UiT
THE ARCTIC
UNIVERSITY
OF NORWAY

Institutt for elektroteknologi

# Transient analysis of road tunnel power system

*Diploma thesis for Master degree in Technology*

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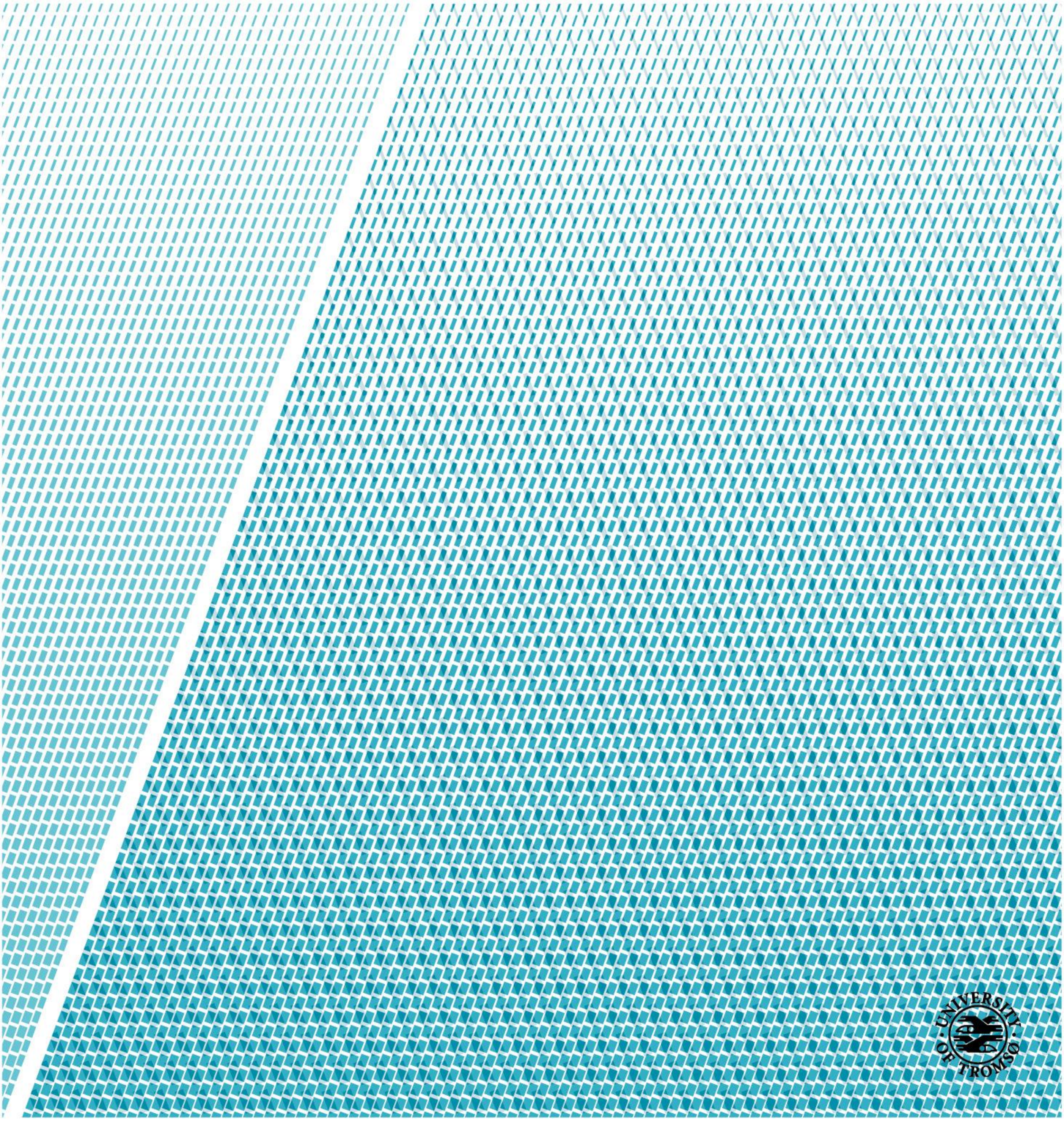
*Master's thesis in Electrical Engineering   June 2018*



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# List of designations

AC – alternating current

DC – direct current

IGBT – Insulated-gate bipolar transistor

Isc3 – 3-phase short circuit current

Nor. – Norwegian

PWM – pulse-width modulator

RMS – root mean square

THD – total harmonic distortion

UPS – uninterruptible power supply

# Foreword

Master thesis is the last part of education at the Arctic University of Norway, Campus Narvik. The problem for this thesis was provided by Statens Vegvesen. The first step for this project was the semester pre-project for one semester before, which allowed in the beginning to make a quick overview and create a basis for the future work. The final variant of this thesis meets the requirements which were set in the pre-project and matches the original plan of work.

During this thesis I was working and consulting with high-qualified experienced people, which were given me new challenges, advices and thereby helping me to understand the most important and difficult parts of my work. It was very interesting to hear their opinions about my problems and tasks. Thus I would like to express my gratitude to my supervisor Trond Østrem for a good guidance and to my counsellor from Statens Vegvesen Tor-Håkon Schultz for his help. Particularly I would like to say, that I'm very thankful and greatly appreciate support and assistance of Bjarte Hoff – Førsteamanuensis ved UiT Campus Narvik. Besides I want to thank Trond Albrigtsen – section leader Elektro by Statens Vegvesen in Bodø for his kind cooperation and special attention to my work. And I want to thank Øystein Jensen – Senior Sales Engineer by Eaton Electric AS for his responsiveness and great practical support in matters of UPS.

Narvik, 11.06.2018

Elizaveta Ivanova

# Abstract

The main tasks of Statens Vegvesen is to plan, build and maintain the roads of Norway. Tunnels are included as a part of this task.  Due to expected changes in usage patterns and needs, the Norwegian authorities decided to adapt to the European model the design of low voltage networks. The backup power system is one of the most important parts of the installation and presents an independent source of electrical power, which is being used as external power supply in case of loss of regular supply. Nowadays most of the Norwegian networks in tunnel for backup power supply system are built up as a 400V TN/230V IT network, using step-down transformer. A transition to the pure TN system is desired.

Backup power system is a complicated system based on usage of uninterruptable power supply (UPS), which has different variations and challenges. That is why it is interesting to investigate how the existing installations of backup power system can be converted according to the new requirements.

# Project assignment

The candidate should perform risk assessment and identify key criterias for a reliable backup power system. The candidate should apply methods for designing 400V TN backup power systems.

Furthermore, the candidate should investigate suitable protection methods for the backup power system, as well as the rest of the circuitry. Protection challenges should be addressed, such as minimum short-circuit current and selectivity, and there should be no use of adjustable circuit breakers on load circuits.

Transient analysis of voltages and load flows should be performed for different kinds of faults, using a convenient simulation tool.

# Introduction

Before the Second World War it was not obligatory to use PE conductors. These conductors were used sometimes in the countryside. Until today there are regions, where the use of PE conductors in residential premises is not required, if the floors are made of non-conductive material. However in most European countries since 1960 it is required to use PE conductors in new constructions.

In the UK, Poland, Hungary, the Czech Republic, Slovakia, Western Austria, most of Germany, the Nordic countries, particularly Switzerland and Finland, TN-C-S is used as the main power supply system. In this system, PE conductor (PEN – before separating and PE – after) provides protection in case of insulation damage.

Nowadays it is Norway's turn to upgrade the power system. The system, that is being used today as a final, consuming system, is 230V IT. It has some disadvantages, which are very essential:

1) Normal current protections do not work when ground faults occur. The leakage current monitoring system, as a rule, is quite complicated and its scheme often does not possess selectivity. In addition, it operates on a signal and requires the intervention of maintenance personnel.
2) When system is working in single-phase ground fault mode, the risk of electric shock increases when a different phase is touched.

