



NTNU – Trondheim
Norwegian University of
Science and Technology

Modeling of electric shaft used by the company Inpower AS

Mikhail Utkin

Master of Science in Electric Power Engineering

Submission date: June 2015

Supervisor: Robert Nilssen, ELKRAFT

Co-supervisor: Øystein Krøvel, Inpower AS

Norwegian University of Science and Technology
Department of Electric Power Engineering

Mikhail Utkin

Modeling of electric shaft used by the company Inpower AS

Master of Science in Electric Power Engineering

Trondheim June 2015

Supervisor: Robert Nilssen

Norwegian University of Science and Technology

Department of Electric Power Engineering



NTNU – Trondheim
Norwegian University of
Science and Technology

Problem description

Design of the propulsion systems for ships has always been a topic where Norwegian companies did maintain the leading roles in the world, in terms of technology production and usage of the proposed solutions. The reason is that Norway has a strong demand in major classes of ships for operation the off-shore oil platforms, ferries, supply vessels etc.

In recent years with a forecasted increase in the price of natural resources and a steady technical progress, one of the main directions in maritime industry has become research and development of the new fuel saving technologies.

Electric propelled ships are one example of the modern solution for increasing the efficiency of the ship fuel usage. This solution has already acquired popularity throughout the world and has proven advantages over convenient combustion engine propulsion systems. Not surprisingly the percent of the ships using electrical propulsion is fast growing.

Inpower AS has come up with a direct diesel electric propulsion solution which is able to lift up the efficiency of electrical propelled ships to an even higher level. With this solution also offers reduced installations costs, improved flexibility and other advantages over diesel-mechanical propulsion systems.

Study and research of this new solution on the level of building mathematical models of the systems has become the topic for this master thesis.

Preface

The study and the modeling process was carried out at the at the Department of Electric Power Engineering at the Department of Electric Power Engineering, Norwegian University of Science and Technology (NTNU) during Spring 2014.

A Norwegian company Inpower AS, specializing in design of the electric propulsion systems for ships has proposed the topic for this study. This study can be considered as a part of the strengthening of the theoretical basis of the current system.

I would like to thank my supervisor Professor Robert Nilssen at the Department of Electric Power Engineering, NTNU for directing my studies in the right goals, helpful support and valuable suggestions on solving the uprising problems throughout this project.

Additional thanks to my supervisor from Inpower AS, PhD Øystein Krøvel for his support with regards the practical part of the project, providing all the necessary data required to fulfil this study, and taking the time and patience to answer any of my questions

I must also thank my friends, colleges and family members for giving me motivation and keeping me going forward with studies even in the hardest times.

Mikhail Utkin

Trondheim, June 2015

Abstract

The master thesis is a further investigation of the steady state performance of the direct connection of the permanent magnet generators and motors, used for the ship propulsion; as proposed in the specializing project study conducted in autumn 2014. The challenge is how to implement the possibility of the salient rotor machines in the power flow calculations.

Another task is to start the investigation of dynamic system behavior.

In order to cope with the tasks the mathematical models of the steady state systems have been developed, as well as the introductory system for the dynamic studies.

Matlab software has been used for both models. Source code functions implementing developed the mathematical algorithm for the steady state, and block diagram form in the Simulink environment for the dynamic model.

A theoretical review is conducted in order to understand the physics behind the complex mathematical equations. Using the attained theoretical background, an algorithm for solving power flow equations with possibility to include saliency has been developed. In addition the theoretical study of the dynamic system has been presented, explaining in details the usage of blocks in the Simulink model.

In general words, a study case consists of a diesel engine which has a permanent magnet synchronous generator on its shaft, which is directly connected with a three phase alternating current transmission line to the permanent magnet synchronous motor. The motor has a propeller on its shaft which is providing the propulsion of the ship. Ships static load has also been taken into account while modeling, as an adjustable power demand on the terminal bus. The system main difference to the convenient electrical ship propulsion systems is the lack of power electronics in the circuit, thus the system is operating with variable frequency and voltage.

The simulations of the steady state mathematical models show stable results in all range of operation points. The desired accuracy of convergence of the iterative solutions for the nonlinear equations is achieved. The results comparison with a real world tests on board the ship show close values of current for the high frequencies and high power, while for the low frequencies the simulation results are driven away from the tests.

The dynamic system model works as intended and has highlighted the problems of synchronization of the motor and the problem of the torque oscillations on the motor shaft with a fast enough change in load.

Both systems gave insight information and valuable experience of the permanent magnet synchronous machine modeling, starting from the very basic level and avoiding usage of the commercial available software.

Contents

Problem description	iii
Preface	v
Abstract	vii
Contents	ix
List of tables	xii
List of figures	xiv
Nomenclature	xvi
1. Introduction	1
1.1 Background	1
1.2 Summary of the autumn project	3
1.3 Objectives	5
1.4 Scope of work	6
1.5 Limitations	7
1.6 Report structure	7
2. Theoretical background and mathematical modeling	9
2.1 Brief description of major system components	9
2.1.1 Ships with electric propulsion	9
2.1.2 PMSM for generation and ship propulsion	11
2.1.3 Diesel engine	11
2.1.4 Propeller	12
2.1.5 Switchboards, distribution systems	13
2.1.6 Cables	14

2.2	Software description	14
2.2.1	Matlab	14
2.2.2	Simulink, Simscape and SimPowerSystems	14
2.3	Mathematical modeling of PMSM	16
2.3.1	Salient pole machines	16
2.3.2	Phasor diagram and equivalent circuit	20
2.3.3	Real and reactive power of the salient pole generator	22
2.3.4	Synchronous reaction correction factor	23
2.4	Theoretical background of the power flow studies	24
2.5	Solution of nonlinear algebraic equations	26
2.5.1	Gauss-Seidel method	26
2.6	Power flow solution	28
3.	System description	31
4.	Adapting power flow analysis to include saliency	35
4.1	Impedance matrix formation	35
4.2	New power flow equations	38
4.3	Solving the new power flow equations in the code	39
4.4	Adapting the code for the possible use and development in future	41
4.5	Current and power factor calculations	42
4.6	Addition or removing machines of the model	43
5.	Simulations, steady state model	45
5.1	Results verification	45
5.2	Electrical parameters against speed and power	48
6.	Discussion steady state model	53
6.1	Power flow solution for modeling PMSM with salient rotors	53
6.2	Gauss-Seidel method	54
6.3	User interface	54

7. Dynamic simulations Theoretical background	55
7.1 Inductances and flux linkages	56
7.2 dqo transformation	58
7.3 Current, voltage and flux linkage equations in the dq0 reference frame	59
7.4 Power and torque	60
7.5 Model blocks	62
7.5.1 PMSM block	62
7.5.2 Inside the PMSM block	63
7.5.3 Electrical model block	64
7.5.4 Simple system block model	65
8. Dynamic simulation results	67
8.1 Synchronizing of PMSM	67
8.2 Reaction to the gradual change in torque	69
9. Discussion dynamic model	73
9.1 Simulink model	73
9.2 Synchronization of the motor	73
9.3 Reaction to the gradual change in load torque	74
10. Conclusion	75
11. Recommendations for future work	77
Bibliography	79
Appendix	83
User manual for m-files	83
Matlab simulation script	84

List of tables

Table 3.1: System proposals	31
Table 4.1: Load flow specifications example, 1 generator one motor.	39
Table 4.2: Load flow specifications, 1 generator 2 motors model.	39
Table 4.3: Load flow specifications, 2 generator 1 motor model.	40
Table 4.4: Load flow specifications, 3 generator 1 motor model.	40
Table 4.5: Load flow specifications, 3 generator 2 motor model.	40
Table 4.6: Reading the machine data from the text file	42
Table 4.7: Matlab algorithm for current calculation	42
Table 4.8: An algorithm of solving the power equations, shown for a single bus	44
Table 5.1: Test results of the one generator – two motors system	46
Table 5.2: Simulation results of the one generator two motors system.	47
Table 5.3 Values for construction of the 3 phasor diagrams, with constant speed and varied power.	50

List of figures

Figure 1.1: Specializing project main study case	4
Figure 2.1: Example of the convenient way of diesel-electric propulsion	10
Figure 2.2 Losses in the convenient diesel-electric system, and eliminated losses in the proposed system	10
Figure 2.3 Typical diesel efficiency graph	12
Figure 2.4: Propeller curves: red-zero pitch, blue-normal pitch, green maximum pitch	13
Figure 2.5: Schematic representation of salient pole synchronous machine	16
Figure 2.6: Reluctance varying with the rotor position	17
Figure 2.7: MMF vector F_a is resolved into d and q axis	18
Figure 2.8: Phasor diagram of the salient pole machine	20
Figure 2.9: Equivalent circuit diagram of the salient pole machine	21
Figure 2.10: Synchronous reactance correction factor illustration	23
Figure 2.11: Graphical illustration of the Gauss-Seidel method	27
Figure 3.1: Proposed systems variations	32
Figure 4.1: Simple system representation for power flow problem	36
Figure 4.2: One machine representation in power flow problem	37
Figure 4.3: Graphical representation of the power flow solution for one generator two motor model, 150Hz, 100kW load	41
Figure 5.1: Comparison of the simulation results with the measured values during tests onboard the tow ship	48
Figure 5.2: Current - Power dependencies with different frequencies for one generator-two motors model.	49
Figure 5.3: Voltage angle change with increasing power (current) constant frequency (50Hz) (A) Power= 10kW; (B) Power=50Kw; (C) Power=100kW	49
Figure 5.4: Terminal voltage change with the increase of power for 150Hz	50
Figure 5.5: Power factor as a function of power, for 4 different frequencies	51
Figure 5.6: losses in the system 1 generator 2 motors, constant frequency 150Hz	51
Figure 5.7: Active losses as function of frequency with constant power, in the system of 1 generator 2 motors	52
Figure 7.1: inductance variance with rotor angle	57
Figure 7.2: Mutual inductance variance with rotor angle	57

Figure 7.3: Change of the input signals abc to dq0, and dq0 to abc on the output	60
Figure 7.4: PMSM model block.	62
Figure 7.5: PMSM block inside	63
Figure 7.6: Electrical model block inside	64
Figure 7.7: Electrical model block i_d/dt transfer function	65
Figure 7.8: Electrical model block i_q/dt transfer function	65
Figure 7.9: Model for dynamic simulations	66
Figure 8.1: Synchronization failure PMSM	68
Figure 8.2: Successful synchronization of the PMSM	69
Figure 8.3: A response of the motor to the slow gradual change of torque	69
Figure 8.4: Voltage angle between machines EMFs as a response to the gradual change in load torque	70
Figure 8.5: Pole wheel oscillations.	70
Figure 8.6: Voltage angle between machines EMFs as a response to the fast gradual change in load torque	71

Nomenclature

Abbreviations

AC	Alternating Current	PMSM	Permanent magnet synchronous machine
DC	Direct Current		
CPU	Central processing unit		
emf	Electromotive force	PMSG	Permanent magnet synchronous generator
IM	Induction motor		
mmf	Magnetomotive force		

Subscripts

<i>abc</i>	Three phase stator variables	<i>o</i>	Output
<i>d</i>	Direct axis	<i>q</i>	Quadratic axis
<i>e</i>	Electrical	<i>qd0</i>	Park qd0 variables
<i>g</i>	Air gap	<i>r</i>	rotor
<i>i-j</i>	Element in the matrix	<i>s</i>	stator
<i>ls</i>	Leakage(inductance)	<i>tot</i>	total
	Magnetizing(current), mutual(inductance),		
<i>m</i>	permanent magnet(flux linkage), mechanical (speed/posion)		

Symbols

β	Angular position	L	Inductance
δ	Voltage angle	M	Magnetization
θ	Angular position	N,n	Number of turns
φ	Current-voltage angle	P	Active power
ω	Angular speed	p	Number of poles
ψ	Flux linkage per second		
μ	Permeability	r	Resistance
μ_0	Vacuum permeability	T	Torque
B	Magnetic induction	V	Average voltage

E	Induced voltage	v	Instantaneous voltage
H	Magnetic field strength	Q	Reactive power
I	Average current	X	Reactance
i	Instantaneous current	Y	Admittance
J	Inertia	Z	Impedance

CHAPTER 1

Introduction

This chapter introduces the background of the problem studied in the project and the motivations for solving it; and consequently state the project objectives, scopes and limitations.

1.1 Background

Nowadays mechanically propelled ships take approximately 95% of the world fleet. These ships have the propulsion system that includes the mechanical shaft, and the internal combustion engine which produce the energy that is used to propel the ship(1). The interaction between the ship, sea and the propeller can cause misalignment and distortion in the shaft. As a result the efficiency of usage of energy can be reduced and the noise and vibrations arise (2).

One solution to the above mentioned problems is the electric propulsion. The idea is not new and is dated back to the early 1990s(1). Today electric propulsion systems become an attractive choice for different types of commercial ships and cruise ships. The number of the ships using electric propulsion in the world is growing from year to year(3).

The lack of the mechanical shaft brings great advantages of the electric propelled ships in comparison with the combustion engine systems. In particular the advantages are(1):

- Better maneuverability. The significant difference with conventional systems is that mechanical propulsion systems have less variability, meaning that for these systems it

is difficult to keep the constant torque at various speeds(4). Electric propelled ships overcome this issue and have better variability at different speeds, which is most evident while maneuvering.

- Better efficiency in terms of the fuel cost. It is known that in conventional mechanical systems there are different engines occupied to provide energy for propulsion and for the functioning of the side systems of the ship. These engines have to run all at the same time during the ship operation. On the contrary the electrical propelled ships are designed to use the prime movers for both purposes, and these systems are flexible to change the usage of the generators according to the current demand. Even though the overall efficiency of energy conversion is slightly lower for electric propelled ships, the usage of the energy is much higher, it compensates for some lack of energy conversion efficiency and makes the electric propelled ships consume approximately 10% less fuel(5).
- The other benefit comes as a consequence of the previous one. This is less NO₂ emissions. Electric propelled ships operate at higher prime mover speeds and generally more flexible drive makes it possible to reduce emissions(6).
- Reduction in the shaft vibrations and noise. The conventional mechanical systems often deal with vibrations caused by the long and relatively heavy shaft line, while the electric propelled ship have the motors installed very close to the propellers, thus reducing these negative aspects(5).
- Easier installation and maintenance. Electric propulsion motors can be installed close to the propellers and no stiff connection between generator(s) is needed, therefore the arrangement of the machine on board the ship can be done in order to make the maintenance easier and leave the space for the possible other needs.

Even taking into account the mentioned advantages only in the recent decades the driving capacity of the electric propelled ships has become sufficient enough for the wide variety of applications. This has become possible with the development of the modern electronics technology and energy storage systems. Nowadays electric propulsion draws interest from the navies, shipyards and ship owners as well as engineers and researchers(1). The demand in the electric propulsion systems steadily increases, thus offering good opportunities for the future development of the technology.

When it comes to the important decision on choosing the electric machines for the propulsion system it should be stated, that both DC and AC motors have been used for this purpose. The main disadvantage of using the DC motors is comparably low power density, and time interval between the maintenance(3). AC machines especially the permanent magnet synchronous machines (PMSM) have relatively high power density high torque to current ratio and high efficiency(7). Thus the PMSM become the first choice for the modern electric propulsion systems.

One example of such a modern approach to the electric propulsion is the direct diesel electric propulsion system developed by the Norwegian company Inpower AS. The above mentioned advantages of the electric propulsion systems can be fully extended to this new approach, where the system represents converterless and transformerless topology. In the proposed system the electric machines have a direct connection. It introduces the radical simplification to the convenient electric propulsion technology(8). It features the smallest possible number of components. As the consequence the capital cost investments is lowered compared to the existing diesel-electric solutions. One of the key features of the proposed system is the implementation and full use of the benefits of the permanent magnet technology.

1.2 Summary of the autumn project

As the pre-thesis work a project with a title “Modelling of the electric shaft used by the company Inpower AS” has been done in the autumn semester 2014 (9).

The main emphasis of the project was to create a steady state mathematical model of the simple system consisting of the PMSG directly supplying the PMSM shown in Figure 1.1. The focus of this simple model was to establish equations utilizing the saliency of the rotors of both machines. The main difficulty was to develop an algorithm and implement it in the Matlab code, without using any professional software, in order to gain understanding of the d-q axis analysis.

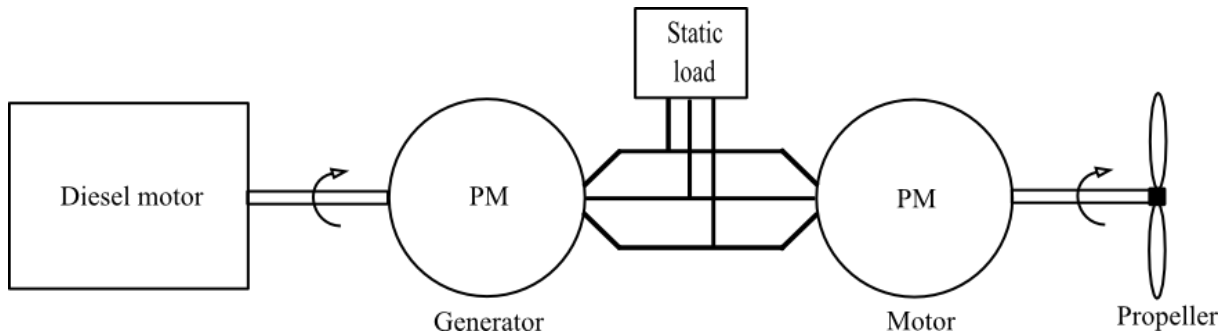


Figure 1.1: Specializing project main study case

First a brief theoretical overview highlighting the relevant topics of the d-q analysis and power equations was presented. This overview however could not be enough for the complete understanding of the theoretical basis of the synchronous machines, thus a more in depth theoretical chapter is following in this thesis work.

With the progress of the project work it has become evident that obtaining the direct solution even of the simple system is not a trivial task. The main challenges were to specify the frequency varying inductions of the machines and to solve the nonlinear many-variable active and reactive power equations.

To solve these equations an iterative method was used, and the solution obtained with a good accuracy.

Further study of the simple case system has shown that the correction factor for the synchronous reactance of one of the machines has to be taken into the account. The reason is that one could not just sum the d and q reactances of the generator and the motor, because the reference voltage angles for these two machines are different. This is one important conclusion made in the preliminary work, which also adds a point for further research of this question in the many-machine case in the thesis work.

As soon as the simple system was solved with desired accuracy and implementation of the reactance correction factor the rest of the time was used to make a first approximation model of the many-machine case. One of the major motivation of creating a an extended model was to verify the results of the mathematical model with the laboratory tests on board the ship designed by Inpower AS.

The extended model consisted of the generator directly supplying power to the static load and one or two motors. As has been learned description of such a system is done with a set of nonlinear power-flow equations, which do not have analytical solution (10). Therefore a power flow solution freeware software Matpower has been used.

In order to fit the system parameters into the Matpower solver many-machine model has taken into account a number of simplifications compared to the analytically solved simple-case model. The most important of these are round rotor approximation, and disabling of the reactance correction factor.

The results obtained were following the experimental data with accuracy of current calculation from 7 to 19 percent, which appears to be not accurate for the professional use. This creates a major point for the further study of the steady state models in the thesis work.

For all mathematical model the Graphical User Interface has been created in Matlab software in order to simplify the use of the models.

Generally it has been concluded that the mathematical model of the simple system shown in the figure 1.1 follow theoretically expected results, while the extended system model need further research in order to obtain better simulations results.

1.3 Objectives

The mater thesis is a further investigation of the steady state model of the directly connected synchronous machines used for the electric propulsion of the ships. The challenge is how to take into the account the saliency of both the generator and the motor, while taking into the account the changing frequency and resistance and therefore losses.

As described in the section 1.2 different study cases have been taken into account while modeling, the variety of the proposed systems has been increased up to 4 study cases in the master thesis, described in chapter 4.

These study cases comprising of permanent magnet machines directly connected by one terminal bus with a possibility to include the static power load or switchboard load, are to be defined simulated and the results analyzed and compared with the real world test onboard of the existing ship.

If the time constraint allows the dynamic model of the same or simplified study cases should be developed in the Simulink software(11-13), by using the prebuilt blocks of the machines and components. The upon the dynamics simulations should be made on detecting the torque oscillations on the motor shaft, after gradual change in the load torque. The change of the voltage angle between the systems electromotive forces (EMF) should also be observed.

It is evident that the above simulations proposed, especially the steady state models will include writing of rather complicated and difficult to understand Matlab code in order to solve the system of nonlinear equations. Therefore some emphasis should be made upon creating a user-friendly code, which will not only serve to solve the limited number of the proposed system discusses in the thesis, but can be possibly used later.

1.4 Scope of work

The scope of work is based on the objectives described above and on the problems and conclusions regarding the future work in the specializing project of the fall 2014(9). Divided by point for better readability:

- Introduce the study cases to the reader, briefly describe the system components and any special changes made in order to use for the ship applications.
- Establish the theoretical basis behind the PMSM mathematical model including saliency and resistance
- Establish the theoretical basis behind the power flow calculation problem
- Develop the extended equations for the extended power flow calculations, including saliency
- Establish the theoretical basis behind solving systems of nonlinear equations, with iterative methods
- Implement the above mentioned theory and mathematical model in the Matlab code
- Achieve the sufficient convergence of the equations and the desired accuracy
- Expand the achieved solution to the arbitrary number of machines case
- Compare the simulation results with the real world tests on board the ship and with the results of the previous simplified model developed in the specializing project

The following tasks should be done if the time permits:

- Create a user friendly interface of the steady state solver code
- Start making the case for the dynamic modeling of the proposed system or systems

1.5 Limitations

- Magnetic saturation in the core is neglected
- Armature windings are assumed to produce pure sinusoidal distribution of magnetic field
- Eddy currents and hysteresis losses are neglected
- Resistances and inductances are assumed to be independent of temperature.
- In the sinusoidal steady state the damper windings are neglected.
- The cables impedances are small due to short distances and therefore neglected.
- All the mechanical losses in the machines are neglected
- The propeller curves are assumed to be cubic functions of the speed

1.6 Report structure

The overall report structure follows the principal of theoretical basis going prior the modeling and simulations studies. It required for better understanding of the proposed solutions and simulation results.

