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Modelling DC Backup system with Simpow

Master's Thesis in the Electric Power Engineering

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Division of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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A UPS cubicle [15]

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ABSTRACT

Oskarshamn Nuclear Power Plants DC backup systems are vital parts of the operation. In case of fault in or outside the power plant this particular system has to continuously supply voltage in order to keep important loads in operation. The DC backup system of the Oskarshamn Nuclear Power Plant has not been modelled and the main purpose of this work is to model the DC backup system with Simpow software. In this master thesis work a small part of the DC backup system is modelled with Simpow.

First the data concerning all the components is gathered from the Oskarshamn Nuclear Power Plant. All gathered information are put into the Simpow power simulation software. Converters in the software and at Oskarshamn Nuclear Power Plant are studied. A Simpow standard converter model is used and parameters are set according to the manufacturers data. The factory acceptance tests that are obtained from the manufacturer are used for Simpow standard model unknown parameter adjustments. A simple battery model is built in the simulation. The Simpow rectifier regulators behaviour is studied. Different values of the important parameters are shown in Chapter 5 figures in modelling steps. The simple battery model responses with different values for its parameters are studied and shown in Chapter 5 figures.

After individual tests of the modelled components, simulations of the UPS system with four different scenarios are executed according to the manufacturers' factory acceptance tests.

This master thesis work concludes that the Oskarshamn Nuclear Power Plant DC backup system can be modelled with Simpow power simulation software.

Key words: Modelling, Rectifier, Inverter, Battery, UPS, Simpow

Contents

Preface

The work is performed between January 2012 and June 2012 for Solvina AB Gothenburg and Oskarshamn OKG Nuclear Power Plant.

I would like to thank my examiner Tuan A. Le for his support and also I would like to thank the director in studies of power electric department, Monika R. Hellsing for all help and support through this study. One special thanks is for Torbjörn Thiringer for his support, expertise and guidance.

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This work is dedicated to my family.

Göteborg September 2012

Hakan Ünal

Notations

pu	Per unit
PI controller	Proportional integral controller
AM	Asynchronous motor
PWM	Pulse with modulation
AC	Alternative current
DC	Direct current
UPS	Uninterruptable power source
SBS	Static bypass switch
CSC	Current source converter
IGBT	Insulated Gate Bipolar Transistors
GTO	Gate turn off
HVDC	High voltage direct current
THD	Total harmonic distortion
FAT	Factory acceptance test
LVC	A line commutated, current source converter
NPP	Nuclear power plant
VSC	Voltage source converter

1 Introduction

Modelling DC backup system with Simpow is a system simulation study. A small part of the DC backup power system of the Oskarshamn NPP is modelled with the help of the Simpow Simulation software.

In July 2006 Forsmark nuclear power plant experienced a major fault with unexpected consequences. A two phase fault in the switchyard propagated in the electrical network and affected the diesel secured DC backup systems, resulting in loss of critical loads. In order to avoid the effects of such faults, the protection system has to be studied. One way of examining and observing the system behaviour can be done by using modelling software.

This work has been carried out at the Solvina AB, Gothenburg, Sweden from January 2012 to June 2012. Solvina AB is a Swedish technical consulting company in power and process industries placed in Gothenburg and Västerås supplying diverse services to their clients [1]. Solvina AB have been participating in the modelling of the auxiliary power system of the Oskarshamn Nuclear Power Plant with Simpow. The DC backup system of the plant have not been modelled before with Simpow.

1.1 Purpose of the work

- The main purpose of this work is to model the DC backup system with the Simpow simulation software.
- The second purpose of this master thesis is to study the DC backup system including power converters and batteries in Oskarshamn Nuclear Power Plant.
- The third purpose is to create a battery model representing the transient behaviour of the onsite battery unit.
- The fourth purpose is to compare the results with tests and to create a reference point for the future studies.
- This work includes gathering necessary information, contacts and data for future continuation work.

1.2 Nuclear power plant Oskarshamn

OKG was founded in 1965 and Sweden’s first commercial nuclear power plant, Oskarshamn 1 was commissioned in 1972. OKG owns and operates three nuclear reactor units called Oskarshamn 1, Oskarshamn 2 which started production in 1974 and Oskarshamn 3 which started production in 1985. All together those three units can produce up to ten percent of the entire Swedish electricity consumption.

The nuclear power plant is located 30 kms north of the city Oskarshamn [2].

1.3 DC system

Battery backup DC systems and diesel backup systems are designed and installed in order to secure important components in case of power outage. The DC system includes rectifiers, batteries and inverters. Rectifiers are connected to the backup network continuously and holding the batteries fully charged. Batteries are installed in order to supply the system with power until the diesel generators start-up. Inverters are installed in order to convert the DC energy to AC in the system.

Redundancy, stability and robustness are the key issues of the battery backed DC systems. The importance of this system is very high. It will take over and secure the energy supply in case of energy outage. Important loads are connected to the DC backup system and fed through this system. In case of power outage, loads do not encounter any interruption of power flow, battery unit supplies the power without interruption.

1.4 Forsmark incident

Forsmark incident in 2006 showed the unexpected effects of the network faults to the DC backup systems. The series of events happened after the fault, have been studied and necessary precautions have been taken in the design of DC backup systems. One way of taking precautions is to simulating the DC backup system with the help of the simulation software. In this chapter, the series of events after the two phase fault occurrence is explained.

In July 2006 at Forsmark NPP a two phase fault at the 400 kV switchyard propagated in the NPP system and affected the diesel secured DC backup systems of the NPP [3]. This particular incident showed the sensitivity of the UPS systems to network and grid faults that was not expected before.

In Figure 1-1 a simple representation of the network topology is given.

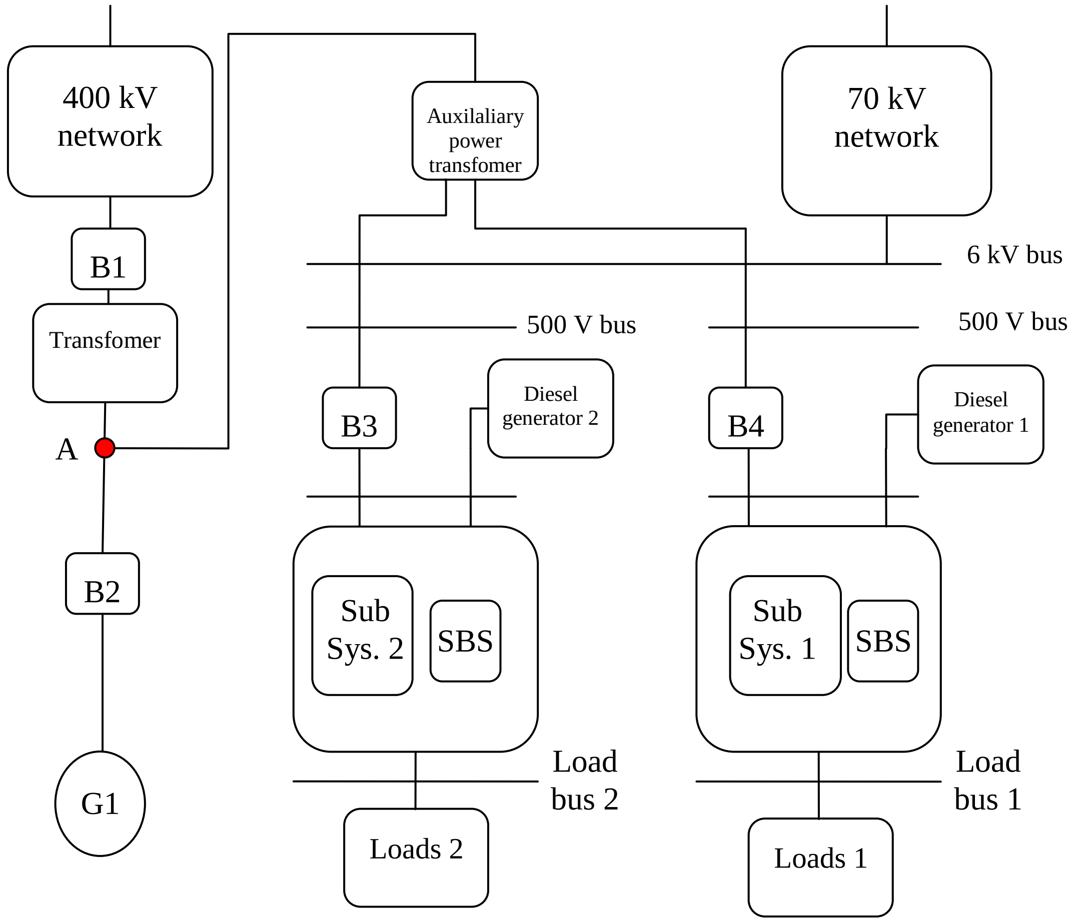

Figure 1-1 A simple representation of the Forsmark electrical network topology

Because of an earth fault protection failure in the 400 kV switchyard, circulating currents caused arcs on the disconnector switch legs. The arcs short circuited two phases. The two phase short circuit fault tripped breaker, B1.

When the breaker (B1) tripped, the in house bus voltage at point A, rose rapidly up to approximately 9 kV for 0.25 seconds. Due to this high voltage, sub system 1 protection in the battery secured network disconnected the UPS system which caused a under voltage at the load bus 1. The UPS unit of the sub system 1 components, rectifier and the inverter were severely affected from the fault. As a result of low voltage on the load bus 1 and the malfunction of the sub system 1, the power to the underlying loads was provided via the SBS.

After the fault, generator circuit breaker, B2, failed to trip for low frequency for three seconds. After three seconds, the circuit breakers, B3 and B4, disconnected the subsystems due to low frequency on the feeding buses above. Subsystem 2 succeeded to changeover to battery supply mode without interruptions, where the connected loads are fed only by the battery units. Simultaneously the diesel generators, Diesel Generator 1 and 2, got connected to the system. However Sub system 1, due to the high voltage transients effect on the UPS system, failed to changeover to battery supply mode. This failure led to loss of Loads 1. The Diesel Generator 1 could not start because its control equipment was fed from Load BUS 1.

Thirty six seconds after the fault, the circuit breaker, B2, trips G1 due to the low power demand from the network. Power supply switched to the 70 kV network connection. The failed Diesel Generator 1 failed to start again due to the absence underlying loads, Loads 1.

After approximately twenty two minutes the system was manually reset and Sub System 1 loads were fed.

The water level in the reactor boiler sank from four meters to 1.9 meters after twenty two minutes which is a high risk situation for the nuclear power plant operation.

1.5 Introduction to the software

The software used in this work is called Simpow. SIMPOW is a software for digital SIMulation and analysis of electrical POWer systems.

In Simpow, calculations are made for symmetrical and unsymmetrical conditions. AC voltages and currents are described as phasors, DC voltages and currents are described by average values. They have time dependent responses under transient conditions.

Simpow offers different kinds of simulations and solutions. In this work OPTPOW and DYNPOW sub-programs are used.

OPTPOW program calculates initial power flow in the network of unlimited number of nodes and components. Basic electrical network elements can be modelled easily with optpow. For instance motor loads, active and reactive productions, transformers, transmission lines can be represented in the model. Most control functions and constraints can be represented. For instance transformers tap changers.

OPTPOWs’ AC solutions electrical state is symmetrical and sinusoidal at the power frequency.

Solution process starts with zero currents at the nodes also known as de-energized system. De-energized system start is followed by energizing the reactive power sources. After energizing the reactive power sources node voltages are established.

Active power is taken into calculations after the nodes are under voltage. Finally the control variables are adjusted where all constraints of power flow and voltages are satisfied.

DYNPOW is the program where the dynamic solutions of electric power systems are made.

DYNPOW inherits the initial conditions for the variables from the OPTPOW file.

Except the existing components in SIMPOW, new components can be modelled with the help of DSL function in simpow and those models can be saved in the DSL libraries.

2 Components of DC system

The DC system of the Oskarshamn Nuclear Power Plant consists of rectifiers, inverters, batteries, active loads, passive loads, and Uninterruptible Power Supplies (UPS). To be able to understand the installed components, a brief theory is given.

2.1 Semi-conductors

Semi-conductors are the foundation of power electronics. Semi-conductors today enable control of high power with stability and high speed. The evolution of the semi-conductors can be followed by studying the three groups of semi-conductor devices where the semi conductors' amount of control over the electrical circuit is divided in to three classes [5].

1. **Diodes**
   Diodes are passive elements and are controlled by the power circuit.
2. **Thyristors**
   Thyristors can be turned on by a turn on signal send to the gate however thyristors cannot be turned off manually. Thyristors turns off when negative voltage is applied to the anode.
3. **Controllable switches**
   There is full control over the switches where they can be turned on and off by only control signals. Controllable switches include BJTs, MOSFETs, GTO thyristors and IGBTs.

2.1.1 Diodes

Diode is a passive element and it has two terminals, anode and cathode. When the applied voltage to the anode is bigger than the cathode, the diode is forward biased. When the diode is forward biased current starts flowing from anode to the cathode. Diodes symbol with anode, A, cathode, K, current flow, i_D and voltage across the diode, $V_{D,}$ are shown in Figure 2-1 a).

During conduction, there is a small voltage drop between the terminals of the diode. However it is smaller than 1 V. It can be considered as an ideal switch at forward conduction [6].

During blocking mode the diode is reverse biased and it blocks the current flow. However there is a small leakage current flowing in reverse direction.

The i-v characteristic of a diode without leakage current is shown in Figure 2-1 b). An applied forward voltage will cause a fast increasing current flow across the diode and the voltage drop, V_F. This current is only limited by an external resistance. Reverse blocking region and forward conduction regions are shown in the Figure 2-1 b). V_{rated} is the reverse blocking withstand voltage of the diode.

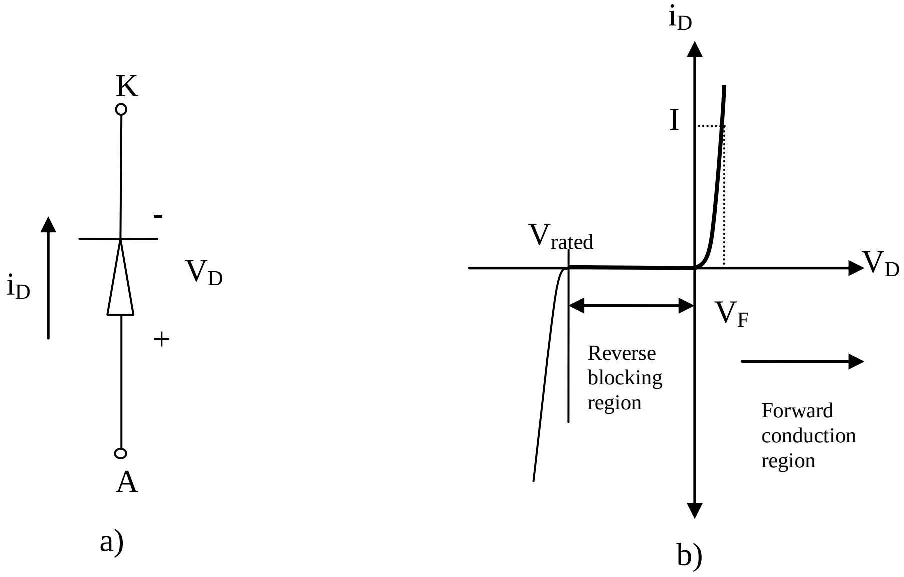

Figure 2-1 a) Diode circuit symbol b) Diode i-v characteristic

2.1.2 Controllable switches and desired characteristics

Controllable switches are controlled with a control signal sent to their control gate where the signal turns on and turns off the switch. This speciality of the controllable switches enables the full control over the power circuit. There are additional desired design characteristics that have to be considered for a suitable controllable switch for the power circuit design. Several desired characteristics in controllable switches are [5]:

1. Off state and On state voltage withstand-ability to block reverse and forward voltages in operation without current leakage.
2. Losses in the converters are a big issue where the efficiency of the converter depends on the losses of the converter.
3. Lossless forward conduction with zero voltage-drop on the switches and the components in total is highly desirable as it is in ideal switches.
4. Fast switching time is highly desired in switch design where a fast full power control is demanded at high switching frequencies.
5. A small amount of power required to control the component.

2.1.3 Thyristor

Thyristors are a part of the semiconductor switches. Thyristors have been used for a long time in different applications. Thyristors have four layers with N and P materials, which create three junction points two main terminals anode and cathode and a triggering terminal gate. Thyristor symbol with gate, anode and cathode is given in Figure 2-2[5].

Thyristors starts conducting with a control signal sent to its gate if it is forward biased as it is shown in Figure 2-3 and in Figure 2-4. Thyristor continues conducting in one direction showing same characteristics as a diode.

The thyristor can only be turned off when a negative voltage is applied to the thyristors anode gate by the power circuit. When the thyristor is turned off the control gate is again in control of the thyristor. Ideal thyristor working principle with gate control is given in Figure 2-3. In Figure 2-4 the current-voltage characteristics and forward and reverse blocking regions of the thyristor is shown when a control current I_g is applied to the control gate in forward biased thyristor [5].

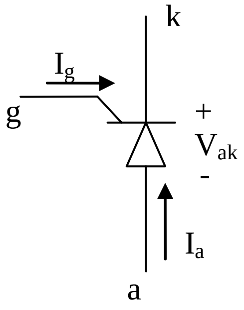

Figure 2-2 Thyristor symbol

Reverse blocking mode

Thyristor is negatively charged at its terminals and therefore thyristor cannot be triggered.

Forward blocking mode

Thyristor is positively charged but not triggered therefore it is blocking in other words not conducting.

Forward conducting mode

When applied voltage to the thyristor is positive and the thyristor is triggered, thyristor starts conducting.

If the applied voltage is above the withstand limits of the thyristor, the thyristor will breakdown. Breakdown areas for forward and reverse blocking points are shown in the Figure 2-4.

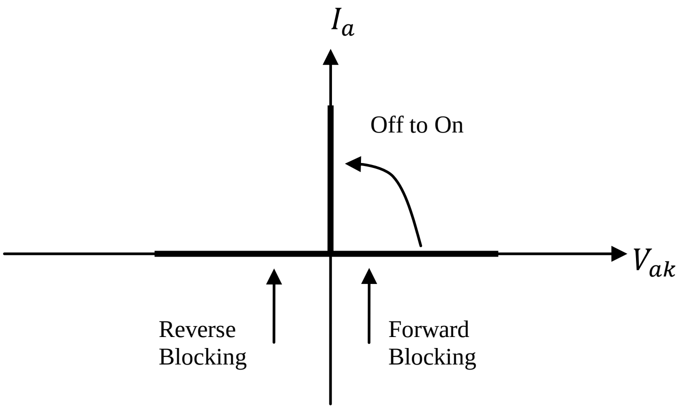

Figure 2-3 Ideal Thyristor working principle with reverse and forward blocking zones

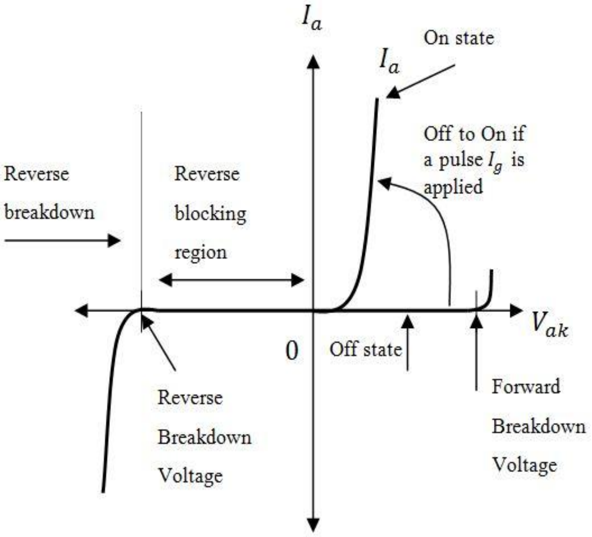

Figure 2-4 Thyristor working principle

2.1.3.1 BJT

Bipolar junction transistors, BJT, are current controlled switches. BJTs can only continue conducting if there is a constant base current supplied from the control circuit to the BJT. The output current is dependent on the supplied base current from the control circuit.

2.1.3.2 MOSFET

Metal-oxide-semiconductor field effect transistors, MOSFETs, are voltage controlled devices. A constant voltage has to be applied in order to keep the MOSFET on state. Gate current is zero during on-state. However in the transition between on and off states, there is a gate current flow according to the charge and discharge of the capacitance. MOSFETs are fast switching devices. Depending on the type of the MOSFET, switching times are from tens of nanoseconds to a few hundred nanoseconds [5].

2.1.3.3 GTO

Gate-Turn-Off Thyristors (GTO) are widely used in high power applications where the full control over the power circuit is required. GTOs can be turned on and off. It can be turned on by sending a positive gate current pulse and can be turned off by applying a negative gate cathode voltage. This speciality of GTO classifies GTO as a controllable switch [6]. In contrast to the thyristors' needs to be fed to the gate on-state, GTOs don't need the constant feeding from the gate, it can remain in on-state without the gate signal applied. For the symbol of the GTO see Figure 2-5.

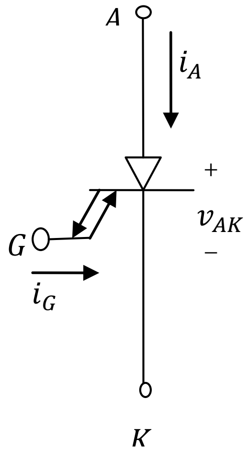

Figure 2-5 GTO symbol

When the GTO is in off-state forward blocking mode, it can be turned on and off by the gate current pulse, I_g, shown In Figure 2-6. Turning off the GTO is accomplished by applying a negative voltage. The negative current, I_g, obtained when a negative voltage applied to negative gate-cathode has to be sufficiently big to secure the turn off. If the applied voltage is sufficiently big the negative gate current created will flow only few microseconds during the turn-off time [5].

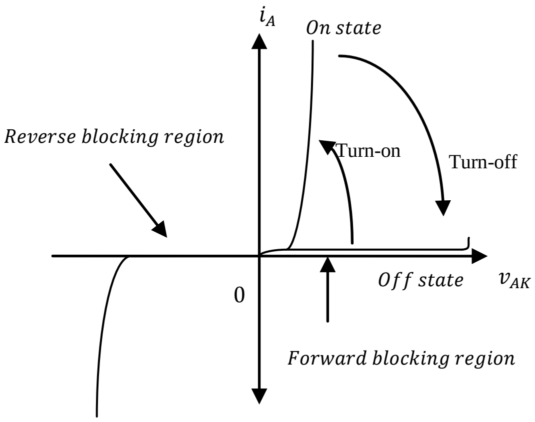

Figure 2-6 i-v characteristics

2.1.3.4 IGBT

Insulated Gate Bipolar Transistor (IGBT) is a three terminal power semiconductor which enables full control of the power circuit with its abilities. Since its introduction to the market in power electronics, it has been widely used. The main advantage of the IGBTs comes from the speed of switching and low switching losses.

The speed and the low energy requirement for turning on the switches, low conduction losses and finally the reverse blocking ability were the main design goals of the IGBTs [5].

IGBTs are controlled through the gate source voltage. The IGBT can be turned on by applying a positive voltage to the gate and emitter, V_{gs}. It can be turned off if a zero or a small negative gate signal applied. IGBTs have high impedance gate which enables control with small energy.

