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**Project group:** 

[Bogdan Ioan Incau]

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SYNOPSIS: A Wavestar system generates electrical energy from wave energy. Among the existing hydraulic or pressure based concepts presented in this report a mechanical transmission based system is described. It consists of a wave, float, gearbox, generator and converter and the goal is to design and test a controller of this system. A Permanent Magnet Synchronous Generator controlled

transmission based system is described. It consists of a wave, float, gearbox, generator and converter and the goal is to design and test a controller of this system. A Permanent Magnet Synchronous Generator controlled through a Field Oriented Control strategy converts the wave power into electricity. The wave energy is converted into to mechanical power using a float technology developed in previous Wavestar projects. The system is modeled and a design of a controller is done for sinusoidal load torque and speed reference. This make the controller more complex compared with standard speed control. The simulation model of the system was created in Matlab/Simulink. A laboratory setup has been made to confirm the simulations, composed by an Induction Motor emulating the wave, connected to a PMSM, both controlled with a dSpace ControlDesk interface system. The experimental work was limited to a maximum speed of 500 [rpm] because of 2.2 kW IM output power. The average power extracted was 0.8 kW comparable with a 1.2 kW power from simulation results. The developed control is tested and the measured signals are torque, speed and power, with a working proposed control strategy. The conclusions are drawn based on system analysis and proceeded tests.

By signing this document, each member of the group confirms that all group members have participated in the project work, and thereby all members are collectively liable for the contents of the report. Furthermore, all group members confirm that the report does not include plagiarism.

# Preface

The Master Thesis was carried out during the 9<sup>th</sup> and 10<sup>th</sup> semester in the Department of Energy Technology at Aalborg University from 1<sup>st</sup> September 2012 to 30<sup>th</sup> of May 2013.

This report is a research for the project entitled *Wavestar Generator*. The project is divided in three parts: problem analysis, modeling of the system and experimental setup.

The chapters of this project are consecutively numbered. Figures and equations are numbered according to the chapters where the first number represents the chapter and the second represents the figure number in the chapter.

The figures, diagrams, schematics and measurement plots are shown in List of figures section.

Literature references are shown in square brackets in the report body and detailed in the *Bibliography* section at the end.

A CD containing the simulation models and the main report is attached to the project.

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# 1. Introduction

The first chapter presents a brief introduction of Wave Energy Converters (WECs) existing in the wave energy production field. Main successful concepts are presented as background for the project emphasizing their characteristics. Description of the considered idea and limitations of the researched subject are also introduced.

#### 1.1. Background of Wave Energy Converters

Because of the continuous growth of price of fossil fuels, more renewable energy solutions have been developed in response to the interest of limiting production costs for electric energy. Nowadays, photovoltaics and wind power have developed from the level attractive alternative solutions to major power generation technologies. At the end of 2011, 26% of the total electric energy in Europe was generated by PV plants and 21% of it by means of wind power plants. As the trend is to replace conversion of power plants, the levels are expected to grow significantly. [1]

However, the main issue of PV and wind power is that the produced power is highly dependent of natural condition variation. Therefore, they are very useful in covering the power usage peaks but would require large energy stocking solutions in order to become major players on the energy market. On the other hand, the grid interest for harvesting renewable energy represents an advantage for the entire world production.

A new form of unexploited energy source is represented by the ocean waves. Wind energy is highly related to this form of energy because it can be transferred in the water. Renewable energy area has reached a high level of extraction because of friendly main characteristic of it. Being a new form of energy, many wave energy converters have been developed in the last 30 years. The prototypes developed in the field, consists from hydraulic subsystems to pure mechanical components with the aim of electric energy as output. The rate of success is relatively wide but many inventions are not suitable for any conditions being limited by external factors like meteorological conditions or desired area of installation. [2]

To build a wave energy converter, an overview of how WECs are categorized must be realized. According to working principles and optimum energy extraction systems like power takeoff the wave energy systems must be well defined for a new design with good expectations for the success rate of it.

Ocean waves consists either in kinetic or potential form of energy in different types, from currents appeared during the flow or tidal because of the rise or ebbs of water. Other particularities like thermal and salinity are the object for different fields than energy extraction but can influence at some points the behavior of the converters. [3]

The Earth's surface has a different level of heating from the solar energy creating winds. The air flowing is not limited covering large areas of water and transferring a part of energy to the liquid state. The amount of energy translated depends on the size of the covered area, wind speed or the time period in which the wind and water interacts. The total worldwide potential of energy form waves is in a range of Terawatts (TW) [4]. It has a uniform distribution, depending on areas where wind constantly flows and as can be seen in Figure 1.1 wave activity can be highly observed on bot hemispheres between the latitudes of approximately 30 and 60 degrees. The red highlighted lines are showing on the entire globe map the most perspective areas from the wave energy availability point of view.



### Figure 1.1: Global distribution of available wave power [3], [5]

The highest wave potentials on the entire earth is represented by some regions and countries as follows: Southern part of Africa and America, New Zealand, few coasts in the Western part of Australia, Canada and United States ocean side parts of them and the Western part of Europe. A high energy density can be found in waves as a renewable energy form comparing to wind or photovoltaic with an easier prediction for a certain period of time being the biggest advantage for this new field. The external factors have almost no effects on the behavior of wave currents being capable to travel large distances with a continuous transfer of energy but almost no losses. [6]

The devices developed with the purpose of energy extraction from the waves and transform it into electrical energy are called WECs. Over the last period, wave energy converter field had gain a great significance for industry research, building more and more appropriate systems. Compared to other renewable energies this area is immature because of not optimum patents developed so far. In some European countries, the industry linked to government-sponsored programs leads more and more projects with the aim of increasing the research level for a competitive place with wind and photovoltaic.

The economic aspects leads a precise designing of energy converters with challenges like reliable and viable ideas implemented and optimized.

- The wave amplitude, period, phase and direction have a random variability making much harder for the energy extraction device to operate efficiently. As the external parameters are in a continuous changing, the challenge for the WECs is represented by increasing conversion efficiency for a wide range of excitation parameters. [7]
- When an ocean storm appears, the loading on WECs can reach levels of 100 times bigger than in normal weather conditions. Therefore, a WEC must be over-dimensioned to be able to withstand these sever conditions and because of this, the building price for the device is highly increased. [8],
- A major challenge is represented by connection of irregular and slow wave motions with frequencies of 0.1 to 0.5 Hz to a drive generator capable to provide energy with an acceptable quality for the network grid. Some problems were taken into account leading to solutions like:
  - Implementing an internal energy storage system like water stored in reservoirs with the aim of energy buffer with hydraulic PTO and accumulators; [9]
  - The use of electrical energy storage systems like fuel cells, supercapacitors, battery storage systems or superconducting magnetic energy storage devices; [10]
  - The torque produced by the waves is very big and it can harm the device. In order to decrease it and in the same time to increase the reference speed for the generator a gearbox is connected between the wave plant and the motor, reducing mechanical stress applied; [8]
- In order to design and build a successful converter many evaluations and vigorous testing procedures must be undertaken on the device. The experience and knowledge are critical for the inventors regarding offshore operating behavior of system and equipment used. For a hydraulic wave energy converter system with parts like structure of WEC, mooring, power take-off equipment or transmission of the power, after 6000 hours of operation, the energy converter has a higher maximum reliability with 15%.

A few fundamental concepts of wave energy systems with their topologies and subsystems are presented in Table 1. As may be notice, only PELAMIS concept is working with fixed speed with hydraulic PTO connected to an induction motor. [11]

Device	Power Take-Off	Speed	Generator
PICO	Oscillating Water Column and Wells turbine with guides vanes	Variable	DFIG
PELAMIS	Attenuator/Hydraulics	Fixed	Induction
OYSTER	Oscillating Wave Surge Converter	Variable	Induction
LIMPET	Oscillating Water Column and Wells turbine	Variable	Induction
OCEANLINX	Oscillating Water Column and Denniss-Auld turbine	Variable	Induction
AWS	Direct drive	Variable	LPMG
SEAREV	Point Absorber	Variable	PMSG
WAVE DRAGON	Overtopping and Kaplan turbine	Variable	PMSG

 Table 1: Wave energy concepts

PICO wave energy converter consists of a pneumatic chamber structure on the top of the water interacting with the incident waves of the sea by a totally water covered opening in the front wall, and through a fiber duct with the atmosphere. Tests made on PICO were realized for a total amount of 1 MWh energy extracted. In Figure 1.2 is shown the operating principle for a typical PICO wave energy concept.