The report can be virtually divided in two parts, one devoted to the detailed static system modeling and the other to the brief introduction of the systems dynamics. Each part followed by the discussion. Conclusion unites the whole study.

Chapter 1 introduces the background of the problem studied in the project and the motivations for solving it; and consequently state the project objectives, scopes and limitations.

Chapter 2 describes major components of the proposed system, and software used further for modeling. It gives a short theoretical revision of the PMSM mathematical modeling.

Chapter 3 describes the proposed by Inpowe AS system variations, and gives a graphical representation of those systems.

Chapter 4 represents the modified solution for the power flow problem with possibility to include PMSM with salient rotors. It defines the study cases in terms of power flow, and gives explanation on the written code and created matlab m-files.

Chapter 5 presents the simulation results of the steady state models.

Chapter 6 discusses the simulation results and other relevant elements of the study of the steady state models.

Chapter 7 introduces the required extension of the theoretical background for the dynamic modeling of the systems. It gives introduction to the bloc diagram it way of modeling and represents the blocks of which the dynamic model is built.

Chapter 8 presents the simulation results of the dynamic model.

Chapter 9 discusses the simulation results and other relevant elements of the study of the dynamic system models.

Chapter 10 presents the conclusions made. Recommendations for future work are presented in chapter 11.

Matlab codes written for the simulations are presented in the appendix, as well as in the attached m-files

Theoretical background and mathematical modeling

This chapter describes major components of the proposed system, and software used further for modeling. It gives a short theoretical revision of the PMSM mathematical modeling.

2.1 Brief description of major system components

2.1.1 Ships with electric propulsion

The most convenient way to design the electric propulsion ships nowadays is to have a diesel-electric propulsion system. These system have the same advantages over the mechanical propelled ships as listed in the section 1.1.

In such systems the diesel engine is used as a prime mover, it has an AC electric generator on its shaft which converts the mechanical energy to the electric. Then voltage and frequency are changed by means of converters and transformers and the energy is distributed between the main consumers on board the ship. These include typically the switchboards supplying all the ships low voltage consumers apart from main motors, and the main motors, which have propeller on its shaft. The typical single line diagram of the “offshore service and supply vessel” is shown in figure 2.1(14).

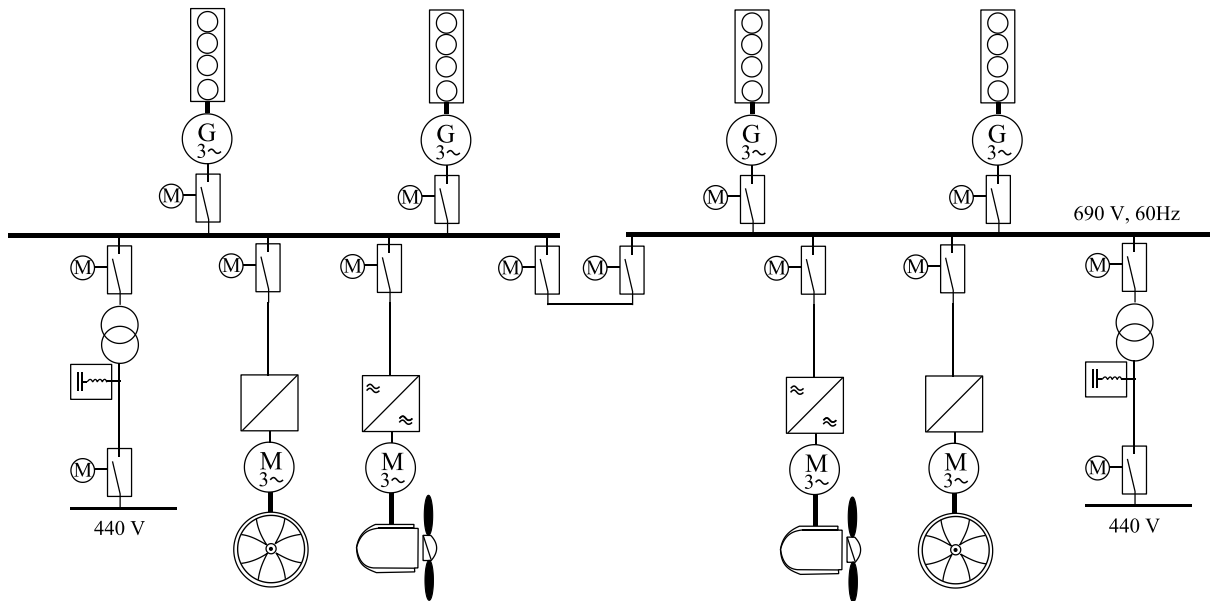


Figure 2.1: Example of the convenient way of diesel-electric propulsion

Based on the above diagram it possible to approximate the power loss of the convenient diesel-electric systems shown in figure 2.2 (15). The losses that are eliminated in the new proposed by the Inpower system are also schematically shown in the same figure 2.2.

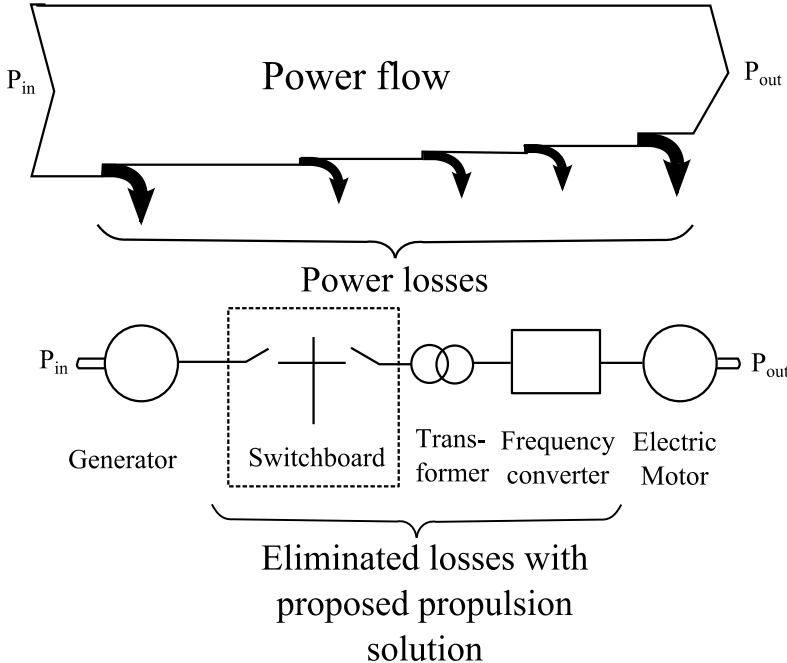


Figure 2.2 Losses in the convenient diesel-electric system, and eliminated losses in the proposed system

For each component, the electrical efficiency is known, typical values at rated power are for; generator: = 0.95-0.97, switchboard: = 0.999, transformer: = 0.99-0.995, frequency converter: = 0.98-0.99, and electric motor: = 0.95-0.97. Hence, the efficiency of a diesel electric system, from the diesel engine shaft, to electric motor shaft, is calculated as multiplication of the above values and normally is between 0.88 and 0.92 at full load. The efficiency depends on the loading of the system (16).

These two figures show a “classic” way to design a ship with electric propulsion. The case studied in the current thesis work represents a different approach. The Norwegian company Inpower AS came up and successfully implemented the idea of the radical simplification of the above circuit. The converters and the transformers are omitted from the distribution network, instead the varying frequency and voltage electric power is directly supplied to the permanent magnet synchronous motor(s). The switchboard load remain the same as of the convenient model. It is easy to see that the losses of the propulsion transformer and the propulsion converter will be no longer presented in such a system and also the capital investments will be lower, while the ship operation will be shown not to be compromised.

2.1.2 PMSM for generation and ship propulsion

The usage of the permanent magnet technology in the proposed system allows for the better efficiency compared to the conventional induction motors. While the usage of permanent magnets for the excitation allows have better power density. Both generators and motors in the proposed system variations are permanent magnet synchronous machines.

2.1.3 Diesel engine

The primary source of energy on board the ship is often a generator set which is driven by the combustion engine, fueled typically with diesel.

In a diesel-electric propulsion system, the diesel engines are normally medium to high-speed engines. These are lighter in weight and less expensive than similar rated low speed diesel engines that are used for direct mechanical propulsion (16).

The diesel engine technology is all the time being improved in terms of achieving higher efficiency and reduced emissions. At present, a medium speed diesel engine has a fuel

consumption of less than 200g per produced kWh at the optimum operation point as seen in figure 2.3(16).

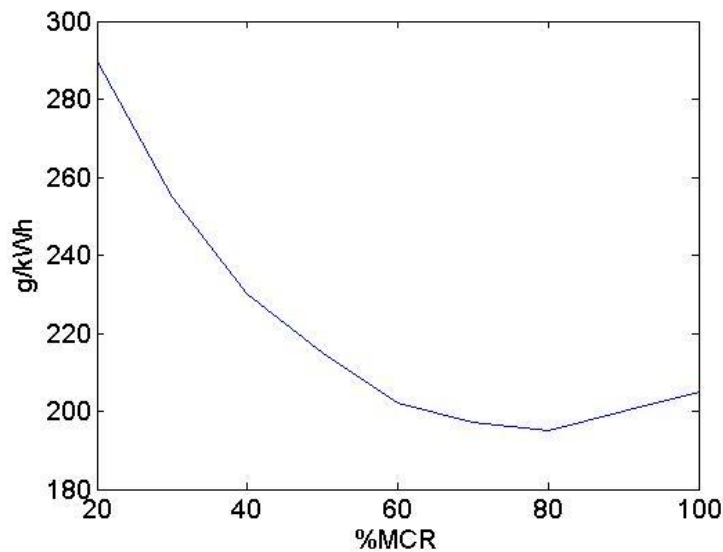


Figure 2.3 Typical diesel efficiency graph

Here g/kWh represents grams of diesel needed to produce 1 kWh of energy. MCR stand for the maximum continuous rating and represents the relative load of the engine compared with the maximum allowed continuous load.

The utilization of fuel is regarded to be high, however even on the modern engines this value is typically around 40%, the rest of the energy is either used or utilized as heat energy

As seen from the graph when the load becomes lower than 50% of the MCR, the efficiency drops very fast. Thus knowing the optimum operating condition it becomes possible to load the diesels in the systems of several diesel engine so that the average loading is as close to the optimum as possible. For detailed description of design and functionality of diesel combustion engines, see (17).

2.1.4 Propeller

The propeller is one type of a fan which transforms the rotational energy into thrust. It acts using the pressure differences between the surfaces of the blade. In current thesis will not go into the fluid dynamics of the propeller types, however in particular to simulate any of the

operating points in the future analysis it required to understand the propeller power – speed characteristics.

In conventional systems the propeller is usually speed controlled FPP (Fixed Pitch Propeller) type, which gives a simple and robust propeller design. In some applications the CPP (Controllable Pitch Propeller) can also be used in order to achieve higher efficiency by operating on the optimum load and faster response. In the proposed thesis study cases the propeller used is a CPP propeller. Therefore it is needed to represent the propeller curves which are approximated to follow the cubic function dependence of speed:

$$P = k_{pitch} h \omega^3 \quad (2.1)$$

Here the coefficients k_{pitch} are different for different values of pitch. The so-called propeller curve for the proposed systems propellers is shown in figure 2.4:

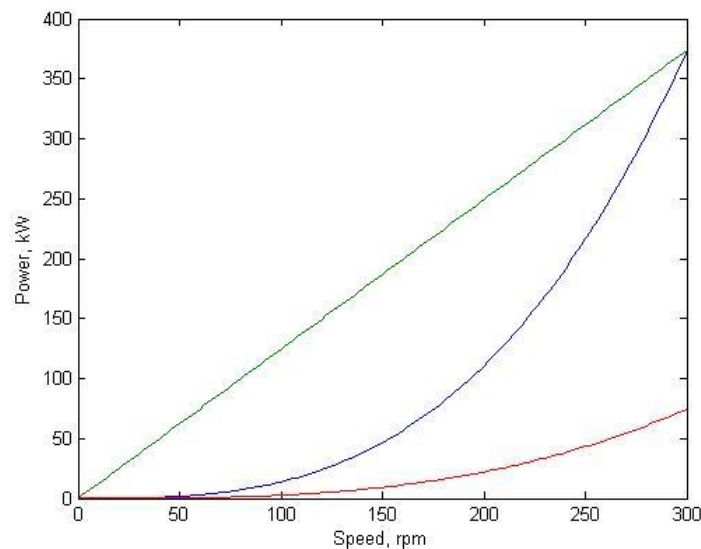


Figure 2.4: Propeller curves: red-zero pitch, blue-normal pitch, green maximum pitch

2.1.5 Switchboards, distribution systems

Marine distribution system consists of the main and emergency switchboards, power panel boards motor controllers lighting and small power panel boards(18). Under the normal operating conditions the power is distributed from the main switchboard. In the proposed case there are no less than two switchboards one, connecting all the machines on the single busbar, and the other supplying power to all the consumers apart from the motors. Low power

converters and electronics are located post the second switchboard. One of the main functions of the switchboard is to offer protection and tripping of the faulty part of the scheme in case of faults overvoltages, overcurrents, etc. For this purpose a wide variety of protection equipment such as circuit breakers is used and located on the switchboards.

2.1.6 Cables

The transmission cables used to connect the machines and equipment together are not the crucial parts of the developed model, since their lengths on board on most of the ships are small, and cables can be safely neglected when creating the models.

2.2 Software description

2.2.1 Matlab

It has been decided to avoid using the top level programming commercial software which allows for the solutions of any power flow problem in order to get the hands on the mathematical model, and in order to implement rather unusual system with varying with frequency parameters.

The choice was made to use the fully available for the NTNU students Matlab ®software. It represent the high level language and interactive environment. For creating and solving the steady state mathematical models of the proposed system the source code was written. Matlab language allows for faster code - writing because one does not need to perform low-level administrative tasks such as declaring variables, specifying data types, and allocating memory(19). Matlab is well designed for the vector and matrix operations which are the crucial parts of the many machines model, for example.

2.2.2 Simulink, Simscape and SimPowerSystems

During the dynamic simulation of the proposed systems, another part of the Matlab package software is chosen. It is united by the name Simulink, and represents a block diagram environment for multidomain simulation and model based design. It generates the code automatically, test and verify the created user systems (11).

Particularly important is an opportunity to model system with block diagrams consisting of blocks that represent different parts of a system and signal lines that define the relationship

between the blocks. This allows to provide an easy to understand graphical representation of real-world systems, understand better the relationship and interdependent signals among different parts of a system and analyze dynamic behavior of the systems(11).

Simscape

Simscape extends Simulink by providing a single environment for modeling and simulating physical systems spanning mechanical, electrical, and other physical domains. It provides fundamental building blocks from these domains that users can assemble into models of physical components, such as electric motors, hydraulic valves, and ratchet mechanisms(12).

All the connections in the models are physical connection, so the structure of the model matches the structure of the real world system. Components (blocks) corresponding to physical elements, such as pumps, motors, and op-amps, are joined by lines corresponding to the physical connections that transmit power. This approach lets users describe the physical structure of a system rather than the underlying mathematics. From the model, which closely resembles a schematic, Simscape automatically constructs the differential algebraic equations that characterize the system's behavior. These equations are integrated with the rest of the Simulink model, and the differential equations are solved directly. The variables for the components in the different physical domains are solved simultaneously, avoiding problems with algebraic loops. (12). This is the main advantage of using Simscape's physical system modeling(20).

Simscape models can be used to develop control systems and system-level performance. Users can extend the libraries using the Matlab based Simscape language, which enables text-based authoring of physical modeling components, domains, and libraries(12).

SimPowerSystems

Yet another extension of the simscape particularly important for modeling electric systems is SimPowerSystems. It provides component libraries and analysis tools for modeling and simulating electrical power systems. The libraries offer models of electrical power components, including three-phase machines, electric drives, and all the components for applications. Load flow, harmonic and other key electrical power system analyses are automated. SimPowerSystems models can be used to develop control systems and test system-level performance(13).

2.3 Mathematical modeling of PMSM

2.3.1 Salient pole machines

The schematic diagram of 2-pole salient pole machine is shown in the figure 2.5. The stator winding of phase A is show as simplified representation of sinusoidally distributed winding. The stator has three axes A, B and C, each corresponding each, to the phase windings. The rotor has two axes: the direct axis (d-axis) and the quadrature axis (q-axis), 90 electrical degrees behind the d-axis.

The introduction of the arbitrary chosen d and q axis is of significant importance while creating the mathematical model of the PMSM.

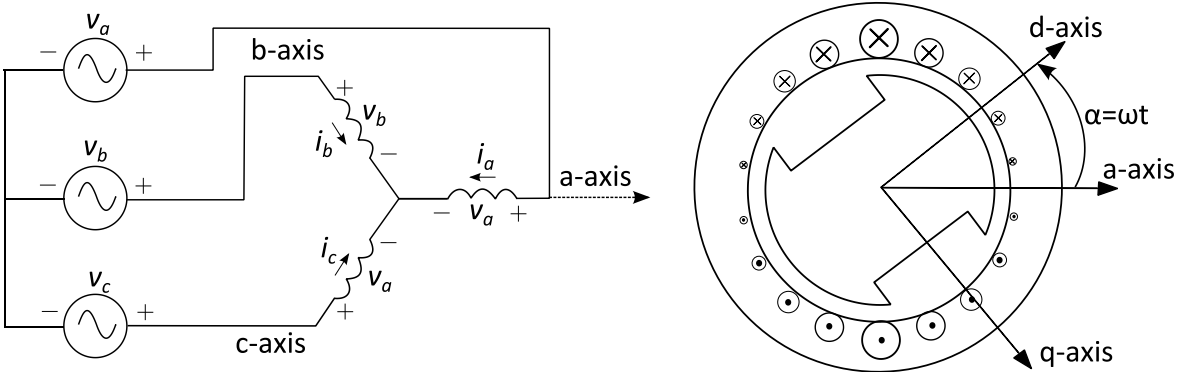


Figure 2.5: Schematic representation of salient pole synchronous machine

Angle $\alpha = \omega_m t$, where ω_m is the rotor angular velocity, defines the instantaneous position of the rotor with respect to stationary reference, here to be chose along a-axis. For a 2 pole machine the electrical rotational speed is equal mechanical rotational speed, this is not the case for many pole generators and motors. In a P-pole machine one mechanical revolution of the rotor is equal to $p/2$ electrical revolutions, therefore the following equations apply:

$$\alpha_e = \frac{p}{2} \alpha_m \tag{2.2}$$

α_m – is the angle in mechanical degrees, α_e – is the same angle in electrical degrees. In the same way the electrical rotational speed ω_e and mechanical rotational speed ω_m are related:

$$\omega_e = 2\pi f = \frac{p}{2} \omega_m \quad (2.3)$$

Round rotor machines are usually used for the high speed applications because of their ability to withstand high centrifugal forces, while generators and motors operating at lower speeds need to have a high many poles in order reach the current frequency of 50 Hz. As will be shown in chapter 4, the proposed system is operating in the range of frequencies from 30 to 150 Hz. Because of the high number of poles the generators have lower speed, and therefore salient pole machines become possible to use because these will be able to withstand the lowered centrifugal forces.

The main difficulty while modeling the salient pole machine is the width of the air gap which varies circumferentially around the rotor, with the smallest value chosen to be along the d-axis and the highest value along the q-axis. As a result the reluctance seen from the windings is not equal, giving the maximum value R_d and minimum R_q as shown in **figure 2.2**.

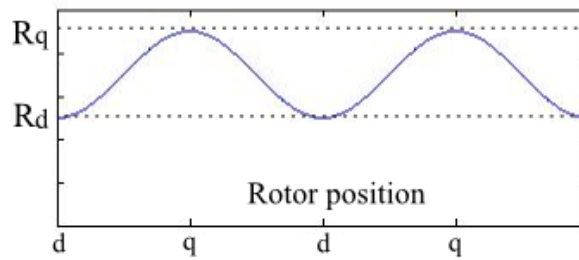


Figure 2.6: Reluctance varying with the rotor position

The flux tends to choose the path with the least reluctance, therefore its vector is shifted towards the d-axis compared with the mmf vector. This gives an important consequence: the flux and the mmf are not in phase at any instant of time except for the 2 moments when the mmf lies along the d-axis giving the minimum reluctance and when it lies along the q-axis when the forces shifting the flux vector balance each other. To overcome the problem of flux being out of phase of the mmf, the mmf vector for any instant of time is resolved into d and q axis, and then treated separately.

The concept is shown in the figure 2.7. Vector \vec{F}_a and the current vector \vec{I} are resolved into d-axis giving $\vec{F}_{ad}; \vec{I}_d$ and q-axis giving $\vec{F}_{aq}; \vec{I}_q$. The excitation mmf is shown as vector \vec{F}_f , there is no need to resolve this mmf, since at any instance of time it is directed along the d-axis.