At medium power and high frequency applications bipolar junction transistors (BJT) and metal oxide field effect transistors (MOSFET) were widely used before the invention of the IGBTs [6]. Drawbacks of the BJT and the MOSFET are:

1-BJTs require complex base drive circuits to provide the base current during on-state which increases the power loss in the control electrode; also, long switching times at turn off are the drawbacks of the BJTs.

2-The unipolar structure of the power MOSFETS decreases the conduction ability with higher voltage ratings than 200 V. The MOSFETs on-state resistance increases with the increasing breakdown voltage and higher voltage ratings leads to higher switching losses [6].

Figure 2-7 shows the symbol, gate connection, *g,* emitter, *s*, and collector connections, *d.* of the IGBT [6].

Idealized IGBT *i-v* switching characteristics are given in Figure 2-8.

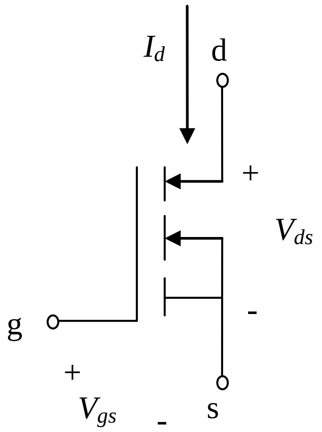

Figure 2-7 IGBT symbol

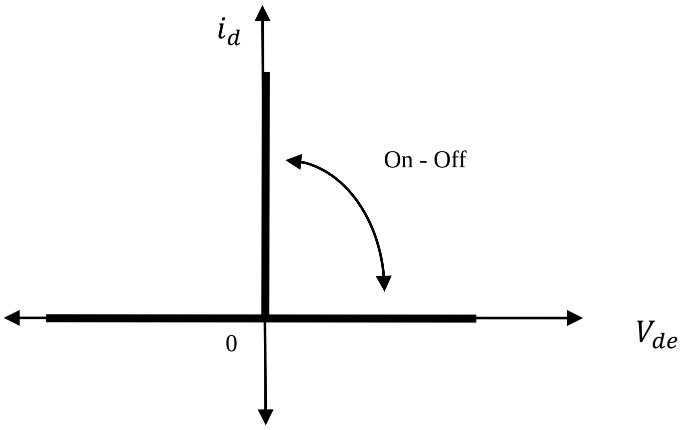

Figure 2-8 Idealized characteristics of IGBT

2.1.4 Overview of controllable switches

In Table 1 the controllable switches BJT, MOSFET, GTO and IGBT are compared in voltage handling ability, current handling ability and switching speed [5].

Table 1- Comparison of controllable switches

Controllable switch	Voltage handling ability	Current handling ability	Switching speed
BJT	Medium- up to 1.4 kV	Up to 0.75 kA	Medium – up to 10 kHz
MOSFET	Low – up to 1 kV	Up to 0.25 kA	Fast- up to 1Mhz
GTO	High – up to 3 kV	Up to 2 kA	Slow- up to 1 kHz
IGBT	Medium – up to 2 kV	Up to 0.5 kA	Medium – up to 80 kHz

2.2 Converters

Converters are the building blocks of power electronic power systems and controls. They are used for the power conversion. There are four main types of converter categories which are:

1. AC to DC
2. DC to AC
3. DC to DC
4. AC to AC

Rectifiers convert AC power to DC power. The voltage output is DC. The power flow is from the AC side to DC side. Inverters are the converters which convert DC power to AC power and power flow is from DC side to AC side where the output is AC. In special arrangements the power flow can flow in both ways [5].

Converters can be classified in two classes based on commutation [7]:

1. Naturally commutated converters

   Switches are turned on and off at the line frequency and the commutation depend on the polarity of the AC voltage. The commutation process starts with the polarity change of the AC voltage. For instance the six-pulse thyristor-bridge converter is a naturally commutated converter. Naturally commutated converters are also called line commutated converters.

2. Force commutated converters

   This type of converters have semiconductor switches which can be turned on and off by triggering pulses. The output from the switches can be varied thus the control over the power circuit is obtained.

Converters can also be classified according to their terminal voltage and current wave forms in two groups [7]:

1. Voltage source converters, VSC

The DC side voltage of the voltage source converter holds the same polarity and the average power flow direction are decided by the DC side current.

2. Current source converters, CSC

The DC side current of the current source converter holds the same polarity. The average power flow direction from the converter is decided by the DC side voltage polarity. Six-pulse thyristor bridge rectifier is a typical current source converter.

Converters design includes power semiconductor switches. Conversion between the DC and the AC signals started with diode converters, followed by thyristor converters and the controllable switches.

Diode converters are uncontrollable in comparison with thyristor converters and converters with controllable switches. However they are cheap and reliable. In diode converters the control is supplied by the power circuit [5].

In difference to diode converters, the thyristor converters can be turned on where one can ignite the thyristors. Thyristor converters are turned off by the power circuit.

Controllable switches improvement through time gave the ability to full power control of the power circuit, thus made HVDC systems, UPS systems and other high power applications possible [5].

2.2.1 Rectifiers

Rectifiers are the components in the electrical system that converts AC to DC. Rectifiers are widely used in electrical systems in various applications from HVDC systems to electrical cars. One area where they are widely used is as chargers for batteries where uninterruptable power is needed.

In DC backup systems the rectifier provides the energy to charge the battery unit and keeps the battery unit constantly charged while feeding the online loads. In Figure 2-9 a general six-pulse thyristor rectifier scheme is given where the AC quantities U_c and $I_c$are converted to the DC quantities I_d and U_d.

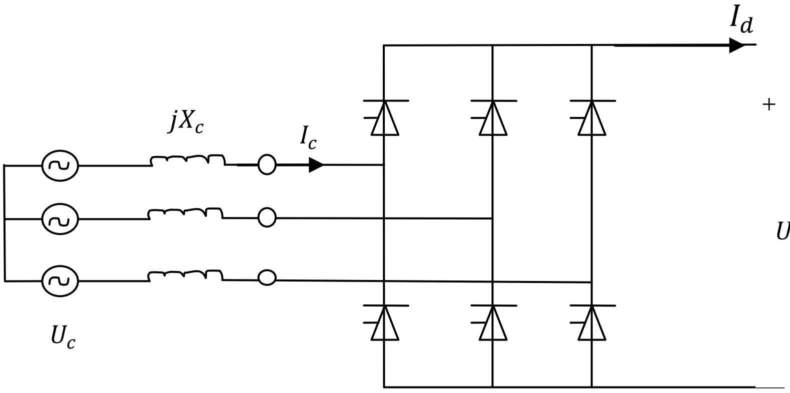

Figure 2-9 6-pulse thyristor rectifier topology

2.2.1.1 Six pulse thyristor controlled rectifiers

The six pulse thyristor controlled converter consists of six valves. The three phase AC network interfaces the AC terminal of the converter and DC network interfaces the DC terminal of the converter. In between the six valves and six pulse groups receive the controllers' orders and executes the firing process. One valve in the upper half and one in the lower half of the six pulse group are conducting simultaneously, thus making a phase to phase connection on the three phase side of the DC terminals during 1/6 of the cycle of the AC voltage. Those instants are controlled by the firing angles of the valves. The precise firing of the valves is made in desired interval of choice [4].

This connection gives a higher voltage handling ability and lower levels of harmonics are generated on the output compared to the three phase half-wave rectifiers [6].

2.2.1.2 Voltage source rectifiers

Voltage source rectifiers have a feedback control loop where it helps to keep the DC link voltage constant at a desired voltage reference value. The difference between the DC link voltage, V_D, and the reference voltage, V_{REF}, create the error signal as shown in Figure 2-10. By using this error signal in the control block and sending the proper firing values to the rectifier valves the DC voltage is kept constant [6].

V_D is the DC link voltage across the C_D as shown in Figure 2-10. The capacitor C_D is connected after the valves for smoothing the output voltage shape of the rectifier.

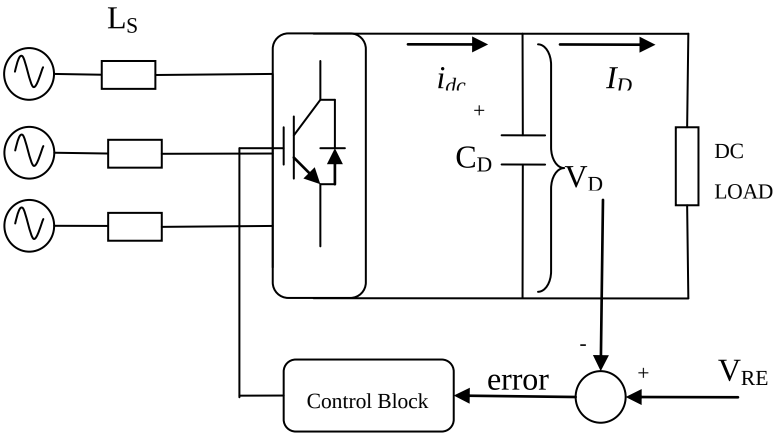

Figure 2-10 Voltage source rectifier

In this work, only six-pulse thyristor controlled rectifiers are used. Other types of rectifiers are [6]:

1. Three-phase half wave rectifier
2. Double star rectifier with inter-phase connection
3. Three-phase Full wave rectifier
4. Half-controlled bridge converter

2.2.2 Inverters

Inverters are used to convert DC to AC in different power sizes. From small battery applications to powerful HVDC applications inverters are increasingly used in electrical applications [5]. Standard topology of an inverter is shown in Figure 2-11.

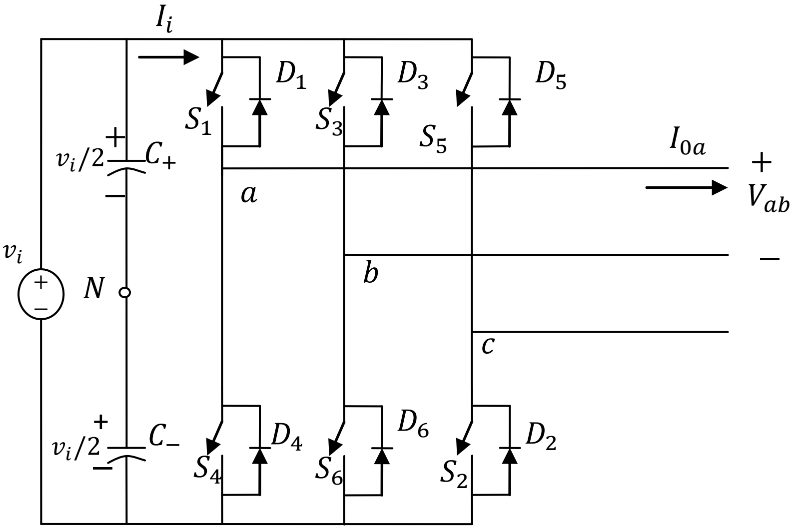

Figure 2-11- Standard 3 phase inverter topology

The history and success of the inverters are parallel to technological improvements and inventions made in power semiconductor switches which enable high power, fast response, control and high efficiency.

There are two types of inverters, voltage source inverters and current source inverters. Current source inverters are not studied in this work.

Three widely used examples of voltage source converters are [5]:

1. Pulse width modulated inverters
2. Square wave inverters
3. Single phase inverters with voltage cancellation.

Pulse width modulated (PWM) inverters input is a constant magnitude DC voltage. In PWM converters the main purpose is to have an AC output that is sinusoidal. The phase magnitude and the frequency of the AC voltage are controlled with the pulse width modulation. A sinusoidal control waveform at the desired frequency is compared to a triangular waveform. Output from the PWM inverter and its fundamental are shown in Figure 2-12. The frequency of the triangular waveform decides the switching frequency which is generally kept constant. When the triangular-wave is equal to or bigger than the control wave the inverters voltage output becomes negative sign of the half of the input DC voltage, else it is positive sign of the half of the input voltage. The sinusoidal control waveforms purpose is to modulate the switch duty ratio with a desired fundamental frequency of the inverter voltage output [5]. Output voltage is filtered in order to obtain sinusoidal AC voltage form.

Low order harmonics are reduced with the PWM inverters. Switching losses due to high switching frequency of PWM is high in the PWM inverters [8].

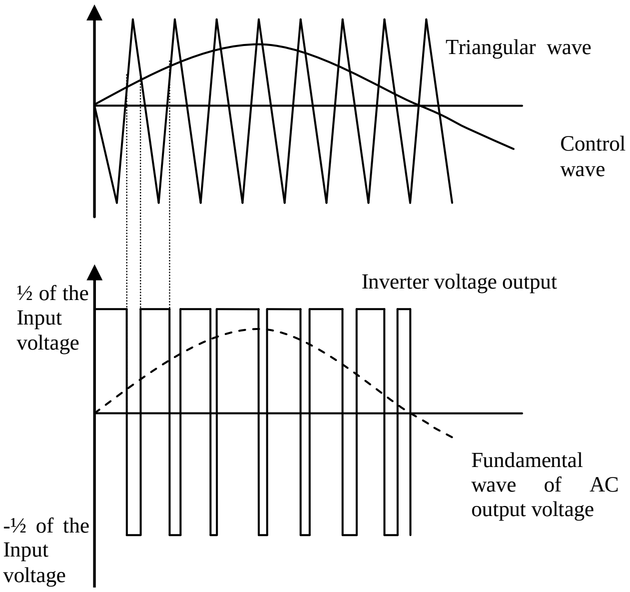

Figure 2-12 PWM working principle

Simple working principle of a square wave inverter is shown in Figure 2-13. Voltage applied to the square wave inverter flows through the valve S_1 at 45 degrees and lasts for 180 degrees. At 135 degrees voltage applied to the S_3 and it lasts for 180 degrees. The difference between the two valve voltages gives the output voltage waveform as shown in V_{ab} at the magnitude of the DC voltage V_i. The fundamental voltage shape is shown as V_{ab1}. The output voltage shape is filtered in order to obtain a similar sinusoidal voltage shape [6].

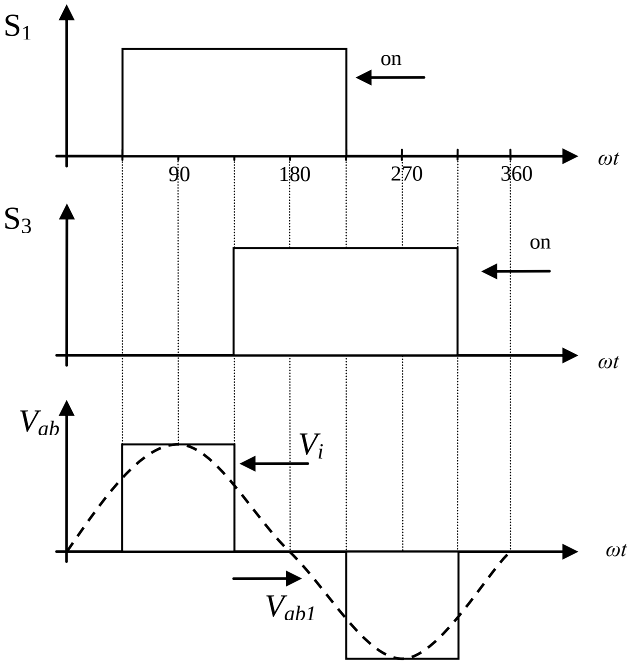

Figure 2-13 Square wave operation

Single-phase inverters use a characteristic combination of other two inverter types. This voltage cancellation technique is only available with single phase inverters. This way of control cannot be used for three phase inverters. With single phase inverters, it is possible to control the magnitude and the frequency of the inverter output voltage [5].

2.3 Batteries

Uninterruptible power supply system's reliability depends on the operation of the battery. In case of AC line outage, the battery unit have to be able to supply the loads without effecting the power magnitude and quality. Also the power supplied to the online loads has to be provided without interruptions. In case of battery failure, the AC line power outage can fail the UPS system thus the loads are out of power supply which is highly undesirable [9]. This undesired case scenario can be solved with a static bypass switch installed to the UPS system which is explained in Chapter 2.5.3

Valve regulated lead-acid batteries, VRLA, stores the energy in chemical form and it takes its name because of its design structure. Valves installed on the battery ensure the pressure release of the build up dangerous gases under operation.

UPS systems topology changed with time in parallel to battery technology. Flooded lead-acid batteries were first used as a single battery unit in the UPS systems where the battery units had their own building, feeding the critical loads from one single battery unit. Because of the maintenance and space issues of the battery unit, the UPS topology is forced to change from one single UPS unit to smaller UPS units where the critical loads are powered through their UPS units. With valve regulated lead acid batteries the space and maintenance issues are solved.

VRLA batteries are very sensitive to temperature differences in the vicinity and they are sensitive to overcharges and discharges. VRLA batteries are also very sensitive to float charging voltage fluctuations where the supplied voltage to the battery has to be almost constant [11].

VRLA batteries and UPS designed VRLA batteries have differences. UPS designed batteries surface area has to be bigger than the normal VRLA batteries in order to supply the necessary amount of current for a short time. Second difference is the losses. The UPS designed batteries must be built with a lower resistance for to conduct more current at low losses.

Charging strategies when the battery unit is continuously connected are constant current, constant voltage or a combination [12]. In this work modelled DC backup system batteries are "Constant current constant voltage charged" stated as CICV characteristic. The constant current and constant voltage combination working principle is given in Figure 2-14. When the open circuit of the battery voltage is low the battery is charged with constant current, $I_{CICV}^{(1)}$ in the constant current mode, CI, of charging. When the battery voltage rises to the set limit,$V_{CICV}^{(1)}$, the battery charging is switched to the constant voltage charging, CV. The main purpose of this two step charging scheme is to avoid the gassing state (when the dangerous gasses is build up in the battery where damaging the battery structure and applying high pressure to the battery valves) of the battery. Battery is fully charged at point t_e.

Desired attributes of energy storage can be listed as follows [10]:

1. Power ratings
2. Energy storage capacity
3. Fast response times
4. Low self discharge
5. Low investment and operating costs

Vented lead acid batteries have most of the desired attributes.

VRLA batteries can be modelled with [13]:

1. Simple battery model
2. Thevenin battery model
3. Linear battery model [14]

In this thesis work the simple battery model is used.

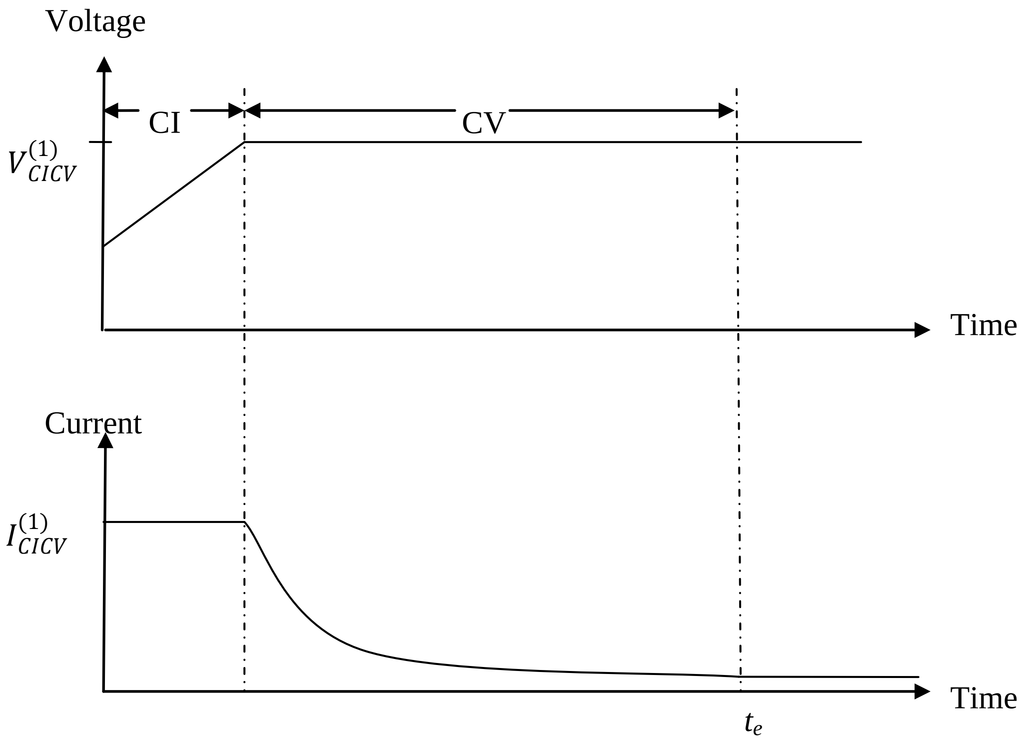

Figure 2-14 CICV charging strategy

2.4 UPS

Uninterruptible power supplies, UPS, are used in very critical applications such as feeding the important loads in Oskarshamn NPP. In case of power outage or in case of under and overvoltage conditions UPSs will continue feeding power to the critical customers without any interruptions. UPS systems also provide a protection against transients and other disturbances. An ideal UPS should deliver uninterrupted necessary amount of power for the design.

The block diagram of a general UPS system is shown in Figure 2-15.

Some ideal characteristics of uninterruptible power supplies are [9]:

1. High reliability and efficiency
2. Bypass option in case of internal failure
3. Low total harmonic distortion (THD), at output voltage
4. Regulated sinusoidal output
5. Low maintenance need, low cost, weight and size
6. Low electromagnetic interference (EMI) and acoustic noise
7. Resilience to external faults

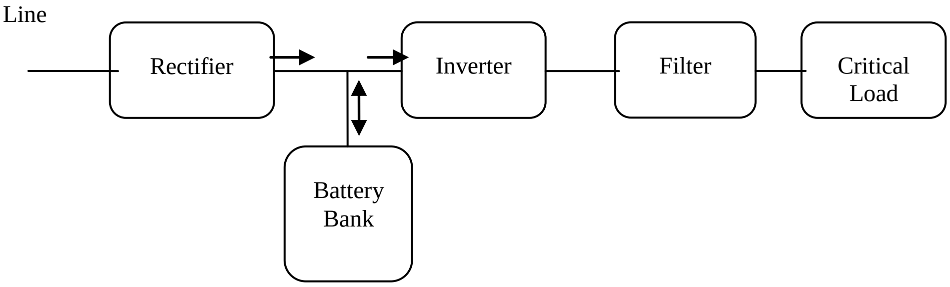

Figure 2-15 UPS scheme

Classification of uninterruptible power supply systems are as follows [9]:

1. Static UPS

   There are three main types of static UPS systems:

- On-line UPS

  In this work static online UPSs are studied therefore only static - online UPS's will be discussed and explained in detail.

- Off-line UPS

  Off-line UPS includes a rectifier, a battery unit, an inverter and a static switch. AC line provides the necessary amount of power to the load via the static switch which is normally on in operation. The static switch is in parallel with the rectifier, the inverter and the battery unit. This parallel branch is turned on only when there is AC line outage in the system. The power to the load is supplied via the battery unit and the inverter. One advantage of this line up is that the rectifiers' size is designed only for charging the battery unit.

- Line-interactive UPS

  Line interactive UPSs consist of a static switch, a transformer, a bidirectional converter and a battery unit. It can be used in on-line or in off-line mode.

2. Rotary UPS

   Rotary UPS is build with an AC motor, a DC machine, an AC generator and a battery bank. There are two modes of operation. In the first mode, the AC line provides power for the AC motor and the mechanically coupled DC machine is driven by the AC motor. The DC machine drives the mechanically coupled AC generator which provides the necessary amount of power to the load.