These are the reasons, that the new constructions are built using already the pure 400V TN-system – but there is still no perfect solution to protect the network from the short circuit currents. This work is devoted to investigate the challenges of the new system and the level of requirement to equipment.

# 1 Standards and regulations

It is a very complicated process to build up a new electrical installation and there are a lot of challenges and dangers – both for people and environment. That is why it is so important to follow some rules, which help to make the installation safe.

The following overview is dedicated to the different relevant standards and regulations.

**FEL**

FEL (forskrifter for elektriske lavspenningsanlegg, nor.) - regulations for electrical low voltage systems where it is described how low voltage electrical installations shall be designed, carried out, modified and maintained. FEL defines its scope as follows:

*«The scope of the regulation is essentially the same as for regulations for electrical building installations, etc., i.e. that it comprises a wide range of different types of low voltage systems connected to an external supply system or to its own generator, solar panel, etc. Electric low voltage systems are systems with the highest nominal voltage up to 1000 V alternating voltage or 1500 V direct voltage»*[2].

**FEF**

FEF (forskrift for elektriske forsyningsanlegg) - regulations for electrical supply systems. The scope of this regulation is design, execution, operation and maintenance of electrical power plants.

**FOL**

FOL (forskrift om leveringskvalitet) - regulation of delivery quality in the power system.

**NEK400**

NEK 400 prescribes the safety requirements for engineering, constructing, etc. of a low-voltage facility, which have to be fulfilled. It is written in § 10 of FEL. To date, 5 editions of NEK 400 have been issued:

- NEK400:2014 5.utgave
- NEK400:2010 4.utgave
- NEK400:2006 3.utgave
- NEK400:2002 2.utgave
- NEK400:1998 1.utgave

# 2 Load modelling

## 2.1 General about load modelling

“Load” in electrical engineering means equipment, which is connected to the grid and which is being feed from it. Load can be simple or compound. The compound load can be represented as the combination of different simple load types.

The simplest models of load are:

- Constant impedance (Z)
- Constant current (I)
- Constant power (P)

ZIP model provides easy and flexible way to represent the load. By the constant impedance is load proportional to the squared voltage magnitude. This model is being used usually by inductive load, which is consuming the reactive power.

By the constant current varies power linearly with the voltage amplitude.

In the third case is the power constant regardless the voltage magnitude. In the reality, it is possible for some certain voltage magnitudes only.

These curves are presented on figure 1:

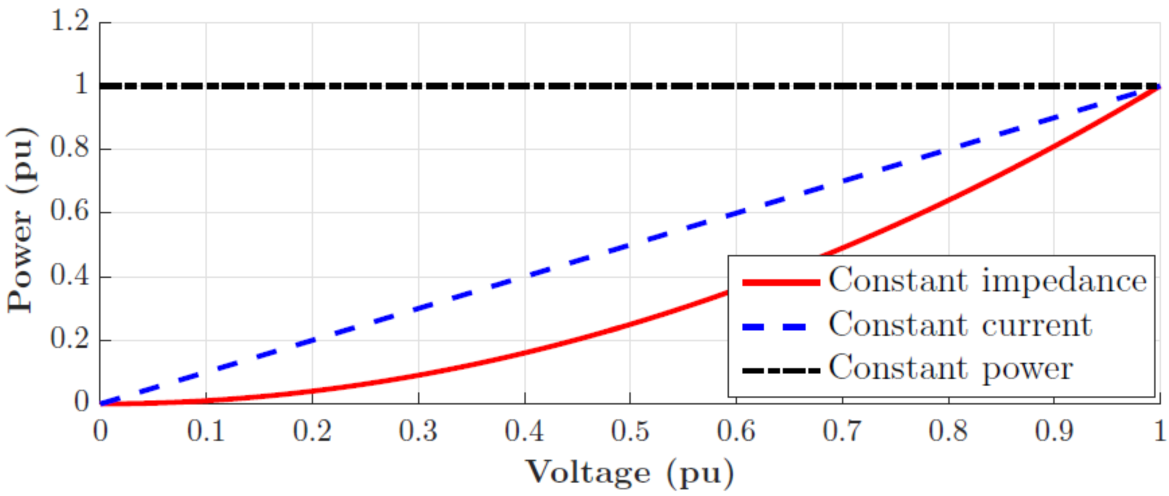


*Figure 1 - Load characteristics for models with constant impedance, constant current and constant power [3]*

Using this ZIP-model the load can be presented quite exactly relative to the voltage magnitude.

ZIP-model for active and reactive loads:

$$P = P_0 \left[ a_1 \left( \frac{V}{V_0} \right)^2 + a_2 \left( \frac{V}{V_0} \right) + a_3 \right] \tag{1.1}$$

$$Q = Q_0 \left[ a_4 \left( \frac{V}{V_0} \right)^2 + a_5 \left( \frac{V}{V_0} \right) + a_6 \right] \tag{1.2}$$

Here P and Q are active and reactive power at operative voltage V; $P_0$ and $Q_0$ - active and reactive power at rated voltage $V_0$; $a_1$ $a_2$ $a_3$ are models coefficients for active power, $a_4$ $a_5$ $a_6$ – models coefficients for reactive power.

## 2.2 Prototype for computations

The tunnel taken as a prototype is called Hamnøytunnelen and is placed close to the city Hamnøy (Lofoten islands). The length of this tunnel is 2 000 m, the backup system is supported by 2 UPS. It means that one UPS supports the backup system on the distance of approx. 1 km. Nominal voltage on the UPS is 400 V from primary and secondary sides; the rated power is 7.9 kW. The back-up system contains a transformer, which converts the voltage from 400V TN to 230V IT on the load side.

## 2.3 Load modeling of backup power system

The load of the backup power system consists mostly of lighting, switchgear and a system for isolation monitoring.

Almost the entire load is the backup light system, which is using LED. LED is treated as resistive load because it conducts and draws current, without giving almost any phase shift between voltage and current. That is why the load is presented as constant power type. But it is important to say that LED's V-I curve is different from resistor's curve, because resistor presents a linear load, while LED is nonlinear, what is shown on figures 2 and 3 on the next page:

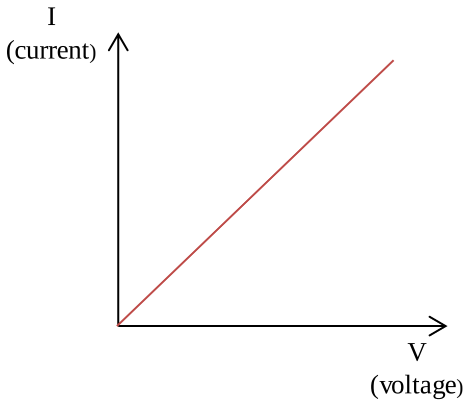


*Figure 2 – Resistor's V-I curve*

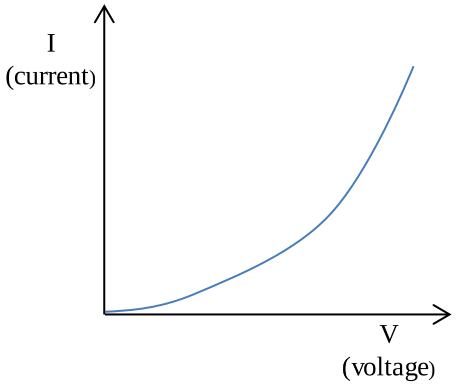


*Figure 3 - LED's V-I curve*

The following schema on figure 4 presents a regular block-schema for LED-armature:

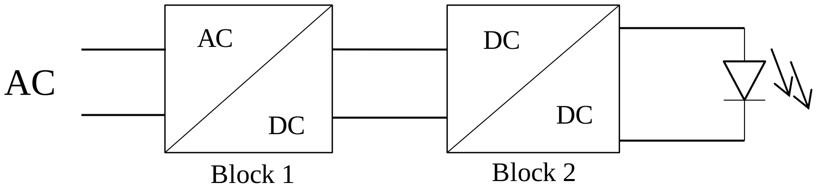


*Figure 4 – Block-schema of LED load circuit*

Here Block 1 presents a rectifier and Block 2 – DC/DC converter, which can be used if it is needed.