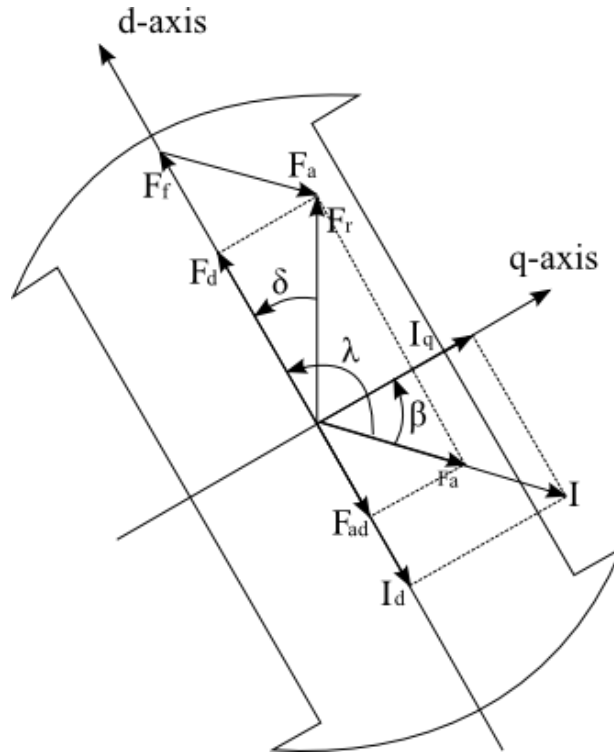


Figure 2.7: MMF vector F_a is resolved into d and q axis

Then it becomes possible to set the equation for the resultant mmf vector $\vec{F}_r = \vec{F}_d + \vec{F}_q$, where $\vec{F}_d = \vec{F}_f + \vec{F}_{ad}$; $\vec{F}_q = \vec{F}_{aq}$ and current:

$$\vec{I} = \vec{I}_d + \vec{I}_q \quad (2.4)$$

Transferring from mmf to efm. In the case shown in the figure 2.3 the resultant emf is equal to the sum of 3 components due to \vec{F}_{ad} ; \vec{F}_{aq} ; \vec{F}_f . The excitation mmf is always directed along the d-axis, therefore the emf E_f that it produces is dependant only on the reluctance R_d and is constant in the permanent magnet machines. E_f lags by 90 degrees the \vec{F}_f so directed along the q-axis.

The emf due to the mmf \vec{F}_{ad} is proportional to the current \vec{I}_d , and lags the corresponding current by 90 degrees, therefore directed also along the q-axis. It can be expressed as:

$$E_{aq} = -jX_{ad}I_d \quad (2.5)$$

Here X_{ad} is the direct-axis armature reaction reactance, it is inversely proportional to reluctance R_d .

Similarly the emf due to the mmf \vec{F}_{aq} is proportional to the current \vec{I}_q and is therefore lagging it by 90 degrees and directed along the d axis and expressed as:

$$E_{ad} = -jX_{aq}I_q \quad (2.6)$$

Here X_{aq} is the quadratic-axis armature reaction reactance, it is inversely proportional to reluctance $R_q \cdot \delta\lambda$

The resultant air gap emf is simply the sum all the emfs:

$$E_r = E_f + E_{ad} + E_{aq} = E_f - jX_{ad}I_d - jX_{aq}I_q \quad (2.7)$$

In order to obtain the expression for the terminal voltage of the machine the voltage drops due to the leakage inductance X_l and resistance R must be substituted from the equation (6):

$$\begin{aligned} V_g &= E_r - jX_l\vec{I} - R\vec{I} = E_f - jX_{ad}I_d - jX_{aq}I_q - jX_l(I_d + I_q) - R\vec{I} = \\ &= E_f - j(X_{ad} + X_l)I_d - j(X_{aq} + X_l)I_q - R\vec{I} = E_f - jX_dI_d - jX_qI_q - R\vec{I} \end{aligned} \quad (2.8)$$

Where $X_d = X_{ad} + X_l$ and represents direct-axis synchronous reactance, $X_q = X_{aq} + X_l$ and represents quadratic-axis synchronous reactance. Reluctance along the q-axis is chosen to be the highest, therefore $X_d > X_q$.

To illustrate the above equation (6), the vector diagram is constructed shown in figure 2.9, it is the extension of the figure 2.3 showing the emfs and terminal voltages resolution into d and q axis.

2.3.2 Phasor diagram and equivalent circuit

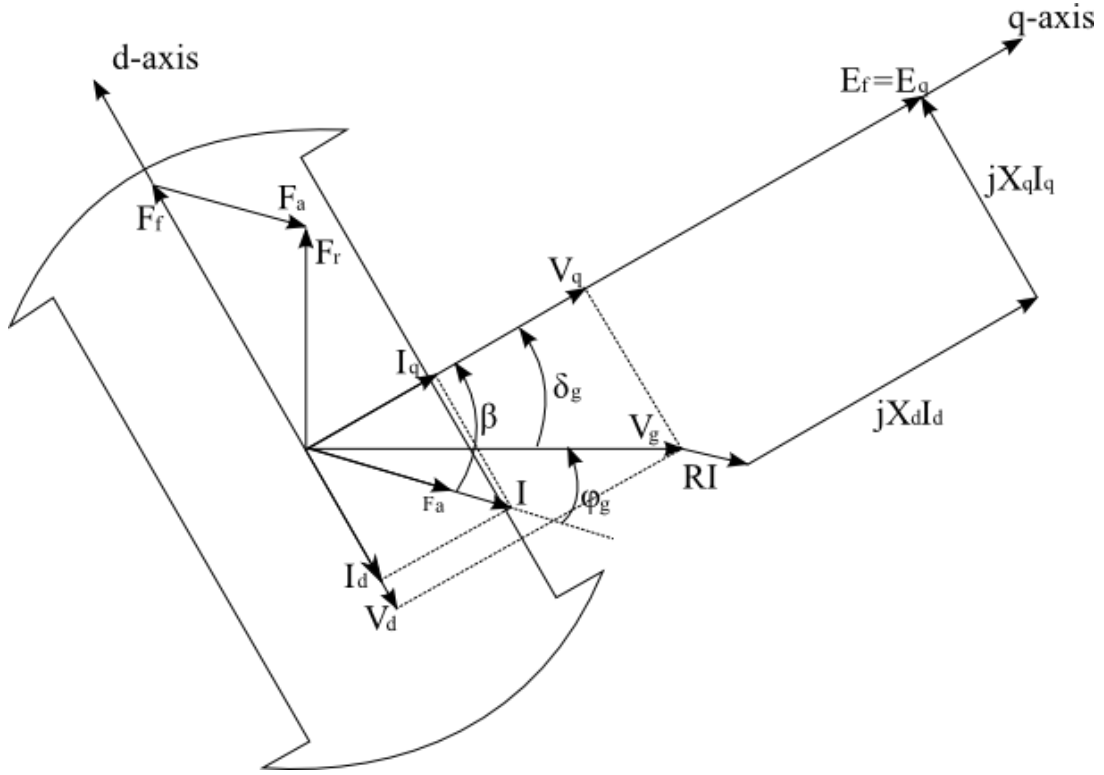


Figure 2.8: Phasor diagram of the salient pole machine

The major difficulty while constructing the diagram and highest point of interest is to allocate the q-axis with respect to terminal voltage V_g . Solving this problem includes the rearrangement of the equation (6) into set of equations for d and q axis separately and finding the angle δ_g . First realizing that E_f lies along the q-axis:

$$\begin{aligned} E_f &= V_g + jX_d I_d + jX_q I_q + R\vec{I} = V_g + jX_d I_d + jX_q I_q + R\vec{I} + jX_q I_d - jX_q I_d = \\ &= V_g + j(X_d - X_q)I_d + jX_q(I_d + I_q) + R\vec{I} = E_Q + j(X_d - X_q)I_d \end{aligned} \quad (2.9)$$

Where:

$$E_Q = V_g + R\vec{I} + jX_q \vec{I} \quad (2.10)$$

The second term $j(X_d - X_q)I_d$ in equation (7) is directed along the q-axis because the current I_d is multiplied with j shifting it 90 degrees counterclockwise to the imaginary axis. As stated before E_f is also laying on the q-axis, therefore E_Q should also be on the q-axis. Therefore vectors \vec{V}_g and \vec{I} are enough to determine the direction of the q-axis hence the angle δ_g .

The resolution of the equation (6) into d and q axis involves realizing that because of the shift that gives multiplication bej , term $jX_q I_q$ is directed along the d-axis, while $jX_d I_d$ is directed in the opposite direction of q-axis thus giving the minus sign. Then the set of equation for separate axis becomes:

$$\begin{aligned}
 \text{d-axis: } E_d &= V_d + RI_d + X_q I_q = 0 \\
 \text{q-axis: } E_q &= V_q + RI_q - X_d I_d = E_f
 \end{aligned}
 \tag{2.11}$$

Since $E_f = E_d + E_q$ is always directed along the q-axis, its d-axis component is equal to zero, while q-axis component is equal to E_f . In equation (9) all the voltages and currents are resolved into d and q axis so these are not vectors, but scalars. So the following equations apply:

$$\begin{aligned}
 V_d &= -V_g \sin\delta; & V_q &= V_g \cos\delta \\
 I_d &= -I \sin\beta; & I_q &= I \cos\beta
 \end{aligned}
 \tag{2.12}$$

Where: δ_g – is the angle between the induced emf E_f and terminal generator voltage V_g .
 $\beta = \varphi_g + \delta_g$ is the angle between the induced emf E_f and the current. The minus signs of V_d and I_d show that these are directed in the opposite direction of the d-axis.

Equations above allow setting the equivalent circuit shown in figure 2.9

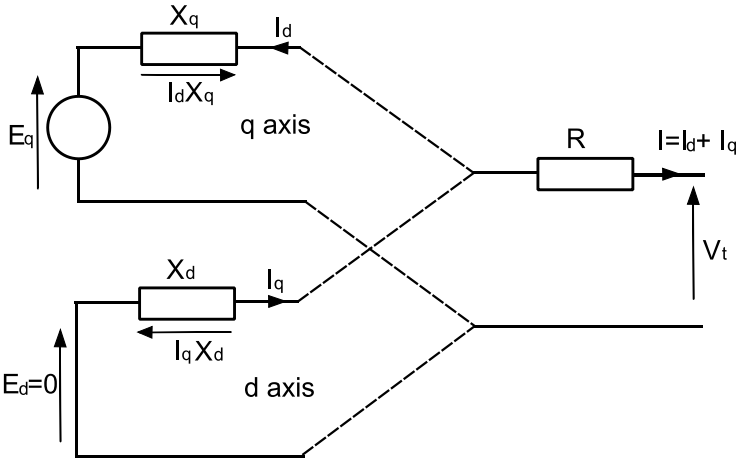


Figure 2.9: Equivalent circuit diagram of the salient pole machine

2.3.3 Real and reactive power of the salient pole generator

As has been stated in the summary of the spring project even solving the simple proposed systems directly is impossible, therefore it was stated that modeling of such systems should be done the same as power flow is modeled. The difference here would be the power flow equations themselves due to the saliency of the machine. Therefore it is needed to determine these new equations.

The derivation starts with a well known expression:

$$P = VI\cos\varphi = VI\cos(\beta - \delta_g) = V\sin\delta_g\sin\beta + V\cos\delta_g\cos\beta \quad (2.13)$$

Substituting for voltages and currents from equation (2.12) we get:

$$P = V_d I_d + V_q I_q \quad (2.14)$$

The currents I_d and I_q can be taken from resolution of equation (9):

$$\begin{aligned} I_d &= \frac{1}{Z^2} (R(E_d - V_d) - X_q(E_q - V_q)) \\ I_q &= \frac{1}{Z^2} (R(E_q - V_q) - X_d(E_d - V_d)) \end{aligned} \quad (2.15)$$

where

$$Z^2 = R^2 + X_q X_d \quad (2.16)$$

Substitution of the above current components into power equation (12) gives the desired power equation:

$$P = \frac{E_g V X_q}{Z^2} \sin\delta_g + \frac{V^2 (X_d - X_q)}{2Z^2} \sin(2\delta_g) - \frac{E_g V R}{Z^2} \cos\delta_g - \frac{V^2 R}{Z^2} \quad (2.17)$$

The similar derivation applies for the reactive power starting from the well know expression:

$$Q = VI\sin\varphi = -V_q I_d + V_d I_q \quad (2.18)$$

Substituting for the current components (13):

$$Q = \frac{E_g V X_q}{Z^2} \cos\delta_g - \frac{V^2 (X_d \sin^2\delta_g + X_q \cos^2\delta_g)}{Z^2} - \frac{E_g V r}{Z^2} \sin\delta_g \quad (2.19)$$

It is important to realize that in equations 15 and 17, the angle δ_g is set with the reference to terminal voltage V. In the other words V has the zero angle which is also shown on the vector diagram in the figure 2.8.

2.3.4 Synchronous reaction correction factor

The angle between the EMFs between the reference machine and any other machine in the system adds complexity to the calculation of the system's d and q reactances, because in the above derivation of the synchronous d and q reactances are supposed to be set for the reference machine, meaning that the zero voltage angle can be only on one machine in the system. This makes an angle shift of δ in the two systems of axis figure 2.10.

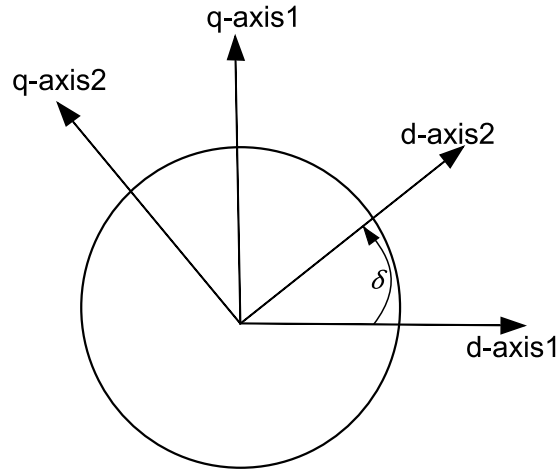


Figure 2.10: Synchronous reactance correction factor illustration

In the developed model the generator EMF is used as the reference for the angle $\delta=0$, therefore the X_{dg} and X_{qg} of all the other machines used need to be adjusted. To do this in each new iteration of the Gauss-Seidel method to solve the system of power flow equations, the new values of the $X_{dq}(n)$ and $X_{qg}(n)$ are calculated:

$$X_{dg}(n) = X_{dg}(0) - (X_{dg}(0) - X_{qg}(0)) \cdot \sin(2\delta) / 2 \quad (2.20)$$

$$X_{qg}(n) = X_{qg}(0) + (X_{dg}(0) - X_{qg}(0)) \cdot \sin(2\delta) / 2$$

Where $X_{dg}(0)$ and $X_{qg}(0)$ are the parameters given for the machine.

As seen from the equation the sinusoidal change in the synchronous reactance is assumed according to (21), so that the X_d sinusoidally decrease to X_q with angle changing from 0 to 90 degrees, the X_q increases in the same manner. This expression is valid for the angles lower 90 because further increase in angle will give the negative signs of sin function.

Reluctance varying with rotor position is well shown in figure 2.6.

2.4 Theoretical background of the power flow studies

In the previous chapter the mathematical modeling of synchronous machines has been described briefly. This chapter deals with basis for the steady-state analysis of those machines connected in simple systems with different topologies. The system is assumed to be operated under balanced condition and represented by a single-phase network. This network contains a number of nodes and branches with impedances specified in the common per unit base.

Network equations are formulated in a node-voltage form. This formulation results in the complex linear simultaneous algebraic equations in terms of node currents. When currents are known this system can rather easily be solved, however in the real power system powers are known rather than currents. The resulting equations in terms of power, known as the power flow equations, become nonlinear and must be solved by iterative techniques. Power flow studies create a necessary background for the further system investigation such as dynamic modeling or transient stability.

In a simple words power flow is a method that allows to calculate voltages, currents and power in a system with arbitrary number of branches and buses. The main task when calculating the system parameters with power flow method is to set the power flow equations and solve those.

2.4.1 Bus admittance matrix

In this chapter the bus admittance matrix in a common way (without saliency included) of the node-voltage equation is formulated.

First all the branch impedances are converted into admittances:

$$Y_{ij} = \frac{1}{r_{ij} + jx_{ij}} \quad (2.21)$$

Here the subscript i stands for the i -bus, and subscript j stands for the j -bus. The resistance r_{ij} and reactance jx_{ij} stand for the impedance of the branch between those buses.

By applying the Kirchoff's current law to any of the nodes in the system and rearranging the branch admittances, the following matrix of equations is obtained:

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_i \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1i} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2i} & \cdots & Y_{2n} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ Y_{i1} & Y_{i2} & \cdots & Y_{ii} & \cdots & Y_{in} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ Y_{n1} & Y_{n1} & \cdots & Y_{ni} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_i \\ \vdots \\ V_n \end{bmatrix} \quad (2.22)$$

or simply:

$$I_{bus} = Y_{bus} V_{bus} \quad (2.23)$$

Where I_{bus} is the vector of injected (external) bus currents. These currents are positive if flowing toward the node and negative if flowing away. V_{bus} is the vector of voltages as seen from the reference node. Y_{bus} is the admittance matrix. The diagonal elements $Y_{11}, Y_{22} \cdots Y_{nn}$ is the sum of all branch admittances connected to it:

$$Y_{ii} = \sum_{j=0}^n y_{ij} \quad j \neq i \quad (2.24)$$

The off-diagonal elements are the branch admittances between those nodes $Y_{ij}=Y_{ji}$. In case there is no connection between the buses the admittance is simple equal to zero.

2.4.2 Power flow equations

Here the equations in the common form are determined so that to for a basis for the further extension of this analysis to salient power flow.

The well know expression:

$$S_i = VI_i^* = P_i + jQ_i \quad (2.25)$$

When substituting for the current from equation 19:

$$\begin{bmatrix} P_1 + jQ_1 \\ P_2 + jQ_2 \\ \vdots \\ P_n + jQ_n \end{bmatrix} = \begin{bmatrix} V_1 & & & \\ & V_2 & & \\ & & \ddots & \\ & & & V_n \end{bmatrix}^* Y_{bus} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{bmatrix} \quad (2.26)$$

In the complex form:

$$\begin{aligned} P_1 + jQ_1 &= Y_{11} V_1^2 e^{-j\theta_{11}} + Y_{12} V_1 V_2 e^{-j(\delta_1 - \delta_2 - \theta_{12})} + \dots + Y_{1n} V_1 V_n e^{-j(\delta_1 - \delta_n - \theta_{1n})} \\ P_2 + jQ_2 &= Y_{21} V_2 V_1 e^{-j(\delta_2 - \delta_1 - \theta_{21})} + Y_{22} V_2^2 e^{-j\theta_{22}} + \dots + Y_{2n} V_2 V_n e^{-j(\delta_2 - \delta_n - \theta_{2n})} \\ &\dots \\ P_n + jQ_n &= Y_{n1} V_n V_1 e^{-j(\delta_n - \delta_1 - \theta_{n1})} + Y_{n2} V_n V_2 e^{-j(\delta_n - \delta_2 - \theta_{n2})} + \dots + Y_{nn} V_n^2 e^{-j\theta_{nn}} \end{aligned} \quad (2.27)$$

Resolving these load-flow equations into real and imaginary parts gives:

$$P_i = \sum_{j=1}^n Y_{ij} U_i U_j \cos(\delta_i - \delta_j - \theta_{ij}) \quad (2.28)$$

$$Q_i = \sum_{j=1}^n Y_{ij} U_i U_j \sin(\delta_i - \delta_j - \theta_{ij})$$

Where δ_i is the angle of the voltage on the i-th node. θ_{ij} is the impedance angle of the branch connecting nodes i and j, $Y_{ij}=1/(Z_{ij}*e^{j\theta})$.

Equations (25) can be written for each bus, and these equations give a mathematical formulation of the power flow problem. It results in a system of algebraic nonlinear equations, which must be solved by iterative techniques.

2.5 Solution of nonlinear algebraic equations

The most common techniques used for the iterative solution of nonlinear algebraic equations are Gauss-Seidel, Newton-Raphson and their modifications. The Newton-Raphson and more modern stationary methods are more effective and have a faster convergence in comparison with Gauss-Seidel method (22) however as will be shown in chapter 4 the proposed systems do not have more than 5-6 nodes, which allows to disregard computation time from the priority list while constructing the mathematical model, and pay more attention to better readability of the physics beyond the mathematical equations. Therefore a more simple yet reliable Gauss-Seidel method is used to solve the load-flow equations.

2.5.1 Gauss-Seidel method

The Gauss-Seidel method is a method of successive displacements. It is a particular case of a more general approach, known as splitting methods, which is described in details in (23). The main idea is briefly described below.

Consider the solution of nonlinear equation given by

$$f(x) = 0 \quad (2.29)$$

Then the function is rearranged and written as:

$$x = g(x) \quad (2.30)$$

It will be shown later that in the salient pole power flow resolution for the particular variable is not possible directly, however issue will be overcome with substitution technique of opening the voltage angles.

$x^{(k)}$ is the initial guess of the variable x , the iterative sequence is formed:

$$x^{(k+1)} = g(x^{(k)}) \quad (2.31)$$

A solution is obtained when the difference between the absolute value of the successive iteration is less than a specified accuracy:

$$|x^{(k+1)} - x^{(k)}| \leq \epsilon \quad (2.32)$$

Where ϵ is the desired accuracy.

Figure 2.11 shows the graphical illustration of the Gauss-Seidel method for the single dimension equation where the straight line is formed by the steps of successive displacements of x until the desired convergence is obtained.

