



NTNU – Trondheim
Norwegian University of
Science and Technology

Simulation of Small Scale Pumped Hydro Power Plant with Permanent Magnet Generator during Faults

Lornts Mikal Sklett

Master of Science in Electric Power Engineering

Submission date: June 2015

Supervisor: Arne Nysveen, ELKRAFT

Co-supervisor: Ivar Vikan, Voith Hydro

Norwegian University of Science and Technology
Department of Electric Power Engineering

Preface

This master thesis is carried out at the Department of Electric Power Engineering at the Norwegian University of Science and Technology (NTNU) during the spring 2015.

Voith Hydro AS has been involved in the establishment of the master thesis description and has contributed with a technological dialogue through the project process, led by Ivar Vikan from Voith Hydro's department in Trondheim.

I would like to thank my Professor Arne Nysveen at the Department of Electric Power Engineering, NTNU, for his valuable guidance, support, motivation and insightful tips and suggestions through this study.

Additional thanks to Associate Professor Trond Toftevåg, Postdoctoral Fellow Mostafa Valavi and Fellow Erlend Engevik for their interesting technical discussions during this study, and fellow Atle Rygg Årdal for his help with Matlab Simulink.

Lornts Mikal Sklett

Trondheim, June 2015

NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

NTNU



MASTER THESIS

Name of the candidate	:	Lornts Mikal Sklett
Field of specialization	:	ELECTRIC POWER ENGINEERING
Thesis description (Norwegian)	:	Analyse av små pumpekraftverk med permanentmagnet generatorer ved feil i kraftnettet
Thesis description (English)	:	Simulation of small scale pumped hydro power plant with permanent magnet generator during faults

Problem description:

Pumped hydro power plant solutions are envisioned an important role in grid auxiliary services in future power systems with an increasing share of unregulated power production, where the locations make such constructions possible. This master thesis will analyze the use of constant speed permanent magnet machines in small-scale pumped hydro power plants (10-20 MW). This solution is proposed as a cost efficient, less complex and space reducing alternative to the traditional wound rotor synchronous machine.

To explore the possibilities and problems with such a pumped power plant solution, simulations are going to be executed against specific fault situations. The simulations will be performed on simulation models both with and without damper windings in the rotor circuit of the synchronous machine. The idea of pumped hydro power-plants and permanent magnet synchronous machines are widely recognized today. However, the combinations of these two technologies are not commonly known. Further, a theoretical study on the relevant literature shall be included.

The different situations that are going to be tested have basis in requirements that a pumped hydro power plant in the active power area around 15 MW can or will encounter. This includes a full short circuit on the machines terminals both during motor and generator operation, to see how long a short circuit can be present without losing the motors/generators synchronism with the corresponding grid. In addition, a fault-ride through test and a test with minor voltage and frequency variations, with basis in the Norwegian TSO (Transmission System Operator) Statnett's requirements FIKS.

Thesis given : January 15, 2015
Thesis description revised : June 3, 2015
Thesis submission deadline : June 11, 2015
Conducted at (Department -University) : Department of Electric Power Engineering - NTNU
Supervisor : Ivar Vikan, Voith Hydro
Course lecturer : Professor Arne Nysveen

Trondheim, June 4, 2015



Arne Nysveen
Professor

Abstract

This master thesis is a further investigation of the possibilities to utilize the permanent magnet synchronous machine technology in small scale pumped hydro power, as a continuation of the specialization project, fall 2014. The focus of this thesis is how the pumped storage plant will operate during four different fault situations.

A theoretical survey is done to get a better understanding of how voltage and frequency deviations in the synchronous machines connected grid affect in generator operation. Available design criteria standards for synchronous generators are reviewed, and a summary of these are formed. The fault period during a short circuit of a synchronous machine has been set in focus, and the different torque contributions during and after the short circuit fault have been investigated.

The simulation models are made in Matlab Simulink SimPowerSystems(MSPS), and the corresponding control circuits for each of the simulation cases are developed here. Both simulation models are established from existing blocks in the simulation program, one with an electrical machine equipped with rotor damper windings and one without. Each of the simulation cases are performed on both simulation models, and the results and conclusions follow each of the four cases.

A full short circuit simulation case is done in both motor and generator operation. For generator operation the results show that the generator that is equipped with damper windings have a smaller rate of rise of the rotational speed increase during the fault, than the generator without the damper windings. The damper windings contributes with a speed reducing torque, which acts as an advantage in the generator mode of operation. For motor operation the same effect is seen, that the motor with damper windings has a larger speed reducing torque, and that the rotational speed has a steeper speed reduction during the fault than for the model without damper windings. In motor operation this effect leads to that the simulation model without damper windings is able to withstand a longer short circuit on the machine terminals, than the model with damper windings, because its speed deviation after the fault is smaller. In motor operation the damper windings speed reducing torque is considered as a disadvantage.

For the simulation case during minor voltage and frequency variations, both of the simulation circuits are able to withstand the tested simulation case. This shows that the requirements for this simulation case are not the most demanding to meet with a permanent magnet synchronous machine.

In the "fault-ride-through" test does none of the simulation circuits operate stable after

the main test, with 85 % voltage drop and a 0,40 seconds time duration at the lowest voltage plateau. The FIKS requirements that are the background for this simulation case are considered more demanding to fulfill with a permanent magnet synchronous machine configuration. Since the simulation models consist of the electrical machine, connected directly to the grid, an insertion of passive elements as transmission lines or/and transformers between the grid and the electrical machine would add a damping effect to the system, and possibly better simulation results.

The main conclusion is that damper winding are considered as a advantage both during three phase short circuit and after a fault in generator operation. In motor operation the result is more complex, where the damper winding contribute with a negative contribution during a three phase short circuit, and with a positive effect after a fault.

Sammendrag

Denne masteroppgaven er en undersøkelse av mulighetene for å utnytte en synkronmaskin med permanentmagnet-teknologi i et småskala pumpekraftverk, som en videreføring av fordypningsprosjektet gjennomført høsten 2014. Fokuset i denne oppgaven er hvordan pumpekraftverket vil operere under fire ulike feilsituasjoner.

Et teoretisk studie er gjort for å få en bedre forståelse av hvordan spennings- og frekvensavvik i nettet påvirker en synkronmaskin i generatordrift. Tilgjengelige standarder med designkriterier for synkrongeneratorer er gjennomgått og en oppsummering av disse er fremstilt. Perioden under en kortslutning av en synkronmaskin er satt i fokus og de ulike momentene som bidrar i løpet av en kortslutning har blitt undersøkt.

Begge simuleringsmodellene, med medfølgende kontrollkretser for hver simulerte feilsituasjon, er etablert fra eksisterende blokker i simuleringsprogrammet Matlab Simulink SimPowerSystems. Hver feilsituasjon er simulert på begge simuleringsmodellene, med medfølgende resultater og konklusjon.

En full kortslutningstest er gjennomført i både motor- og generatordrift. For generatordrift viser resultatene at modellen som er utstyrt med dempevikling har en lavere økning i rotasjonshastighet i løpet av feilen enn modellen uten dempevikling. Dempeviklingen bidrar med et hastighetsreducerende moment, som betraktes som en fordel i generatordrift. For motordrift kan den samme effekten observeres. Motoren med dempevikling har et større hastighetsreducerende moment og rotasjonshastigheten synker raskere i løpet av feilen enn for motoren uten dempevikling. I motordrift fører denne effekten til at simuleringsmodellen uten dempevikling er i stand til å tåle en lengre kortslutning på terminalene, enn modellen med dempeviklingen. I motordrift er det hastighetsreducerende momentet fra dempeviklingene under feil ansett som en ulempe.

Simuleringen med endringer i nettets frekvens og spenning viser at begge simuleringsmodellene er i stand til å operere stabilt under simuleringsforløpet. Simuleringen viser at kravene som ligger til grunn for denne simuleringstesten ikke er de mest krevende å møte for en synkronmaskin med permanentmagnet-rotor .

I "fault-ride-through" testen klarer ingen av de to simuleringsmodellene å operere stabilt etter testen med 85 % spenningsreduksjon over 0,40 sekunder. Kravene fra FIKS som er bakgrunnen for denne simuleringen blir ansett som mer krevende å oppfylle med en synkronmaskin med permanentmagnet-rotor . Siden simuleringsmodellene i denne oppgaven består av den elektriske maskinen direkte tilkoblet nettmodellen, ville en utvidelse av simuleringsmodellen med passive elementer som overføringslinjer og/eller transfor-

matorer gitt en dempende effekt til systemet, og mulig bedre simuleringsresultater.

Hovedkonklusjonen er at dempeviklinger i rotor anses som en fordel både under en full trefase kortslutning og etter en feil under generatordrift. I motordrift er resultatet mer komplekst, der dempeviklingen bidrar negativt i løpet av en trefase kortslutning og deretter med en positiv effekt etter en feil.

Contents

Preface	i
Problem Description	v
Abstract	v
Sammendrag	vii
List of Tables	xiii
List of Figures	xv
Nomenclatures	xvii
1. Introduction	1
1.1. Background	1
1.2. Objectives	1
1.3. Scope of work	2
1.4. Limitations	2
2. Theoretical background and mathematical models	3
2.1. Design criterias for permanent magnet synchronous generators - voltage and frequency	3
2.1.1. Design criterias for hydro power synchronous generators - operation requirements during minor voltage,- and frequency deviations	3
2.1.2. Design criterias for hydro power synchronous generators - fault ride through	6
2.2. Per-phase diagram and operational principle of a PM-synchronous generator with 12 poles in the rotor	9
2.2.1. Round rotor	11
2.2.2. Salient rotor	12
2.3. Effect of a varying grid voltage on a PM-generator with round rotor . . .	13
2.3.1. Nominal-case	14
2.3.2. Undervoltage-case	15
2.3.3. Overvoltage-case	16
2.3.4. Conclusion of grid voltage variation	17

2.4. Effect of varying grid frequency on a PM-synchronous generator with round rotor	19
2.5. Per-unit System	19
2.6. Torque in synchronous machine during short circuit	20
2.7. Torque in a synchronous machine after a short circuit	20
3. Study cases- and model development	23
3.1. Study cases	23
3.1.1. Study cases description on PM-generator	23
3.1.2. Study case description on PM-motor	27
3.2. Model development - PM-machine simulation blocks	27
3.2.1. Parametrization	27
3.3. Model development - generator operation	30
3.3.1. PM-generator block - Initial simulation values	30
3.3.2. PM-generator block - Input parameters	34
3.3.3. Grid connection block	35
3.4. Model development - motor operation	36
3.4.1. PM-motor block - Initial simulation values	36
3.4.2. PM-motor block - Input parameters	38
3.4.3. Grid connection block	40
4. Simulation	41
4.1. General	41
4.1.1. PM-generator simulations	41
4.1.2. PM-motor simulation	42
4.2. Simulation results PM-generator, simulation case 1	42
4.2.1. Stability studies generator operation	42
4.3. Simulation results PM-generator, simulation case 2	45
4.4. Simulation results PM-generator, simulation case 3	45
4.4.1. Stability boarders	45
4.5. Simulation results PM-motor	47
4.5.1. Stability studies motor operation	47
5. Discussion	49
6. Conclusion	53
7. Recommendation for further work	55
Bibliography	57
Appendices	59
A. Input circuit controllable voltage source	61
A.1. Simulation case 2	61

A.2. Simulation case 3	65
B. Simulation case details	67
B.1. Simulation case 2 - generator	67
B.2. Simulation case 4 - motor	69
C. Attached files	71

List of Tables

2.1. Summarized parameters for varying grid voltage	17
3.1. Machine parameters	28
3.2. Base value equations for Synchronous Machine Block	28
3.3. Regulator parameters	34
3.4. Parameters for grid simulation block	35
3.5. Currents for PM motor case	36
3.6. Grid parameters for simulation case 4	40
4.1. Simulation results PM-generator with damper windings, case 1	43
4.2. Simulation results PM-generator without damper windings, case 1	44
4.3. Magnitudes of rotor speed increase and disturbance time at short circuit on PM-generator	44
4.4. Simulation results PM-generator with damper windings, case 3	45
4.5. Simulation results PM-generator with damper windings, case 3	46
4.6. Simulation results PM-motor with damper windings	47
4.7. Simulation results PM-generator without damper windings	47
4.8. Magnitudes of rotor speed decrease and disturbance time at short circuit on PM-motor	48
A.1. Parameters for sine grid simulation block phase A	65

List of Figures

2.1.	Graphical representation of Statnett’s FIKS requirements for generators	4
2.2.	Graphical representation of IEEE requirements for generators	5
2.3.	Graphical representation of NEK/IEC requirements for generators	7
2.4.	FIKS - fault ride through requirements for production units in Norwegian regional- and central grid [15]	8
2.5.	Operational chart - generator operation	10
2.6.	Per-phase equivalent circuit of PM-synchronous generator with round rotor	11
2.7.	Per-phase equivalent circuit of PM-synchronous generator with salient rotor [8]	12
2.8.	Operational chart - generator operation	13
2.9.	Nominal grid voltage $V_f=1.0$ pu.	15
2.10.	Undervoltage. Grid voltage is equal to $V_f=0.9$ pu.	16
2.11.	Overvoltage. Grid voltage is equal to $V_f=1.05$ pu.	18
3.1.	Simulation case 1 - Short circuit - variable definition	24
3.2.	Simulation case 2 - Stability during voltage- and frequency variation - simulation case definition 1	25
3.3.	Simulation case 3 - Fault ride through - parameter definition	26
3.4.	Without damper windings	27
3.5.	With damper windings	27
3.6.	Salient pole synchronous generator operational diagram	31
3.7.	Three phase grid block	35
3.8.	Per-phase grid simulation block	36
3.9.	Salient pole synchronous generator operational diagram	37
3.10.	Simulation case 4 - Torque characteristic	39
4.1.	Stability borders simulation case 3	46
A.1.	Input circuit simulation case 2. Per-phase controllable voltage source	62
A.2.	Input circuit simulation case 2. Frequency modulation	63
A.3.	Input circuit simulation case 2. Amplitude modulation	64
A.4.	Per phase input signal circuit. Simulation case 3	65
B.1.	Simulation case 2 - Stability during voltage- and frequency variation - simulation case definition 2	68
B.2.	Simulation case 4 - Damper winding effect - variable definition	69

Nomenclatures

Abbreviations

MSPS	Matlab SimPowerSystems	AC	Alternating Current
DC	Direct Current	NTNU	Norwegian University of Science and Technology
PM	Permanent Magnet	rpm	Revolutions per minute
PMSM	Permanent Magnet Synchronous Motor	PMSG	Permanent Magnet Synchronous Generator
HV	High Voltage	LV	Low Voltage
rms	root-mean-square	FIKS	Functional requirements for the Norwegian regional and central grid
PQ-controller	Power-Quality controller	MVA	Mega Volt-Amperè
MW	Mega-Watt(10^6 watt)	TSO	Transmission system operator

Subscripts

e	Electrical (angle, torque)	m	Mechanical (angle,torque)
r	Rotor	a	Armature
ϕ, f	Phase	d	Direct axis
q	Quadrature axis	p.u	Per-unit
ll	Line to line	l	Line
D	Damping (torque)	a,b,c	Three phases (currents)
0, ref, base	Reference value	n	Nominal

Symbols

n	Rotational speed [rpm]		p	Number of poles
ω	Angular speed [rad/s]		f	Power system frequency
E, V	Voltage [V]		Φ	Flux
R	Resistance [Ω]		k, K	Constant
P	Active power [W]		i, I	Current [A]
Q	Reactive power [VAr]		S	Apparent power [MVA]
L	Inductance [H]		J	Inertia [$\text{kg}\cdot\text{m}^2$]
τ, T	Torque [Nm]		H	Inertia constant [sec]
Z	Impedance [Ω]		$\phi, \delta, \gamma, \Theta$	Angle

Introduction

1.1. Background

This master thesis has its background and origin from PQ-controllers delivered to the wind industry, and extended into the idea to use a permanent magnet machine in a small scale pumped hydro power plant, together with a multi-purpose frequency converter. When a synchronous PM-machine is mentioned this implies a synchronous machine built with permanent magnets in the rotor to set up a magnetic field, and that the electrical machine can operate as both a generator and motor. A multi-purpose frequency converter is a converter envisioned with more than one purpose where it is installed. The use and implementation of a multi-purpose frequency converter is treated in the project made in advance of this thesis [13], and after completion of this project the topic with permanent magnet machines during specific faults became relevant and interesting to invest further. The reason for further investigating the use of permanent magnet machines in small scale hydro power plants during faults are to set focus on possible advantages and disadvantages by using this technology in the pumped hydro industry, and to potential set focus on factors and problems that may arise during development of new technological configurations. The location of NTNU is also part of the project background, since Norway has potential power-plant sites where such constructions are possible to install.

1.2. Objectives

The objective of this project is to provide an understanding and to set focus on challenges during and after faults, for a small scale pumped hydro power plant with and without damper windings. This is done by simulation and evaluation of four different simulation cases/situations that are considered relevant and interesting for a pumped hydro power plant in the 15 MW active power range. One simulation case for motor operation, and

three for generator operation. By this the damper windings effect during and after different fault situations can be examined.

See problem description for further details.

1.3. Scope of work

The following scope of work is based on the objectives described:

- Establish equal electrical parametrization of both electrical machine simulation blocks.
- Define and describe the four simulation cases - describe simulation cases background, when these are referred to.
- Establish simulation circuits both with- and without damper windings.
- Establish control circuits that describe each of the four simulation cases in the simulation models.
- Summarize and analyze simulation results.

1.4. Limitations

The following limitations are applied:

- The master thesis duration lasts from the 8'th of January to the 11'th of June.
- Existing blocks in MSPS are used.
- Cost considerations will not be included in this study.

Theoretical background and mathematical models

2.1. Design criterias for permanent magnet synchronous generators - voltage and frequency

2.1.1. Design criterias for hydro power synchronous generators - operation requirements during minor voltage,- and frequency deviations

There are different regulations that can be followed during design of a PM-synchronous generator to set requirements for the generators ability to keep the voltage and frequency within given limits. The design criterias depends on the generators grid connection and the area licensee of the corresponding grid. Three different regulations are described and illustrated below.

FIKS

The functional requirements in the Norwegian power-system (FIKS), are a guiding document used during planning of new parts and rehabilitation of grid- and production-parts in the Norwegian regional- and central-grid [15]. The FIKS are also used as a dimensioning document for some cases in the distribution grid. For work and changes in the regional- and central-grid, the FIKS document shall provide help and guide the contractors to ensure an as efficient as possible review and approval of the planned changes in the power system, from the power system administrator (STATNETT) point of view. For the distribution grid, the FIKS requirements are dimensioning if the planned changes or new-built parts of the grid are considered to influence the operation of the over-laying grid. Such changes in the distribution grid also needs to be approved by STATNETT

before they are commissioned. The FIKS requirements regarding voltage and frequency are illustrated in figure 2.1.