In the second mode the battery unit provides the necessary amount of power to the DC machine. The DC machine drives the mechanically coupled AC generator which provides the necessary amount of power to the load.

The block diagram of a rotary UPS system is given in Figure 2-16.

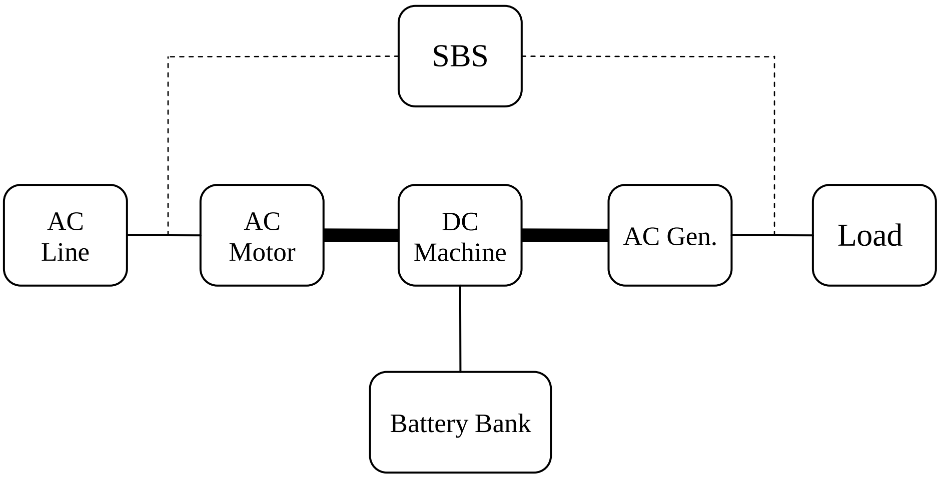

Figure 2-16 Rotay UPS block diagram

3. Hybrid static/Rotary UPS

   Hybrid static/rotary UPS system combines the static and the rotary UPS schemes into one. It consists of a bidirectional AC/DC converter, an AC motor, an AC generator, a battery bank and a static switch. This system works in two modes.

   In the first mode, AC line drives the AC motor and the AC motor drives the generator. The generator provides the necessary amount of power to the load. At the same time the bidirectional converter is fed by the AC line and it charges the battery. Bidirectional converter works in rectifier mode in this operation.

   In the second mode of operation, the battery bank provides the necessary amount of power to the load via the bidirectional converter and the AC motor and the generator. The converter in this mode works as an inverter. The block diagram of a Hybrid static/rotary UPS system is given in Figure 2-17.

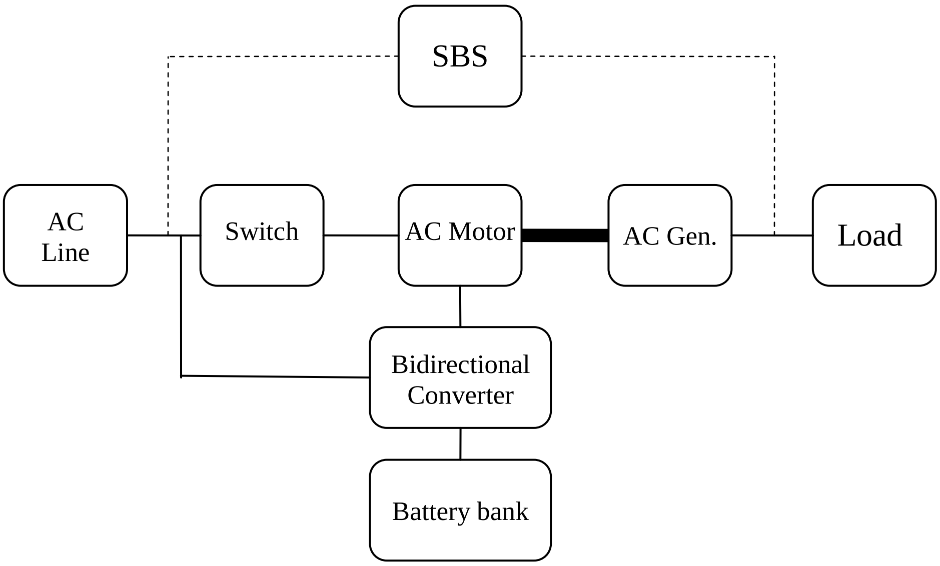

Figure 2-17 Hybrid static/rotary UPS block diagram

Static online UPS systems offer diverse power variety, wide tolerance at input voltage variation and good control of the output regulation. Also there is no transition time between the two operation modes and it is possible to control the output frequency.

The disadvantages of the static online UPS system are the high THD at the input, low efficiency and low power factor.

The static online UPS systems are mostly preferred in comparison to other classes of UPS systems because of the wide application range of power [9]. However the rotary UPS and the hybrid static/rotary UPS have lower THD, higher reliability and higher power quality than the static UPS systems.

Online UPS systems include a rectifier, a battery unit, an inverter and a static bypass switch Figure 2-18 shows an online UPS system with a bypass switch. The main advantage of the online UPS is the exact regulation of the voltage and the tolerance to the input voltage variation. The second main advantage of this topology is that there is no hold time or in other words no delay time in transition of modes of operation [9].

Online UPS works in three modes of operation [9]:

1. Normal mode of operation

   The rectifier continuously provides power to the battery unit and the connected loads. The power obtained from the AC side of the UPS system is first converted in to DC by the rectifier. The DC power from the rectifier, in this case the rectifier also known as charger, is supplied to the battery bank and the UPS systems inverter. The inverter converters the DC input to AC output and supplies the consumers underlying after the UPS system. The normal charging voltage of the battery is 2.3 V/cell.

2. Stored energy mode of operation

   In case of power outage, overvoltage or undervoltage of the AC input, the protection shutdowns the rectifier. The power is provided by the battery unit via the inverter of the UPS. Until the AC input to the UPS is present and in synch, the power is supplied from the battery unit. Afterwards the operation is in normal mode.

3. Bypass operation

In case of a failure in the UPS system components, the bypass switch is triggered. Loads after the UPS are fed by the network. This operation mode can be used in case of fault or maintenance.

4. Boost Charge operation

Boost charge operation is applied to the UPS system where the battery unit is partially discharged or fully discharged. The rectifier feeds the battery unit with a higher voltage, 2.5 V/cell, in order to charge back the battery unit to its nominal value as fast as possible. One advantage of that scheme is that the battery unit will be charged faster and will be in operation for a longer time in case of power outage or rectifier outage

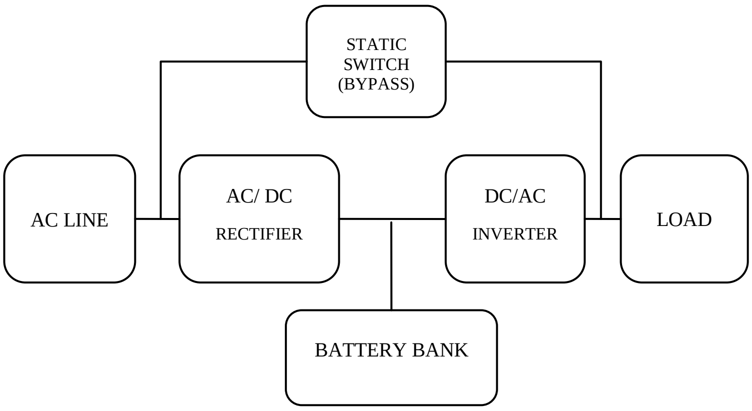

Figure 2-18 UPS scheme with bypass switch

2.4.1 Flywheels for UPS applications

There are several different technologies other than the VRLA batteries. Flywheel application implemented to the UPS system is one of them [9]. According to the system requirements of the connected system, the UPS systems with flywheels are more efficient than the commonly used VRLA batteries. Features of this flywheel for UPS application are [9]:

- Power rating more than 200kVA
- Disturbances in the system are regular and lasts not more than one minute
- Flywheel installed UPS application works with a diesel generator
- One of the biggest design parameter is the amount of space required for this setup

A configuration of the flywheel with the UPS system is shown in Figure 2-19. This topology consists of a rectifier, an inverter and a flywheel system. The rectifier supplies power to the DC bus for the full power amount of load and for the charging and it controls the speed of the flywheel. The flywheel is in operation when the AC line is not available. The rating of the flywheel is to provide necessary amount of power to the load during the backup time. The backup time duration of the flywheel depends on the start-up characteristics of the diesel generator. The inverter is rated after the load size which will be able to provide full amount of power to the load in normal operation and in backup operation [9].

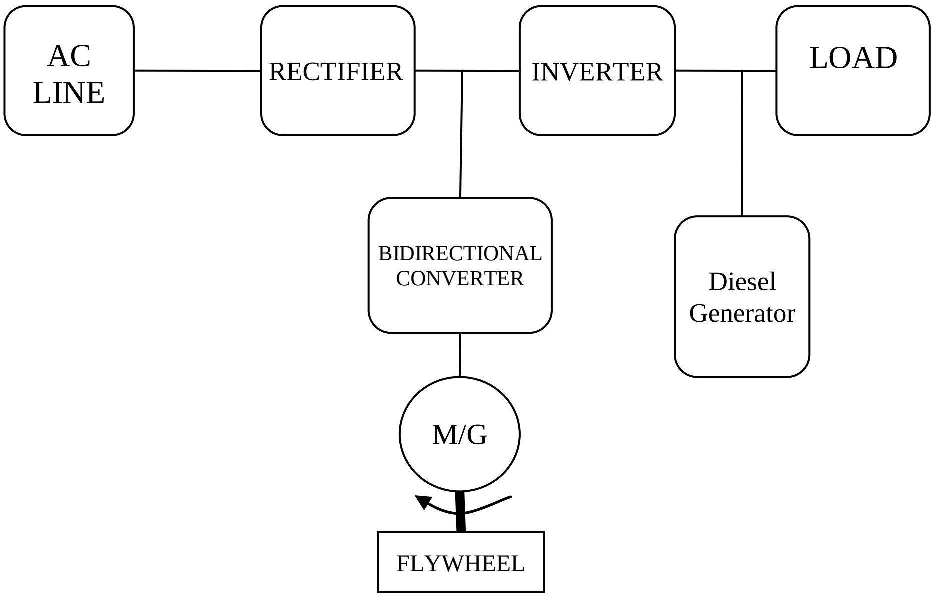

Figure 2-19 UPS system with flywheel configuration

2.5 Oskarshamn DC backup system and components

The DC backup system in OKG has a number of setups. In this report three different setups which are common for NPP will be described. The first one is for only DC loads where the backup system consists of one rectifier and battery unit feeding the DC load. In the second scheme the DC backup system have rectifier, battery unit and inverter. In this scheme the DC part of the system can have external DC loads. After the inverter AC loads are connected. The third scheme is the UPS units where the rectifier, battery unit and the inverters are built as one system. The battery unit have the same purpose in three schemes which is to feed the loads in case of power outage.

One security aspect is that the DC system should be online and independent from power outage. One fault should not break down or take out of order all rectifiers. This design criterion can be explained as the redundancy of the DC system. Diversification is secured with installing rectifiers from different manufacturers.

System is divided in to four major parts which are called trains and those trains are divided into small sub systems where all necessary components are fed via branches.

2.5.1 Studied rectifiers

This thesis work is focused on Gutor UPS [15] system. Gutor UPS system is studied because detailed factory acceptance tests are provided from the manufacturer. These factory acceptance tests include the necessary information needed for modelling the system.

Gutor UPS system rectifier is equipped with overload protection. The main purpose of this protection scheme is to avoid overloading the rectifier and cause undesired component failures at such a vital part of security network. This security scheme ensures the system reliability, stability and safety.

Overload protection keeps the output voltage level at a desired constant value in operation. Simultaneously sensors take readings on the line DC side of the rectifiers and analyses the current. If the measured current level reaches the rated current level (which is also the set value for the current regulator start signal) due to a load change, the current regulator takes over the rectifier regulation operation. Until the oscillations in the current are stabilized, the current regulator keeps the current value under controllable safe values for the safety of the rectifier. Batteries response to load changes is described in following Chapter 2.5.2.

Another need of this protection system is for to supply constant voltage to the batteries which gives a longer battery life time in float charge operation [11]. Therefore this regulation system ensures the constant voltage which is an advantage for battery system and enables current limitation in order to avoid overloading [12].

2.5.2 Studied batteries

The purpose of the batteries in the system is to supply energy to the internal customers in case of power outage or other severe failures in the system. Batteries are sized to feed the underlying loads up to two hours without any interruptions.

VRLA batteries [16] for the Gutor UPS system [15] are supplied from Hoppecke Batterien Gmbh & Co. Their battery unit consists of 108 VRLA battery cells.

Batteries are kept fully charged at float charging mode of operation at 2.3 V/cell. Charging mode voltage per cells are 2.4 volts and there are 108 cells to be charged. Fully discharged batteries takes up to 8 hours to be fully charged in boost charging mode where the inverter is manually turned off and bypassed with the SBS in order to not to trip the protection. Bypassing the inverter allows power flow to the underlying systems from the main bus. Partially discharged batteries preferably charged to full as fast as possible in the limits of the DC system protections. Battery charging strategy is constant current constant voltage.

When the batteries supply the energy to underlying branches, the diesel generators located above in the DC system will start. It will supply the energy for at least 2 hours if the diesel generators buses are not powered due to the fault.

2.5.3 Studied inverters

Gutor UPS have force commutated IGBT PWM inverters equipped with static bypass switches, SBS [15]. The inverter converts 240 V DC to three phase 400 V AC.

2.5.3.1 SBS

In the inverter cubicle there is a static bypass switch which increases the stability, availability and reliability of the DC backup system. It provides an uninterruptible change of power of source [15]. A simple construction topology and location of the SBS is shown in Figure 2-20.

SBS is activated in case of internal failure of the UPS system, as support in short circuit case and if the inverter cannot provide the necessary amount of power to the underlying loads.

To facilitate the maintenance of the UPS system, inverter cubicle is equipped with a manual bypass. With the manual bypass the power is delivered directly to the underlying system from the mains without any interruptions.

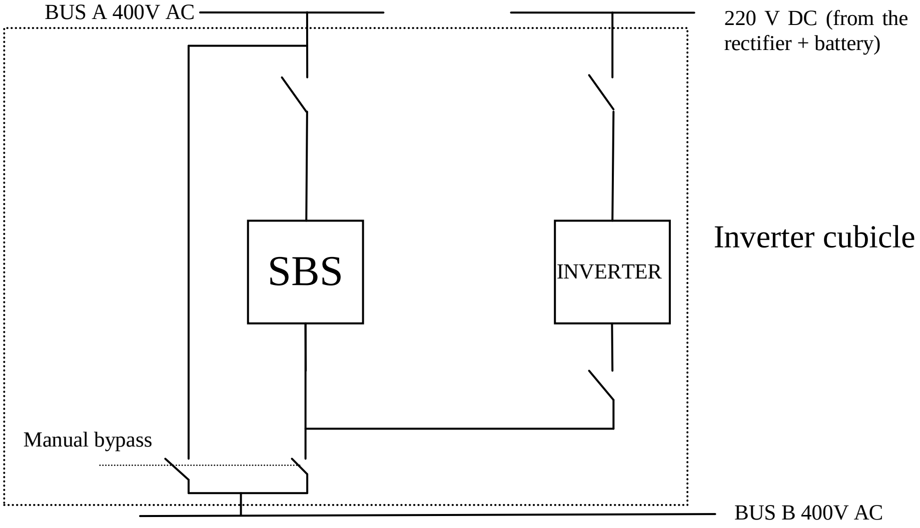

Figure 2-20 - SBS topology

The SBS is equipped with two devices, the synchronization device and the automatic change back device.

The purpose of the synchronization device is to make sure that the phase and the frequency of the inverter voltage are permanently in synchronism with the mains, BUS A 400V AC, see Figure 2-20.

If the UPS system is malfunctioning, underlying loads are fed via SBS until the UPS system is ready to operate again. When the UPS system is ready to operate, the automatic change back device in SBS ensures the uninterruptible load changeover from the SBS to the UPS system.

The SBS operation is dependent on the mains frequency and the voltage. If the mains frequency and the voltage are in specified limits the SBS is in operation, otherwise changeover happens with a gap.

3 Components in simpow

Simpow program has prebuilt converters models for different applications that can be used in system analysis. Simpows pre-build converter models are [4]:

1. **LVC, Line commutated CSC**
   LVC connects three phase AC network with DC network converting AC to DC and DC to AC. From the DC side of the network the LVC converter can be seen as a DC current source.
2. **PWM converter**
   PWM inverters converts DC signal to AC signal and in Simpow it is especially modeled for working with LVC. The AC signals frequency, magnitude and phase angle can be controlled with the PWM regulator. From the AC side of the network the PWM converter can be seen as an AC voltage source.
3. **Cyclo-converter**
   This model has the function of connection between a three phase AC system and one phase AC system in different frequencies.
4. **Rotary converter**
   Rotary converter includes two synchronous machines where their rotors are connected on the same shaft, connecting two AC networks with different frequencies.

In this work the LVC converter is chosen as the rectifier with proper regulator, LVC3, as explained in Chapter 3.1. The Simpow LVC rectifier is a CSC however the onsite rectifier is VSC. Despite the fact that the chosen Simpow rectifier is CSC and onsite UPS rectifier is VSC, their DC link voltage regulation and current control is the same. Because of that reason the LVC rectifier is a proper match for the UPS system. The Simpow rectifier LVC and Simpow rectifier LVC3 regulation is explained in Chapter 3.1.

The chosen inverter from the existing models is the PWM inverter. The output AC signals phase angle, magnitude and frequency can be controlled with the Simpows model and matching output signal with same amount of control can be obtained. In addition, Simpow PWM converter and the installed onsite inverter are both force-commutated converters, enabling full control of the AC signal.

3.1 Simpow LVC rectifier and LVC3 regulation

In this thesis work the modelled DC backup system rectifiers are six-pulse controlled rectifiers. Rectifiers are equipped with overload protection (current limiters) as mentioned in Chapter 2.5.1.

Simpows line commutated current source converter, LVC, model has six-pulse connection. It converts the AC input to DC output by proper firing of the valves. By varying the firing angle, the DC output voltage can be controlled.

In Simpow there are two different regulator models for the LVC rectifier.

The first regulator model, LVC1, regulator controls the firing angle in order to keep the DC current constant at a given level. The voltage and current controller of the LVC1 regulation are in series.

In the second regulator model, LVC3, regulator controls the firing angle via two parallel PI regulator [17] branches with a switch. In the first branch PI regulator controls the firing angle in order to keep the DC voltage constant. In the second parallel branch, the PI regulator controls the firing angle when the current level on measured point reaches a given maximum current level. This parallel current regulators aim is to avoid overloading. The LVC3 regulator functioning logic is build in order to avoid the effects of the harmonic content of the current under normal conditions. This rectifier regulator is essentially built for the railway applications where the current have high harmonic content. When the load size is within the limits of the rectifier, controlling only the DC voltage avoids the effects of the current harmonics.

This six pulse thyristor controlled rectifier model, LVC, in Simpow with LVC3 regulation is chosen because it is working in the same manner as the Gutor which is explained in the Chapter 2.2.1.2 .

LVC3 rectifier regulation is given in Figure 3-1. The difference between measured voltage, U_d, and desired voltage level, U_{d0}, is sent into the proportional part of the PI controller as an error signal. This error signal is amplified with the proportional block and sent to the integrator. The output of the integrator is applied to the firing angle limits between y_{max} and y_{min} where y_{max} is equal to the α_{max} and $y_{min}$is equal to the α_{min}. The total output signal, y, is equal to the angle, α, which is sent to the gates of the thyristor [4] as shown in Figure 3-1.

The switches after the parallel PI regulators are controlled depending on the operation mode. For instance when the voltage regulator is in operation the voltage regulators switch is in operation. In case of an overload situation the voltage regulators switch opens and current regulator switch turns on.

The LVC3 regulator in details is given in Chapter 5.3 Figure 5-1 with output signal points on detailed block scheme.

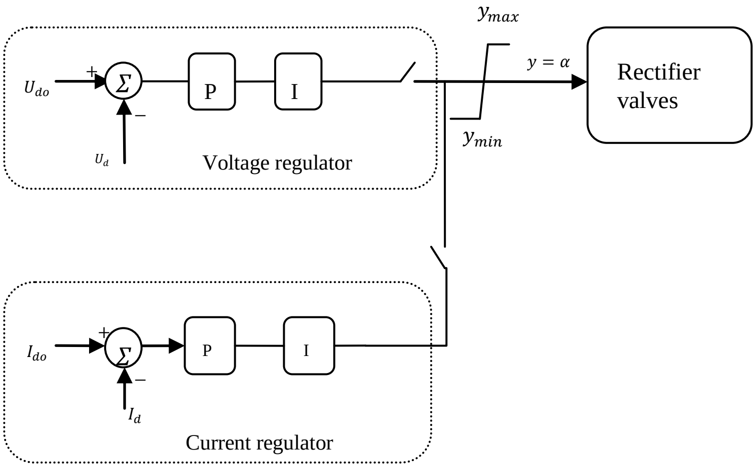

Figure 3-1 LVC3 Regulator block scheme

3.2 Simpow PWM inverter and regulator

A pulse width modulated inverter converts DC input to AC output. Simpow PWM model inverter is made up of GTO (gate turned off) thyristor valves with reverse parallel connected diodes.

PWM inverters in Simpow enable control of the phase angle and the magnitude of the AC voltage.

In simpow the PWM inverters are equipped with two PI regulators representing a phase angle and a magnitude regulator. One extra regulator is used for current limiting in order to prevent overloading which also contributes to the phase and the magnitude controllers of the inverter. See Figure 3-3.

The input to the current limiter is the actual current, $|I|$, and the permitted limit of the AC current value I_{lim}. The difference is the control error, $I_{lim} - |I|$, which is sent into the current limiters PI controller. Outputs of the current limiter are the control signals to the phase angle regulator and the magnitude regulator, $\Delta\emptyset_{il}$ and ΔV_{il} respectively.

The phase angle of the AC output voltage, $\emptyset_u$, is controlled by creating a fictive voltage, E_{ac}, in Simpow. This fictive voltage is equal to the relation between the phasor voltage of the converter, $\bar{U}_{ac}$, and the phasor AC current, $\bar{I}_{ac}$, and reactance as given in Equation 3-1 . The phase angle of the fictive voltage is followed in order to control the phase angle of the phasor AC voltage. See Figure 3-2.

$$\overline{E_{ac}} = \bar{U}_{ac} + \mathrm{j}\, x_q\, \bar{I}_{ac} \tag{3-2}$$

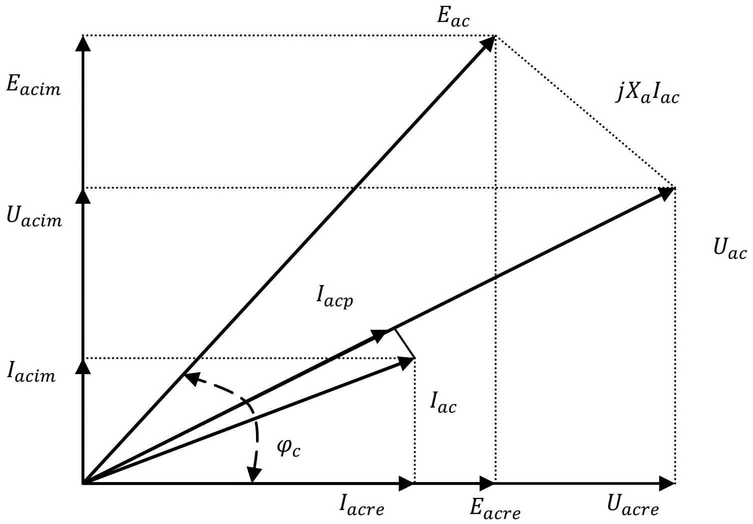

Figure 3-2- Phasor diagram of the inverter

The magnitude of the PWM converters' AC voltage is controlled with a PI regulator implemented. The magnitude controllers output signal is the amplitude factor, τ, as shown in Figure 3-3. Input to the regulator is the difference between fictive voltage reference value and a measured value of the voltage. Also the current limiter control signal, ΔV_{il}, is taken as an extra input for calculating the error which is sent in to the magnitude PI controller of the PWM converter.