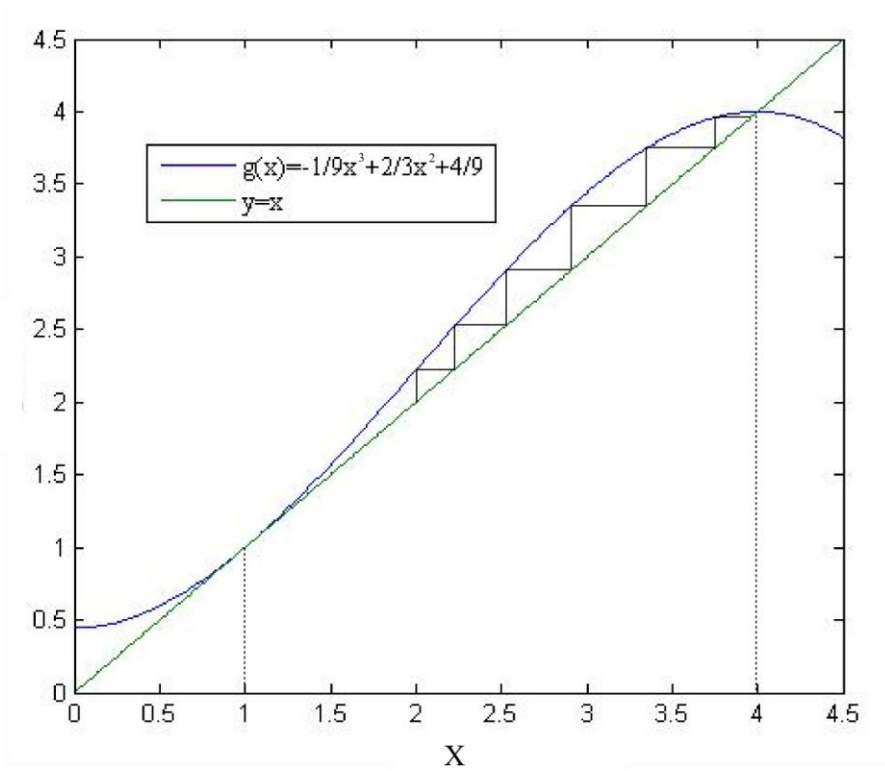


Figure 2.11: Graphical illustration of the Gauss-Seidel method

Then the above analysis is extended to the system of n equations in n variables, which has particularly been implimented in chapter 4. The system of equations first given as:

$$\begin{aligned}
 f_1(x_1, x_2, \dots x_n) &= c_1 \\
 f_2(x_1, x_2, \dots x_n) &= c_2 \\
 &\dots \dots \dots \\
 f_n(x_1, x_2, \dots x_n) &= c_n
 \end{aligned}
 \tag{2.33}$$

Each of these equations is resolved for the new variable:

$$\begin{aligned}
 x_1 &= c_1 + g_1(x_1, x_2, \dots x_n) \\
 x_2 &= c_2 + g_2(x_1, x_2, \dots x_n) \\
 &\dots \dots \dots \\
 x_n &= c_n + g_n(x_1, x_2, \dots x_n)
 \end{aligned}
 \tag{2.34}$$

The iteration procedure is started by guessing the approximate value of each of the independant variable.

The first equation is solved with initial guess values $(x_1^{(0)} x_2^{(0)} \dots x_n^{(0)})$ for all variables, except x_1 . So resolving the first equation for x_1 the new value of $x_1^{(1)}$ is obtained. This value is then used in the next equations to find $x_2^{(1)} \dots x_n^{(1)}$. In the other words in the Gauss-Seidel method the updated values of the variables calculated in the preceding equations are immediately used in the solution of the subsequent equations. At the end of each iteration the calculated new values for all variables are compared with the values from the previous loop, if the mismatch is less than the specified accuracy then the iteration loop is terminated, else it is continued.

2.6 Power flow solution

As described above a part of the problem of the power flow is to find the voltage magnitude and phase angles at each bus as well as active and reactive power flow in each line. The current can be obtained from knowing these variables afterwards.

In solving a power flow problem four quantities are determined for each bus. These are: voltage magnitude (V), phase angle (δ), real power (P) and reactive power (Q). The buses are classfied into three types:

- **Slack bus:** which is chosen to be a reference bus, with voltage magnitude equal to $V_{slack\ bus} = 1 pu < 0^\circ$. This bus is typically a generator bus, which makes a

difference with consumed and generated power, and allows to see the losses in the system.

- **Load buses:** where active and reactive power is specified, also commonly called P-Q buses.
- **Regulated buses:** where voltage magnitude and real power is specified, also called P-V buses.

•

CHAPTER 3

System description

This chapter describes the proposed by Inpower AS system variations, and gives a graphical representation of those systems.

In order to start the discussion of the power flow solution for the salient pole machines interconnected in a small system it is necessary to establish the particular system which have been modeled in the steady state simulation chapter.

So that to have a close connection to the industry and make a valuable research which can be used in the real world, the simulated systems were limited to the ones proposed by the Inpower AS, these are shown in the table 1:

1:1 (PMG:PMM)	with/without static load	salient rotor (L_d and L_q)
1:2 (PMG:PMM)	with/without static load	salient rotor (L_d and L_q)
2:1 (PMG:PMM)	with/without static load	salient rotor (L_d and L_q)
3:2 (PMG:PMM)	with/without static load	salient rotor (L_d and L_q)

Table 3.1: System proposals

The proposed systems are also shown in the figure 3.1.

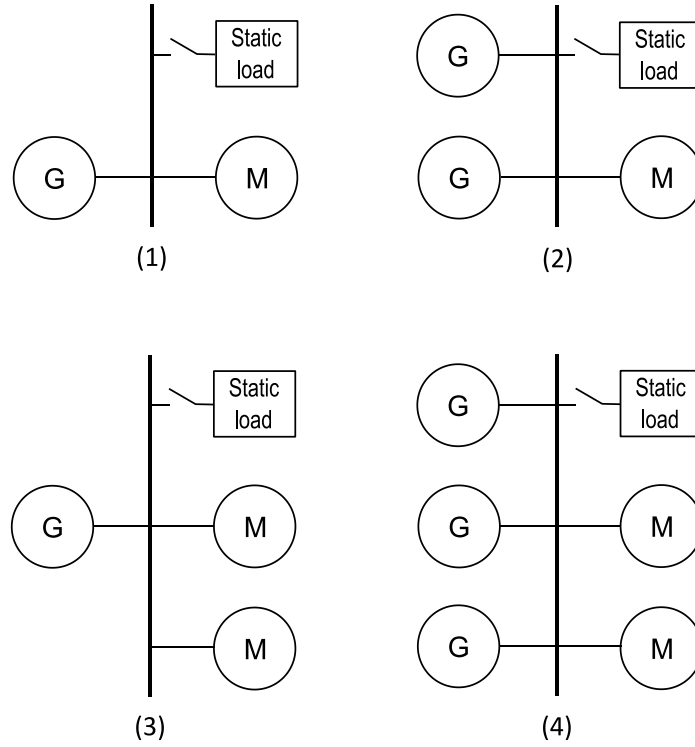


Figure 3.1: Proposed systems variations

In these systems the power from the generator supplies the motor or motors which drive the ship. Therefore in order to control the ship the actual torque produced by the motors should be known. Each of the motors has a propeller on its shaft with known propeller curve, as an example the propeller curves are shown in figure 2.4. Knowing the power needed to drive the ship and the pitch angle the speed can be obtained from the propeller curve. Here the speed dependence on the pitch angle is mentioned, the control strategy of the ship meaning which pitch to use with respect to power is not mentioned, it is among others dependant on the diesel engine efficiency. For this analysis it is assumed that the pitch is always kept at normal value shown by blue line in figure 2.4.

As discussed above, at any instant of time the input parameters to the modeled system are motor(s) active power and speed. Since all the electric machines used in the system are permanent magnet synchronous machines with a constant number of poles, the induced EMF of this type of machines is simply proportional to the rotational speed of the rotor:

$$E_f = k_e \omega_m \quad (3.1)$$

Making use of this equation in terms of power flow analysis gives the induced EMF of the motor also known from knowing the propeller speed. Moreover as the generator is directly connected to the motor, it has to produce the current of the same frequency as the motor needs to maintain the specified rotational speed. Therefore the generator induced EMF also becomes known.

The static load shown on the figure 3.1 consists of the converter supplying the ships internal load such as lighting, heating, deck hoists etc. It is assumed to be known, and also assumed to be constant, not dependant any motor parameters.

CHAPTER 4

Adapting power flow analysis to include saliency

This chapter represents the modified solution for the power flow problem with possibility to include PMSM with salient rotors. It defines the study cases in terms of power flow, and gives explanation on the written code and created matlab m-files.

Based on the power flow theory discussed in chapter 2 and the equation for active and reactive power transfer of the salient pole machine it becomes possible to set the equations for the so-called power flow with included saliency.

There has been made an assumption that the structure of the power flow equations (25) remains the same, but the type of the power flow equation changes.

4.1 Impedance matrix formation

First as noticed from (25) the power flow equations use the admittance matrix formed as stated in (18). This equation is no longer valid for the salient pole machine, because quadratic and direct axis synchronous reactances must be treated separately. Therefore the new algorithm to create an impedance matrix has been developed. In the algorithm the new impedance matrix is set in 3 dimensions.

First the connections matrix consisting of simple 1 and 0 is created. Each element this in the matrix stands for one bus. 1 stands if there is a connection between the buses, 0 if there is

no connection. The diagonal elements in this matrix are always 1. The off-diagonal represent the connections. For example the simplest of the proposed configuration, shown in figure 2.7 has 3 buses. The schematic for power flow calculation of this configuration is shown in figure 2.8.

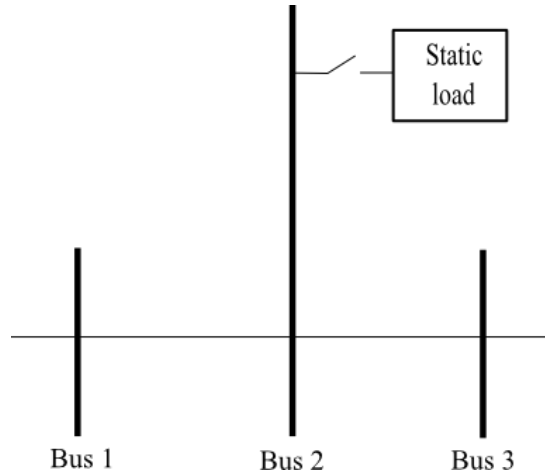


Figure 4.1: Simple system representation for power flow problem

Based on this system the idea of 3-dimensional matrix is described. First the connection matrix becomes:

$$\begin{bmatrix} 1 & 1 & 0 \\ 1 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix} \quad (4.1)$$

Further formation of the impedance matrix is done simply by multiplying the connection matrix with R , X_d and X_q each in separate dimension. The values R , X_d and X_q are the values between buses. For the diagonal elements the impedance is a sum of all impedances coming into the bus.

Here an important note must be considered. It is known from (10) that the admittance matrix is preferred to use because the division operation in equation (18) is time consuming in the simulations. However in the model developed in the thesis the impedance is used instead, it is done in order to simplify the representation and reading the code, also the as has been known from simulation the described system appear to be very small and with the available CPU frequency of the modern personal computers it is not slowing the simulations significantly.

To get these values the concept of treating the salient pole machine in the power flow is needed to be discussed. It has been made an assumption to include the machine internal impedance in the power flow model, therefore describe the system on the lower possible level. For example the system representation between buses 1 and 2 is stated in the figure 4.2:

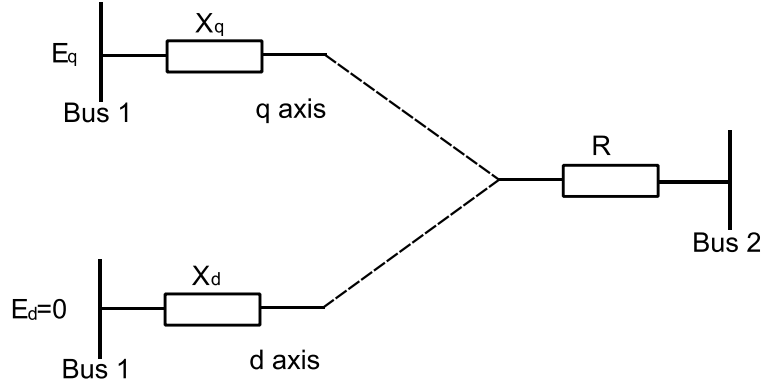


Figure 4.2: One machine representation in power flow problem

As discussed earlier the cable length between the buses is assumed low, and the impedance of the cable neglected. Thus all needed impedances for creation of the 3 dimensional matrix are taken from the machines.

The impedance matrix of the simple system from figure 4.1 becomes:

Dimension 1 – R

$$\begin{bmatrix} R_g & R_g & 0 \\ R_g & R_g + R_m & R_m \\ 0 & R_m & R_m \end{bmatrix} \quad (4.2)$$

Dimension 2 – X_q

$$\begin{bmatrix} X_{qg} & X_{qg} & 0 \\ X_{qg} & X_{qg} + X_{qm} & X_{qm} \\ 0 & X_{qm} & X_{qm} \end{bmatrix} \quad (4.3)$$

Dimension 3 – X_d

$$\begin{bmatrix} X_{dg} & X_{dg} & 0 \\ X_{dg} & X_{dg} + X_{dm} & X_{dm} \\ 0 & X_{dm} & X_{dm} \end{bmatrix} \quad (4.4)$$

Here: $R_g=R_{12}=R_{21}$; $X_{qg}=X_{q12}=X_{q21}$; $X_{dg}=X_{d12}=X_{d21}$; $R_g+R_m=R_{22}$; $X_{dg}+X_{dm}=X_{d22}$;
 $X_{qg}+X_{qm}=X_{q22}$; $R_m=R_{23}=R_{32}$; $X_{qm}=X_{q23}=X_{q32}$; $X_{dm}=X_{d23}=X_{d32}$;

4.2 New power flow equations

Now based on equations 2.16, 2.18), 2.27 it has become possible to set the equations for the power flow with included saliency.

$$P_i = \sum_{j=1}^n \left[\frac{V_i V_j x_{qij}}{Z_{ij}^2} \sin(\delta_j - \delta_i) + \frac{V_i^2 (X_{dij} - X_{qij})}{2Z_{ij}^2} \sin 2(\delta_j - \delta_i) - \frac{V_i V_j R_{ij}}{Z_{ij}^2} \cos(\delta_j - \delta_i) - \frac{V_i^2 R_{ij}}{Z_{ij}^2} \right] \quad (4.5)$$

$$Q_i = \sum_{j=1}^n \left[\frac{V_i V_j x_{qij}}{Z_{ij}^2} \cos(\delta_j - \delta_i) - \frac{V_i^2 (X_{dij} \sin^2(\delta_j - \delta_i) + X_{qij} \cos^2(\delta_j - \delta_i))}{Z_{ij}^2} - \frac{V_i V_j R_{ij}}{Z_{ij}^2} \sin(\delta_j - \delta_i) \right] \quad (4.6)$$

The above equations are set for each of the buses in the system, thus in the simple system of figure 4.1, there will be 6 equations. To solve the equations buses need to be specified as stated in 2.6 chapter.

In all of the proposed systems the generator bus (number 1) is chosen to be a reference bus, with known voltage and angle δ_1 .

Bus number 2 is also same for all the proposed systems. It is a load bus, or P-Q bus, where the $P_2=Q_2=0$ if the static load is disconnected, and $P_2=P_{\text{static load}}$ $Q_2=Q_{\text{static load}}$ if it is connected.

Motor buses are all P-V buses, here the voltage is known and the power is specified. The voltage becomes possible to calculate for this bus because there is a stiff connection between the generator and the motor, it gives the electric frequency of the system equal for all machines. And from the fact that all the machines are permanent magnet machines with fixed number of poles (this could be though as the machine with constant excitation current) it gives the linear proportion between the frequency and the voltage.

4.3 Solving the new power flow equations in the code

To sum everything concerning the power flow with included saliency up, when considering the simple system of the figure 2.8 there are 2 power equations (active and reactive) for each of the buses, so 6 in total. It is smart to use the equation where the power on the left hand side is known, there are 3 equations of this type, where P_2, Q_2 and P_3 are set by the user, so known. All the impedances are known, from the machine data. V_1 and V_3 are known as the emf of the machines. Angle δ_1 is known as the reference angle. Therefore there are 3 equations with 3 unknowns, δ_2, δ_3, V_2 , or in the more easy to read form:

Bus no	U(pu)	δ (deg)	P(pu)	Q(pu)	Type
1	Eg	0	-	-	Reference
2	-	-	P2	Q2	P-Q
3	Em	-	P3	-	P-V

Table 4.1: Load flow specifications example, 1 generator one motor.

To solve the above equation the matlab code has been developed implementing the algorithm described in Gauss-Seidel method chapter. The source code of this case contains 2 files *runpower_salient.m* and *salient_power_flow.m*. These 2 files create and solve the case of the 1 generator- 1 motor problem. The user guide on how to use the created m-files is presented in appendix.

The coding style keeping all the parameters indexes as i and j, has a major advantage of the possibility to easily extend the system to any of the proposed variation shown in figure 2.7. For this purpose separate pair of files has been created for each of the system.

Load flow specifications for the other proposed systems are presented in the tables 4.1-4.5, the corresponding matlab files are also listed.

Bus no	U(pu)	δ (deg)	P(pu)	Q(pu)	Type	M-files
1	Eg	0	-	-	Reference	<i>runpower_1gen_2motors.m</i>
2	-	-	P2	Q2	P-Q	
3	Em	-	P*0.5	-	P-V	<i>salient_power_flow_1gen_2motors.m</i>
4	Em	-	P*0.5	-	P-V	

Table 4.2: Load flow specifications, 1 generator 2 motors model.

Bus no	U(pu)	δ (deg)	P(pu)	Q(pu)	Type	M-files
1	Eg	0	-	-	Reference	<i>runpower_2gen_1motor.m</i>
2	-	-	P2	Q2	P-Q	
3	Em	-	P	-	P-V	<i>salient_powe_flow_2gen_1motors.m</i>
4	Eg	-	-P*0.5	-	P-V	

Table 4.3: Load flow specifications, 2 generator 1 motor model.

Bus no	U(pu)	δ (deg)	P(pu)	Q(pu)	Type	M-files
1	Eg	0	-	-	Reference	<i>runpower_3gen_1motor.m</i>
2	-	-	P2	Q2	P-Q	
3	Em	-	P	-	P-V	<i>salient_powe_flow_3gen_1motors.m</i>
4	Eg	-	-P*0.33	-	P-V	
5	Eg	-	-P*0.33	-	P-V	

Table 4.4: Load flow specifications, 3 generator 1 motor model.

Bus no	U(pu)	δ (deg)	P(pu)	Q(pu)	Type	M-files
1	Eg	0	-	-	Reference	<i>runpower_3gen_2motors.m</i>
2	-	-	P2	Q2	P-Q	
3	Em	-	P*0.5	-	P-V	
4	Em	-	P*0.5	-	P-V	<i>salient_powe_flow_3gen_2motors_read.m</i>
5	Eg	-	-P*0.33	-	P-V	
6	Eg	-	-P*0.33	-	P-V	

Table 4.5: Load flow specifications, 3 generator 2 motor model.

As seen from the specifications, when there are 2 and more generators the power is assumed to be equally divided in between the machines. The generated power comes with a minus sign while the consumed power with plus sign. The power division between the motors if the number is two is also assumed equal. These values can easily be adjusted in order to obtain the necessary operating point of the system. There are only two types of machines in the proposed models: generators and motors. Generators are assumed to be equal meaning that the impedances and the voltage coefficient is the same, same applies to the motors. The values of the machines can also be easily changed, in order for example to simulate with different power ratings of generators, etc.

The solution of the above set power flow equations gives a vector of voltage magnitudes $U(i)$ and the vector of voltage angles $\delta(i)$. Schematically one of the solutions of power flow equations is shown on the single line diagram in figure 4.3, for the one generator two motors system, 150Hz 100kW load.

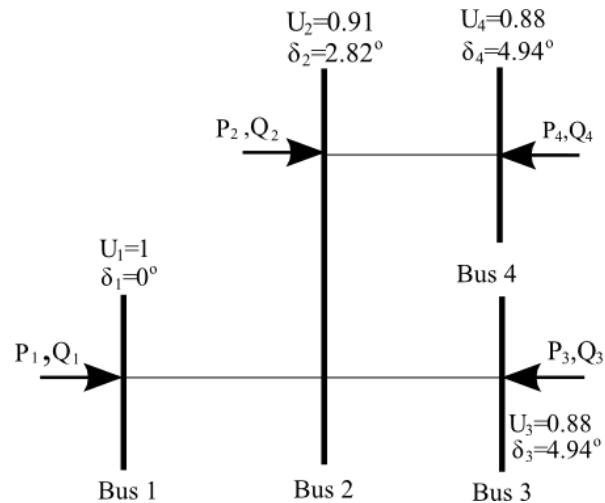


Figure 4.3: Graphical representation of the power flow solution for one generator two motor model, 150Hz, 100kW load

4.4 Adapting the code for the possible use and development in future

To solve the problem of the great complexity of the code for the first time user there has been made a decision to move the maximum possible data input from the source code to the rather simple and easy to use text file called (Machine_data.txt), shown in the table 4.6:

```
Specify the percent load for each motor:
Mot1 Mot2
50 50
Specify the percent load of the generators:
Gen2 Gen3
33.33 33.33
Gen 1 is always a slak bus, therefore the power generated can not be specified

Specify parameters of the machines:
Ld -d-axis inductance(mH)
Lq -q-axis inductance(mH)
r - resistance (mOhm)
p - number of poles
w - nominal speed (rpm)
Vn - nominal voltage (V)
```

If any of the machines is not presented in the model leave parameters as zero
Possible variances: 1g-1m; 1g-2m; 2g-1m; 3g-2m

```

Generator 1
  Ld   Lq   r   p   w   Vn
0.189 0.486 1.78 4 1800 550

Generator 2
  Ld   Lq   r   p   w   Vn
0.189 0.486 1.78 4 1800 550

Generator 3
  Ld   Lq   r   p   w   Vn
0.189 0.486 1.78 4 1800 550

Motor 1
  Ld   Lq   r   p   w   Vn
0.282 0.364 6.27 24 300 485

Motor 2
  Ld   Lq   r   p   w   Vn
0.282 0.364 6.27 24 300 485

```

Table 4.6: Reading the machine data from the text file

The text file works with the model of 3 generators and 2 motors, but following the same principles can easily be adapted to any of the proposed systems.

