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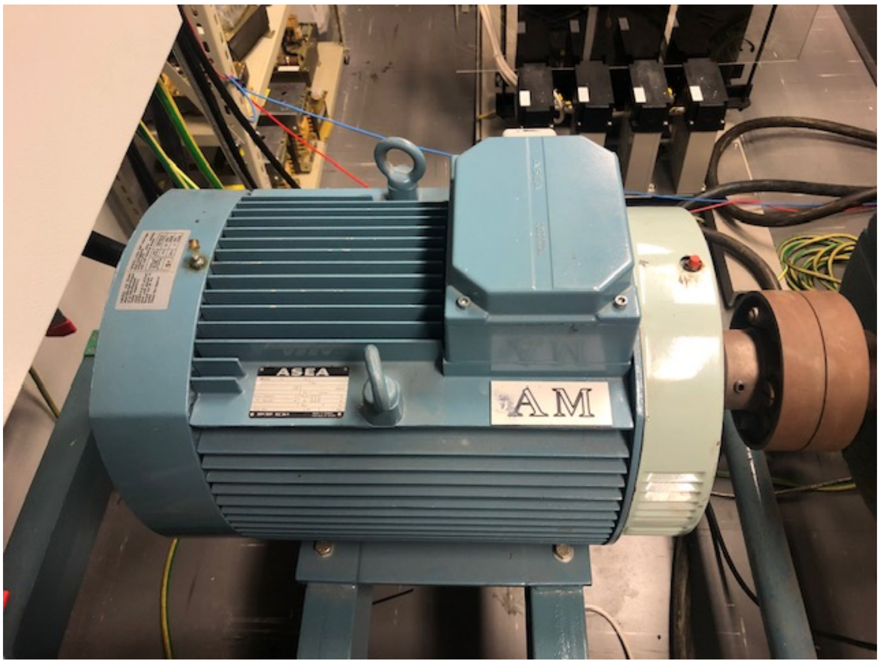

Induction Motor Voltage Dependence

A Chalmers University of Technology Degree Project Report

How the consumption of Active- and Reactive power of 1-phase & 3-phase Induction Motors are affected by voltage dips

Degree project report in Electrical Power Engineering

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DEPARTMENT OF ELECTRICAL POWER ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
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Degree project report 2024

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Cover: The 3-phase induction motor test object, ASEA MBG 180L-4 used in the 3-phase experiments carried out in this degree project.

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Abstract

Today, the electrical grid can be subject to disturbances of various severities where power outages for short durations can be costly, not only economically but societally as well. Since the most common load objects of today's electrical grid are induction machines, it is important to have the knowledge of how they behave in order to either prevent or restore disturbances in the grid as fast as possible. The objective for this degree project is to provide understanding of how voltage dependent the consumption of active- and reactive power are for induction machines during a shortage of voltage for a specified duration of time. To achieve this, data for previous work in the field was analyzed and collected before own experiments were executed in the Chalmers power system laboratory. The experiments consisted of performing voltage dips of various magnitudes and duration times on both single- and three-phase induction machines.

The findings of the project reveal that the active- and reactive power show good linear dependence on the voltage amplitude during step dips for single-phase and unloaded three-phase induction machines. For loaded three-phase induction machines, the active power show less dependence on the voltage, keeping at a stable level around its original value. The reactive power however, show good linear dependence on the voltage for loaded three-phase induction machines, for step dips of up to 70% of light load and step dips of up to 50% of semi-heavy load.

Sammanfattning

Dagens elnät kan bli utsatta för störningar av olika allvarlighetsgrader där korta strömavbrott kan bli kostsamma, inte bara ekonomiskt utan även samhällsmässigt. Asynkronmaskiner är det vanligaste lastobjektet i dagens elnät och därför är det viktigt att skapa och förbättra kunskapen om dem för att kunna förhindra eller reparera en störning i elnätet så fort som möjligt. Målsättningen för detta examensarbete är att skapa förståelse för hur beroende aktiv- och reaktiv effekt är av spänningen när en störning i spänningen sker i form av ett spänningsfall. För att uppnå detta har tidigare arbeten inom liknande områden analyserats och sammanställts i en litteraturstudie, efter det utfördes egna experiment i Chalmers kraftelektroniska laboratorium. Experimenten bestod av att utföra spänningssänkningar av olika storlekar och under olika lång tid för både en- och tre-fasiga asynkronmaskiner.

Resultaten visar att den aktiva- och reaktiva effekten är mycket beroende av spänningens amplitud under stegvisa spänningsänkningar för den en-fasiga och olastade tre-fasiga asynkronmaskinen. Med last på den tre-fasiga asynkronmaskinen, visar sig den aktiva effekten inte vara särskilt beroende av spänningen, där den aktiva effekten håller sig på en stabil nivå runt sitt ordinarie värde. Den reaktiva effekten visar sig å andra sidan vara beroende av spänningen för stegvisa spänningssänkningar upp till 70% upp till lätt last eller upp till 50% upp till semi-tung last.

Keywords: Induction motor voltage dependence, voltage dip, voltage drop, voltage stability, induction motor, voltage dependence.

Acknowledgements

We would like to express our most genuine thanks to senior principal engineer D Karlsson, DNV and adjunct professor, Chalmers University of Technology for giving us the opportunity to research this problem and for his continuous aid and valuable advice.

We would also like to direct a massive thank you to Docent P Chen, department of Electrical Engineering, Chalmers University of Technology for his kind support, interesting discussions and for his cherished assistance during the conduction of the experiments.

Leo Holst, Jesper Gregart Malmberg, Gothenburg, June 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AC	Alternating Current
DC	Direct Current
ECU	Electronic Control Unit
IM	Induction Machine
p.u.	Per-Unit
PF	Power Factor
SG	Synchronous Generator
SM	Synchronous Machine

Nomenclature

Below is the nomenclature of parameters that have been used throughout this thesis.

Parameters

P	Active Power
Q	Reactive Power
V	Voltage
I	Current
T	Period time
θ	Phase angle
PF	Power Factor
f	Frequency

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1
Introduction

This chapter presents the projects background, purpose, goals, demarcations and methodical approach that will be considered in this report.

1.1 Background

The background for this thesis work are the power outages that occurred in Sweden in 1983 and 2003. It was estimated according to [1] that the energy that was unsupplied, as a result of the power outage in 2003, amounted to around 10 GWh. Through a standard interruption cost assessment, carried out by Svenska Elverksföreningen, it was concluded that the outage could be valued at around 500 million Swedish crowns. A power outage also have several other consequences on society beyond economical losses, such as elevators, trains, trams and electrical doors, locks and heating all not being able to function properly. Since today's society rely so heavily on the electrical grid to keep operating as usual, it is imperatively important that there is knowledge on what to do when a power outage occurs and how to tackle the problem as fast and as smooth as possible. To be able to do that, it is highly beneficial to know how the load objects connected to the grid reacts to voltage changes of different amplitudes and duration. In today's electrical grid, one very common type of load object is the electric machine. The most common electrical machine is the Induction Machine (IM) which consumes 40% of the electrical energy produced globally [2].

1.2 Purpose

The purpose of the degree project is to study how voltage dips of different amplitudes and duration impact the active- and reactive power consumption for both single- and three-phase induction machines, since they are common load objects in the grid.

1.3 Goals

The objectives for the degree project are to compile a literature review including available research on input voltage changes to induction motor loads and execute own experiments on single- and three-phase induction machines for loads of:
no-load, Light load, Semi-Heavy load and Heavy load.
Execute voltage dips of: 5%, 10%, 15%, 20%, 30%, 50%, 70%, for different duration

times of: 100 ms, 500 ms, 2 s, 5 s, 30 s, 2 min. Measurements of the following quantities on the IM shall be executed: the terminal voltage magnitude (RMS), the terminal current, the terminal active power and the terminal reactive power.

1.4 Demarcations

- The degree project will not study frequency changes, the frequency will be constantly 50 Hz for the laboratory experiments.
- The literature review will be limited to topics within the research area that catches our interest in the research process.
- The experiments will not be executed in a real operational facility but in the Chalmers power system laboratory.
- The induction motor will only be used as a motor/load object, not as a generator, as this more accurately corresponds to reality in our scenario.
- Swells of the input voltage will not be executed in the laboratory experiments.
- The project will be limited to 3-phase and 1-phase.
- The experiments will be limited to 400 Volt (RMS).
- There will not be any unbalanced experiments made, i.e. not simulating line to line or line to ground faults.
- The duration of the voltage dip needs to be customized so the voltage at the induction machine is stabilized at the dip voltage before the voltage is recovered.
- The 1-phase test object will only be tested for one load case and can not be tested unloaded.

1.5 Methodology

The approach for this degree project was to first find available research on induction motor voltage dependence, to gain knowledge and conduct the findings in a literature review. First of all, was to search for digital sources in places such as IEEE Xplore and Chalmers Library. Secondly, was to plan own experiments from the set goals to be executed on IM in the Chalmers laboratory. The approach was to then learn about the equipment in the laboratory and how it is controlled, with help from the examiner and then plan the order to execute the different experimental objectives and the preparations that had to be made. The plan was to execute the experiments together with the examiner and to start off with test experiments on the 1-phase induction motors and get measurements that could be processed and evaluated. Then plan the following experiments step by step from the knowledge made from the first and following experiments. After the physical experiments were executed the data that was collected had to be processed and plotted in graphs, these graphs were subsequently put in the report alongside the writing of the report. However, since the measurements resulted in a huge total number of graphs, not all graphs could be included in the report, a decision of which graphs to display had to be made. This decision resulted in the approach to display a linear progression of the experiments, and thus the displayed graphs in this report can be seen.

2

Theory

In this chapter the technical background and the equations used in the project are presented.

2.1 Voltage dip

A voltage dip is a temporary drop in the voltage magnitude [3]. The causes for this can be faults in the transmission or distribution networks, faults in the connected equipment or high inrush- and switching currents. A voltage dip can affect connected equipment and other sensitive parts of equipment connected to the grid. The consequences of this depends on the duration and magnitude of the dip but also on the ability the equipment has to withstand the reduction in voltage. In this project, when it is stated that a voltage dip of for example 30% is executed, that means that the voltage level dips by a magnitude of 30%, i.e. from 100% to 70%.

2.2 Numerical calculation

In this section, all of the mathematical equations that have been used in this project will be presented.

2.2.1 Per-Unit

The Per-Unit (p.u.) system is a value in relation to the base quantity of a given quantity, i.e. voltage or current [9]. This system is popular in the power system industry to express values of voltage, current, active- and reactive power or impedances of power equipment. Perhaps the biggest benefit of using this system is that, for a given quantity, it is very straightforward to compare with their "normal" values. In other words, 1 p.u. is equal to the "normal" or nominal value of the given quantity, which means that 0.7 p.u. would be a reduction of 30% of the quantity.

2.2.2 Calculation of rms voltage, rms current and complex power

Table 2.1 show the parameters that were used for the equations.

Table 2.1: Parameters used in equations

Parameter	Symbol	Unit
Positive integer number	k	
The moment when the measurement starts	τ	s
The period time	T	s
Phase angle	θ	rad

Equation 2.1 shows how the single-phase active power, averaged over a period of kT is calculated.

$$P = \frac{1}{kT}\int_{\tau}^{\tau+kT} pdt = \frac{1}{kT}\int_{\tau}^{\tau+kT} p_{\mathrm{a}}dt \tag{2.1}$$

Equation 2.2 shows instantaneous active power single-phase.

$$p_{\mathrm{a}} = VI\cos\theta[1-\cos 2\omega t] \tag{2.2}$$

Equation 2.3 shows active power.

$$P = VI\cos\theta \tag{2.3}$$

Equation 2.4 shows reactive power single-phase over the measurement time interval.

$$Q = \frac{\omega}{kT}\int_{\tau}^{\tau+kT} i[\int vdt]dt \tag{2.4}$$

Equation 2.5 shows reactive power.

$$Q = VI\sin\theta \tag{2.5}$$

Equation 2.6 shows power factor.

$$PF = \cos\theta \tag{2.6}$$

Equation 2.7 shows sinusoidal single-phase voltage source.

$$v = \sqrt{2}\cdot U\sin(\omega t) \tag{2.7}$$

Equation 2.8 shows sinusoidal single-phase current.

$$i = \sqrt{2}\cdot I\sin(\omega t-\theta) \tag{2.8}$$

2.3 Software and hardware used in the project

2.3.1 MATLAB

MATLAB is a programming platform designed for engineers and scientists to analyze data, develop algorithms and create models and applications [4]. MATLAB

Equation 2.9 shows phase angle.

$$\theta = \omega t = 2\pi f t \tag{2.9}$$

Equation 2.10 shows period time.

$$T = \frac{1}{f} \tag{2.10}$$

Equation 2.11 shows average/RMS.

$$x_{\mathrm{RMS}} = \sqrt{\frac{1}{n}(x_1^2 + x_2^2 + ... + x_{\mathrm{n}}^2)} \tag{2.11}$$

uses the MATLAB programming language, which allows for a natural expression of computational mathematics. MATLAB is widely popular both in academia but also in several industries.

2.3.2 Simulink

Simulink is a multi-domain modeling and simulation environment [5]. Simulink is integrated with MATLAB, but in comparison to MATLAB, Simulink is designed for engineers and scientists who design controls, wireless and dynamic systems. With Simulink it is possible to design and simulate systems before testing with actual hardware.

2.3.3 Regatron TopCon TC.ACS

The Regatron TopCon TC.ACS is a full digital, full 4 quadrant 3-phase Alternative Current (AC) power source [6]. The Regatron comes with multi-level inverter technology, programming features and a three-in-one configuration. Meaning that it has a programmable RLC-load mode, it can function as a 3-phase grid simulator and more importantly for this project, it can run as a full 4-Quadrant 1- to 3-phase amplifier.

2.3.4 dSPACE

dSPACE is a company providing validation and simulation solutions.

2.3.5 ControlDesk

ControlDesk is an experimental software tool by dSPACE for Electronic Control Unit (ECU) development [7]. ControlDesk combines different functions that would otherwise require several specialized tools. It gives access to simulation platforms, connected bus systems and can perform ECU measurements, calibrations and diagnostics.

2.3.6 Induction Machine

Induction Machines are the most commonly used electrical machines in the world and consumes up to 40% of all produced electrical energy in the world [2]. The most typical usage is in industrial applications, such as fans, compressors, conveyors and hoists and so forth. This is due to the fact that the IM has relatively high efficiency, is robust and easy to manufacture. The IM consist of a rotor and a stator, where the currents in the windings of the stator will create a rotating magnetic field that makes the rotor rotate. The rotor rotates with a slightly different speed than the magnetic field of the stator which is called slip. The rotor usually consist of two types of structures, squirrel-cage and wound rotor.

2.3.7 DC Machine

The DC machine can be characterised from that the input voltage and current are Direct Current (DC) [2]. It consists of a field winding connected to an armature conductor transferring the electricity to the rotor via the commutator which has brushes [8]. In this project the DC machine will be used in two different applications, as a load object for the IM and as a mechanical torque provider to the Synchronous Generator (SG).

2.3.8 Synchronous Machine

The Synchronous Machines (SM) biggest characterization is that the rotor rotates synchronously with the magnetic field in the stator [2]. There are several different variations of synchronous machines, two popular ones are the permanent magnet synchronous machine and the synchronous reluctance machine, that have high power density and high efficiency. In this project, for the 3-phase experiments, the synchronous machine will be used as a synchronous generator to feed the IM.

2.3.9 Synchronous Generator

A synchronous generator generates electricity instead of consuming it as a motor. Synchronous machines are commonly used as generators in electric power generator stations of types such as hydro-generators and turbo-generators. Common applications are nuclear power stations, thermal power stations and hydro-power stations. It consists of field windings in the rotor compared to magnets in the permanent magnet synchronous motor.

3
Literature Review

Voltage dips in the electrical grid can have different reasons which characterizes the shape of the voltage dip. The characteristics can consist of the duration of the dip and if the voltage changes gradually or rapidly in steps. These characteristics have different impacts on the active- and reactive power consumption of IMs exposed to the dips.

According to [10] abrupt voltage dips are more severe. For single- and three phase motors ranging from 0.17 to 1 kW running on 230-415 V exposed to balanced voltage dips of 90-0% of nominal voltage the conclusion is that the recovery time of the current is longer for abrupt dips than for gradual dips. This influences the active power consumed by the IM which is concluded to be lower for an abrupt voltage dip compared to a gradual dip.

The current peaks always occurs at the voltage drop point and recovery point. It is concluded that the higher the voltage dip is, the higher is the current peak. For the three-phase, the phase A current is higher than for the other two phases. It is concluded that the tested 1 kW single phase motor has the highest current peaks up to 10 p.u. in the voltage dip event compared to the two other tested three-phase motors.

Shorter voltage dip duration of around 75-200ms for dips below 20% of nominal voltage is concluded to generate higher current peaks than longer voltage dip duration for the same voltage dip. If the voltage drops below 20% of nominal voltage and the duration exceeds 1.5 seconds the speed drops below 85% of normal operational speed. When the voltage drops to 10% of nominal voltage and the duration exceeds 1.5 seconds the motor stalls.

From mathematical models of three-phase IM, the power losses are concluded to be higher when the IM runs at undervoltage compared to at overvoltage [11]. It is also concluded that the power factor is less good for overvoltage condition than undervoltage condition.

To describe the voltage dependence of different loads connected to the electrical grid, load models can be used. Simulations of the electrical power system can be dependent on time or time independent, which corresponds to dynamic or static load models [12].

The static load models for active power and reactive power are described in the exponential form according to Le Dous [12] as below:

$$P = P_0(\frac{V}{V_0})^a \tag{3.1}$$

$$Q = Q_0(\frac{V}{V_0})^B \tag{3.2}$$

Table 3.1: Variable explanation

Parameter	Symbol
Value describing the voltage dependence for active part of the load	a
Value describing the voltage dependence for reactive part of the load	B
Consumed active power	P
Consumed reactive power	Q
Active power working point before the disturbance	P_0
Reactive power working point before the disturbance	Q_0
Voltage working point before the disturbance	V_0
Disturbance voltage	V

From computer simulations from Svenska Kraftnät common values for aggregate loads for a is 0.8 and 1.7 for B. Reference [13] describe the exponential form for active and reactive power with an addition of a dimensionless variable z for the load demand as below:

$$P = zP_0(\frac{V}{V_0})^a \tag{3.3}$$

$$Q = zQ_0(\frac{V}{V_0})^B \tag{3.4}$$

The static load voltage dependence can be described with a polynomial model called ZIP as well, representing a constant impedance term (Z), a constant current term (I) and a constant power term (P) [12].

$$P = P_0(a_1(\frac{V}{V_0})^2 + a_2(\frac{V}{V_0}) + a_3) \tag{3.5}$$

$$Q = Q_0(b_1(\frac{V}{V_0})^2 + b_2(\frac{V}{V_0}) + b_3) \tag{3.6}$$

The a and b parameters representing each load fraction can be build up by either constrained parameter fitting or accurate parameter fitting [12]. In constrained parameter fitting ($a_1 + a_2 + a_3 = 1$ and $b_1 + b_2 + b_3 = 1$) where the a and b parameters range from 0 to 1. In the accurate parameter fitting only the sum of the parameters is equal to 1 p.u. According to Le Dous [12] the accurate fitting model is the best fit to the data compared to the constrained fitting model that gives a significant deviation to the measured data.

Le Dous [12] concludes that when a voltage drop occurs in the electrical system will lead to a power recovery in the system which will increase the current in it. The consequence of that is that the losses will increase. It was also concluded from voltage dip experiments in the 130kV grid in the Sydkraft area of Sweden, that voltage dips of 5% affected the 230V office wall socket to the same percentage level as in the 130kV grid.

4

Experiments and data handling

In this chapter it is explained how the 1-phase and 3-phase IM experiments were carried out.

4.1 1-phase IM experiments

For the 1-phase IM experiments, two industrial heaters fans (El-Björn E8726332), 16A/400V were chosen, including a 1-phase fan motor on 72W connected phase to phase 400V RMS. To control the supply voltage to the motors they were connected to a Regatron TopCon TC.ACS converter.

Figure 4.1: Figure showing the test object for the 1-phase experiments: Elbjörn Electrical fan heater E8726332, including a 1-phase fan induction motor on 72W and 400V.

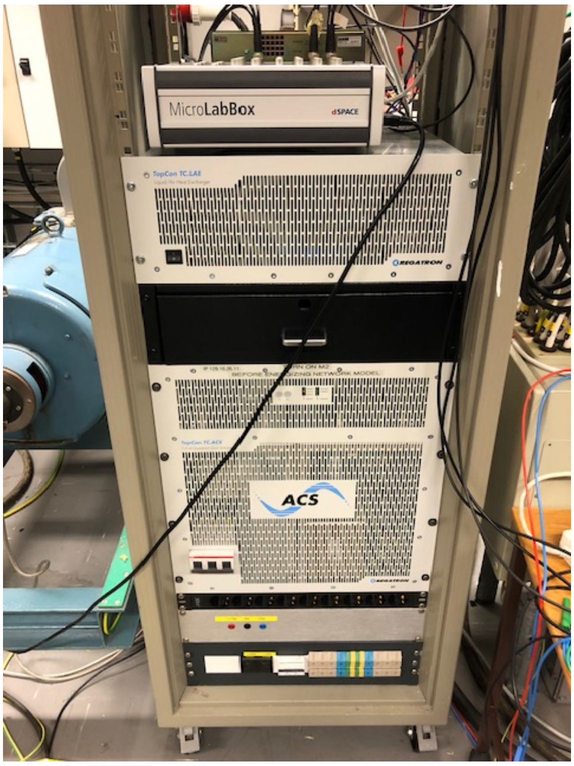


Figure 4.2: Figure showing the Regatron TopCon TC.ACS which was used as voltage supply generating the voltage dips for the 1-phase experiments.