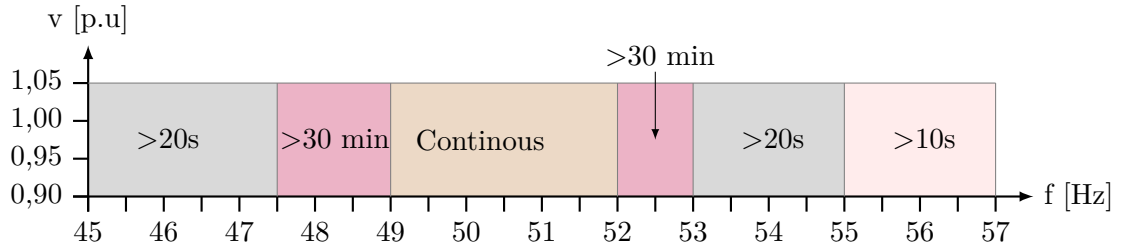


Figure 2.1.: Graphical representation of Statnett's FIKS requirements for generators

From the FIKS requirements it is clear that the synchronous generator shall remain in its continuous mode of operation when the grid voltage is between 0,9 and 1,05 p.u, and with a frequency between 49 and 52 Hz.

IEEE

IEEE is an international association that provides a wide range of publications and standards, and thus permits an exchange of knowledge and guidelines among technology interests. The IEEE standards are documents where specifications and design of certain products, methods, materials or services are detailed to ensure a safe, reliable and functional way of operation.

The voltage- and frequency requirements for generators from the IEEE standard C50.12, recognized as an American National Standard (ANSI), are illustrated in figure 2.2 [14]. This standard holds reproduced information from the International Electrotechnical Commissions (IEC) standard IEC 60034-3. The requirements in this standard are intended for salient-pole generators rated 5 MVA and above, for use in hydraulic turbine and pump/turbine applications. The usage of this standard in Norway is voluntary, and is therefore merely a proposition for a possible solution to design and construct a given generator.

In figure 2.2 the generators shall be thermally capable of continuous operation within its reactive capabilities over a defined range between $\pm 5\%$ in voltage and $\pm 2\%$ in frequency, portrayed by the shaded area in the middle of the figure. The operation of the generators does not necessarily have to be in accordance with the performance requirements established for operation at rated voltage and frequency [14]. The generators will also be capable of operation over a wider frequency range, defined by the outer boarder in figure 2.2, but will then experience a further reduction in insulation lifetime. Due to this extended reduction of lifetime at operation outside the shaded area, this should be limited in occurrence, with reduced output or other mitigation measures.

2.1. DESIGN CRITERIAS FOR PERMANENT MAGNET SYNCHRONOUS GENERATORS - VOLTAGE AND FREQUENCY

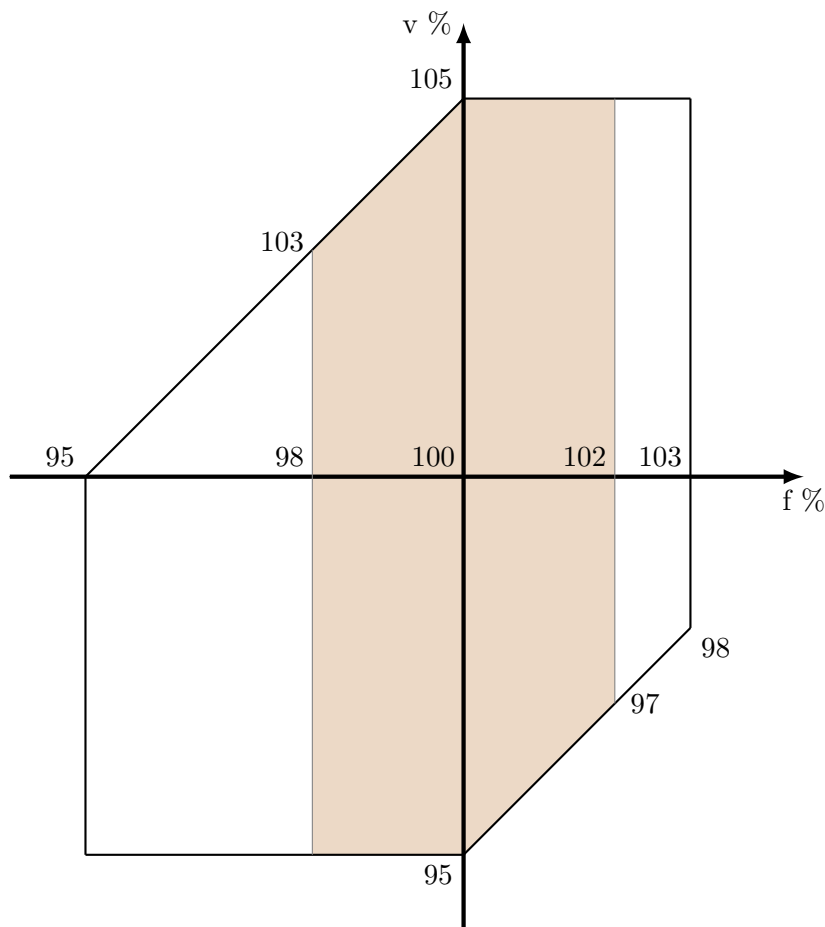


Figure 2.2.: Graphical representation of IEEE requirements for generators

IEC - NEK

The Norwegian electrotechnical standard NEK EN 60034-1:2010 contains requirements for rotating electrical machines and their rating and performance. The text of this standard is taken from the International Standard IEC 60034-1:2010, with some modifications given in the standard [10]. The requirements from the standard NEK EN 60034-1:2010 regarding voltage- and frequency variations during operation are illustrated in figure 2.3, with its two different areas with different requirements. The inner area (shaded) is called area A and the outer area is called area B. The differences of these two areas will be explained.

Area A represents the spectrum where the generator shall be able to perform its primary function, and operate with its rated apparent power (MVA) and its rated power factor. The generator does not have to fully comply with its performance at rated voltage and

frequency, and may operate with some deviations. Temperatures may increase during operation with different voltage and frequency than the generators nominal case, and must be kept within safe limits.

Area B represents the area where the generator shall be able to perform its primary functions, but possibly with larger deviations than during operation in area A. Temperature is a greater challenge during operation in this area, especially with respect to temperature. Operation in area B should be limited in time, duration and frequency, and temperature should be kept under control to minimize the risk of reduced lifetime of the equipment.

For operation on a stiff intercontinental grid a frequency variation exceeding ± 1 Hz from the nominal 50 Hz frequency is considered highly unusual, together with a voltage deviation exceeding the ± 5 % for over- or undervoltage. This is the reason why voltage- and frequency deviations exceeding this level are rarely referred to in the industry.

2.1.2. Design criterias for hydro power synchronous generators - fault ride through

FIKS

Production units connected to the Norwegian central- and regional grid with a nominal voltage smaller than 220 kV shall help the corresponding power system to keep a stable mode of operation before, during and after a faulty situation. In the functional requirements for the Norwegian central- and regional grid there are given a voltage-time curve explaining the voltage deviation a production unit shall be able to handle, thus the voltage deviation that the production units shall be able to operate and deliver power within [15]. This voltage-time curve is displayed in figure 2.4.

2.1. DESIGN CRITERIAS FOR PERMANENT MAGNET SYNCHRONOUS GENERATORS - VOLTAGE AND FREQUENCY

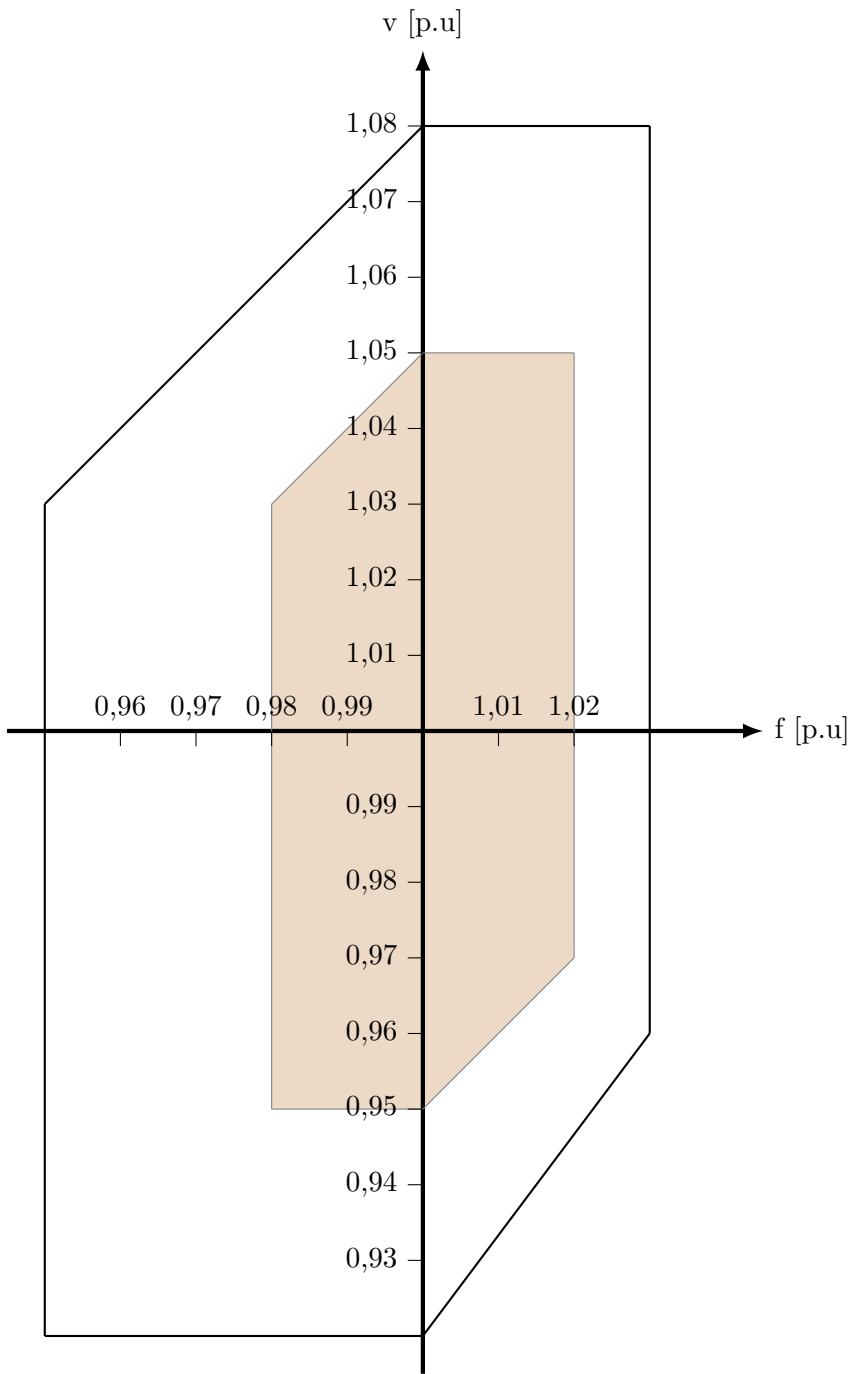


Figure 2.3.: Graphical representation of NEK/IEC requirements for generators

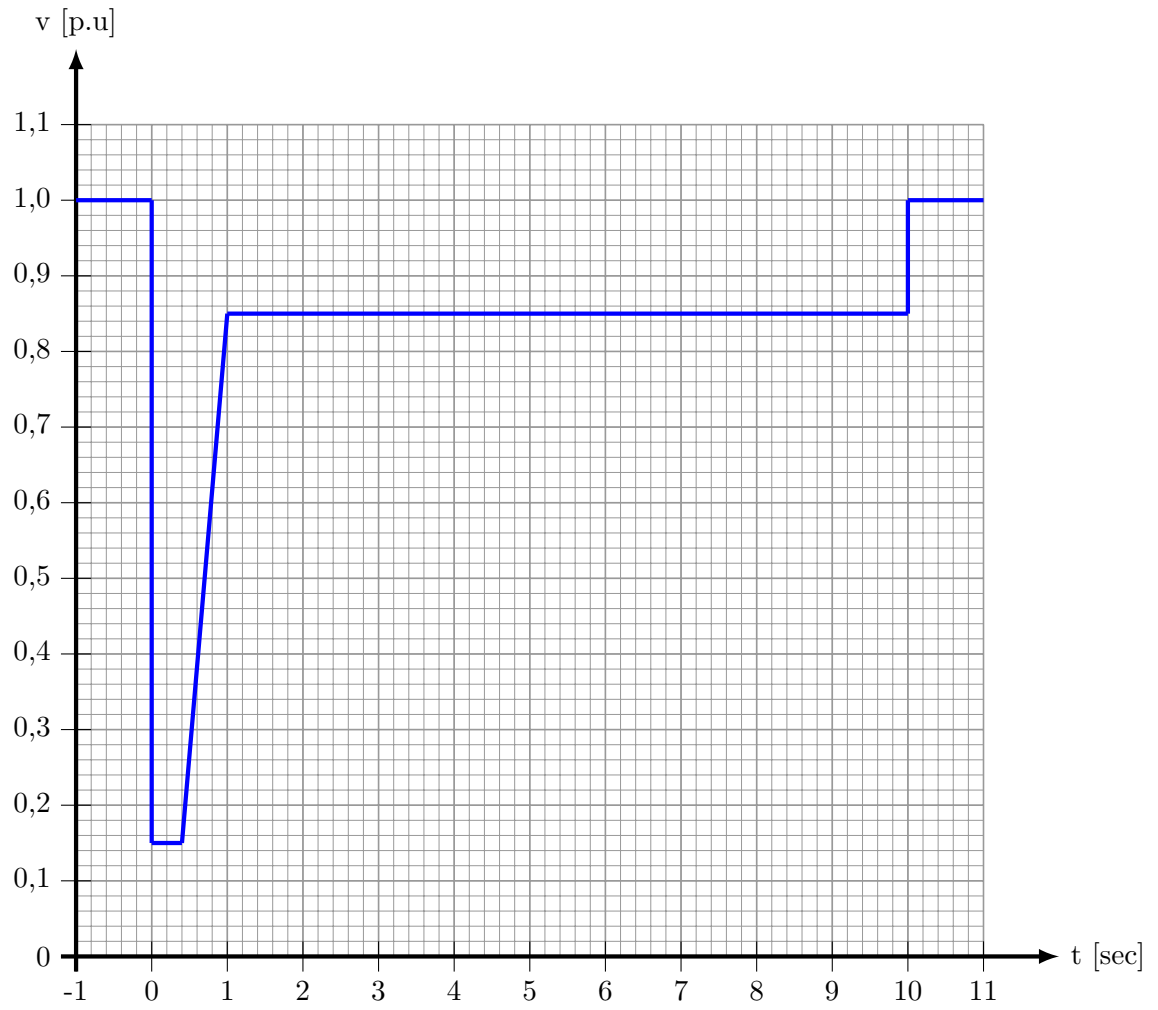


Figure 2.4.: FIKS - fault ride through requirements for production units in Norwegian regional- and central grid [15]

2.2. Per-phase diagram and operational principle of a PM-synchronous generator with 12 poles in the rotor

At steady state operation a synchronous generator connected directly to the power grid has a constant mechanical rotational speed established by the line-fed stator windings. When the generator has a rotor configuration with 12 poles the electrical and mechanical rotational speed is unequal, and the only time these two rotational speeds are equal is with a rotor configuration with 2 poles. If the generator has 12 poles, one mechanical revolution will correspond to 6 electrical cycles, and from this the expression that relates the mechanical and electrical angles can be expressed as in equation (2.1). In figure 2.5 the stator voltage vectors are displayed in a purple color, one vector for each of the three phase voltages. The inner circle of vectors represents the permanent magnet configuration in the synchronous machine rotor. A red vector represents a magnetic north pole and a black vector corresponds to a magnetic south pole. The illustration is built up to show how the angle relations between mechanical and electrical angles will relate for a 12 pole synchronous machine (6 pole pairs), when the rotor position is assumed 90 electrical degrees behind the phase A axis, when the phase A voltage is zero.

$$\gamma_e = \frac{p}{2}\gamma_m \quad (2.1)$$

The important thing to remember with figure 2.5 is that the inner and outer set of vectors rotate with different rotational speed. The purple voltage vectors rotate with a speed dependent on the connected grid frequency f , as explained in equation (2.2). The inner set of magnet vectors rotates at a speed dependent on both the number of poles in the rotor p and the grid frequency f , as explained in equation (2.3).

$$n_e = 60f = \frac{p}{2}n_r = 60 \cdot 50 = 3000 \text{ rpm} \quad (2.2)$$

$$n_r = \frac{120f}{p} = \frac{120 \cdot 50}{12} = 500 \text{ rpm} \quad (2.3)$$

The set of equations (2.2) and (2.3) shows, as commonly known, that the rotors rotational speed decreases with an increasing number of poles in the synchronous machines rotor for a constant suppressed frequency. In addition, that during synchronous operation the voltage vectors induced in a generator holds a constant speed depending on the corresponding grid frequency. Figure 2.5 is used when calculating the synchronous machine initial conditions for the simulation cases.

The two different per-phase diagrams and corresponding operational $P - \delta$ diagrams for the round and the salient pole rotor configuration are explained further in sections 2.2.1 and 2.2.2.

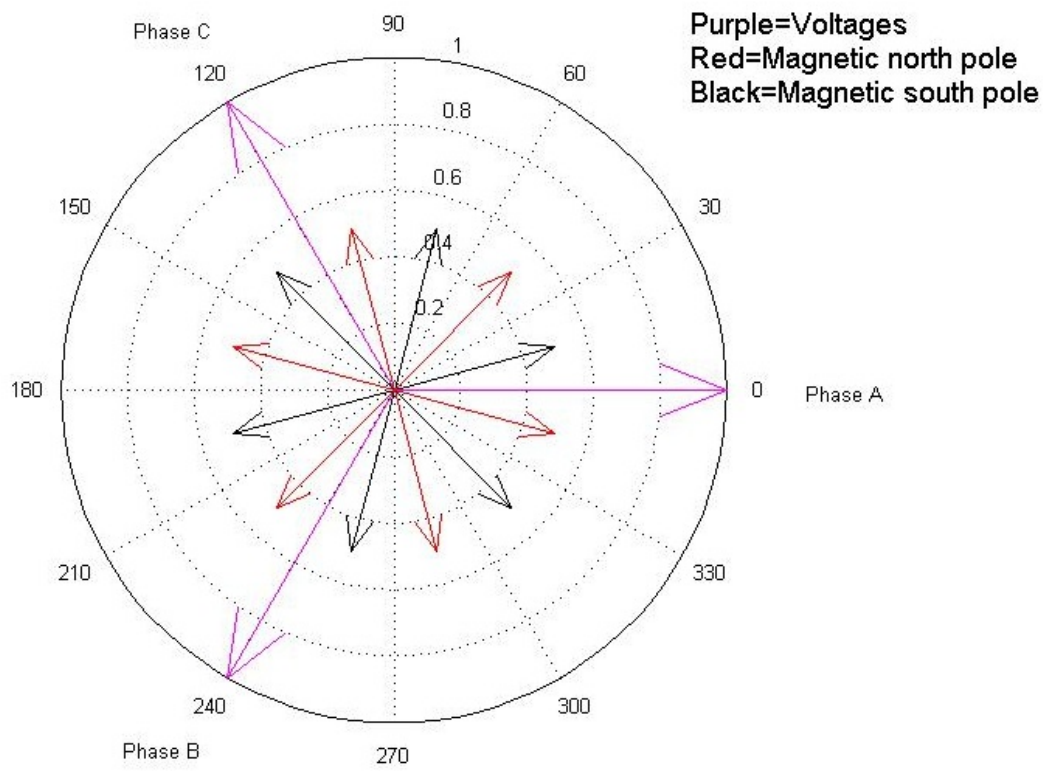


Figure 2.5.: Operational chart - generator operation

2.2.1. Round rotor

On a per-phase basis the round rotor synchronous generator is represented as two voltages. The internal induced voltage E_a and the grid voltage V_f , together with the reactance X_d and the resistance R representing the combined reactance and resistance between the internal induced voltage and the connected grid. Since the synchronous reactance $X_d \gg R$, the armature resistance is often neglected. E_a , V_f and I_a all represents phasors, and the current is defined as being supplied by the synchronous generator following the generator convention, as shown in figure 2.6.