# 3 Background

## 3.1 TN system

TN-system (Terra Neutral) is the system, where one of the points is connected to the earth and the open conductive parts of the electrical installation are connected to the neutral source via neutral protective conductor which is called protective earth (PE). The conductor that connects to the neutral point in a three-phase system or that carries the return current in a single-phase system, is called neutral (N).

Nowadays in the tunnels by 230V/400V transfer from the high-voltage side is being used the 400V TN-C-S – system, where conductors PE and N are combined near the power source, but are split up in one point into PE and N conductors. It is shown on figure 5:

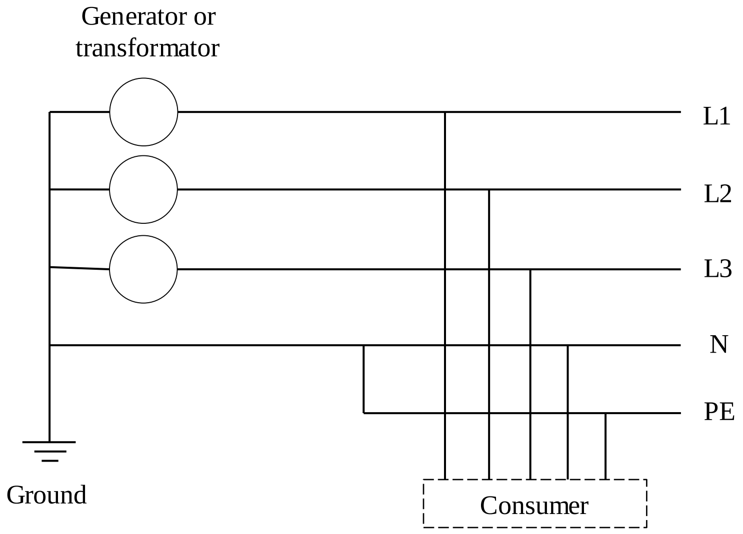


*Figure 5 – TN-C-S – system*

Advantages:

- It is possible to provide both voltages – 230V and 400V
- No need for transformer
- There is less power losses because of higher voltage which is causing lower current
- Efficiency is higher
- Diameter of cables might be less than by IT-systems

Disadvantages:

- Residual currents are much higher, what requires a disconnection from net by the first fail
- Fracture of N conductors can lead to 400V-voltage through 230V equipment
- Provides load currents in the grounding system
- This system has a significant drawback - in case of damage or burnout of the PEN wire in the substation-building section, a dangerous voltage will appear on the conductor PE, and, consequently, all associated body parts of electrical appliances. Therefore, when

using the TN-C-S system, which is a quite common, regulatory document requires special facilities to protect the PEN conductor from damage.

## 3.2 Frequency quality

The frequency in the fundamental harmonic voltage is the less possible parameter, which may cause some troubles in the Norwegian power grid. However, in an error situation, where the regional network operates in separate mode, frequency stability will be a topical issue. According to FoL §3-2, in areas that are temporarily without physical connection to adjacent transmission networks the system administrators has to ensure, that the voltage frequency is normally maintained within 50 Hz ± 2%.

## 3.3 Voltage quality

In the low-voltage distribution network in Norway, the distributors must comply with delivery quality standards. This will ensure that delivery quality in the Norwegian power system is satisfactory. In other words, it takes into account all the factors that give an end user a good and stable supply of energy. Here are KILE (kvalitetsjusterte inntektsrammer ved ikke levert energy, Nor. - quality-adjusted revenue frameworks for non-delivered energy), delivery reliability, voltage quality, frequency, over and under voltages, harmonic distortions, etc.

The requirement for value frames of voltage is described below § 3-3 in FOL:

*”The network company must ensure that slow variations in the effective value of the voltage are within an interval of ± 10% of rated voltage, measured as an average of one minute, in connection point with the low voltage network.”*[4]

## 3.4 UPS

### 3.4.1 Common information

UPS-type, which is being used by backup power supply, is Online/Double conversion, according to the manual from Statens Vegvesen Vegdirektoratet § 9.3 [5] and is presented on the figure 6:

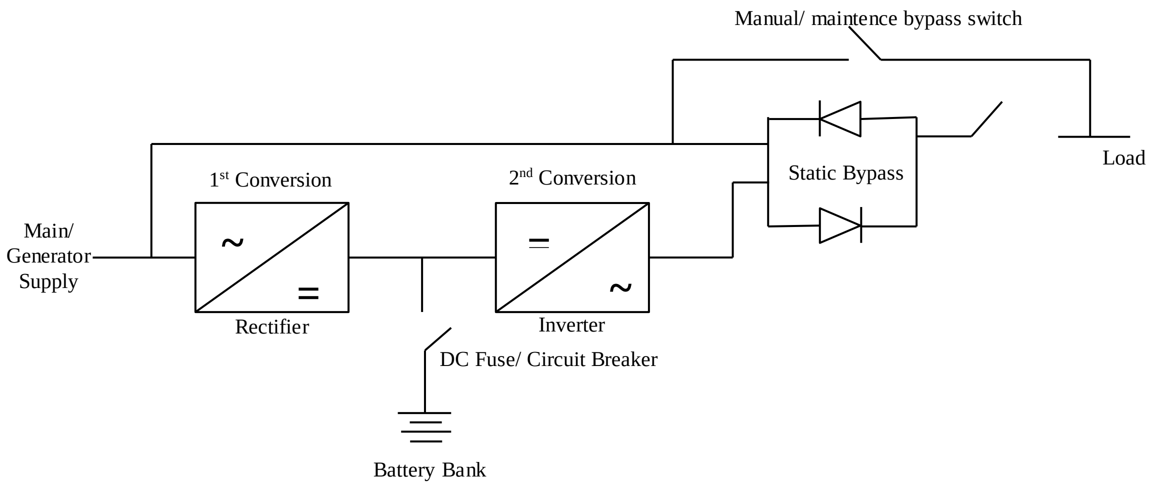


*Figure 6 – Online/double conversion UPS*

<ins>Advantages [6]:</ins>

- Continuous and total power conditioning
- Failsafe/overload protection with static bypass facility
- No break on mains failure
- Wide input voltage tolerance
- Recommended with Generator sets

Disadvantages [6]:

- More expensive than other types of UPS technology

### 3.4.2 Operative modes

The UPS operates in 3 different modes:

1. Online (double-converting)
2. Static bypass
3. Battery operation

1. UPS rectifier and then inverter on the output. This also involves filtering of unwanted noise. It is also in this mode the batteries are being charged when it is needed.

2. This is a parallel run to Online (inside UPS). Switching takes place via the electronics of the UPS through components called thyristors. This also involves filtering of unwanted noise.

3. Energy is collected from batteries, directly to inverter, from the UPS output.

### 3.4.3 The advantages and issues of the different modes of the UPS

1. Online: This mode is active when the connection to the power grid is available. Here appear all the benefits of using UPS: noises are removed, AC output presents a smooth sin-formed curve. The batteries are being charged if it’s needed. Inverter provides power as needed, even at "leading / lagging" from load.