Figure 1.2: PICO WEC operating principle [12]

PELAMIS is a wave energy converter installed with a big rate of success a few kilometers off the northern coast in Portugal being first concept in the industry field of scaled wave energy harvesting system in the world. The system operates half floating over the water surface and consists of three cylinders connected through joints. Each unit has approximately 3.5 meters diameters and 140 meters long. The total weight of the power conversion system is 700 tons made of carbon steel. The interior of cylinders contains hydraulic rams opposed to the movement and driving induction generators. For a scaled converter, the amount of power extracted per working unit is 750 kW. PELAMIS P-750s working principle is depicted in Figure 1.3: [13]



Figure 1.3: PELAMIS wave energy converter [14]

The OYSTER wave energy concept was designed to be installed near the coasts and the aim of energy extraction from the near shore waves, around half a kilometer away. It operates almost entirely covered with water. The system consists in hinged flaps connected to a groundwork almost 10 meters depth on the bottom of the ocean. The water flow pushes the hinged flaps backward and forward driving two hydraulic pistons. The generator used is an induction motor operating at variable speed. First full-scale converter was named OYSTER 1 in Orkney, Scotland in 2009 and Figure 1.4 shows the working principle of it.



Figure 1.4: OYSTER WEC system [14]

Land Installed Marine Powered Energy Transformer is also called LIMPET designed for strong waves and placed on shoreline. The system contains an induction motor which operates at variable speed. First WEC concept was installed on the island of Islay, off Scotland west coast. LIMPET 500 produces energy for United Kingdom and the operating principle is shown in Figure 1.5.



## Figure 1.5: LIMPET energy converter [15]

As a floating system, OCEANLINX operates on oscillating water column principle. It consists in a piston which pushes the air through a column driving a variable speed induction generator. The Denniss-Auld turbine, Figure 1.6, has been designed with variable pitch blades in order to control and smooth the speed for the generator and making the direction to be constant.



Figure 1.6: OCEANLINX converter [16]

The AWS concept is fixed on the bottom of the ocean having a cylinder filled with air, called floater. The floater moving is in the vertical direction creating a high pressure in the air pushing it up and down. The AWS contains a variable speed drive, the energy being extracted from the floater reciprocating motion as can be seen in Figure 1.7. [17]



Figure 1.7: AWS wave energy systems [17]

The SEAREV wave energy concept represents a floating device with a horizontal axis wheel as a gravity reference acting like a pendulum. A power take-off hydraulic system drives a variable speed permanent magnet synchronous generator. The SEAREV system is depicted in Figure 1.8 as follows: [18]



Figure 1.8: SERAEV wave energy converter [19]

Wave Dragon is a wave energy converter for offshore areas with the principle of floating device. It is composed by two arms displaced in mirror one of another, a curved ramp situated on the top, a reservoir for water and low pressure turbines. The aim of arms is to concentrate from their moving the water on the ramp and after that into the reservoir situated above the sea level. The electric power conversion is realized by modified Kaplan-turbines typically for low pressure. The wave energy converter system is designed for offshore operation, moored but it has a level of freedom in order to change the position according to the wave direction. A grid connected scale-model was successful installed in 2003, located in Nissum Bredning, Denmark. The operating principle of a Wave Dragon is depicted in Figure 1.9.



Figure 1.9: Wave Dragon operating principle [17]

## 1.2. Problem formulation

On the surface of the sea or any areas with big amount of water the wind can produce short differences of depths forming waves. This movement is producing energy which can be transformed into electricity and also exploited.

A good solution to capture a big amount of this energy can be the use of a Wavestar Generator which contains only mechanical elements for the plant, making this different than other wave promoted systems.

As it was presented before, wave energy concepts are based mostly on hydraulic elements, high pressure based equipment which represents a more complex maintenance.

Even though the mechanical system is not so reliable one of the advantages is that the power is directly transferred to the generator through a gearbox, therefore the system has minimum losses.

The Wavestar generator system is drawn in Figure 1.10 and is composed by a float directly linked to a gearbox. A Permanent Magnet Synchronous Generator is connected to the output, feeding with mechanical power in meaning of speed and torque both having positive and negative values described by a sinusoidal waveform motion.

The arm has a circular movement rotating a wheel in both directions when the float is lifted up by the wave and limited by the  $\alpha$  angle. The waveform of the speed and torque at the output is also shown and it can be seen that both are sinusoidal with respect to the time.

The gearbox linked to the generator must be fixed on the bottom of the water but situated on the surface also making easy to maintain or change the system. For a simpler control of the converter a modified gearbox can be integrated in the system. The variation of the speed from positive to negative can be replaced by only a positive one and also mechanical energy storage system can be added to the system.

Wavestar Generator is designed similar to the classic Wavestar concept from the float point of view having a hemisphere shape and with one level of freedom.

Because of the inertia and considering the hydrostatic coefficient, the speed produced by the float is shifted 180 degrees of the transferred torque.



Figure 1.10: Wavestar generator proposed system

Having a variation of the speed and torque both with positive and negative values but shifted, the control part of the generator is not an issue for a desired output.

## 1.3. Objectives

The goals of this project represent the designing of a control technique according to input type for the Permanent Magnet Synchronous Motor applied for the generator mode. The objectives of the project are stated bellow:

- Build an accurate model for the wave;
- Build the system model to observe the behavior;
- Design a control technique suitable for the input type of parameters;
- Choose an optimum solution for the system;
- Implement the control technique through dSpace software on the PMSM drive;
- Validate the control strategy;

## 1.4. Limitations

The main objective of this project is to develop a new method of harvesting energy from waves. Considering this, wave movement can only be simulated but it will not result in a precise behavior of waves. Limitations are pointed as follows:

- Inaccurate wave model for the simulation;
- Induction motor represents the wave emulator and feds the PMSM;
- The laboratory setup is limited by only 2.2 kW power fed by the Induction Motor;

## 1.5. Report layout

The 1<sup>st</sup> chapter represents an overview of existing Wave Energy Converters. Based on developed prototypes the Wavestar Generator is designed and modeled in order to be tested. A project description is also presented, emphasizing further the objectives and limitations for the subject.

The 2<sup>nd</sup> part of the project deals with the wave model described from the physical point of view. The wave behavior and its output are detailed in order to define the input parameters for the drive. A Permanent Magnet Synchronous Motor mathematical model is presented and implemented into the simulation model.

In the 3<sup>rd</sup> chapter of the project the control part of the motor is presented. Field Oriented Control technique with some optimizing strategies for the control of the motor are detailed. A complex calculation and stability analysis is made in order to be implemented into the experimental model of the Wavestar Generator. The ideal system behavior is reflected through output waveforms of the system in order to prove the validity of the concept.

4<sup>th</sup> chapter contains a description of the laboratory setup with the hardware and software equipment and tools used. The implemented model is also described for a better understanding of the system conditioning and limitations.

The 5<sup>th</sup> chapter presents the experimental results for the real behavior of the system. The system outputs measured are depicted in order to have a comparison with the simulation model results.

The last chapter presents the conclusions of the report. Advantages and disadvantages of designing a Wavestar Generator are emphasized together with the future work regarding the presented topic.

# 2. Simulation model

The wave generator system is presented in this chapter. A real wave model is designed according to the system parameters and external factors like wave movement or applied force. The Permanent Magnet Synchronous Motor mathematical model is also presented in details.