To measure the voltage at the motors, voltmeters (Le Croy AP032) were connected to each phase line and neutral in between the Regatron and the motors. To measure the current phase line, one phase line was turned ten times around a current sensor of type ProSys CP35 100mV/A. The average current consumption of the two fan motors is under 1A, which makes it necessary to turn the cable ten times around the sensor to increase the measured current and gain a more precise measurement because of the rating of the current sensor. The measurement value is then divided by ten in the Regatron Simulink model to create the actual current consumed. The measuring equipment were connected to input channels on a dSPACE MicroLabBox connected to a computer that displays the measurements in the dSpace ControlDesk software.

Figure 4.3: Figure showing dSPACE MicroLabBox that is used to control the Regatron ACS and includes the input ports for the voltage and current measurements.

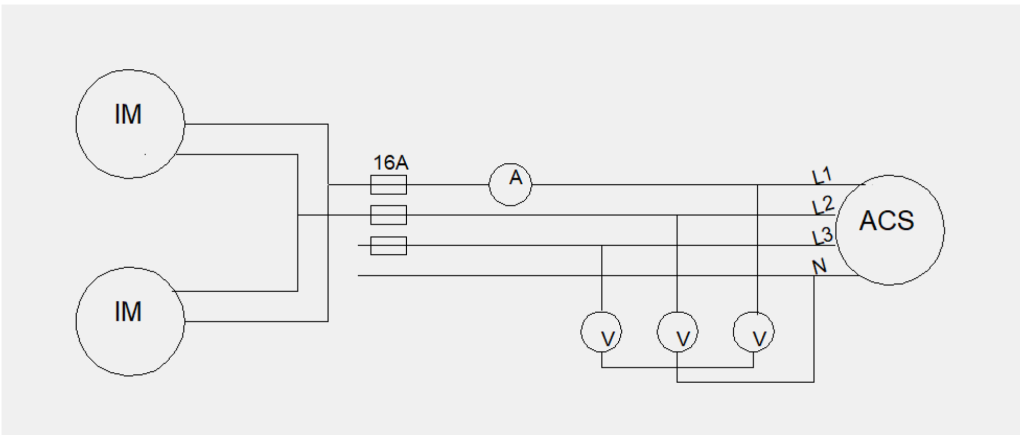


Figure 4.4: Figure of the setup for the 1-phase experiments. The test objects are the two IM (Elbjörn) which are two spinning fans. They are electrically supplied from the Regatron ACS which generates the voltage dips. Close to the ACS, external voltage meters are connected to each phase measuring the voltage and a current clamp to the first phase used by the IMs. The Neutral of the ACS is grounded to protective earth (PE).

To generate a ramp voltage dip to the motors a program was created in the ControlDesk software creating a ramp dip of the voltage when pressing a button. By accessing the variables in the Simulink model that controls the output voltage from the Regatron the desired voltage could be controlled in the ControlDesk. A duration time limiter was programmed as well that creates a window to ensure that the voltage return to the normal value after the duration time of the dip is completed. In the Regatron Simulink model a trigger function of the measured voltage was added to trigger a recording of the measurements of voltage and current when the voltage dips. The recording saves 100ms before the trigger signal went active and Xs after the voltage returned to normal. By manually inserting the dip voltage level and the desired duration time in the ControlDesk program, each experiment was executed.

To create gradual voltage dips, measurements of two real voltage dips that happened in the Swedish grid in 2003 were used as references. One from Odensala in the 400 kV grid and one from Öland in the 50 kV grid. The two consists of different characteristics, but with similarities as well in terms of both including parts of slow voltage decrease over time in the beginning and faster decrease over time towards the end of the dip. To imitate the two dips, a Simulink model was programmed to generate different gradients for different time periods. The model consists of three exponential functions with different exponents that are enabled with a timer for different times and merged together to a voltage output. The voltage output is connected to the Regatron voltage output model which multiplies the voltage output with three sine waves creating the three phase voltage output from the Regatron. The Regatron Simulink control model is then controlled from the Control Desk software.

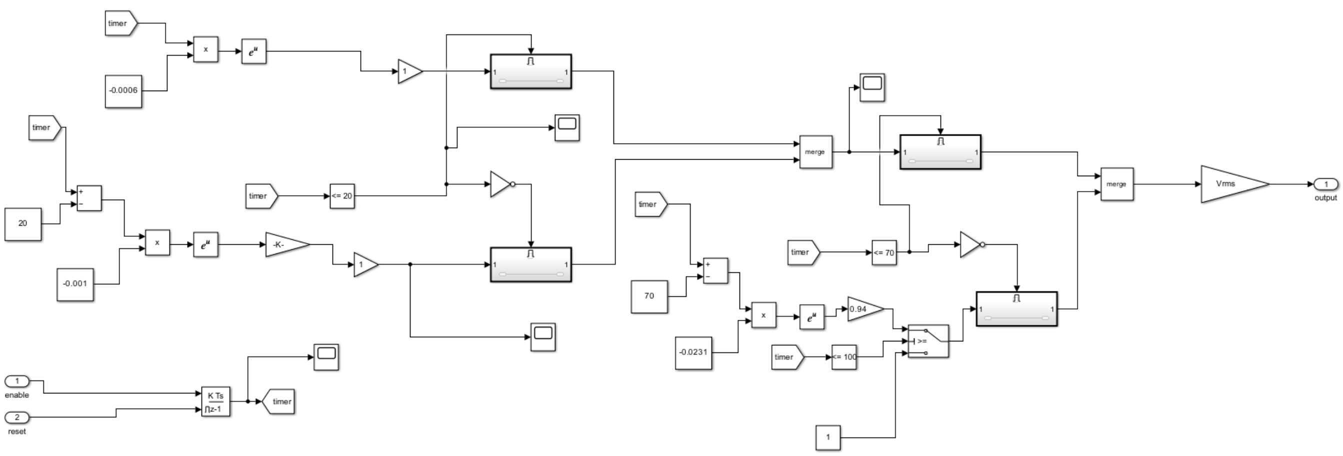


Figure 4.5: Figure showing the Simulink gradual dip model simulating the voltage dip in the 50kV grid at Öland in Sweden in 2003.

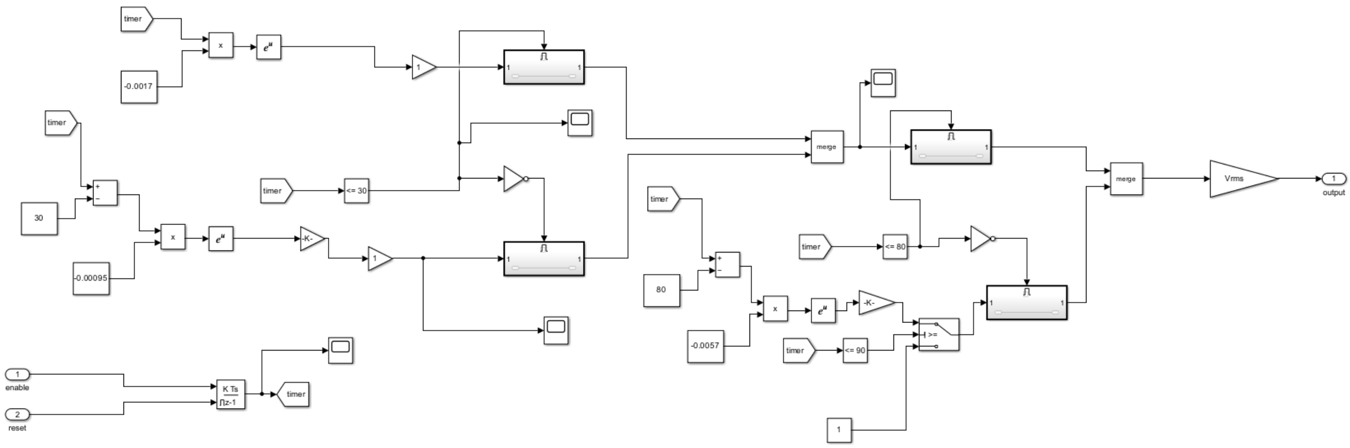


Figure 4.6: Figure showing the Simulink gradual dip model simulating the voltage dip in the 400kV grid in Odensala in Sweden in 2003.

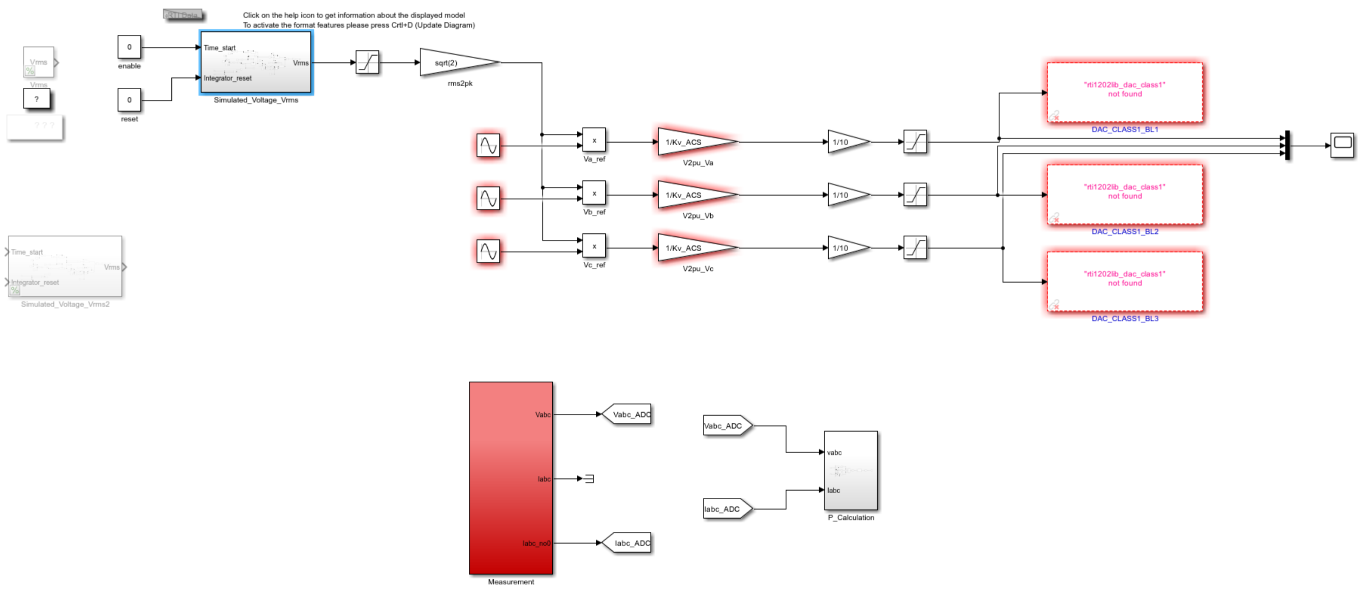


Figure 4.7: Figure showing the Regatron ACS voltage output model creating a 3-phase output. The blue marked block is the Gradual dip model.

To record the measurements a trigger function was implemented in the Control Desk software. A variable was created from the voltage measurement in the Simulink model and the trigger function is activated when the voltage starts to drop and the recording saves the measurements from 100 milliseconds before the drop until the voltage is stabilized.

4.2 Measurement data handling for 1-phase

The recorded measurement data of current and voltage were saved in data.mat files where the voltage, current and time are saved every 0.0002 seconds in one array respectively. These recordings need processing in matlab to plot the voltage's and current's RMS values over time as well as calculate and plot the frequency, the active and reactive power as well as remake them into the p.u. scale.
The processing and calculation of each unit were implemented in a function respectively in matlab. A program for each unit were constructed for calling the calculation function with the selected measurement file. To calculate the frequencies in the voltage measurement the Fast Fourier Transform (FFT) function, was used on the voltage measurement data and then plotted to review the frequencies.

To remake the instantaneous values of voltage and current into RMS values the measurements were integrated over an electrical period with a for-loop and summed together from equation 2.11 in matlab. The saved array of sums is then plotted over the time.

For the power calculations the Power Factor (PF) for the 1-phase induction motors was calculated. A PF of 0.6 was provided from the motor supplier Euro Motors Italia but it was calculated from the measurements still to be sure of the accuracy. For the PF calculation, the phase angle between the voltage and current needed to be calculated. The phase shift/angle was calculated by first plotting a graph of one dip over one duration time, with both the voltage and the current present. For this, the dip of 5% for 100ms was the chosen one. From this graph, the time where one period started for both the voltage and the current was established and the difference between these times were calculated. This new variable t was then put into ωt, that stems from (2.7) and (2.8). The result from the two different ωt was then converted from radians to an angle in degrees by multiplying with $\frac{180}{\pi}$. Lastly, we got the phase angle after calculating the difference between the voltage angle and the current angle.

To calculate the Active- and Reactive Power, the power from equation 2.3 and 2.5 for each voltage and current were integrated over an electrical period with a for-loop and summed together from equation 2.11 in matlab. The saved array of sums is then plotted over the time. To plot the Active and Reactive power and the voltage in p.u. the values in the respective arrays are divided with the first value (stable value) in the arrays.

4.3 3-phase IM experiments

For the three phase induction machine experiments the ASEA MBG 180 L 30kW, delta connected 380V 61A was used. Its load consists of a DC machine from ASEA of type LAC 225 35kW 400V 96A.

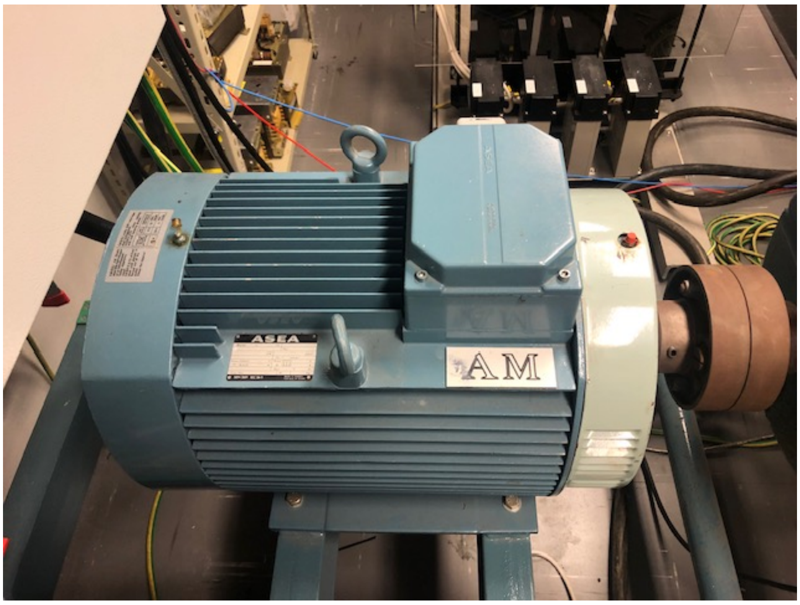


Figure 4.8: Figure showing the 3-phase induction motor test object, ASEA MBG 180L-4, 380 V, 62A, 33kW, 1450r/min, cos $\phi = 0.81$.

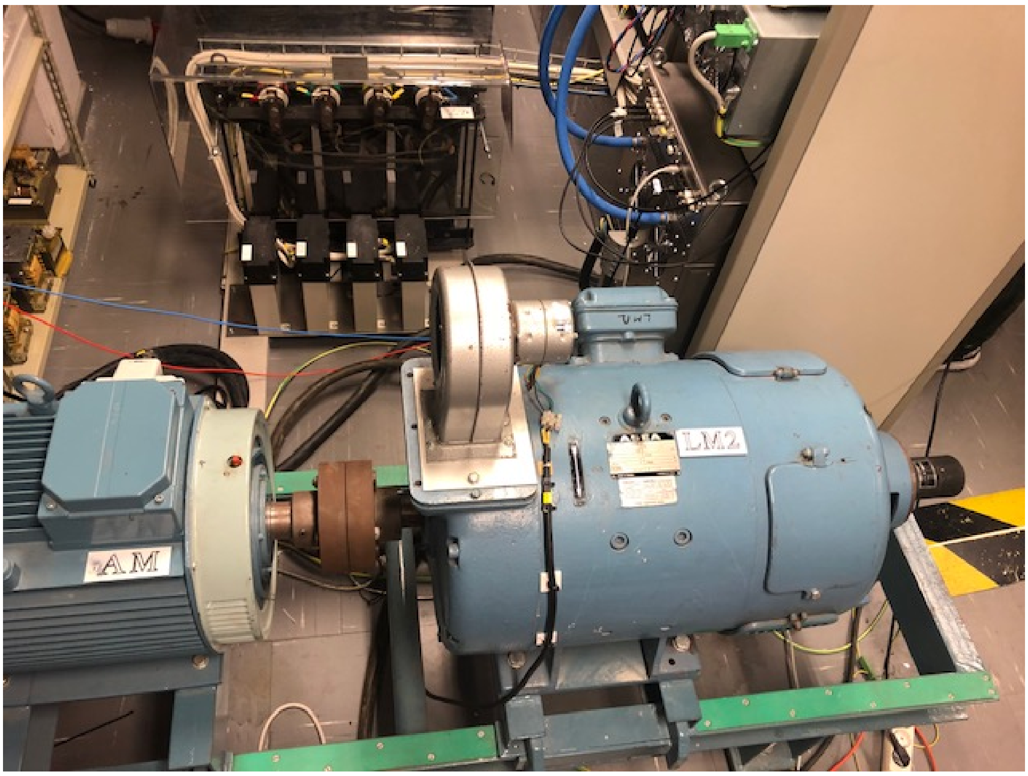


Figure 4.9: Figure showing the load object for the IM, a DC machine of specification: ASEA LAC225, 400 V, 96 A, field: 220 V, 1850 r/m

The induction motor is supplied from a synchronous generator ASEA 1976618 75kVA 400V 108.3A Y-connected which is supplied from a DC machine from ASEA of type 1976621 85kW 220V 420A. The DC-machine is supplied from a thyristor converter equipment which is controlled from dSPACE.

Figure 4.10: Figure showing the SG ASEA 1976618 75kVA 400V 108.3A to the left and DC-machine ASEA 1976618 75kVA 400V 108.3A to the right that are mechanically connected and they are the voltage supply for the IM.

The voltage and current measurements for the IM comes from built-in measuring equipment at the supplying SG. The speed of the IM is measured from a built on tachometer on the DC-machine load object. The measuring equipment are connected to individual channels on dSPACE "input box" and the measurements are displayed in dSPACE control desk.

Figure 4.11: Figure showing the dSPACE control unit for the SG and DC-machine and includes the input ports for voltage, current, speed and other parameters for the machines.

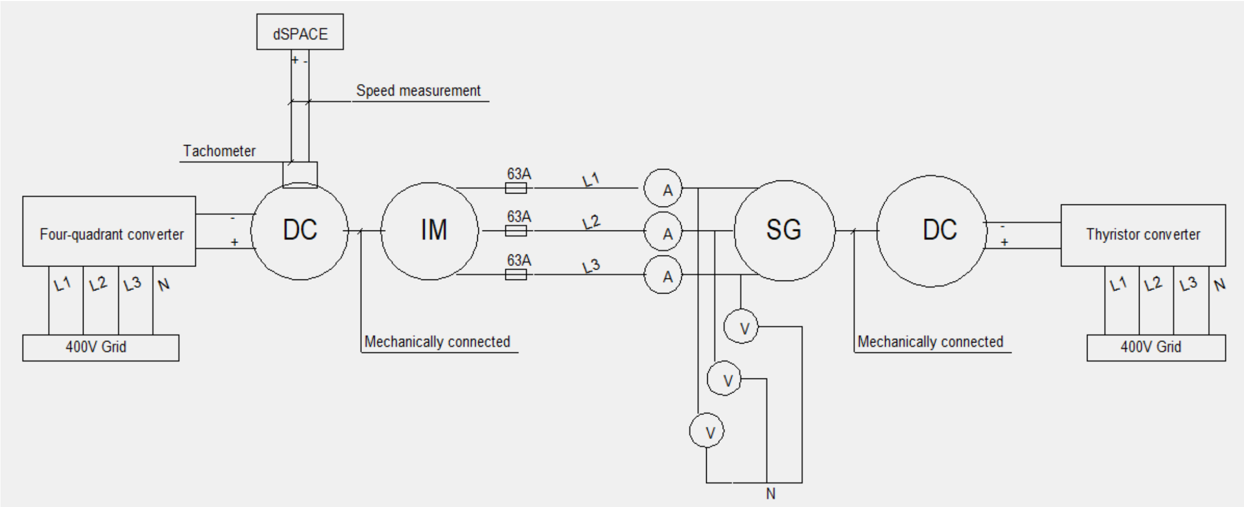


Figure 4.12: Figure of the laboratory setup for the 3-phase experiments. The test object is the IM which has a mechanically connected DC-machine as load. The DC-machine is connected to the 400V grid via a four-quadrant converter. The electrical source of the IM is the SG. It is at the SG the measurements of current (A) and voltage (V) is conducted. The SG is mechanically connected to a DC-machine. The electrical source of the DC-machine is a thyristor equipment which is connected to the 400V grid and controlled from dSPACE and from where the voltage dips are generated.