Detailed block scheme of the PWM inverter is given in Chapter 5.5 in Figure 5-12.

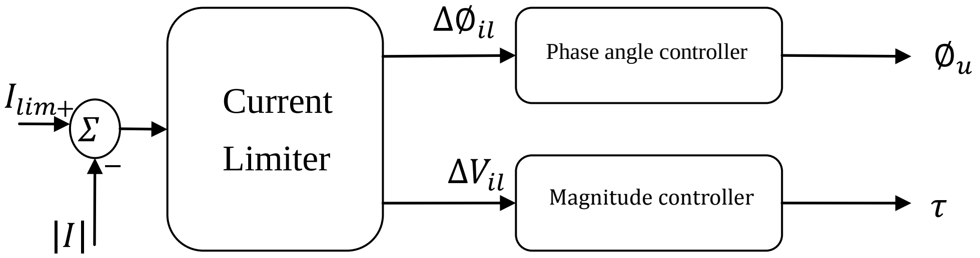

Figure 3-3 PWM Inverter regulator

4 Factory acceptance tests

Factory acceptance tests are made by the UPS manufacturer to test the UPS systems. Factory acceptance tests from the manufacturer Gutor were chosen as the proper tests to be simulated. The main reason of this choice was dependent on the detailed information that has been included in the report which shows the step response of the UPS system to different step voltages in three different points of the UPS system. According to the outputs of these FATs, modelling of the components was made by adjusting the simulation component parameters until they behave as the real components in NPP DC backup system. Another reason was the good contacts that have been established with the Gutor headquarters who accepted to help in great extend. The test set up is shown in Figure 4-1.

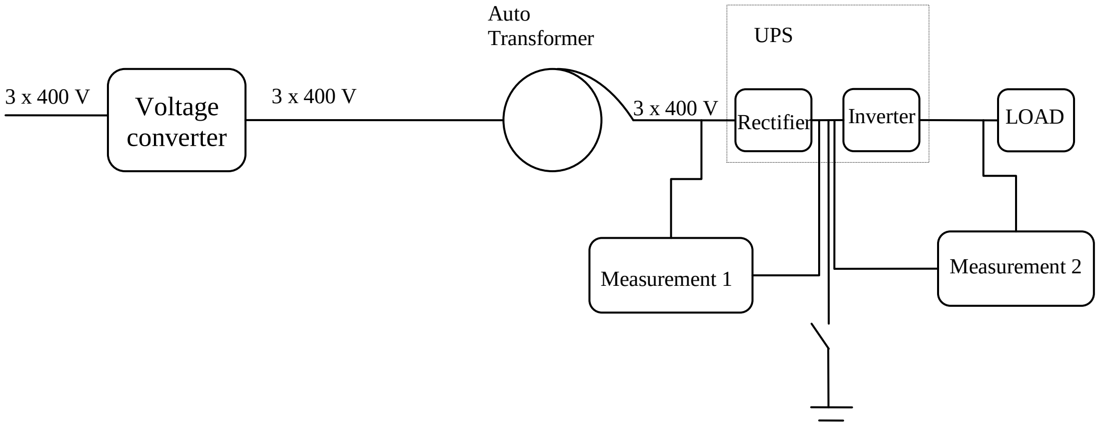

Figure 4-1- Dynamical special test setup

Voltage converter creates voltage steps between 0.7 pu to 1.15 pu. Those signals are applied to the UPS system via an auto transformer. Measurement devices take measurements in three points, before the UPS, in the UPS and after the UPS. The auto-transformer has nominal voltages of 3*400V/3*400V with 300kVA power.

In this work four dynamical tests are simulated, which are:

1. Voltage 100% - 85% (350ms) – 100% at 10% load
2. Voltage 100% - 70% (350ms) – 100% at 10% load
3. Voltage 100% - 109% (350ms) – 100% at 10% load
4. Voltage 100% - 115% (350ms) – 100% at 10% load

4.1 Factory acceptance 0.85 pu test

In test one, applied voltage to the UPS unit is decreased from 1 pu to 0.85 pu for 350 milliseconds and AC input, AC output and DC battery voltage measurements are shown in the Figure 4-2 and Figure 4-3 respectively.

In Figure 4-2 the yellow lines show the input voltage to the rectifier and the red lines show the bus voltage where the DC battery is connected.

In this test the rectifier and the battery is in operation. It can be seen from the Figure 4-2 that the DC bus voltage where the battery unit is connected decreases when the 0.85 pu voltage is applied. The DC battery voltage during the fault is approximately

0.94 pu where the battery keeps the DC line bus voltage on a certain level and the rectifier is in operation. The battery bus voltage after the applied voltage step is higher than the initial value where the battery is charged.

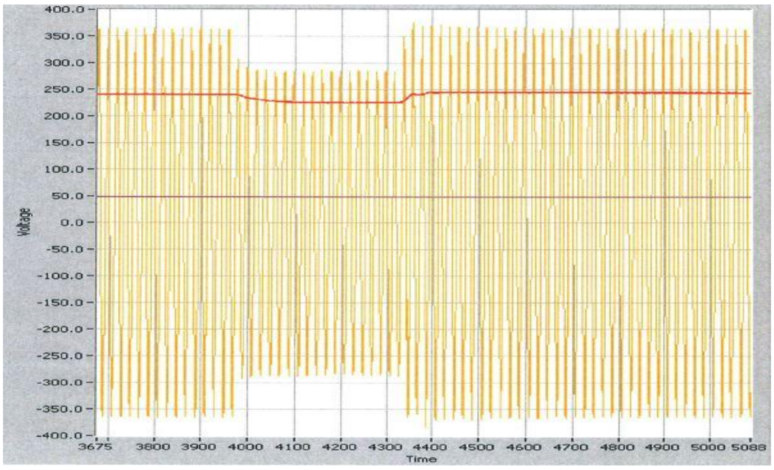

Figure 4-2 Factory Acceptance 0.85 pu Test.
Yellow line - AC input voltage, 0.85 pu during the step, otherwise 1 pu.
Red line - DC battery voltage, 0.94 pu during the step, otherwise 1 pu [18]

In the Figure 4-3 the AC output voltage and the DC battery voltage is shown. The blue lines show the AC output level and the red lines show the bus voltage where the DC battery is connected.

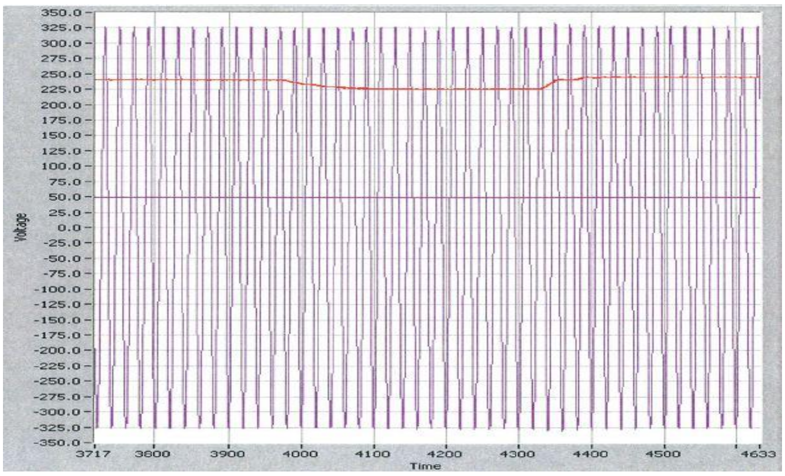

Figure 4-3 Factory Acceptance 0.85 pu Test
Blue line - AC output voltage, 1 pu
Red line - DC battery voltage [18]

4.2 Factory acceptance 0.7 pu test

In test two, applied voltage to the UPS unit is decreased from 1 pu to 0.70 pu for 350 milliseconds and AC input, AC output and DC battery voltage measurements are shown in the Figure 4-4 and Figure 4-5 respectively.

In Figure 4-4 the dark blue lines show the input voltage to the rectifier and the red lines show the bus voltage where the DC battery is connected.

It can be seen from the Figure 4-4 that the DC battery voltage decreases when the 0.70 pu voltage is applied. The rectifier is force shutdown when the 0.70 pu voltage applied and the DC battery voltage during the fault drops to 0.94 pu as shown in red. The battery provides the necessary amount of power to the load and the DC battery voltage is decreasing.

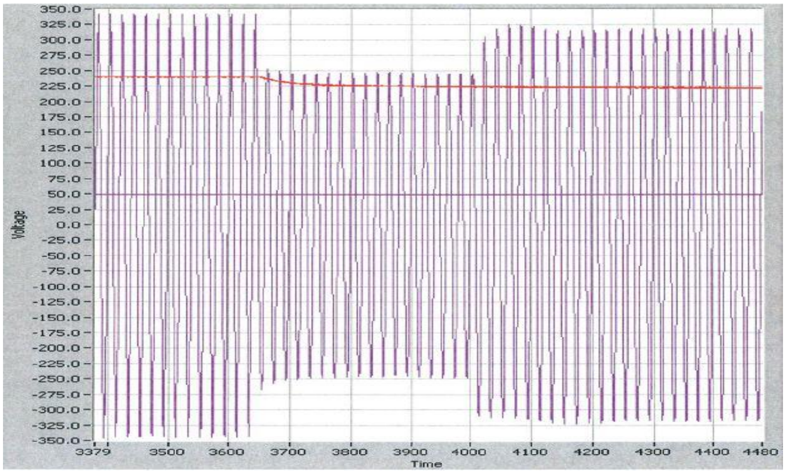

Figure 4-4 Factory Acceptance 0.7 pu Test
Blue line - AC input voltage, until the step it is 1 pu, during the step 0.7 pu
Red line - DC battery voltage 0.95 pu after the fault, decreasing with time [18]

Figure 4-5 Factory Acceptance 0.7 pu Test
Yellow line - AC output voltage, 1 pu
Red line - DC battery voltage [18]

In the Figure 4-5 the AC output voltage and the DC battery voltage is shown. The yellow lines show the AC output level and the red lines show the bus voltage where the DC battery is connected. It can be seen from the figure that the AC output is affected by the applied voltage step however the effect is very small. The load side of the UPS system is not affected from this fault which the rectifier is force shutdown.

4.3 Factory acceptance 1.09 pu test

In test three the applied voltage is increased to 1.09 pu for 350 ms. The rectifier and the battery is in operation. Measurements for AC input, AC output and DC battery voltage are shown in Figure 4-6 and Figure 4-7 respectively.

In Figure 4-6 the dark blue lines shows the AC input applied and the red line shows the bus voltage where the DC battery is connected.

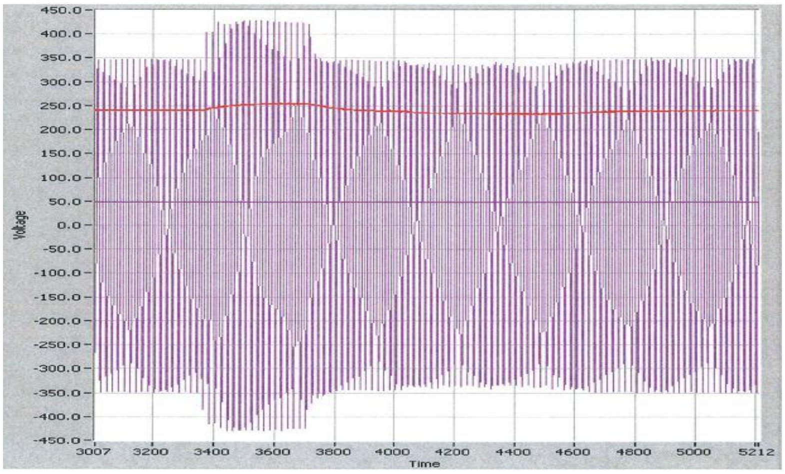

Figure 4-6 Factory Acceptance 1.09 pu Test
Blue line - AC input voltage, 1.09 pu during step voltage, otherwise 1 pu
Red line - DC battery voltage, during step voltage the DC battery voltage is around 1.06 pu, otherwise 1 pu [18]

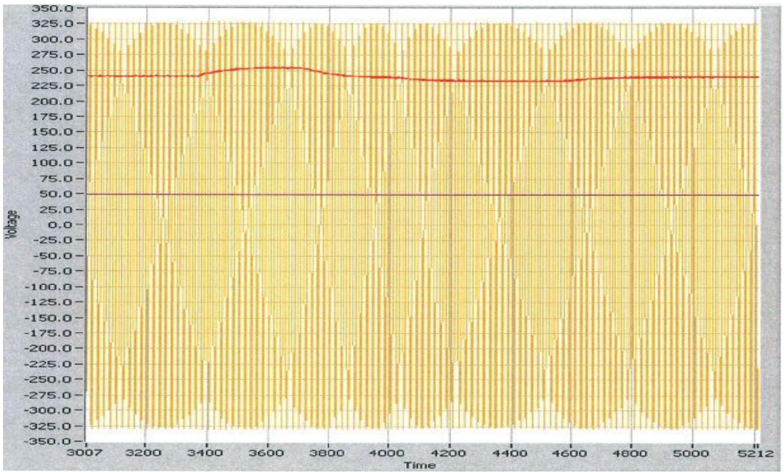

Figure 4-7 Factory Acceptance 1.09 pu Test
Yellow line - AC output voltage, 1 pu
Red line - DC battery voltage [18]

In the Figure 4-7 the AC output voltage and the DC battery voltage is shown. The yellow lines show the AC output level and the red lines show the bus voltage where the DC battery is connected. It can be seen from the figure that the AC output is affected by the applied step voltage however the effect is very small. The load side of the UPS system is not affected from this overvoltage.

4.4 Factory acceptance 1.12 pu test

Measurements for AC input, AC output and DC battery voltage are shown in Figure 4-8 and Figure 4-9 respectively.

In Figure 4-8 the red line show the DC voltage where the battery is connected and the dark blue line shows the applied 1.12 pu AC voltage.

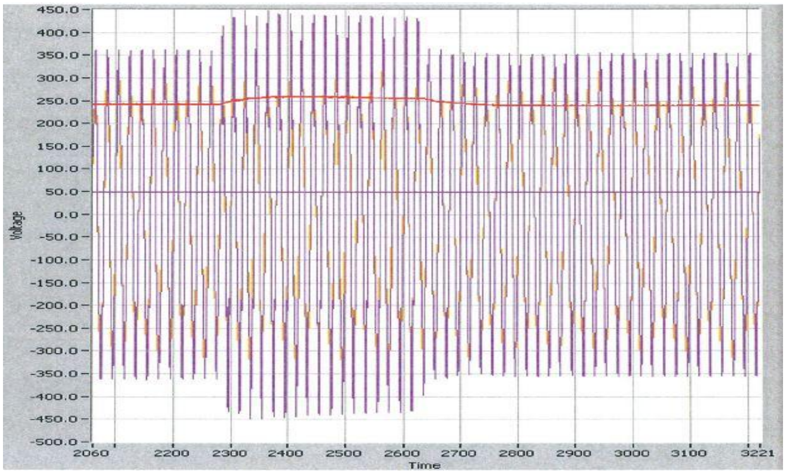

Figure 4-8 Factory Acceptance 1.12 pu Test
Blue line - AC input step voltage 1.12 pu
Red line - DC battery voltage 1.07 pu during the step voltage and 1 pu before and after step voltage [18]

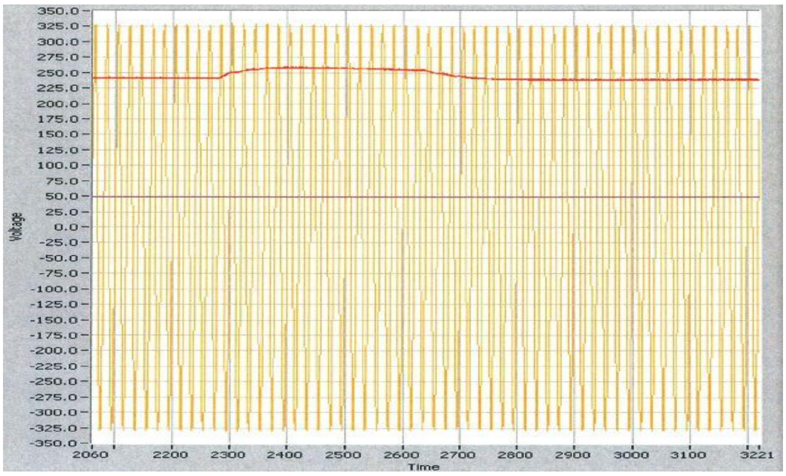

Figure 4-9 Factory Acceptance 1.12 pu Test
Yellow line - AC output voltage, is 1 pu
Red line - DC battery voltage plot [18]

In the Figure 4-9 the AC output voltage and the DC battery voltage is shown. The yellow lines show the AC output level and the red lines show the bus voltage where the DC battery is connected. It can be seen from the figure that the AC output is affected by the applied step voltage however the effect is very small. The load side of the UPS system is not affected from this overvoltage.

5 Modelling

Modelling the DC backup system is done in steps. First the supply network and loads are modelled. The second step is to set the parameters of the rectifier and the rectifiers' regulator. Those parameters are adjusted according to the factory acceptance overvoltage 1.09 pu test. Third step is to model a preliminary inverter that converts the DC signal to AC to feed the modelled loads on the load side of the UPS. Fourth step is introducing the battery model to the system. In this step the modelled battery parameters are adjusted according to the factory acceptance undervoltage 0.7 pu test. These four steps are explained in detail with test setups in proceeding sections.

5.1 Supply network modelling

The electrical network above the feeding bus of the DC backup system is modelled as an infinite power source. The voltage level of the AC infinite power source is given as 400 V which is the bus voltage of connected the DC backup system.

Base power in Simpow is chosen as 100MW for entire system.

Line parameters are estimates and based on the line data from the site.

Transformer parameters are taken from the site.

A transformer with a tap changer is installed in order to apply voltages step for tests which represent disturbances that might occur and affect the DC backup system.

5.2 Rectifier modelling

Explanation of the parameters of the LVC rectifier for OPTPOW and DYNPOW files are given in Table 2.

Table 2 - Simpow LVC Optpow variables list

K	Number of six pulse groups
TYPE	Converter working type (inverter or rectifier has to be stated here)
UDN	The rated ideal no load DC voltage in kV
IDN	The rated direct current in *kA*
DX, DR	The inductive and resistive relative direct voltage drop
AN	Desired delay angle of a rectifier, in ° *el.*, when it is controlling the direct current
AM	Minimum delay angle, in ° *el*
GM	Minimum margin of commutation angle, in ° *el*
L	The inductance between the AC- and DC-terminals, in *H*. Includes DC reactor

MODE	Converter transformer working mode in or outside of the rectifier
UN1	The rated voltage of the network side of the converter transformer, in *kV*
TMAX	The maximum turns ratio of the converter transformer, in *pu* of $\frac{UN1}{UDN}1.35$
TMIN	The minimum turns ratio of the converter transformer, in pu of $\frac{UN1}{UDN}1.35$

K, TYPE, UDN, IDN, MODE, UN1 and L parameters are obtained from the manufacturer [18].

No information about the parameters DX and DR were obtained therefore they are set to zero. These two parameters can be neglected because the DC output voltage of the rectifier can be adjusted with the rectifier regulator as shown in Chapter 5.3.2.

Maximum and minimum turn ratios are given as 1. Main purpose of this is to simulate the isolation transformer of the converter [15].

A proper value of AN is found after tests are made in Chapter 5.3.2.

Minimum delay angle, AM, and desired delay angle, AN, are set equal. Lower values of AN yields higher DC average output and changes the DC bus voltage which thereby differs from the FAT overvoltage test 1.09.

An example of OPTPOW file where the rectifier parameters are given as follows:

POWER CONTROL

LIKRIKT694 TYPE=LVC RTYP=UD UD=0.241

LVC CONVERTERS

LIKRIKT694 BUS51 BUS6 K=1 TYPE=RECT UDN=0.241 IDN=0.731 DX=0 DR=0 AN=5 AM=5 GM=17 L=0.000440 MODE=0 UN1=0.4 TMAX=1 TMIN=1

5.3 Rectifier regulator modelling

Two different setups of tests are applied to the rectifier for finding the values of the voltage regulator and the current regulator as explained in Chapter 5.3.2 and in Chapter 5.3.3.

LVC Rectifiers LVC3 regulator parameter explanations are given in Table 3 and the block scheme is shown in Figure 5-1.

Table 3 - Simpow LVC3 Dynpow variables list

TYPE	DSL type. LVC1 or LVC3 from the DSL library can be chosen

KU	Gain of the voltage regulator, pu of rated DC current/ *pu* of rated DC voltage
TU	Time constant of the integrator of the voltage regulator, *s*
TUF	Filter time constant for the DC voltage, *s*
KS	Constant in the integrator of the voltage regulator
IDN	The rated DC current, in *kA*
UDN	The rated DC voltage, in *kV*
IMAX	Maximum DC current, *kA*
KI	Gain of the current regulator
TI	Time constant of the integrator of the current regulator, *s*.
TIF	Filter time constant for the current, *s*
KIS	Constant in the integrator of the current limit regulator
TT1	Time constant in the denominator of the current transfer function, *s*
TN1	Time constant in the nominator of the current transfer function, *s*
TT2	Time constant in the denominator of the current transfer function, *s*.
TN2	Time constant in the nominator of the current transfer function, *s*
TA	Filter time constant for ALFA, *s*
AMIN	Minimum value of ALFA, ° *el*
AMAX	Maximum value of ALFA, ° *el*

Known DYNPOW parameters of LVC3 regulator of the LVC rectifier are obtained from Oskarshamn NPP which are IDN, UDN and IMAX.

After studying the system descriptions of the modelled UPS system, IDN is set equal to the IMAX. In the system descriptions it is stated that the maximum allowed current is set equal to the rated current of the current limiter of the rectifier to avoid overloading. The main purpose is to have an overload protection as explained in Chapter 2.5.1. Overload protection function test result is shown in Chapter 5.3.3.

LVC3 type is defined in TYPE parameter as LVC3.

TYPE parameter is given as LVC3 which is the decision made in modelling Chapter 3.1.

TIF and TUF are the filter parameters however in simpow solution harmonics are neglected therefore they are given as zero.

KS, TA and KIS are the constant parameters of the PI regulator. They are taken from the Simpow LVC3 regulator example from Simpow user manual [4] because the real values of the PI regulator couldn’t be obtained or calculated.