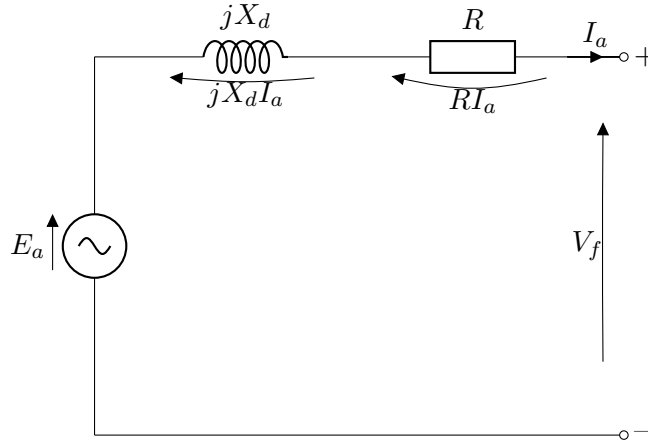


Figure 2.6.: Per-phase equivalent circuit of PM-synchronous generator with round rotor

The equation describing the per-unit power delivered from a round rotor synchronous generator when the armature resistance is neglected is developed from the generators per-phase diagram, corresponding phasor diagram and per-unit considerations into equation (2.4). V_f and E_a is voltage per-unit quantities and X_d is the synchronous reactance in per-unit.

$$P_{pu} = \frac{V_{fpu} E_{apu}}{X_{dpu}} \sin \delta \quad (2.4)$$

For a PM-synchronous generator the internal induced voltage E_a is assumed constant since the flux set up by the rotor is constant depending on the magnet configuration in the rotor, and since the rotational speed of the rotor also is assumed constant. This is described in equation (2.5). The grid voltage is further assumed constant equal to its nominal value, and the synchronous reactance has a defined value.

When these assumptions are made, it is clear that the delivered power from the PM-synchronous generator can be simplified into equation (2.6). The power-angle diagram for a PM round rotor synchronous generator is drawn as the red line in figure 2.8 with

a grid voltage and internal induced voltage of 1,0 p.u, and a synchronous reactance of 0,5 p.u. A active power production of 1,0 p.u is obtained with a power angle(δ) of 30 degrees.

$$E_a = K\Phi\omega \quad (2.5)$$

$$P = K \sin \delta \quad (2.6)$$

2.2.2. Salient rotor

For a salient-pole generator the per-phase equivalent diagram is shown in figure 2.7, resolved into d- and q-axis components.

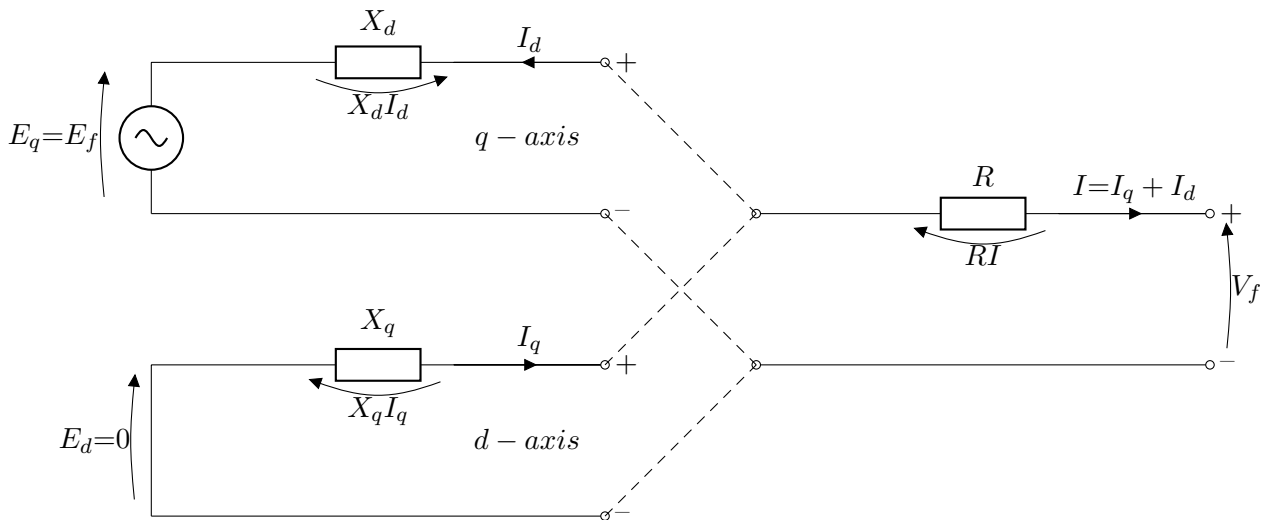


Figure 2.7.: Per-phase equivalent circuit of PM-synchronous generator with salient rotor [8]

For the d- and q-axis components in figure 2.7 all the corresponding variables are in phase with each other and are real numbers. This is the reason why the reactances X_d and X_q are shown by the symbol of resistances rather than reactances, to give a voltage drop that is in phase with the corresponding current [8]. The resistance is also for the salient pole case often neglected because of its small size compared to X_d and X_q .

From the per-phase diagram, corresponding phasor diagram and per-unit considerations the equation describing the per unit active power from a salient pole generator can be derived, as shown in equation (2.7). From this equation the power-angle diagram can be plotted for defined values. If the voltage values are set to 1,0 p.u, the direct synchronous

2.3. EFFECT OF A VARYING GRID VOLTAGE ON A PM-GENERATOR WITH ROUND ROTOR

reactance X_d is set to 0,5 p.u and the quadrature synchronous reactance is set to 0,6 p.u, the blue line in figure 2.8 represents the active power as a function of power-angle δ . An active power production of 1,0 p.u is obtained with a power angle of 35,36°. Thus the salient pole generator will operate at a larger power angle than the round rotor configuration, at power angles below 90°.

$$P = \frac{E_a V_\phi}{x_d} \sin(\delta) + \frac{V_\phi^2}{2} \frac{x_d - x_q}{x_d x_q} \sin(2\delta) \quad (2.7)$$

If real-value parameters are used in equation (2.7), the real power is per-phase.

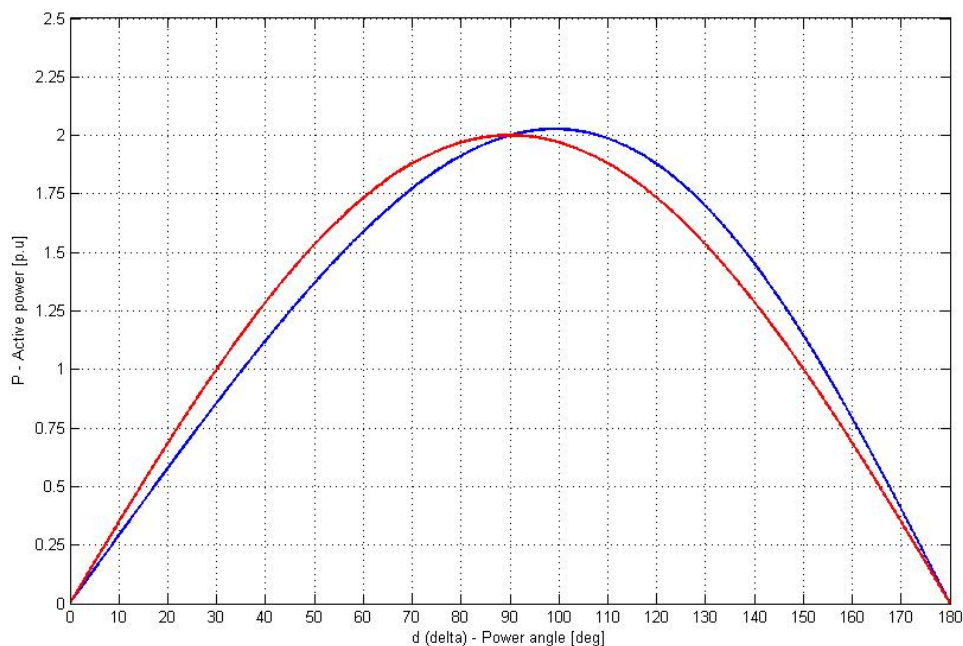


Figure 2.8.: Operational chart - generator operation

2.3. Effect of a varying grid voltage on a PM-generator with round rotor

The effects of a varying grid voltage on a PM-generator with round rotor and star-connected stator winding are explained with three different cases; the nominal-, undervoltage- and overvoltage-case. The reason that the round-rotor generator design is chosen for deriving the effects of a varying grid voltage is that this generator design leads to a

somewhat simpler set of equations that gives a good understanding of the corresponding effects.

If the grid voltage changes during operation of a PM-synchronous generator, the current and power-angle will change from their initial values. The induced voltage E_a will be equal in magnitude for each operating condition due to the constant flux linkage from the permanent magnets, and the constant frequency in the connected grid. The active power production from the PM-machine is also assumed constant, thus the generator experiences a constant torque from its prime mover. The stator resistance is neglected since $X_d \gg R_a$. The synchronous reactance is marked jX_d , and the phase voltage of the stator terminals is marked V_f . The active and reactive power contributions for each of the three operating points are marked with red color in the corresponding phasor diagrams. The equation used for calculations are shown in equations (2.4) and (2.8), and further calculations are based on geometrical relationships taken from each phasor diagram.

$$P = \sqrt{3}V_{ll}I_l \cos \phi \quad (2.8)$$

2.3.1. Nominal-case

The nominal-case is described as when the magnitude of the stator terminal voltage(grid voltage) is equal in magnitude to the internal induced voltage in the PM-synchronous machine. At this case the voltage at no-load of the PM-machine in generator operation is equal in magnitude to the corresponding grid voltage, and a synchronization of the PM-machine can be executed without any further measures to reduce or increase the voltage magnitude at the generator terminals to ensure a safe synchronization with the grid. The power-factor in the rated situation is set to 20° to have a reference operating condition to explain the effect of varying grid voltage on such a PM-synchronous machine. The rated active power P is 15 MW, and the reactive power Q_1 is calculated in equation (2.9). By geometrical considerations the synchronous reactance X_d is found to be $1,84 \Omega$, and the corresponding power angle δ_1 can be calculated, as shown in equation (2.10). The current is calculated in equation (2.11), and the phasor diagram is shown in figure 2.9.

$$Q_1 = P \tan \phi = 15 \cdot 10^6 \cdot \tan(20^\circ) = -5,46 \text{ MVA}r \quad (2.9)$$

$$\delta_1 = \arcsin \left(\frac{PX_d}{3E_a V_f} \right) = \arcsin \left(\frac{15 \cdot 10^6 \cdot 1,84}{6600^2} \right) = 39,86^\circ \quad (2.10)$$

$$I_{l1} = \frac{P}{\sqrt{3}V_{ll} \cos \phi} = \frac{15 \cdot 10^6}{\sqrt{3} \cdot 6600 \cdot \cos 20^\circ} = 1396,4 \text{ A} \quad (2.11)$$

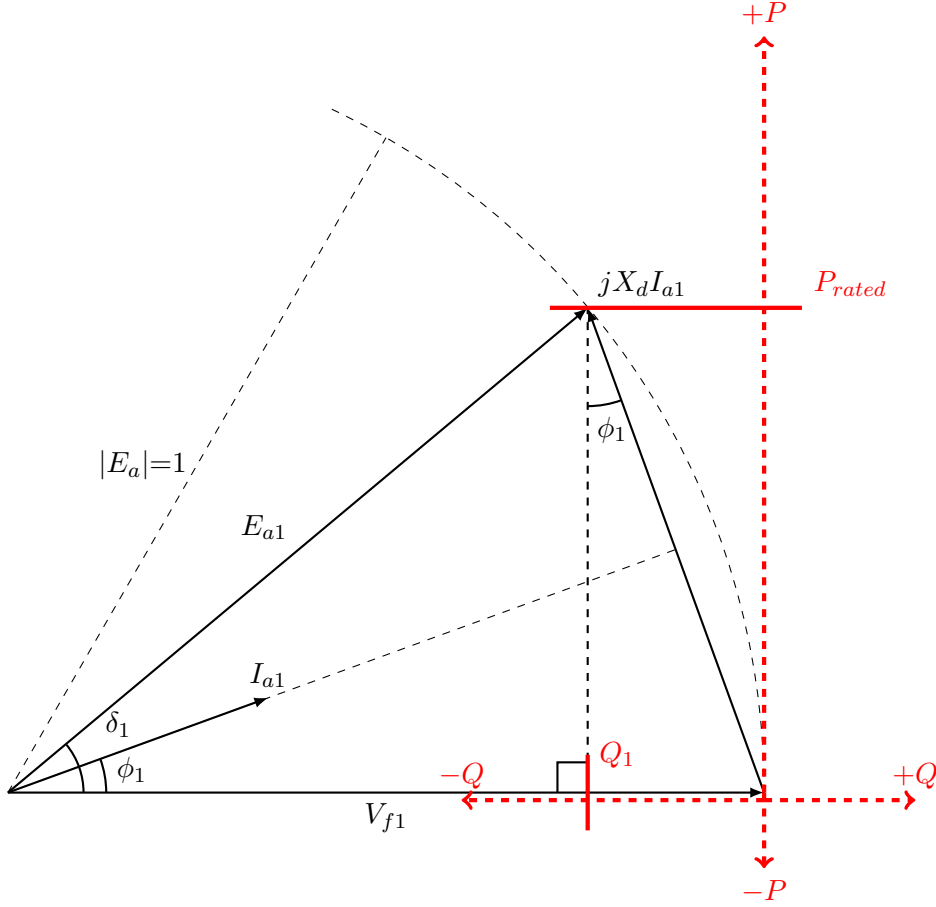


Figure 2.9.: Nominal grid voltage $V_f=1.0$ pu.

2.3.2. Undervoltage-case

The undervoltage-case is shown with a grid voltage of 0,9 p.u. The reason that an undervoltage of 10% is chosen is because that the Norwegian grid requirements for the regional- and central-grid require that a generating unit operates continuous during such a reduction in the connecting grid voltage [15]. From the phasor diagram in figure 2.10 the power factor ($\cos \phi$) is found equal to 0,966, and thus the phase angle ϕ is equal to $15,08^\circ$. From this same phasor diagram it can be obtained that the per-phase terminal voltage on the generator (V_{f2}) is 10% shorter in magnitude than the internal induced voltage E_{a2} . The reactive power during this reduced grid voltage is calculated in equation (2.12), the current in equation (2.13) and the corresponding power angle δ_2 in equation (2.14).

$$Q_2 = P \tan \phi = 15 \cdot 10^6 \cdot \tan(15,27^\circ) = -4,09 \text{ MVar} \quad (2.12)$$

$$I_{l2} = \frac{P}{\sqrt{3}V_{ll} \cos \phi} = \frac{15 \cdot 10^6}{\sqrt{3} \cdot 6600 \cdot 0,9 \cdot \cos 15,08^\circ} = 1511,3 \text{ A} \quad (2.13)$$

$$\delta_2 = \arcsin \left(\frac{PX_d}{3E_a V_f} \right) = \arcsin \left(\frac{15 \cdot 10^6 \cdot 1,84}{6600^2 \cdot 0,9} \right) = 44,75^\circ \quad (2.14)$$

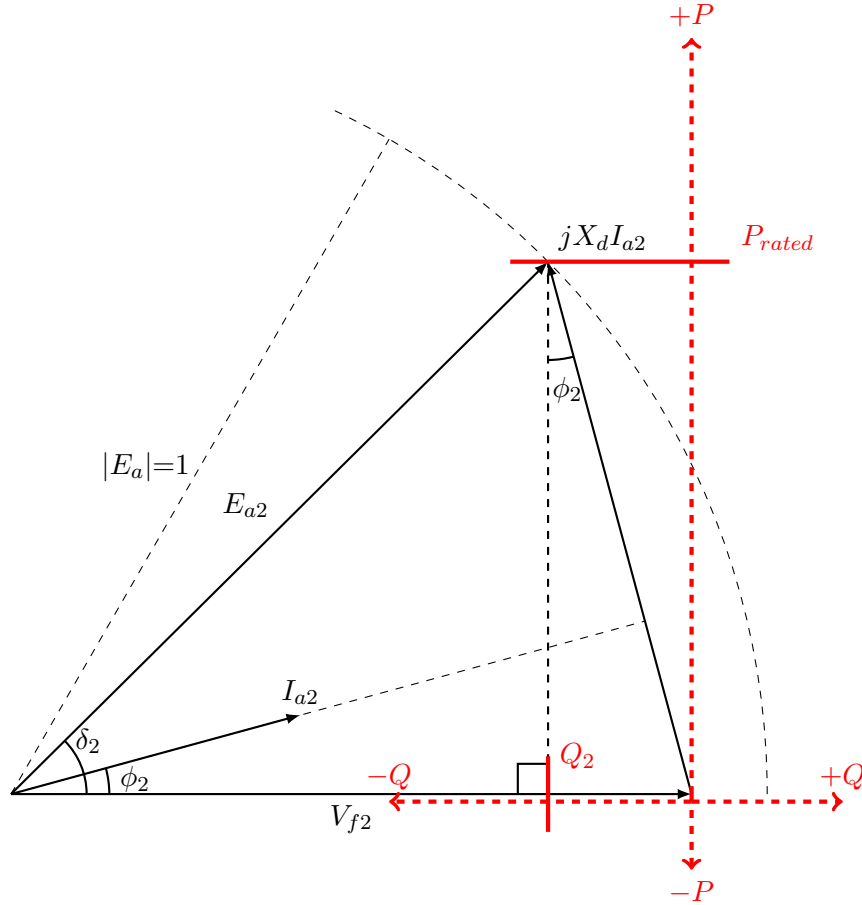


Figure 2.10.: Undervoltage. Grid voltage is equal to $V_f=0.9$ pu.