To generate the ramp and gradual voltage dip the same Simulink models were used as for the 1-phase experiments. The ramp model, the Odensala model and the Öland model were put in parallel in one subsystem block each with switch blocks switching between them. By connecting a variable block to each switch block the variable could be changed from a button in the Control Desk software deciding which simulation model to run. All blocks use a voltage dip enable variable and a voltage dip reset variable as inputs, the variables were changed from two buttons in the Control Desk software.

To record the measurements the recording trigger was triggered by the enable variable when turning from low to high. For the step dips the recording duration was set to 60 seconds and the dip duration was set to 30 seconds. For the gradual dip the total duration was 120 seconds. 2 seconds before the dip is captured by the recording.

The IM has a current limit of 61A and is fused to 63A which sets the limits for the experiments. With the current limits taken into consideration the voltage dips was tested step by step, with the smallest dip first and then it was increased if the current limits was not expected to be passed.

The SG has a big inductive winding in the stator which results in that it takes time to reduce its current when requesting a voltage dip from the SG. This results in that it takes some milliseconds for the voltage to drop at the IM. This eliminated the possibility to do voltage dips for duration of 100 and 500 milliseconds and 1 second with a stabilized dip voltage at the IM before the voltage is recovered. It was concluded that reaching the dip voltage at a clear stabilized level meets the scope of the project and changing the duration is not necessary.

Firstly all experiments was conducted on the IM unloaded (no-load), then the load from the DC-machine was increased to 7.5kW (Light load), 15kW (Semi-Heavy load) and 26kW (Heavy load). The load provided is proportional to the speed, which corresponds to constant torque load characteristic, the torque limit is set so the decided active power of the IM is consumed. For a step voltage dip of 50% at Semi-Heavy load it was decided to not proceed to a 70% voltage dip because of that it was expected to pass the current limit. For a step voltage dip at Heavy load the voltage dips were executed in small steps to see to which extent the current increased. It was decided to not proceed any further than 20% voltage dip for heavy load because of the current limit. Because of this all load cases were executed at 20% to be comparable. For the gradual voltage dip of Öland the IM was not exposed to Heavy load because of the current limit.

4.4 Measurement data handling for 3-phase

For the 3-phase experiments the measurements of current, voltage, active power, reactive power, speed and time were saved every 0.0002 second in one array respectively in data.mat files. All recordings need processing in matlab to plot the measurement's RMS values over time as well as calculate and plot the frequency as well as remake them into p.u. scale.

To remake the instantaneous values of voltage and current into RMS values, the measurements were integrated over an electrical period with a for-loop and summed together from equation 2.11 in matlab. The saved array of sums is then plotted over the time. The measurements of active- and reactive power and speed were noisy and to improve the readability of the plots the instantaneous values where integrated over an electrical period with the same for loop as for equation 2.11 in matlab.

5

Results

In this chapter the results are presented.

5.1 Calculations

In this section significant calculations are presented.

5.1.1 Phase shift for 1-phase IM

In this section it is described how the calculations for the phase shift for the 1-phase IM were executed. Table 5.1 lists the parameters that were used during the calculations of the phase shift for the 1-phase IM.

Table 5.1: Parameters used for the calculations of the phase angle for 1-phase IM

Parameter	Symbol	Value	Unit
Frequency	f	50	Hz
Time duration for one electrical period for the voltage	t(V)	0.004958798	s
Time duration for the corresponding electrical period for current	t(I)	0.0077863200	s
Phase angle	θ	50.89	°

Equation 5.1 shows the calculation of the phase angle between the voltage and current.

$$\theta = 2\pi f(t(I) - t(V))\frac{180}{\pi} = 50.8947° \tag{5.1}$$

5.1.2 Static Load Model for 3-phase IM

In this section, static load model parameters were used in order to try to put the results from the 3-phase IM into perspective. The parameters relation are as follows for active- and reactive power respectively, $\frac{\frac{dP}{P_0}}{\frac{dV}{V_0}}$ and $\frac{\frac{dQ}{Q_0}}{\frac{dV}{V_0}}$. They describe how to calculate the increase or decrease in percentage of the active- or reactive power due to the change in voltage during the voltage dip. dP, dQ and dV is the difference in relation to their "normal" or nominal value P_0, Q_0 and V_0. However, the values in p.u. can be used, this means that since P_0, Q_0 and V_0 are then equal to 1 p.u. the equations can be simplified. We get $\frac{dP}{dV}$ and $\frac{dQ}{dV}$ which can be used to calculate the difference in active- or reactive power in relation to the difference in voltage.

5.2 1-phase IM experiments

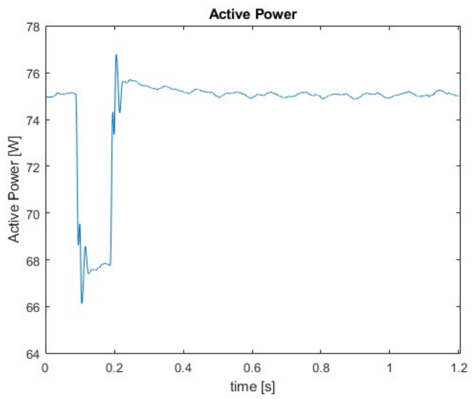
In this section, the results from the 1-phase experiment are presented. This consists of the step dips and the gradual dips, where graphs of the active- and reactive power are shown, as well as graphs where both the voltage and active power and both the voltage and reactive power are shown in the same graph in p.u respectively. In the latter graphs, the voltage is characterized by the orange colour.

5.2.1 Step dips

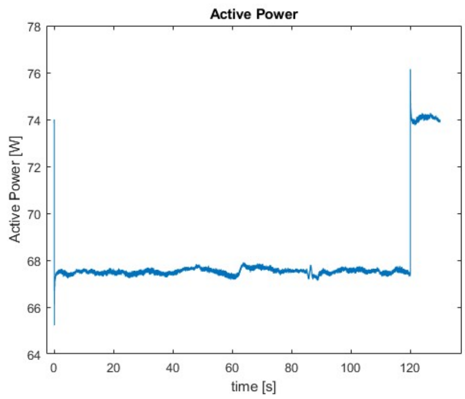
In this section, graphs of step dips of three different magnitudes, 5%, 30% and 70% are shown.

5.2.1.1 5% dips

In this subsection the 5% dips are presented in Fig. 5.1 to 5.4 for two different duration times, 100ms and 2 minutes.

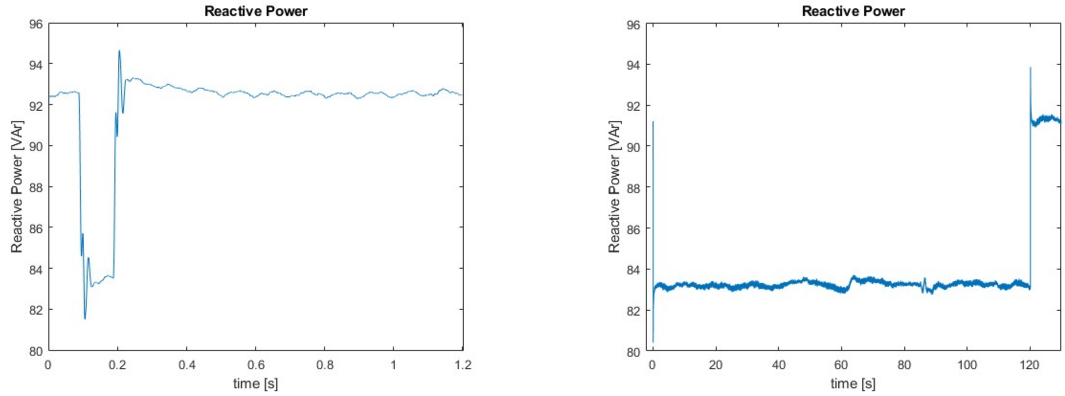


(a) 5% dip for 100ms



(b) 5% dip for 2 minutes

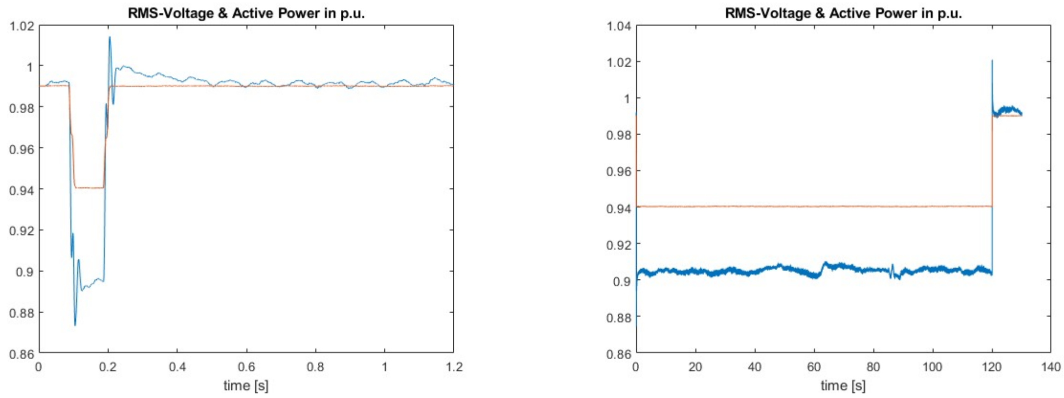
Figure 5.1: Active power for 1-phase during two voltage dips of 5% for different durations.



(a) 5% dip for 100ms

(b) 5% dip for 2 minutes

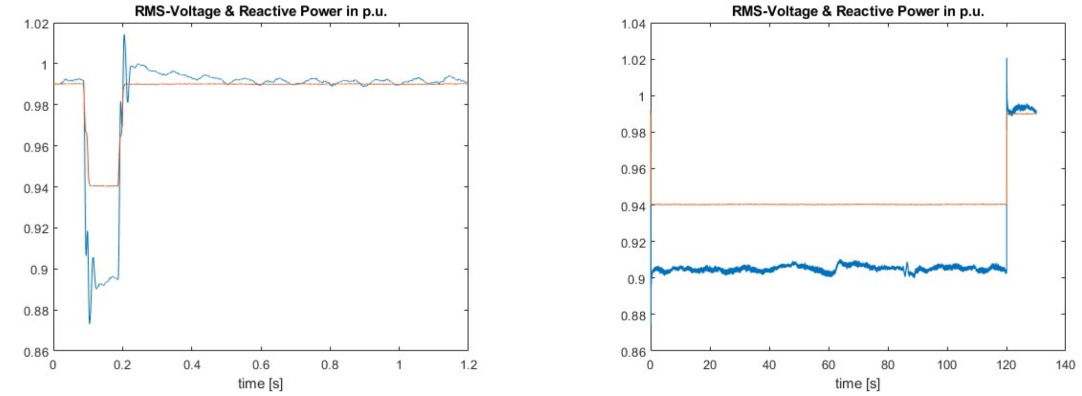
Figure 5.2: Reactive power for 1-phase during two voltage dips of 5% for different durations.



(a) 5% dip for 100ms

(b) 5% dip for 2 minutes

Figure 5.3: Voltage and active power in p.u., where the active powers base value is 75W, for 1-phase during two voltage dips of 5% for different durations.

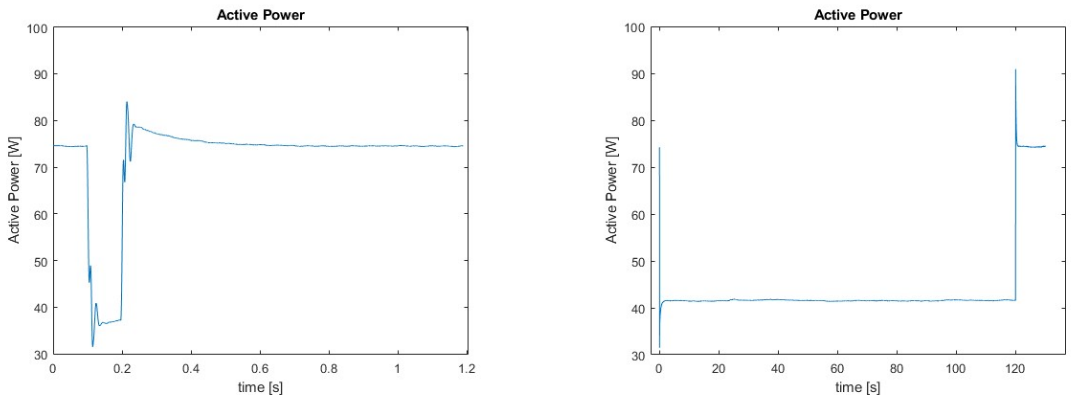


(a) 5% dip for 100ms (b) 5% dip for 2 minutes

Figure 5.4: Voltage and reactive power in p.u., where the reactive powers base value is 92.5VAr, for 1-phase during two voltage dips of 5% for different durations.

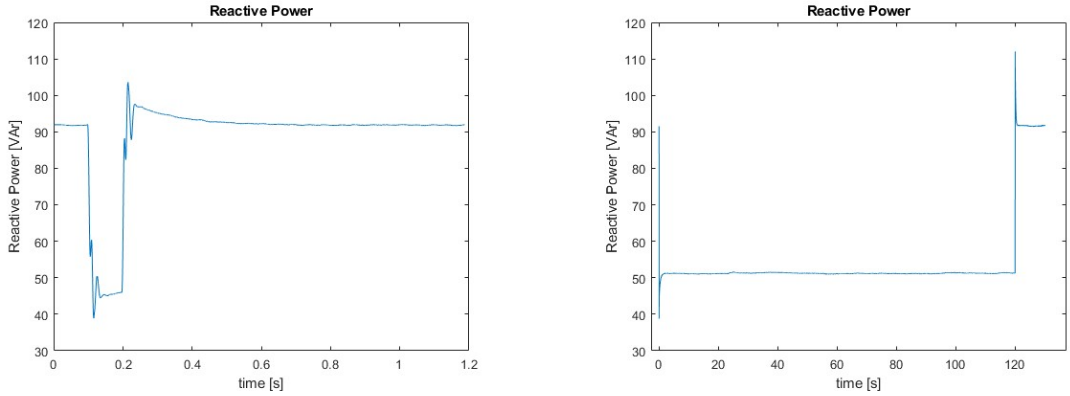
5.2.1.2 30% dips

In this subsection the 30% dips are presented in Fig. 5.5 to 5.8 for two different duration times, 100ms and 2 minutes.



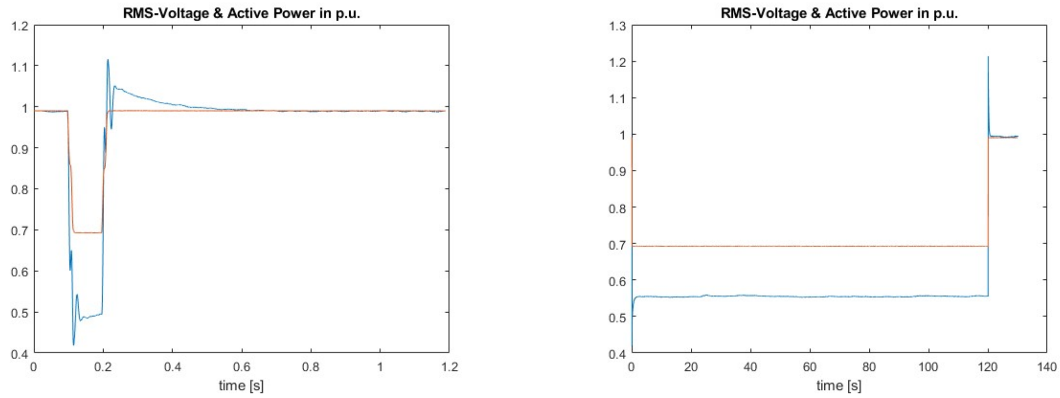
(a) 30% dip for 100ms (b) 30% dip for 2 minutes

Figure 5.5: Active power for 1-phase during two voltage dips of 30% for different durations.



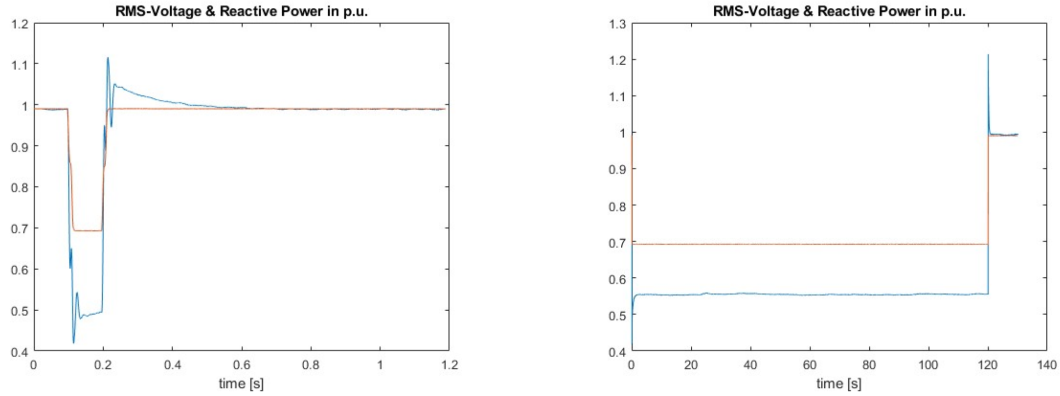
(a) 30% dip for 100ms **(b)** 30% dip for 2 minutes

Figure 5.6: Reactive power for 1-phase during two voltage dips of 30% for different durations.



(a) 30% dip for 100ms **(b)** 30% dip for 2 minutes

Figure 5.7: Voltage and active power in p.u., where the active powers base value is 75W, for 1-phase during two voltage dips of 30% for different durations.

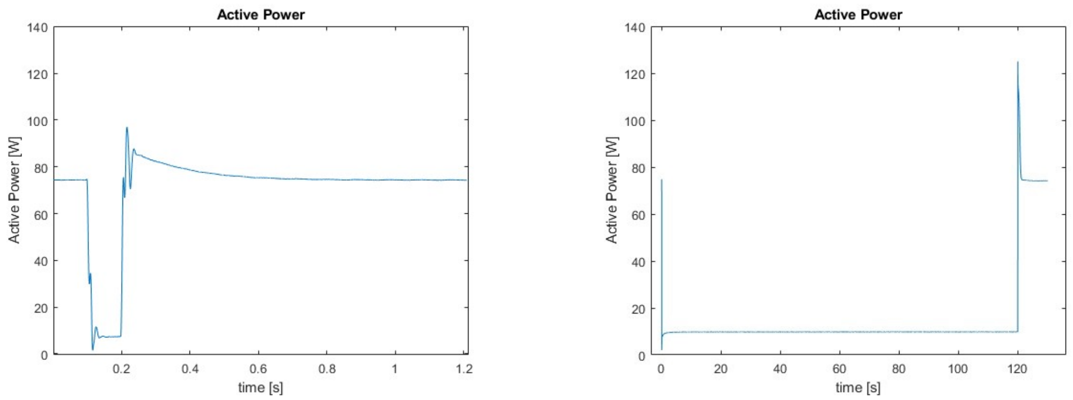


(a) 30% dip for 100ms
(b) 30% dip for 2 minutes

Figure 5.8: Voltage and reactive power in p.u., where the reactive powers base value is 92.5VAr, for 1-phase during two voltage dips of 30% for different durations.

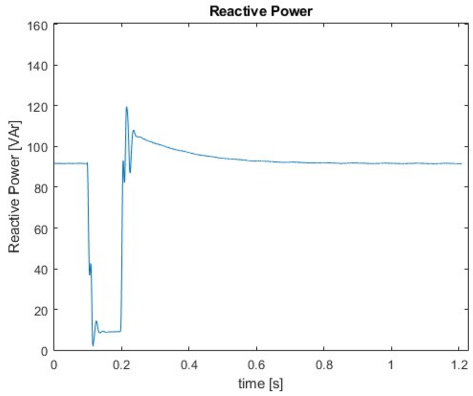
5.2.1.3 70% dips

In this subsection the 70% dips are presented in Fig. 5.9 to 5.12 for two different duration times, 100ms and 2 minutes.