TT1, TN1, TT2, TN2 parameters are the variables of the DC current transfer function which are taken from the Simpow LVC3 regulator example from Simpow user manual [4].

AMIN, AMAX are given in the working range from 5 degrees to 120 degrees which are given in the rectifier model example of the Simpow.

KU, TU and KI, TI are adjusted after voltage and current tests as explained in Chapter 5.3.2 and Chapter 5.3.3 respectively.

The DYNPOW code for the LVC3 regulator is as follows:

```
TYPE=DSL/LVC3/ KU=7.5 TU=9.5 TUF=0 KS=2.5
                    IDN=0.731 UDN=0.241 IMAX=0.731
                    KI=7 TI=0.5 TIF=0 KIS=200
                    TT1=0.004 TN1=0.001 TT2=0.007 TN2=0.08E-3
                    TA=0.025 AMIN=5 AMAX=120
```

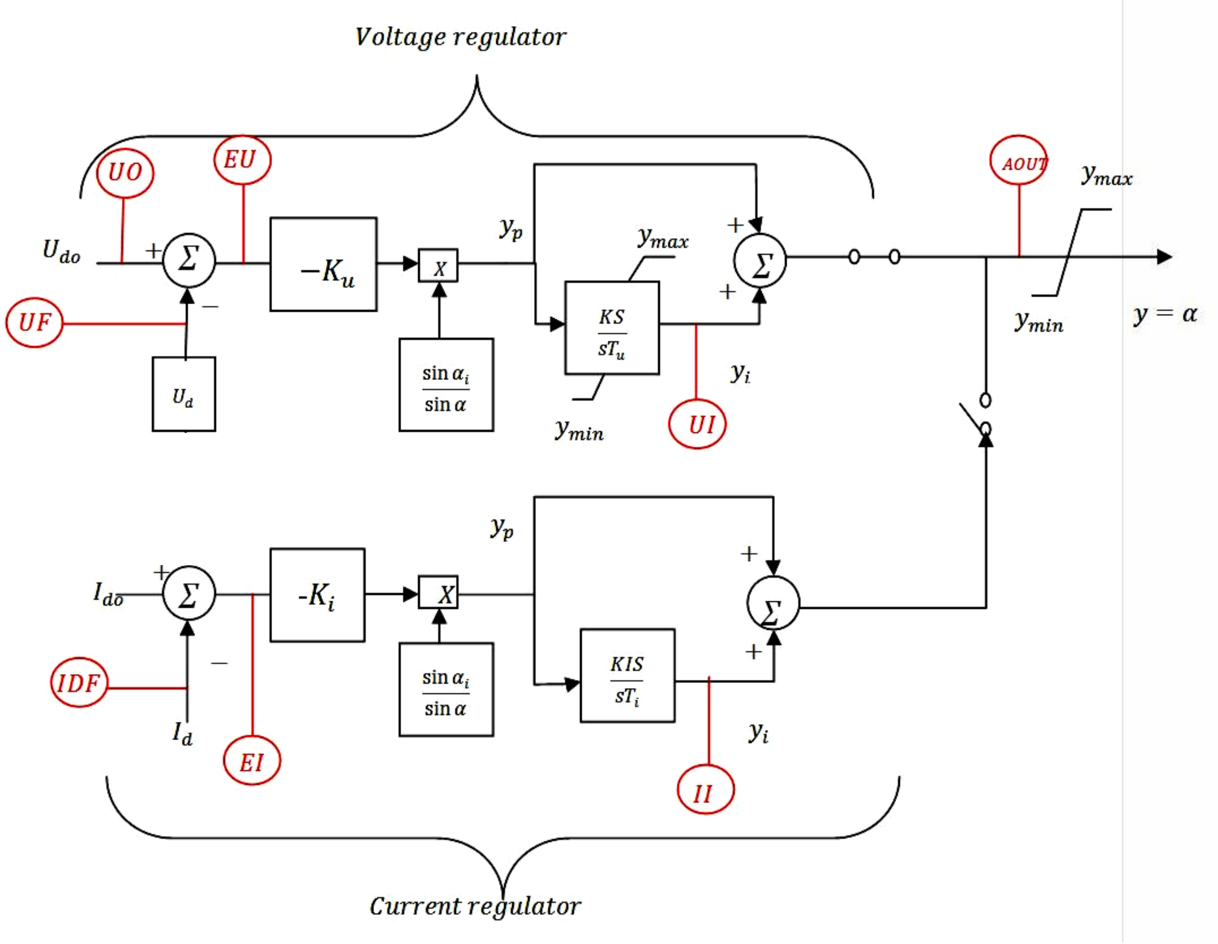

Figure 5-1 LVC3 PI regulator control system

In Figure 5-1 signal plot-points are shown in red. In Simpow, output signals on these plot-points can be visually seen.

UO, shows the desired value of the bus voltage signal sent into the PI regulator.

EU, shows the size of the error.

UI, shows the integration block contribution signal to the PI regulator.

EI, is the error signal sent into the current regulator.

II, is the current PI regulators integrator branch signal which will be summed.

UF, filtered measured DC voltage that has been fed from the DC side of the rectifier. UFs' difference with the desired bus voltage, UO, gives the error sent into the voltage regulator. Harmonics are neglected therefore in this work this signal is equal to the measured bus voltage.

IDF, filtered DC current which is the measured DC current because filter parameter TIF is set to zero.

AOUT, this is the signal sent into the limit integral to apply given limits of the firing angle.

The α is sent into the rectifier valves as the firing angle.

5.3.1 Single rectifier regulation tests

Two separate tests were applied to the rectifier, which were voltage step tests and current regulation tests.

An extra transformer with a tap changer and a single load is introduced in voltage regulation test. In current regulation test, shunt loads in various sizes are introduced to the system. A load size equal to the maximum power of the rectifier is applied to test the overload protection regulator function.

5.3.2 Voltage regulation

A voltage step test is made in order to observe the voltage regulation of the modelled rectifier with a test load of 12.2 kW. The main purpose of this test is to obtain similar behaviour of the modelled rectifier regulator as the onsite rectifier regulator. Voltage regulator final parameters and the reconstruction of the factory acceptance are given in Figure 5-7 and Figure 5-8.

The tap changer is applying a voltage step to the rectifier. The test setup is given in Figure 5-2.

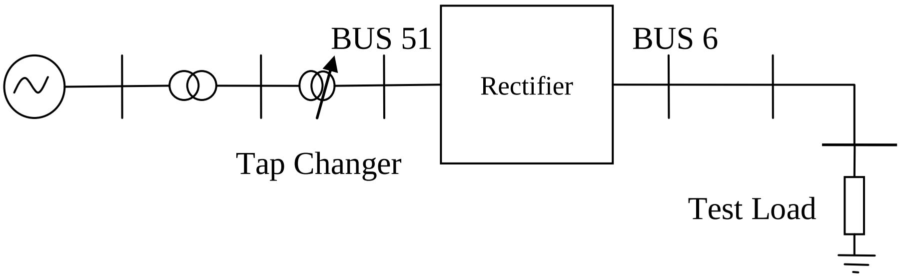

Figure 5-2- Simulation test setup for voltage regulation tests of the rectifier

After applying the 1.090 pu overvoltage to the rectifier, the voltage shape obtained at bus BUS 6 is adjusted according to the Factory acceptance 1.090 overvoltage test by tuning the KU, TU and AN parameters of the LVC rectifier and LVC3 regulator with a set of trial simulations made.

KU is the gain of the LVC3 regulator. KU value is adjusted until the DC bus BUS 6 voltages reach the Factory acceptance test 1.090 pu DC bus voltage. This particular FAT is chosen as reference because in that test the battery has no effect on the DC bus. The battery is fully charged and an overvoltage is applied. The regulation of the rectifier determines the DC bus BUS 6 voltage. KU with different values are shown in Figure 5-3 and Figure 5-4. The TU value is kept constant in order to show the real effect of the KU parameter.

In Figure 5-3 the relation between the applied voltage step and the rectifier regulation is shown. The gain is set to KU=0.5. The DC bus BUS 6 voltage is 1.075 pu when 1.090 is applied. This value of the KU is not regulating the DC voltage as in factory acceptance 1.090 pu overvoltage test.

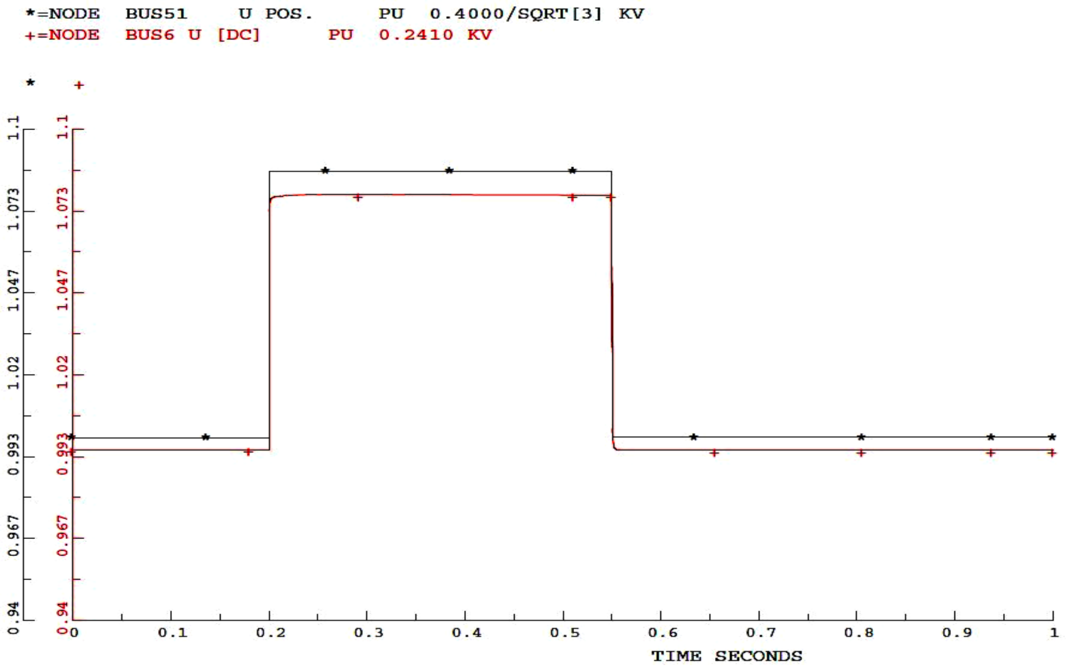

Figure 5-3 Voltage regulation test KU parameter adjustment
KU =0.5
Black line – AC line voltage
Red line – DC line voltage

In Figure 5-4 the gain, KU, with the value 2.5 is shown. The DC bus BUS 6 value reaches 1.070 pu. This DC bus BUS 6 value is higher than the factory acceptance 1.090 pu overvoltage test.

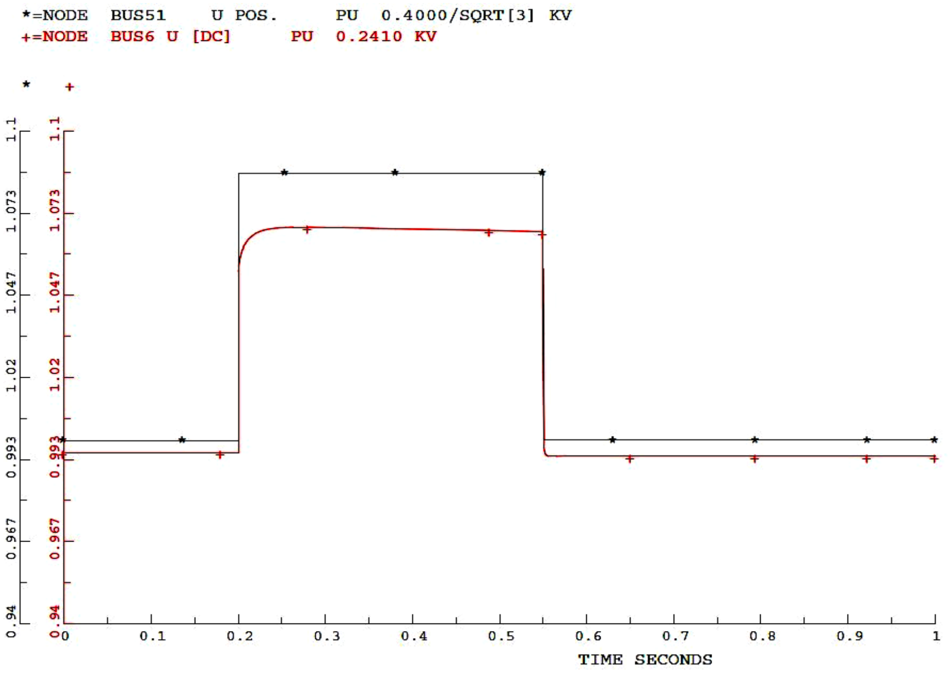

Figure 5-4 Voltage regulation test KU parameter adjustment
KU= 2.5
Black line – AC line voltage
Red line – DC line voltage

The KU value is increased until the DC bus BUS 6 voltage reaches 1.050 pu as it is in the factory acceptance 1.090 pu overvoltage test as shown in Figure 5-7. See Figure 5-8.

TU determines the relaxation time of the signal obtained with KU. Different values of TU and the outputs are shown in Figure 5-5, Figure 5-6 and Figure 5-8 while the KU is kept constant.

In Figure 5-5 the time constant value, TU, is set to 0.5. The DC bus BUS 6 voltage recovers to 1 pu during the applied overvoltage. This value of the TU is fast and not representing the Factory acceptance 1.090 overvoltage test. The integrator blocks denominator in the PI controller, *sTU*, has to have a higher value which should have a slower integration block in terms of time constant.

In Figure 5-6, the DC bus BUS 6 voltage when the TU value is increased to 2.5 is shown. The difference between the DC bus BUS 6 peak voltage point (at second 0.250) and the lowest DC bus BUS 6 voltage point (at second 0.540) is 0.014 pu. When the overvoltage recovers to 1 pu at 0.550 seconds the DC bus BUS 6 voltage decreases to 0.980 pu and recovers to 1 pu gradually.

In factory acceptance 1.090 overvoltage test the DC bus voltage is almost constant. The TU value is increased until the DC bus voltage during the applied voltage step is almost constant. TU value of 9.5 gives the almost constant relaxation time of the DC bus voltage as shown in Figure 5-8. The difference between the DC bus BUS 6 peak voltage (at second 0.270) point and the DC bus BUS 6 lowest peak point (at second 0.540) is 0.0022 pu.

AN value determines magnitude of the DC average output voltage.

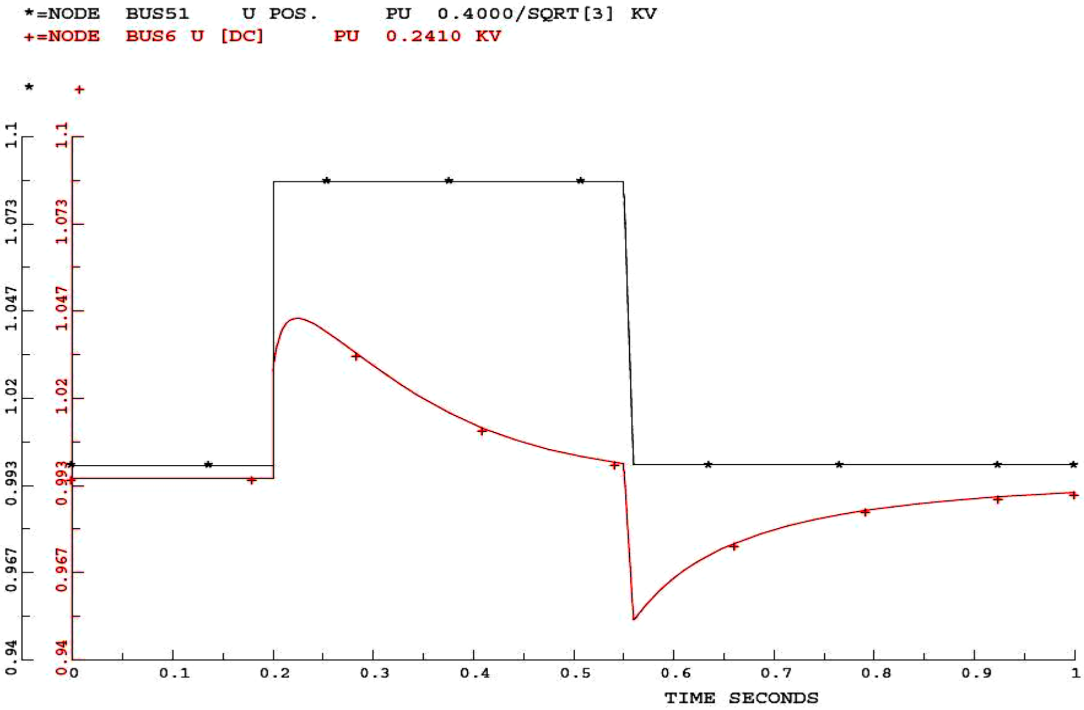

Figure 5-5 Voltage regulation test TU parameter adjustment
TU=0.5
Black line – AC line voltage
Red line – DC line voltage

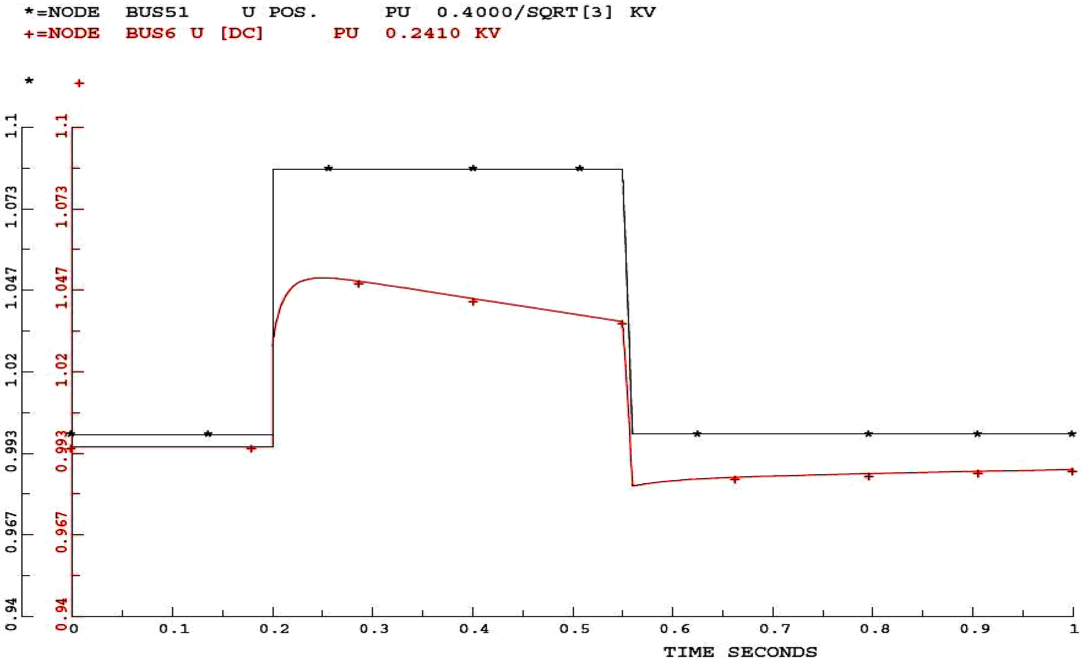

Figure 5-6 Voltage regulation test, TU adjustment
TU=2.5
Black line – AC line voltage
Red line – DC line voltage

Figure 5-8 shows the final obtained DC bus BUS 6 voltage after adjusting the KU, TU and AN parameters after trial simulations made by trying different values. These obtained values shows the same behaviour of the FAT 1.09 pu test which has been taken as the reference. Also a reconstruction of the FAT 1.09 pu is shown in Figure 5-7 for a comparison. The difference between the DC bus BUS 6 peak voltage point (at 0.278 seconds) and the lowest DC bus BUS 6 voltage point (at 0.550) during the voltage step, is 0.00331 pu.

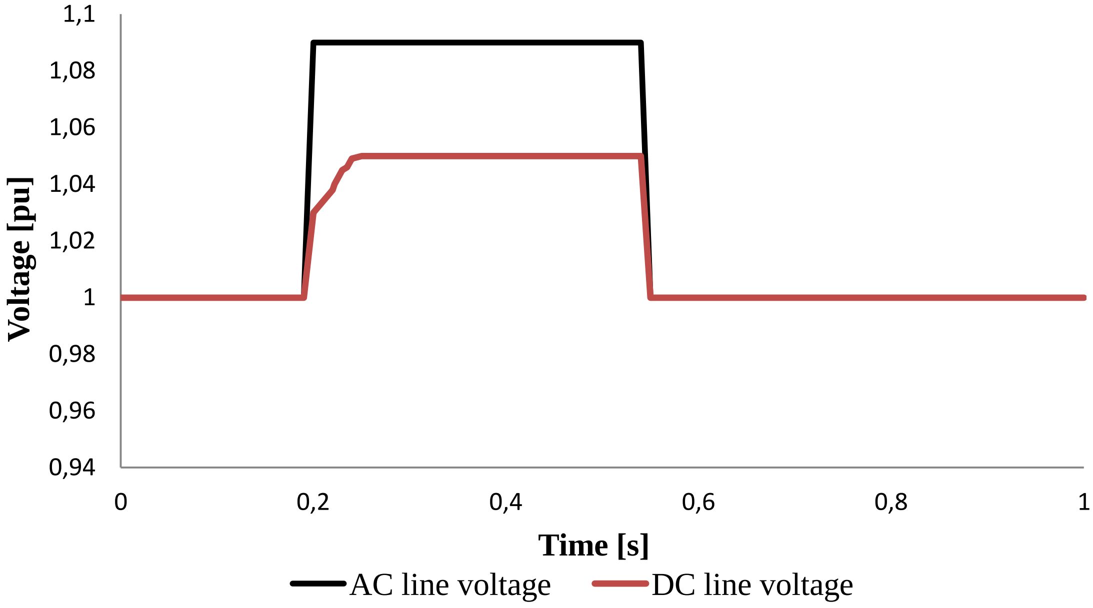

Figure 5-7 Gutor Factory Acceptance 1.09 pu Test reconstruction

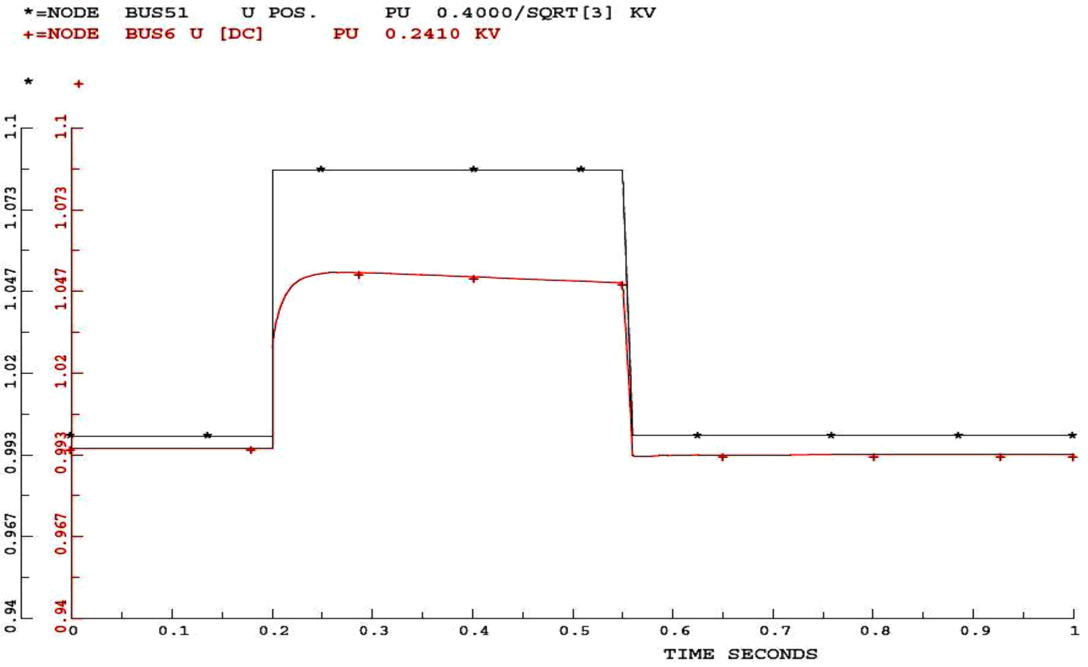

Figure 5-8 Final parameters of the rectifier voltage regulator
KU=7.5 and TU=9.5
Black line – AC line voltage
Red line – DC line voltage

5.3.3 Current regulation

In normal operation rectifiers are providing necessary amount of power to the loads. Number of loads connected to the rectifier can vary in size with time. During normal operation, the total connected load size can exceed the rated value of the rectifier for a short period of time. During overload the current regulator has to be in operation and limit the current to maximum allowed current. In order to test the current handling ability of the rectifier current regulation test is made.