4.5 Current and power factor calculations

After the power flow solution obtained it becomes possible to calculate all the power input and outputs of the system using equations 34 and 35.

Further study of the model involves calculation of current and power factor. This is done with the following algorithm implemented in Matlab code in table 4.7:

```

% _____ Current calculation _____
% _____ From bus 1 to bus 2 _____
Vd=0-U(9,2)*sind(deg(9,2));
Vq=U(9,2)*cosd(deg(9,2));
for fil=-90:0.001:0;
Ia1=(Vd)/((Z(1,2,3))*sind(deg(9,2)+fil)-(Z(1,2,1))*cosd(deg(9,2)+fil));
EFG=Vq+(Z(1,2,3))*Ia1*cosd(deg(9,2)+fil)+(Z(1,2,2))*Ia1*sind(deg(9,2)+fil);
if (abs(EFG-U(9,1)))< 0.002;
    break
end;
end;

```

Table 4.7: Matlab algorithm for current calculation

In the above code, first the terminal voltage $U(9.2)$ is resolved in its d and q components (here index 9 stands for the number of iterations). Then the angle between the current and terminal voltage $\phi = \varphi$ is varied from the -90° to 0 with a small step.

Substituting for current from the equation 10 into 9 gives:

$$I_a = \frac{V_d}{R_{12} * \sin(\delta_{12} + \varphi) - X_{q12} * \cos(\delta_{12} + \varphi)} \quad (4.7)$$

At each step the new value for the current is calculated. Then it is substituted in the equation 9 for the d-axis resolved for $E_f = E_q = E_g$:

$$E_f = V_q + R_{12} I_a \cos(\delta_{12} + \varphi) + X_{d12} I_a \sin(\delta_{12} + \varphi) \quad (4.8)$$

This gives the new value of generator EMF at each step. It becomes possible to compare it with the known value of the generator EMF=1pu, if the difference is lower than the supposed accuracy then the last calculated value for current and angle φ become the solution.

4.6 Addition or removing machines of the model

The enclosed to the manuscript files contain the developed models for the proposed systems. All of the models are based on the same algorithm, the differences apply in the system configurations. As discussed earlier for each of the buses the power flow equations 34 or 35 are solved depending on the known parameters set in the tables 1.1-1.4. In the Matlab code the algorithm of solving the power equations is shown in table 4.8:

```
%
% FIND THE VALUE OF deg(3)1 Using
% Power flow equation P3=0.5 - equal loading of both motors
% initial guess for deg(2)=0
% initial guess for U(2)=1
for i=3;
    for dd=-30 : 0.001 : 0;
        deg(t,3)=dd;
        for j=1:1:n;
            Zsys=Z(i,j,3)^2+Z(i,j,2)*Z(i,j,1); %Z^2
            if Zsys==0 %avoid division by zero
                p1=0;p2=0;p3=0;p4=0;
            else
                p2=U(t,i)*U(t,i)*(Z(i,j,2)-Z(i,j,1))*sind(2*(deg(t,i)-deg(t,j)))/(2*Zsys);
                p4=U(t,i)*U(t,i)* Z(i,j,3)/(Zsys);
                p1=U(t,i)*U(t,j)*(Z(i,j,1))*sind(deg(t,i)-deg(t,j))/Zsys;
                p3=U(t,i)*U(t,j)*(Z(i,j,3))*cosd(deg(t,i)-deg(t,j))/Zsys;
            end
            P(i,j)=p1+p2+p3-p4;
```

```
end
P3=P(3,1)+P(3,2)+P(3,3)+P(3,4);
if (abs(P3+0.5)) < 0.03;
    break
end
end
end
```

Table 4.8: An algorithm of solving the power equations, shown for a single bus

Here the substitution method is applied. The input parameters are either initial guesses or calculated beforehand in the equations for the other buses. In this example the angle $\text{deg}(4)$ is varied from -30 degrees to 0 degrees with a step of 0.001degrees. Then the power is calculated and compared to the power specified by the user. If the difference is less than 0.03W the for-loop brakes and the solution is obtained.

In order to add or remove machines from the model these for loops shown in the above figure should be either deleted or added, no changes to the equations are needed.

CHAPTER 5

Simulations, steady state model

5.1 Results verification

System variation shown in figure 3.1, are implemented in the natural scale commercial models by the Inpower AS. All of them are used as electric propulsion solutions for the tow ships. During the work on the master thesis the tests of the system shown in figure 2.7(3) have been done.

Test protocol included several operation points. First the rotational speed of the propeller was kept constant (meaning constant electrical frequency) and the pitch angle of the propeller was varied from 0 to 60degrees with 20 degrees step. As seen from the figure 2.4 changing the pitch angle on the constant speed will result in change of the power, therefore 3-4 different power levels have been recorded for each frequency.

During the tests electrical parameters voltage, current and power factor on the terminal bus have been measured. On the generator side power has been recorded. This power produced by the generator was used not only to supply the motors but also for a static load of the ship, including lighting, smaller upper deck induction motors etc.

The tests results are presented in the table 5.1:

Frequency f [Hz]	Power, generator Pg [kW]	Power static load Pst [kW]	Voltage U [V]	Power factor PF	Current I [A]	Pitch [degrees]
119	327	25	492	0,89	420	60
120	194	25	496	0,76	280	40
120	134	25	497	0,64	240	20
120	151	25	498	0,7	260	0
98	93	25	401	0,54	240	0
97	153	25	398	0,72		20
98	88	25	401	0,51	230	0
97	120	25	400	0,63	255	40
97	196	25	398	0,79	340	60
74	94	25	299	0,58	360	60
74	66	25	301	0,42	330	40
74	46	25	302	0,34	230	20
67	39	25	275	0,32	235	20
67	54	25	275	0,41	250	40
67	70	25	274	0,51	270	60

Table 5.1: Test results of the one generator – two motors system

The missing value of the current measurement in the line 6 is simply approximated from the other measured values as:

$$I = \frac{P}{U\sqrt{3}\cos\varphi} = \frac{153}{398 * \sqrt{3} * 0.72} = 308A \quad (5.1)$$

The values that have been taken on the frequencies below 67 appear to be of great uncertainty, and therefore excluded from the table. The power of the static load has been measured as the difference between the sum of the powers of the motors and the generated power, this measurement was performed only for the two first operation points (two first lines in the table 2) and the result was recorded to be 25kWt. This value was approximated constant during all other measurements, because no significant changes in the consumption of energy by the crew or on the upper deck were made.

The above described system was simulated at exactly the same operating points using the developed theory for the power flow calculation with included saliency. Two of the motors are assumed to be equally loaded. Matlab m-files runpower_1gen_2motors.m and

salient_power_flow_1gen_2motors.m have been used, the results are presented in the table 5.2:

Frequency f [Hz]	Power, generator Pg [kW]	Current [A]	Power factor	Voltage, terminal [V]	Voltage angle δ_1 δ_2 [degrees]	Voltage angle $\delta_3=\delta_4$ [degrees]
119	327	418,00	0,99	482,40	12,00	20,30
120	194	253,29	0,96	495,00	6,85	11,40
120	151	200,00	0,93	498,63	5,28	8,65
120	134	181,26	0,92	499,00	4,67	7,58
97	196	310,00	0,98	398,00	8,65	14,36
97	153	245,50	0,96	401,00	6,66	10,90
97	120	195,50	0,93	407,00	5,10	8,24
98	93	158,16	0,88	408,00	3,95	6,18
98	88	151,50	0,87	409,00	3,70	5,80
74	94	200,00	0,93	307,00	5,32	8,32
74	66	149,70	0,87	309,00	3,70	5,50
74	46	116,00	0,76	309,00	2,58	3,50
67	39	170,00	0,90	279,00	4,36	6,52
67	54	138,44	0,84	280,00	3,35	4,75
67	70	110,00	0,73	280,00	2,35	2,99

Table 5.2: Simulation results of the one generator two motors system.

The data presented in the above tables for better understanding is plotted in the figure 5.1. Here for each of the graph the frequency is kept constant while the power is different, changing with pitch angle as seen from the tables. The green line represents the measured values of the current, and the blue straight line represents the simulation results for the current on the same operation points. Results are plotted for 4 frequencies from 120Hz to 67Hz.

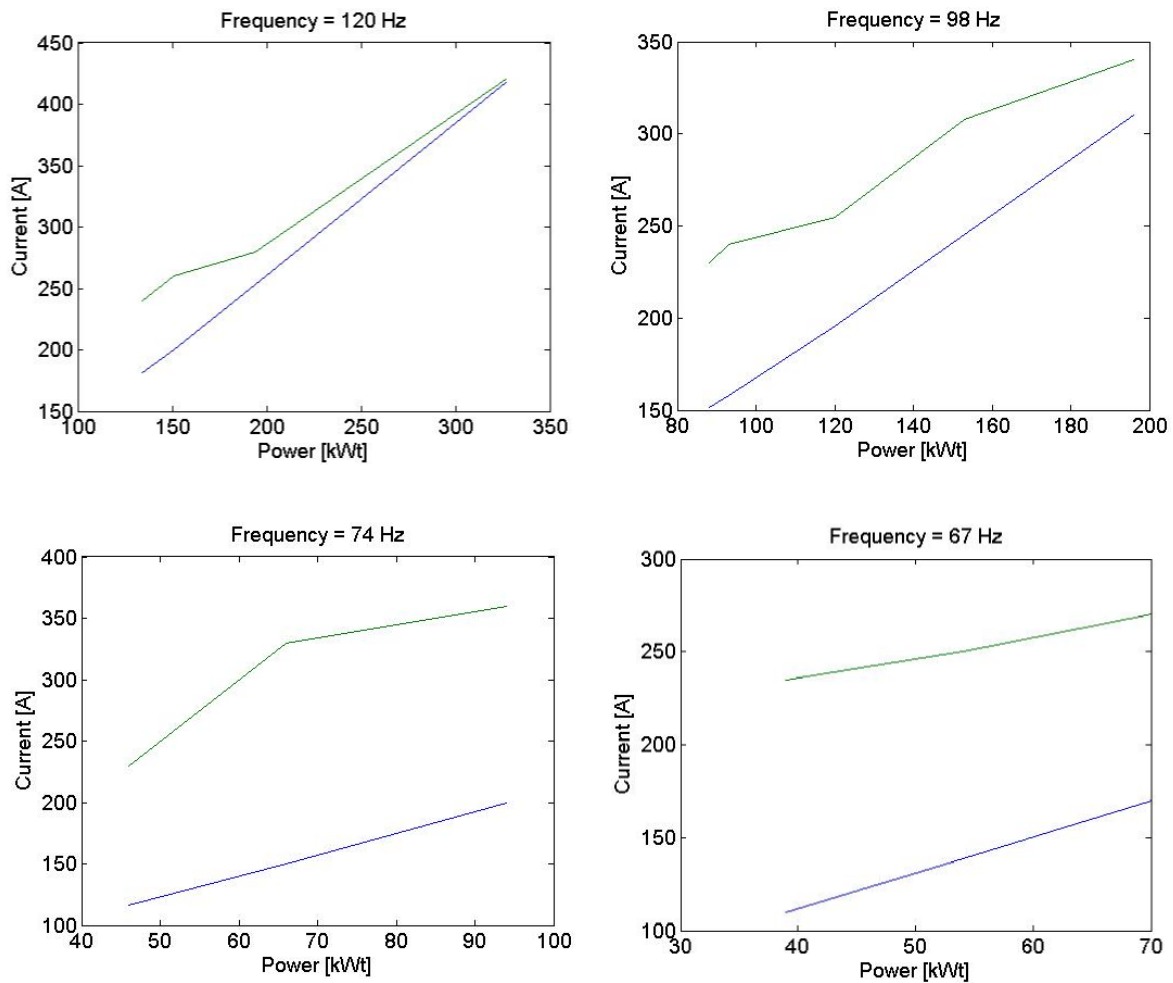


Figure 5.1: Comparison of the simulation results with the measured values during tests onboard the tow ship

5.2 Electrical parameters against speed and power

The model of the proposed system with one generator and two motors has been simulated in order to obtain the current-power dependencies. For this purpose the frequency was kept constant while the power was varied in steps of 10kWt. The graphs for different frequencies were plotted in one figure 5.2.

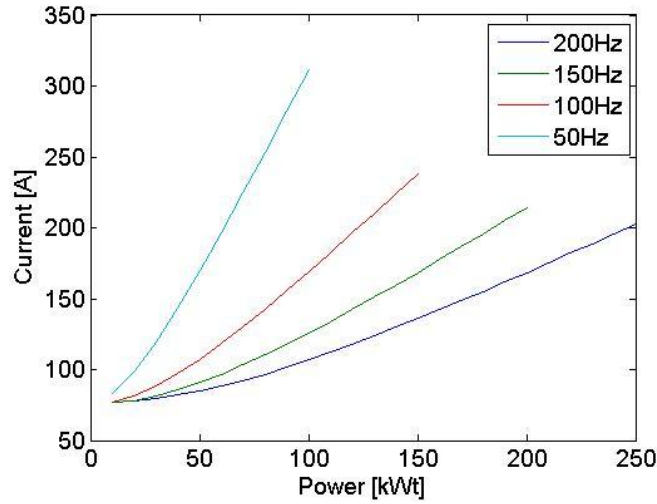


Figure 5.2: Current - Power dependencies with different frequencies for one generator-two motors model.

For any of the used frequencies the voltage angle between generator EMF and motor EMF is growing with the growth of power and current, while the voltage magnitudes stay the same due to constant frequency. To show these dependencies the phasor diagram was adapted and shown in figure 5.3.

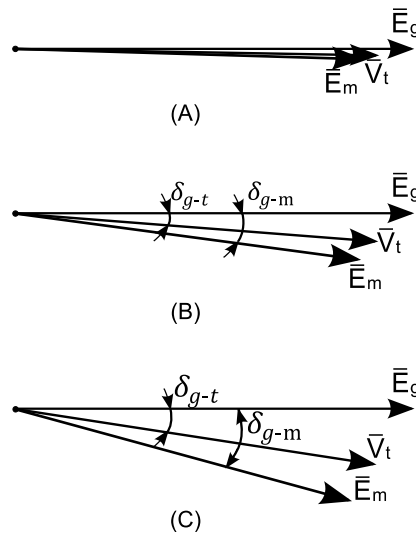


Figure 5.3: Voltage angle change with increasing power (current) constant frequency (50Hz)
 (A) Power= 10kW; (B) Power=50Kw; (C) Power=100kW

The table of values corresponding to the above phasor diagrams is shown in table 5.3:

Frequency [Hz]	Power, Generator [kW]	EMF Generator [V]	Voltage terminal [V]	EMF Motor [V]	Voltage angle generator-terminal [degrees]	Voltage angle generator-motor [degrees]
50	10	229	209	202	1,0	1,7
50	50	229	208	202	4,4	7,6
50	100	229	204	202	8,7	15,1

Table 5.3 Values for construction of the 3 phasor diagrams, with constant speed and varied power.

Another dependence of interest could be a terminal voltage against the increasing power. This graph is shown in figure 5.4, and represents increase in the voltage drop with increase of power (current).

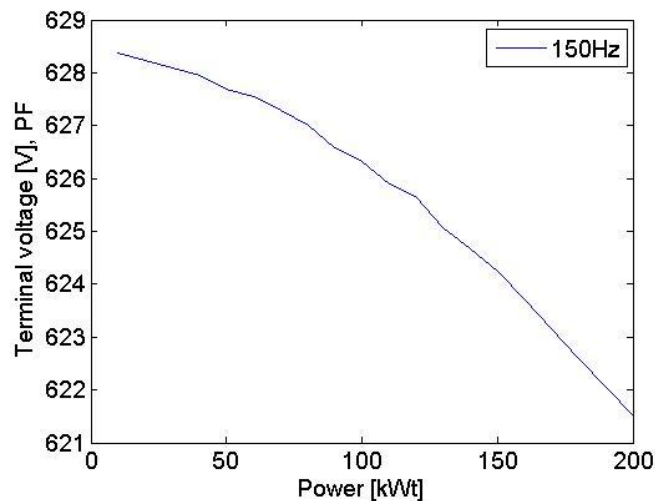


Figure 5.4: Terminal voltage change with the increase of power for 150Hz

The corresponding rise of the power factor with the rise of power and current for different frequencies is shown in figure 5.5:

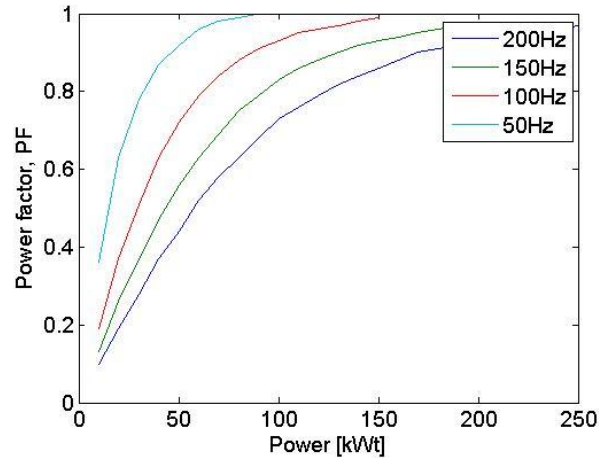


Figure 5.5: Power factor as a function of power, for 4 different frequencies

The active losses in the system are just proportional to the current flowing through each of the resistances. So the total active power losses are the sum of the losses in each of the branches.

$$P_{loss\ i-j} = I_{ij}^2 R_{ij} \quad (5.2)$$

To show the varying losses with power, the results of the corresponding simulations for the system of one generator and two motors are plotted in figure 5.6:

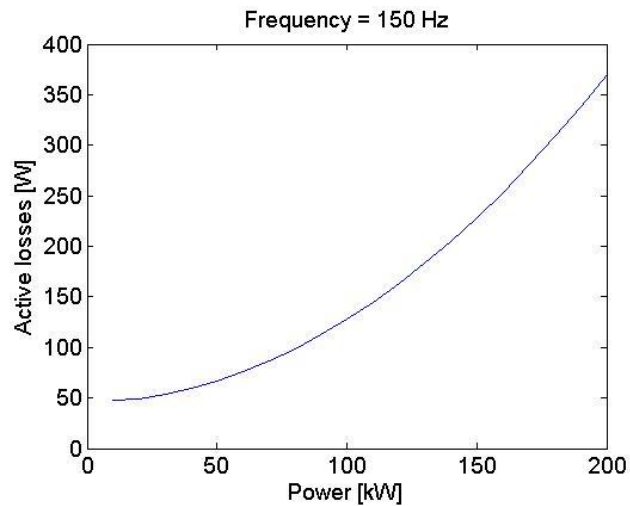


Figure 5.6: losses in the system 1generator 2 motors, constant frequency 150Hz

More interesting is to see the rise of the losses with the decreasing frequency keeping the power constant. This graph of the corresponding simulations is plotted in figure 5.7:

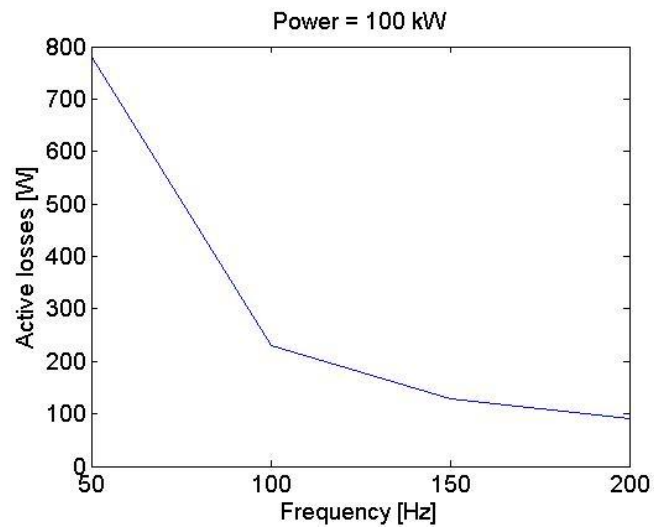


Figure 5.7: Active losses as function of frequency with constant power, in the system of 1 generator 2 motors

CHAPTER 6

Discussion steady state model

This chapter discusses the simulation results and other relevant elements of the study of the steady state models.

6.1 Power flow solution for modeling PMSM with salient rotors

While doing the study the proposed set of equations establishing the new approach for calculation of the power flow with included saliency were solved and gave the expected results.

The addition of the static load as a P-Q bus has affected the power flow in the expected manner.

Proposed system variations were implemented as extension to the simple one generator- one motor. The extended systems show expected results, the power flow is divide equally between machines.

Results verification chapter shows graphically and in numbers the comparison between the simulated system and actual real-world system tests. The difference in the results is smallest with simulations on the high frequency, and is much higher for the low frequencies, which indicates a constant disturbance in the system of low frequencies. Since voltages in the

simulated system and in tests are the same, the difference in the current values is the reason of very low power factor measured. The simulated model always operates on the highest possible PF, while the real-world control strategy is also a function of many variables, such as diesel engine, and propeller pitch curves, which are not taken into account in the steady state modeling.

6.2 Gauss-Seidel method

Implementation of the Gauss-Seidel method for solving system of nonlinear equations was successfully done in the models. The accurate convergence is achieved. Accuracy of solution of each single equation by iterative method is sufficient enough for the convergence of the set of equations as whole.