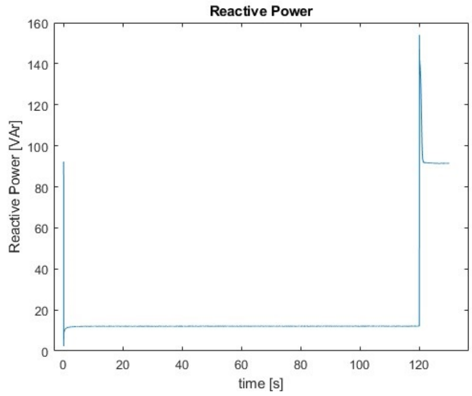


(a) 70% dip for 100ms
(b) 70% dip for 2 minutes

Figure 5.9: Active power for 1-phase during two voltage dips of 70% for different durations.

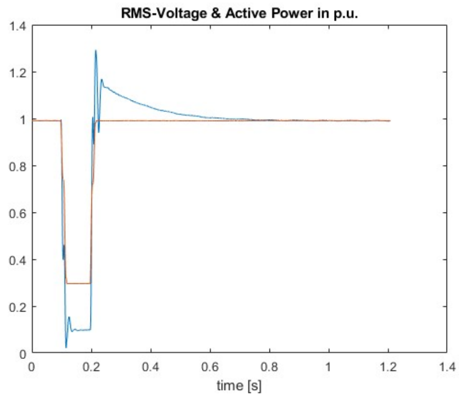


(a) 70% dip for 100ms

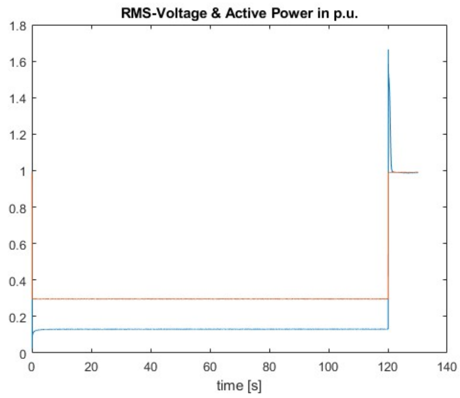


(b) 70% dip for 2 minutes

Figure 5.10: Reactive power for 1-phase during two voltage dips of 70% for different durations.

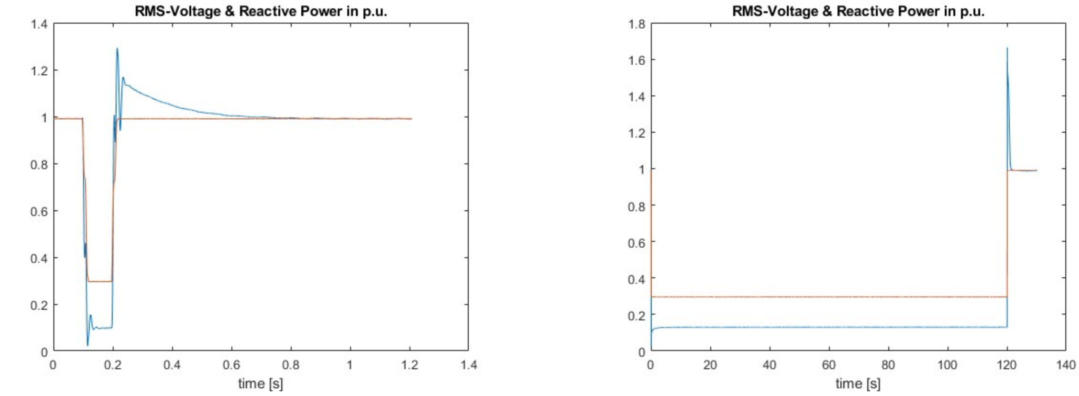


(a) 70% dip for 100ms



(b) 70% dip for 2 minutes

Figure 5.11: Voltage and active power in p.u., where the active powers base value is 75W, for 1-phase during two voltage dips of 70% for different durations.



(a) 70% dip for 100ms

(b) 70% dip for 2 minutes

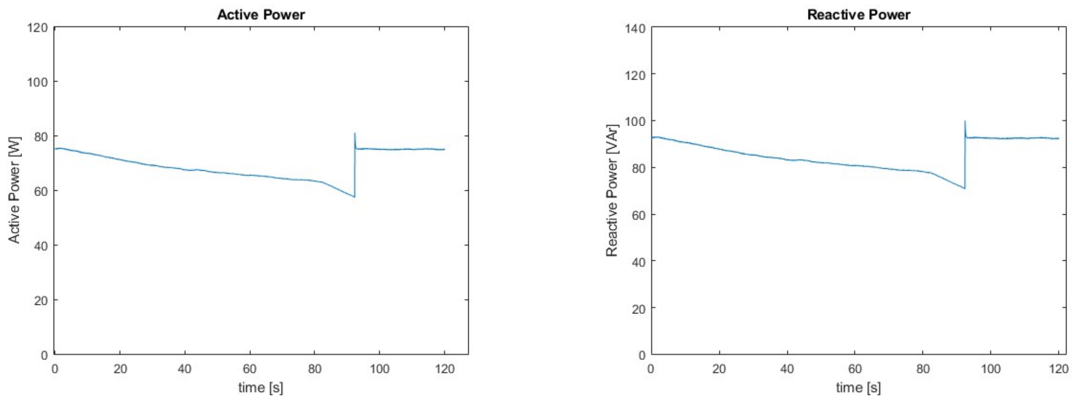
Figure 5.12: Voltage and reactive power in p.u., where the reactive powers base value is 92.5VAr, for 1-phase during two voltage dips of 70% for different durations.

5.2.2 Gradual dips

In this section, graphs of the two gradual voltage dips representing what happened in Odensala and Öland during the power failure in Sweden 2003 are shown.

5.2.2.1 Odensala

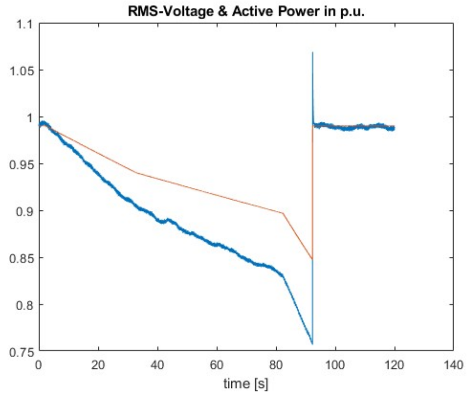
In this subsection the gradual voltage dip representing Odensala are presented in Fig. 5.13 and 5.14.



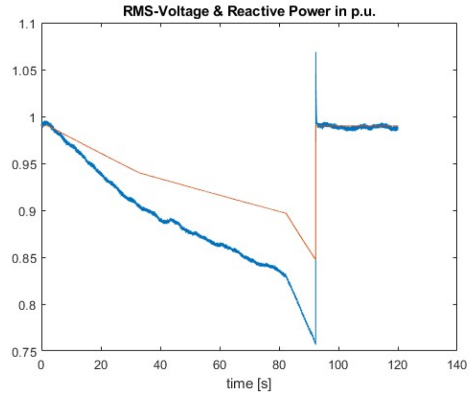
(a) Active power during the Odensala case.

(b) Reactive power the Odensala case.

Figure 5.13: Active- and reactive power for 1-phase during a gradual voltage dip Odensala.



(a) Voltage and active power in p.u. during the Odensala case.

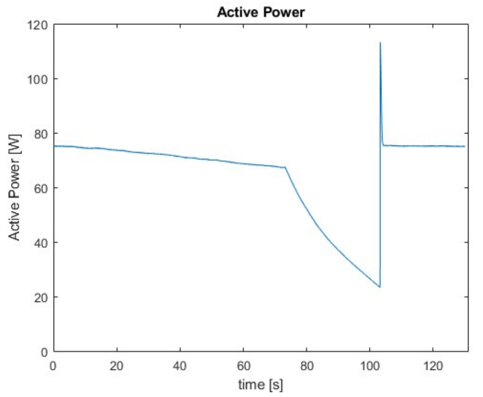


(b) Voltage and reactive power in p.u. during the Odensala case.

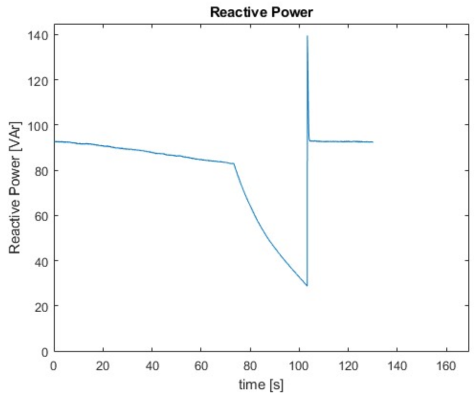
Figure 5.14: Voltage together with active- and reactive power in p.u. for 1-phase during a gradual voltage dip Odensala, where the active powers base value is 75W and the reactive powers base value is 92.5VAr.

5.2.2.2 Öland

In this subsection the gradual voltage dip representing Öland are presented in Fig 5.15 and 5.16.

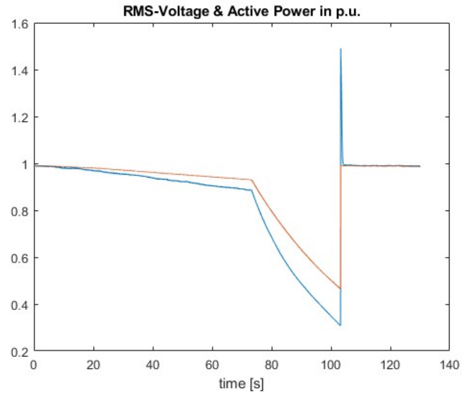


(a) Active power during the Öland case.

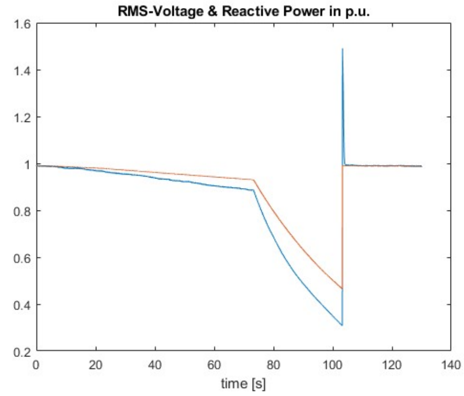


(b) Reactive power during the Öland case.

Figure 5.15: Active- and reactive power for 1-phase during a gradual voltage dip Öland.



(a) Voltage and active power in p.u. during the Öland case.



(b) Voltage and reactive power in p.u. during the Öland case.

Figure 5.16: Voltage together with active- and reactive power in p.u. for 1-phase during a gradual voltage dip Öland, where the active powers base value is 75W and the reactive powers base value is 92.5VAr.

5.3 3-phase IM experiments

In this section, the results from the 3-phase experiment are presented. This consists of the step dips and the gradual dips, where graphs of the active- and reactive power are shown, as well as graphs where both the voltage and active power and both the voltage and reactive power are shown in the same graph in p.u respectively. In the latter graphs, the voltage is characterized by the orange colour.

5.3.1 Step dips

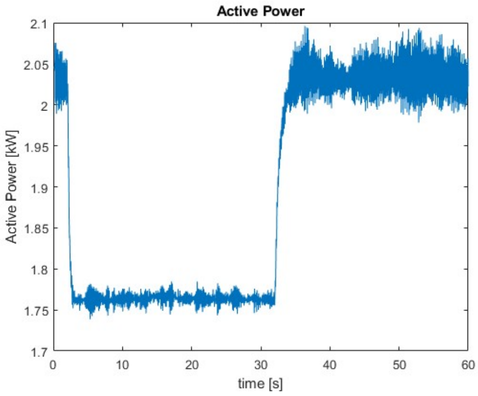
In this section, graphs of step dips of three different magnitudes, 5%, 20% and 70% are shown.

5.3.1.1 5% dips

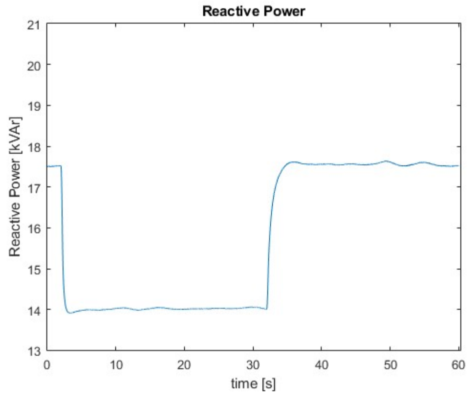
In this subsection the 5% dips are presented in Fig. 5.17 to 5.22 for three different loads, that is no-load, Semi-Heavy load and Heavy load.

5.3.1.1.1 No-load

In this paragraph the 5% dips are are presented in Fig. 5.17 and 5.18 for the no-load case.

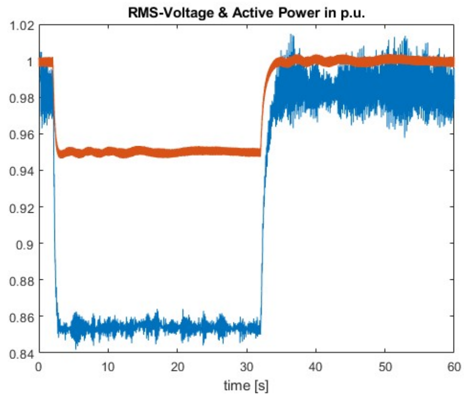


(a) Active power during 5% dips for no-load.

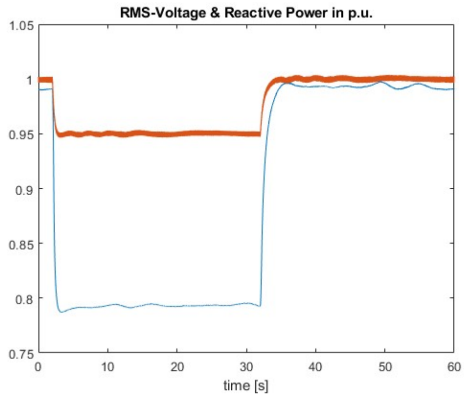


(b) Reactive power during 5% dips for no-load.

Figure 5.17: Active- and reactive power for 3-phase during a 5% voltage dip for no-load.



(a) Voltage and active power in p.u. 5% dips for no-load.

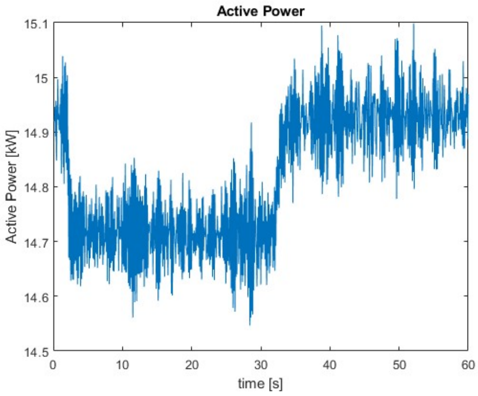


(b) Voltage and reactive power in p.u. 5% dips for no-load.

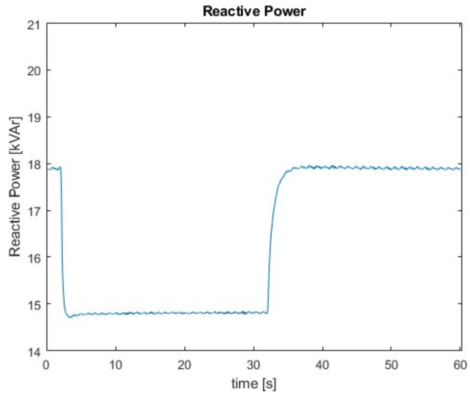
Figure 5.18: Voltage together with active- and reactive power in p.u. for 3-phase during a 5% voltage dip for no-load. Where the active powers base value is 2.05W and the reactive powers base value is 17.5VAr.

5.3.1.1.2 Semi-Heavy load

In this subsection the 5% dips are presented in Fig. 5.19 and 5.20 for the Semi-Heavy load case.

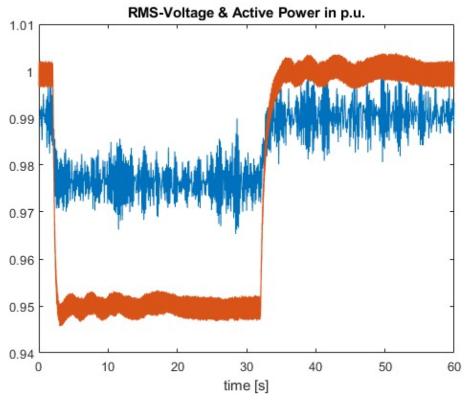


(a) Active power during the 5% dips for Semi-Heavy load.

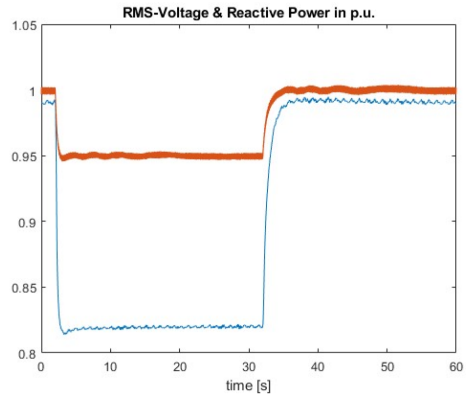


(b) Reactive power during 5% dips for Semi-Heavy load.

Figure 5.19: Active- and reactive power for 3-phase during a 5% voltage dip for Semi-Heavy load.



(a) Voltage and active power in p.u. during the 5% dips for Semi-Heavy load.

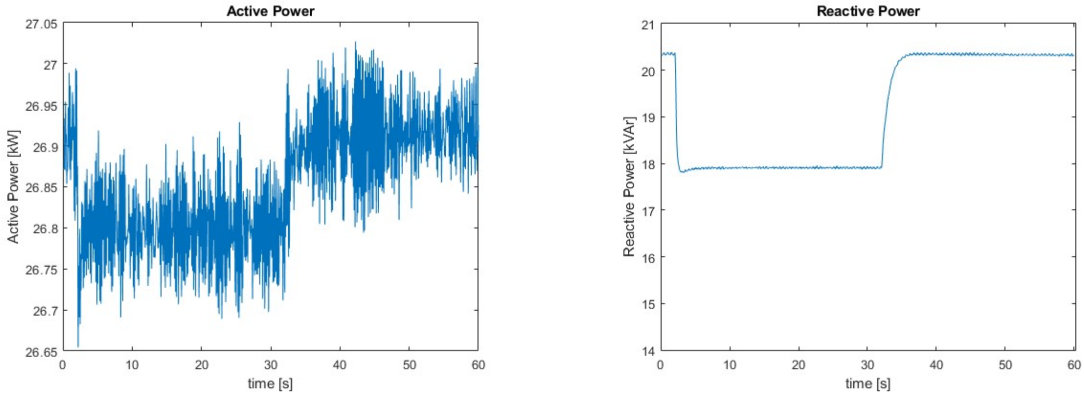


(b) Voltage and reactive power in p.u. during the 5% dips for Semi-Heavy load.

Figure 5.20: Voltage together with active- and reactive power in p.u. for 3-phase during a 5% voltage dip for Semi-Heavy load. Where the active powers base value is 14.92W and the reactive powers base value is 17.88VAr.

5.3.1.1.3 Heavy load

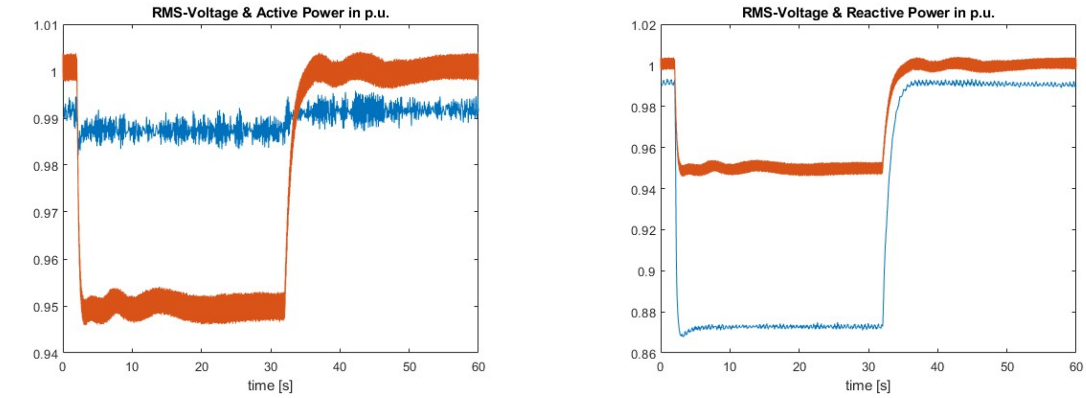
In this subsection the 5% dips are presented in Fig. 5.21 and 5.22 for the Heavy load case.



(a) Active power during the 5% dips for Heavy load.

(b) Reactive power during the 5% dips for Heavy load.

Figure 5.21: Active- and reactive power for 3-phase during a 5% voltage dip for Heavy load.



(a) Voltage and active power in p.u. during the 5% dips for Heavy load.

(b) Voltage and reactive power in p.u. during the 5% dips for Heavy load.