## 2.1. Wave model

The wave model is presented and built in order to obtain a behavior close to the real situation. As for different dimensions of floats, from 5 [m] to 0.25 [m], the main parameters are implemented for a 1 [m] float. The resonant frequency of the plant is higher than the frequency of the wave being more efficient from the design point of view in meaning of a slower float. Related to the control strategy a random signal can be used as an average of 0 [m] position instead of a sinusoidal waveform for displacement of the float.

For simplicity, the water flow can be considered as interacting with the float on a vertical direction with an excitation of single frequency basically set for 2.75 seconds the entire period. Therefore, the displacement can be expressed as in Equation 2-1: [20]

$$x = A \cdot \sin(\omega \cdot t) = A \cdot \sin(2 \cdot \pi \cdot f \cdot t) \ [m] \ (2-1)$$

The power existing in waves is defined by:

$$P_{wave} = \frac{\rho \cdot g^2 \cdot T \cdot A^2}{64 \cdot \pi} \approx 0.49 \cdot T \cdot A^2 \left[\frac{kW}{m}\right] (2-2)$$

Where:

 $\rho$ =1025 [kg/m<sup>3</sup>] is the density of sea water;

g=9.81  $[m/s^2]$  is the acceleration due to gravity;

 $T=f^{-1}$  is the wave period;

A is the amplitude of the wave;

Having a hemisphere shape, the weight of the float can be determined from the next equation:

$$m_f = \frac{\rho \cdot 2 \cdot \pi \cdot r^3}{24} [Kg] (2-3)$$

Where:

r represents the radius of the float; [21]

The wave model block diagram is depicted in Figure 2.1:

#### Wave movement



Figure 2.1: Block diagram of the wave model

A large variation of the wave in meaning of 0 crossing waveforms means a more complex control for the system. If the wave can be transferred to the generator in a rectified waveform the quadrant jumping in the control part will disappear. Therefore, a positive speed for the generator can be obtained modifying the gearbox as can be seen in Figure 2.2.

This new idea of mechanical power transfer has a big consequence on the total inertia of the system. In the same time the speed controller has difficulties in following the reference speed because the time constant of the system will be considerably changed. [22]



Figure 2.2: Modified gearbox for absolute value of speed [23]

The wave model loads the Permanent Magnet Synchronous Motor with mechanical power in meaning of torque. The speed is adjusted through a gearbox to a desired value according to the generator requirement input.

It contains three subsystems according to the elements which can influence the behavior of the system. First block represents the transfer function of a low-pass filter which transforms the displacement of the float, from [m] into the torque applied by the wave, [Nm].

The parameters for the wave model were taken from a tested float and can be seen in TABLE.

 Table 2: Wave model parameters [24]

Subsystem	Frequency [Hz]	DC gain	Туре
Elevation to torque	9.15	13260	4 <sup>th</sup> order low-pass filter
Plant	K=22404	J=1314.6	3 <sup>rd</sup> ord. transfer function
Damping	1.32	1364.6	2 <sup>nd</sup> order filter

Where:

K [Nm] represents the stiffness coefficient;

J [kg $\cdot$ m<sup>2</sup>] represents the inertia of the float;

It is a  $4^{\text{th}}$  order filter having a dc-gain of 13260 and a frequency of 9.15 [Hz]. The transfer function of the filter is depicted in equation (2-6). It is known from classic control theory that a second order transfer function has the following form: [25]

$$H_{2nd}(s) = \frac{N(s)}{\frac{s^2}{\omega_n^2} + \frac{s}{Q \cdot \omega_n} + 1} (2-3)$$

Where:

N(s)=k represents the DC gain of the filter;

 $\omega_n = 2\pi f \text{ [rad/s]}$  represents the frequency of the filter;

$$\omega_n = 2 \cdot \pi \cdot f_{LPF} = 57.49 \ [rad/s] \ (2-4)$$

Therefore, the transfer function can be expressed for a unity gain as: [25]

$$H_{2nd}(s) = \frac{1}{1+2\cdot\zeta \cdot \frac{s}{\omega_n} + \left(\frac{s}{\omega_n}\right)^2} = \frac{\omega_n^2}{s^2 + 2\cdot\zeta \cdot \omega_n \cdot s + \omega_n^2} (2-5)$$

The 4<sup>th</sup> order low-pass filter was designed with two second orders unity filters having the same parameters and the DC gain was added to the system after implementing the filters. The damping coefficient is implemented as  $\zeta$ =0.707 for all transfer functions existing in system. Substituting the parameters into the transfer function, the desired filter has the following form: [25]

$$H_{LPF}(s) = \frac{3305.1}{s^2 + 81.29 \cdot s + 3305.1} \cdot \frac{3305.1}{s^2 + 81.29 \cdot s + 3305.1} (2-6)$$

Adding also the DC to the system, the final transfer function for the system became:

$$H_{LPF}(s) = \frac{144.8 \cdot 10^9}{s^4 + 162.6 \cdot s^3 + 13220 \cdot s^2 + 537.3 \cdot 10^3 \cdot s + 10.92 \cdot 10^6}$$
(2-7)

As can be seen in the frequency response of the filter is outlined the resonant frequency with design value. The system stability is not affected by the filter.

In Figure 2.3 the frequency response of the filter is depicted.



Figure 2.3: The frequency response of the filter

The second subsystem is represented by the plant with a value for the inertia of 1314.6  $[kg \cdot m^2]$  and hydrostatic stiffness of 22404 [N·m].

The transfer function which characterizes the float can be expressed as: [25]

$$H_{Float}(s) = \frac{1}{1314.6 \cdot s + 22404} \,(2-8)$$

The behavior of the float must be adjusted and in a real situation the total transfer function which transforms the torque into speed has a phase shift of 180 degrees. Therefore, the transfer function added into the plant block can be expressed as:

$$H_{Adit}(s) \frac{s}{s^2 + 2 \cdot s + 1}$$
 (2-9)

Therefore, the plant transfer function can be expressed as:

$$H_{Plant}(s) = H_{Float}(s) \cdot H_{Adit}(s)$$
 (2-10)

The final expression implemented into the simulation model has the next form:

$$H_{Plant}(s) = \frac{s}{1315 \cdot s^3 + 25030 \cdot s^2 + 46120 \cdot s + 22404}$$
(2-11)

The frequency response of the plant is depicted in Figure 2.4:



#### Figure 2.4: Frequency response of the plant

Because the system is modeled with real parameters, for the plant must be added a new subsystem in meaning of a damping factor.

It is designed with a frequency of 1.3208 [Hz] and a dc-gain of 1364.6. Its transfer function is expressed as a second order filter as follows: [25]

$$H_{D_{2nd}}(s) = \frac{68.89}{s^2 + 11.73 \cdot s + 68.89} \,(\textbf{2-12})$$

The transfer function of the damping factor is expressed as:

$$H_{Damp}(s) = \frac{94010}{s^2 + 11.73 \cdot s + 68.89} \, (2-13)$$

In the following picture, the frequency response for the damping transfer function is depicted:



**Figure 2.5: Frequency response of the damping transfer function** 

The transfer function which makes the conversion from torque to speed has the following expression:

$$H_{T-\omega} = \frac{H_{Plant}(s)}{1 + H_{Plant}(s) \cdot H_{Damp}(s)}$$
(2-14)

The frequency response of this transfer function is depicted in Figure 2.6 as follows:



Figure 2.6: Bode diagram for the Torque to Speed transfer function

As can be seen the torque to speed transfer function shifts the input signal with 180 degrees. Therefore, having different signs for parameters at any certain moment, the PMSM operates always in the generator mode. The float displacement is made for a typically value of 0.6 meters with a sinusoidal waveform which reflects an ideal case. It can also be seen in the figure bellow that the frequency of the wave is fixed with a value of 0.36 Hz:



Figure 2.7: Wave displacement variation in time

The output of the system is shown after the gearbox in order to have a clear resolution for the input signal to the generator. The frequency is the same value as 0.36 Hz but the amplitude is increasing in order to reach almost 500 [rpm] for the chosen generator.