6.3 User interface

While writing the code, it has become evident that the code itself and the algorithm would expand, contain many loops and matrixes, therefore becoming increasingly difficult for understanding from the reader point of view. In order to overcome this issue code functionality has been shifted to read maximum possible data from the simple text file. As a result the basic parameters of for the 3 generator 2 motor model, can be rather easily modified.

The paragraph giving explanations on the current and PF calculations has been added to the report. Also the explanations on how to add or delete new machines/buses have been written.

CHAPTER 7

Dynamic simulations Theoretical background

This chapter introduces the required extension of the theoretical background for the dynamic modeling of the systems. It gives introduction to the bloc diagram it way of modeling and represents the blocks of which the dynamic model is built.

The dynamic simulations use the same components as described in chapter 2, thus there is no need to duplicate the description of the components. However the theoretical background representing the steady state model is not enough for the dynamic applications, since the time derivatives omitted from the notation previously, are no longer equal to zero, and must be taken into account.

For a permanent magnet synchronous machine the applied to the stator phases voltage is balanced by a resistive drop and the flux change over time term, it can be expressed in the equations(24):

$$v_{abc} = r_s i_{abc} + \frac{d}{dt} \lambda_{abc} \text{ or in the matrix form:} \quad (7.1)$$
$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = r_s \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \end{bmatrix}$$

where $r_{s\ is}$ is the stator per phase resistance, v_{abc} , i_{abc} and λ_{abc} are the stator phase voltage, current and flux linkage respectively(20).

7.1 Inductances and flux linkages

In the above, the parameters of interest for creating the mathematical model of the machine are the flux linkages. The flux linkage matrix λ_{abc} can be obtained as the result of the flux linkage $\lambda_{abc}(s)$ due to the stator phase currents, and $\lambda_{abc}(r)$ due to flux linkage of the permanent magnets in the rotor.

$$\lambda_{abc} = \lambda_{abc}(s) + \lambda_{abc}(r) \quad (7.2)$$

$$\lambda_{abc}(s) = \mathbf{L}i_{abc} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} i_{abc} \quad (7.3)$$

Where in the L matrix, diagonal elements represent self inductances, and off-diagonal represent mutual inductances.

$$\lambda_{abc}(r) = \lambda'_m \begin{bmatrix} \sin\theta_r \\ \sin(\theta_r - \frac{2\pi}{3}) \\ \sin(\theta_r + \frac{2\pi}{3}) \end{bmatrix} \quad (7.4)$$

λ'_m - is the mutual flux linkage of the permanent magnets in the rotor seen from the reference a-axis. θ_r - is the angle between a-axis and rotor axis (q-axis).

The self inductances can be calculated as follows(25):

$$\begin{aligned} L_{aa} &= L_{aa0} + L_{aa2}\cos(2\theta) \\ L_{bb} &= L_{aa0} + L_{aa2}\cos(2(\theta - \frac{2\pi}{3})) \\ L_{cc} &= L_{aa0} + L_{aa2}\cos(2(\theta + \frac{2\pi}{3})) \end{aligned} \quad (7.5)$$

Where L_{aa2} includes the leakage inductance term, the variations of the self inductance with rotor angle are shown in figure 7.1:

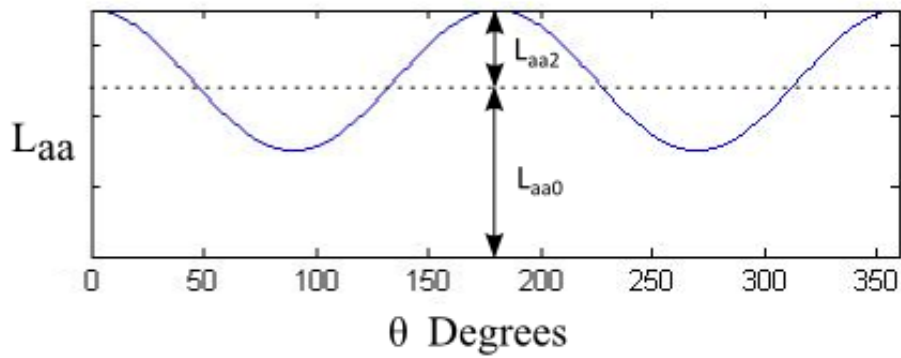


Figure 7.1: inductance variance with rotor angle

The mutual inductances are represented as follows:

$$\begin{aligned}
 L_{ab} &= L_{ba} = -L_{ab0} - L_{ab2} \cos\left(2\theta + \frac{\pi}{3}\right) \\
 L_{bc} &= L_{cb} = -L_{ab0} - L_{ab2} \cos\left(2\theta - \frac{\pi}{3}\right) \\
 L_{ca} &= L_{ac} = -L_{ab0} - L_{ab2} \cos\left(2\theta - \frac{\pi}{3}\right)
 \end{aligned}
 \tag{7.6}$$

For these equations the inductance variance is shown in figure 7.2:

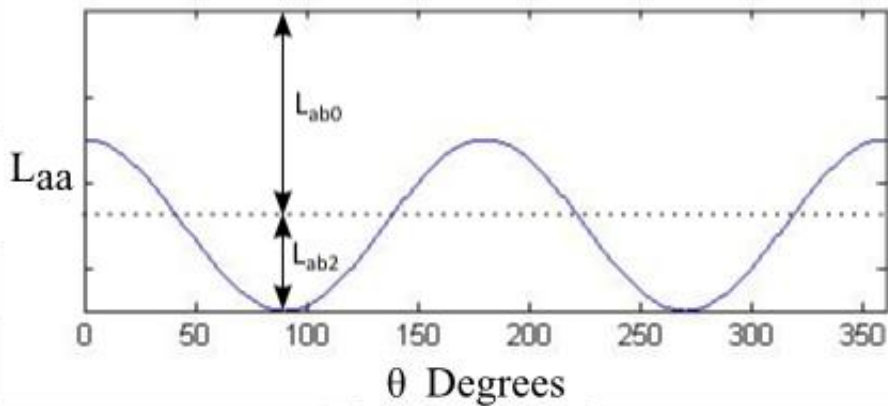


Figure 7.2: Mutual inductance variance with rotor angle

Knowing all the inductances from (40) it is possible to extend the flux linkage equations to:

$$\begin{aligned}
\lambda_a &= -i_a [L_{aa0} + L_{aa2} \cos 2\theta] + i_b [L_{ab0} + L_{aa2} \cos(2\theta + \frac{\pi}{3})] \\
&\quad + i_c [L_{ab0} + L_{aa2} \cos(2\theta - \frac{\pi}{3})] + \lambda_m \sin \theta \\
\lambda_b &= i_a [L_{aa0} + L_{aa2} \cos(2\theta + \frac{\pi}{3})] - i_b [L_{ab0} + L_{aa2} \cos(\theta - \frac{2\pi}{3})] \\
&\quad + i_c [L_{ab0} + L_{aa2} \cos(2\theta - \pi)] + \lambda_m \sin(\theta - \frac{2\pi}{3}) \\
\lambda_c &= i_a [L_{aa0} + L_{aa2} \cos(2\theta - \frac{\pi}{3})] - i_b [L_{ab0} + L_{aa2} \cos(2\theta - \pi)] \\
&\quad - i_c [L_{ab0} + L_{aa2} \cos(\theta - \frac{2\pi}{3})] + \lambda_m \sin(\theta + \frac{2\pi}{3})
\end{aligned} \tag{7.7}$$

7.2 dq0 transformation

The above equations completely describe the electrical performance of the permanent magnet synchronous machine, however they contain inductance terms which are varying with angle θ , which itself varies with time. This introduces the computational and understanding difficulties. A much simpler form of the same equation can be obtained if the reference axis is changed and chosen to rotate together with rotor, at the same angular speed. The transformation of the above equation to the new reference frame is called Park transform, and the new reference frame dq0.

The transformation can be presented as follows(20):

$$f_{qd0} = T_{qd0} f_{abc} \tag{7.8}$$

Where, f_{qd0} is the component matrix in dq0 reference frame, f_{abc} is the (abc) component matrix, T_{qd0} is the Park transformation matrix. Hence, the following matrix equations apply:

$$f_{qd0}^T = [f_q \quad f_d \quad f_0] \tag{7.9}$$

$$f_{abc}^T = [f_a \quad f_b \quad f_c] \tag{7.10}$$

$$T_{dq0} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin \theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \tag{7.11}$$

The zero sequence component f_0 is represented as:

$$f_0 = \frac{1}{3} (f_a + f_b + f_c) \tag{7.12}$$

Under the steady state condition $f_a + f_b + f_c = 0$

7.3 Current, voltage and flux linkage equations in the dq0 reference frame

By definition of the new rotating reference frame the space (abc) vectors are related to the corresponding dq vectors as follows(24):

$$\vec{v}_{abc} = \vec{v}_{dq} e^{j\theta} \quad (7.13)$$

$$\vec{i}_{abc} = \vec{i}_{dq} e^{j\theta} \quad (7.14)$$

$$\vec{\lambda}_{abc} = \vec{\lambda}_{dq} e^{j\theta} \quad (7.15)$$

Inserting these equations into 38 gives:

$$\begin{aligned} \vec{v}_{abc} &= r_s \vec{i}_{abc} + \frac{d}{dt} \vec{\lambda}_{abc} \\ \vec{v}_{dq} e^{j\theta} &= r_s \vec{i}_{dq} e^{j\theta} + \frac{d}{dt} \vec{\lambda}_{dq} e^{j\theta} \\ \vec{v}_{dq} &= r_s \vec{i}_{dq} + \frac{d\vec{\lambda}_{dq}}{dt} + j \frac{d\theta}{dt} \vec{\lambda}_{dq} \end{aligned} \quad (7.16)$$

Where the angle change over time $j \frac{d\theta}{dt} \vec{\lambda}_{dq}$ is known to be the rotational speed, thus rewriting:

$$\vec{v}_{dq} = r_s \vec{i}_{dq} + \frac{d\vec{\lambda}_{dq}}{dt} + j\omega_r \vec{\lambda}_{dq} \quad (7.17)$$

It is possible to separate the real and imaginary part as follows:

$$v_q = r_s i_q + \frac{d\lambda_q}{dt} + \omega_r \lambda_d \quad (7.18)$$

$$v_d = r_s i_d + \frac{d\lambda_d}{dt} - \omega_r \lambda_q \quad (7.19)$$

Using the flux linkage equations (44), and substituting for the dq0 components, with suitable reduction of terms involving trigonometric terms, the following equations are obtained:

$$\begin{aligned} \lambda_d &= -\left(L_{aa0} + L_{ab0} + \frac{3}{2}L_{aa2}\right) i_d + \lambda_m \\ \lambda_q &= -\left(L_{aa0} + L_{ab0} - \frac{3}{2}L_{aa2}\right) i_q \end{aligned} \quad (7.20)$$

The new inductances are defined:

$$L_d = L_{aa0} + L_{ab0} + \frac{3}{2}L_{aa2}$$

$$L_q = L_{aa0} + L_{ab0} - \frac{3}{2}L_{aa2}$$
(7.21)

These are the magnetizing inductances of the salient pole machine, here the difference in the d and q inductances is evident. These values are specified for each of the machine by the manufacturer, thus there is no need to calculate the values from down to the top of the derivation.

The flux linkages for the permanent magnet salient pole machine then simply become:

$$\lambda_d = L_d i_d + \lambda_m$$

$$\lambda_q = L_q i_q$$
(7.22)

And substituting these into the d-q voltage expression gives the well known expressions:

$$v_q = r_s i_q + L_q \dot{i}_q + \omega_r (L_d i_d + \lambda_m)$$
(7.23)

$$v_d = r_s i_d + L_d \dot{i}_d - \omega_r L_q i_q$$
(7.24)

As seen from the above equation none of the inductances is time dependent, and the equations obtained are simpler for computation than same equations in abc reference frame. Hence usually all the dynamic system models, deal with the d-q voltages and currents rather than with abc values. It is implemented simply as Park transform block on the input signals to the dynamic model of the system. It is shown in figure 7.3 with direct and reverse transform:

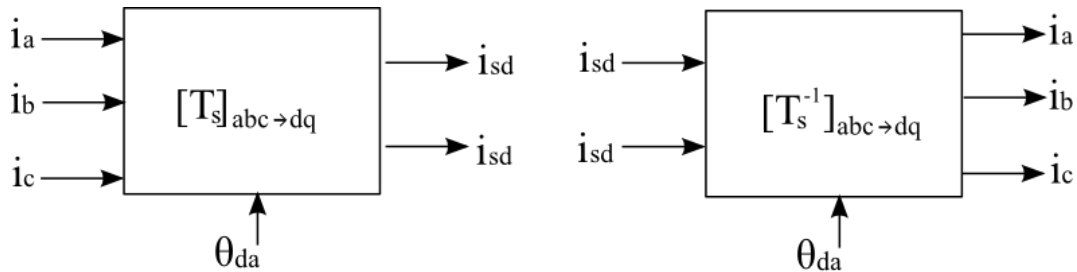


Figure 7.3: Change of the input signals abc to dq0, and dq0 to abc on the output

7.4 Power and torque

When using the dynamic models of the systems the values of interest are the power and torque rather than flux linkages, therefore it is necessary to derive the equation for these parameters.

Instantaneous power by definition:

$$P_t = v_a i_a + v_b i_b + v_c i_c \quad (7.25)$$

Transferring to the dq0 reference frame, and assuming balanced condition, where $i_0=0$, gives:

$$P_t = \frac{3}{2} (\vec{v}_d \vec{i}_d + \vec{v}_q \vec{i}_q) \quad (7.26)$$

In order to determine losses and power transfer the dq0 voltages in the above equation can be represented with flux linkages and inductances as follows:

$$\begin{aligned} p_t &= \frac{3}{2} [(i_d)^2 + (i_q)^2] + \frac{3}{4} \frac{d}{dt} [L_d (i_d)^2 + L_q (i_q)^2] + \frac{3}{2} \omega_r [\lambda_d i_q - \lambda_q i_d] \\ &= p_{rl} + p_{dW} + p_{em} \end{aligned} \quad (7.27)$$

Where p_{rl} – represents resistance loss, and is negative, p_{dW} – represents the rate of change of armature magnetic energy, and p_{em} – represents the electromechanical power which is transferred through the air gap(25).

The output torque is obtained by a well know expression:

$$T_{em} = \frac{P_{em}}{\omega_m} \quad (7.28)$$

Here it should be noticed that the speed is not the electrical speed used in the above derivation, but mechanical speed. These values are related by the number of poles of the machine:

$$\frac{d\theta_r}{dt} = \omega_r = \frac{p}{2} \omega_m \quad (7.29)$$

Where, p - is the number of poles.

Inserting the above equation in the torque equation and substituting for the power gives:

$$T_{em} = \frac{3p}{4} [\lambda_m i_q + (L_d - L_q) i_d i_q] \quad (7.30)$$

Including mechanical terms

The accurate model of the real system would be incomplete without including the inertia, and friction:

$$\frac{d\omega_m}{dt} = \frac{1}{J} (T_{em} - T_{fric} - T_m) \quad (7.31)$$

In this equation the inertia J is a sum of all the system inertial seen from the motor shaft, T_m is the load torque(26).

7.5 Model blocks

7.5.1 PMSM block

The model used for the dynamic simulations is taken from the `simscape=>simpowersystems` library and is shown in figure 7.4:

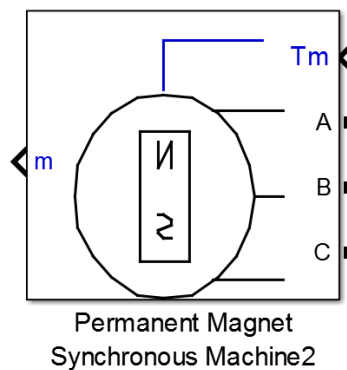


Figure 7.4: PMSM model block.

It is the synchronous machine on the very basic level, meaning it implements only the electrical and mechanical equations described above. The model lacks any control feedback loops or power electronics, thus making it ideal for the simulations of the proposed systems.

The block operates either in generator mode or in the motor mode, the parameter that defines the mode of operation is the sign of the applied torque, for the generator torque should be negative while for the motor positive.

There are a number of parameters to be specified in the PMSM block, including the ones suitable for the proposed systems simulations:

- Sinusoidal distribution of flux established by the permanent magnets, meaning sinusoidal EMF in the machine.
- Salient-pole rotor type
- Torque as the input signal.

Electrical parameters include specifying stator resistance R_s , inductances L_d and L_q , one of the machine constants (flux linkage established by the permanent magnets).

Mechanical parameters include specification of inertia, viscous damping, pole pairs and static friction.

It is also possible to define the initial conditions of the machine, such as speed, rotor angle and currents.

7.5.2 Inside the PMSM block

The figure 7.5 below shows the PMSM block from the inside:

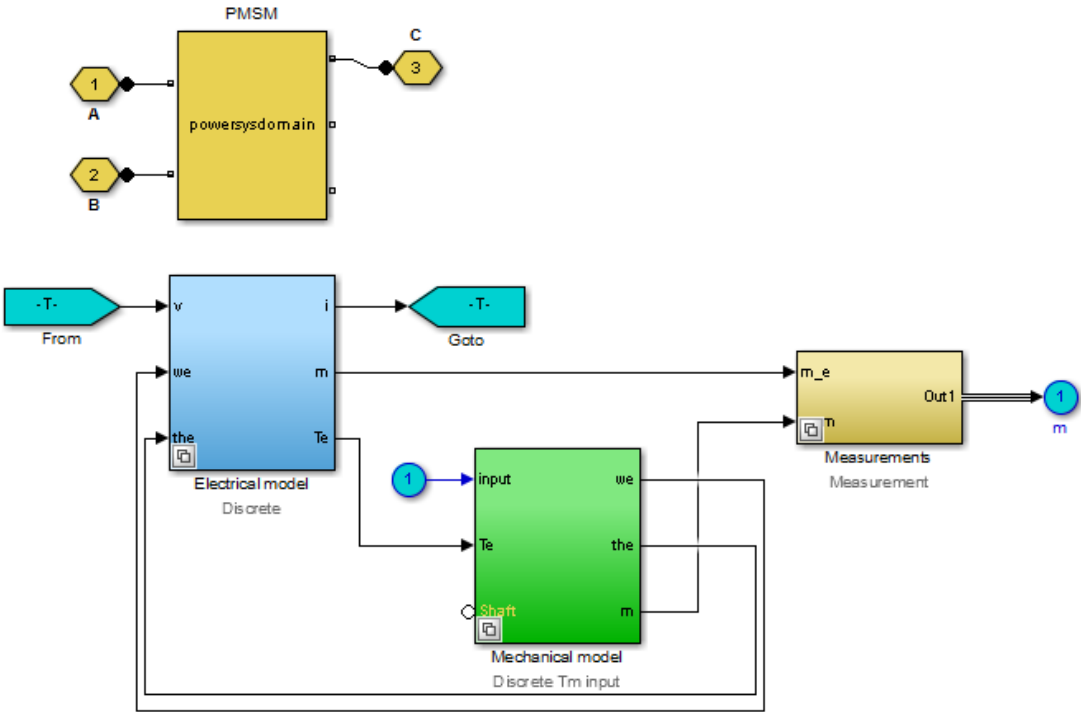


Figure 7.5: PMSM block inside

Here the “powersysdomain” block is used in order to link the model which is built in the signal form to the Simscape/Simpowersystems library, thus allowing for the connection of the other electrical block from the same library.

The measurements block is just a bus selector, which allows the user to select the parameters that he wants to output.

7.5.3 Electrical model block

Electrical model, from the inside is shown in figure 7.6:

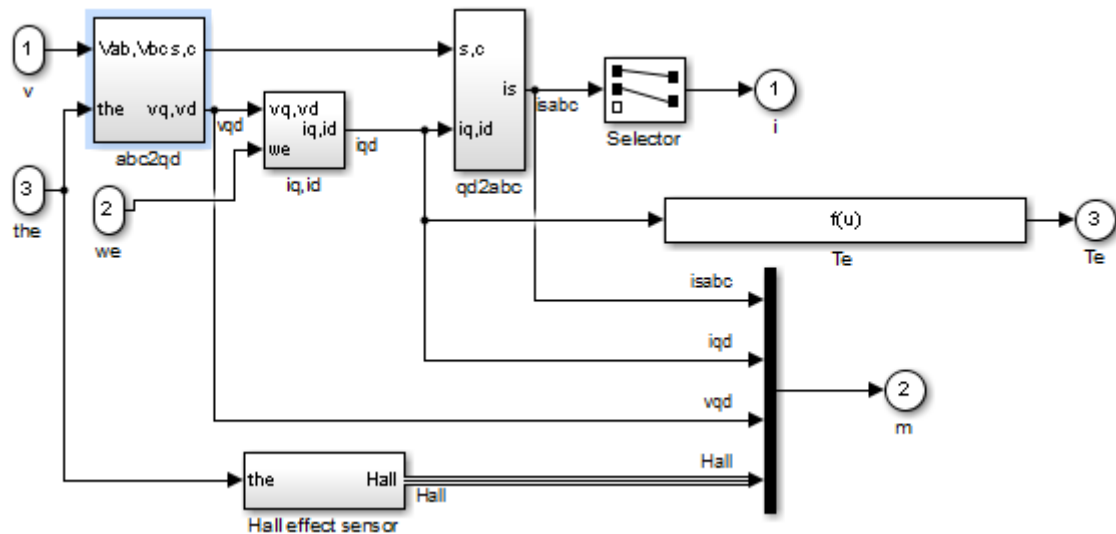


Figure 7.6: Electrical model block inside

Here first the abc voltage is transformed to the dq0 reference frame, by means of already discussed equations (7.8-7.12). The same procedure but in the reverse direction is done for the output signal.