In current regulation test, the DC test loads in various sizes are connected and disconnected in sequence showing the response of the current regulator and also the overload protection. In this test setup the current regulator parameters KI and TI are adjusted after a set of simulation. Simulation setup is given in Figure 5-9.

Gain of the current regulator, KI, is adjusted until the response of the current regulator is fast as the onsite rectifier regulator. To achieve a fast response, the TI parameter is set to a short time value after tests made.

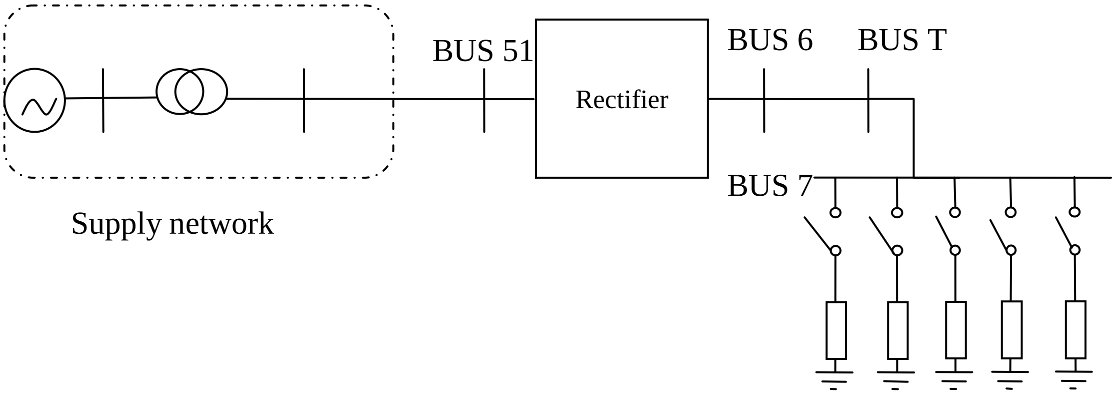

Figure 5-9-Simulation test setup for current regulation tests of the rectifier

Figure 5-10 shows the result. The DC shunt loads are connected at second one, at second three and second five. The total load size applied at the fifth second exceeds the maximum load of the rectifier. At this instant the overload protection starts and the voltage regulation is disconnected. Voltage drop in the bus BUS6 between seconds five and seven can be explained according to this operation of change of regulators in LVC3. The maximum allowed current is flowing under the control of the LVC3s' current regulator and it is kept constant between seconds five and seven.

In Figure 5-10 between second five and second seven the current value is equal to the maximum allowed current which is given as IMAX in rectifier current regulation thus the maximum allowed current is fed to the loads.

At the seventh second the excessive load size is disconnected. Because of this load disconnection, the voltage regulation restarts and the current regulation is disconnected. The voltage regulator regulates the BUS6 voltage back to 1 pu at the instant of excessive load disconnection.

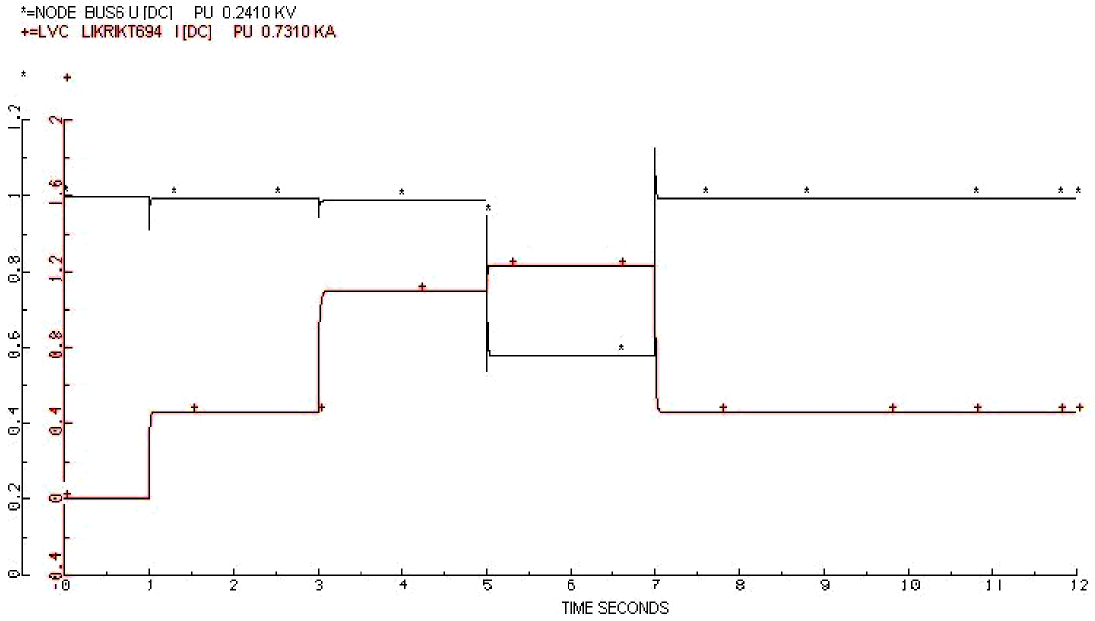

Figure 5-10 Current regulation and voltage regulation test

5.4 Inverter modelling

In this master thesis, the inverter model was not studied into detail as it was studied for the rectifier. Simpows predefined PWM inverter was used as the inverter of the system. The gathered information from the manufacturer for the inverter parameters were set. The voltage magnitude values of the PWM inverter were adjusted after the simulations made. The main reason was the lack of time and the size of the work.

PWM inverter OPTPOW parameters and power control parameters are given in Table 4 and Table 5 respectively.

Table 4- Optpow file main circuit part parameters

SN	The rated power of the PWM converter in MVA
UN	The rated AC voltage of the PWM converter in kv
XQ	The compounding reactance between the AC voltage of the PWM converter and a fictive voltage given by CKNODE parameter
CTETA	A constant phase angle between the fictive AC voltage behind XQ of the PWM converter and the reference AC voltage given by CKNODE parameter
FR	The ratio between the frequency of the voltage of the reference AC voltage (CKNODE) and that of AC voltage of the PWM converter

R	Internal resistance per phase, seen from the AC terminals in pu of $\frac{UN^2}{SN}$ R>0
RP	Internal shunt resistance per phase connected at the AC terminal in pu of $\frac{UN^2}{SN}$

SN, UN values are obtained from manufacturer.

FR is adjusted after OPTPOW tests where the AC voltage magnitude reaches 1 pu on the AC side of the inverter.

R parameter is set to zero because of the lack of information. The internal resistance of the inverter will cause a voltage drop between the terminals of the inverter. The voltage drop effect to the inverter output voltage can be simulated by adjusting the gain in the voltage magnitude regulator.

Power control parameters:

Type of the inverter is given as PWM.

DTETA is neglected and C is chosen in order to amplify the voltage to 1 pu at AC side.

An infinite bus is connected to the inverters' AC side and given as a reference bus in order to implement the inverter to the model.

CKNODE is chosen as the fictive power sources node, BUS K, which is connected as reference. Bus BUS K and the inverter AC side have open connection as shown in Figure 5-11. The purpose of this is to create the fictive voltage for the PWM inverter for to regulate the phase angle and the magnitude of the AC voltage.

Table 5- Optpow file power control part

TYPE	The type of the controllable system element. CTETA is chosen which means that the amplitude factor and the phase angle of the AC voltage are kept constant
CKNODE	The identification of the AC node, which is used as a reference for the phase angle of the fictive voltage behind XQ of the PWM converter
C	The amplitude factor in the power control of the inverter
DTETA	The value of a controllable phase angle is kept constant. It is added to the constant phase angle, CTETA, and referred to the phase of the AC voltage of the CKNODE

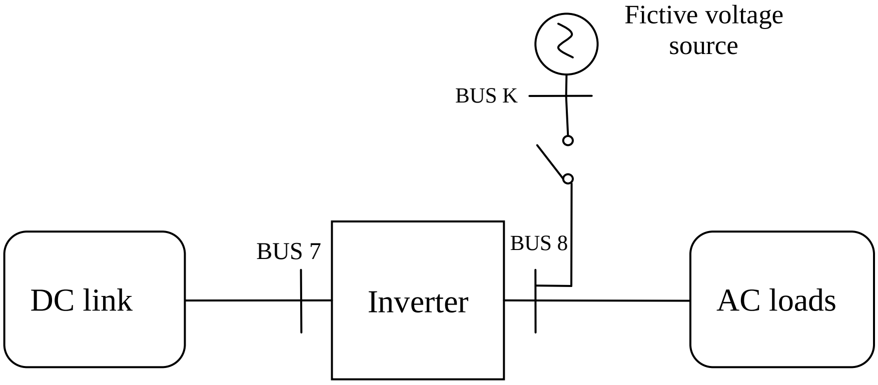

Figure 5-11 Fictive voltage source and reference bus BUS K

5.5 Inverter regulator modelling

PWM inverter DYNPOW phase angle regulator parameters and magnitude regulator parameters are given in Table 6 and Table 7 respectively. All parameters of the PWM inverter regulator are given in the Table 6 and Table 7. Block diagram is shown in Figure 5-12.

Dynpow variables of the phase angle regulator are given in Table 6.

Table 6- Dynpow part 1- Phase angle regulator

TYPE	Type of the dynamic solution language, DSL, is given
UN	The rated AC voltage of the PWM converter in kV
SN	The rated power of the PWM converter in MVA
CKNODE	The three phase node, which is used as a reference for the phase angle of the fictive internal voltage behind XQ
CNODE	The identification of the AC node where the AC voltage is controlled
DTETA	The value of a controllable phase angle in radians. It is added to the constant phase angle, CTETA and referred to the phase of the AC voltage of the CKNODE
K	Gain of the angle regulator
T	Time constant for the integrator of the angle regulator in s
TA	Time constant for the output filter of the angle regulator in s
IALIM	Limit for the AC current of the PWM, rms value, in kA. Used for control of the phase angle
KIA	Gain of the current limit regulator

TIA	Time constant for the integrator of the current limit regulator
TFIA	Time constant for the output filter of the current limit regulator
CREG	The identification of the voltage regulator
IVLIM	Limit for the AC current of the PWM, rms value, kA. Used for control of the voltage magnitude
KIV	Gain of the current limit regulator, in pu of UBASE
TIV	Time constant for the integrator of the current limit regulator in s
TFIV	Time constant for the output filter of the current limit regulator in s
DUT	Output signal from the current limitation regulator for the voltage magnitude used as input to the voltage regulator

CKNODE, TYPE, CNODE, CREG, DUT are modelling parameters according to the design type. Connected buses and reference buses are given for the inverter.

UN, SN, IVLIM, IALIM are the parameters that can be found in the manufacturers product brochures.

TA, is taken from the simpow PWM inverter example because the real value of the parameter couldn't be obtained.

K, T, KIA, TIA, KIV, TIV are obtained in Chapter 5.6.

Magnitude regulator of the PWM inverter parameters are given in Table 7.

Table 7- Dynpow variables list 2- Magnitude regulator

TYPE	The dynamic solution language, DSL, file type is defined
CMIN	Minimum of the amplitude factor of the controlled AC voltage of the PWM converter
CMAX	Maximum of the amplitude factor of the controlled AC voltage of the PWM converter
K	Gain of the voltage regulator
T	Time constant for the integrator of the voltage regulator
TA	Time constant for the output filter of the voltage regulator
NREG	The identification of the line on the PWM side of the converter, whose active and reactive power is measured
SW	Selection of measurement

UCB	The base voltage of the converter AC node in kV
UN1	The rated voltage of the converter transformer converter winding in kV
UN2	The rated voltage of the converter transformer station winding in kV
SN	The rated power of the converter transformer in MVA
SS	The rated power of the converter station in MVA
XC	Compounding reactance for the converter current in pu of UN2 and SN
XS	Compounding reactance for the station current in pu of UN2 and SS
QF	The rated reactive power of the filter of the converter at base voltage, in MVar. The base voltage of the filter node must be the same as the base voltage of the controlled station node
XL	Series reactor impedance in ohm
DIN	Input signal to the voltage regulator. Output signal from the current limitation regulator for the voltage magnitude
DU	Input signal to the voltage regulator. The value of a controllable voltage in pu of UBASE of controlled node. It is added to the constant voltage reference

CMIN, CMAX are given after the optpow file.

TYPE, SW, NREG, DIN, DU are the model parameters according to the chosen model.

K, T are adjusted after tests done in Chapter 5.6.

UN1, UN2, SN, SS values are taken from manufacturer.

XC, XS, XL are taken from the Simpow PWM inverter example because the real values of these parameters couldn’t be obtained or calculated.

The PWM inverter regulator Simpow code is as follows:

Phase angle regulator is given in PWM converters data group in simpow

PWM CONVERTERS

VAXELRIK694 TYPE=DSL/PWMC/ CKNODE=BUSK DTETA=0 K=10 T=0.01 TA=0.033 UN=0.4 SN=0.160 IALIM=10 KIA=10 TIA=0.01 TFIA=0.02 IVLIM=1 KIV=10 TIV=0.1 TFIV=0.020 CNODE=BUSK CREG=3 DUT=_DVLIM

The PWM inverter magnitude regulator is given in the regulators data group.

REGULATORS

TYPE=DSL/VR/ CMIN=0 CMAX=2.3 K=7 T=0.1 TA=0.036 NREG= BUS8 BUS10 SW=1 UN1=1 UN2=2 UCB=0.4 SN=0.16 SS=0.2 XC=0.05 XS=0.05 QF=5.5 XL=0.5 DIN=_DVLIM

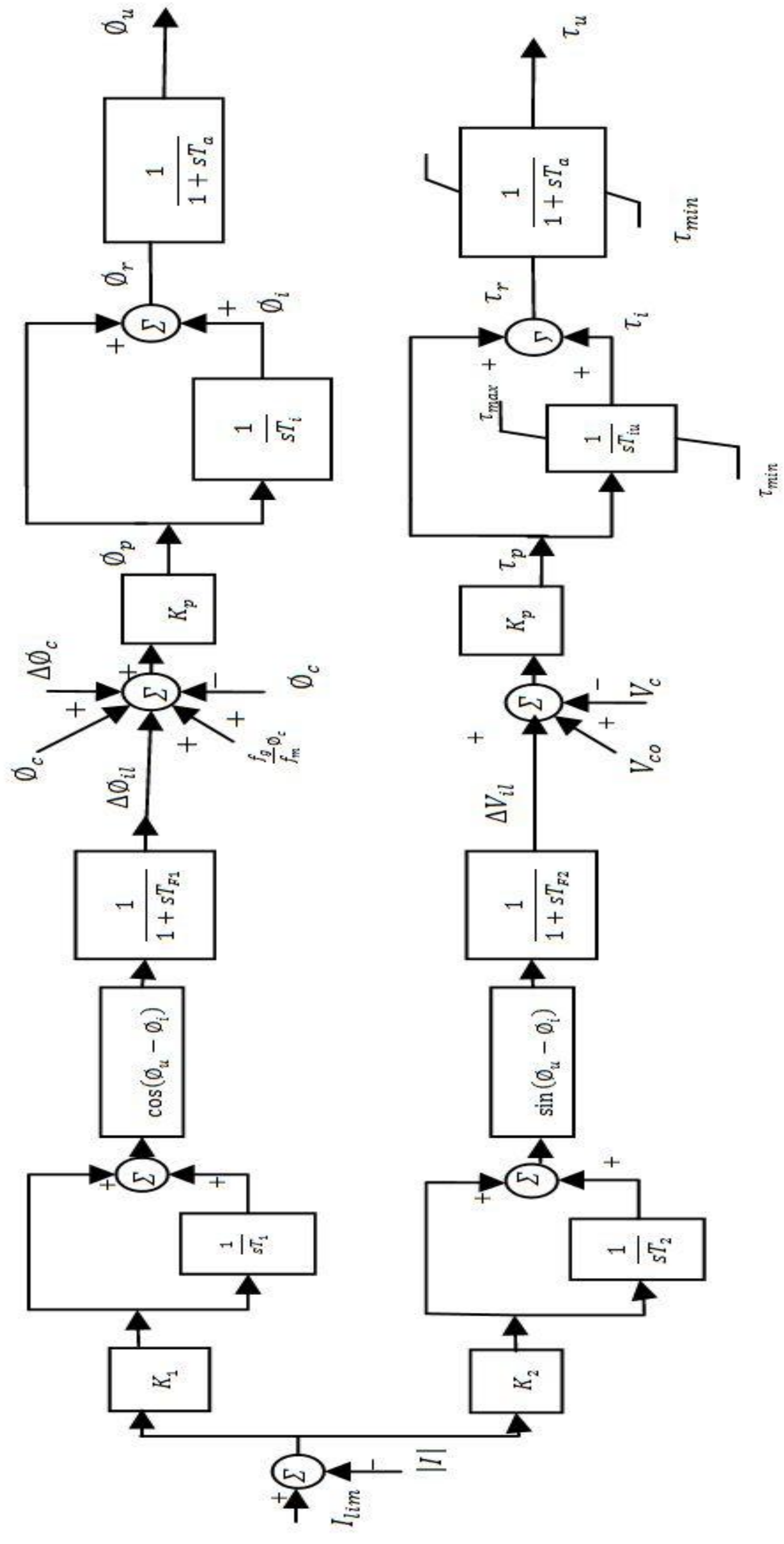

Figure 5-12 PWM inverter regulator block scheme

5.6 Battery modelling

The battery model created in this thesis work consists of a resistance and a capacitance connected in series shunt to the DC part of the system representing the battery unit. The factory acceptance undervoltage 0.70 pu test is taken as the reference test to adjust the battery model parameters. The purpose is to simulate and adjust the values of the battery to the existing battery bus voltage which is given in Chapter 4.2

In the factory acceptance undervoltage 0.70 pu test, rectifier is force shutdown due to the undervoltage applied to the rectifier. The system is fed through the battery only.

The test setup is given in Figure 5-13.

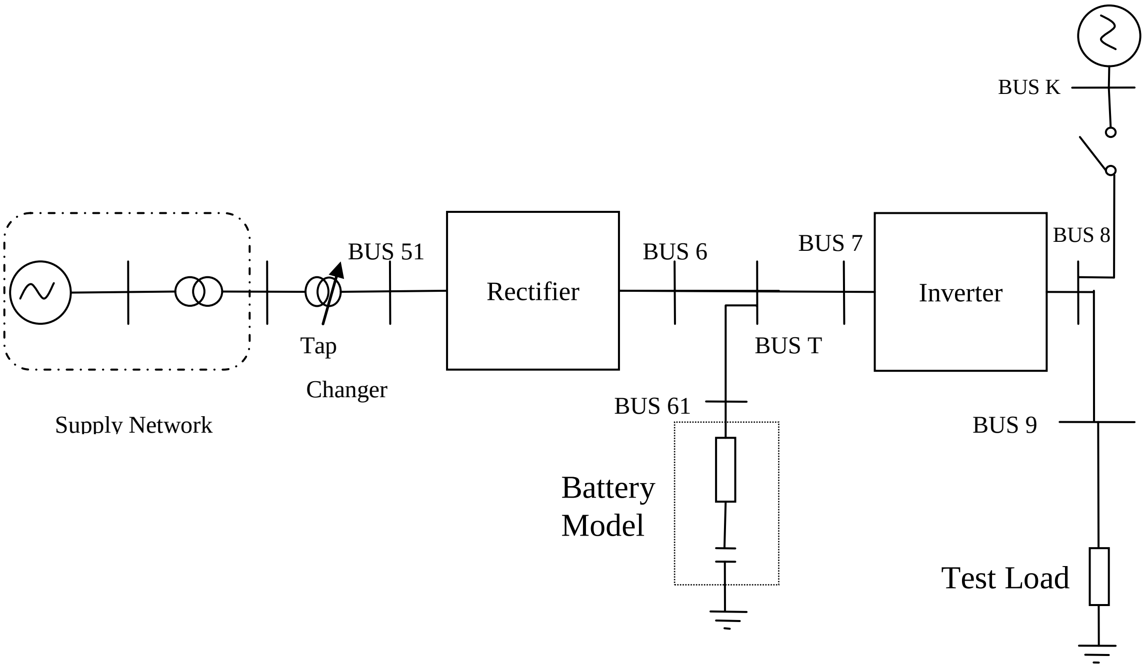

Figure 5-13- Battery model test

Resistance size is calculated from the voltage drop on the battery bus. Figure 5-14 and Figure 5-15 shows two different resistance sizes and the voltage drop they cause on the battery models' bus BUS 61. The capacitance of the battery model is kept constant in order to show the behaviour of the battery models' resistance and voltage drop effect on BUS 61.

In Figure 5-14 battery is modelled with resistance size 0.1 Ohms. The voltage on the BUS 61 is approximately 0.99 pu.

Figure 5-15 the battery is modelled with resistance size 0.25 Ohms. The voltage on Bus 61 is 0.97 pu.