The mechanical reference speed for the PMSG is obtained from the float with the square of gear ratio: [26]

$$\omega_{Gref} = \omega_w \cdot n_{gearbox}^2 \ (2-15)$$

Where:

 $\omega_{\text{Gref}} \, [\text{rpm}]$  represents the reference speed of the generator;

 $\omega_w$  [rpm] represents the speed produced by the wave motion;

n<sub>gearbox</sub> represents the gearbox ratio;

The load toque transmitted to the generator is obtained with the following relationship:

$$T_l = T_w \cdot \frac{1}{n_{gearbox}^2} (2-16)$$

Where:

 $T_1$  represents the load torque for the generator;

T<sub>w</sub> represents the torque produced by the wave;

In order to simulate the system, the maximum speed which could be reached was 500 [rpm]. From this condition a 1:14 gearbox was chosen and implemented into the system. To simplify the response of the system, gearbox influence like friction factor was neglected.



Figure 2.8: Reference speed for the generator

The load torque of the generator is depicted in Figure 2.9.

As the nominal torque of the motor is 20 [Nm], it can be seen that the gearbox is well chosen because the maximum value of the torque transmitted to the generator has the same value.

The torque has a waveform described by a cosine function and depends also on the wave period. It can be seen that for both speed and torque the period is almost 0.36 [Hz] which means 2.75 seconds.



Figure 2.9: Load torque for the generator

To observe a situation closer to reality, a random signal was introduced instead of the sinusoidal one. The frequency is varying in a small range of a few hertz and the amplitude of the signal is also changing from 0.3 to -0.3 meters. A randomized signal used for the wave subsystem can be seen in Figure 2.10 as follows:



Figure 2.10: Random signal to the input of wave subsystem

The Wavestar generator float control is valid also for random signals not only for a specified frequency and displacement as can be seen at the output:



Figure 2.11: Wave velocity with random signal

#### 2.2. Permanent Magnet Synchronous Generator model

Variable speed drives must have a well-designed control topology during the transient and steady-state operating mode in order to obtain high performances. In the past the dc machine with separate excitation was used for high performance applications. Problems like limitation of the speed range operation, a low level for the load capabilities, wearing of brushes or being not so robust, prevented the use of the machines for high performances applications. Therefore, the ac machine was preferred instead because of advantages like higher reliability or low maintenance. Permanent Magnet Synchronous Motors have many advantages as lack of external excitation, weighting less and a more compact design for that size compared to dc motors. When compared to an Induction Motor, the PMSM have a better full load capability regarding the power factor and a better efficiency for the steady-state operating mode. An important drawback of PMSM is the difficulty in rotor flux control compared to the dc motors where it represents just a variation for the armature current. [27] [28] [29]

#### 2.2.1. Dynamic Modeling of PMSM

The internal design of a Permanent Magnet Synchronous Motor depends on the place where the permanent magnets are mounted, like Surface Mounted PMSM, but does not affect the operating principle. The only difference can be made in the quadrature axes inductance values, as noted before, being approximated as equals for SPMSM. With this property and considering the permeability of the magnets almost the one of air, the air gap is uniform. Centrifugal forces does not affect any internal component during high speed operation because the magnets are glued using a sleeve or adhesive as can be seen in Figure 2.12. Only the rotor is represented here due to simplicity. The PMSM type presented is preferred in low speed applications, up to 3000 rpm. [27]



Figure 2.12: SMPMSM rotor sectionSection [27]

Further will be presented the mathematical model of the motor used in the simulations. The most used method to represent the parameters of the machine is d-q reference frame because through these transformations motor variables became DC quantities presented from the rotor side. In Figure 2.13 and Figure 2.14 are presented the electric circuit diagrams for d and q axes. Therefore, on the rotor side d and q axis voltages can be written as follows:



Figure 2.13: d-axis equivalent circuit [27]





 $v_d = R_s * i_d + p * \lambda_d + \omega_r * \lambda_q (2-17)$ 

$$v_q = R_s * i_q + p * \lambda_q - \omega_r * \lambda_d$$
(2-18)

The flux linkage is given by the next equations in d-q reference frame:

$$\lambda_d = L_d * i_d + \lambda_{af} (2-19)$$
$$\lambda_q = L_q * i_q (2-20)$$

Where:

V<sub>d</sub>, V<sub>q</sub> are the d-q axis voltages;

 $I_d$ ,  $I_q$  are the d-q axis stator currents;

 $L_d$ ,  $L_q$  are the inductances on the two axes;

 $\lambda_d$ ,  $\lambda_q$  represents the d-q axis stator flux linkages;

R<sub>s</sub> represents the stator phase resistance;

p is the Laplace operator d/dt;

 $\omega_r$  in rad/s represents the electrical speed of the rotor.

The electromagnetic torque is:

$$T_{e} = \frac{3}{2} * n_{pp} * [\lambda_{af} * i_{q} + (L_{d} - L_{q}) * i_{d} * i_{q}]$$
(2-21)

T<sub>e</sub> – represents the electromagnetic torque, in [N\*m]

 $n_{pp}$  – represents the number of pole pairs of the motor

For a Surface Mounted Permanent Magnet Synchronous Motor, the d axis inductance is approximately equal to the one of q axis. Therefore the electromagnetic torque can be expressed as follows:

$$T_{e} = \frac{3}{2} * n_{pp} * \lambda_{af} * i_{q} \ (2-22)$$

The mechanical movement equation can be described by the equation:

$$Jp\omega_m = T_e - T_L - B * \omega_m (2-23)$$

Where:

 $T_L$  is the load torque;

 $B_f$  is the friction coefficient;

 $\omega_m$  is the mechanical angular speed;

J is the moment of inertia;

p is the denote the differential operator d/dt.

Therefore, the mechanical speed is expressed by:

$$\omega_m = n_{pp} * \omega_r \ (2-24)$$

The rotor angle is obtained from the speed as follows:

$$\theta = \int \omega_r dt (2-25)$$

The mathematical equations of the PMSM were presented for modeling the electric converter [3]. Special requests and limitations of the drive system leads to a control strategy well designed presented in the next chapter.

#### 2.3. Wavestar generator system

The wave generator system consists of three main blocks as can be noticed in Figure 2.15. The green block in the left side represents the model of PMSM and the other green one, from the right represents the control block of the generator. The blue subsystem represents the implemented wave model which was presented before.



Figure 2.15: Wavestar Generator simulation model

The motor drive model is depicted in Figure 2.16. The inputs of the model are abc voltages and load torque. Transforming to dq reference frame the motor is modeled in order to output the rotor speed, electromagnetic torque and currents used further in the field oriented control system



Figure 2.16: PMSM model

# 3. Control strategies and simulation results

In this chapter the Field Oriented Control strategy is presented together with other optimization methods applied for Permanent Magnet Synchronous Motors. A detailed presentation of PI controller design is also made for the main topology. The ideal system behavior is emphasized also, for a further comparison with the real situation.

3.1. Permanent Magnet Synchronous Motor control

## **Field Oriented Control Strategies**

The main idea of field oriented control method is to emulate an individually excitation for the drive by controlling the torque and flux separately. As for AC drives the most used vector control strategy is field oriented control (FOC), it will be described in the next part of the chapter. [27]

The inverter which controls the drive is commanded with a space pulse based vector modulation technique. In the simulation model only reference frame transformation blocks will be used but for the experimental setup a pulse width modulation technique is implemented. The speed control schematic for the drive is depicted in Figure 3.1



Figure 3.1: FOC drive schematic [30]

The Field Oriented Control schematic contains two loop controls for d respectively q axis currents and a loop control for the speed. The speed controller influences the reference and measured torque of the motor. The difference between these two values in meaning of an error is computed through a Proportional Integral controller. The aim of the controller is to cancel the steady state error. As the speed is tracked in meaning of ramp and peaks of torque, the error represents also a variable torque. In Permanent Magnet Synchronous Motors the q axis current is

produced by the torque while the d axis current is produced by the flux. The permanent magnets produce constant torque and the control strategy sets the d axis current on zero. Therefore, the nominal current in the stator is reduced and in the same time losses are decreased. [31]

The mechanical speed can be measured with special equipment and the rotor position can be determinate in this way aligning the flux with first axis from quadrature.