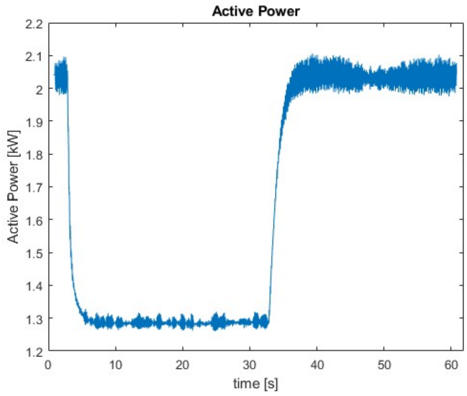
Figure 5.22: Voltage together with active- and reactive power in p.u. for 3-phase during a 5% voltage dip for Heavy load. Where the active powers base value is 26.87W and the reactive powers base value is 20.31VAr.

5.3.1.2 20% dips

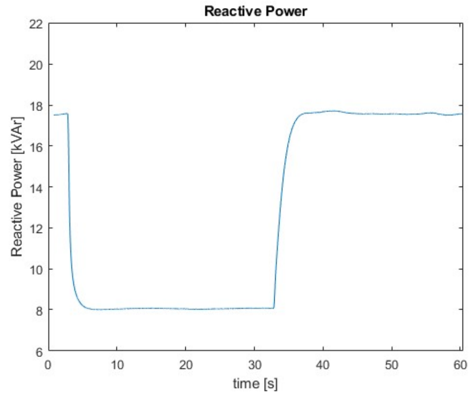
In this subsection the 20% dips are presented in Fig. 5.23 to 5.28 for three different loads, no-load, Semi-Heavy- and Heavy load. 20% dips were executed instead of 30% because of that the heavy load case was assumed to reach too high current.

5.3.1.2.1 No-load

In this paragraph the the 20% dips are are presented in Fig. 5.23 and 5.24 for the no-load case.

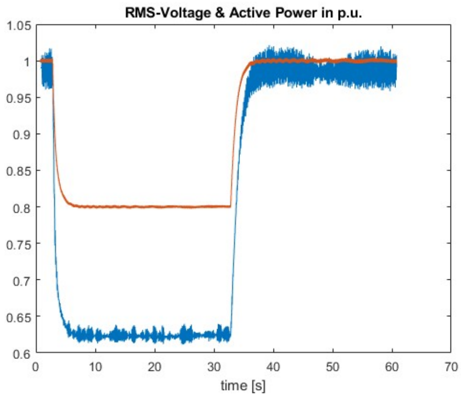


(a) Active power during 20% dips for no-load.

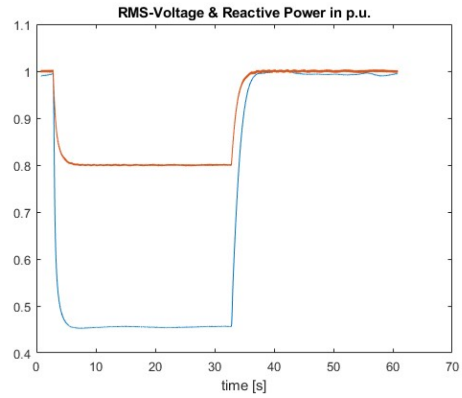


(b) Reactive power during 20% dips for no-load.

Figure 5.23: Active- and reactive power for 3-phase during a 20% voltage dip for no-load.



(a) Voltage and active power in p.u. 20% dips for no-load.

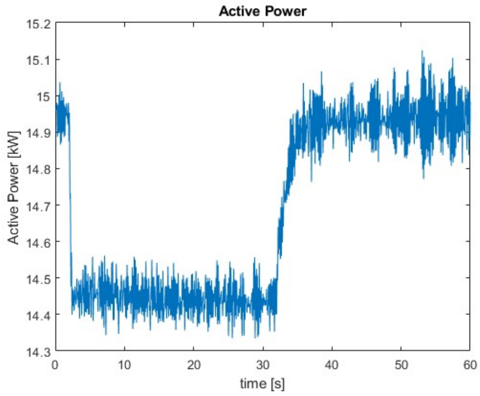


(b) Voltage and reactive power in p.u. 20% dips for no-load.

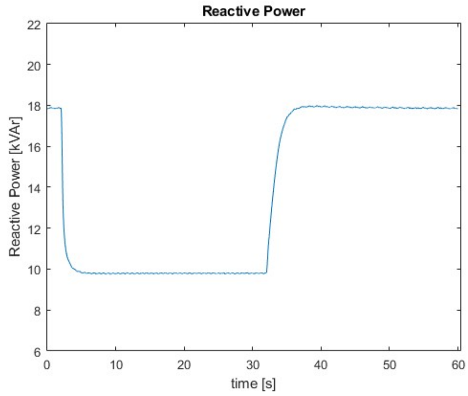
Figure 5.24: Voltage together with active- and reactive power in p.u. for 3-phase during a 20% voltage dip for no-load. Where the active powers base value is 2.05W and the reactive powers base value is 17.5VAr.

5.3.1.2.2 Semi-Heavy load

In this subsection the 20% dips are presented in Fig. 5.25 and 5.26 for the Semi-Heavy load case.

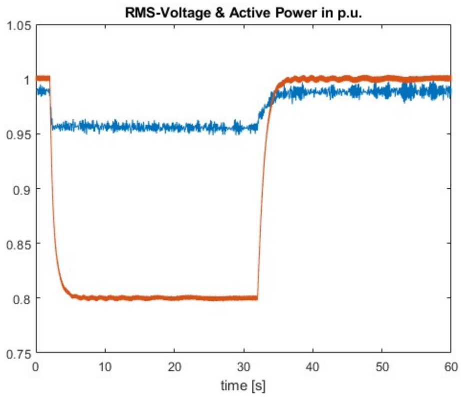


(a) Active power during the 20% dips for Semi-Heavy load.

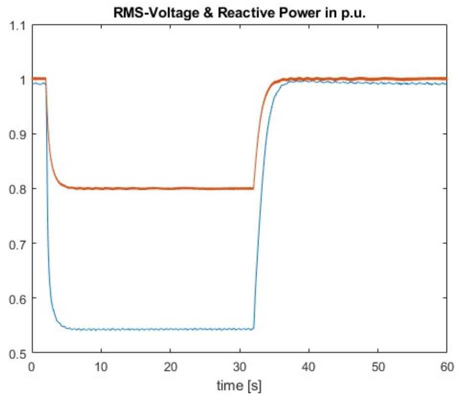


(b) Reactive power during 20% dips for Semi-Heavy load.

Figure 5.25: Active- and reactive power for 3-phase during a 20% voltage dip for Semi-Heavy load.



(a) Voltage and active power in p.u. during the 20% dips for Semi-Heavy load.

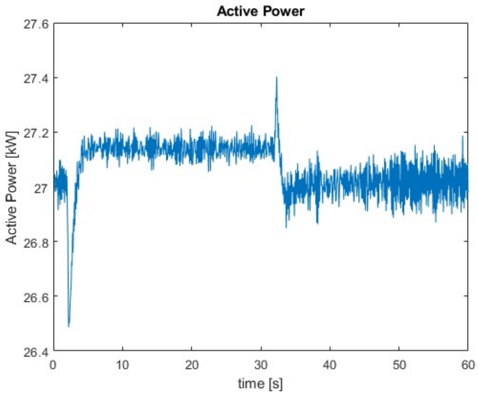


(b) Voltage and reactive power in p.u. during the 20% dips for Semi-Heavy load.

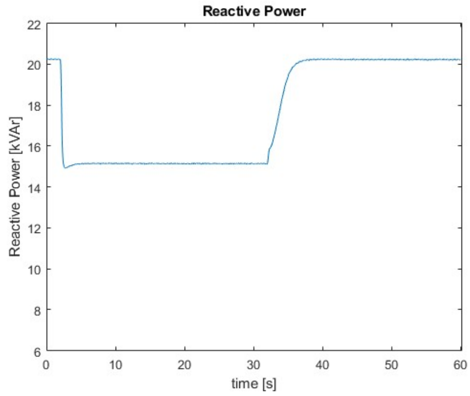
Figure 5.26: Voltage together with active- and reactive power in p.u. for 3-phase during a 20% voltage dip for Semi-Heavy load. Where the active powers base value is 14.92W and the reactive powers base value is 17.88VAr.

5.3.1.2.3 Heavy load

In this subsection the 20% dips are presented in Fig. 5.27 and 5.28 for the Heavy load case.

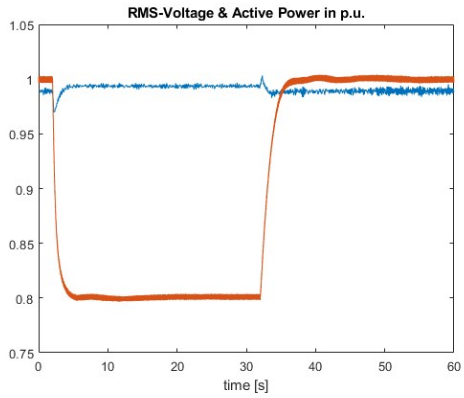


(a) Active power during the 20% dips for Heavy load.

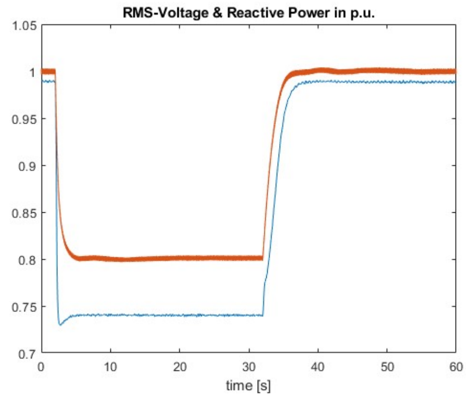


(b) Reactive power during the 20% dips for Heavy load.

Figure 5.27: Active- and reactive power for 3-phase during a 20% voltage dip for Heavy load.



(a) Voltage and active power in p.u. during the 20% dips for Heavy load.



(b) Voltage and reactive power in p.u. during the 20% dips for Heavy load.

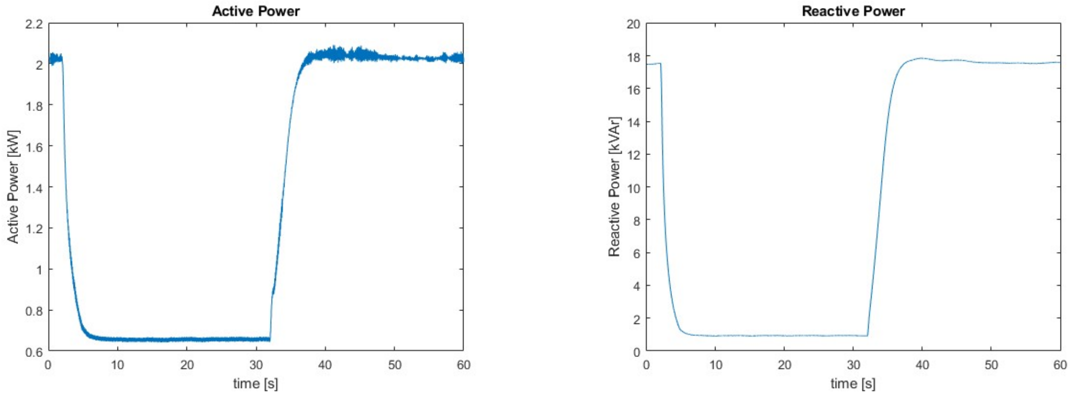
Figure 5.28: Voltage together with active- and reactive power in p.u. for 3-phase during a 20% voltage dip for Heavy load. Where the active powers base value is 26.87W and the reactive powers base value is 20.31VAr.

5.3.1.3 70% dips

In this subsection the 70% dips are presented in Fig. 5.29 to 5.34 for three different loads, no-load, Light- and Semi-Heavy load. With the exception for the Semi-Heavy load where the magnitude of the dip is 50% instead of 70%, since 50% was the most severe dip that could be executed for that load.

5.3.1.3.1 No-load

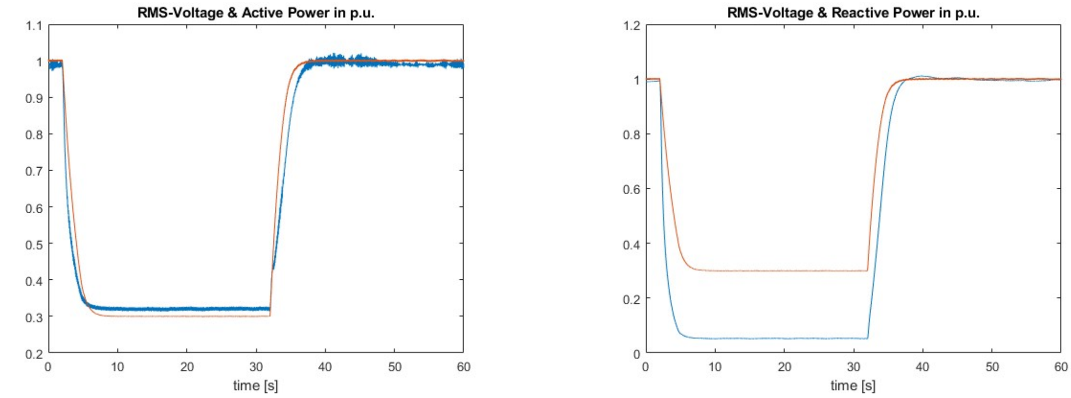
In this paragraph the the 70% dips are are presented in Fig. 5.29 and 5.30 for the no-load case.



(a) Active power during 70% dips for no-load.

(b) Reactive power during 70% dips for no-load.

Figure 5.29: Active- and reactive power for 3-phase during a 70% voltage dip for no-load.



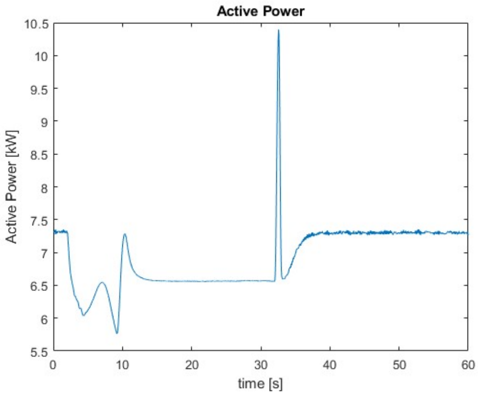
(a) Voltage and active power in p.u. 70% dips for no-load.

(b) Voltage and reactive power in p.u. 70% dips for no-load.

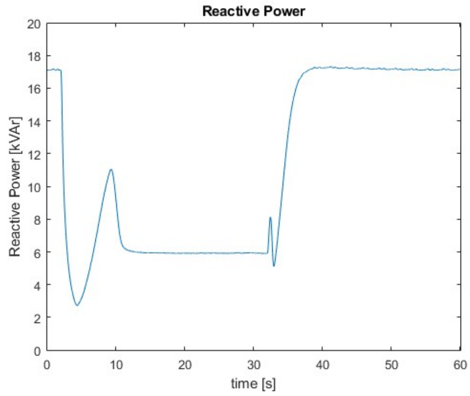
Figure 5.30: Voltage together with active- and reactive power in p.u. for 3-phase during a 70% voltage dip for no-load. Where the active powers base value is 2.05W and the reactive powers base value is 17.5VAr.

5.3.1.3.2 Light load

In this subsection the 70% dips are presented in Fig. 5.31 and 5.32 for the Light load case.

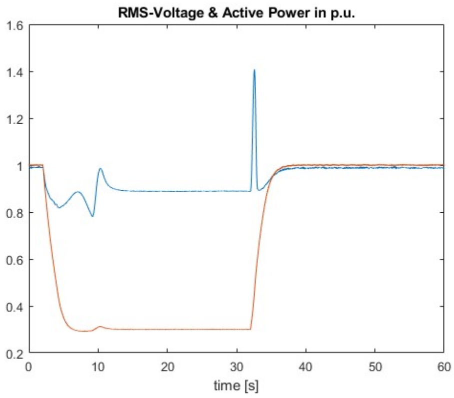


(a) Active power during the 70% dips for Light load.

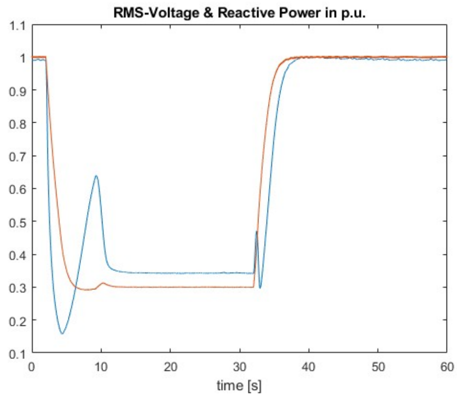


(b) Reactive power during 70% dips for Light load.

Figure 5.31: Active- and reactive power for 3-phase during a 70% voltage dip for Light load.



(a) Voltage and active power in p.u. during the 70% dips for Light load.

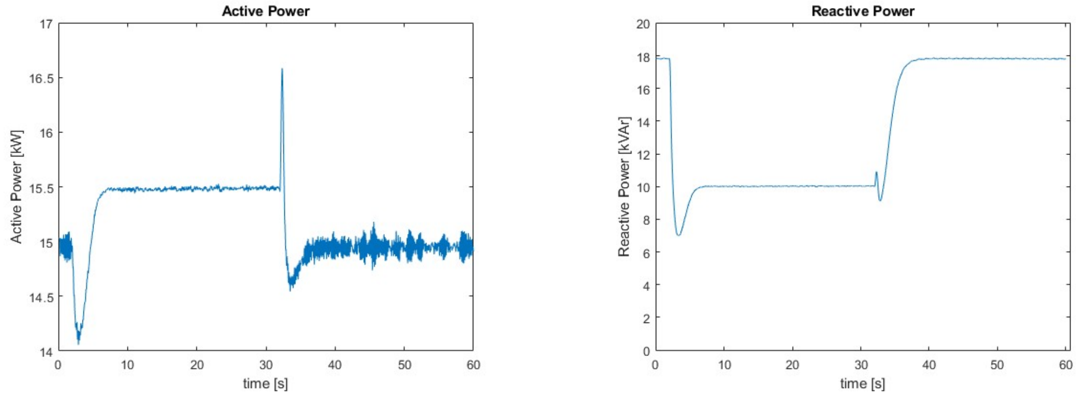


(b) Voltage and reactive power in p.u. during the 70% dips for Light load.

Figure 5.32: Voltage together with active- and reactive power in p.u. for 3-phase during a 70% voltage dip for Light load. Where the active powers base value is 7.31W and the reactive powers base value is 17.11VAr.

5.3.1.3.3 Semi-Heavy load

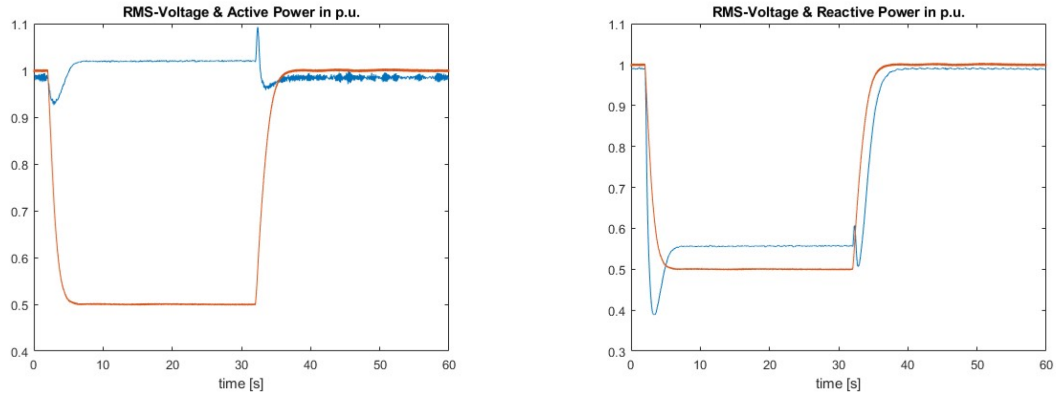
In this subsection the 50% dips are presented in Fig. 5.33 and 5.34 for the Semi-Heavy load case.



(a) Active power during the 50% dips for Semi-Heavy load.

(b) Reactive power during the 50% dips for Semi-Heavy load.

Figure 5.33: Active- and reactive power for 3-phase during a 50% voltage dip for Semi-Heavy load.



(a) Voltage and active power in p.u. during the 50% dips for Semi-Heavy load.

(b) Voltage and reactive power in p.u. during the 50% dips for Semi-Heavy load.

Figure 5.34: Voltage together with active- and reactive power in p.u. for 3-phase during a 50% voltage dip for Semi-Heavy load. Where the active powers base value is 14.92W and the reactive powers base value is 17.88VAr.

5.3.2 Gradual dips

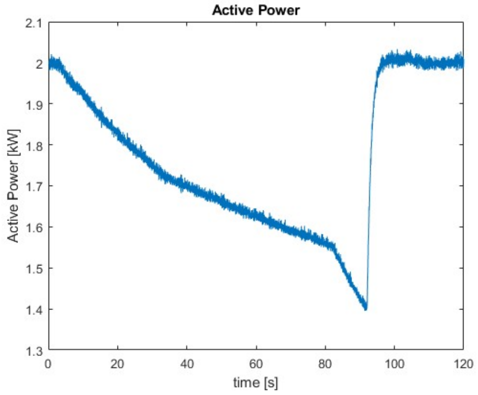
In this section, graphs of the two gradual voltage dips representing what happened in Odensala and Öland during the power failure in Sweden 2003 are shown in Fig. 5.35 to 5.46.