2.3.3. Overvoltage-case

The overvoltage-case is performed on the same basis as the undervoltage-case, where the functional requirements for the Norwegian regional- and central-grid are followed. These requirements require that a generating unit shall remain in its continuous state of operation during a 5% overvoltage in the connected grid. From the phasor diagram

2.3. EFFECT OF A VARYING GRID VOLTAGE ON A PM-GENERATOR WITH ROUND ROTOR

in figure 2.11, it can be obtained that the per-phase terminal voltage V_{f3} of the PM-machine is 5% longer than the magnitude of the internal induced voltage E_{a3} . By geometric considerations of the phasor diagram in figure 2.11, the phase angle is found to be $\phi = 22,82^\circ$, and the reactive power from the PM-machine can be calculated as in equation (2.15). The current and power angle δ_3 are further calculated in equation (2.16) and equation (2.17) respectively.

$$Q_3 = P \tan \phi = 15 \cdot 10^6 \cdot \tan(22,82^\circ) = -6,31 \text{ MVar} \quad (2.15)$$

$$I_{l3} = \frac{P}{\sqrt{3}V_{ll} \cos \phi} = \frac{15 \cdot 10^6}{\sqrt{3} \cdot 6600 \cdot 1,05 \cdot \cos 22,82^\circ} = 1355,8 \text{ A} \quad (2.16)$$

$$\delta_3 = \arcsin \left(\frac{PX_d}{3E_a V_f} \right) = \arcsin \left(\frac{15 \cdot 10^6 \cdot 1,84}{6600^2 \cdot 1,05} \right) = 37,1^\circ \quad (2.17)$$

2.3.4. Conclusion of grid voltage variation

From the three explained cases above, the effects of an over- or undervoltage on a PM-machine affects the current, reactive power and power angle with respect to the reference case. The summarized values are shown in table 2.1.

	Nominal case	Undervoltage case	Overvoltage case
Power angle δ	39,32°	44,75°	37,12°
Reactive power Q	-5,46 MVar	-4,09 MVar	-6,31 MVar
Current I_l	1396,4 A	1511,3 A	1355,8 A

Table 2.1.: Summarized parameters for varying grid voltage

From table 2.1 it is shown that the power-angle increases in a situation with an undervoltage in the grid. Thus the generator operates closer to the boarder of transient instability. At a grid over-voltage the generator decreases its power-angle, and becomes more rigid and stable regarding transient stability.

The reactive power consumption from the generator decreases from the reference case during under-voltage, and increases at a situation with grid over-voltage. If there is installed phase-compensation equipment together with the PM-machine, this decrease in reactive power consumption will have an effect on the sizing of this equipment. A case with either over- or under-voltage will result in a increased phase-compensation requirement from the corresponding phase-compensation equipment, and thus the dimensioning of this equipment have to take this effect into account during design. If there is no phase compensation equipment, the grid will not have to supply as much reactive power during undervoltage as in the reference case, and this is seen as an advantage. At overvoltage

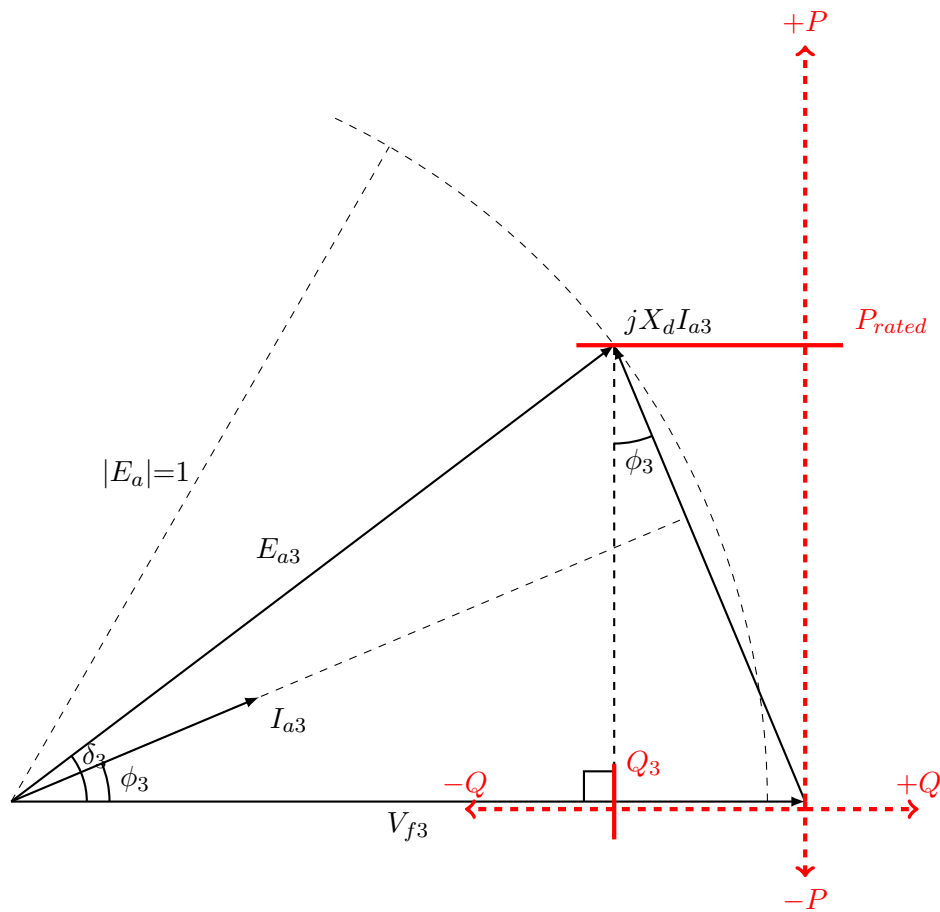


Figure 2.11.: Overvoltage. Grid voltage is equal to $V_f=1.05$ pu.

the grid has to supply even more reactive power than in the reference case, this is seen as a disadvantage.

The current from the PM-machine during over- and under-voltage will change in the opposite direction as the voltage. As the active power delivered from the PM-machine is constant, the current increases when the voltage decreases, and opposite with decreasing current at over-voltage. This effect entails that the PM-machine must be dimensioned to carry the increased current without being over-heated. This is a design criteria that is of high importance since over-heating of electrical equipment has dramatical effects on the equipments lifetime.

2.4. Effect of varying grid frequency on a PM-synchronous generator with round rotor

During changes in the grid frequency, away from the nominal frequency, the connected synchronous generator with round rotor is affected in the manner that all the inductive reactances will change proportionally with the frequency as shown in equation (2.18). When the frequency changes for the grid, the nominal rotational speed for the generator changes, and the induced voltage by the rotor magnetic field changes through equation (2.5), assuming that the flux from the permanent magnet rotor is constant. This effect leads to that the power angle δ changes with the change in frequency. The change in power angle does implicit mean that the generator operates closer to its stability boarder at an over-frequency, and more stable at a under-frequency. A frequency deviation of i.e +4% and -2% which are the requirements from FIKS for continuous mode of operation are considered to contribute with minor effects for the operation of a synchronous generator [3].

If the generator has axle mounted fans for cooling, an over-frequency situation will improve cooling, and thus increase the generators load-carrying capabilities. A speed reduction at under-frequency reduces generator cooling, and together with it the load-carrying capabilities [11].

$$X_l = \omega L = 2\pi f L \quad (2.18)$$

2.5. Per-unit System

The per-unit system of measurements is used to give a consistent system description of a power system or power system components, in order to normalize system variables. This leads to simplified comparison, and simpler evaluation and computations than with usage of physical quantities, if the base values are chosen wisely. Normally the base values are chosen so that the per-unit variables are equal to 1 p.u under nominal rated conditions. The per-unit system eliminates units and expresses system quantities as dimensionless ratios, as shown in equation (2.19).

$$\text{quantity in per-unit} = \frac{\text{actual quantity}}{\text{base value of quantity}} \quad (2.19)$$

For a synchronous machine the per-unit system can be used to remove constants and simplify mathematical equations so that its mathematical equations can be expressed as equivalent circuits.

2.6. Torque in synchronous machine during short circuit

When a synchronous machine is subjected to a 3-phase short-circuit, the individual phase fault currents contain both an unidirectional and a fundamental frequency component, where both of them decay with time [5]. The fault currents are several times larger than the normal load current, and thus the short-circuit leads to a considerable increase in the magnetic energy of the electrical machines circuits. This increase in magnetic energy is balanced by a reduction in the kinetic energy of the rotor, and over time the magnetic energy is dissipated in the resistive elements of the electrical machine. The conversion from kinetic to magnetic energy gives rise to an oscillatory torque component [12].

The oscillatory torque component is one of two air-gap torque components that can be observed during a short-circuit of an electrical machine, and their scope depends on the electrical machines construction [9]. These two torque components can be defined as [7]:

- A unidirectional component, due to rotor resistance losses caused by the fundamental frequency currents induced in the rotor.
- A fundamental frequency oscillatory component, due to interaction with the rotor field

The unidirectional component of the torque is due to the rotor resistive losses and can be quite high. The resistive losses are in the armature-, field- and damper winding circuits. This torque component has a braking effect, and is often called the *dc breaking torque*, which reduces the acceleration of the rotor during the fault sequence.

The oscillatory components decelerates the rotor during the first cycle of the oscillation, and further accelerate the rotor during the second half cycle repeating, for each oscillatory cycle. The net effect of the oscillatory torque is a reduction of the mean speed of the rotor [12].

The overall effect of these speed-reducing torque components are opposite for motor and generator operation. In generator operation they are considered as an advantage, since the speed increase during a fault is decreased due to the opposing torques acting on the rotor. In motor operation the torque contributions are disadvantageous [6], since they lead to an even larger speed decrease during the fault, than if they were not present.

2.7. Torque in a synchronous machine after a short circuit

After a short circuit on a electrical machine, the rotational speed is often different than the nominal speed. The torque equilibrium equation is shown in equation (2.20) for generator operation, and in equation (2.21) for motor operation. These equations show how the speed changes in a synchronous machine when the total torque is unbalanced (not zero), and how the damping torque acts in both modes of operation. J is the electrical machine inertia (both turbine and generator combined), T_m and T_L are mechanical

2.7. TORQUE IN A SYNCHRONOUS MACHINE AFTER A SHORT CIRCUIT

torques on the motor/generator shaft, T_e is the electromechanical torque and T_D is the damping torque contribution.

T_D for generator and motor operation is shown in equation (2.22).

$$J \cdot \frac{d\omega}{dt} = T_m - T_e + T_D \quad (2.20)$$

$$J \cdot \frac{d\omega}{dt} = T_e - T_L + T_D \quad (2.21)$$

$$T_D = k \cdot \left(\frac{\omega_0 - \omega}{\omega_0} \right) \quad (2.22)$$

The damping torque contribution holds the damping effect on speed oscillations from the rotors damper windings. If the damper windings are excluded, the damping torque coefficient is smaller, than if the damper windings are included.

Study cases- and model development

3.1. Study cases

Four different simulation cases are wanted performed. Three different simulation cases on permanent magnet generator circuits, and one simulation case on the permanent magnet motor configuration. These simulation cases will be described in detail in the following sections.

3.1.1. Study cases description on PM-generator

Short circuit - generator operation

The first study case is conducted to investigate permanent magnet generators ability to remain in or regain a stable mode of operation after a full short circuit on the generator terminals for a given time duration. The effect of damper windings during the short circuit are thus examined, and further evaluated by comparing the two different test circuits in MSPS. The variable that is changed in every simulation is named *Time* and is described in figure 3.1.

Stability during voltage- and frequency variation

The second study case is performed to investigate the PM-generators ability to keep their continuous mode of operation during variations in grid voltage and -frequency over time. The simulation case is built up with a start-up at nominal voltage and frequency, and individual changes in voltage and frequency according to the red numbering in figure 3.2 until the initial condition is reached as the 15th stage of the simulation. Both frequency

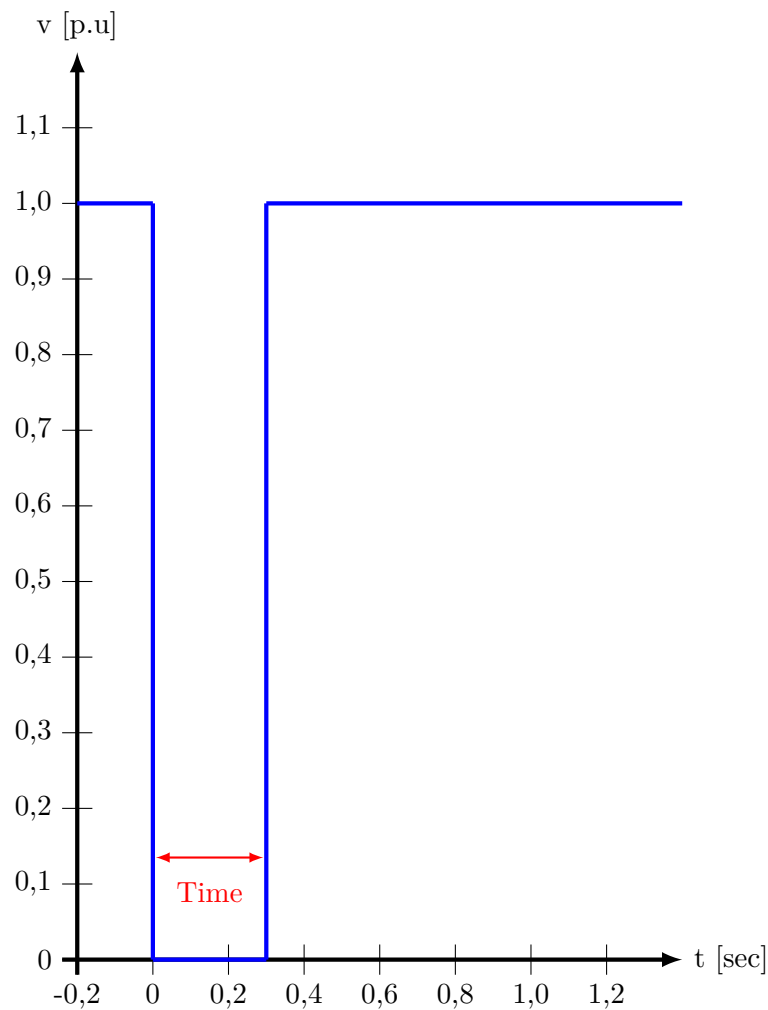


Figure 3.1.: Simulation case 1 - Short circuit - variable definition

and voltage changes are done as a ramp over 10 seconds, and at each of the operational stages the simulation conditions are kept constant for 10 seconds. This study case has its background in the Norwegian FIKS requirements stated in section 2.1.1. The voltage and frequency sequence related to this simulation case is shown as a function of time in figure B.1.

Fault-ride-through for production units in the Norwegian regional and central grid

The third simulation case is the "fault-ride-through" simulation case. This case is conducted to investigate if the two PM-generator circuits are able to meet the "Fault-ride-through" requirements from the Norwegian TSO Statnett, for production units connected

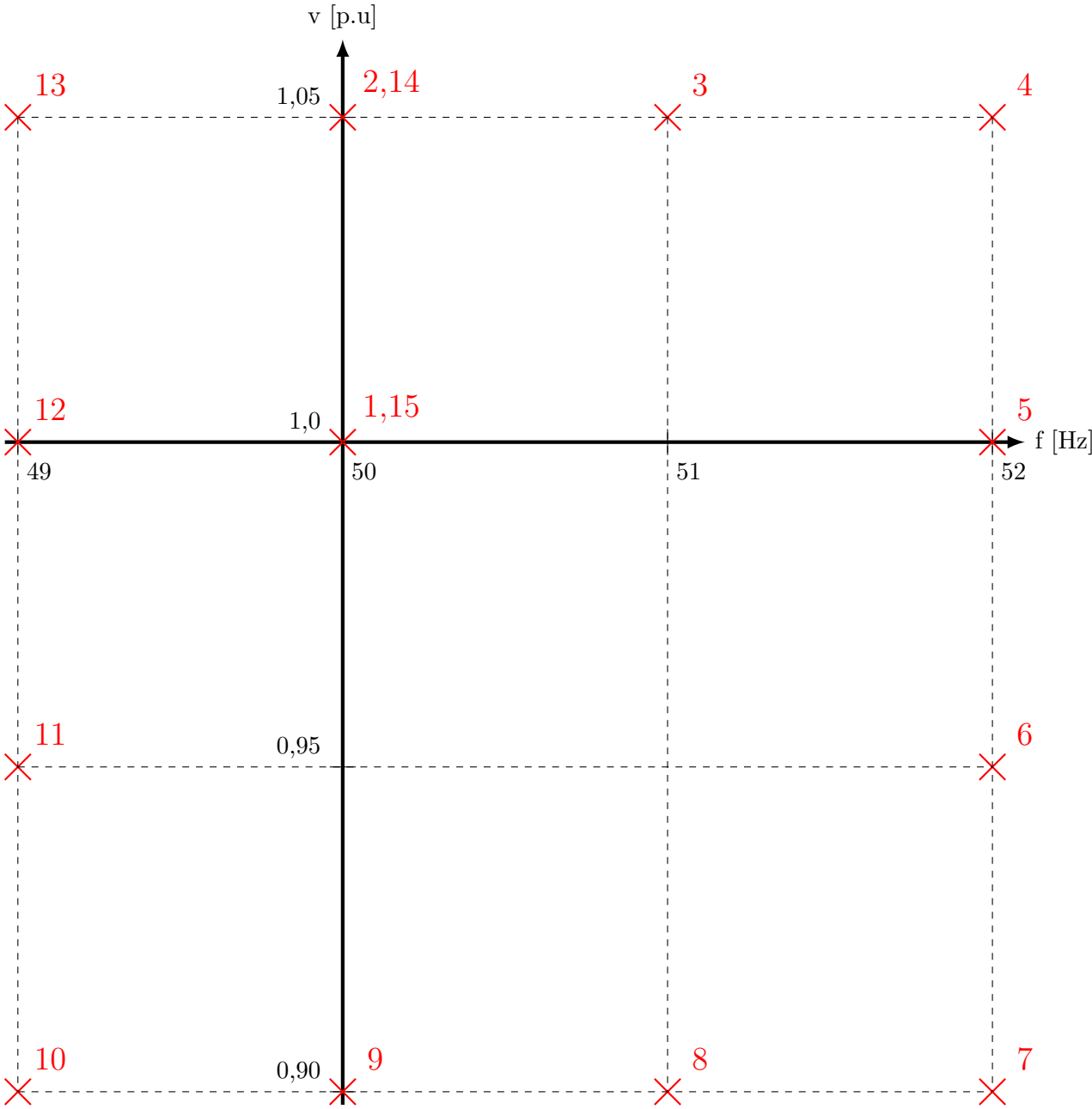


Figure 3.2.: Simulation case 2 - Stability during voltage- and frequency variation - simulation case definition 1

to the Norwegian regional- og central grid with a voltage below 220 kV.

If the circuits are unable to meet the requirements stated by FIKS [15], the instantaneous

voltage-drop down to 15 % voltage and initial duration of the flat voltage drop plateau of 0,40 seconds in figure 3.3 (variables named *Voltage drop* and *Time*) are decreased until a stable mode of operation after the fault is obtained.

The simulations are executed such that for each of the voltage drop magnitudes tested, the duration of the period where the voltage is constant at its minimum value is tested from the initial time of 0,40 seconds and decreasing in time-steps of 100 milliseconds until a stable mode of operation is obtained. By changing only one parameter at the time in the simulations, a stability-boarder for each of the simulation models is able to form.