The Hall effect signal provides a logical indication of the back EMF positioning, it can be used to directly control the power switches(27)

The only left block is “iq, id” which corresponds to the electrical model of the system. The block is shown in figures 3.10 and 3.11. It implements equation 7.18-7.19 with substituted variables from equations 7.22, solved for $\frac{di_q}{dt}$ and $\frac{di_d}{dt}$ correspondingly.

$$\frac{d}{dt} i_q = \frac{v_q}{L_q} - \frac{r_s}{L_q} - \frac{L_d}{L_q} i_d \omega_r - \frac{\lambda_m \omega_r}{L_q} \quad (7.32)$$

And the representation in the diagram in figure 7.7:

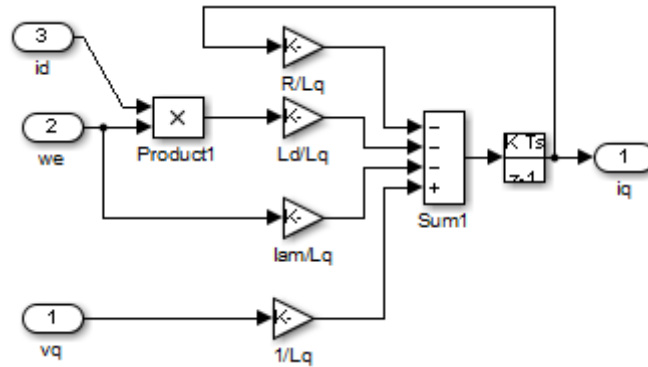


Figure 7.7: Electrical model block i_d/dt transfer function

$$\frac{d}{dt} i_d = \frac{v_d}{L_d} - \frac{r_s}{L_d} - \frac{L_q}{L_d} i_q \omega_r \quad (7.33)$$

And the representation in the block diagram, figure 7.8:

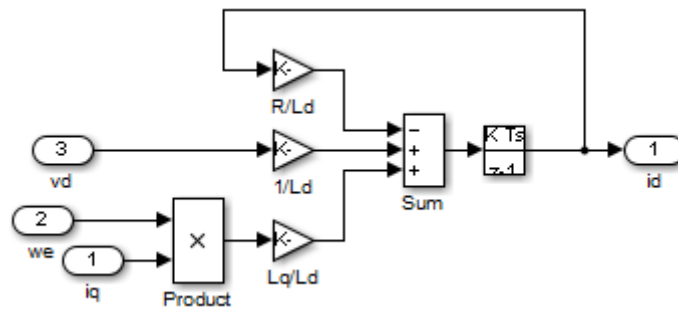


Figure 7.8: Electrical model block i_q/dt transfer function

7.5.4 Simple system block model

The simulated system is rather easy, it consists of two directly connected machines. Here, in order to connect the machines together a large enough resistor so that it does not affect much the power flow is added to the circuit in parallel with both of the machines. The reason for the addition of this block is that the generator is modeled as a current source. It is impossible to connect the large inductive loads in series with the current source because the current cannot change instantaneously in the inductance which will create an error for the solver of differential equations(28). The system is shown in figure 7.9.

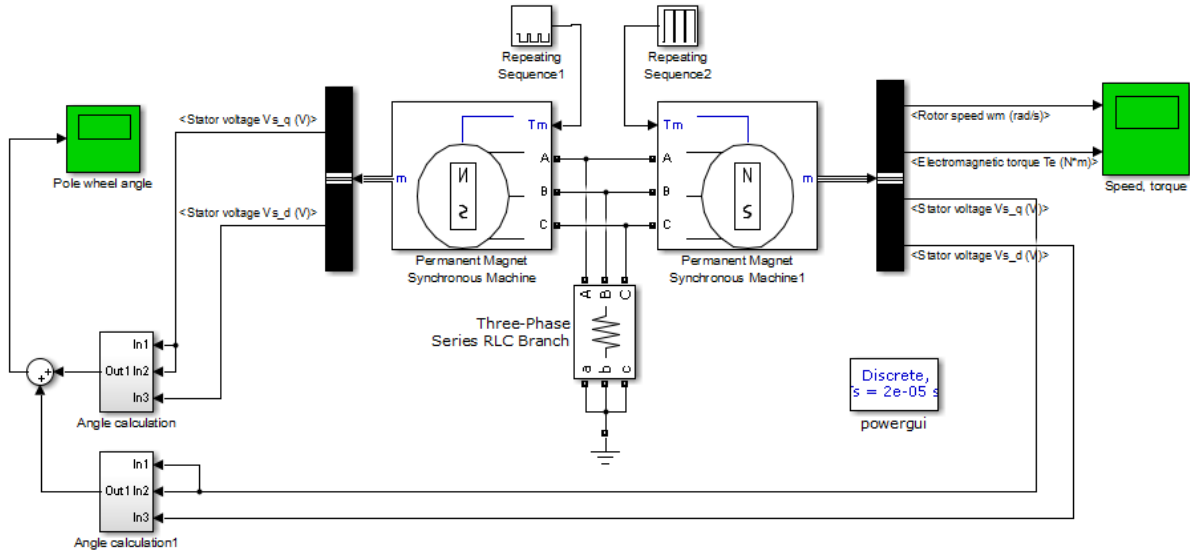


Figure 7.9: Model for dynamic simulations

The input the model is torque both for the generator and the motor, it is seen on the block diagram as the repeating sequence blocks. On the generator side simply by creating a torque profile the ideal diesel engine is modeled, assuming that it is connected directly to the generator. On the motor side the torque profile represents the propeller load. Here the propeller load is assumed to be changing linearly.

In this model the angle between the Generator EMF and terminal voltage is calculated based on the output magnitudes of V_d and V_q and the simple trigonometric equation evident from the phasor diagram in figure 2.4

$$\delta_{g-t} = \arctan\left(\frac{V_q}{V_d}\right) \quad (7.34)$$

$$\delta_{g-m} = \delta_{g-t} + \delta_{t-m}$$

Where δ_{g-t} is the angle between generator EMF and terminal voltage, δ_{m-t} is the angle between motor EMF and terminal voltage, δ_{g-m} is the angle between generator EMF and motor EMF.

Dynamic simulation results

This chapter presents the simulation results of the dynamic model.

8.1 Synchronizing of PMSM

As stated in(29) reliable start and synchronization from standstill can be achieved simply by a proper current and a frequency control, without any rotor position feedback, The stator frequency is gradually increased, until it is sufficiently high for the position estimator to be phased in safely. Also the closed loop control strategies can be employed for the start up of the synchronous machines.

However the system modeled in the current thesis is lacking any control or feedback loops, thus making it a difficult task to synchronize two of the machines. Figure 8.1 shows the synchronizing failure when the PMSM fails to accelerate from stand-still and oscillates in one position.

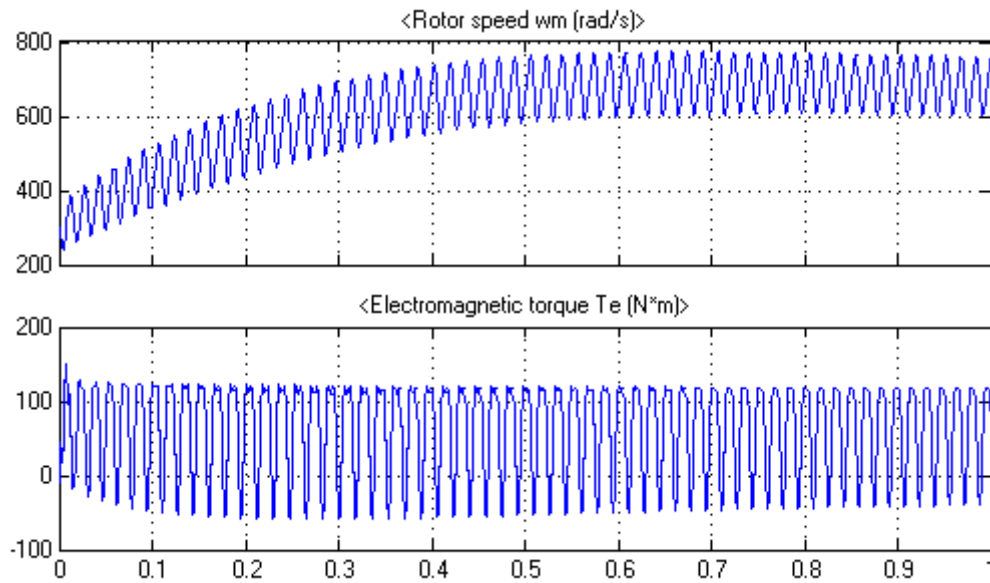


Figure 8.1: Synchronization failure PMSM

Here the motor was defined with initial condition of the rotational speed slightly less than synchronous speed, however the machine fails to synchronize with generator. (20, 30) highlight the problem as a positive net torque over an electrical cycle is required in order to accelerate the rotor. This can be achieved by reducing the speed of the stator magnetic field, and thus the electrical frequency to a low enough value so that the rotor can accelerate and lock in with it during one half-cycle of the magnetic field's rotation. This should be achieved with one of the control techniques.

However even in the proposed system lacking the control loops it is possible to synchronize the motor to the generator, a careful choice of input torque directly proportional to the rotational speed is required. Figure 8.2 shows a successful lock of the motor to the generator frequency:

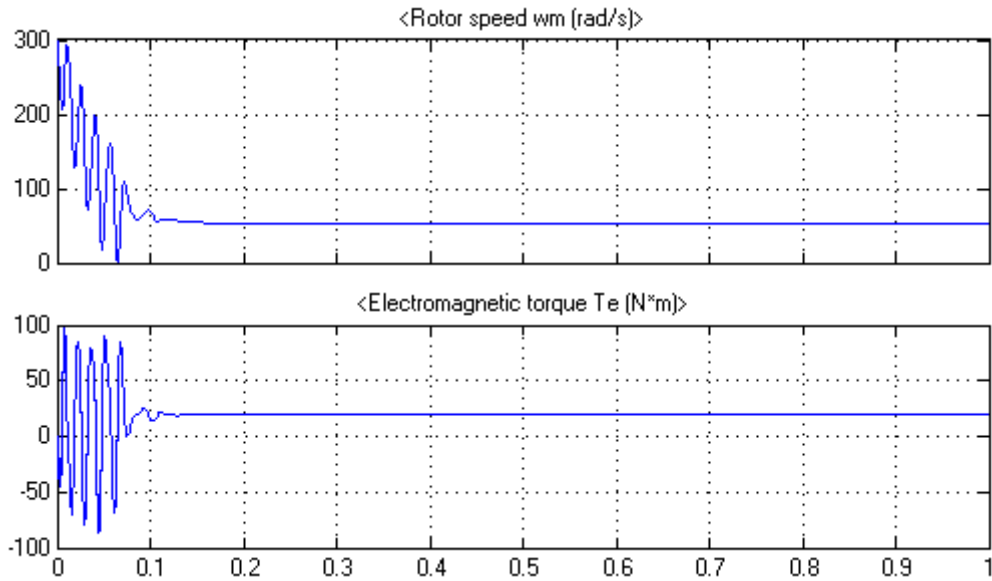


Figure 8.2: Successful synchronization of the PMSM

8.2 Reaction to the gradual change in torque

Figure 8.3 shows a response of the motor to the slow gradual change of torque first from 20Nm to 55Nm, and then the decrease to 30Nm.

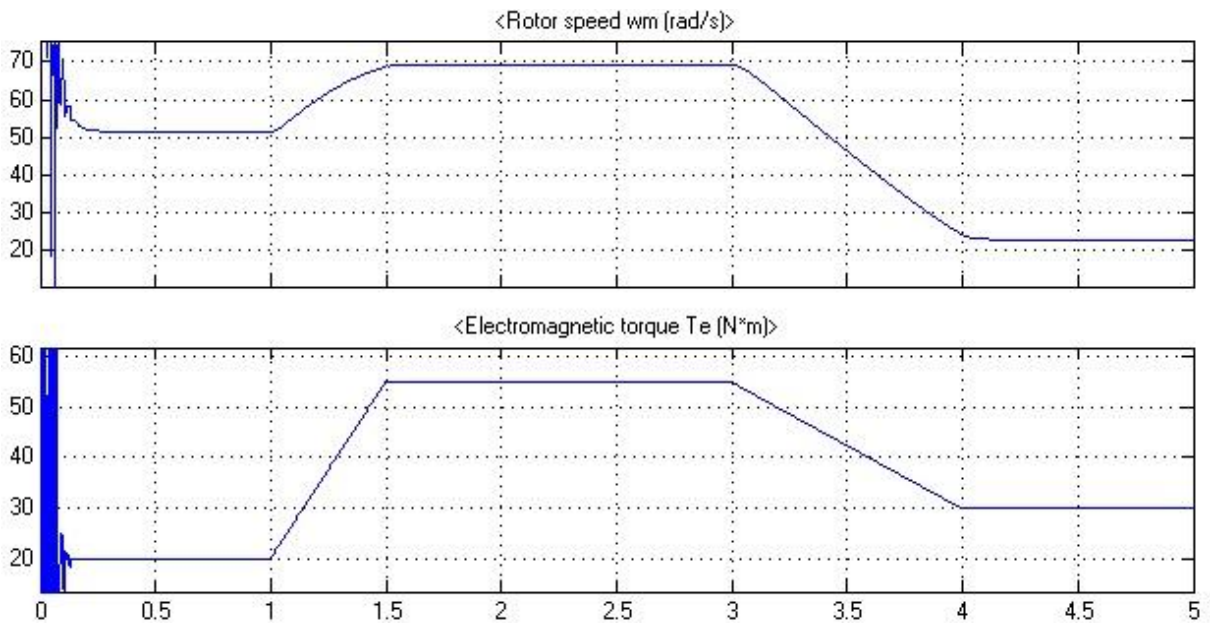


Figure 8.3: A response of the motor to the slow gradual change of torque

The corresponding change in the voltage angle between machines EMFs is shown in figure 8.4:

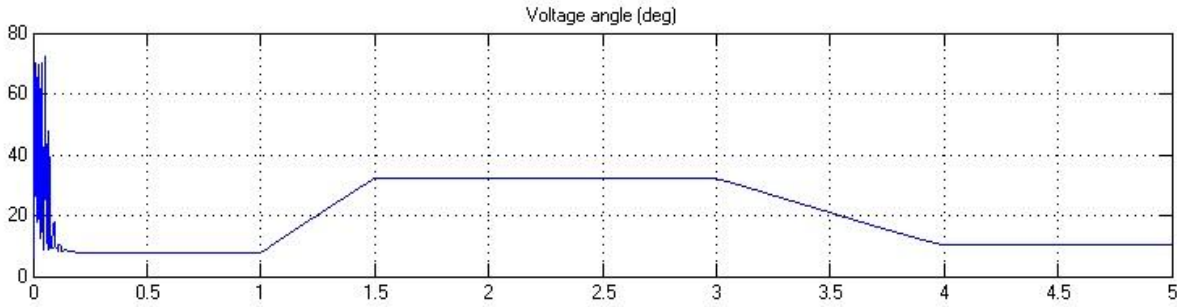


Figure 8.4: Voltage angle between machines EMFs as a response to the gradual change in load torque

The simulation input signal was changed to higher value of torque in between 1.5seconds and 3seconds. Figure 8.5 shows a faster change in the load torque and thus the pole wheel oscillations

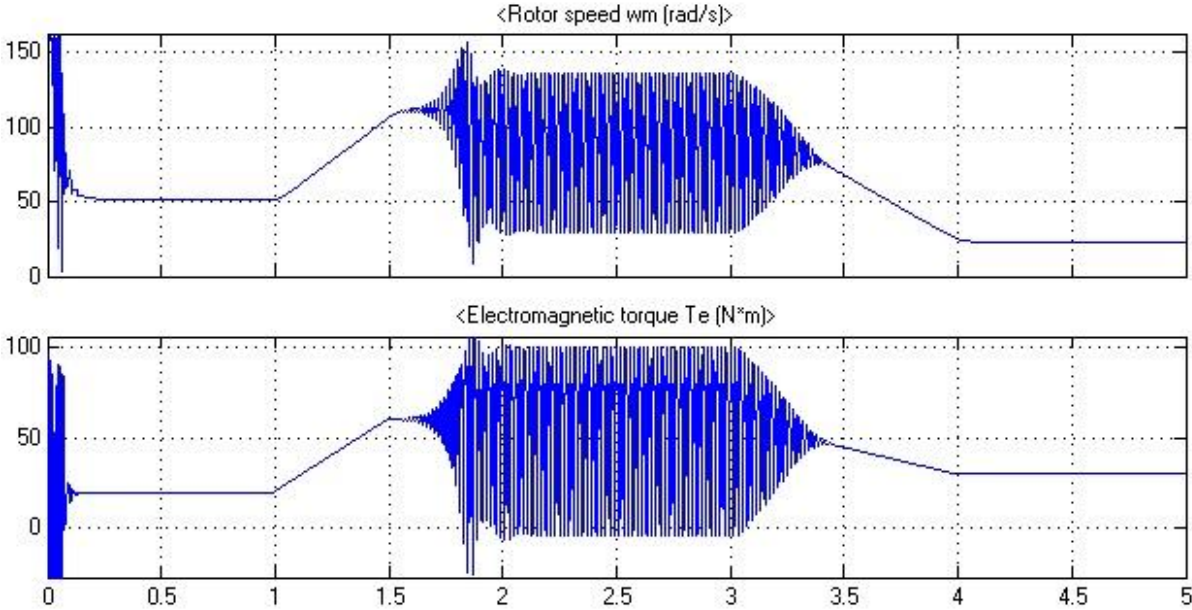


Figure 8.5: Pole wheel oscillations.

The corresponding oscillations in the voltage angle between machines EMFs is shown in figure 8.6

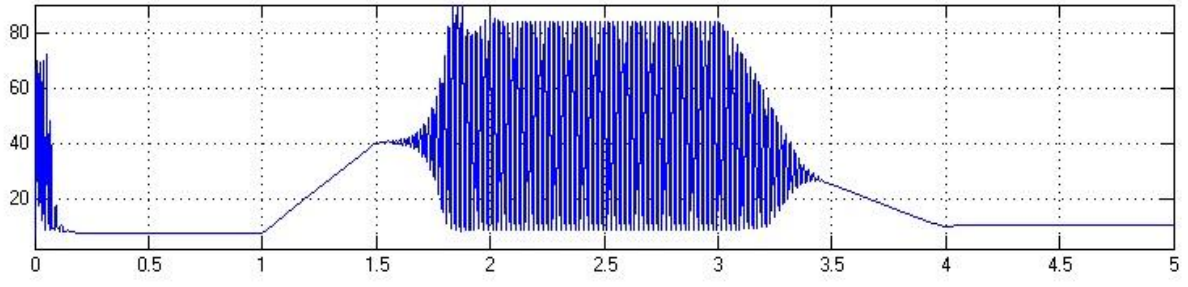


Figure 8.6: Voltage angle between machines EMFs as a response to the fast gradual change in load torque

CHAPTER 9

Discussion dynamic model

This chapter discusses the simulation results and other relevant elements of the study of the dynamic system models.

9.1 Simulink model

The dynamic system model was successfully built of the lowest possible level blocks in SimPowerSystems/Simulink library. It is lacking the feedback loops however it was possible to achieve the expected results.

An extension block for calculating the voltage angles between generator and motor EMFs was built and functioning as intended.

9.2 Synchronization of the motor

While doing the study of the dynamic model, it has been learnt that synchronization of the motor in the system of no power electronics can be a serious issue, thus a number of simulations led to the oscillations on the motor electric torque failing to satisfy the load needs. Therefore the control over the generator should be done more carefully, taking into account propeller pitch angles and power curves.

9.3 Reaction to the gradual change in load torque

It has been shown that with a slow enough change in the load torque the system is able to follow the profile of the changing load torque. However with rise of the slope at some point the motor is starting to experience significant oscillations of torque and therefore rotational speed. It was possible to synchronize the motor after the oscillations were registered by reducing the load torque.

CHAPTER 10

Conclusion

The study has produced four steady state models mathematical models of the directly connected permanent magnet synchronous machines, so-called electrical shaft. And a simple yet reliable dynamic system model built in the Simulink environment.

Steady state models.

The developed mathematical models of the systems have successfully implemented in the Matlab source code functions. These model work as intended and are able to produce stable results.

An algorithm for the power flow calculations with a possibility to accurately include salient pole machines has been developed from scratch and implemented in the code. While creating the algorithm different problems have been solved, such as reactance correction factor and iterative solution of a set of nonlinear equations. The algorithm shows sufficient convergence and desired accuracy is achieved.

There has been made an effort to simplify the usage of the produced code for the future reader. For this purpose a routine reading the machine parameters and information on the model state of operation has been added to the system. This allows for easy change of the system variations, because the algorithm is written on the circuit level, thus allowing extension of systems. The paragraphs explaining the calculation of additional parameters after the power flow study is finished have been added, also the explanation of the adding or deleting new machines/busses has been added for the same reason.

The results comparison of the simulations with real world tests onboard the ship show close values for the high frequencies, while for the low frequencies the results are driven away. There might be several reasons for that, such as not taken into account mechanical losses or temperature dependence of impedance of the machines.

Dynamic model

Dynamic system model, have been created on the block level in Matlab Simulink environment. Theoretical background of the dynamic behavior of the system has been made and implemented in the Matlab software.

The created system is a simple introductory part of the broad future studies of the dynamic models. However it is a fully functioning model, which implements the desired operation proposal with no feedback loops. The system works as intended.

The brief dynamic study has highlighted the synchronization problem of the permanent magnet synchronous motor to the generator, and the problem of torque oscillations on the motor shaft with fast enough change in the load.