In a symmetric system at any instance the sum of the currents amplitudes is zero having a balanced load. The abc currents are transformed into dq reference frame with the position obtained from the speed. The difference between the transformed current and measured one represents the input for the Proportional Integral controller. The outputs of the PI blocks are represented by quadrature voltages. [31]

The decoupling terms are shown in the voltage equations for the PMSM depending on speed and currents respectively. For the d axis the decoupling terms are added while in case of q axis the terms are reduced from the equation canceling the effect of back electromotive force. [29] [31]

Further few control strategies based on motor parameters are presented in order to optimize the drive performances.

#### 3.1.1. Constant Torque Angle Control [27]

In the industry field, the Constant Torque Angle is preferred because of the simplicity. Its main principle is to maintain a constant 90 electrical degrees angle  $\delta$ , between the flux space vector of permanent magnet and the stator current axis. The control strategy is based on a zero direct axis current (ZDAC) method, therefore, the d axis current reference is set on zero vale.

For the stator side of the PMSM can be written:

$$\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = i_s \begin{bmatrix} \sin \delta \\ \cos \delta \end{bmatrix} (3-1)$$

Where  $\delta$  is the angle between the stator current vector and the field produced by the magnets.

As the  $i_d$  current is zero, the quadrature current represents the absolute value of the current in the stator:

$$|i_s| = i_q (3-2)$$

The electromagnetic torque can be expressed as follows:

$$T_e = \frac{3}{2} n_{pp} i_q \lambda_{af}$$
(3-3)

The torque is proportional to the q axis current as can be seen in Equation (3-3). A linearized torque-current relationship provides an easier control for the motor. The phasor diagram for constant torque angle strategy is depicted in Figure 3.2.



Figure 3.2: Constant torque angle control phasor diagram [27] [32]

#### 3.1.2. Unity Power Factor Control [3]

The main idea of this control technique is to keep the power factor of the system to a unity proportion by optimizing the apparent power. Therefore, the phase shift between the stator currents and stator voltages must be zero.

The real power is used entirely form the inverter, through a range of variation for the torque according to the motor parameters. The stator currents can be described by the following relationships:

$$I_{qs}^{r} = I_{s} \cdot sin\delta (3-4)$$
$$I_{ds}^{r} = I_{s} \cdot cos\delta (3-5)$$

The mathematical expression for the torque is:

$$T_{en} = I_{sn} \cdot \left\{ I_{sn} \cdot \frac{L_{dn} - L_{qn}}{2} \cdot sin2\delta + sin\delta \right\} (3-6)$$

The stator voltages can be written as:

$$v_{qsn}^{r} = \omega_{rn} \left\{ 1 + L_{dn} \cdot I_{sn} \cdot \cos\delta + \frac{R_{sn} \cdot I_{sn}}{\omega_{rn}} \cdot \sin\delta \right\} (p.u.) (3-7)$$
$$v_{dsn}^{r} = \omega_{rn} \cdot I_{sn} \left\{ \frac{R_{sn}}{\omega_{rn}} \cdot \cos\delta - L_{qn} \cdot \sin\delta \right\} (p.u.) (3-8)$$

Considering that the angle of the power factor is zero, the torque angle can be determined by the following expression:

$$\delta = \cos^{-1}\left\{\frac{-1\pm\sqrt{1-4\cdot L_{qn}\cdot I_{sn}^2\cdot (L_{dn}-L_{qn})}}{2\cdot I_{sn}\cdot (L_{dn}-L_{qn})}\right\} \ [rad](3-9)$$

To avoid the saturation of the motor, the angle  $\delta$  must have a value bigger than 90°, the rotor speed being independent of the flux linkage.

The output performance of the drive is increased by unity power factor strategy because the torque is maintained constant in a specific region while the speed is increased.

#### 3.1.3. Constant Mutual Flux Linkages Control [27]

The aim of this control strategy is to maintain the requirement for the stator voltages as low as possible, therefore the mutual flux linkage is constant and its value is equal to the rotor flux linkage. The flux weakening supports the speed range operation higher than the base speed and the mutual flux can be expressed as:

$$\lambda_m = \sqrt{\left(\lambda_{af} + L_d \cdot I_{ds}^r\right)^2 + \left(L_q \cdot I_{qs}^r\right)^2}$$
(3-10)

For a Surface Mounted PMSM the saliency ratio has the value of 1 while the buried or interior magnet PMSM the value for saliency ratio is 3. The angle of torque can be expressed in two forms as follows:

$$\delta = \begin{cases} \cos^{-1}\left\{-\frac{I_{sn}\cdot L_{dn}}{2}\right\} [rad] \\ \cos^{-1}\left\{\frac{1}{L_{dn}\cdot I_{sn}\cdot (1-\rho^2)} \pm \sqrt{\left\{\frac{1}{L_{dn}\cdot (1-\rho^2)\cdot I_{sn}}\right\}^2 - \frac{1}{(1-\rho^2)}\right\}} [rad] \end{cases}$$
(3-11)

A well choose value for  $\delta$  bigger than 90° means a low value of the demagnetization current. The Constant Mutual Flux Linkage Control strategy is more used than unity power factor the torque produced is considerably bigger for a high range of current, even smaller than 2 p.u.

# 3.1.4. Angle Control of Air Gap Flux and Current Phasors [27]

The air gap mathematical equation can be obtained from:

$$T_e = \frac{3}{2} * n_{pp} * \lambda_m * i_s * sin\theta_{ms}$$
(3-12)

A constant 90 degrees angle for  $i_d$  is desired in this control strategy. As for dc motors with external excitation the air gap flux can be varied by modifying the armature current. In Figure 3.3 mutual flux linkages phasor diagram is shown.



Figure 3.3: PMSM phasor diagram of flux linkages [27]

From the previous figure the flux linkage and stator current axis projection can be determined as:

$$\theta_{ms} = \delta - \theta_{\lambda} (3-13)$$

$$\lambda_{qs}^{r} = \lambda_{m} \sin \theta_{ms} (3-14)$$

$$\lambda_{ds}^{r} = \lambda_{m} \cos \theta_{ms} (3-15)$$

$$i_{qs}^{r} = i_{s} \sin \delta (3-16)$$

$$i_{ds}^{r} = i_{s} \cos \delta (3-17)$$

The angle of the current relates the flux with the torque angle as:

$$\delta = \theta_{ms} + \theta_{\lambda} = \frac{\pi}{2} + \theta_{\lambda}$$
 (3-18)

Therefore the following expression can be derived

$$\sin \delta = \cos \theta_{\lambda}$$
 (3-19)

#### 3.1.5. Optimum Torque Per Ampere Control [27]

The strategy adds a minimization of the power losses in copper by providing a higher torque for a certain current.

Electromagnetic torque can be expressed as:

$$T_e = \frac{3}{2} * n_{pp} * \left[ \lambda_{af} \, i_s \sin \delta + \frac{1}{2} \left( L_d - L_q \right) i_s^2 \sin 2\delta \right] \, (3-20)$$

Normalizing the previous expression, is obtained:

$$T_{en} = i_{sn} \left[ \sin \delta + \frac{1}{2} \left( L_{dn} - L_{qn} \right) i_{sn} \sin 2\delta \right]$$
(3-21)

The torque base can be written as:

$$T_b = \frac{3}{2} * n_{pp} \lambda_{af} I_b$$
 (3-22)

Therefore, the torque per ampere proportion is:

$$\left(\frac{T_{en}}{i_{sn}}\right) = \left[\sin\delta + \frac{1}{2}\left(L_{dn} - L_{qn}\right)i_{sn}\sin2\delta\right] (3-23)$$

The torque angle requirement can be obtained through a zero value differential equation with respect to  $\delta$  as follows:

$$\delta = \cos^{-1}\left\{-\frac{1}{4a_1i_{sn}} + \sqrt{\left(\frac{1}{4a_1i_{sn}}\right)^2 + \frac{1}{2}}\right\} (3-24)$$

Where:

$$a_1 = (L_{dn} - L_{qn}) = L_{dn}(1 - \rho)$$
 (3-25)

 $\rho$  represents the ratio of saliency.