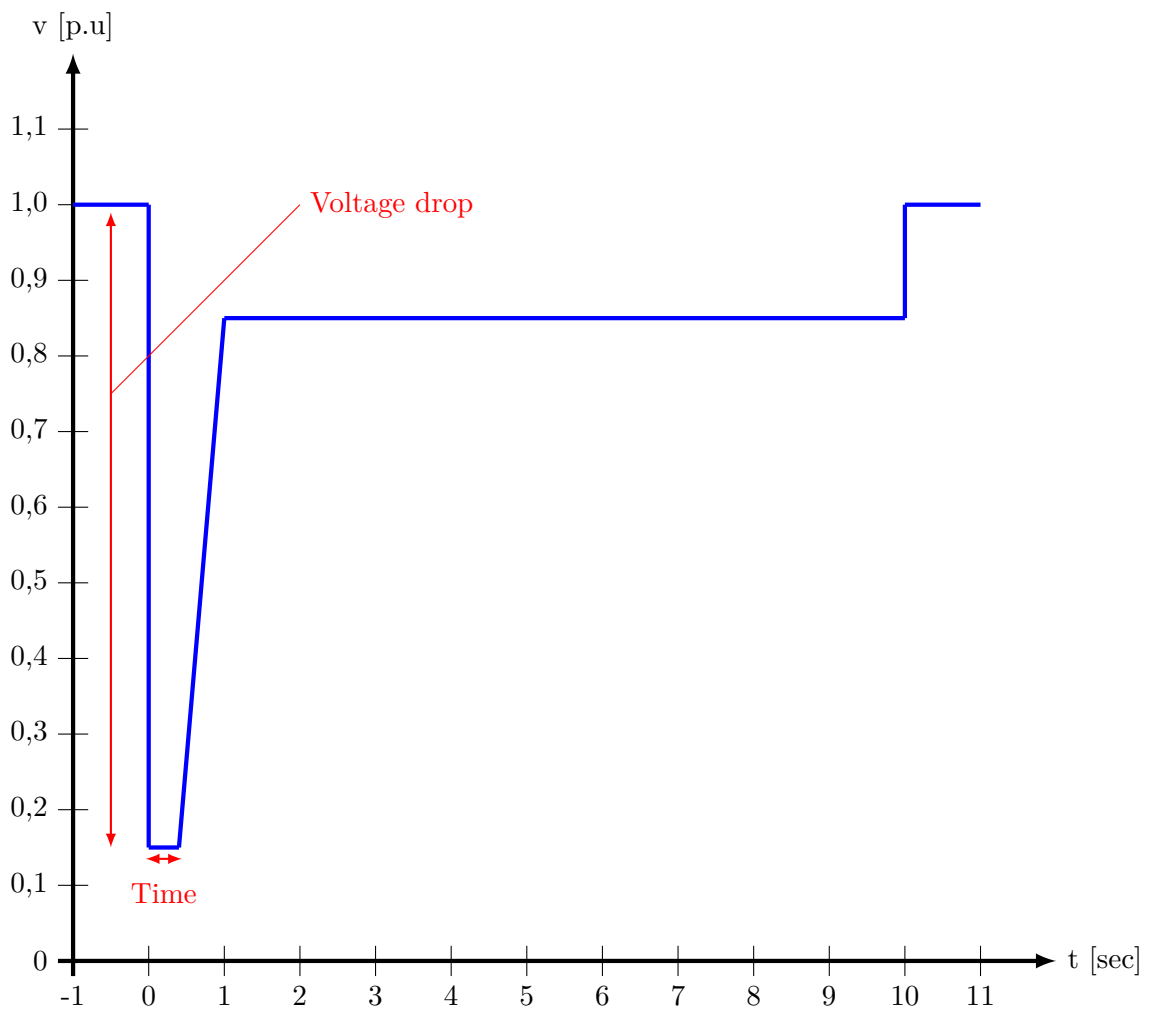


Figure 3.3.: Simulation case 3 - Fault ride through - parameter definition

3.1.2. Study case description on PM-motor

Short circuit - motor operation

The study case with a permanent magnet motor connected to the grid is developed to investigate the two PM-motors ability to remain in- or regain a stable mode of operation after a full short circuit on the motor terminals for a given time duration *Time*. The study case variable description is shown in figure B.2.

3.2. Model development - PM-machine simulation blocks

For the study cases on the PM-generator and PM-motor there are built up two different test circuits with basis in two different available built-in simulation blocks. The first circuit is built up with the permanent magnet machine block without damper windings in the rotors d- and q- axis, as shown in figure 3.4. The second circuit is built with the traditional synchronous machine block with damper windings, modeled without field winding and with a constant field current to perform as a PM-machine, as shown in figure 3.5.

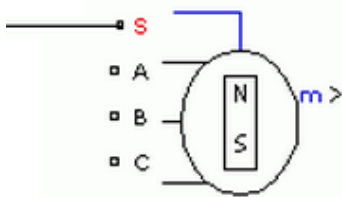


Figure 3.4.: Without damper windings

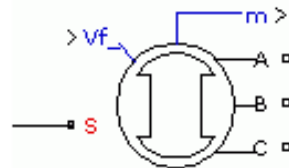


Figure 3.5.: With damper windings

Both simulation blocks are configured as three-phase machines with salient pole rotor, and the shift between motor and generator operation is done with the mechanical input parameter denoted "S" in figures 3.4 and 3.5.

3.2.1. Parametrization

PM Synchronous machine block with constant field current

The synchronous machine block with constant field current used is copied from the project work executed in advance of this master thesis [13]. The machine parameters are listed in table 3.1. The parameter X_d' can not be set equal to zero in MSPS to neglect the d-axis field winding, and is thus set equal to the parameter X_d'' to neglect its contribution. The simulation block is programmed so that 1 p.u of field voltage

gives 1 p.u voltage at the stator terminals during no-load of the machine. The machine configuration with 1 p.u field voltage is used in the simulations.

Nominal power P_n	$15 \cdot 10^6$ [VA]	V_{rms}	6600 [V]
f_n	50 [Hz]	Inertia coefficient H	3 [s]
Pole pairs	6	Field voltage	1 [pu]
R_s	0,0547 [pu]	X_l	0,12 [pu]
X_d	0,5 [pu]	X_q	0,6 [pu]
X_d'	0,18 [pu]	X_q''	0,18 [pu]
X_d''	0,18 [pu]	$T_{q0''}$	0,052 [s]
T_d'	0,019 [s]		
T_d''	0,019 [s]		

Table 3.1.: Machine parameters

Built-in PM block

The permanent magnet machine block in MSPS needs insertion of real value data, so the p.u values from the synchronous machine block have to be calculated to actual values. In the PM-block, only the d- and q-axis armature inductances are present, due to the lack of field- and damper-windings. Together with the inertia, resistance, number of pole pairs and machine constant.

To calculate the actual inductance- and resistance values from the synchronous machine block the base values from the simulation block documentation needs to be used. The equations for the synchronous machine base values are stated in table 3.2 [2].

Base Stator Voltage	$V_{base} = \frac{V_n \sqrt{2}}{\sqrt{3}}$
Base Stator Current	$I_{base} = \frac{P_n \sqrt{2}}{\sqrt{3} V_n}$
Base Stator Impedance	$Z_{base} = \frac{V_{base}}{I_{base}} = \frac{V_n^2}{P_n}$
Base angular frequency	$\omega_{base} = 2\pi f_n$
Base stator inductance	$L_{base} = \frac{Z_{base}}{\omega_{base}}$

Table 3.2.: Base value equations for Synchronous Machine Block

To find the d- and q-axis armature inductances needed for the built-in PM-machine block in MPSP the base stator impedance value needs to be calculated, through equation (3.1).

$$X_l = \omega L \quad (3.1)$$

By combining the equation for Base Stator Impedance ($Z_{base} = \frac{V_n^2}{P_n}$) with equation (3.1), equation (3.2) can be deduced.

$$L = \frac{X_{p.u} V_n^2}{P_n 2\pi f_n} \quad (3.2)$$

Equation (3.2) is used to calculate the stator armature inductances for the d- and q-axis in equations (3.3) and (3.4).

$$L_d = \frac{0,5 \cdot 6600^2}{2 \cdot \pi \cdot 15 \cdot 10^6 \cdot 50} = 4,622 \cdot 10^{-3} \text{ H} \quad (3.3)$$

$$L_q = \frac{0,6 \cdot 6600^2}{2 \cdot \pi \cdot 15 \cdot 10^6 \cdot 50} = 5,546 \cdot 10^{-3} \text{ H} \quad (3.4)$$

The inertia J is calculated from the inertia constant H given for the synchronous machine block with constant field current which is given as 3 seconds. The formula relating H and J are given in equation (3.5) [7], and the inertia J are calculated in equation (3.6).

$$H = \frac{\text{stored energi at rated speed in MW}\cdot\text{s}}{\text{MVA rating}} \quad [\text{sec}] \quad (3.5)$$

$$J = \frac{2HS}{\omega^2} = \frac{2 \cdot 3 \cdot 15 \cdot 10^6}{\left(500 \cdot \frac{2\pi}{60}\right)^2} = 32827,91 \text{ [kg} \cdot \text{m}^2] \quad (3.6)$$

The stator phase resistance is calculated over to its real value through equation (2.19) in equation (3.7).

$$R = R_{p.u} Z_{base} = 0,00547 \cdot \left(\frac{6600^2}{15 \cdot 10^6}\right) = 0,0159 \text{ } \Omega \quad (3.7)$$

The number of pole pairs is the same as for the synchronous machine model with constant field current, equal to 6 pole pairs for a rotational speed of 500 rpm. For the machine constant, the parameter "Voltage constant" is chosen. This parameter is specified as the peak line to line voltage per 1000 rpm. The voltage constant represents the peak open circuit voltage when the machine is driven as a generator at 1000 rpm [1]. By this definition the voltage can be calculated for the specific simulation case, as shown in equation (3.8).

$$V_{constant} = \frac{V_{l_{peak}}}{krpm} = \frac{6600 \cdot \sqrt{2}}{0,5} = 18667,62 \text{ [V]} \quad (3.8)$$

3.3. Model development - generator operation

3.3.1. PM-generator block - Initial simulation values

Built-in PM block

Before the initial values can be calculated for the PM-block the reference parameters used for the per-unit defined parameters has to be defined. The voltage reference is defined as the line-to-line voltage at the electrical machines stator terminals, which is equal to the internally induced line-to-line voltage in the PM-electrical machine, 6600 V. The apparent power reference is defined as the electrical machine nominal active power, equal to 15 MW. Impedance- and current references are further defined in equations (3.9) and (3.10).

$$Z_{ref} = \frac{(U_{ref})^2}{S_{ref}} = \frac{6600^2}{15 \cdot 10^6} = 2,90 \Omega \quad (3.9)$$

$$I_{ref} = \frac{S_{ref}}{\sqrt{3}U_{ref}} = \frac{15 \cdot 10^6}{\sqrt{3} \cdot 6600} = 1312,16 \text{ A} \quad (3.10)$$

Real value impedances are calculated to be used in the calculation of power-angle and currents in equations (3.11) and (3.12).

$$X_d = X_{dpu} Z_{ref} = 0,5 \cdot 2,90 = 1,45 \Omega \quad (3.11)$$

$$X_q = X_{qpu} Z_{ref} = 0,6 \cdot 2,90 = 1,74 \Omega \quad (3.12)$$

Since both of the test circuits used have electrical machines with salient pole rotors, equation (3.13) is used to derive the power angle at the initial mode of operation.

$$P_{salient} = \frac{3V_\phi E_a}{X_d} \sin \delta + \frac{3V_\phi^2}{2} \left(\frac{X_d - X_q}{X_d X_q} \right) \sin(2\delta) \quad (3.13)$$

By inserting all the known variables from section 3.2.1 it is found that the operating power angle of this machine will be equal to $\delta_{generator} = 35,356^\circ$ [deg]. Since both the internal induced voltage and the voltage of the stator terminals of the synchronous machine are equal in magnitude, as shown by the red dashed arc in figure 3.6 it is known that the PM-machine operates under-excited, thus with a current I leading the stator terminal voltage V_ϕ . Figure 3.6 can further be used to derive the rest of the missing angles and parameters.

The d- and q-axis components of the armature current is found from figure 3.6, and are expressed in equations (3.14) and (3.15) with real value parameters (not per-unit).

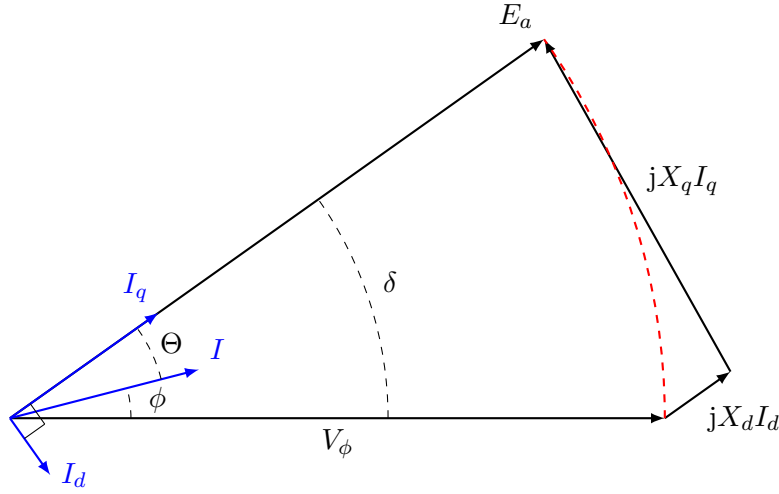


Figure 3.6.: Salient pole synchronous generator operational diagram

The total armature current is calculated in equation (3.16). The values inserted in these equations are rms-values, and all answers needs to be multiplied with $\sqrt{2}$ to get the peak-values. The total peak current is calculated in equation (3.17).

$$|I_q| = \frac{V_\phi \sin \delta}{X_q} = \frac{\frac{6600}{\sqrt{3}} \cdot \sin(35,356^\circ)}{1,74} = 1265,48 \text{ A} \quad (3.14)$$

$$|I_d| = \frac{E_a - V_\phi \cos \delta}{X_d} = \frac{\frac{6600}{\sqrt{3}} - \frac{6600}{\sqrt{3}} \cdot \sin(35,356^\circ)}{1,45} = 484,00 \text{ A} \quad (3.15)$$

$$|I| = \sqrt{I_q^2 + I_d^2} = \sqrt{1265,48^2 + 484,00^2} = 1354,88 \text{ A} \quad (3.16)$$

$$|I_{peak}| = |I| \cdot \sqrt{2} = 1354,88 \cdot \sqrt{2} = 1913,09 \text{ A} \quad (3.17)$$

The angle theta (Θ) is calculated from the two currents I_q and I_d , as stated in equation (3.18).

$$\Theta = \arctan\left(\frac{I_d}{I_q}\right) = \arctan\left(\frac{484,00}{1265,48}\right) = 20,930^\circ [\text{deg}] \quad (3.18)$$

The angle ϕ is then calculated in equation (3.19).

$$\phi = \delta - \Theta = 35,356 - 20,930 = 14,426^\circ [\text{deg}] \quad (3.19)$$

When these considerations have been made the initial conditions can be inserted for the built-in PM block. The initial rotational speed in rad/s is the same speed as the nominal rotational rotor-speed in radians per second, as calculated in equation (3.20).

$$\omega_r = \left(\frac{120f}{p}\right) \left(\frac{2\pi}{60}\right) = \left(\frac{120 \cdot 50}{12}\right) \left(\frac{2\pi}{60}\right) = 52,36 \text{ rad/s} \quad (3.20)$$

The mechanical angle "thetam" shall be inserted in degrees. By using the considerations in section 2.2 and in figure 2.5 it is seen that the rotor lags the phase A axis by 90° degrees when the phase A voltage is zero. This electrical angle needs to be translated to the corresponding mechanical angle before inserting it in the simulation block. The relationship between mechanical and electrical angles in the synchronous machine relates on the number of pole-pairs in the synchronous machine rotor as explained in equation (2.1), and are calculated in equation (3.21).

$$\gamma_{mdeg} = \gamma_{deg} \frac{2}{p} = -90^\circ \cdot \frac{2}{12} = -15^\circ [\text{deg}] \quad (3.21)$$

The last two initial condition parameters to be inserted for the built-in PM block is the two instantaneous (peak-value) stator currents in the A- and B-phase in amperes. By using the angle Θ from equation (3.18) which is the angle that each phase current lags each of the internal induced phase-voltage, and the amplitude peak current I_{peak} calculated in equation (3.17), it is possible to calculate each of the initial phase currents instantaneous value. Equations to calculate the initial phase currents are shown in equations (3.22) to (3.24).

$$i_{ag} = |I_{peak}| \cdot \sin(-\Theta) = 1913,09 \cdot \sin(-20,930^\circ) = -684,48 \text{ A} \quad (3.22)$$

$$i_{bg} = |I_{peak}| \cdot \sin(-\Theta - 120^\circ) = 1913,09 \cdot \sin(-20,930^\circ - 120^\circ) = -1207,65 \text{ A} \quad (3.23)$$

$$i_{cg} = |I_{peak}| \cdot \sin(-\Theta + 120^\circ) = 1913,09 \cdot \sin(-20,930^\circ + 120^\circ) = 1892,13 \text{ A} \quad (3.24)$$

By this all the four initial conditions for the built-in PM simulation block are defined, and the block is ready for the simulations.

Synchronous machine block with constant field current

For the synchronous machine block with constant field current there are nine different initial condition parameters that have to be defined to ensure an as smooth as possible start of the simulations. The first parameter is the initial speed deviation of the rotor, this speed deviation is wanted to be zero during start-up of this simulation. The next initial condition is the electrical angle of the rotor at the initial time of the simulation. By using the considerations in section 2.2, this angle is set to -90° degrees.

The next six initial condition parameters are the three different phase currents in per-unit, in the moment of initialization, and each phase-currents corresponding phase angle in degrees. To calculate these phase-currents in per-unit, the reference values stated for the synchronous machine block in table 3.2 are used together with the current considerations in section 3.3.1 under the "Built-in PM block" part. Angles are defined from section 3.3.1, "Built-in PM block" part. To start with the currents in per-unit, the reference current is calculated in equation (3.25).

$$i_{ref} = \frac{\sqrt{2}P_n}{\sqrt{3}V_n} = \frac{\sqrt{2} \cdot 15 \cdot 10^6}{\sqrt{3} \cdot 6600} = 1855,67 \text{ A} \quad (3.25)$$

The three different instantaneous phase currents in the moment of initialization are calculated in section 3.3.1 under the "Built-in PM block" part, and needs to be divided on the current reference to get the corresponding per-unit value. The three per-unit calculations are done in equations (3.26) to (3.28).

$$i_{apu} = \frac{i_a}{i_{ref}} = \frac{-684,48}{1855,67} = -0,369 \text{ [p.u]} \quad (3.26)$$

$$i_{bpu} = \frac{i_b}{i_{ref}} = \frac{-1207,65}{1855,67} = -0,651 \text{ [p.u]} \quad (3.27)$$

$$i_{c pu} = \frac{i_c}{i_{ref}} = \frac{1892,13}{1855,67} = 1,020 \text{ [p.u]} \quad (3.28)$$

The three different angles for the three different phase-currents are recognized as the angle Θ lagging each phase-induced voltage. The three phase currents are displaced by $\pm 120^\circ$, and at the moment of initialization the phase A induced voltage is assumed being zero. The three different phase-angles are calculated and displayed in equations (3.29) to (3.31).

$$i_{a,angle} = -\Theta = -20,93^\circ \text{ [deg]} \quad (3.29)$$

$$i_{b,angle} = -\Theta - 120^\circ = -20,93^\circ - 120^\circ = -140,93 \text{ [deg]} \quad (3.30)$$

$$i_{c,angle} = -\Theta + 120^\circ = -20,93^\circ + 120^\circ = 99,07^\circ \text{ [deg]} \quad (3.31)$$

The last initial parameter that needs to be defined for the synchronous machine block is the initial field voltage V_f in per-unit, and is set equal to the nominal field voltage at 1,0 p.u.