2. Static Bypass: This mode is active in the following cases and only when the power grid is presented:

   1- In case of rectifier errors, UPS will switch to Static Bypass to support load. Switching depends on UPS inputs.

   2- In case of overload on inverter, more than $1.00 \cdot I_n$ ($I_n$ - nominal current ). Operational certain amount of time, depending on how big the overload is.

   3- At short circuit (power supply available). Short-circuiting energy is being passed through Static Switch to the network for to disconnect the responsible protection.

The problem here is the tolerance of the thyristors. In case of too high $I_{sc\ 3p\ max}$ in the main grid (input power), the thyristors will be destroyed and, in the worst case, explode.

Here, protection before and after UPS comes as part of the solution. What characteristic they have, type, trigger time etc.

3. Battery Operation: This mode is active when the connection to the main grid is lost. Energy from the batteries goes through inverter and out to load. In battery operation, the UPS is potentially at its weakest. In this mode only inverters are available, and their properties determine the technical levels. Here's a lot of difference between the different manufacturers. In addition, the duration of this short-circuit performance is different from manufacturer to manufacturer.

# 4 Dimension of breakers

When an electrical installation is being projected, it is very important to follow some protection rules, which make the system be safe. In Norway these rules are collected in “Forskrifter for elektriske anlegg (FEL)”. It is written: “*The electrical installations must be carried out to ensure the safety and function of the installation. It has to be no risk for the life and health or loss of material values. That means that it supposes to be the protection against electrical shock, thermal influence, overvoltage, undervoltage, overcurrent, short circuit or fault currents*” [7]. These are the main rules, which have to be fulfilled.

The reasons for the necessity of breaker might be different:

- Mechanical overload
- Atmospheric overvoltage
- Fault caused by material or equipment
- Human failure by assembly or working mode

There are different types of breakers, which are used for high-voltage and low-voltage systems.

The types of low-voltage breakers are the following:

- Auto fuse
- Circuit breaker
- Fuse
- RCD (residual-current device)
- Overvoltage protection
- Undervoltage protection.

Adjustable protection is not been considered, according to requirements of the problem. It is used for loads that are fixed and larger – for example, fans and light in the tunnel. That makes to ensure the selectivity of the facility.

The consumers’ parts should not be adjustable, because it can cause bad selectivity to group fuses. Sockets should be designed to withstand the highest load, since it is not always known what kind of equipment is going to be used.

# 4.1 Overcurrent protection

## 4.1.1 Auto fuse

An overcurrent protection has two main functions: to reduce the dangerous current through the human or animal body and to prevent high temperatures which can lead to the fire. It consists of 2 parts – thermal and electromagnetic. The thermal part is melting and disconnecting the system if the temperature rises too high. The electromagnetic part consists of a coil around an anchor. When the magnetic field becomes too big caused by rise up of the current, the anchor disconnects the protection. Usually there are the follow types of this type of protection: 6A, 10A, 13A, 15A, 16A, 20A, 25A, 32A, 40A, 63A. These fuses have different characteristics, which show that the fuses are very quick (A), quick (B), quite slow (C), slow (D) and very slow (K), what is presented in Table 1:

*Table 1- Characteristics of different types of fuses*

| **Fuse** | **Rated current** | **I1** | **I2** | **I4** | **I5** |
|---|---|---|---|---|---|
| A | 6-63 | $1.13 \cdot I_n$ | $1.45 \cdot I_n$ | $2 \cdot I_n$ | $3 \cdot I_n$ |
| B | 6-63 | $1.13 \cdot I_n$ | $1.45 \cdot I_n$ | $3 \cdot I_n$ | $5 \cdot I_n$ |
| C | 6-63 | $1.13 \cdot I_n$ | $1.45 \cdot I_n$ | $5 \cdot I_n$ | $10 \cdot I_n$ |
| D | 6-63 | $1.13 \cdot I_n$ | $1.45 \cdot I_n$ | $10 \cdot I_n$ | $20 \cdot I_n$ |
| K | 6-63 | $1.05 \cdot I_n$ | $1.2 \cdot I_n$ | $8 \cdot I_n$ | $12 \cdot I_n$ |
| Motor | 0.5-40 | $1.05 \cdot I_n$ | $1.2 \cdot I_n$ | $10 \cdot I_n$ | $15 \cdot I_n$ |

Here $I_n$ is nominal current.

The program FEBDOK allows evaluating fuses efficiency. The curve which shows a standard FEBDOK's curve of fuse's (or any other protective elements) analysis is presented on the figure 7:

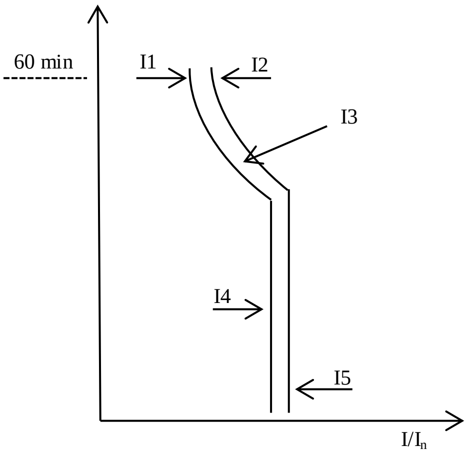


*Figure 7 - Characteristic of an auto fuse [8]*

Here:

$I_n$ - nominal current
I1 - the minimum current that guarantees disconnection over an hour of overload
I2 - the largest current that guarantees disconnection within one hour of overload
I3 - tolerance range
I4 - the biggest current which does not guarantee electromagnetic disconnection
I5 - instantaneous disconnection.

Characteristics of fuses, circuit breakers, etc. are never considered separately. Characteristics of protective elements, considered simultaneously, give a full overview for the analysis of selectivity, which is studied more detailed further, in the chapter number 5.

### 4.1.2 Circuit breaker

Circuit breaker can tolerate higher short circuit currents then the auto fuse. It can be tuned according to the other protective elements. Circuit breaker is more advanced then the fuse, which determines its cost.

The circuit breaker of ABB, which is used by the main distribution line of the Hamnøytunnel system on figure 8:

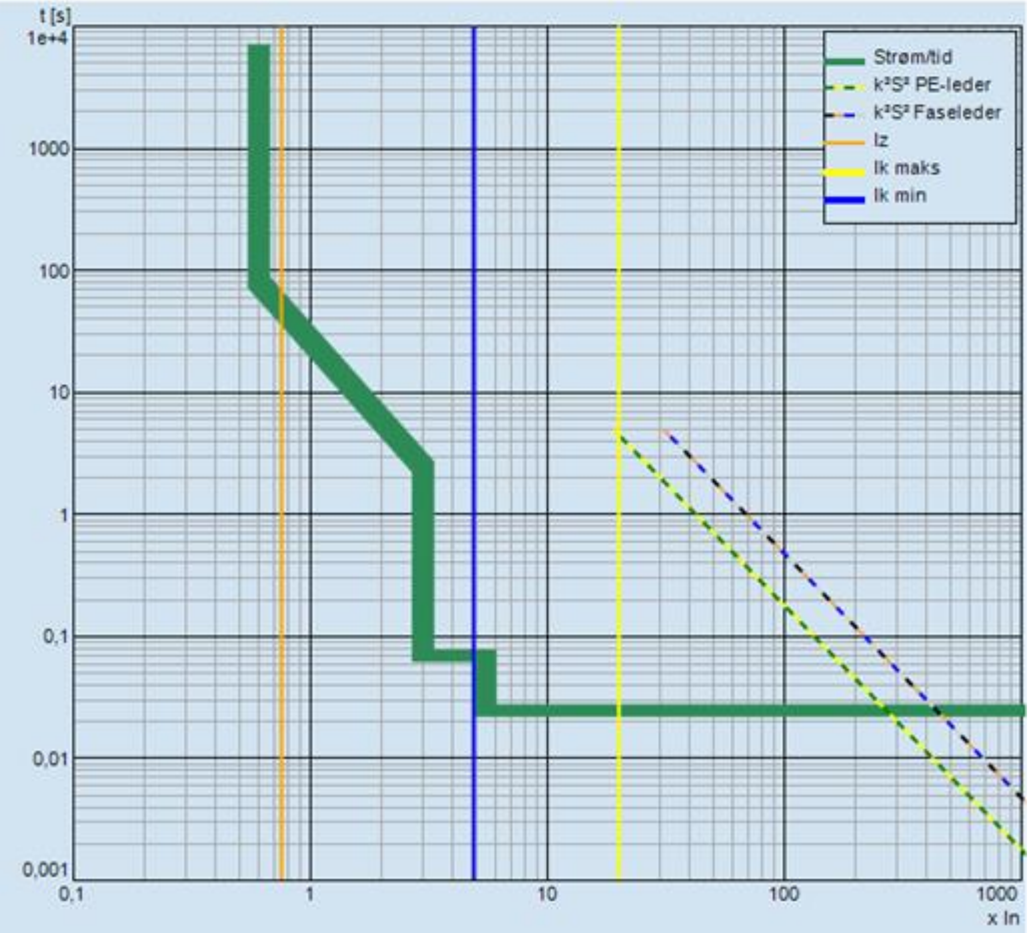


*Figure 8- Circuit breaker, ABB, FEBDOK*

On this figure green line presents a current curve, which depends on time, orange – current conductivity of the cable, blue – maximum short circuit current, and yellow – minimum short circuit current.

### 4.1.3 Fuse

Fuses are small electrical devices which consist of a relatively short piece of conducting material, with a cross-sectional area insufficient to carry currents quite as high as those which may be permitted to flow in the protected circuit, is sacrificed, when necessary, to prevent healthy parts of the circuit being damaged and to limit the damage to faulty sections or items to the lowest possible level.

It's being used different types/names of fuses, depending on the part of the world. Continental European fuses are the follows:

- Blade contact (NH-type):

generally available for applications up to and including 1250 A, for AC circuits operating at levels up to 500 V and DC circuits of voltages up to 440 V.

- End contact or screw type (D-type, D - for 'Diazed'):

are mainly produced with ratings up to 63 A for the use in AC circuits operating at levels up to 500 V. The limitation in current rating is largely caused by the difficulty of producing satisfactory contact with the holders, rather than with shortcomings in the fuselink design [9].

- Cylindrical cap contact:

for industrial applications these fuses are available in the following standardized ratings:

400 V AC up to 125 A;
500 V AC up to 100 A;
690 V AC up to 50 A.

When a fuse link melts, the striker moves out through the end cap and actuates a micro switch, which may initiate an alarm.

### 4.1.4 Overload protection

The overload current is the current, which are bigger than the circuits rated value. The task of the overload protection is to disconnect the circuit before the cable isolation is destroyed because of the high temperature, caused by overload. In NEK400:2014 is the following requirement to the characteristics of overload protection:

1. $I_B \leq I_n \leq I_Z$; (1.3)

2. $I_2 \leq 1{,}45 \cdot I_Z$, (1.4)

Where
$I_2$ - the largest current that guarantees disconnection within the determinate time of overload;
$I_B$ - load current;
$I_Z$ – current conductivity of the cable;
$I_n$ - nominal current.

## 4.2 Short circuit computation

### 4.2.1 Types

Short circuit computation is a very important part to define the protection of the system.
It is important to know:

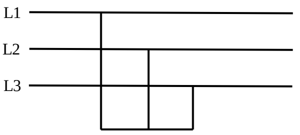
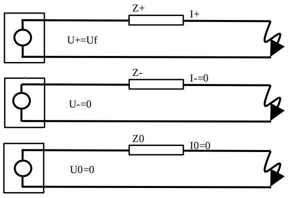
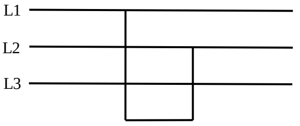
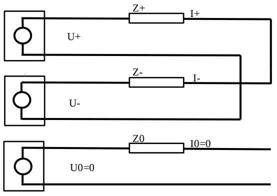
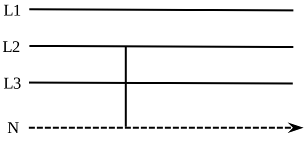
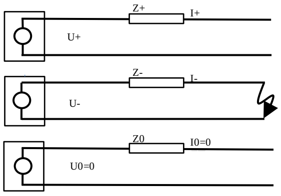
1) The maximum short-circuit current:
- Fusing capacity
- Defining parameters of the switch panels
- Measurement of mechanical forces.

2) The minimum short-circuit current:
- Fuse reaction speed.

There are 3 different types of short circuits: 3-phase, 2-phase and 1-phase. 3- and 2-phase short circuits are between phases while 1-phase is between one phase and neutral. For to define breaker's type, is it very important to know the highest and the lowest currents which might appear during the short circuit. The highest current gives the information about the breaker's type and the lowest – the value of current, when the protection has to break the circuit during the required time period (according to NEK400 requirements). The required time period is so short so the dangerous situations do not appear [10].

In the TN-net it is necessary to compute all 3 types of short circuits, because the maximal 1-phase fault might be bigger than the 3-phase maximal fault and the smallest 2-phase fault might be smaller than the smallest 1-phase fault [11]. That is why is it so important to know the minimum short circuit current – to choose the right protection, which would work out on the right time.

*Table 2- 1-phase, 2-phase and 3-phase short circuit*

| **Short circuit type** | **Illustration** | **Equivalent schema** |
|---|---|---|
| Isc3<br>3-phase short circuit |  |  |
| Isc2<br>2-phase short circuit |  |  |
| Isc1<br>1-phase short circuit |  |  |

There is a difference between minimum and maximum currents. The maximum currents are the currents by the minimum impedance. The minimum impedance is possible by the minimum temperature in the cables, which is usually taken to be $20^0$C. The minimum currents are, in the opposite, the currents by the maximum impedance. Here the temperature may vary depending on isolation type of cable (PVC or EPR). That is the reason that the maximum currents are measured right after UPS, while the minimum currents – on distance, at the end of the load circuit.

*Table 3 – formulas for different types of short circuit current*

| **3-phase short-circuit current** | **Equation** | **Alternative equation** |
|---|---|---|
| Maximum 3-phase | $I_{3\max} = \frac{c \cdot U_{phase}}{Z}$ | $I_{sc3} = \frac{c \cdot U_{line}}{\sqrt{3} \cdot Z}$ |
| Maximum 2-phase | $I_{sc2\max} = \frac{c \cdot U_{line}}{2 \cdot Z}$ | $I_{sc2\max} = \frac{\sqrt{3}}{2} \cdot I_{3\max}$ |
| Maximum 1-phase | $I_{sc1\max} = \frac{c \cdot \sqrt{3} \cdot U_{line}}{(2 \cdot Z_{\max} + Z_0)}$ | $I_{sc1\max} = \frac{c \cdot 3 \cdot U_{phase}}{\sqrt{(2 \cdot R_{\max} + R_0)^2 + (2 \cdot X_{\max} + X_0)^2}}$ |
| Minimum 3-phase | $I_{3\min} = \frac{c \cdot U_{phase}}{Z}$ | $I_{sc3\min} = \frac{c \cdot U_{line}}{\sqrt{3} \cdot (1{,}2R + jX)}$ |
| Minimum 2-phase | $I_{sc2\min} = \frac{c \cdot U_{line}}{2 \cdot Z}$ | $I_{sc2\min} = \frac{c \cdot U_{line}}{2 \cdot (1{,}2R + jX)}$ |
| Minimum 1-phase | $I_{sc1\min} = \frac{c \cdot \sqrt{3} \cdot U_{line}}{(2 \cdot Z_{\min} + Z_0)}$ | $I_{sc1\min} = \frac{c \cdot 3 \cdot U_{phase}}{\sqrt{(2 \cdot 1{,}2 \cdot R_{\min} + 1{,}2 \cdot R_0)^2 + (2 \cdot X_{\max} + X_0)^2}}$ |