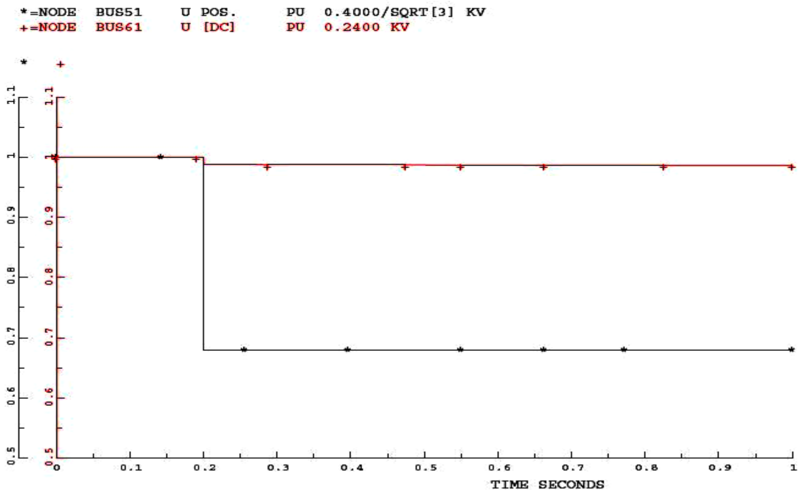

Figure 5-14 Battery model parameter adjustment
Resistance is 0.1 Ohms and capacitance is 50 Farads

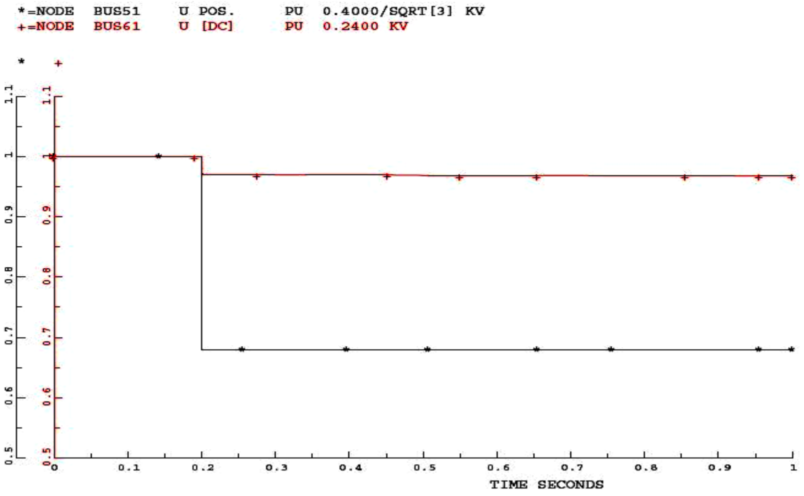

Figure 5-15 Battery model parameter adjustment
Resistance is 0.25 Ohms and capacitance is 50 Farads

The capacitance size of the battery model affects the battery bus voltage curve. The shape of the DC bus voltage is given by adjusting the capacitance. Trial runs are made with the purpose of finding the proper value for the battery model simulating the given battery bus voltage in Chapter 4.2. Two examples with two different capacitance values of the battery model are given in Figure 5-16 and Figure 5-17. In both simulations, the resistance size of the battery is kept constant in order to show the capacitance size effect on the battery bus curve.

In Figure 5-16 the battery is modelled with capacitance size of 0.5 Farad. It can be seen that the battery model bus voltage is decreasing rapidly. This value is not fulfilling the real case test conditions, factory acceptance undervoltage 0.70 pu test as shown in Figure 5-19. The capacitance size has to be increased in order to have a more constant voltage on BUS 61.

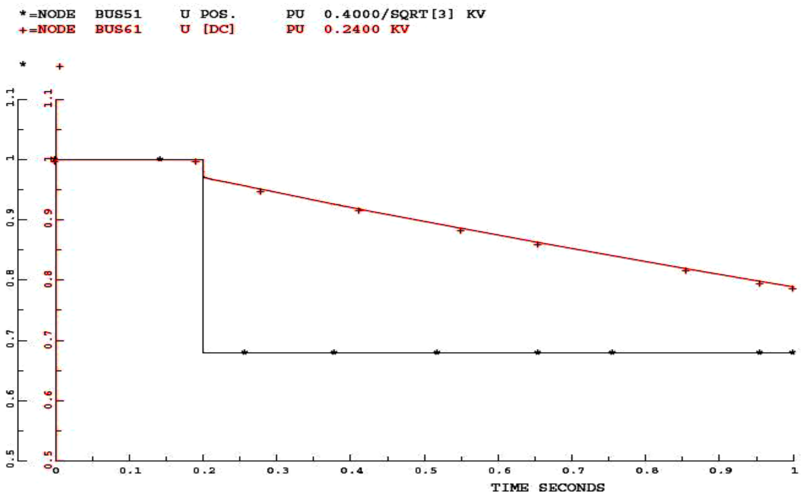

Figure 5-16 Battery model parameter adjustment
Resistance is 0.51 Ohms and capacitance is 0.5 Farads

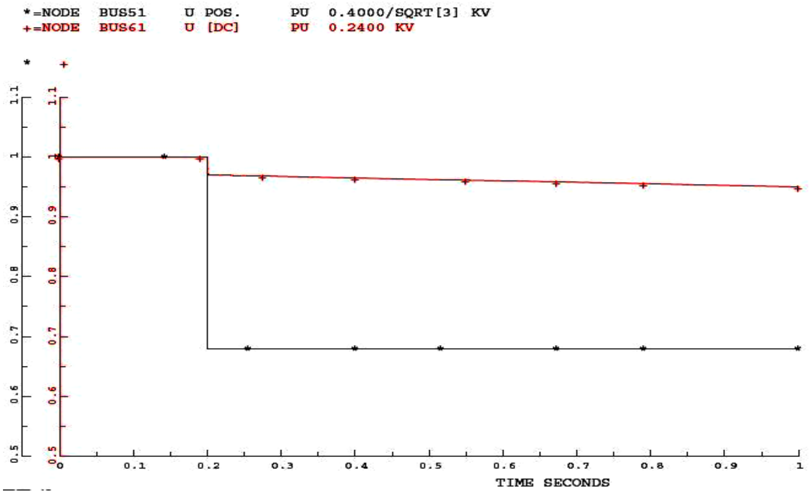

Figure 5-17 Battery model parameter adjustment
Resistance is 0.51 Ohms and capacitance is 5 Farads

Figure 5-17 the battery is modelled with capacitance size of 5 Farad. It can be seen that the battery model bus voltage is decreasing. It is not decreasing as fast as it is in with capacitance size of 0.5 Farad. However this size is still not satisfying the real case test voltage behaviour, the factory acceptance undervoltage 0.70 pu test.

The Figure 5-18 shows the final battery model response on the DC bus BUS 61 obtained after adjusting the parameters of resistance and capacitance. When the rectifier is out of operation, the battery model sets the DC bus BUS 61 voltage to approximately 0.95 pu, decreasing gradually with time. In Figure 5-19 a reconstruction of the reference FAT is shown for comparison of the result. It can be seen from the Figure 5-19 that the results of the simulations show similar results to the actual tests.

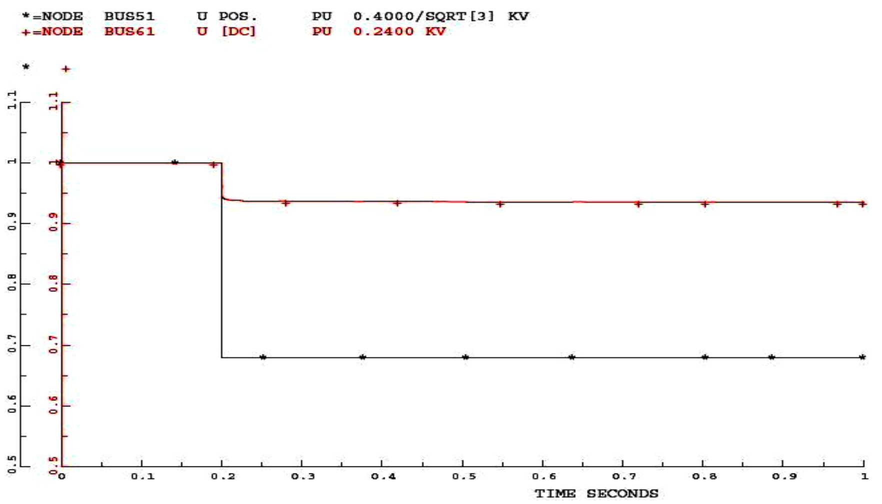

Figure 5-18 Final battery model response to the 0.7 pu step voltage.
Red line - shows the DC battery bus voltage.
Black line – AC line voltage
Battery model resistance is 0.51 Ohms and capacitance is 50 Farads

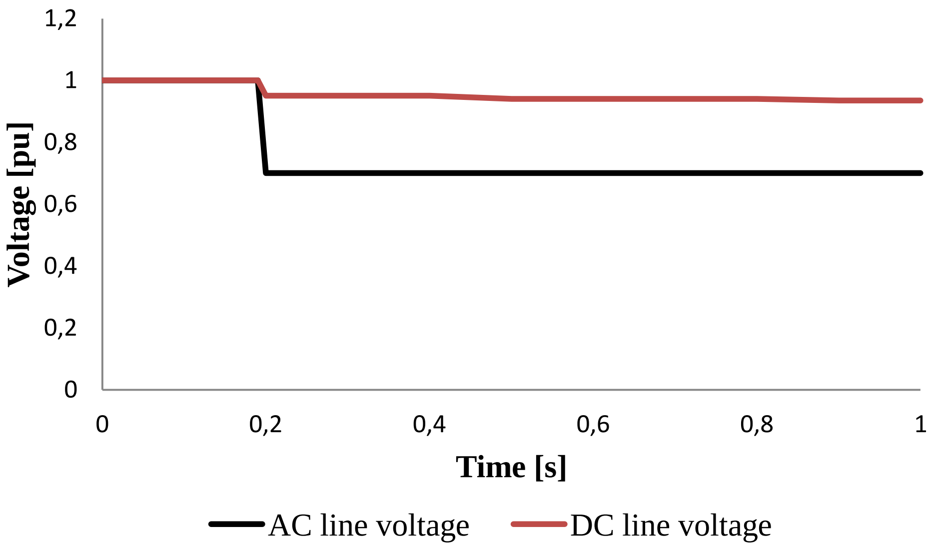

Figure 5-19 Reconstruction of Factory Acceptance 0.7 pu Test

The battery model code is given in the Shunt Impedances data group in OPTPOW as follows:

SHUNT IMPEDANCES

BUS61 NO 1 TYPE=A_DC R=0.51 C=50

6 Test of the entire model

UPS systems components are modelled separately in the Chapter 5. In this chapter these three separately modelled components are connected into one UPS system. This UPS system is tested in four different tests scenarios according to the FATs in Chapter 4. The factory acceptance tests are provided from the manufacturer as explained in Chapter 4. In this chapter the factory acceptance test scenarios simulations are studied.

The system setup is made according to the factory acceptance test setup. A tap changer is introduced to the system in order to create the voltage steps. Voltage steps are applied to the system in the simulations. Studied simulations are:

1. Undervoltage 0.70 pu test
2. Undervoltage 0.85 pu test
3. Overvoltage 1.09 pu test
4. Overvoltage 1.12 pu test

Load size is 6.625 kW [18]. Test setups for four simulations are shown in Figure 6-1.

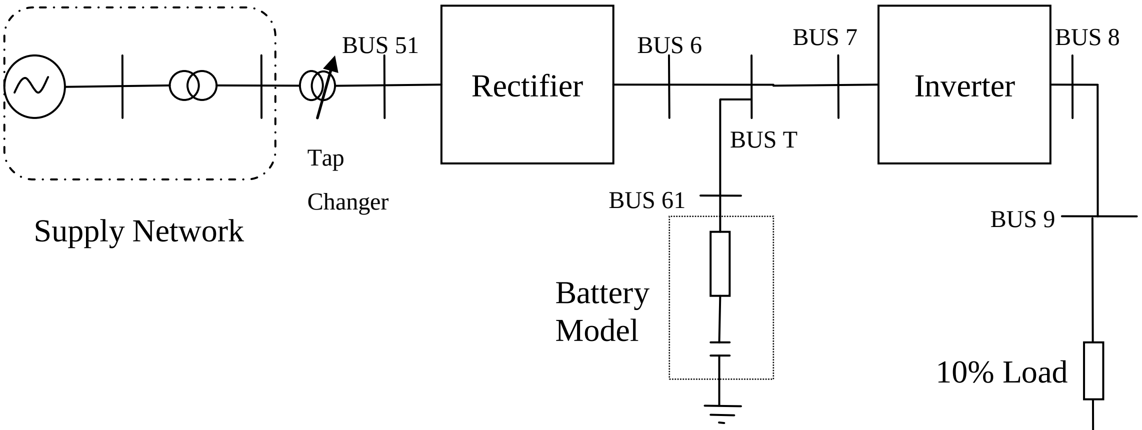

Figure 6-1- Simulation test setup

6.1 Undervoltage 0.70 pu test

In simulation 0.70 pu voltage is applied to the rectifier for 350 milliseconds. In the test, the rectifier is disconnected after 0.20 seconds due to the low voltage and the battery unit feeds the loads. Power flow is shown in Figure 6-2.

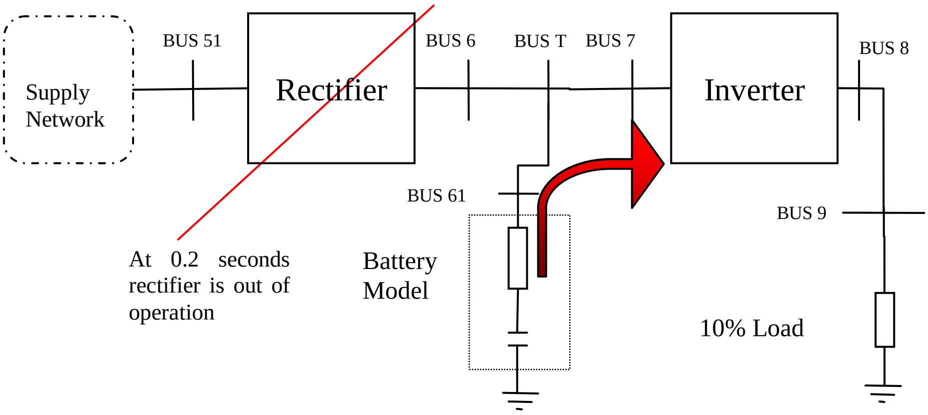

Figure 6-2 Powerflow in simulation

In Figure 6-3 applied 0.7 pu undervoltage and the response of the UPS system is shown. The DC bus BUS 61 voltage and the load side AC bus BUS 8 voltage are shown in red and blue respectively. The black line shows the bus BUS 51 applied voltage. Bus BUS 51 voltage is 0.68 pu and the bus BUS 61 voltage is 0.94 pu decreasing with time. The AC bus voltage makes a voltage drop at the fault instant however it recovers to 1 pu rapidly.

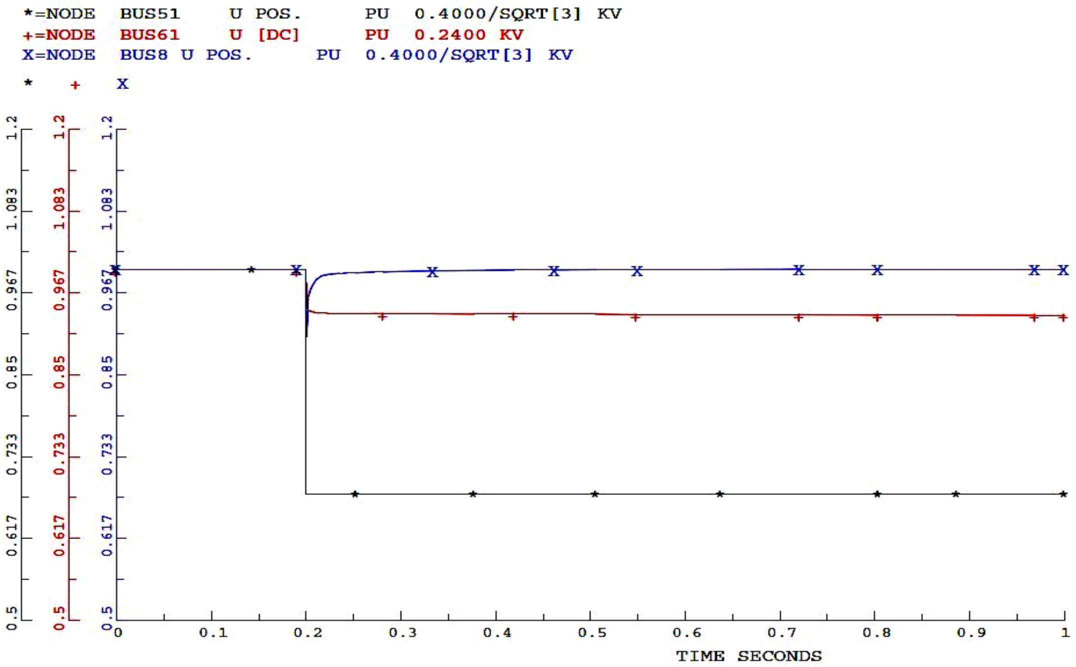

Figure 6-3 0.70 pu applied voltage simulation.
Black line - AC BUS 51
Red line - DC BUS 61 and Blue line - load side AC BUS 8 voltages

In Figure 6-4 a reconstruction of the Factory acceptance 0.7 pu test is given to show the similarity between the 0.7 pu simulation and the factory acceptance 0.7 pu test.

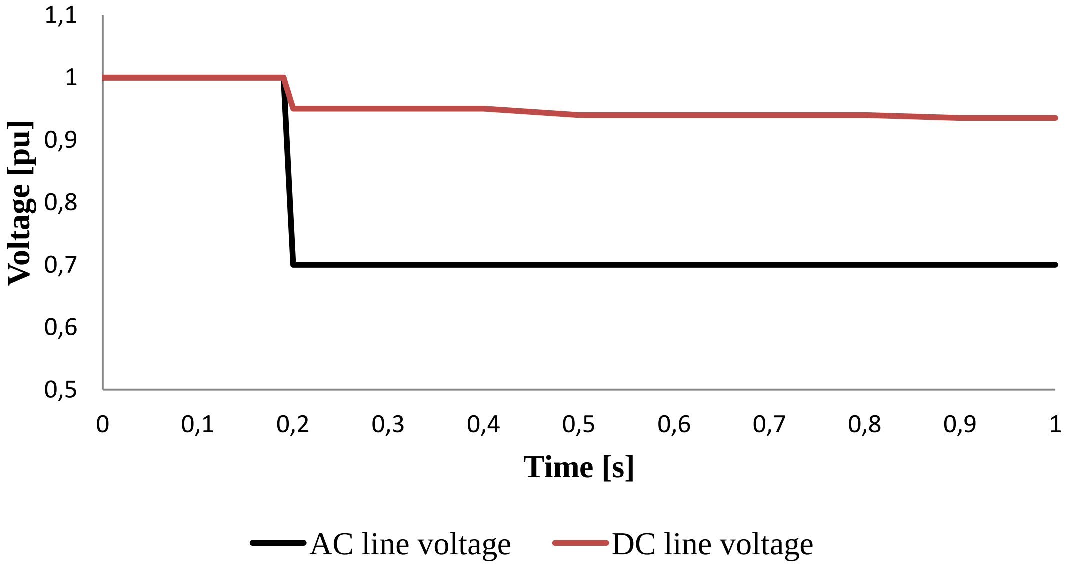

Figure 6-4 Reconstructed Factory Acceptance 0.7 pu Test

In Figure 6-5 the battery model voltage and current output is given, SHUNT BUS 61. Before the fault the battery model is fully charged. When the fault occurs in 0.20 seconds the battery reacts instantly providing the system with the required amount of energy, in other words the battery model is discharging. The current flow from the battery is zero before the fault. The current rises instantly and provides the connected test load at the fault second, at 0.20 seconds. Voltage decreases after the fault event as it shown in the Figure 6-5. The battery models' bus Bus 61 voltage is shown and it is following the battery voltage, SHUNT BUS 61.

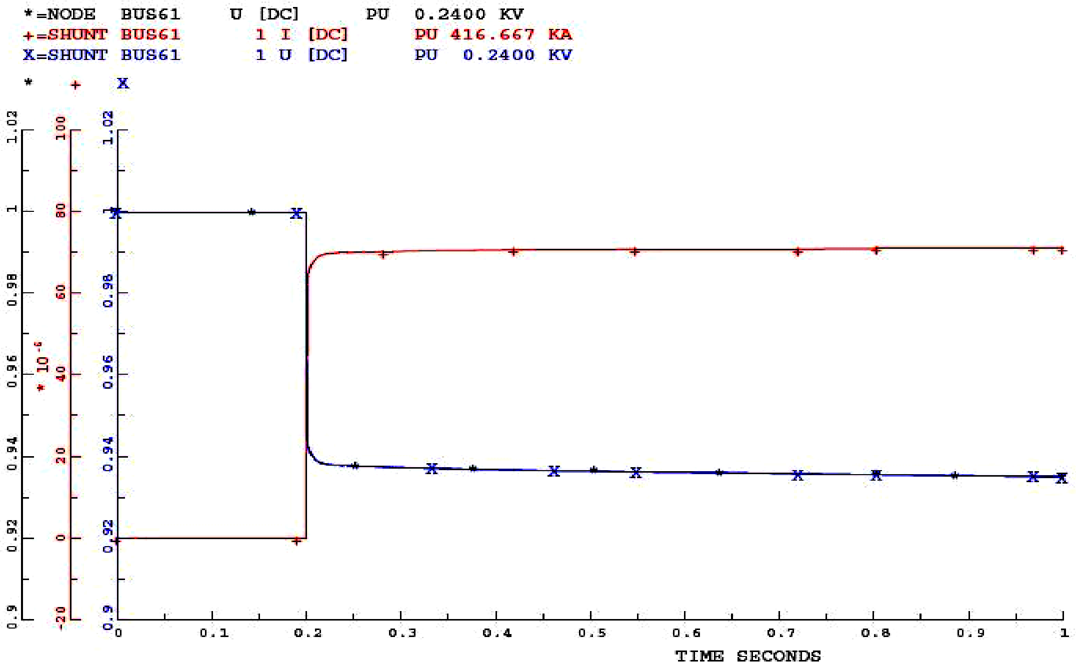

Figure 6-5 Battery model response to the applied fault voltage. Battery current and voltage

6.2 Undervoltage 0.85 pu test

For 350 milliseconds an undervoltage with 0.85 pu is applied to the system test setup showed in Figure 6-1. In this test the applied voltage is within the limits of the rectifier. The rectifier, the battery model and the inverter are in operation.

In Figure 6-6 and Figure 6-8 bus voltages of AC bus BUS 51, DC bus BUS 61 and AC load side bus BUS 8 are shown.

0.85 pu voltage is applied at 0.20 seconds and this voltage step lasts for 350 milliseconds, changes to 1 pu at 0.550 seconds.

During the fault, the DC BUS 61 voltage is held constant at 0.94 pu by the battery model as shown red in Figure 6-6.

After 0.551 seconds the DC BUS 61 voltage recovers approximately to 1 pu.