3.3.2. PM-generator block - Input parameters

Mechanical input

For the generator simulations the mechanical input is configured as "Mechanical rotational port" where the torque is controlled such that the generator operates with constant active power. The torque suppressed the generator is inversely proportional to speed deviations away from the nominal rotational speed, and the speed change is only mechanically limited by the generators inertia. The mechanical torque suppressed the generator is calculated after equation (3.32), where P is the mechanical power and ω_r is the rotational speed of the generator shaft.

$$\tau = \frac{P}{\omega_r} \text{ [Nm]} \quad (3.32)$$

Synchronous machine block with constant field current

For the synchronous machine block with constant field current there is one more input parameter defined. This is the field voltage V_f , and this input parameter is controlled with the same PID-control that were used in the project done in advance of this thesis [13]. This auto-tuned PID-controller is parametrized to ensure a constant field current equal to 1 p.u in the synchronous generator, and such ensure that the synchronous machine operates as a PM-machine. The PID-controller parameters are summarized in table 3.3.

Parameter	Quantity
P - proportional	1,3185
I - integral	117,4006
D - derivative	-0,0052
N - filter coefficient	253,6981

Table 3.3.: Regulator parameters

3.3.3. Grid connection block

Three phase grid simulation block

The grid connection in simulation case 1 is done with the "Three-Phase Programmable Voltage Source" displayed in figure 3.7. This programmable voltage source is used since simulation case 1 needs the ability to adjust the grid voltage magnitude during the simulations, thus the fault-sequence in this study case can be modeled with the grid block.

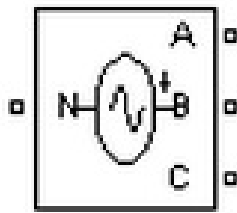


Figure 3.7.: Three phase grid block

The grid block has three different parameters set regarding to the grid-specific behavior. This is the voltage amplitude (phase to phase), the voltage phase-shift and the grid frequency. These three parameters and their values are given in table 3.4. The phase-shift of the grid voltage is recognized as the negative power angle δ calculated in section 3.3.1.

Voltage (V_{rms} peak-peak)	6600	[V]
Phaseshift	-35.356	[deg]
Frequency	50	[Hz]

Table 3.4.: Parameters for grid simulation block

Per-phase grid simulation block

For the simulation cases 2 and 3 on the PM-generator circuits the fault-sequence requires the ability to change both grid voltage and -frequency at the same time for simulation case 2, and a linear change in grid voltage for simulation case 3. These simulations are unable to be met with the same grid simulation block that is used in simulation case 1. Therefore the per-phase "Controlled Voltage Source" is used. This voltage source converts its input signal to an equivalent voltage source, where the generated voltage is driven by the input signal of the block. The simulation block is shown in figure 3.8. This means that the fault-sequence in these two simulation cases are included in the grid simulation block.

The grid voltage and frequency sequence for simulation case 2 is shown in figure B.1, and the input signal circuit for the per-phase controllable voltage source is attached in appendix A.1. For simulation case 3, the input signal circuit for the per-phase controllable voltage source is attached in appendix section A.2.

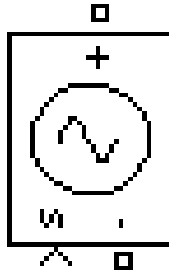


Figure 3.8.: Per-phase grid simulation block

3.4. Model development - motor operation

3.4.1. PM-motor block - Initial simulation values

Built-in PM block

By using the same considerations that are used in section 3.3.1 for the Built-in PM block, the power angle is found equal to $\delta_{motor} = -35,356^\circ$. The power angle found for motor operation has the same size as the power angle for generator operation, but with the opposite sign. This is reasonable since the active power is the only parameter that has changed, with opposite sign.

The three absolute value currents I_d, I_q and I does also have the same magnitude as in section 3.3.1 since all the factors still have the same size, and are summarized in table 3.5. However all of these motor currents have different angles than for the generator situation.

$ I_d $	484,00	[A]
$ I_q $	1265,48	[A]
$ I $	1354,88	[A]
$ I_{peak} $	1916,09	[A]

Table 3.5.: Currents for PM motor case

The operational diagram for a synchronous salient pole motor, with per-phase induced

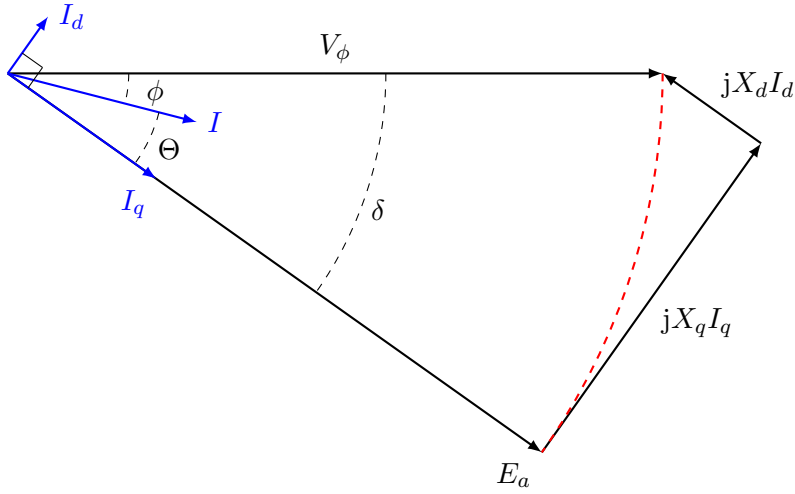


Figure 3.9.: Salient pole synchronous generator operational diagram

voltage E_a and grid voltage V_ϕ that are equal in magnitude, is drawn in figure 3.9. From this figure the motor angle contexts can be derived as shown in equations (3.33) and (3.34).

$$\Theta = \arctan\left(\frac{I_d}{I_q}\right) = \arctan\left(\frac{484,00}{1265,48}\right) = -20,930^\circ \text{ [deg]} \quad (3.33)$$

$$\phi = \delta - \Theta = -35,356^\circ - (-20,930^\circ) = -14,426^\circ \text{ [deg]} \quad (3.34)$$

The initial speed in motor mode of operation is the same rotational speed as in generator operation, equal to 52,35 [rad/s], and the mechanical angle "thetam" is defined in degrees with the same considerations as for generator operation equal to -15 degrees. The two last initial conditions are the phase A, and phase B currents at the initial moment, given in ampere[A]. The three absolute value currents are calculated in equations (3.35) to (3.37).

$$i_{a_m} = |I_{peak}| \cdot \sin(-\Theta) = 1913,09 \cdot \sin(-(-20,930^\circ)) = 684,48 \text{ A} \quad (3.35)$$

$$i_{b_m} = |I_{peak}| \cdot \sin(-\Theta - 120^\circ) = 1913,09 \cdot \sin(-(-20,930^\circ) - 120^\circ) = -1892,13 \text{ A} \quad (3.36)$$

$$i_{c_m} = |I_{peak}| \cdot \sin(-\Theta + 120^\circ) = 1913,09 \cdot \sin(-(-20,930^\circ) + 120^\circ) = 1207,65 \text{ A} \quad (3.37)$$

Synchronous machine block with constant field current

For the synchronous machine block with constant field current the same nine initial condition parameters as for the generator operation needs to be defined to ensure the optimal start-up of the simulations. The initial field voltage is set to 1 p.u, the initial speed deviation to zero, and the electrical angle of the rotor in degrees are set to -90° with the same considerations as for generator operation. The remaining six initial condition parameters are initial phase currents in per-unit, and their corresponding phase in degrees. These currents in per-unit are calculated with the reference current from equation (3.25), and are displayed in equations (3.38) to (3.40).

$$i_{apu} = \frac{i_{am}}{i_{ref}} = \frac{684,48}{1855,67} = 0,369 \text{ [p.u]} \quad (3.38)$$

$$i_{bpu} = \frac{i_{bm}}{i_{ref}} = \frac{-1892,13}{1855,67} = -1,020 \text{ [p.u]} \quad (3.39)$$

$$i_{cpu} = \frac{i_{cm}}{i_{ref}} = \frac{1207,65}{1855,67} = 0,651 \text{ [p.u]} \quad (3.40)$$

All of the per-unit phase currents have their corresponding phase angle, recognized as the positive angle Θ , since the induced voltage in phase A is assumed being zero at the moment of initialization. The three different phase-angles are calculated and displayed in equations (3.41) to (3.43).

$$i_{a,angle} = -\Theta = 20,93^\circ \text{ [deg]} \quad (3.41)$$

$$i_{b,angle} = -\Theta - 120^\circ = 20,93^\circ - 120^\circ = -99,07 \text{ [deg]} \quad (3.42)$$

$$i_{c,angle} = -\Theta + 120^\circ = 20,93^\circ + 120^\circ = 140,93^\circ \text{ [deg]} \quad (3.43)$$

3.4.2. PM-motor block - Input parameters**Mechanical input**

For the PM-motor circuits the mechanical input is configured as "mechanical rotational port" as the input parameter. This mechanical input is chosen since it is the only common input parameter for the two different motor simulation blocks. The mechanical input is controlled such that the PM-motor is operating with a torque that changes with the square of the rotational speed times a constant, as a typical pump torque. At nominal

rotational speed, the motor draws the nominal active power from the grid. The torque characteristic is calculated in equation (3.44).

$$\tau_n = k\omega_n^2 \quad k = \frac{\tau_n}{\omega_n^2} = \frac{P_n}{\omega_n^3} = \frac{15 \cdot 10^6}{\left(\frac{500 \cdot 2 \cdot \pi}{60}\right)^3} = 104,5 \left[\frac{Nm \cdot s^2}{rad^2} \right] \quad (3.44)$$

This gives the following torque characteristic as a function of rotational speed, as shown in figure 3.10. Where the nominal operational point is marked at nominal rotational speed of 500 rpm and torque equal to 286478 Nm.

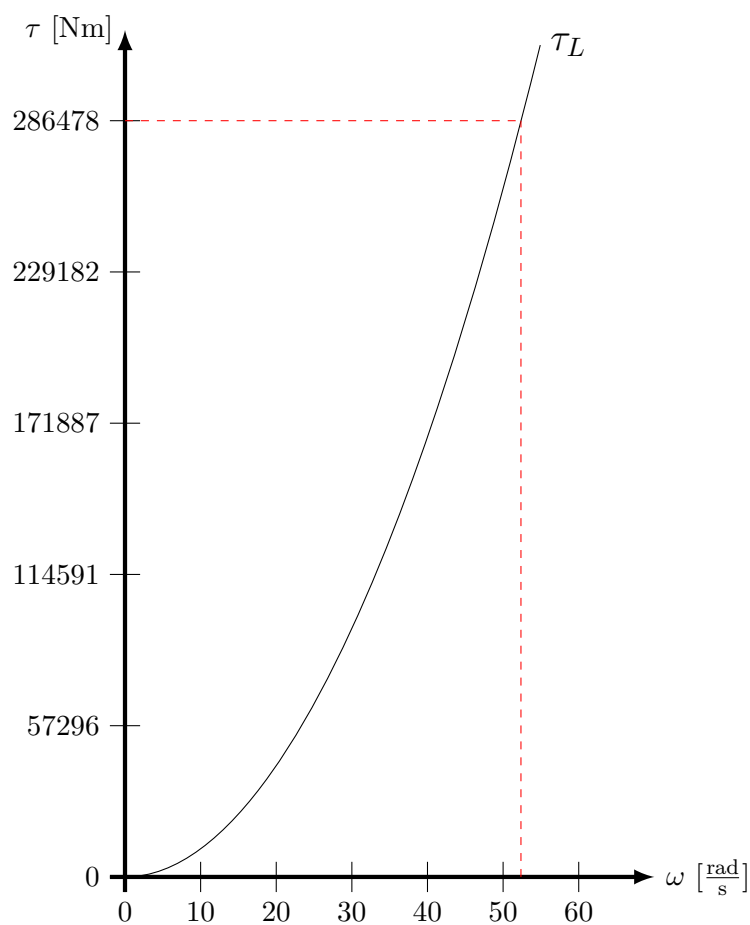


Figure 3.10.: Simulation case 4 - Torque characteristic

Synchronous machine block with constant field current

For the PM-motor block with constant field-current there is one more input parameter. This input parameter is the field voltage V_f . The field voltage input is set to a constant value of 1 p.u, thus the PM-motor neither use or provide reactive power during no-load.

3.4.3. Grid connection block

The PM-motor simulation case is performed with a constant grid voltage and frequency, and the same grid simulation block as in simulation case 1 is chosen to represent the grid connection of the motor, as presented in section 3.3.3. This grid connection block has three parameters defined when disregarding parameters that change the voltage amplitude during the short circuit fault. These three parameters are summarized in table 3.6. The phase-shift is recognizes as the positive power angle δ_{motor} found in section 3.4.1.

Voltage (V_{rms} peak-peak)	6600	[V]
Phaseshift	35.356	[deg]
Frequency	50	[Hz]

Table 3.6.: Grid parameters for simulation case 4

Simulation

4.1. General

4.1.1. PM-generator simulations

The PM-generator simulations contains two different simulation circuits, where three different simulation cases are tested on both of the simulation circuits. The two test circuits are built up equal, except from the PM-generator block. The first simulation circuit is built up with the synchronous machine block that is configured with constant field current and damper windings, the second simulation circuit is built up with the built-in PM-machine block without damper windings.

The first simulation case performed is a total dip in the grid voltage in a defined time interval. Time intervals tested are between 0,01 to 0,40 seconds, in steps of 0,01 second. The voltage-dip is introduced to the two simulation circuits when the PM-generator block has gained a stable mode of operation after the transient simulation start-up, after 20 seconds of simulation.

The second simulation case is performed to test the permanent magnet simulation blocks against varying grid voltage and frequency. The grid voltages tested are between 1,05 and 0,9 p.u at grid frequencies between 49 and 52 Hz, over a simulation time of 290 seconds. The simulation contains of 15 different operational stages where each operational point has a time duration of 10 seconds.

The third simulation case is built up with basis in figure 2.4, where the simulations are executed on both of the PM-generator circuits. The fault is presented to each of the simulation circuits after 20 seconds of simulation.

4.1.2. PM-motor simulation

The PM-motor simulations are executed on the two different simulation circuits, with one specified fault situation. Both of the test circuits are built up similarly except for the PM-motor simulation blocks. The first simulation circuit is equipped with the synchronous machine block with constant field current and damper windings, the second simulation circuit is built up with the PM-machine block without damper windings. The simulation case tested regards how long a full short circuit between all phases and earth on the motor terminals can be present before the PM-motor is unable to achieve its synchronous speed defined by the corresponding grid after the fault. The fault is presented to the circuits after 10 seconds of simulations, when the transient start-up of the simulations has faded out.

4.2. Simulation results PM-generator, simulation case 1

The simulation results from simulation case 1 are displayed in tables 4.1 and 4.2. For each of the fault times the resulting mode of operation of the corresponding generator is denoted either *stable* or *unstable*.

4.2.1. Stability studies generator operation

For a deeper understanding of simulation case 1, two new parameters at the fault time of 0,15 seconds are studied. This is the rate of rise of the speed increase during the fault, and the time from the fault is cleared to the first speed oscillation that is within 0,2 % of the nominal rotational speed. These parameters are studied see which one of the simulation models that are able to regain their stable mode of operation fastest after the given fault situation. The results are presented in table 4.3

This results in the rate of rise for the fault period shows that the permanent magnet generator model with damper windings has a slower speed increase during short circuit than the generator model without damper windings. This means that the speed deviation from nominal speed increases faster for the model without damper windings than with, and this difference in speed deviation for the same fault time gives the permanent magnet generator block with damper windings a better basis for regaining its stable mode of operation after the fault is disconnected. The theory behind this result is presented in section 2.6.

After the grid is reconnected the model with damper windings has a much faster and effective return to nominal speed. The damping effect of the damper windings contribute to this, and the effect is presented in section 2.7.

Time	stable/unstable	Time	stable/unstable
0,01	stable	0,21	stable
0,02	stable	0,22	stable
0,03	stable	0,23	stable
0,04	stable	0,24	stable
0,05	stable	0,25	stable
0,06	stable	0,26	stable
0,07	stable	0,27	stable
0,08	stable	0,28	unstable
0,09	stable	0,29	unstable
0,10	stable	0,30	unstable
0,11	stable	0,31	unstable
0,12	stable	0,32	unstable
0,13	stable	0,33	unstable
0,14	stable	0,34	unstable
0,15	stable	0,35	unstable
0,16	stable	0,36	unstable
0,17	stable	0,37	unstable
0,18	stable	0,38	unstable
0,19	stable	0,39	unstable
0,20	stable	0,40	unstable

Table 4.1.: Simulation results PM-generator with damper windings, case 1

Time	stable/unstable	Time	stable/unstable
0,01	stable	0,21	unstable
0,02	stable	0,22	unstable
0,03	stable	0,23	unstable
0,04	stable	0,24	unstable
0,05	stable	0,25	unstable
0,06	stable	0,26	unstable
0,07	stable	0,27	unstable
0,08	stable	0,28	unstable
0,09	stable	0,29	unstable
0,10	stable	0,30	unstable
0,11	stable	0,31	unstable
0,12	stable	0,32	unstable
0,13	stable	0,33	unstable
0,14	stable	0,34	unstable
0,15	stable	0,35	unstable
0,16	stable	0,36	unstable
0,17	stable	0,37	unstable
0,18	stable	0,38	unstable
0,19	stable	0,39	unstable
0,20	unstable	0,40	unstable

Table 4.2.: Simulation results PM-generator without damper windings, case 1

	Circuit 1 - No damper winding	Circuit 2 - Damper winding
$\frac{d\omega}{dt} \left[\frac{\text{rad}}{\text{s}^2} \right]$	8,467	6,033
$t(\omega_r = \omega_0 \pm 0,2 \%) \text{ [sec]}$	22,370	1,250

Table 4.3.: Magnitudes of rotor speed increase and disturbance time at short circuit on PM-generator

4.3. Simulation results PM-generator, simulation case 2

The simulation results from simulation case 2 on the permanent magnet generators shows that both of the generator circuits are able to remain stable and keep synchronism during the corresponding changes in grid voltage and -frequency.

4.4. Simulation results PM-generator, simulation case 3

The simulation results from simulation case 3 on the permanent magnet generators are displayed in tables 4.4 and 4.5, and are marked with an "s" to indicate that the electrical machine operates stable during the corresponding operating considerations, and an "u" to mark if the electrical machine is unable to operate stable at the current operating condition. To meet the requirements from FIKS [15], the two different PM-generator circuits shall remain stable for the situation with a voltage-drop of 0,85 p.u together with a minimum voltage level duration of 400 milliseconds.