Reducing the current through the stator to a prescribed value means a speed-torque profile decreasing. A lower current means smaller losses in copper for the drive at the nominal speed.

This strategy deals with optimizing the speed-torque profile in order to minimize the losses in variable speed drive applications.

A power loss feedback is used with the help of motor equations in dq reference frame. From Figure 3.4 and Figure 3.5 the following equations can be derived:



Figure 3.4 q-axis equivalent circuit [27]



Figure 3.5 d-axis equivalent circuit [27]

$$\begin{bmatrix} I_{qs}^{r} \\ I_{ds}^{r} \end{bmatrix} = \begin{bmatrix} 1 & \frac{L_{d}\omega_{r}}{R_{c}} \\ -\frac{L_{q}\omega_{r}}{R_{c}} & 1 \end{bmatrix} \begin{bmatrix} I_{q} \\ I_{d} \end{bmatrix} + \begin{bmatrix} \frac{\lambda_{af}\omega_{r}}{R_{c}} \\ 0 \end{bmatrix} (3-26)$$
$$\begin{bmatrix} V_{qs}^{r} \\ V_{ds}^{r} \end{bmatrix} = \begin{bmatrix} R_{s} & L_{d}\omega_{r}\left(1 + \frac{R_{s}}{R_{c}}\right) \\ -L_{q}\omega_{r}\left(1 + \frac{R_{s}}{R_{c}}\right) & R_{s} \end{bmatrix} \begin{bmatrix} I_{q} \\ I_{d} \end{bmatrix} + \begin{bmatrix} \lambda_{af}\omega_{r}\left(1 + \frac{R_{s}}{R_{c}}\right) \\ 0 \end{bmatrix} (3-27)$$

Therefore, the electromagnetic torque can be described by:

$$T_{e} = 0.75 n_{pp} \left( \lambda_{af} I_{q} + (L_{d} - L_{q}) I_{d} I_{q} \right) (3-28)$$

The core losses can be expressed by:

$$P_{c} = \frac{1.5\omega_{r}^{2}(L_{q}I_{q})^{2}}{R_{c}} + \frac{1.5\omega_{r}^{2}(\lambda_{af} + L_{d}I_{d})^{2}}{R_{c}} = \frac{1.5}{R_{c}}\omega_{r}^{2}\lambda_{m}^{2} (3-29)$$

 $\lambda_{\rm m}$  [Wb] represents the value for the mutual flux linkage through the air gap.

The total amount of the power losses is:

$$P_{l} = 1.5R_{s} \left( I_{qs}^{2} + I_{ds}^{2} \right) + \frac{1.5}{R_{c}} \omega_{r}^{2} \left[ \left( L_{q} I_{q} \right)^{2} + \left( \lambda_{af} + L_{d} I_{d} \right)^{2} \right] (3-30)$$

#### 3.1.7. Tuning of PI Controllers

The Constant Torque Angle control strategy was chosen for the FOC strategy because of the simplicity. For a typically synchronous reference frame the dq current errors are dc values but for this system the input is a sinusoidal waveform, therefore, the controllers must be well designed in order to keep the error as low as possible. In this case the bandwidth of the processor used for the control has just a small influence which can be neglected and the difference between the reference and the measured value of the currents is zero. [27]

The main idea of this method is to keep the d-axis current to a zero constant value, simplifying the control. In Figure 3.6 is depicted the block diagram of the control for this strategy. An independent type of control for the currents divided into d respectively q axis is highlighted by the decoupling terms from the mathematical model of the motor.



Figure 3.6: FOC block diagram for constant torque angle [33]

#### • Current Control Loop

In case of a Surface Mounted PMSM the d axis inductance is almost equal to the q axe one, therefore, the difference between them is neglected. Thus, is expressed by the same parameters applied to the d respectively q axis. [27]

The Figure 3.7 shows the block diagram of the d axe current control loop.



Figure 3.7: Current control loop for d-axis [33]

• The Controller C represents a PI controller designed for the current control. The transfer function for the controller can be expressed as:

$$C(s) = K_{Pi} \cdot \frac{1 + s \cdot T_i}{s \cdot T_i} (\mathbf{3-31})$$

• The Plant, G<sub>PMSM</sub> represents the transfer function of the stator and can be written in the next form:

$$G_{PMSM}(s) = \frac{1}{R_s + s \cdot L_s} = \frac{1}{R_s} + \frac{1}{1 + s \cdot \frac{L_s}{R_s}} = K_{PMSM} \cdot \frac{1}{1 + s \cdot T_{PMSM}} (3-32)$$

• The Sampling, H depends on other equipment implemented in the system which can produce delay for the signal. In this case no other influences appears in the system, therefore, the transfer function can be expressed as:

$$H(s) = 1$$
 (3-33)

The open loop transfer function for the current controller is:

$$G_{OL}(s) = C(s) \cdot G_{PMSM} = K_{Pi} \cdot \frac{1 + s \cdot T_i}{s \cdot T_i} \cdot K_{PMSM} \cdot \frac{1}{1 + s \cdot T_{PMSM}}$$
(3-34)

The constant of the motor is calculated depending on the stator resistance with the following expression:

$$K_{PMSM} = \frac{1}{R_s} = 5.55$$
 (3-35)

The stability of the system can be increased by canceling the pole of the controller. Thus, can lead to the time constant of the PMSM calculated depending on both stator resistance and phase inductance as follows:

$$T_i = T_{PMSM} = \frac{L_s}{R_s} = 0.011 [s]$$
 (3-36)

The open loop transfer function becomes:

$$G_{OL}(s) = K_{Pi} \cdot \frac{1 + s \cdot T_i}{s \cdot T_i} \cdot 5.55 \cdot \frac{1}{1 + s \cdot 0.011} (3-37)$$

Having all parameters the proportional and integral constants are determined based on Optimum Modulus Criterion as follows [3]:

$$K_{Pi} = \frac{T_i}{K_{PMSM}} = 0.002 \ \textbf{(3-38)}$$
$$K_{Ii} = \frac{K_{Pi}}{T_i} = 5.55 \ \textbf{(3-39)}$$

The stability of the system can be analyzed for the calculated values of the controller. The Root Locus of the controller gives information about the stability. In Figure 3.8 can be observed that both pole and zero of the transfer function are located in the left half plane. Therefore, it can be concluded that the system is stable having the presented controller.



Figure 3.8: Root Locus of the current controller

The motor used is a Surface Mounted PMSM, therefore in the dq-reference frame can be considered that inductances are equal. Thus leads to a simplified control where PI controller for d axis has the same constants as for q axis.

## Speed Control Loop

The speed loop transfer function is determined based on mechanical model of the motor. A slower response is obtained than in the other case and because of the control strategy it can be assumed that the current is also zero.

The system is considerably simplified with no effect on the stability. The tuning process of the controller became much easy also. The block diagram of the speed controller is depicted in Figure 3.9.



Figure 3.9: Speed control loop [34]

Further, each transfer function corresponding to included blocks will be detailed.