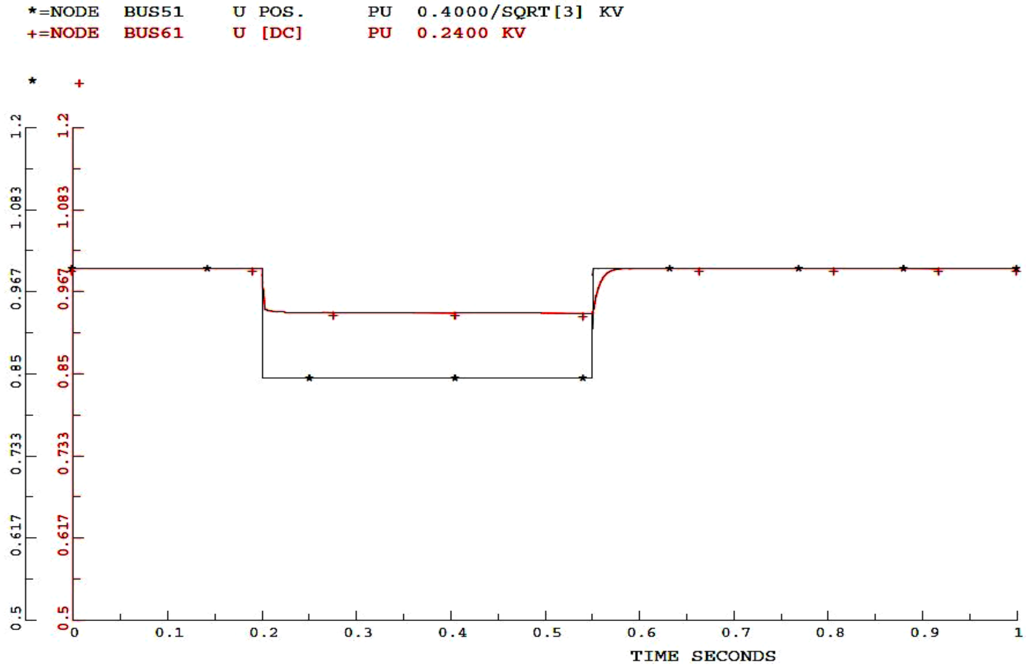

Figure 6-6 0.85 pu applied voltage simulation
Black line – AC line voltage, AC BUS 51.
Red line – DC line voltage, DC BUS 61 voltages

In Figure 6-7 is given to show the similarity between the 0.85 pu simulation in Figure 6-6 and the factory acceptance 0.85 pu test. It can be seen from the both figures when the step voltage is applied to the UPS simulation the response of the simulation is similar to the Gutor UPS system.

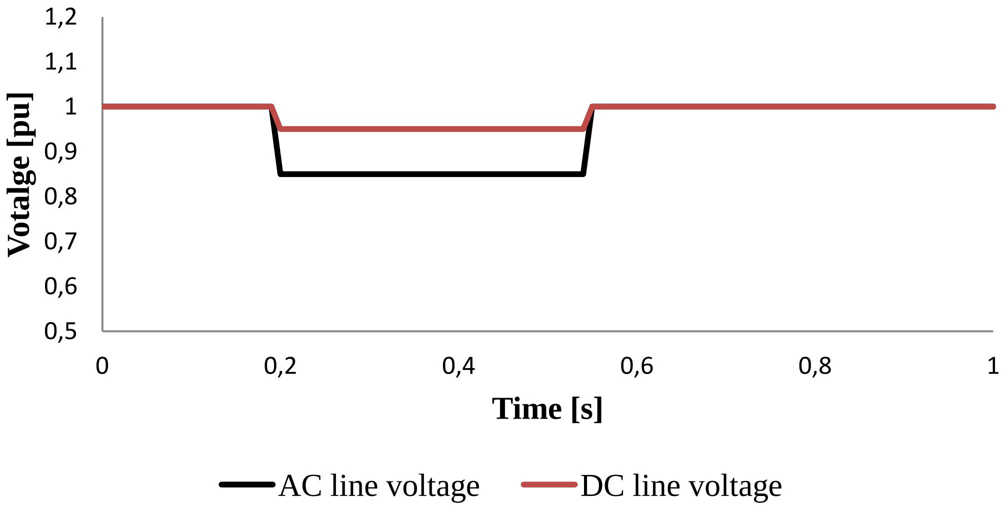

Figure 6-7 Reconstructed from the Factory Acceptance 0.85 pu test

In Figure 6-8 the relationship between the applied voltage and the AC output voltage is shown. The AC bus BUS 8 voltage is affected at the beginning and at the end of the voltage step applied, 0.200 seconds and 0.550 seconds respectively. The AC bus BUS 8 voltage makes a drop to 0.96 pu at the beginning of the applied 0.85 pu step voltage and recovers to 1 pu after 150 milliseconds. At the end of the applied voltage step the AC BUS 8 voltage overshoots to 1.03 pu and reaches 1 pu after 150 milliseconds.

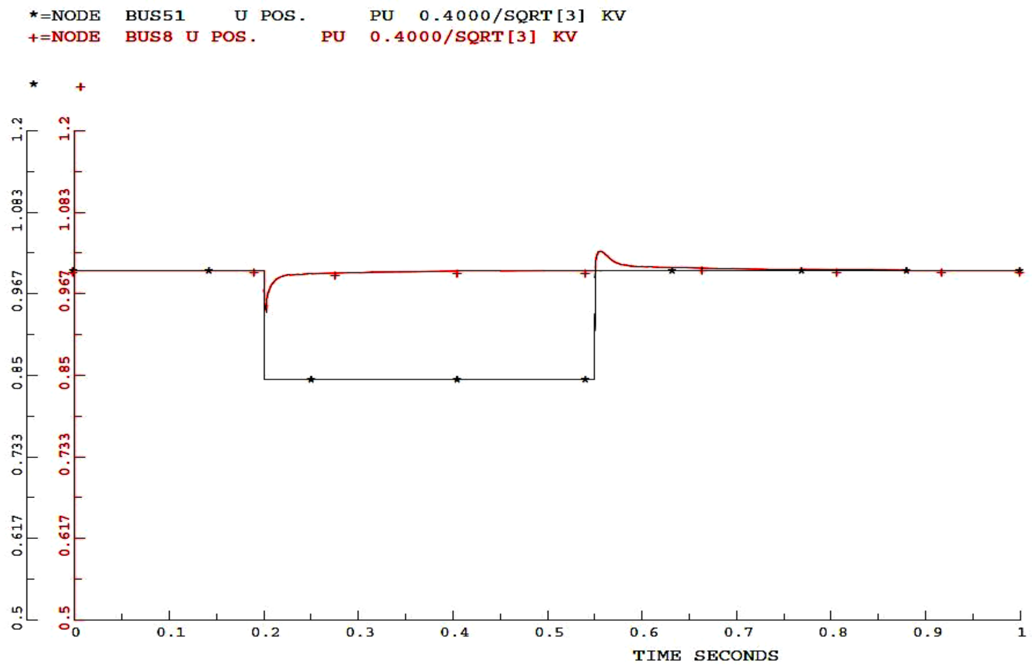

Figure 6-8 0.85 pu applied voltage simulation
Black line – AC line voltage, AC BUS 51 and Red line – AC BUS 8 voltages

Overvoltage for 350 milliseconds with 1.09 pu starting at 0.200 seconds and ending at 0.550 seconds is applied to the rectifier. Applied voltage at AC bus BUS 51, DC bus BUS 61 voltage and AC load side bus BUS 8 voltages are given in Figure 6-9 and Figure 6-11.

In Figure 6-9 it is shown that the applied voltage at AC bus BUS 51 is regulated down to 1.06 pu at the bus BUS 61 by the rectifier regulator. The rectifier and the battery are in operation. The battery is in standby mode without any contributions to the DC BUS 61 voltage. In Figure 6-10 the reconstruction of Factory acceptance 1.09 pu test is given to show the similarity between the 1.09 pu simulation and the factory acceptance 1.09 pu test. In this particular test the affect of the battery unit is negligible because it is assumed that the battery unit is fully charged before the applied step voltage. When the UPS is exposed to the step voltage, the modelled UPS output readings are similar to the Gutors' UPS system readings.

In difference to the rectifier modelling tests, these factory acceptance tests include all the connected components, for instance the inverter and the loads.

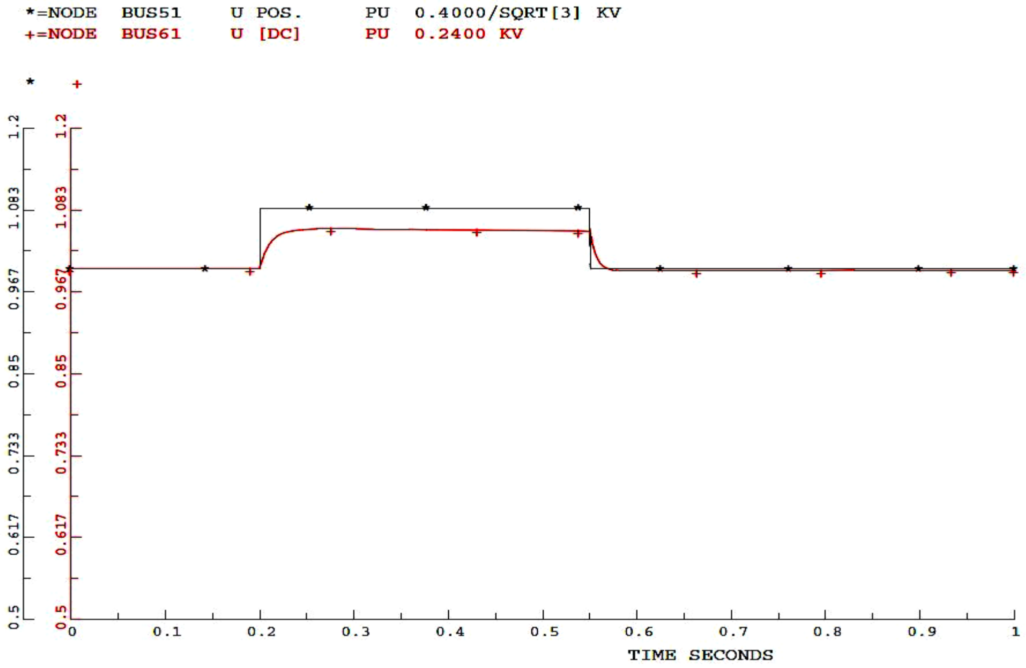

Figure 6-9 1.09 pu applied voltage simulation –
Black line – AC line voltage, AC BUS 51
Red line – DC line voltage DC BUS 61

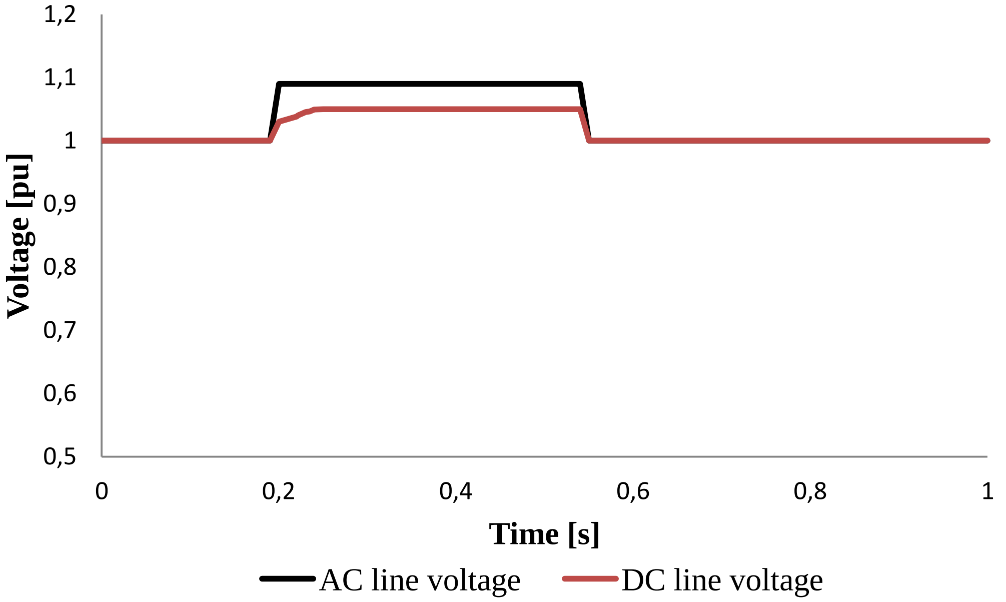

Figure 6-10 Reconstructed from the Factory Acceptance 1.09 pu Test

In Figure 6-11 the AC load side BUS 8 voltage (red line) in relation with the applied voltage step is shown. At 0.20 seconds the AC bus BUS 8 voltage gets affected at the beginning of the event and increases to 1.02 pu. After 100 milliseconds the inverter magnitude regulator decreases the AC output signal to the 1 pu. At 0.551 seconds applied voltage decreases to 1 pu and the inverter magnitude regulator observes the voltage change and recovers the voltage to 1 pu in 100 milliseconds from 0.98 pu.

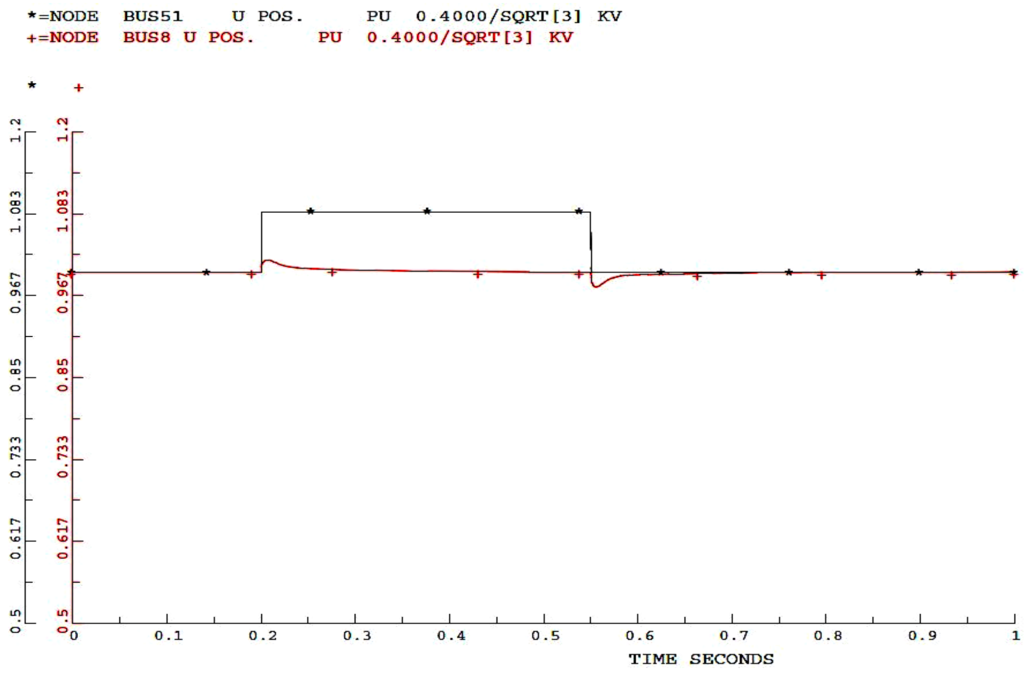

Figure 6-11 1.09 pu applied voltage simulation
Black line- AC line Voltage, AC BUS 51
Red line – AC output voltage of UPS, AC BUS 8

6.4 Overvoltage 1.12 pu test

After the contact have been made with the manufacturer the 1.15 pu test is rescaled to 1.12 pu. According to the manufacturer, the 1.15 test that have been made on the system does not reflect the given voltage level. The real applied voltage level is around 1.12 pu instead of 1.15 pu. In Figure 6-12 and in Figure 6-14 the relation between the applied voltage and the UPS system are given.

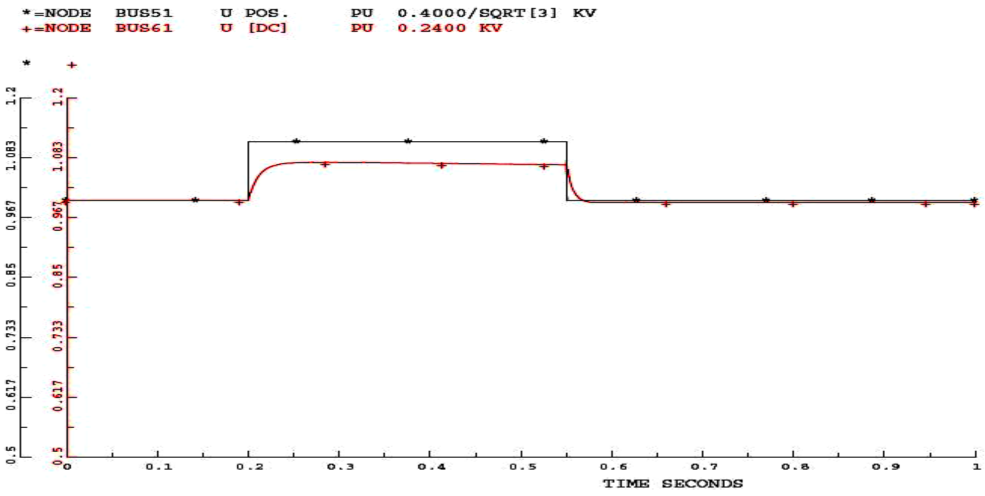

Figure 6-12 1.12 pu applied voltage simulation
Black line – AC line voltage, AC BUS 51
Red line – DC line voltage, DC BUS 61

Overvoltage magnitude applied to the rectifier is higher in this test in comparison with the Chapter 6.3-1.09 pu test, therefore the DC BUS 61 voltage is higher during the fault case around 1.07 pu, between 0.20 seconds and 0.56 seconds as shown in Figure 6-12. At 0.551 seconds the DC BUS 61 voltage recovers approximately to 0.998 pu and increases gradually to 1 pu.

In Figure 6-13 the reconstruction of Factory acceptance 1.12 pu test is given to show the similarity between the 1.12 pu simulation and the factory acceptance 1.12 pu test. Measurements are taken at the same points in the simulation and in the factory acceptance test. It can be seen that the parameters of the modelled UPS system are well tuned so that the response of the simulation to applied voltage is similar to the Gutors' factory acceptance tests.

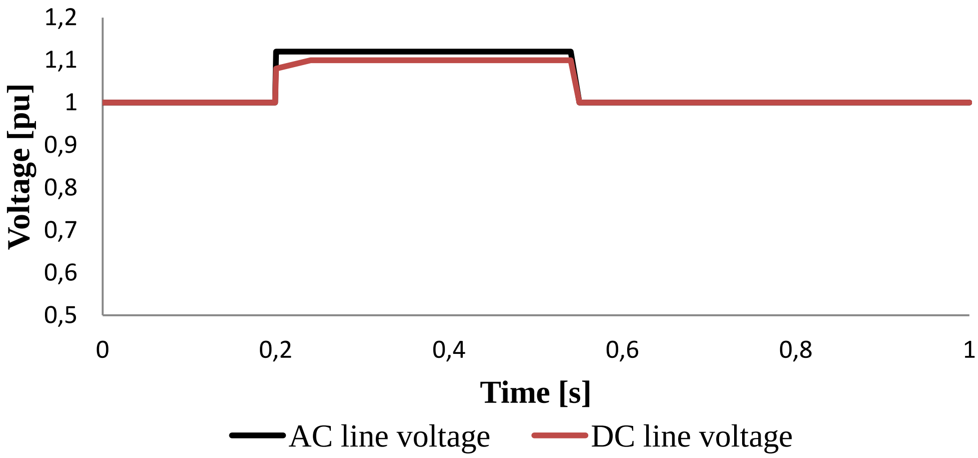

Figure 6-13 Reconstruction of the Factory Acceptance 1.12 pu Test

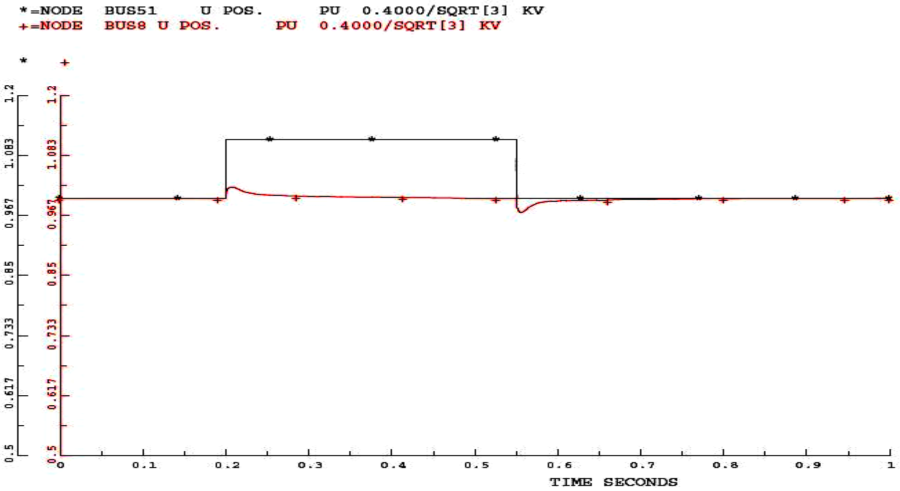

Figure 6-14 1.12 pu applied voltage simulation
Black line – AC line voltage, AC BUS 51 and Red line - AC BUS 8 output voltage

In Figure 6-14 the relation between the applied overvoltage step and the AC output from the UPS system is shown. The AC load side of the UPS overshoots at the beginning of event and regulated down to 1 pu by the PWM inverter magnitude regulator. At the end of the applied overvoltage the bus voltage decreases to 0.97 pu and the PWM magnitude regulator corrects the bus voltage to the given 1 pu value in approximately 150 milliseconds.

7 Conclusions and future work

In this thesis part of a DC backup system is modelled. The main purpose of this work is to study, model the components and simulate different case scenarios.

7.1 Conclusions

Simpow converter models are studied and LVC rectifier of Simpow is chosen as the proper rectifier for the DC backup system. Tests have been made to build a rectifier with current and voltage regulation where regulators work in parallel with overload protection feature. Parameters of the rectifier and rectifier regulator are adjusted after matching the voltage and current wave forms according to the FATs.

It is observed that the inductance value of the rectifier plays a crucial role in the modelling. According to the inductance value, the rectifier output voltage changes drastically. In further studies and modelling projects this precise inductance value between the AC and DC terminals have to be obtained from the manufacturer.

The rectifier modelling tests show that this single rectifier model can have a further usage in DC backup system. Furthermore the Simpows current source LVC rectifier with LVC3 regulator can be used for modelling the onsite voltage source rectifier.

A simple battery model is modelled where it consists of a resistance and a capacitance representing the battery unit installed in this particular DC backup system. Battery model parameters are adjusted according to the factory acceptance 0.7 pu undervoltage tests. Battery modelling tests show similar results to the chosen factory acceptance test.

Inverter model of the Simpow is preliminarily modelled and installed. Voltage magnitude regulator of the inverter shows acceptable results. Results are in the range of plus minus five percent voltage oscillation.

All components are compiled and four factory acceptance scenarios simulated. Simulation bus voltage readings from the DC side of the UPS and the AC output of the UPS system shows similar results in comparison with the real factory acceptance tests.

7.2 Future Work

Further adjustments and improvements of the rectifier can be made if different case scenarios are found and studied. The inverter model built in this work is just a preliminary model. The phase angle controller of the inverter can be studied into detail by applying tests to the phase angle regulator. The battery model can be changed into more detailed dynamical battery model.

Separately modelled and simulated component models in this work can be converted into one single UPS DSL model. The UPS DSL model should include the least amount of unknown design parameters that can be obtained from the Oskarshamn NPP and the manufacturers. The UPS DSL model has to be easy to use and it should be easy to modify. Important aspects that have to be considered while modelling the UPS DSL model are:

- The SBS logic
- UPS system protections
- The battery unit behaviour.

- DC backup system topology and the interconnections between the UPS systems.

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Document name: FAT Protocol UPS system 694