		Time [milliseconds]				
		400	300	200	100	0
Voltage drop [p.u]	0,85	u	u	u	u	s
	0,80	u	u	u	u	s
	0,75	u	u	u	u	s
	0,70	u	u	u	u	s
	0,65	u	u	u	s	s
	0,60	u	u	s	s	s
	0,55	u	u	s	s	s
	0,50	s	s	s	s	s
	0,45	s	s	s	s	s
	0,40	s	s	s	s	s
0,35	s	s	s	s	s	

Table 4.4.: Simulation results PM-generator with damper windings, case 3

4.4.1. Stability borders

From the simulation results shown in tables 4.4 and 4.5 it is able to sketch a figure to illustrate the stability borders for the two different permanent magnet generator circuits, with respect to the two different parameters *Voltage drop* and *Time*. The sketched stability borders are shown in figure 4.1, where the blue area represents the stable operational area for the built-in PM-generator block without damper windings, and the red area together with the blue area represents the stable operational area for the synchronous machine block with constant field current, the simulation block with

		Time [milliseconds]				
		400	300	200	100	0
Voltage drop [p.u]	0,85	u	u	u	u	u
	0,80	u	u	u	u	u
	0,75	u	u	u	u	u
	0,70	u	u	u	u	s
	0,65	u	u	u	u	s
	0,60	u	u	u	u	s
	0,55	u	u	u	s	s
	0,50	u	u	s	s	s
	0,45	s	s	s	s	s
	0,40	s	s	s	s	s
	0,35	s	s	s	s	s

Table 4.5.: Simulation results PM-generator with damper windings, case 3

damper windings. The white area represents the operational area where both of the PM-generator blocks are unable to achieve stable operation during and/or after the fault situation.

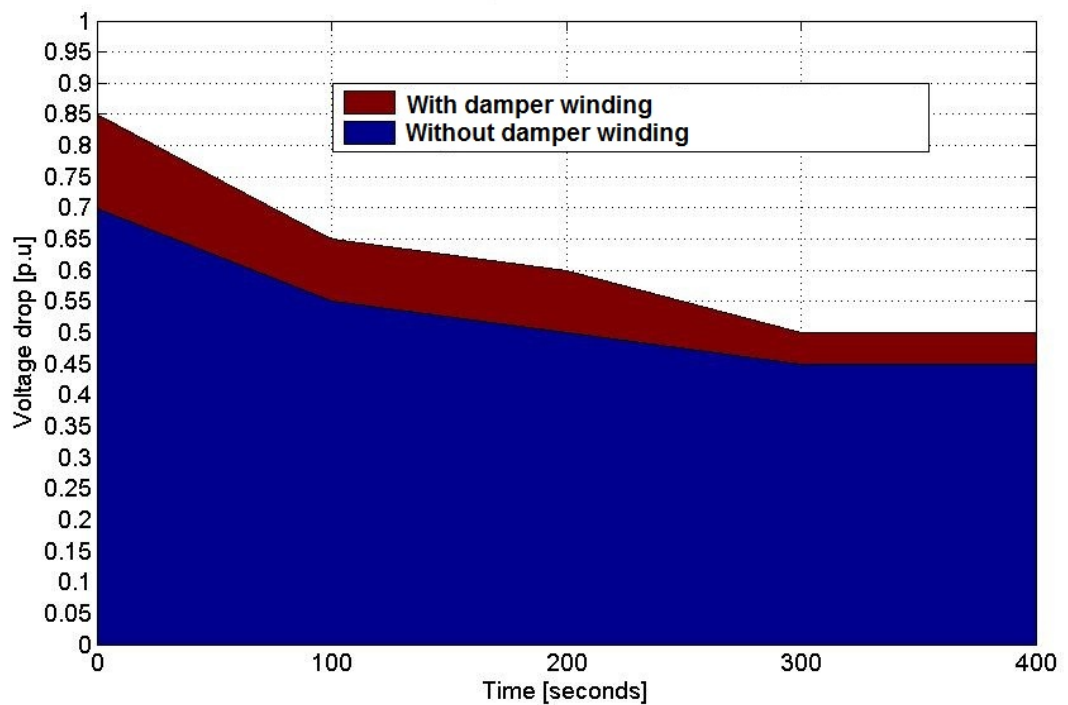


Figure 4.1.: Stability borders simulation case 3

4.5. Simulation results PM-motor

The simulation results from simulation case 4 on the permanent magnet motor circuits are displayed in tables 4.6 and 4.7. Each of the short circuit durations are marked either *stable* or *unstable* to show whether or not the corresponding simulation results in the motor having a stable or unstable mode of operation after the fault.

Time	stable/unstable	Time	stable/unstable
0,01	stable	0,11	stable
0,02	stable	0,12	stable
0,03	stable	0,13	stable
0,04	stable	0,14	stable
0,05	stable	0,15	unstable
0,06	stable	0,16	unstable
0,07	stable	0,17	unstable
0,08	stable	0,18	unstable
0,09	stable	0,19	unstable
0,10	stable	0,20	unstable

Table 4.6.: Simulation results PM-motor with damper windings

Time	stable/unstable	Time	stable/unstable
0,01	stable	0,11	stable
0,02	stable	0,12	stable
0,03	stable	0,13	stable
0,04	stable	0,14	stable
0,05	stable	0,15	stable
0,06	stable	0,16	stable
0,07	stable	0,17	stable
0,08	stable	0,18	unstable
0,09	stable	0,19	unstable
0,10	stable	0,20	unstable

Table 4.7.: Simulation results PM-generator without damper windings

4.5.1. Stability studies motor operation

The simulations results in the motor-mode of operation gives a surprising result, that the permanent magnet motor model with damper windings withstands a shorter duration of the short circuit than the PM-motor model without damper windings. This result needs to be investigated further, and at a fault duration of 0,12 seconds, the rate of rise of the speed decrease during the fault is found from simulations for the two simulation

models. The time from the fault is cleared to the first speed oscillation that is within 0,2 % of the nominal rotational speed is also measured, to see which one of the simulation models that are able to regain their stable mode of operation fastest after the given fault situation. The results are presented in table 4.8

	Circuit 1 - No damper winding	Circuit 2 - Damper winding
$\frac{d\omega}{dt} \left[\frac{\text{rad}}{\text{s}^2} \right]$	-9,167	-12,333
$t(\omega_r = \omega_0 \pm 0,2 \%) \text{ [sec]}$	15,305	1,705

Table 4.8.: Magnitudes of rotor speed decrease and disturbance time at short circuit on PM-motor

This results in the rate of rise for the speed decaying period, shows that the permanent magnet motor model with damper windings has a steeper speed decrease during short circuit than the motor model without damper windings. This means that the speed deviation from nominal speed increases faster for the model with damper windings than without, and this difference in speed deviation for the same fault time makes the permanent magnet motor block without damper windings able to withstand larger fault times than the model with damper windings. The theory behind this result is presented in section 2.6.

After the grid is reconnected the model with damper windings has a much faster and effective return to nominal speed. The damping effect of the damper windings contribute to this, and the effect is presented in section 2.7.

Discussion

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

Mechanical input in generator operation

The selection of mechanical input in the generator simulations were chosen as torque, with the generators operating as constant power machines. The torque to the generators were controlled as shown in equation (3.32). This choice does not take the time constants to any regulatory or water-way system into account, when adjusting the torque to the generator, and the generator speed changes are only limited by the machine inertia. This was a simplification in this thesis, but since the machine inertia and the mechanical is the same for both simulation models, this simplification is considered sufficient for the simulations executed.

Simulation cases

The simulation cases executed have focused on fault situations and requirements that a small scale pumped hydro power plant may experience, and which are considered interesting and relevant to examine when studying the effect of damper windings during and after a short circuit fault. A full short circuit at the synchronous machine terminals is considered as an uncomplicated way of investigating the effect of damper windings, and lays the basis for two of the simulation cases. The last two simulation cases has its background from FIKS. The simulation cases are selected by the student in dialog with Professor Arne Nysveen. Other procedures could have been chosen to meet the problem description, but the selection of the four simulation cases are considered to give a good representation of the investigated problems.

Simulation models

All of the simulations are executed with the electrical machine simulation block and the grid block, without any elements between these two, as transmission lines or transformers. This leads to a very tough and demanding test condition for the electrical machine, since passive elements between the electrical machine and the fault will lead to damping, and thus a reduced stress during the fault. This means that the simulation models are tested for the worst-case scenario, and that if more elements had been included in the simulation model, the possibilities are present that the simulation results for the simulation cases could have been more promising.

Simulation case 2

For simulation case 2 does both of the simulation circuits remain in a stable mode of operation during the changes in frequency and voltage. The scope of this simulation case can be discussed in the manner that it is not expanded or further developed when it became evident that both of the circuits were able to withstand the suppressed conditions. On the other hand the simulation case shows that the two simulations circuits are able to meet the corresponding simulation case requirements, which were intended to investigate in this simulation case.

Start-up procedure in motor operation

The start-up procedure of a permanent magnet synchronous motor was originally intended executed, but this simulation case was excluded in the favor of the short-circuit simulation in motor operation. This change was done in collaboration with Professor Arne Nysveen, when the focus of the thesis was directed against faults and damper winding contributions. Ideally should all operational modes of a technological innovation be simulated, but in this thesis, with its limitations, the choice of operational modes became the two steady-state modes, generator and motor operation.

Simulation results

The simulation results are considered good with respect to the theoretical and physical justifications that are done. The results show that the permanent magnet machines have a more stable mode of operation during transient when equipped with damper windings, and that damper windings is an advantage during short circuit faults on a generator and a disadvantage during short circuit in motor operation.

If a small scale pumped hydro power plant equipped with a permanent magnet machine is planned built, a deeper analysis of the system is recommended both at steady state and during fault situations.

Simulation blocks

Permanent magnet machine blocks

The use of the permanent magnet machine block established in the project work done ahead of this master thesis [13], and the permanent magnet machine block included in the MSPS Specialized technology library [1] are used and compared against each other without ensuring that these simulation blocks have the same basic fundamental behavior that is assumed. Since these two machine models represents two different physical machines, an adequate comparison through simulation has not been possible to obtain, and a theoretical comparison off the simulation block equations has not been done. The machines have used the same machine parameters that were used in the project ahead of this master thesis, except from the inertia constant H , which was changed from 4 to 3 seconds, after input from supervisor Ivar Vikan [4]. A inertia constant of 3 seconds is more realistic for this machine size. These considerations make room for discussion and is a factor for further work.

Application of simulation results

If large permanent magnet motors or generators are supposed to be installed at either on- or offshore industry, these simulation results can be applied in the early planning. The results sets focus on the effect by damper windings after disturbances in motor and generator operation, together with the positive effect by damper windings during a three phase short circuit on a synchronous generator and the negative effect of damper windings during a three phase short circuit on a synchronous motor. The results will also apply for traditional synchronous machines with wound rotor. At a more detailed project processes, a more comprehensive analysis after specific demands are recommended to get a complete overview of all challenges. The level of detail in this thesis can be discussed, but is considered sufficient with respect to answering to the problem description.

It is pointed out a set of different possible topics for further work in both specialization projects and master thesis work, which is regarded as a useful part of this master thesis, for the department at the university.

Conclusion

This master thesis has modeled and evaluated two simulation circuits of permanent magnet electrical machines, envisioned as parts of small scale pumped hydro power plants. The two simulation circuits are considered equal except that one of them contains rotor damper windings and the other simulation circuit lack them. The difference in the two simulation circuits play a role in the simulation blocks behavior during and after a fault. The simulations executed are three simulation cases in generator operation and one in motor operation, for both of the simulation circuits.

For simulation case 1 and 3 does the simulations show that the permanent magnet machines with damper windings are able to withstand larger disturbances and longer fault durations than the machine without damper windings. This is mainly explained by the speed reducing torque acting during a fault, and the damper windings effect at small disturbances.

To meet the requirements from FIKS [15], the two different PM-machine blocks shall remain stable during all the tested conditions in simulation case 2. The simulations results in this case show that both of the simulation circuits meets the corresponding requirements and operates in synchronism with the grid during the simulated fault sequence.

For a short circuit on the terminals in motor operation the opposite operational conditions are obtained at nominal loading than for simulation case 1. The motor keeps synchronized with the grid for a longer short circuit duration at the configuration without damper windings than the configuration with. This result is explained such that the damping torque during fault in motor operation decreases the rotational speed faster for a motor with damper windings than without, and thus the speed deviation for a given fault duration is larger for the motor with damper windings. The larger speed deviation for a given fault duration leads to that the motor with damper windings can handle a shorter fault time duration than the motor without dampers.

The main conclusion regarding damper windings at a short circuit can be divided into

two parts. The first part is the damper windings contribution during the short circuit fault. From the short-circuit simulations executed in this thesis it is clear that the damper windings contribute with a speed-reducing torque at short circuit, both for motor and generator operation. This speed reducing torque is an advantage for generator operation, because the speed deviation that occur under the fault is reduced by the damper windings, and the speed increase gets a reduced rate of rise during the fault time. In motor operation the speed reducing torque provided by the damper windings is a disadvantage, since the rate of the speed decrease during the fault time is further decreased, and the speed deviation during the fault time is getting even larger than the motor would had experienced without damper windings. The second part of the damper windings effect during a short circuit is the damper windings contribution after the fault is cleared. At this situation the damper windings contribute with torque that are "active" at rotational speeds which differ from nominal rotational speed. This positive effect by the damper windings is acting the same way both in motor and generator operation, and is considered as the main advantage for having installed damper windings in synchronous motors and generators. The damper windings effect is proposed as a separate topic for further work in chapter 7.

Recommendation for further work

- Establish and carry out adequate simulations that can test and validate that the two permanent magnet synchronous machine blocks operate equal during stable conditions. Further the test and validation can be executed theoretically, by exploring the equations describing each of the simulation blocks.
- In simulation case 2 both of the simulation circuits are able to operate in synchronism with the grid during the fault sequence. This result does not state any specific operational difference between the two simulation circuits, and the simulation case has potential for expansion to investigate the operational differences for the two simulation cases during minor voltage and -frequency variations further.
- Compare the two developed simulation circuits with actual systems or laboratory setups for tests and verification of simulation models and simulations results validity.
- The motor simulation case gives room for further work and deeper analysis and evaluation. Different industrial sectors both onshore and offshore uses large electrical motors, where their operational performance during faults are important aspects to familiarize with. The importance of behavior during failure is strongly dependent on the operational criterias for the given motor operation. Due to the limitations in this master thesis, the scope of the motor part is limited to one simulation case, but the work with this part of the thesis has gained an even deeper interest by the student than predicted before the work with the thesis started. Different suggestions for further study of motor operation are listed below.
 - Investigate the differences in behaviors for a electric motor during a short circuit and a disconnection from the grid
 - Define and evaluate in details the different factors that determines the speed decrease during both a short circuit and a disconnection of an electrical motor under operation

- Investigate and evaluate the load torques influence on a fault situation on an electrical motor
- Investigate and evaluate the current during a fault on an electrical motor.
- Explore in detail the damper windings effect for motor and generator operation, at steady state and during fault situations. The damper windings effect during nominal conditions seems well discussed in the literature, but the effect during fault does not seem as well documented and handled.
- Investigate the unidirectional and oscillatory components of torque acting on a synchronous machine during short circuit, both for motor and generator mode of operation.
- Include time constants related to control systems and water-way in the mechanical input circuit in generator mode of operation. The torque-characteristics in motor mode of operation can also be developed further, to get a more realistic and advances torque modeling.

Bibliography

- [1] Mathworks, simulink, permanent magnet synchronous machine. <http://se.mathworks.com/help/physmod/sps/powersys/ref/permanentmagnetsynchronousmachine.html>.
- [2] Mathworks, simulink, synchronous machine. <http://se.mathworks.com/help/releases/R2014a/physmod/sps/powersys/ref/synchronousmachine/>.
- [3] Project relevant information, data sheets and figures. From the professor Arne Nysveen, NTNU.
- [4] Project relevant information, data sheets and figures. From the supervisor of the project in Voith Hydro AS , Trondheim.
- [5] Stephen Chapman. *Electric machinery fundamentals*. Tata McGraw-Hill Education, 5 edition, 2012.
- [6] Ronald G Harley and B Adkins. Calculation of the angular back swing following a short circuit of aloaded alternator. *Electrical Engineers, Proceedings of the Institution of*, 117(2):377–386, 1970.
- [7] Prabha Kundur, Neal J Balu, and Mark G Lauby. *Power system stability and control*, volume 7. McGraw-hill New York, 1994.
- [8] Jan Machowski, Janusz Bialek, and Jim Bumby. *Power system dynamics: stability and control*. John Wiley & Sons, 2 edition, 2011.
- [9] DB Mehta and B Adkins. Transient torque and load angle of a synchronous generator following several types of system disturbance. *Proceedings of the IEE-Part A: Power Engineering*, 107(31):61–74, 1960.
- [10] NEK. *Norwegian electrotechnical standard. Rotating electrical machines, part 1, rating and performance*. NEK, 2010 edition.
- [11] Donald Reimert. *Protective relaying for power generation systems*. CRC press, 2005.
- [12] G Shackshaft. Effect of oscillatory torques on the movement of generator rotors. In *Proceedings of the Institution of Electrical Engineers*, volume 117, pages 1969–1974. IET, 1970.
- [13] Lornts Mikal Sklett. Pump storage design - permanent magnet generator, 2014.

BIBLIOGRAPHY

- [14] IEEE Power Engineering Society. *IEEE Standard for Salient-Pole 50 Hz and 60 Hz Synchronous Generators and Generator/Motors for Hydraulic Turbine Applications Rated 5 MVA and Above*. IEEE, 2005 edition.
- [15] Norwegian TSO Statnett. Funksjonskrav i kraftsystemet. <http://www.statnett.no/Global/Dokumenter/Kraftsystemet/Systemansvar/FIKS%202012.pdf>, 2012.

Appendices

Input circuit controllable voltage source

A.1. Simulation case 2

For simulation case 2 the three phase input signal circuit for the per-phase controllable voltage sources is displayed in figure A.1, with each of the per-phase signal outputs in the right of the figure. The insides of the "Frequency modulation" and "Amplitude modulation" blocks are shown in figures A.2 and A.3 respectively.

In figures A.2 and A.3 the changes in frequency and voltage magnitude accordingly are changed as ramp functions over time, and each ramp function is again repealed by an opposing ramp function, after the given time that the ramping is supposed to be active. These pairs of ramp functions can be seen in each of the figures, and in simulation case 2 all of the ramp-changes of voltage magnitude and frequency has a duration of 10 seconds.

The block in top of figure A.2 defines the nominal angular frequency equal to 100π [rad/s]. The top block in figure A.3 defines the nominal phase voltage amplitude equal to 5388,9 [V].

