different applications. This comparison gives a clear vision to different suppliers to have their optimal option subjected to constraints and requirements. In this work more than 200 motor with different technologies were considered to give crystal clear quantitative comparison. This comparison covered all electrical motor technology which are commercially available.

The results of this study will be published as a conference paper. Studying on axial-flux motors due to its compactness and high torque in low speeds is extremely important in automotive industry. Therefore focusing in this technology can lead to sustainable solution for automotive industry and could be considered as the future job.

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Appendix A

Motor types

A.1 Cogging torque

Cogging torque is a consequence of gap between Rotor and Stator, Therefore a small gap will lead to a small cogging torque. On the other hand maximising magnetic field requires gap. Its a trade off between cogging torque and magnetic field and suppliers consider this issue subjecting to their constraints. Motor vibration is a consequence of cogging torque and should be minimised during the design; for instance the number of slots should be chosen is a sense that avoid cogging torque. As it was explained earlier depending the application and its objectives accordingly, the design will be different. for instance in automotive applications a bad design due to high cogging torque can consequently lead to motor vibration and affect the comfort parameters.