5.3.2.1 Odensala

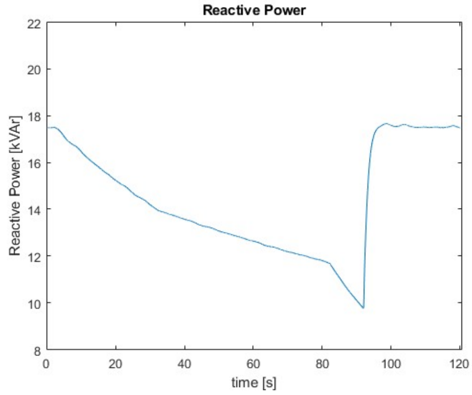
In this subsection the gradual voltage dip representing Odensala are presented in Fig. 5.35 to 5.40 for three different loads, no-load, Semi-Heavy- and Heavy load.

5.3.2.1.1 No-load

In this paragraph the gradual voltage dip representing Odensala are presented in Fig. 5.35 and 5.36 for the no-load case.

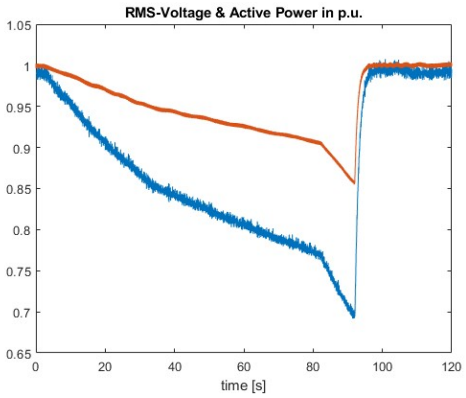


(a) Active power during the Odensala case for no-load.

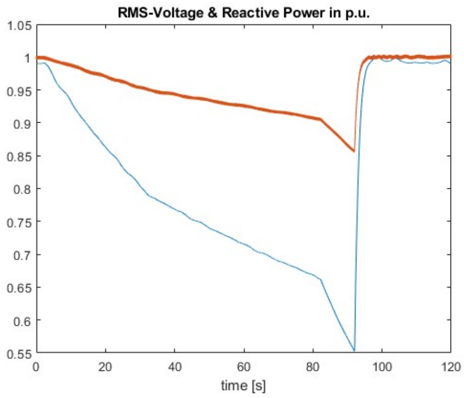


(b) Reactive power during the Odensala case for no-load.

Figure 5.35: Active- and reactive power for 3-phase during a gradual voltage dip Odensala for no-load.



(a) Voltage and active power in p.u. during the Odensala case for no-load.

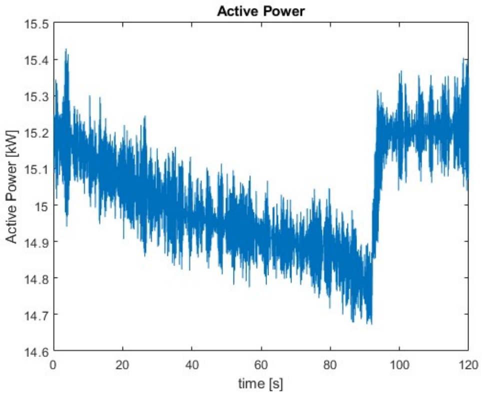


(b) Voltage and reactive power in p.u. during the Odensala case for no-load.

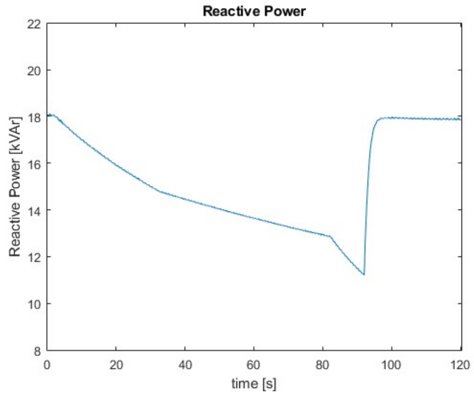
Figure 5.36: Voltage together with active- and reactive power in p.u. for 3-phase during a gradual voltage dip Odensala for no-load. Where the active powers base value is 2.00W and the reactive powers base value is 17.5VAr.

5.3.2.1.2 Semi-Heavy load

In this paragraph the gradual voltage dip representing Odensala are presented in Fig. 5.37 and 5.38 for the Semi-Heavy load case.

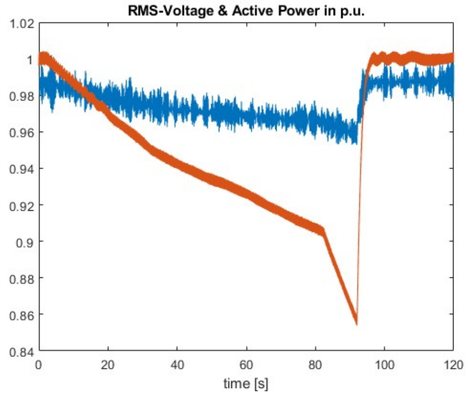


(a) Active power during the Odensala case for Semi-Heavy load.

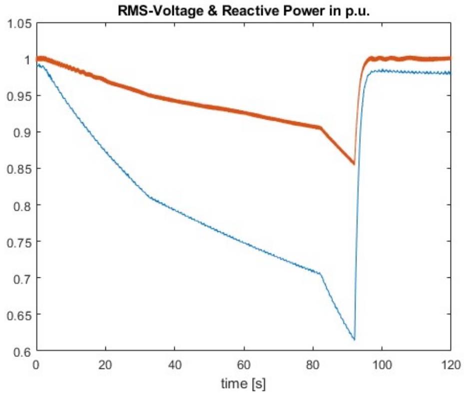


(b) Reactive power during the Odensala case for Semi-Heavy load.

Figure 5.37: Active- and reactive power for 3-phase during a gradual voltage dip Odensala for Semi-Heavy load.



(a) Voltage and active power in p.u. during the Odensala case for Semi-Heavy load.

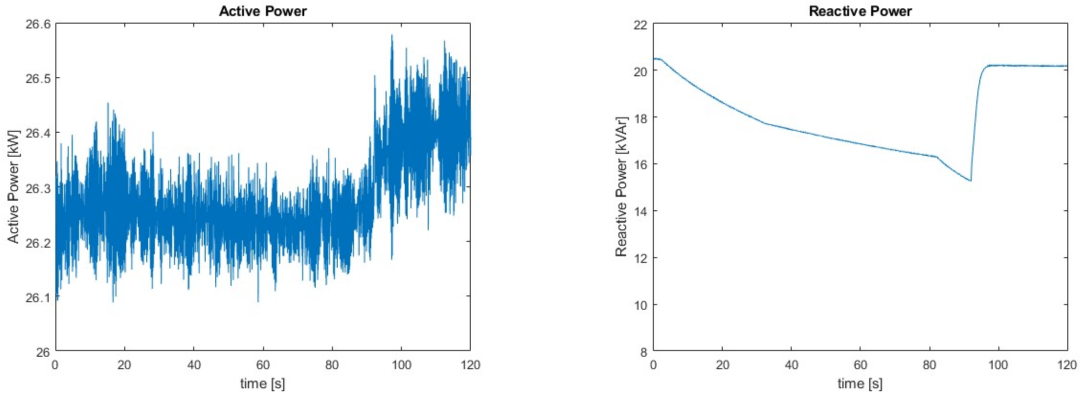


(b) Voltage and reactive power in p.u. during the Odensala case for Semi-Heavy load.

Figure 5.38: Voltage together with active- and reactive power in p.u. for 3-phase during a gradual voltage dip Odensala for Semi-Heavy load. Where the active powers base value is 15.24W and the reactive powers base value is 18.05VAr.

5.3.2.1.3 Heavy load

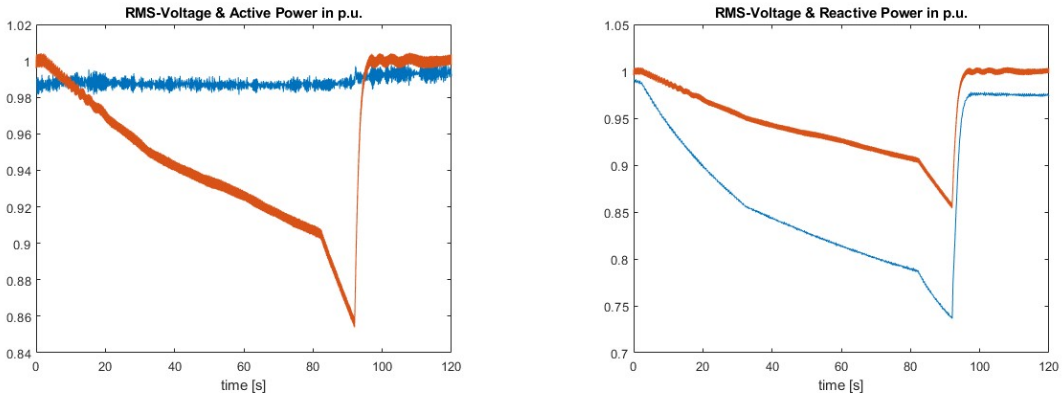
In this paragraph the gradual voltage dip representing Odensala are presented in Fig. 5.39 and 5.40 for the Heavy load case.



(a) Active power during the Odensala case for Heavy load.

(b) Reactive power during the Odensala case for Heavy load.

Figure 5.39: Active- and reactive power for 3-phase during a gradual voltage dip Odensala for Heavy load.



(a) Voltage and active power in p.u. during the Odensala case for Heavy load.

(b) Voltage and reactive power in p.u. during the Odensala case for Heavy load.

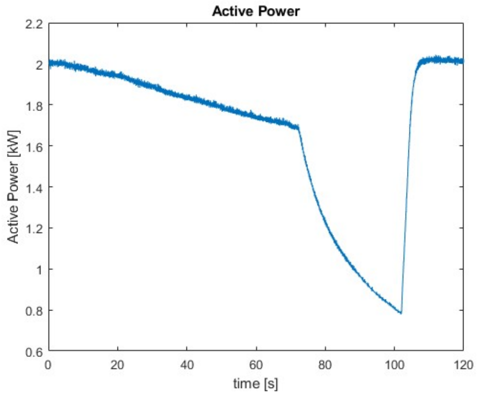
Figure 5.40: Voltage together with active- and reactive power in p.u. for 3-phase during a gradual voltage dip Odensala for Heavy load. Where the active powers base value is 26.31W and the reactive powers base value is 20.31VAr.

5.3.2.2 Öland

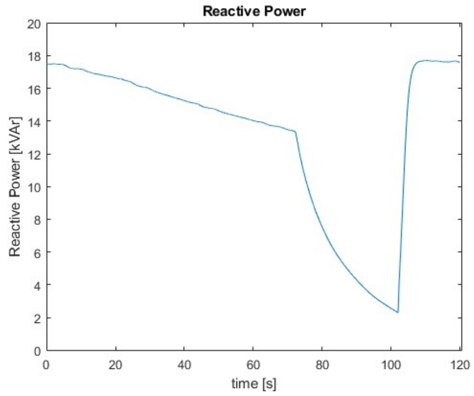
In this subsection the gradual voltage dip representing Öland are presented in Fig. 5.41 to 5.46 for three different loads, no-load, Light- and Semi-Heavy load.

5.3.2.2.1 no-load

In this paragraph the gradual voltage dip representing Öland are presented in Fig. 5.41 and 5.42 for the no-load case.

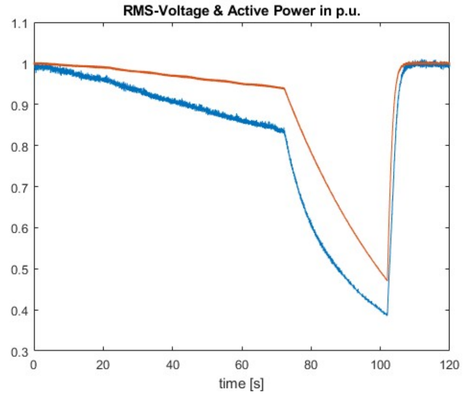


(a) Active power during the Öland case for no-load.

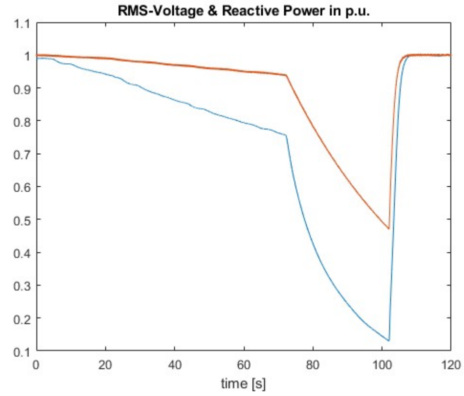


(b) Reactive power during the Öland case for no-load.

Figure 5.41: Active- and reactive power for 3-phase during a gradual voltage dip Öland for no-load.



(a) Voltage and active power in p.u. during the Öland case for no-load.

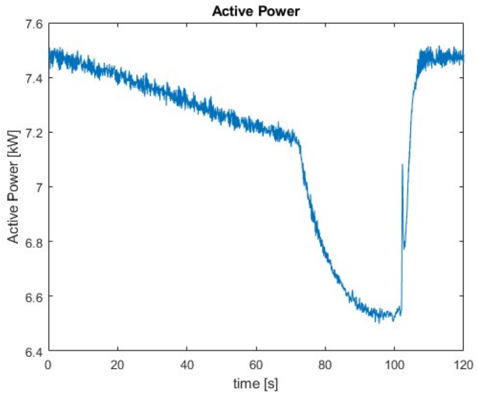


(b) Voltage and reactive power in p.u. during the Öland case for no-load.

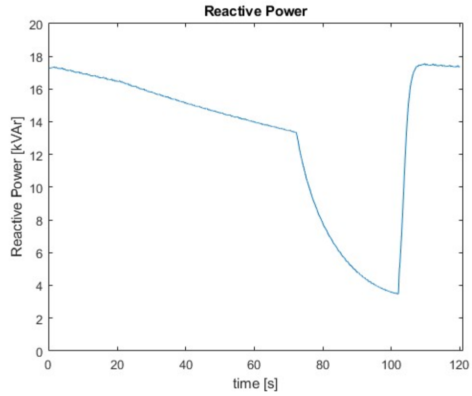
Figure 5.42: Voltage together with active- and reactive power in p.u. for 3-phase during a gradual voltage dip Öland for no-load. Where the active powers base value is 2.00W and the reactive powers base value is 17.05VAr.

5.3.2.2.2 Light load

In this paragraph the gradual voltage dip representing Öland are presented in Fig. 5.43 and 5.44 for the Light load case.

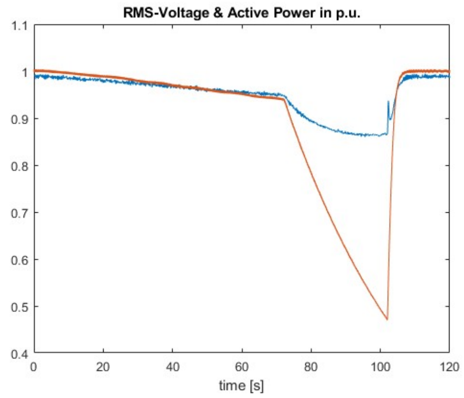


(a) Active power during the Öland case for Light load.

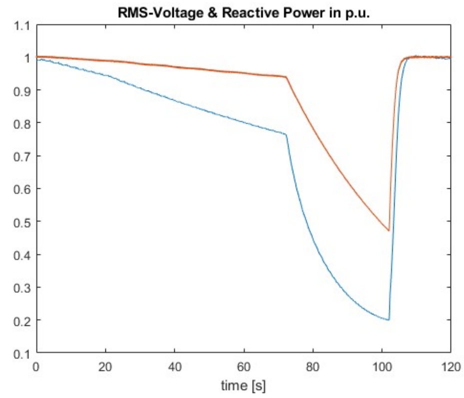


(b) Reactive power during the Öland case for Light load.

Figure 5.43: Active- and reactive power for 3-phase during a gradual voltage dip Öland for Light load.



(a) Voltage and active power in p.u. during the Öland case for Light load.

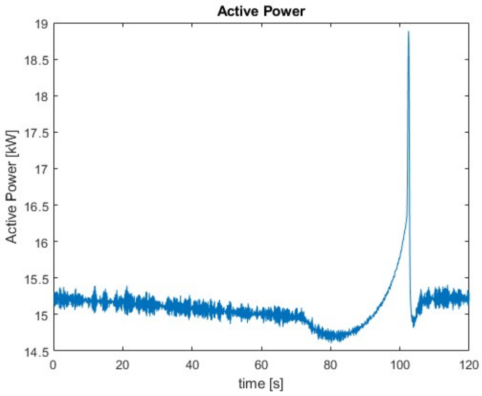


(b) Voltage and reactive power in p.u. during the Öland case for Light load.

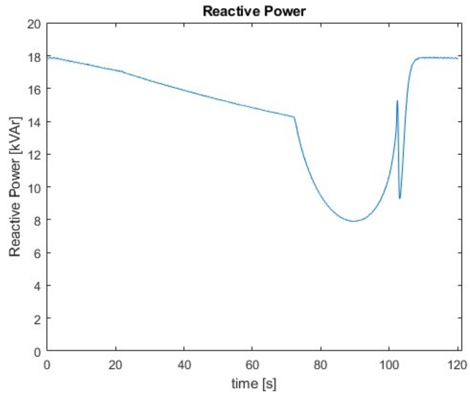
Figure 5.44: Voltage together with active- and reactive power in p.u. for 3-phase during a gradual voltage dip Öland for Light load. Where the active powers base value is 7.5W and the reactive powers base value is 17.27VAr.

5.3.2.2.3 Semi-Heavy load

In this paragraph the gradual voltage dip representing Öland are presented in Fig. 5.45 and 5.46 for the Semi-Heavy load case.

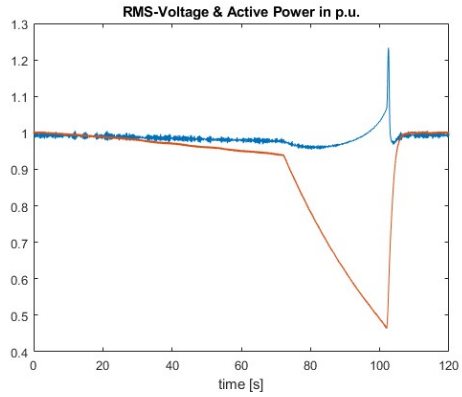


(a) Active power during the Öland case for Semi-Heavy load.

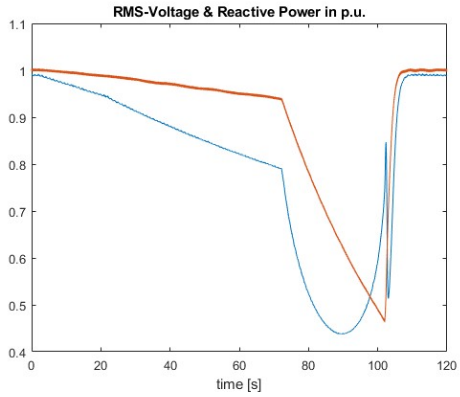


(b) Reactive power during the Öland case for Semi-Heavy load.

Figure 5.45: Active- and reactive power for 3-phase during a gradual voltage dip Öland for Semi-Heavy load.



(a) Voltage and active power in p.u. during the Öland case for Semi-Heavy load.



(b) Voltage and reactive power in p.u. during the Öland case for Semi-Heavy load.

Figure 5.46: Voltage together with active- and reactive power in p.u. for 3-phase during a gradual voltage dip Öland for Semi-Heavy load. Where the active powers base value is 15.16W and the reactive powers base value is 17.87VAr.

5.4 Summary of results from the graphs

In this section, the observations made from the graphs from both the 1-phase and 3-phase IM experiments will be presented.

5.4.1 1-phase IM summary

For the single-phase experiment it can be observed from the plots in p.u. that both the active- and reactive power dips by the same magnitude, as can be seen in fig.

5.47. However, the difference is that the reactive power has a higher value than the active power.

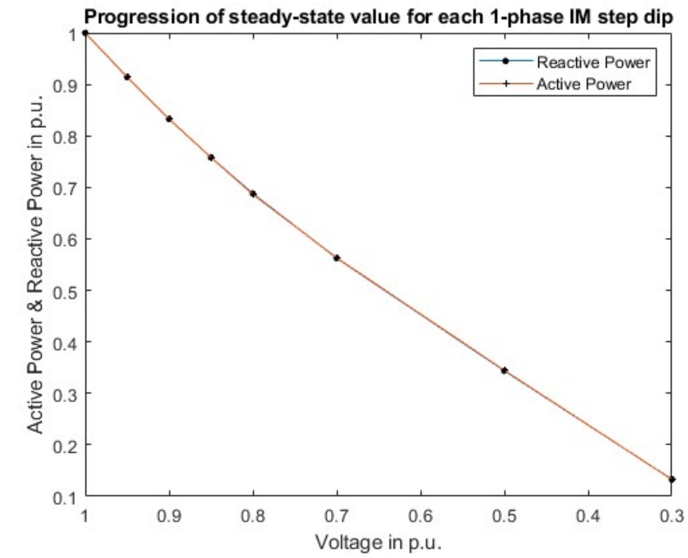


Figure 5.47: The voltage compared to active- and reactive power of the steady-state values for 2 min duration of step dips 5%, 10%, 15%, 20%, 30%, 50% and 70%. Where the base value for active power is 73.85W, reactive power is 91.0VAr and voltage is 400V.