Where $U_{line}$ – line voltage, $U_{phase}$ – phase voltage, c – voltage correction factor, Z – impedance, R – resistance, X – reactance, $Z_0$, $R_0$, $X_0$ – impedance, resistance and reactance in zero-system, $Z_{min}$, $R_{min}$, $X_{min}$ – impedance, resistance and reactance by minimum temperature, $Z_{max}$, $R_{max}$, $X_{max}$ – impedance, resistance and reactance by maximum temperature.

The loop-impedance by $I_{sc1\min}$ in a TN-net is the reason of asymmetric conditions, voltage shift and difficult calculations [8]. Nowadays there are different programs, which make these calculations. One of them is FEBDOK.

### 4.2.2 Unsymmetrical influence

1) 3-phase fault influences a system symmetrically:
- All the wires are being influenced similar
- It is enough with computations of the one single wire.

2) The rest faults influence a system unsymmetrically:

- The system can be observed as the sum of symmetrical components (what is presented on the figure 9 below):
  a) Positive phase-sequence
  b) Negative phase-sequence
  c) Zero phase-sequence.

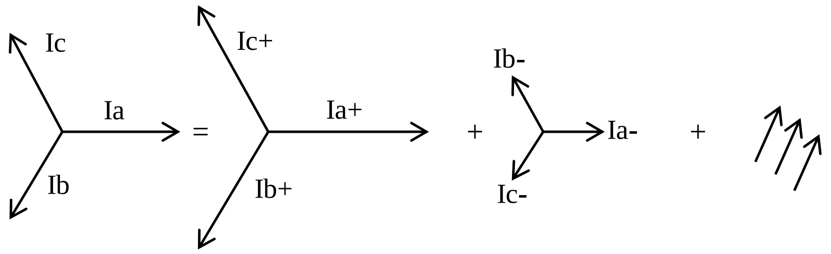


*Figure 9 - Unsymmetrical system*

### 4.2.3 Correction factors

The voltage

It is important by short-circuit currents computation to take into account the voltage correction factor, which is present in the formulas as “c”. By this factor is it assumed, that the voltage does not change more than ±5% of the nominal (for the low-voltage system).

The temperature

Maximum operating temperature by cables PFSP, PR is $70^0$C and by BFSI, IFSI it is $90^0$C. The lowest (normal operational mode) is $20^0$C. The resistance in cables changes approximately linearly to the temperature. For to compute the short-circuit currents is it important not to take into account only one temperature (for example, by normal operational mode), but to consider both of them – the lowest and the highest, as it is shown in the formula [8] :

$$K_{temp} = \left(1 + \alpha\left(t_{\max} - t_{\min}\right)\right), \tag{1.5}$$

where $K_{temp}$ is the temperature correction factor and α - temperature coefficient of resistance. For copper (Cu) it is 0.0039 $\left[\frac{1}{°C}\right]$ and for aluminum (Al) 0.00403 $\left[\frac{1}{°C}\right]$.

*Table 4 - The temperature correction factor for different isolation types*

| **Isolation** | **Temperature** | **Computation** | $K_{temp}$ |
|---|---|---|---|
| PVC | $70^0$C | $=(1+0.0039\cdot(70-20))$ | 1.2 |
| EPR | $90^0$C | $=(1+0.004003\cdot(90-20))$ | 1.28 |

The impedance of the cable is:

$$Z = K_{temp} \cdot R + jX \left[\Omega\right] \tag{1.6}$$

Where R is the resistance, the real part of impedance and X is the reactance – the imaginary part of impedance.

# 5 Selectivity

Selectivity is necessary in back-up systems, UPS- supply and distribution of auxiliary voltage. It is almost not mentioned in FEL or NEK 400. There might be life threat, danger of accident or total shutdown if selectivity is not present. The experience of previous years shows that the selectivity is not always the priority, while it should be paid more attention to it. In addition, the presented short-circuit current may be insufficient, what could cause that the equipment supplied by the UPS doesn't withstand the undervoltage that occurs during a short circuit. Selectivity in UPS facilities and auxiliaries should not only be documented, but must be based on a security strategy: it means that the dangerous situations have not just to be prevented, but predicted as well.

The protection strategy must therefore contain the following steps in order to be able to protect and operate under all operational conditions:

1. A functional description and operating strategy of the industrial power supply (or installation), all operational alternatives and configurations.

2. A general protection overview.

3. Strategy for protection and selectivity in auxiliary voltage and UPS systems.

4. Strategy for how equipment must withstand undervoltage and how the undervoltage protection co-ordinates with each other and with short-circuit protection.

5. Protection against overvoltage not handled by relay protection.

6. Strategy for blocking and intertrip (mechanical, hardwired and programmed).

7. Interface control.

8. Results of short-circuit, load, transient and dynamic analysis, together with their purposes.

If these main points are not checked, it will not be possible to choose or configure the protection system optimally. Then there may be some "surprises", when the protection system is suddenly activated.

Traditional assessment of selectivity is based on the use of time-current curve overlays. These have proven to be a useful tool to evaluate selectivity over the long-time and short-time devices. For circuit breakers, the curves are also used to document the operation of overcurrent devices in the instantaneous range. [12]

It might be a requirement to complete selectivity, which means that the protection system is synchronized almost perfect and all the fuses and breakers will function in a very exact moment.

There is the software which allows to make such analyses. One of them is Febdok, which is widely used in Norway. This program has the widest overview over the most popular protective units which were tested together and gives the analysis about the selectivity boarders by their cooperation.

The figure 10 shows the selectivity analysis from this program:

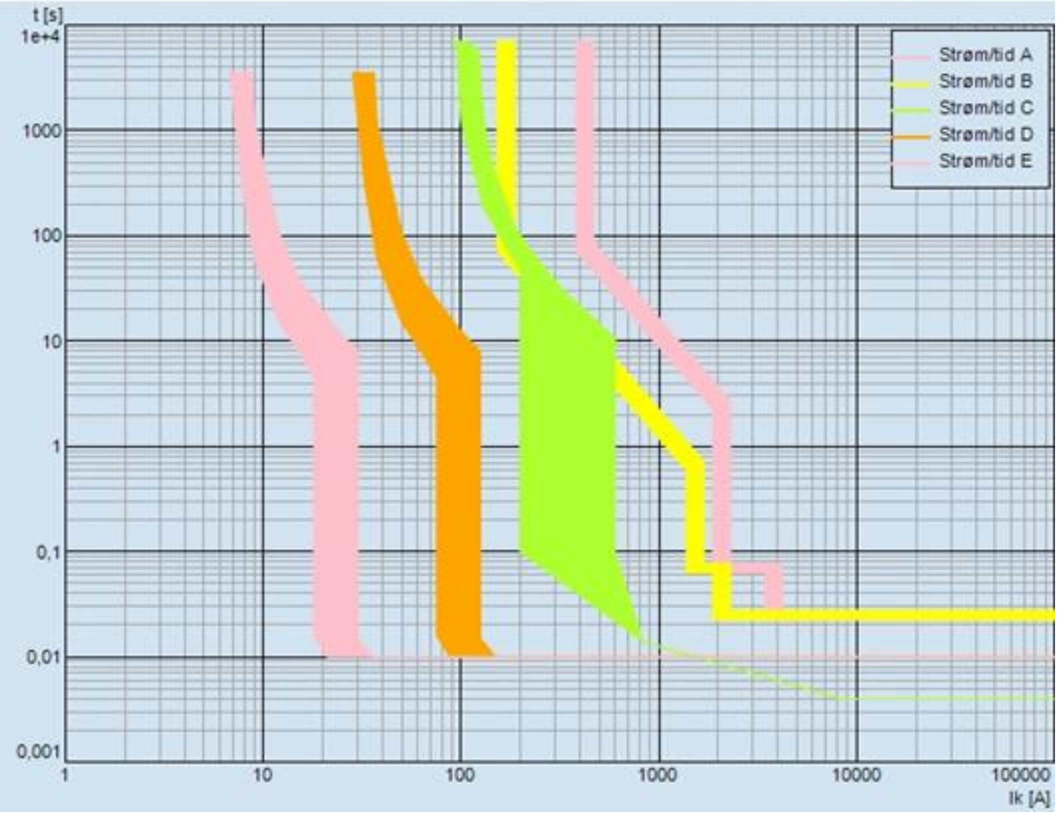


*Figure 10 – Example of low selectivity*

Here it is possible to see that all of the elements give a satisfactory protection to the system, but the selectivity of this operational line is quite low because of current protectors green (50 A) and yellow (160 A), which selectivity lines are crossing each other. It means that these units do not have an exact sequence and in case of fault might behave unpredictable.

Complete selectivity is the central concept. It is always connected to the one concrete facility and means that the breaker which is closest to the fault is the first one which reacts on it. In other words, that the working sequence is well defined in advance of all the protection units and that the units follow it in case of fault.

The figure 11 shows an example of complete selectivity:

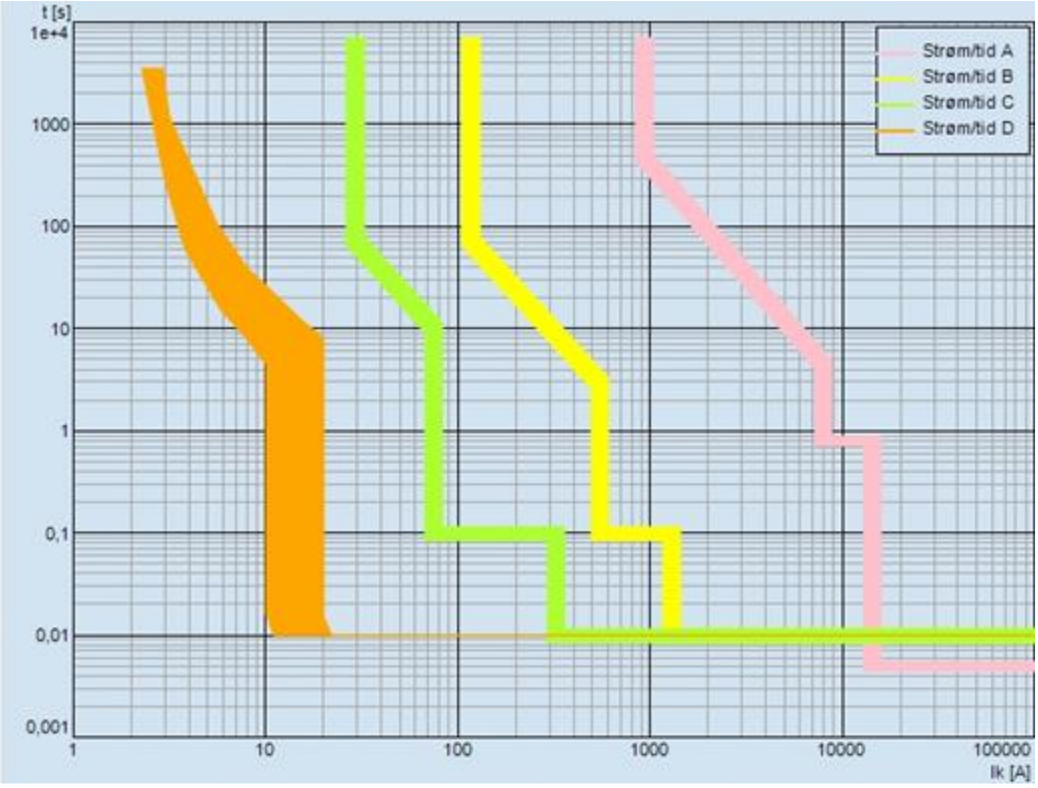


*Figure 11 – Complete selectivity*

Lines are not crossing each other and give a good space in-between, what shows the strict sequence of their functional mode.

Another way to control the system in Febdok is to pay attention to the automatic program check, which gives the overview over the whole system and allows identifying the systems weak and critical points, according to the system requirements. It is shown on the figures 12 and 13:

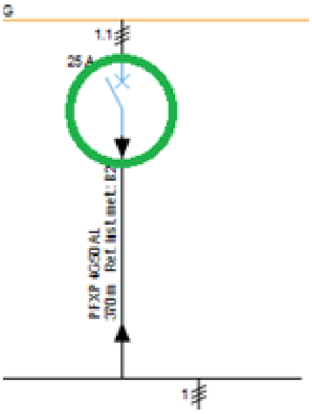


*Figure 12 - FEBDOK, protection challenges: warning, caused by low protection*

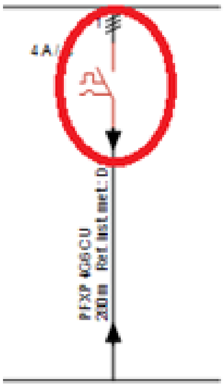


*Figure 13 - FEBDOK, protection challenges: warning, caused by unsatisfactory protection*

The blue color of protection sequence shows that the protection disconnects UPS from the rest of the system too late and the fault current keeps going through the system. However, the UPS will be disconnected so that the requirements for protection against electric shock are met.

The red color shows, that the decision about the protective sequence is critical and that the system is not meeting any of safety requirements.

# 6 Vector control

Vector control is the regular way to control the three-phase converter in electrical circuits. It became widely used because of its accuracy and fast reaction. This control was an actual issue for the thesis, because by the modeling it was necessary to use a converter with current limitation. That is why it was used a converter with cascade regulation.

Vector control is that the real signal is compared to the desirable and then the deviation signal is sent to the controller, which generates a reference signal for the system. The original vector V can be referred to a stationary αβ or a rotational system dq. In the first case the transformation is called Clarke transformation, in the second – Park (or DQ) transformation. The angle between α and β is permanent and the value is 90 degrees; it is the same accordingly to the angle between d and q. The angle θ shows the position of the rotational system to a stationary at any moment of time and is presented in equation 1.7:

$$\theta = \omega t + \varphi \tag{1.7}$$

Here ω is the rotational speed and φ – a phase-shift angle.

The angle ϑ is an angle between d-axis and original vector. At the beginning it is important first to choose how the rotational system dq is placed according to the original abc. On the figure 14 it is shown the case, when the rotational frame is aligned to the A axis. Further formulas are written for the system, where the rotational frame dq is aligned 90 degrees behind A axis, because this position was chosen for the Simulink modeling.