Both systems gave insight information and valuable experience of the PMSM modeling, starting from the very basic level and avoiding usage of the commercial available software.

Recommendations for future work

Following are the point for future study of the models:

- Include impedance temperature dependence in the model, and run the verification of the results simulations again.
- Further development of the user interface, thus making it look like professional software.
- Verify and compare the results of the steady state simulations with the commercial software.
- Efficiency study, based on the diesel engine motor.
- Include mechanical losses in the models.
- Further development and study of the dynamic model.
- Addition of damper windings to the models.

Bibliography

1. Zhixiong Li, Xinping Yan, Peng Z. Ship electric propulsion with a sensorless permanent magnet synchronous motor: A simulation study. *Engineering for the Maritime Environment*. 2012:1-9.
2. SCHULTEN PJM. The interaction between diesel engines, ship and propellers during manoeuvring. Netherlands: Technische Universiteit Delft; 2005.
3. McCoy TJ, editor Trends in ship electric propulsion. Power Engineering Society Summer Meeting, 2002 IEEE; 2002 25-25 July 2002.
4. M Figari MA. Dynamic behaviour and stability of marine propulsion systems. *Proc IMechE Part*. 2007;221(4):187–202.
5. Gao H CH, Lin Z. Development of civil ship electric propulsion system. *Chin Water Transport* 2005;1:43–4.
6. Fujita M. OH. Electric propulsion systems for ships driven by inverter – applicability and trends in electric propulsion systems for ships. *Jpn Inst Marine Engng*. 2005;40(2):33–7.
7. Batzel TD, Lee KY. Electric Propulsion With Sensorless Permanent Magnet Synchronous Motor: Implementation and Performance. *Energy Conversion, IEEE Transactions on*. 2005;20(3):575-83.
8. Inpower AS ØK. PhiDrive - direct diesel electric propulsion Norway, Molde. Available from: <http://www.inpower.no/products/phidrive>.
9. Utkin M. Modelling of the electric shaft used by the company Inpower AS. Norway: NTNU, 2014.
10. Saadat H. Power system analysis. 3rd ed. United States: PSA Pub.; 2010. xix, 752 p. p.

11. MathWorks. Simulink [cited R2014a]. Available from:
<http://www.mathworks.se/products/simulink/>.
12. MathWorks. Simscape. R2014a:[Available from:
<http://www.mathworks.se/products/simscape/>.
13. MathWorks. SimPowerSystems. R2014a:[Available from:
<http://www.mathworks.se/products/simpower/>.
14. MAN MES. Diesel-electric Propulsion Plants - Guideline Germany. Available from: <http://marine.man.eu/>.
15. Giuffrida M. Electrical Plants and Electric Propulsion on Ships: Lulu Com; 2013.
16. Adnanes AK. Maritime Electrical Installations and Diesel Electric Propulsion2003; 86.
17. Mahon LLJ. Diesel generator handbook. Oxford: Butterworth-Heinemann; 1992. viii, 646 s. : ill. p.
18. Marine D. Ship's electrical system described2000. Available from:
<http://www.dieselduck.info>.
19. MathWorks. Matlab. R2014a:[Available from:
<http://www.mathworks.se/products/matlab>.
20. Baricuatro K. Sensorless Start-up and Control of Permanent Magnet Synchronous Motor with Long Tieback: Norwegian University of Science and Technology, NTNU; 2014.
21. Gurakuq Dajaku DG. The correct analytical expression for the phase inductance of salient pole machines. Electric Machines & Drives Conference, 2007; IEMDC '07. : IEEE International; 2007. p. 992-6.
22. T. KC. Iterative Methods for Linear and Nonlinear Equations. Philadelphia: North Carolina State University, 1995.
23. Byrne CL. Applied Iterative Methods2007 2007.

24. Mohan N. Advanced electric drives : analysis, control, and modeling using MATLAB/Simulink. Hoboken, New Jersey: Wiley; 2014. pages cm p.
25. Kundur P, Balu NJ, Lauby MG. Power system stability and control. New York: McGraw-Hill; 1994. xxiii, 1176 p. p.
26. Mohan N. Electric machines and drives : a first course. Hoboken, NJ: Wiley; 2012. xi, 276 p. p.
27. MathWorks. Permanent Magnet Synchronous Machine 2015. R2015a:[Available from: <http://se.mathworks.com/help/physmod/sps/motors-and-generators.html>].
28. MathWorks. SimPowerSystems User's Guide2003; 620.
29. Jansson M, Harnefors L, Wallmark O, Leksell M. Synchronization at startup and stable rotation reversal of sensorless nonsalient PMSM drives. Industrial Electronics, IEEE Transactions on. 2006;53(2):379-87.
30. Chapman SJ. Electric machinery fundamentals. 5th ed. New York: McGraw-Hill; 2012. xxiv, 680 p. p.

Appendix A

User manual for m-files

In order to start the work with the functions all the m-files and one text file have to be extracted to the folder and the user must set a path to this folder in the Matlab program. Only after that the code can be executed.

Figure 3.1 and tables 4.1-4.2 fully describe the proposed systems, and give the names of the files for each of the cases.

For each case file name starting with “runpower” is the command file which sets values to all the variables and calls the function starting with “salient_power_flow”.

Functions “salient_power_flow” solve the nonlinear power flow equations by iterative Gauss-Seidel method. These functions cannot be called by themselves, the command file “runpower” should be run first.

For the case of 3 generators and 2 motors the code of the command file has been extended in order to allow reading the impedances and power loads from the text file. The text file is called Machine_data.txt. User must first change the parameters of the machines and the percent of the power flow for each machine in the text file, and only after that run runpower_3gen_2motors_read.m file.

The results of the power flow calculations for all the cases will be presented in the command window of Matlab. Typically it is 9 lines of voltage angle vector called “deg”, and 9 lines of voltage magnitudes called “U”, here 9 stands for the number of iterations. Other electrical parameters can be calculated using hints from tables 4.7-4.8. The text file where the parameters are specified is presented in table 4.6.

Appendix B

Matlab simulation script

In this appendix the fully designed from scratch matlab m-files source codes are presented. These are used for modeling of steady state system.

Matlab source code for the 3 generator 2 motors model. Corresponding M-file is salient_power_flow_3gen_2motors.m:

```
function salient_power_flow_3gen_2motors(Z,deg,U,t);
global P Q degit Uit it P4 P2 Pstatic Qstatic PM1 PM2 PG2 PG3;
t=t+1;
it=t;
n=6; % number of machines/ buses
% _____ Gauss-Seidel Method

% _____ FIND THE VALUE OF deg(3)1 Using
%Power flow equation P3=0.5 two motor mode
%initial guess for deg(2)=0
%initial guess for U(2)=1
    for i=3;
        for dd=-40 : 0.001 : 0;
            deg(t,3)=dd;
            for j=1:1:n;
                Zsys=Z(i,j,3)^2+Z(i,j,2)*Z(i,j,1); %Z^2
                if Zsys==0 %avoid division by zero
                    p1=0;p2=0;p3=0;p4=0;
                else
                    p2=U(t,j)*U(t,j)*(Z(i,j,2)-Z(i,j,1))*sind(2*(deg(t,i)-
deg(t,j)))/(2*Zsys);
                    p4=U(t,j)*U(t,j)* Z(i,j,3)/(Zsys);
                    p1=U(t,i)*U(t,j)*(Z(i,j,1))*sind(deg(t,i)-deg(t,j))/Zsys;
                    p3=U(t,i)*U(t,j)*(Z(i,j,3))*cosd(deg(t,i)-deg(t,j))/Zsys;
                end
                P(i,j)=p1+p2+p3-p4;
            end
            P3=P(3,1)+P(3,2)+P(3,3)+P(3,4)+P(3,5)+P(3,6);

            if (abs(P3+PM1))< 0.002;
                break
            end
        end
    end
    % _____ FIND THE VALUE OF deg(3)1 Using
    %Power flow equation P6=0.5 two motor mode
    %initial guess for deg(2)=0
    %initial guess for U(2)=1
```

```

for i=6;
    for dd=-40 : 0.001 : 0;
        deg(t,6)=dd;
        for j=1:1:n;
            Zsys=Z(i,j,3)^2+Z(i,j,2)*Z(i,j,1); %Z^2
            if Zsys==0 %avoid division by zero
                p1=0;p2=0;p3=0;p4=0;
            else
                p2=U(t,j)*U(t,j)*(Z(i,j,2)-Z(i,j,1))*sind(2*(deg(t,i)-
deg(t,j)))/(2*Zsys);
                p4=U(t,j)*U(t,j)* Z(i,j,3)/(Zsys);
                p1=U(t,i)*U(t,j)*(Z(i,j,1))*sind(deg(t,i)-deg(t,j))/Zsys;
                p3=U(t,i)*U(t,j)*(Z(i,j,3))*cosd(deg(t,i)-deg(t,j))/Zsys;
            end
            P(i,j)=p1+p2+p3-p4;
        end
        P6=P(6,1)+P(6,2)+P(6,3)+P(6,4)+P(6,5)+P(6,6);

        if (abs(P6+PM2))< 0.02;
            break
        end
    end
end
end

%_____FIND THE VALUE OF deg(5)1 Using
%Power flow equation P5=0.333 three generator mode
%initial guess for deg(2)=0
%initial guess for U(2)=1
for i=5;
    for dd=-20 : 0.001 : 10;
        deg(t,5)=dd;
        for j=1:1:n;
            Zsys=Z(i,j,3)^2+Z(i,j,2)*Z(i,j,1); %Z^2
            if Zsys==0 %avoid division by zero
                p1=0;p2=0;p3=0;p4=0;
            else
                p2=U(t,j)*U(t,j)*(Z(i,j,2)-Z(i,j,1))*sind(2*(deg(t,i)-
deg(t,j)))/(2*Zsys);
                p4=U(t,j)*U(t,j)* Z(i,j,3)/(Zsys);
                p1=U(t,i)*U(t,j)*(Z(i,j,1))*sind(deg(t,i)-deg(t,j))/Zsys;
                p3=U(t,i)*U(t,j)*(Z(i,j,3))*cosd(deg(t,i)-deg(t,j))/Zsys;
            end
            P(i,j)=p1+p2+p3-p4;
        end
        P5=P(5,1)+P(5,2)+P(5,3)+P(5,4)+P(5,5)+P(5,6);
        if (abs(P5-PG2))< 0.02;
            break
        end
    end
end
end

%_____FIND THE VALUE OF deg(4)1 Using
%Power flow equation P4=0.333 - assumed equal production for generators
%initial guess for deg(2)=0
%initial guess for U(2)=1
for i=4;
    for dd=-5 : 0.001 : 5;
        deg(t,4)=dd;
        for j=1:1:n;
            Zsys=Z(i,j,3)^2+Z(i,j,2)*Z(i,j,1); %Z^2
            if Zsys==0 %avoid division by zero

```



```

        p1=0;p2=0;p3=0;p4=0;
    else
        p2=U(t,j)*U(t,j)*(Z(i,j,2)-Z(i,j,1))*sind(2*(deg(t,i)-
deg(t,j)))/(2*Zsys);
        p4=U(t,j)*U(t,j)* Z(i,j,3)/(Zsys);
        p1=U(t,i)*U(t,j)*(Z(i,j,1))*sind(deg(t,i)-deg(t,j))/Zsys;
        p3=U(t,i)*U(t,j)*(Z(i,j,3))*cosd(deg(t,i)-deg(t,j))/Zsys;
    end
        P(i,j)=p1+p2+p3-p4;
    end
    P4=P(4,1)+P(4,2)+P(4,3)+P(4,4)+P(4,5)+P(4,6);

    if (abs(P4-PG3))< 0.02;
        break
    end
    end
    end
%_____FIND THE VALUE OF deg(2)1 Using
%Power flow equation P2=0
%above calculated deg(3)
%initial guess for U(2)=1
for i=2;
    for ddd=-30 : 0.01 : 15;
        deg(t,2)=ddd;
        for j=1:1:n;
            Zsys=Z(i,j,3)^2+Z(i,j,2)*Z(i,j,1); %Z^2
            if Zsys==0 %avoid division by zero
                p1=0;p2=0;p3=0;p4=0;
            else
                p2=U(t,j)*U(t,j)*(Z(i,j,2)-Z(i,j,1))*sind(2*(deg(t,i)-
deg(t,j)))/(2*Zsys);
                p4=U(t,j)*U(t,j)* Z(i,j,3)/(Zsys);
                p1=U(t,i)*U(t,j)*(Z(i,j,1))*sind(deg(t,i)-deg(t,j))/Zsys;
                p3=U(t,i)*U(t,j)*(Z(i,j,3))*cosd(deg(t,i)-deg(t,j))/Zsys;
            end
                P(i,j)=p1+p2+p3-p4;
        end
        P2=P(2,1)+P(2,2)+P(2,3)+P(2,4)+P(2,5)+P(2,6);

        if (abs(P2+Pstatic))< 0.02;
            break
        end
    end
end
%_____FIND THE VALUE OF U(2)1 Using
%Power flow equation Q2=0
%above calculated deg(2)
%above calculated deg(3)
for i=2;
    for UU=0.6 : 0.0002 : 1.2;
        U(t,i)=UU;
        for j=1:1:n;
            Zsys=Z(i,j,3)^2+Z(i,j,2)*Z(i,j,1); %Z^2
            if Zsys==0 %avoid division by zero
                Q22=0;Q33=0;Q44=0;
            else
                Q22= (U(t,i)*U(t,j)*Z(i,j,1)*cosd(deg(t,i)-deg(t,j)))/ Zsys
            end
        end
    end
end
;

```

```

                Q33= (U(t,j)*(U(t,j))/(Zsys)) * (Z(i,j,2)*(sind(deg(t,i)-
deg(t,j)))^2 + Z(i,j,1)*(cosd(deg(t,i)-deg(t,j)))^2);
                Q44= (U(t,i)*U(t,j)*(Z(i,j,3))*sind(deg(t,i)-
deg(t,j))/(Zsys));
                end
                Q(i,j)=Q22-Q33-Q44;
            end
            Q2=Q(2,1)+Q(2,2)+Q(2,3)+Q(2,4)+Q(2,5)+Q(2,6);
            if (abs(Q2+Qstatic))< 0.02;
                break
            end
        end
    end
end
degit=deg(t,:);
Uit=U(t,:);

end

```

Matlab source code for the 3 generator 2 motors model. Corresponding M-file is
runpower_salient_3gen_2motors_read.m:

```

function runpower_salient_3gen_2motors_read;
global degit Uit it Pstatic Qstatic PM1 PM2 PG2 PG3;

%_____INPUT FROM USER_____
Pmech=input('Pmech load(kWt)= ');
Welhz=input('HZ= ');
Pstatic=input('Pstatic load(kWt)= ');
Qstatic=input('Qstatic load(kvar)= ');

%_____READ MACHINE DATA FROM file: Machine_data.txt_____
n=6; %number of buses
PM1=dlmread('Machine_data.txt','',[2 0 2 0])/100; %percent load M1
PM2=dlmread('Machine_data.txt','',[2 1 2 1])/100; %percent load M2
PG2=dlmread('Machine_data.txt','',[5 0 5 0])/100; %percent load G2
PG3=dlmread('Machine_data.txt','',[5 1 5 1])/100; %percent load G3
Gen1= dlmread('Machine_data.txt','',[24 0 24 5]);
Gen2= dlmread('Machine_data.txt','',[28 0 28 5]);
Gen3= dlmread('Machine_data.txt','',[32 0 32 5]);
Mot1= dlmread('Machine_data.txt','',[36 0 36 5]);
Mot2= dlmread('Machine_data.txt','',[36 0 36 5]);

%_____REFERENCE PU CALCULATIONS_____
Sref=Pmech*1000; %Reference power=shaft power
needed
Wel=Welhz*2*pi; %Rotational speed in rad/s
Pstatic=Pstatic*1000/Sref;
Qstatic=Qstatic*1000/Sref;

Welg1_nominal=(Gen1(5)*Gen1(4)/60)*2*pi; %nominal generator1 el speed,
rad/s
Keg1=Gen1(6)/Welg1_nominal; %Ke generator1 calculation RMS line-line,
induced rated voltage

```

```

Uref=Keg1*Wel                                     %Reference voltage=Generator
EMF
Iref=Sref/(1.732*Uref);                           %Reference current obtained from power and
voltage
Zref=(Uref*Uref)/Sref;                             %reference impedance

%_____MACHINE DATA in
PU
%_Generator1:
Xqg1=Gen1(1)/(1000*Zref)*Wel;                       %ohm /phase
Xdg1=Gen1(2)/(1000*Zref)*Wel;                       %ohm /phase
Rg1=(Gen1(3)/1000)/Zref;                             %ohm /phase
Ygen1=[Xqg1;Xdg1;Rg1];
%_Generator2:
Welg2_nominal=(Gen2(5)*Gen2(4)/60)*2*pi;           %nominal gen2 el speed, rad/s
Keg2=Gen2(6)/Welg2_nominal;%Ke gen2 calculation RMS line-line, induced
rated voltage
Xqg2=Gen2(1)/(1000*Zref)*Wel;                       %ohm /phase
Xdg2=Gen2(2)/(1000*Zref)*Wel;                       %ohm /phase
Rg2=(Gen2(3)/1000)/Zref;                             %ohm /phase
Ygen2=[Xqg1;Xdg1;Rg1];
%_Generator3:
Welg3_nominal=(Gen3(5)*Gen3(4)/60)*2*pi;           %nominal gen3 el speed, rad/s
Keg3=Gen3(6)/Welg3_nominal;%Ke gen3 calculation RMS line-line, induced
rated voltage
Xqg3=Gen3(1)/(1000*Zref)*Wel;                       %ohm /phase
Xdg3=Gen3(2)/(1000*Zref)*Wel;                       %ohm /phase
Rg3=(Gen3(3)/1000)/Zref;                             %ohm /phase
Ygen3=[Xqg1;Xdg1;Rg1];
%_Motor1:
Welm1_nominal=(Mot1(5)*Mot1(4)/60)*2*pi;           %nominal motor1 el speed, rad/s
Kem1=Mot1(6)/Welm1_nominal;%Ke motor1 calculation RMS line-line, induced
rated voltage
Xqm1=Mot1(1)/(1000*Zref)*Wel;                       %ohm /phase
Xdm1=Mot1(2)/(1000*Zref)*Wel;                       %ohm /phase
Rm1=(Mot1(3)/1000)/Zref;                             %ohm /phase
Ymot1=[Xqm1;Xdm1;Rm1];
%_Motor2:
Welm2_nominal=(Mot2(5)*Mot2(4)/60)*2*pi;           %nominal motor1 el speed, rad/s
Kem2=Mot2(6)/Welm2_nominal;%Ke motor1 calculation RMS line-line, induced
rated voltage
Xqm2=Mot2(1)/(1000*Zref)*Wel;                       %ohm /phase
Xdm2=Mot2(2)/(1000*Zref)*Wel;                       %ohm /phase
Rm2=(Mot2(3)/1000)/Zref;                             %ohm /phase
Ymot2=[Xqm1;Xdm1;Rm1];

%_____EMF OF THE
MACHINES
Efg1=Keg1*Wel/(Uref);                               %Generator1 voltage (magnitude) RMS
line-neutral
Efg2=Keg2*Wel/(Uref);                               %Generator2 voltage (magnitude) RMS
line-neutral
Efg3=Keg3*Wel/(Uref);                               %Generator3 voltage (magnitude) RMS
line-neutral
Efm1=Kem1*Wel/(Uref);                               %Motor1 voltage (magnitude) RMS
line-neutral
Efm2=Kem2*Wel/(Uref);                               %Motor2 voltage (magnitude) RMS
line-neutral

```

```

% _____ CONNECTIONS
MATRIX
Conn=[1 1 0 0 0 0;
      1 1 1 1 1 1;
      0 1 1 0 0 0;
      0 1 0 1 0 0;
      0 1 0 0 1 0;
      0 1 0 0 0 1];

%n=6; %n-number of machines (rows and
columns in a matrix)
Z=[ ; ; ; ; ];
% _____ MATRIX
for DIM=1:1:3; %3-dimension matrix
%1-dimension Xq
%2-dimension Xd
%3-dimension R
imp=[Ygen1 (DIM); 0; Ymot1 (DIM); Ygen2 (DIM); Ygen3 (DIM); Ymot2 (DIM) ];
for r=1:1:n; %Generator always connected to bus 2
l=1;
Z(1, r, DIM)=Conn(1, r)*imp(1);
end
for l=1:1:n;
r=1;
Z(1, r, DIM)=Conn(1, r)*imp(1);
end

for x=2:1:n; %Motors connected always to bus 2
for l=2:1:n;
r=x;
Z(1, r, DIM)=Conn(1, r)*imp(x);
end
for r=2:1:n;
l=x;
Z(1, r, DIM)=Conn(1, r)*imp(x);
end
end
Z(2, 2, DIM)=1/(1/imp(1)+1/imp(3)+1/imp(4)+1/imp(5)+1/imp(6));
%Diagonal impedance of bus 2 always a sum of all machines
end
Z(:, :, 1)
Z(:, :, 2)
Z(:, :, 3)

% _____ Initial guesses _____
deg(1, 1)=0;
deg(1, 2)=0;
deg(1, 3)=0;
deg(1, 4)=0;
deg(1, 5)=0;
deg(1, 6)=0;
U(1, 1)=Efg1;
U(1, 2)=1;
U(1, 3)=Efm1;
U(1, 4)=Efg2;
U(1, 5)=Efg3;
U(1, 6)=Efm2;

t=0;

```

```
it=0;

while it<10;
salient_power_flow_3gen_2motors(Z,deg,U,t);
deg((it+1),:)=degit;
U((it+1),:)=Uit;
t=it;
end
deg
U
end
```