The following fig. 5.48 is a zoomed in version of fig. 5.47, which shows that the active- and reactive power does not follow the exact same percentage voltage dependent drop, but a very similar drop path.

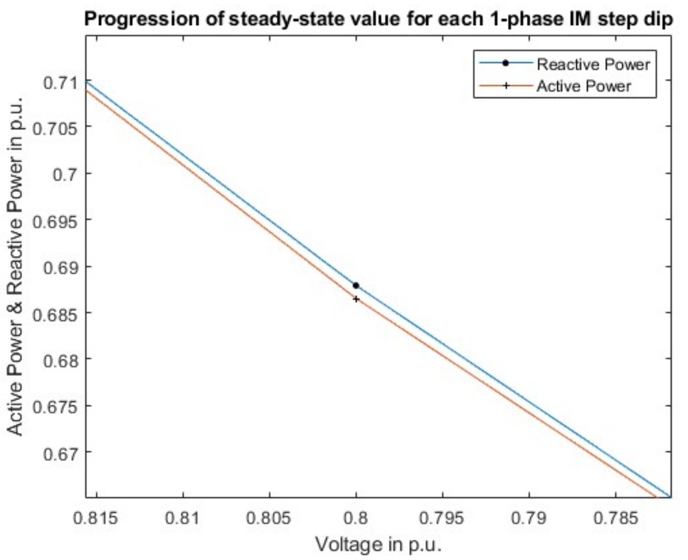


Figure 5.48: A zoomed in version of fig. 5.47 at the point of 20% voltage drop.

It can also be seen for all experiments that the peaks of both the active- and reactive power that occur when the voltage recovers from the dip to stable voltage, increase with both a greater voltage dip and a longer duration time of the voltage dip. This can be related to the start-current induced by the motor windings. At the voltage drop point and voltage recovery point for the step voltage dips for 5% and 30% a spike in active and reactive power can be observed. It can as well be observed a spike in the current measurments at the same points. For the 70% voltage drop case the active and reactive power have a very small downward spike at the voltage drop point which is very close to 0 W and 0 VAr. There is no current spike observed at the voltage drop point for 100ms drop duration and for 2 minutes duration a small spike can be observed.

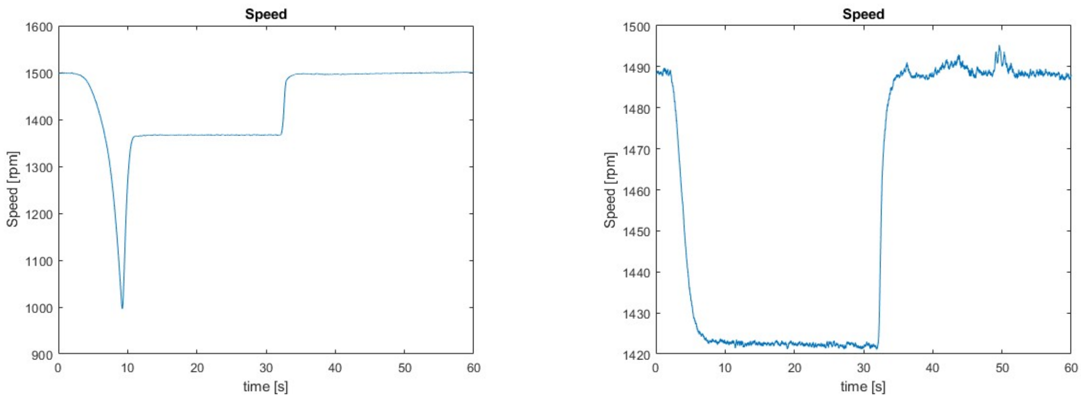
5.4.2 3-phase IM summary

For the 3-phase experiment it can be observed that when the IM is unloaded, the active- and reactive power drops linearly with the magnitude of the voltage dip. In other words, the reduction of active power and reactive power is greater for a greater voltage dip. But when there is a load applied, the reactive power follows the same pattern of dropping linearly with the magnitude of the voltage dip. The active power on the other hand, does not dip to the same extent, instead it keeps itself on a stable level close to 1 p.u. during the step dips. However, when the IM is loaded it can be seen that for voltage dips of 5% and 20% decrease in nominal voltage, the dips of the active- and reactive power decreases with the increase of load. For example, the active- and reactive power drops to a lower level for Semi-Heavy load than it does for Heavy load.

For the 20% voltage drop at Heavy load the Active power increases slightly during the voltage drop. It can be observed that the current increases during the voltage drop from approximately 45A to approximately 52A. For the 50% voltage drop for semi heavy load the active power increases about 0.5W during the voltage drop with a spike at the voltage recovery point. It can be observed that the current increases as well during the voltage drop from about 30 A to about 50A. At the voltage drop point the current has a downward spike to about 26A and an unreadable spike at the voltage recovery point.

For 70% dip for light load the active power has a high upward spike at the voltage recovery point from about 6.6W to 10.5W where there is a current spike as well at about 45A from the nominal current at about 25A. For the Öland case at semi heavy load there is a high active power peak at the voltage recovery point from about 15W to about 19W. At the voltage recovery point the current has a steep upward spike from about 30A to about 65A. For the Odensala case for heavy load the Active power increases to about 0.3W at the voltage recovery point and stays at the higher value when the voltage has stabilized, this might be because of some malfunction at the measuring start resulting in a lower start measuring value.

Moreover, there are also two notable special cases, these are the voltage dips of 70% for Light load (see figure 5.32) and 50% for Semi-Heavy load (see figure 5.34). For both of these cases, the reactive power stabilizes at a level above the newly reduced voltage level, which is unusual since the reactive power stabilizes below the reduced voltage level for all the other step dips. According to the static load model, the difference of reactive power in relation to the voltage dip for 70% Light load was 1.14 or 114%, while for 50% Semi-Heavy load it was 1.11 or 111%. In the 70% Light load case, the IM takes longer than usual to reach steady-state at the reduced voltage level, it takes approximately 10 seconds compared to almost immediately for all the other step dips. In addition, there is also a significant drop of speed from 1500rpm to 1000rpm during the transition period until it stabilizes at 1370rpm. At this speed drop, the sound of the engine changed drastically and the current peaked ut to the limit at 63A but decreased before the fuses could blow. The static load model for this case shows that the active power was 2.97 or 297% in relation to the voltage. For the case of the 50% voltage dip for Semi-Heavy load, the active power increases slightly keeping close to 1 p.u. instead of decreasing as it would normally do. For this case the static load model for active power was 2.04 or 204%. The speed for this case stabilizes at around 1425rpm, which is the lowest stable speed that the IM reached for any step dips.



(a) Speed in rpm during a voltage dip of 70% for Light load.

(b) Speed in rpm during a voltage dip of 50% for Semi-Heavy load.

Figure 5.49: Speed in rpm for the 3-phase IM during two different step dips.

For the gradual voltage dips, the active- and reactive power follows the voltage dip proportionally when the IM is unloaded. When a load is applied however, the active power is more stable and drops less the higher the load is. For the Öland case with Semi-Heavy load (see figure 5.46), the active power is heavily increased towards the end of the voltage dip and peaks at slightly above 1.2 p.u. at the point when the voltage is recovering. The static load model for active power for this case was 1.23 or 123%. When the voltage dip is heavily increased the active power at first starts to drop before is starts to increase. At the same point as the active power drops, the speed of the IM starts to drop and keeps on dropping (when the active power starts to increase) to approximately 1370 rpm until the voltage is recovered (see figure 5.50). When the speed reduced in this way the sound of the engine changed and the current peaked and hit the limit of 63A but decreased before the fuses were blown. The reactive power also behaves unlike it does during the other gradual dips, in this case it starts to increase when the voltage is still decreasing and only stops because the duration time for the voltage dip ended and the voltage recovered to nominal voltage. The static load model shows that the reactive power for this case was 1.84 or 184%.

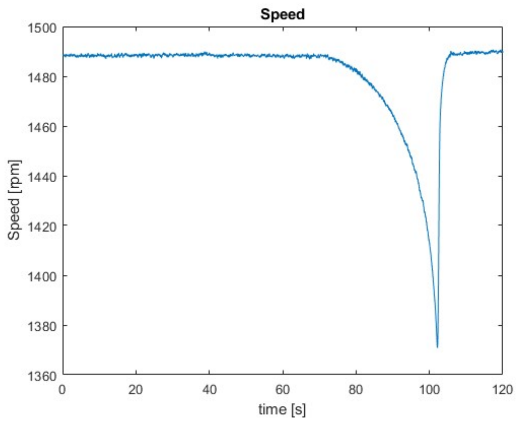


Figure 5.50: Speed in rpm during the Öland case for Semi-Heavy load.

6
Conclusion

Experiments on the voltage dependence for the consumption of active- and reactive power during voltage dips on induction motors of single- and three-phase has been performed and evaluated. For voltage dips of the step dip characteristic, the active- and reactive power show good linear dependence on the voltage amplitude for single phase IM. The active power also show good linear dependence for unloaded 3-phase IM but not for loaded 3-phase IM, where the active power keeps at a stable level around its original value. The reactive power however, show great linear dependence for unloaded 3-phase IM and for voltage dips of up to 70% of up to light load or for voltage dips of up to 50% for loads up to Semi-heavy load.

For voltage dips of the gradual dip characteristic, the active- and reactive power also show good linear dependence on the voltage amplitude for both 1-phase and unloaded 3-phase IM. For loaded 3-phase IM, the active power keeps at a stable level around its original value for gradual voltage dips of Odensala of all loads but only for Öland of up to Semi-heavy load. The reactive power show good linear dependence for Odensala of all loads and for Öland of loads of up to Semi-Heavy load.

For the 3-phase IM experiments executed in this degree project it is possible to make limited conclusions because of the fuse current limit of the IM. The current limit of 63A limited the load experiments to light load for 70% voltage dip and semi-heavy load to 50% voltage dip. From those limits it can be concluded that for loaded IM the voltage dip sensitiveness for the voltage dip level increases. The speed is affected for both limits, for the 70% voltage drop the speed drops to 1000rpm which touches the fuse blow level before the voltage and speed is recovered. For this case the active power drops with the speed and stays under 1 p.u. as long as the speed is below nominal speed. For a higher load at the 50% voltage drop the active power drops at the speed drop as well but increases above 1 p.u. when the speed is stabilised at a lower speed than nominal speed at 1420 rpm. From these limited experiments it can be concluded that for higher load the active power increases after a speed drop, and the level is decided by the stabilised speed level after the speed drop.

The active and reactive power peaks that occur at the voltage recovery point when the three phase machine is loaded might be an issue if all IM loads react in the same way causing an overload of the electrical grid resulting in that it breaks down.

From the literature review the research from Le Dous [12] shows that the percentage magnitude of a voltage dip in the 130kV grid is transferred to the same percentage magnitude in the 230V grid. This indicates that the gradual dip models designed to imitate the measured voltage dips at Öland and Odensala in 2003 could be a reliable simulation for the voltage dip at IM loads.

From an environmental point of view the voltage dependence and active power and reactive power consumption of IMs is important to study to learn about how the losses behaves and changes during voltage dips. Since the IMs consume about 40% of the produced electrical energy worldwide, the knowledge of their behaviour is of great importance to use the produced electrical energy environmentally friendly. This to be able to minimize the losses of the produced electrical energy and to use the produced electrical energy more efficiently.

The electricity production in Sweden and in many parts of the world is transferring into more and more renewable electrical production in terms of solar power and wind power which are weather dependent and sensitive to disturbances which creates different conditions to handle. These power sources can cause production instabilities which makes it important to know the voltage instability behaviour of IMs.

From an ethical point of view it is of importance from which electrical power production source the electricity comes and of great importance to make use of it. If the produced electrical power comes from an unsustainable power production source such as CO2 polluting coal it would be unethical to not make use of it to the highest extent. So by increasing the knowledge of voltage drop operation of IMs, the effects and presence of voltage drops can have minimized effects or be prevented and thereby minimize the waste/losses of the produced electricity.

7

Future work

Further work in this field may be field measurements of industrial IM loads with a greater voltage amplitude.

Execute the same experiments for a 3-phase IM with higher current limit to be able to examine if increased load increases active power consumption linearly after the speed drop during a voltage dip for all cases of increased load for the IM during voltage dip.

Evaluate how power electronics controlled IMs are affected by the same experiments.

Perform short circuit experiments and evaluate how they affect IMs. These faults can be symmetrical to all three lines or unsymmetrical faults, with short circuits line to line or line to ground.

Bibliography

[1] Svenska Kraftnät, "Elavbrottet 23 september 2003 - händelser och åtgärder," Svenska Kraftnät, Stockholm, Sweden, Nr 1:2003, 2003. [Online]. Available: https://www.svk.se/siteassets/om-oss/rapporter/2015-och-aldre/rapport_avbrott_20030923_for_webb.pdf, Accessed: 2024-06-01.

[2] Y. Liu, J. Tang, N. Sharma, A. Rodionov, Electrical Machines: Design and Analysis , 1st Edition. 1st.Edition., Gothenburg, Sweden: Springer, 2019.

[3] SUNPOWER electronics, "Voltage Dip," 2019. [Online]. Available: https://www.sunpower-uk.com/glossary/what-is-a-voltage-dip/ (Accessed: 2024-06-01).

[4] MathWorks, "What Is MATLAB?," 2024. [Online]. Available: https://se.mathworks.com/discovery/what-is-matlab.html (Accessed: 2024-06-01).

[5] MathWorks, "What Is Simulink?," 2019. [Online]. Available: https://se.mathworks.com/videos/simulink-overview-61216.html (Accessed: 2024-06-01).

[6] REGATRON, "Series Overview," 2024. [Online]. Available: https://www.regatron.com/product/overview/programmable-bidirectional-ac-power-sources/tc-acs-series/#general-overview (Accessed: 2024-06-01).

[7] dSPACE, "ControlDesk," 2024. [Online]. Available: https://www.dspace.com/en/inc/home/products/sw/experimentandvisualization/controldesk.cfm (Accessed: 2024-06-01).

[8] ElProCus, "What is a DC Machine : Construction & Its Working," 2024. [Online]. Available: https://www.elprocus.com/dc-machine-types-and-their-applications/ (Accessed: 2024-06-01)

[9] MathWorks, "Per-Unit System of Units," 2024. [Online]. Available: https://se.mathworks.com/help/sps/ug/per-unit-system-of-units.html (Accessed: 2024-06-01).

[10] S. Hardi, S. Hs, M. Hafizi, Z. Pane and R. Chan, "Induction motors performance under symmetrical voltage sags and interruption - Test result," 2013 IEEE 7th International Power Engineering and Optimization Conference (PEOCO), Langkawi, Malaysia, 2013, pp. 630-635. [Online] doi: 10.1109/PEOCO.2013.6564624, Accessed: 2024-06-01.

[11] Prateeksha and P. Thakur, "Assessment of Voltage Unbalance Factor to Evaluate its Effect on Three Phase Induction Motor," 2023 3rd International Conference on Emerging Frontiers in Electrical and Electronic Technologies (ICEFEET), Patna, India, 2023, pp. 1-6. [Online] doi: 10.1109/ICEFEET59656.2023.10452198, Accessed: 2024-06-01.

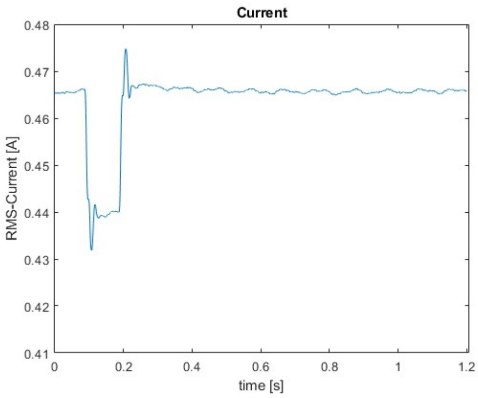
[12] G. Le Dous, "Voltage Stability in Power Systems," Chalmers University Of Technology, Gothenburg, Sweden, No. 324 L, 1999.

[13] T. Van Cutsem, C. Vournas, "Voltage stability of electric power systems," University of Illinois, Urbana, USA, 1998.

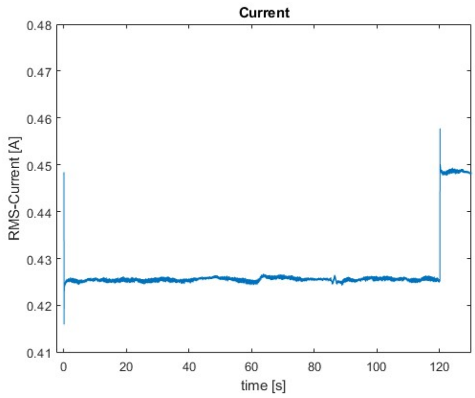
A

Appendix 1

A.1 Currents from 1-phase experiments

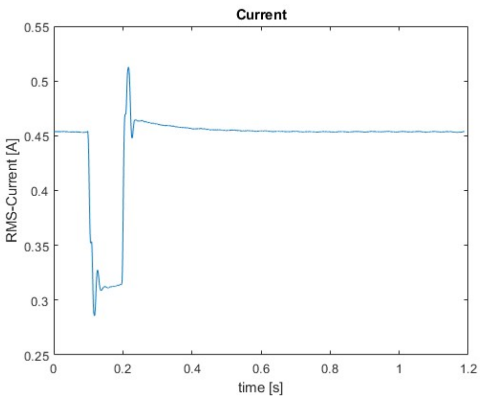


(a) Current during a voltage dip of 5% for 100ms.

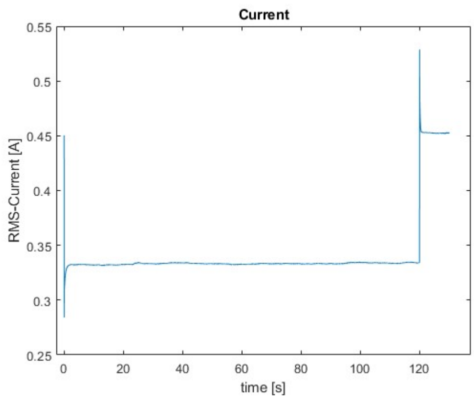


(b) Current during a voltage dip of 5% for 2 minutes.

Figure A.1: Current during two different durations for a 5% step dip for the 1-phase IM.

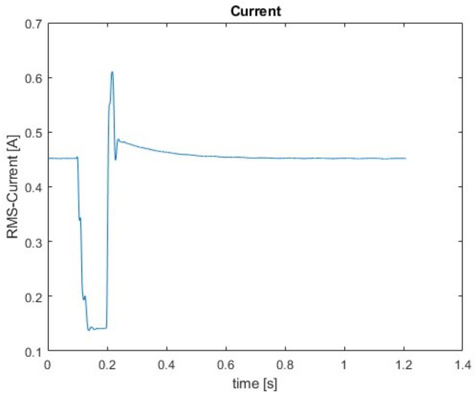


(a) Current during a voltage dip of 30% for 100ms.

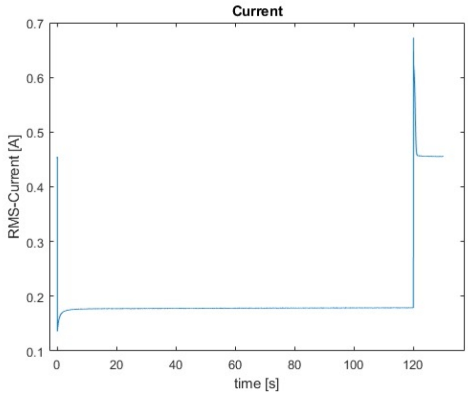


(b) Current during a voltage dip of 30% for 2 minutes.

Figure A.2: Current during two different durations for a 30% step dip for the 1-phase IM.



(a) Current during a voltage dip of 70% for 100ms.



(b) Current during a voltage dip of 70% for 2 minutes.

Figure A.3: Current during two different durations for a 70% step dip for the 1-phase IM.

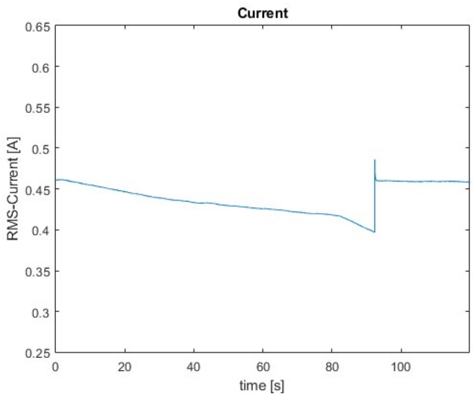


Figure A.4: Current during a gradual dip of the Odensala case for the 1-phase IM.