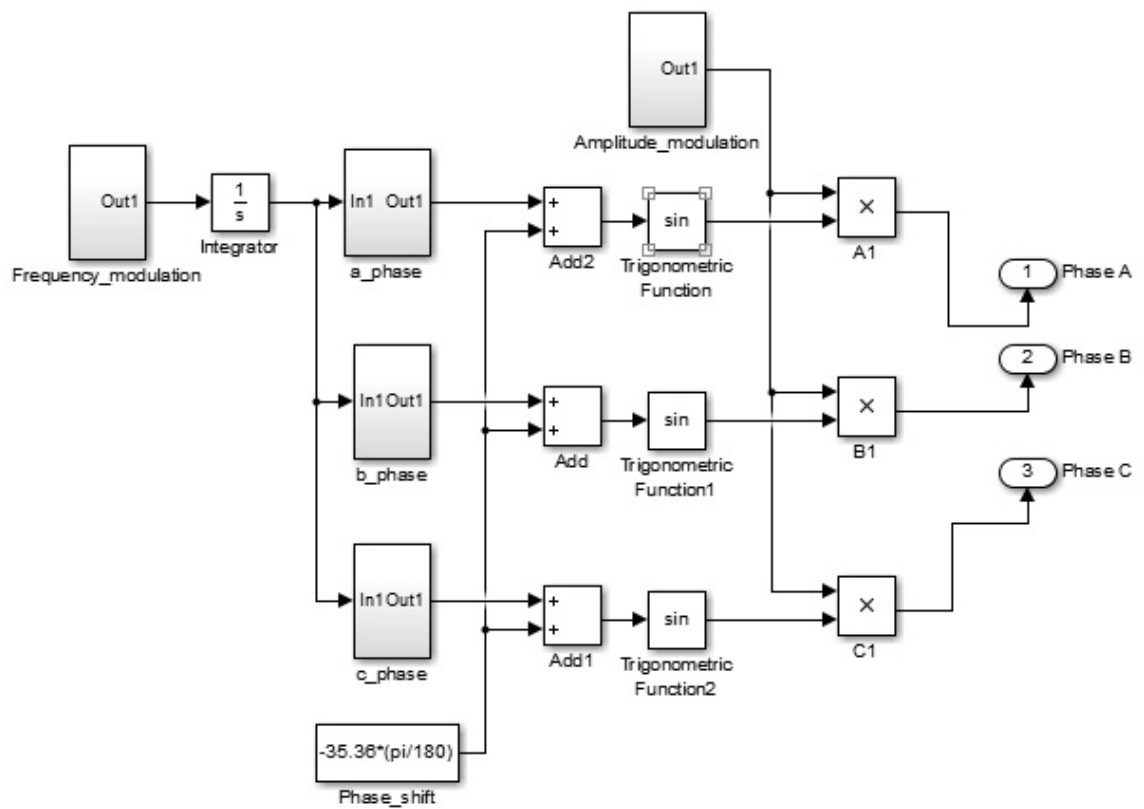


Figure A.1.: Input circuit simulation case 2. Per-phase controllable voltage source

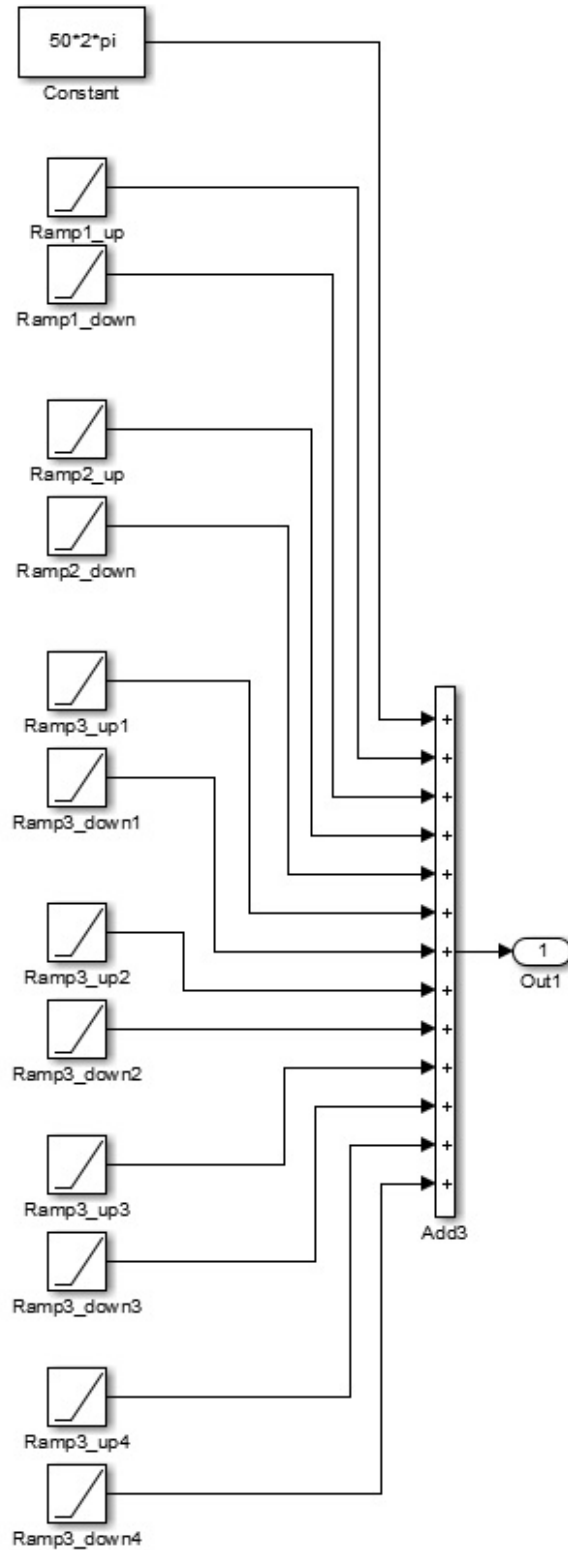


Figure A.2.: Input circuit simulation case 2. Frequency modulation

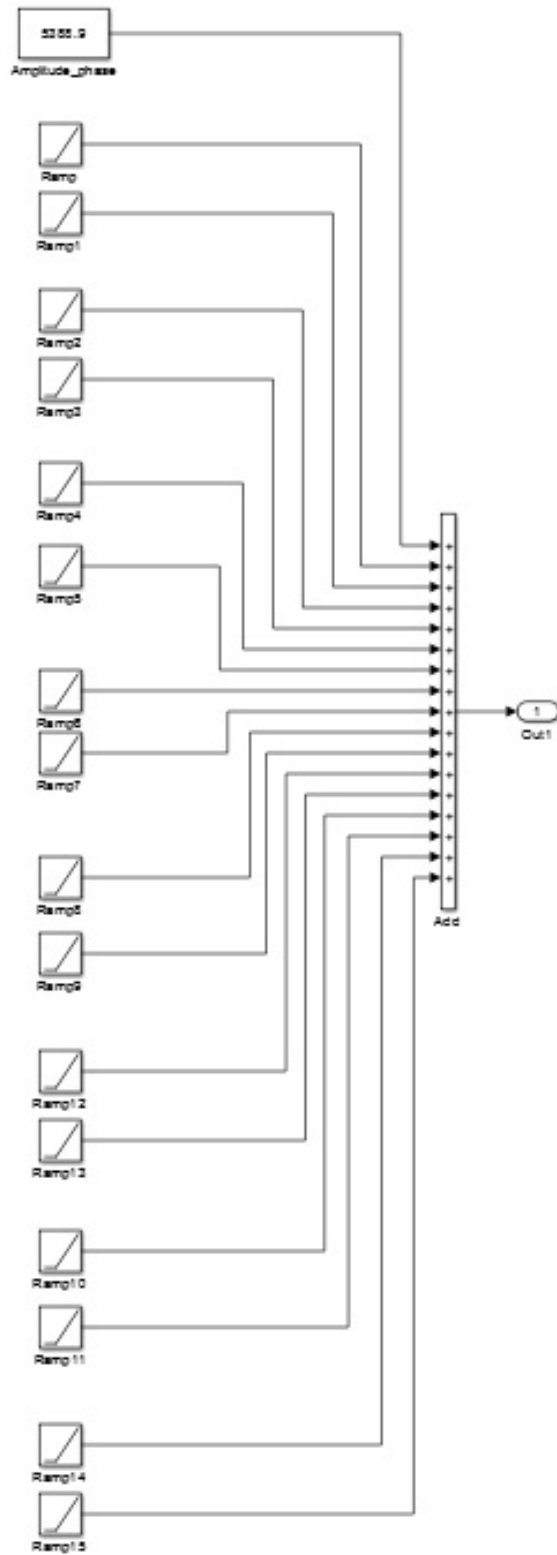


Figure A.3.: Input circuit simulation case 2. Amplitude modulation

A.2. Simulation case 3

In simulation case 3 the input signal circuit is used three times to get the wanted three phase grid system. The phase shift between each of the phases are introduces in each of the three sine-wave blocks. Per-phase input signal circuit shown in figure A.4.

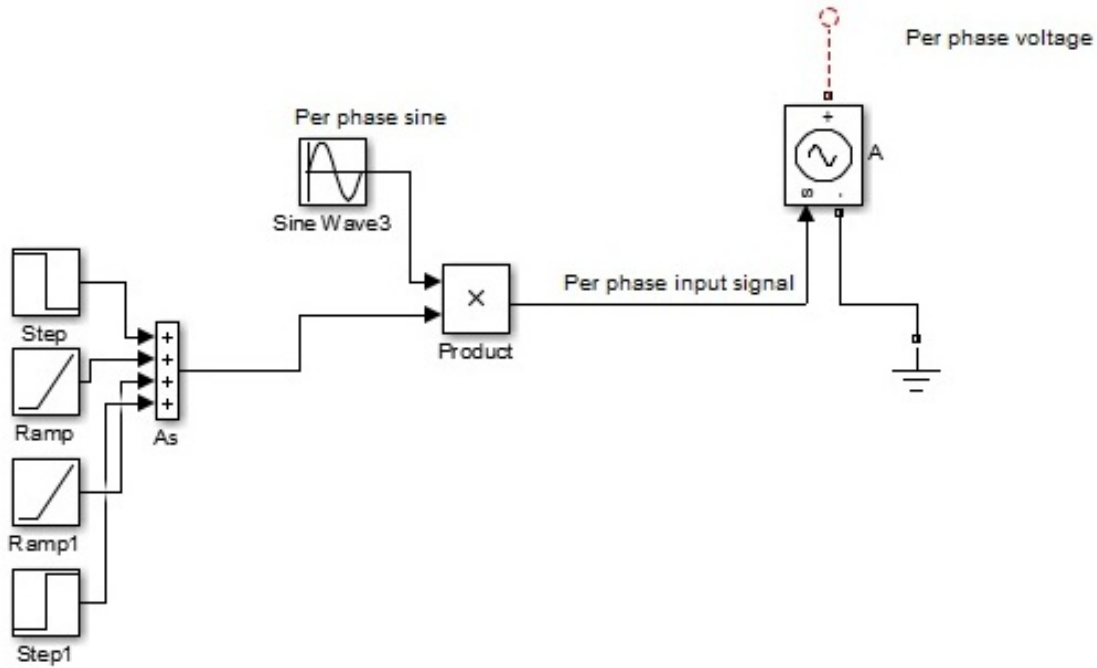


Figure A.4.: Per phase input signal circuit. Simulation case 3

The two parameters that are changed in simulation case 3 *Time* and *Voltage drop* are changed with the step- and ramp blocks on the left side of figure A.4, and the parameters of these blocks are changed according to the wanted specifications. The per-phase sine wave block has constant parameters for each of the three phases, except for the parameter *Phase*, and all these parameters are listed in table A.1.

Per-phase voltage amplitude	$\frac{U_n * \sqrt{2}}{\sqrt{3}} = \frac{6600 * \sqrt{2}}{\sqrt{3}} = 5388,9$	[V]
Frequency	$2 * \pi * f = 100\pi$	[rad/sec]
Phase - Phase A	$-35.356^\circ * (\frac{\pi}{180^\circ}) = -0,617$	[rad]
Phase - Phase B	$(-120^\circ - 35.356^\circ) * (\frac{\pi}{180^\circ}) = -2,711$	[rad]
Phase - Phase C	$(120^\circ - 35.356^\circ) * (\frac{\pi}{180^\circ}) = 1,477$	[rad]

Table A.1.: Parameters for sine grid simulation block phase A

APPENDIX B

Simulation case details

B.1. Simulation case 2 - generator

For simulation case 2 both the voltage magnitude and frequency is changed, but only one parameter at the time. The 15 different operational points are marked with red numbers in figure B.1.

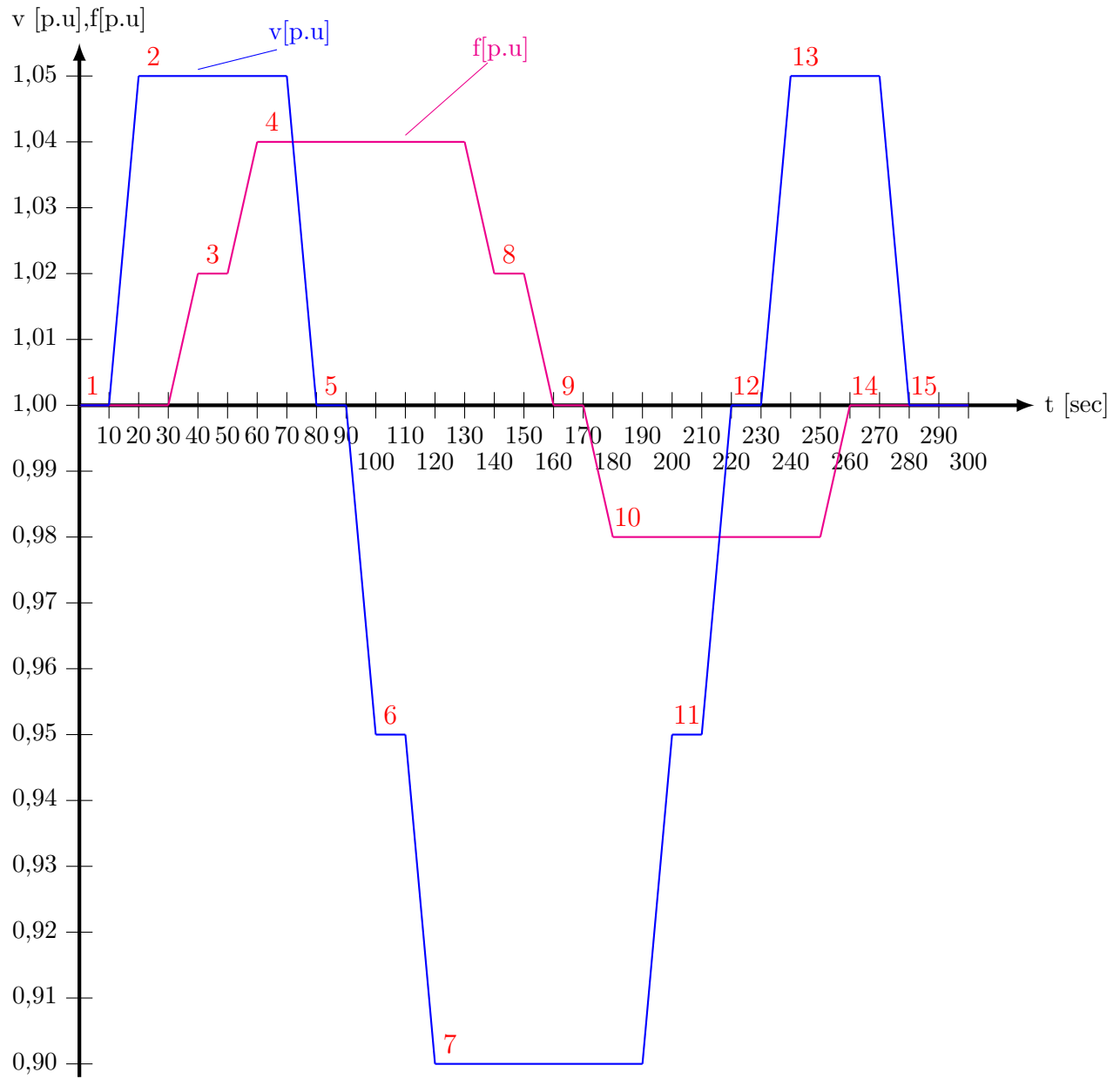


Figure B.1.: Simulation case 2 - Stability during voltage- and frequency variation - simulation case definition 2

B.2. Simulation case 4 - motor

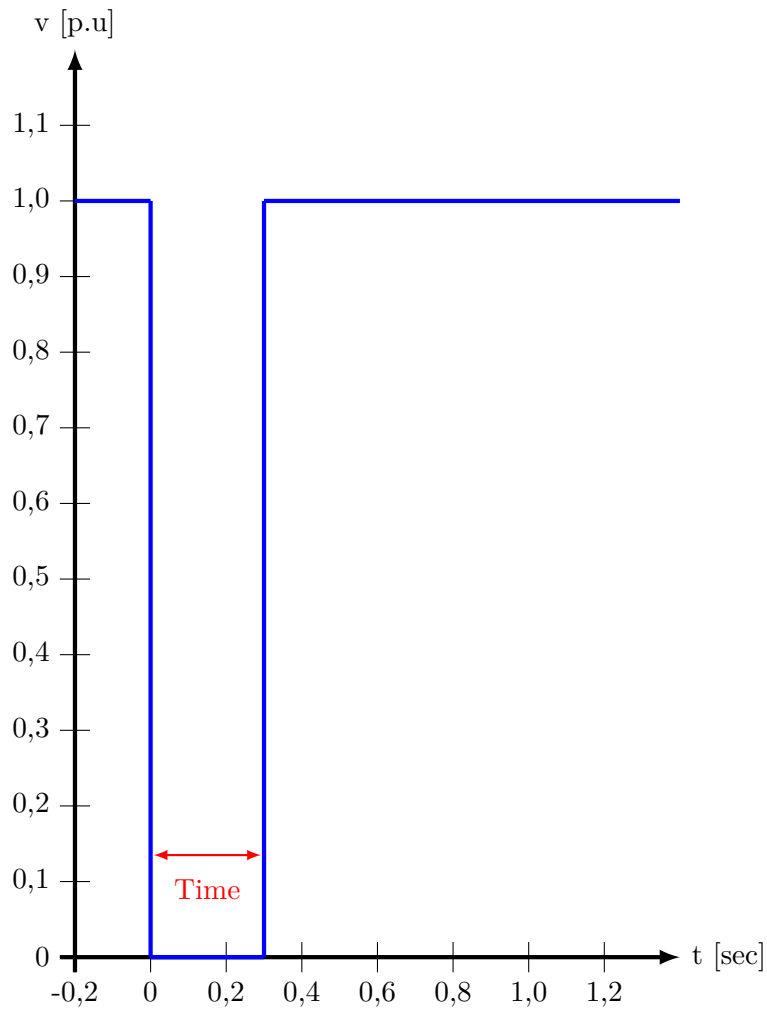


Figure B.2.: Simulation case 4 - Damper winding effect - variable definition

Attached files

Following are the attached files:

Simulation models

- Simulation case 1 - 2 circuits
- Simulation case 2 - 2 circuits
- Simulation case 3 - 2 circuits
- Simulation case 4 - 2 circuits