• The Controller C has the same form as the one from the current controller. Therefore, the transfer function has the same order but different constants as follows:

$$C_{\Omega}(s) = K_{P\Omega} \cdot \frac{1 + s \cdot T_{\Omega}}{s \cdot T_{\Omega}} (3-40)$$

• The Current controller has a transfer function approximated as a first order:

$$H_I(s) = \frac{1}{1+s \cdot T_{iq}} (3-41)$$

Where:

$$T_{iq} = \frac{T_i}{K_{Pi} \cdot K_{PMSM}} = 1$$
 (3-42)

• The plant of the controller is given by mechanical relationship of the motor:

$$n_{pp} \cdot (T_e - T_l) = J \cdot \frac{dw_r}{dt} + w_r \cdot B_f$$
 (3-43)

Where:

 $n_{pp}$  represents the pole pairs number of the motor;

T<sub>e</sub> represents the electromagnetic torque produced by the PMSM;

 $T_1$  is the load torque from the wave;

J represents the motor inertia;

w<sub>r</sub> represents the mechanical speed of the rotor;

B<sub>f</sub> represents the friction factor;

The electromagnetic torque of the motor is described by the next formula:

$$T_e = \frac{3}{2} \cdot n_{pp} \cdot \lambda_{PM} \cdot i_{qs} \ \textbf{(3-44)}$$

Where:

 $\lambda_{PM}$  [Wb]is the flux of permanent magnets;

From equation (3-44) can be obtained the constant H1(s) as follows:

$$H_1(s) = \frac{3}{2} \cdot n_{pp} \cdot \lambda_{PM} = 0.738 \ (3-45)$$

The mechanical equation for the motor gives the transfer function for the plant block:

$$G_{Mec}(s) = \frac{1}{s \cdot J + B_f} (\mathbf{3-46})$$

The open loop transfer function for the speed controller is:

$$G_{OL\Omega} = C_{\Omega}(s) \cdot H_{I}(s) \cdot H_{1}(s) \cdot G_{Mec}(s)$$
$$G_{OL\Omega} = K_{P\Omega} \cdot \frac{1 + s \cdot T_{\Omega}}{s \cdot T_{\Omega}} \cdot \frac{1}{1 + s \cdot T_{iq}} \cdot 0.738 \cdot \frac{1}{s \cdot J + B_{f}} (3-47)$$

Like in the case of current controller the proportional gain is determined with the following equation:

$$G_{OL\Omega} = K_{P\Omega} \cdot \frac{1 + s \cdot T_{\Omega}}{s \cdot T_{\Omega}} \cdot \frac{1}{1 + s} \cdot 0.738 \cdot \frac{1}{B_f} \frac{1}{1 + s \cdot \frac{J}{B_f}}$$

$$G_{OL\Omega} = K_{P\Omega} \cdot \frac{1 + s \cdot T_{\Omega}}{s \cdot T_{\Omega}} \cdot \frac{1}{1 + s} \cdot 0.738 \cdot K_m \cdot \frac{1}{1 + s \cdot T_m} (3-48)$$

Where:

$$K_m = \frac{1}{B_f} = 3333.33;$$
  
 $T_m = \frac{J}{B_f} = 16;$ 

For a simple calculation without affecting the controller gains, it is assumed that:

$$1 + s \cdot T_{iq} = s \cdot T_{iq}$$
 (3-49)

For a better stability of the system, the zero of the controller is reduced by the pole with the biggest time response.

Therefore:

$$T_{\Omega} = 16;$$

The proportional and integral constants can be determined as follows:

$$K_{P\Omega} = \frac{T_{\Omega}}{0.738 \cdot K_m} = 0.0065$$
$$K_{I\Omega} = \frac{K_{P\Omega}}{T_{\Omega}} = 4.06 \cdot 10^{-4}$$

For stability analysis the Root Locus of the transfer function is determined and shown in Figure 3.10.

It can be observed that al poles and zeroes of the new created system are located in the left half plane.

Therefore, it can be concluded that the PI controller does not affect the stability of the system.



**Figure 3.10: Root Locus for the speed controller** 

The controllers were automatically tuned with Simulink library blocks for a better performance of the system using default Simulink blocks. The system performance is increased in this way having smaller steady-state errors and time response.

According to the experimental setup in the following section were used smaller parameters in meaning of maximum 500 rpm speed peaks for the comparable output waveforms.

#### 3.2. System control

The system was tested with a constant speed of 1500 rpm for the PMSM in case of generator working mode.

The phase voltage has a peak value of 250 [V] and the current value is relatively high as can be seen in Figure 3.11 and Figure 3.12:



Figure 3.11: Output voltages of the generator at constant speed



Figure 3.12: Output currents of the generator at constant speed

For a sinusoidal waveform of the speed profile the model outputs has a good behavior successfully tracking the reference parameters from the wave.

The reference and measured speeds are shown in Figure 3.13 as follows:



**Figure 3.13: Speed tracking of the generator** 

Due to the variation of the speed and inertia of the motor, the difference between the measured and reference speed can be observed, but the system has a good behavior. The system has also a good response for the torque profile successfully tracking the load.

The torque profile is depicted in Figure 3.14:



Figure 3.14: Load and Electromagnetic Torque of the PMSM



In Figure 3.15 and output currents of the PMSG are depicted.

Figure 3.15: Output currents of the PMSG

The output phase voltages of the PMSG are shown in Figure 3.16.



Figure 3.16: Output phase voltages of the PMSG

For a maximum speed input of 500 [rpm] the current values are relatively big, approximately 25 [A] and the output voltages has variations from 75 to -75 [V].

It can be seen that the graphic is made from the beginning and the voltages has bigger values on the first alternation of the speed but after this the voltages are stabilizing in an approximate range from 65 to -65 [V].

From the dq reference frame, the output active power can be calculated as follows: [35]

$$P_{out} = \frac{3}{2} (i_d \cdot V_d + i_q \cdot V_q) [W]$$
(3-50)

Where:

 $i_d$  and  $i_q$  represents the dq reference frame currents;

v<sub>d</sub> and v<sub>q</sub> represents respectively the dq reference frame voltages;

As the power was measured for a very low value of a resistor, in the experimental results might appear a difference because the power must be measured with equipment which contains internal resistances.

Taking into account that the power shown further in the setup experimental results chapter is positive by convention, it was easier to change the sign in the simulation model. Therefore, a better comparison between the simulation and experimental results can be performed.

In Figure 3.17 the total power produced by the generator is depicted.



Figure 3.17: Output power of the PMSG

It can be seen from the picture that the average power harvested for a 0.3 [m] wave amplitude is 1.2 [kW].

In the case of a closer to the real behavior for the wave, a random signal was introduced in the system as input. For this situation the control part of the generator works also well even though the speed ramp has a more often variation and a variable frequency. The power extracted in this case is depicted in Figure 3.18.

Because of the motor inertia the power has zero crossings even alternating on the negative part in meaning of a reverse power flow. This bidirectional power feeding is not possible because the float inertia is much bigger compared to the motor.



Figure 3.18: Extracted power in case of a random signal form waves

# 4. Setup description

The laboratory setup is presented in this part of the project. The system is described with the hardware equipment and software programs used. A Simulink program was used to control and operate the motors under different conditions.

Because of the project limitations the laboratory setup consists in two motors directly connected shown in Figure 4.1. The wave behavior will be emulated by a 2.5 [kW] Induction Motor for different cases and controlled with a Danfoss inverter of 2.2 [kW] through a dSpace software interface.



Figure 4.1: Experimental setup diagram

The control part was already realized for a real model and applied to the setup but because of the desired variable speed waveform, the Induction Motor control had to be modified.

Each motor is connected to a Danfoss FC302 inverter, a 2.2 [kW] for the Induction Motor and 15 [kW] for the Permanent Magnet synchronous Motor.

The dSpace system represents the communication interface for the PMSM model existing in the Matlab/Simulink software shown in Figure 4.2. Data acquisition model contains communication blocks from Simulink library linked further with sensors and LEM boxes.

A Space Vector Pulse Width Modulation technique is used to control the parameters and implemented on internal control circuits of inverters. [36]



## Figure 4.2: Simulink model of the setup

In order to connect and run the motors few steps has to be made for a good behavior during specific operating conditions. Alignment of the rotor and position detectors through with Phase Locked Loop subsystems represents just a few important operations which had to be carried out for a proper behavior of the setup.

The Graphical User Interface of designed in dSpace is depicted in Figure 4.3. The picture shown was taken during the setup testing process where the PMSM was connected to the grid feeding the Induction Motor with mechanical power. [37]

Each motor has the option to fed the other one through speed or torque with specific increments for parameters. The DC-link voltages are also measured and displayed also. Options like modifying control parameters for each motor, waveform snapshots or saved data to files are available for a user friendly interface.



Figure 4.3: Graphical user interface for the setup [37]

All parameters for the equipment used in laboratory is presented at the end of the project as appendix.