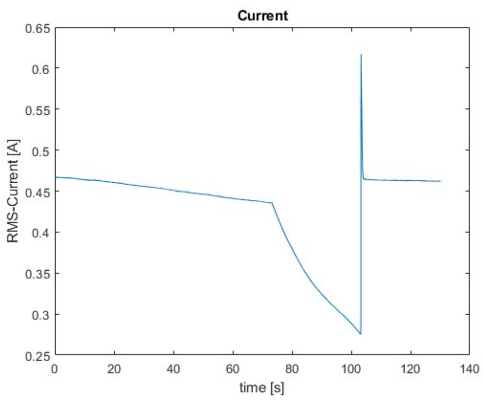
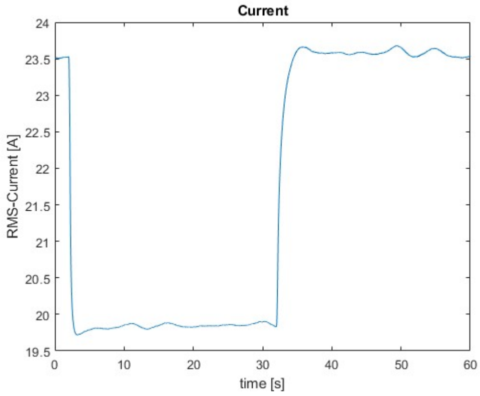


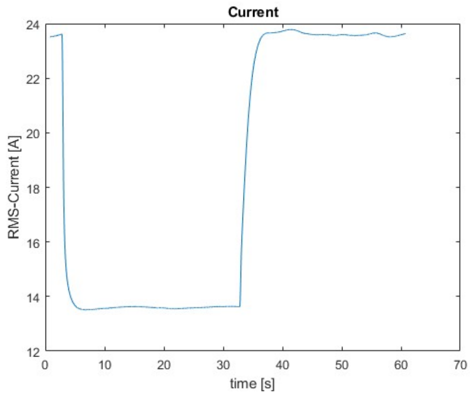
Figure A.5: Current during a gradual dip of the Öland case for the 1-phase IM.

A.2 Currents from 3-phase experiments



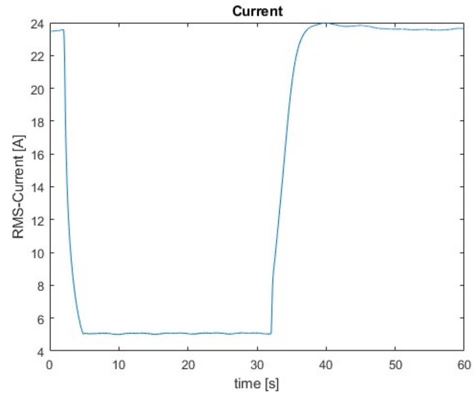
(a) Current during a voltage dip of 5% for no-load.

Figure A.6: Current during a 5% step dip for no-load for the 3-phase IM.



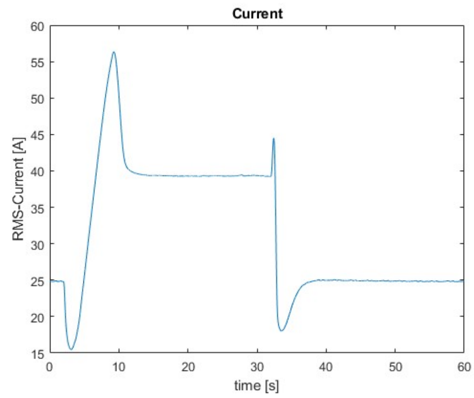
(a) Current during a voltage dip of 20% for no-load.

Figure A.7: Current during a 20% step dip for no-load for the 3-phase IM.



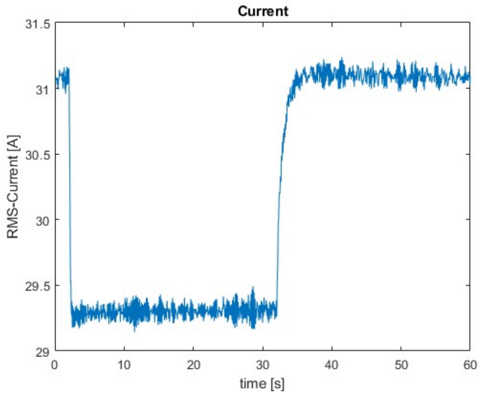
(a) Current during a voltage dip of 70% for no-load.

Figure A.8: Current during a 70% step dip for no-load for the 3-phase IM.



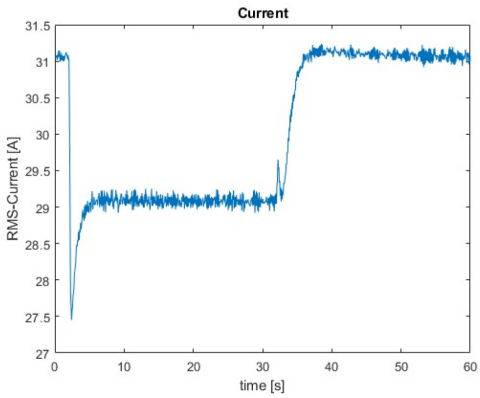
(a) Current during a voltage dip of 70% for Light load.

Figure A.9: Current during a 70% step dip for Light load for the 3-phase IM.



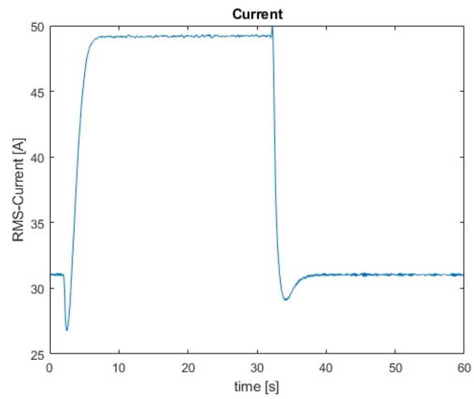
(a) Current during a voltage dip of 5% for Semi-Heavy load.

Figure A.10: Current during a 5% step dip for Semi-Heavy load for the 3-phase IM.



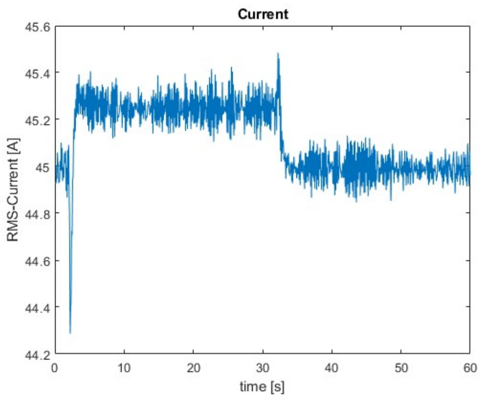
(a) Current during a voltage dip of 20% for Semi-Heavy load.

Figure A.11: Current during a 20% step dip for Semi-Heavy load for the 3-phase IM.



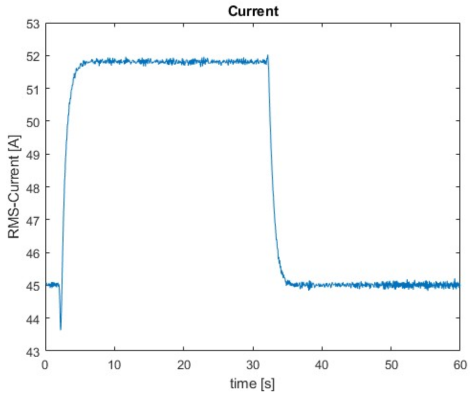
(a) Current during a voltage dip of 50% for Semi-Heavy load.

Figure A.12: Current during a 50% step dip for Semi-Heavy load for the 3-phase IM.



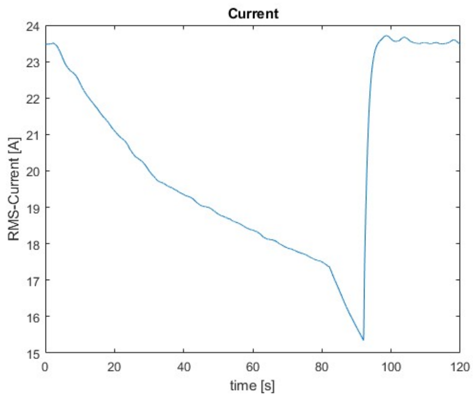
(a) Current during a voltage dip of 5% for Heavy load.

Figure A.13: Current during a 5% step dip for Heavy load for the 3-phase IM.



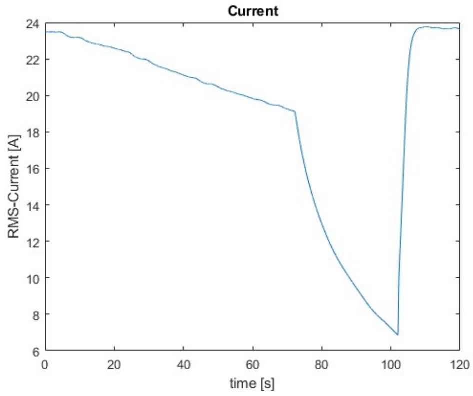
(a) Current during a voltage dip of 20% for Heavy load.

Figure A.14: Current during a 20% step dip for Heavy load for the 3-phase IM.



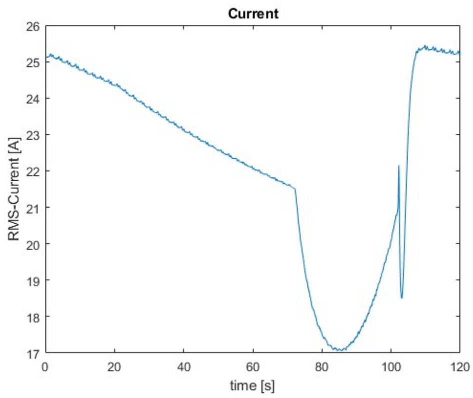
(a) Current during a gradual voltage dip Odensala for no-load.

Figure A.15: Current during a gradual dip Odensala for no-load for the 3-phase IM.



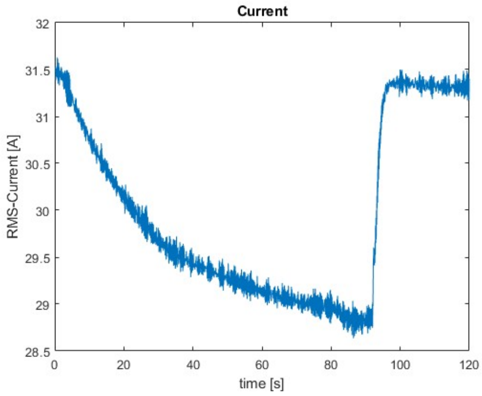
(a) Current during a gradual voltage dip Öland for no-load.

Figure A.16: Current during a gradual dip Öland for no-load for the 3-phase IM.



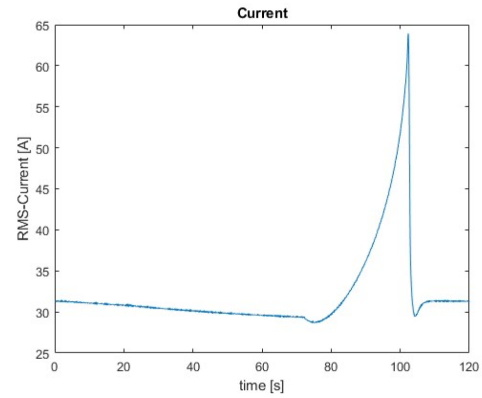
(a) Current during a gradual voltage dip Öland for Light load.

Figure A.17: Current during a gradual dip Öland for Light load for the 3-phase IM.



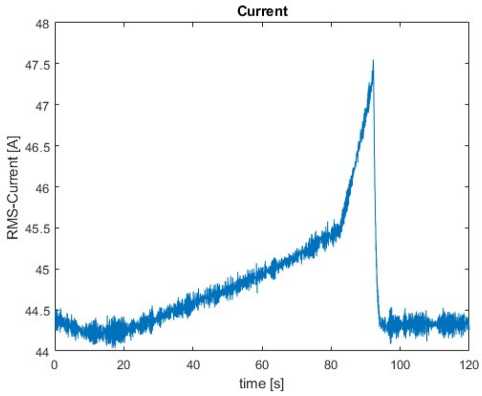
(a) Current during a gradual voltage dip Odensala for Semi-Heavy load.

Figure A.18: Current during a gradual dip Odensala for Semi-Heavy load for the 3-phase IM.



(a) Current during a gradual voltage dip Öland for Semi-Heavy load.

Figure A.19: Current during a gradual dip Öland for Semi-Heavy load for the 3-phase IM.



(a) Current during a gradual voltage dip Odensala for Heavy load.

Figure A.20: Current during a gradual dip Odensala for Heavy load for the 3-phase IM.

B
Appendix 2

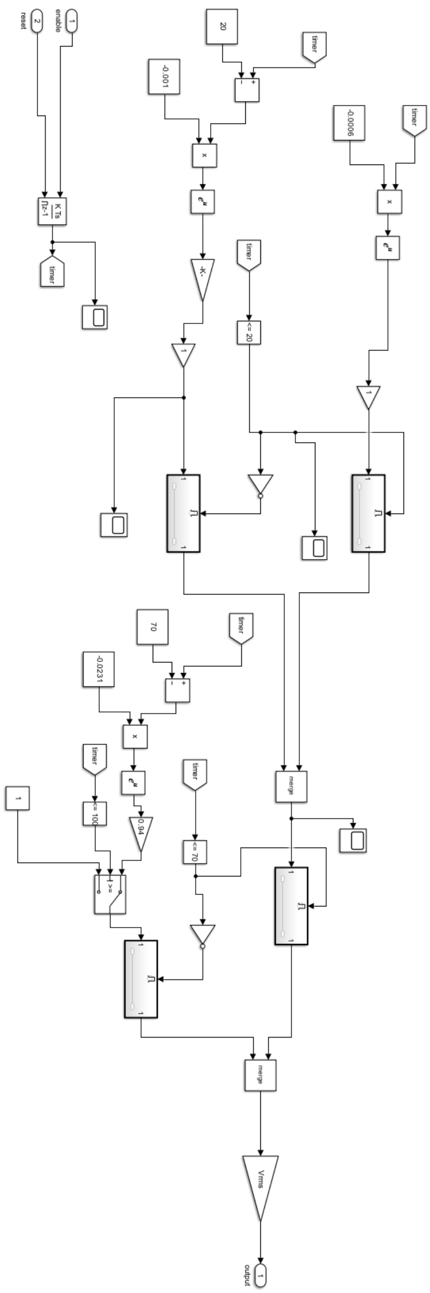


Figure B.1: Figure showing the Simulink gradual dip model simulating the voltage dip in the 50kV grid at Öland in Sweden in 2003.

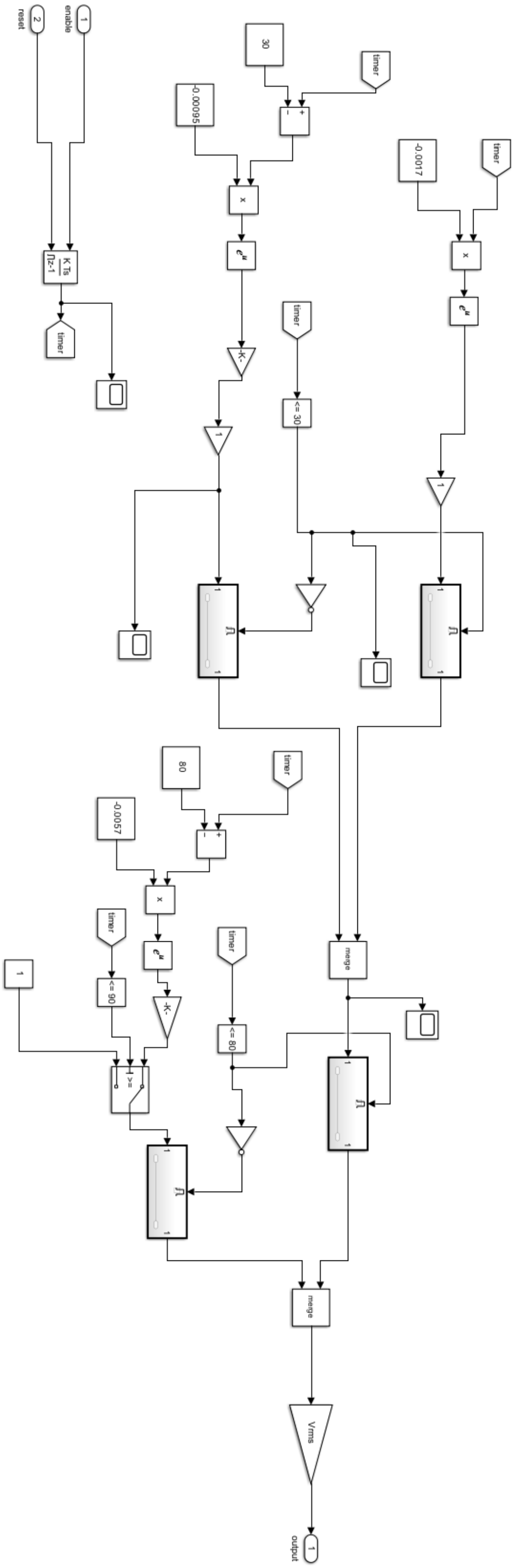


Figure B.2: Figure showing the Simulink gradual dip model simulating the voltage dip in the 400kV grid in Odensala in Sweden in 2003.

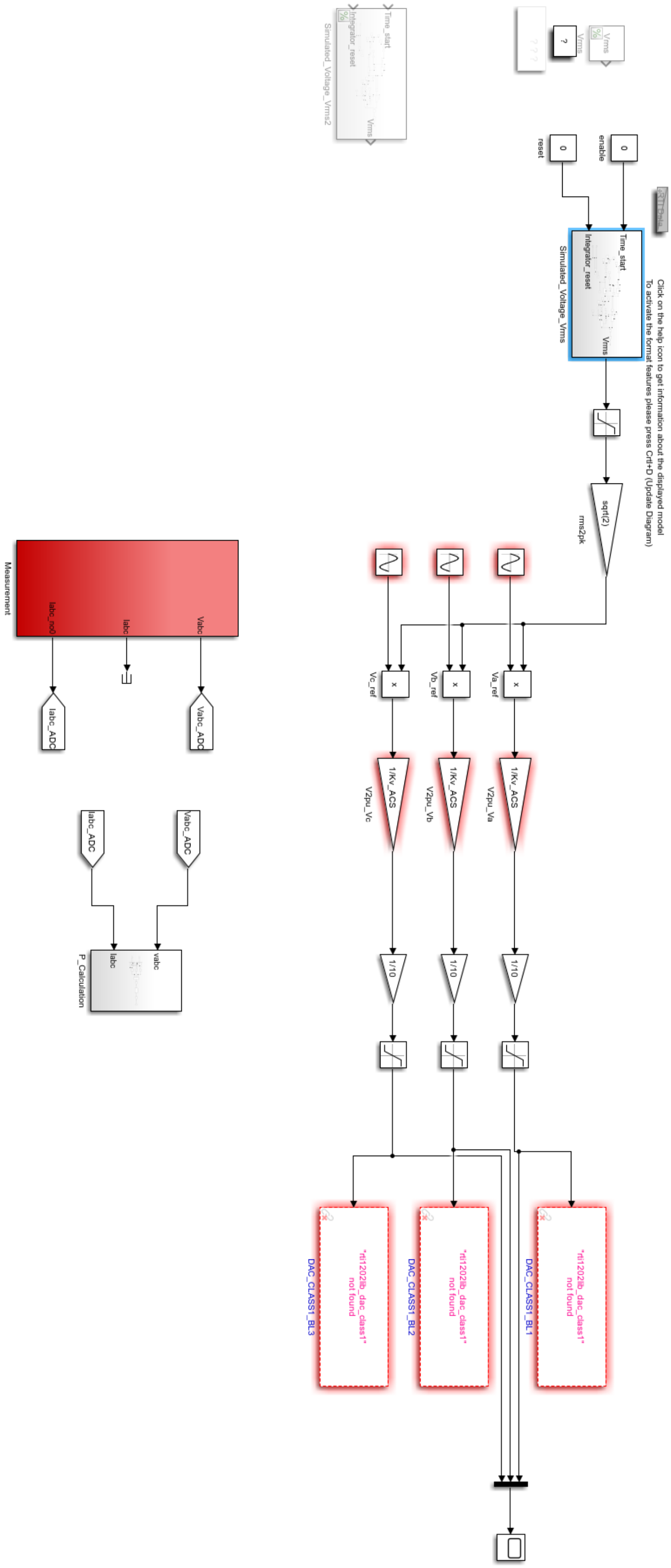


Figure B.3: Figure showing the Regatron ACS voltage output model creating a 3-phase output. The blue marked block is the Gradual dip model.

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