# 5. Experimental results

In this chapter the laboratory measurements are presented for one speed because of the limitations. The output power is presented in order to prove that the concept can be successfully built, implemented and tested on a scaled prototype of wave energy converter. All the measurements were carried out through the dSpace interface linked to sensors and measurement equipment.

The laboratory system was presented in the previous chapter in Figure 4.1, and the behavior of the float with the gearbox was emulated by the Induction Motor. The most important limitation in testing the PMSM in generator mode was that IM output power was limited to 2.4 kW. Therefore, the input power for the PMSM had a low range of variation.

The step response of the Induction Machine was very small and the speed was limited for a desired value, therefore, from a sinusoidal input in meaning of speed the waveform became trapezoidal. If the model is designed with a larger stabilizing time, the inertia of the PMSG represents a problem expressed in a lower limit for the output power.

The output speed generated was around 550 rpm, and the torque produced was almost 22 Nm. It can be seen in Figure 5.1 that the output power of the generator is stabilized around 1.3 kW and by then it has a ripple because the speed ramp is high.



Figure 5.1: Output power of the PMSG

The sign convention was established as positive power for generator mode and negative for motor operation of PMSG. A higher value of speed was not allowed because increasing step for IM was 250 rpm and in the case of 750 rpm the Induction Motor side inverter was tripping, the input parameters were higher than inverter devices can stand.

In Figure 5.2 the output currents are shown for 3 periods of input speed variation. It can be seen that in the first part of increasing for each period that the currents values are higher because the ramp of the speed has a big value. After the ripple, the currents are stabilizing a while until the inertia of the motor reduces the currents to zero values but only for few milliseconds.





The system can easily be connected to the utility grid from this point of view supplying with a desired voltage in order not to harm plugged equipment. Because of the variation of produced power, storage equipment represents a good idea to be placed either on the dc-link or at the output, for a further connection to the utility network.

The measured currents are depicted in Figure 5.3 in order to show the sinusoidal waveform and also the frequency. The peak to peak value of each current is approximately 45 [A] given by a measuring high power resistor. The phase shift between phase a and phase b is 120 electrical degrees.



It can be seen that the filter is well designed, the currents presents smooth waveforms having no noise, the harmonic distortion level is low.

#### Figure 5.3: Detailed PMSM output currents

For a better behavior of the system, the highest and lowest limit of the speed was highlighted having a small step response for the Induction Motor which emulates the wave. Therefore, the speed ramp has big values and the limits were reached in a very short time.

The setup was modified and because of the laboratory limitations, output voltages waveform could not be performed. A detailed measurement of output voltages and currents when the speed waveform has zero crossings, in meaning of phase shifting, can represent another aspect in further investigations for Wavestar Generator system.

The PMSM speed waveform is depicted in Figure 5.4 having a variation from almost 500 [rpm] to -500 [rpm]. The real speed transmitted to the generator was higher than the one depicted but the speed sensor implementation had an increment of 250 [rpm] so a speed between 500 and 750 [rpm] could not be displayed. This difference can be better observed from the power waveform where the power is higher than it should be. The power is electrical and it was obtained on the PMSG terminals with a power analyzer and merged into the dSpace model in order to create the waveform.

As the motor has a considerable inertia it can be notice that the speed reference is influenced after stabilizing, when the ramp is zero the speed is decreased.



Figure 5.4: PMSM measured speed waveform

The load and electromagnetic torque are depicted in Figure 5.5 for a period of 3.14 seconds chosen with this value for safety reasons. A smaller period could not be performed because even for this one the Induction Motor side inverter was tripping when the speed was changed.

The electromagnetic torque of the motor has a waveform similar to the load torque and as can be seen in the picture inertia affects the behavior of the mechanical system. The waveform was not depicted from the same time as the speed but the torque alternates reversed also having a 180 degrees shift as in the simulation.

It is also seen from the torque that the time response of the system is very small therefore a small overshoot appears.



Figure 5.5: Load and Electromagnetic Torque

# 6. Conclusions

A Wavestar Generator system like the one presented in this report can be designed, build and integrated among other Wave Energy Converter systems.

The wave interaction model was created including, wave forces, float and gearbox. Both sinusoidal and random signals for the wave elevation were modeled.

The simulation model was based on the laboratory setup parameters, for a better comparison of graphic results. A Permanent Magnet Synchronous Motor model was implemented in Simulink and controlled by a Field Oriented Control strategy. The modeled generator produces power with this type of control even if the speed ramp has a high frequency variation, in case of random input signal.

The behavior of the laboratory setup is compared with the simulation results even though is a difference in the amount of extracted power. For a variable input waveform the generator operates in good conditions being stable and controlled through PI regulators specific for DC values.

The difference between simulation and experimental results in meaning of produced power is also influenced by the frequency difference of speed inputs.

#### 6.1. Merits

- A sinusoidal and a random wave behavior was modeled and successfully tested in the simulation part;
- The control of the generator works in both cases for a variable speed input waveform;
- The main objective of the project was accomplished in meaning of valid model of energy converter;
- A laboratory setup consisting in an Induction Motor and a Permanent Magnet Synchronous Generator, based on the system requirements was build;
- The Induction Motor emulates with success the wave behavior;
- A Field Oriented Control strategy was successfully applied to the system. The classic type of controller works as well for variable input waveforms;
- The experimental setup confirms the simulation results denoted by the produced power;

### 6.2. Demerits

- The wave period in simulations was taken from a real situation from Wavestar concepts but the setup was run for a 3.14 seconds period of time. A smaller period could harm the setup equipment;
- The reference speed was only up to 500 [rpm] because of the Induction Motor limitation;
- A more real situation for a random signal of the wave could not be implemented in the setup because of the same considerations;

## 6.3. Future works

- A high level of speed should be tested because the amount of available power is considerably large compared to the harvested one;
- A random signal more close to the wave behavior can be implemented in the experimental setup;
- The mechanical power can be also stored through a modified gearbox having a big difference between the inertias but also can produce a variable speed with only one direction for the generator;
- A scaled prototype of Wavestar Generator can be build and tested, based on the results obtained in this project;
- Efficiency optimization and system reliability could be another subject of research regarding Wavestar Generator system;

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# Appendix A

Equipment specifications:

- Siemens PMSM ROTEC 1FT6084-8SH7:
  - $\circ P_{n}: 9.4 [kW]$
  - $\circ \ T_n = 20 \ [Nm]$
  - $\circ I_n = 24.5 [A]$
  - $\circ \ f_n = 300 \ [Hz]$
  - $\circ \ n_n = 4500 \ [rpm].$
- ABB three phase induction motor type M2AA100LA:
  - $\circ P_n = 2.2 [kW]$
  - $U_n = 380 ... 420 [V] rms (Y)$
  - $\circ$  f<sub>n</sub>= 50 [Hz]
  - $\circ$  I<sub>n</sub>= 5.0 [A] rms
  - $\circ \cos \varphi = 0.81$
  - $\circ \ n_n = 1430 \ [rpm]$
  - $\circ \ n_{pp}=2$
- Danfoss FC300VLT (FC 302) frequency inverter:
  - $\circ$  U<sub>n</sub>: IN =3 phase AC 380 [V], OUT = 3 phase AC 380 [V]
  - $\circ$  f<sub>0</sub>=0..1000 [Hz]
  - $\circ~$  In: IN= 5.3 [A] , OUT=5.6 [A]
  - $\circ$  P<sub>n</sub>=2.2 [kVA]
  - $\circ f_s = 3 ... 5 [kHz]$
- DS1103 PPC -Motorola PowerPC 604e running at 333 MHz
  - Slave DSP TI's TMS320F240 Subsystem
  - 16 channels (4 x 4ch) ADC, 16 bit , 4 \_s, \_10 V
  - $\circ$  4 channels ADC, 12 bit , 800 ns, \_ 10V
  - $\circ~$  8 channels (2 x 4ch) DAC, 14 bit , \_10 V, 6 \_s
  - o Incremental Encoder Interface -7 channels
  - 32 digital I/O lines, programmable in 8-bit groups
  - Software development tools (Matlab/Simulink, RTI, RTW, TDE, Control Desk)