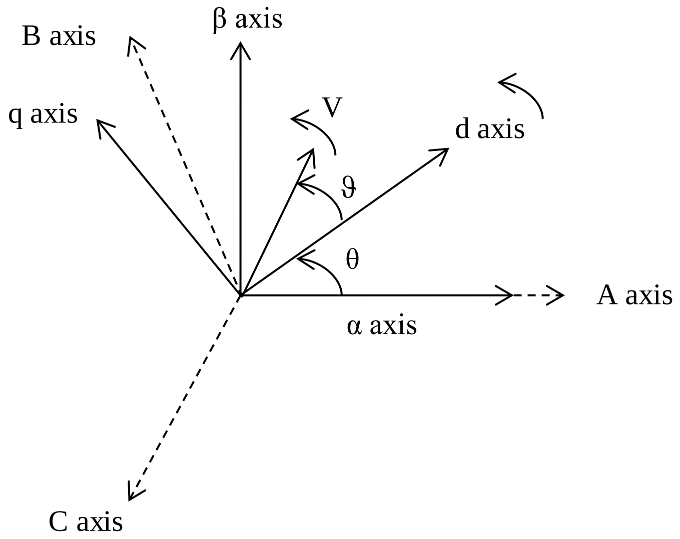


*Figure 14 - Vector diagram of Clarke and Park transformation*

## 6.1 Clarke transformation

The original current vectors, referred to αβ-coordinate system:

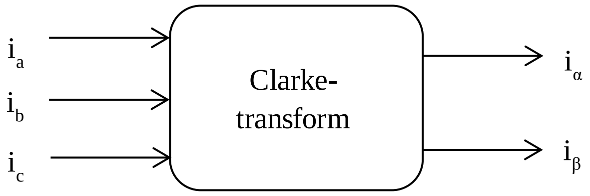


*Figure 15 - Clarke-transform of current vectors*

$$\begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \qquad (1.8)$$

Where $u_a$ , $u_b$ , $u_c$ – phase voltages; $u_\alpha$, $u_\beta$ , $u_0$ – original voltage vector, referred to the αβ0-system.

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (1.9)$$

Where $i_a$ , $i_b$ , $i_c$ – phase currents; $i_\alpha$, $i_\beta$ , $i_0$ – original current vector, referred to the αβ0-system.

If the 3rd component of Clarke transformation ($u_0$ or $i_0$) =0, it means, that the three-phase signal is balanced – the sum of all the three phases is 0:

$$u_a + u_b + u_c = 0 \qquad (1.10)$$

$$i_a + i_b + i_c = 0 \qquad (1.11)$$

Where $u_a$ , $u_b$ , $u_c$ – phase voltages; $i_a$ , $i_b$ , $i_c$ – phase currents.

## 6.2 Dq (Park) transformation

Originally dq transformation is used to analyze and control synchronous machines. [13]

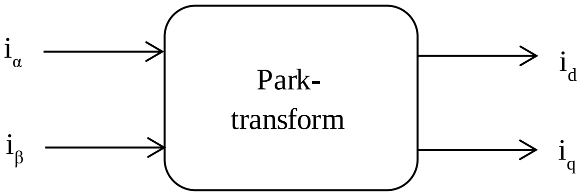


*Figure 16 - Park-transform of Clarke-transformed current vectors*

Signals are transformed by:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} \tag{1.12}$$

Where $u_d$, $u_q$ – original voltage vector, referred to the dq-system; $u_\alpha$, $u_\beta$ – original voltage vector, referred to the αβ0-system, θ - the reference angle.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{1.13}$$

Where $i_d$, $i_q$ – original current vector, referred to the dq-system; $i_\alpha$, $i_\beta$ – original current vector, referred to the αβ0-system, θ - the reference angle.

The d-component is called the direct-axis component, the q- component - the quadrature-axis component, so the name 'dq-transformation' is direct-quadrature- transformation. The reference angle θ shows how the rotational system dq0 is oriented to the stationary αβ at any moment of time.

This transformation, due to its properties, allows transferring the AC-signal to the DC. That makes possible to use PID-controller, which can be hardly used by curved signal.

# 7 Harmonics

## 7.1 General about harmonics

The massive introduction of power electronics into various types of equipment led to the fact that the presence of harmonics began seriously affect the industrial equipment. The presence of harmonics indicates a distorted form of current or voltage. Distortion of current or voltage curves means the disturbances in the distribution network and lower quality of the supplied power.

The sources of current harmonics are nonlinear loads connected to the distribution network. The flow of current harmonics through a network, which has a certain impedance, leads to the appearance of harmonic voltages and, accordingly, to distortion of the form of the supply voltage. Different types of load and its curves are shown on figures 17 and 18:

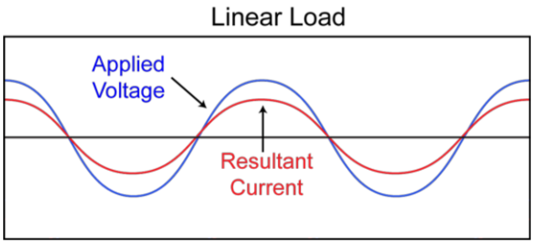


*Figure 18 – Voltage and current curves from source by linear load [1]*

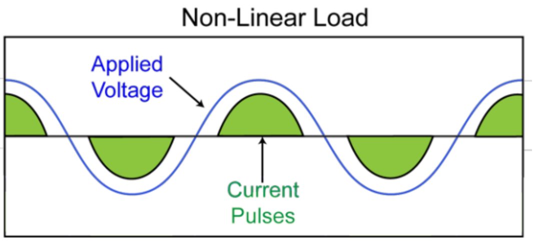


*Figure 17 - Voltage and current curves from source by non-linear load [1]*

The non-linear loads consume the harmonics currents in the distribution network. Voltage harmonics are caused by the flow of harmonic currents along the impedance of the supply circuits. Example is shown on the figure 19 below:

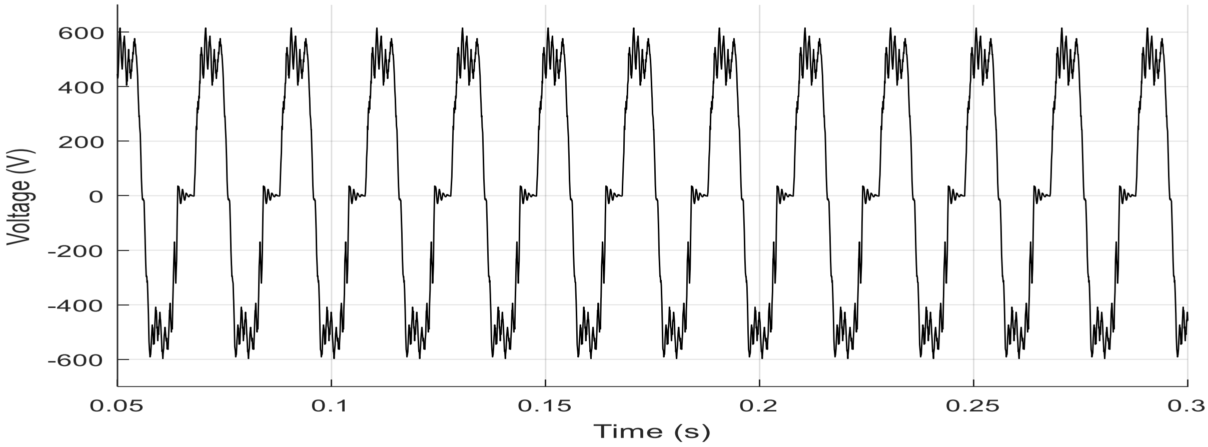


*Figure 19 – Voltage harmonics caused by current harmonics*

Harmonics in the electrical signals (voltage, current) cause the decline of electric power quality. This may cause some negative influences:

- Overload in distribution networks due to an increase of the current value
- Overload in zero (neutral) conductors due to the summation of higher harmonics currents, which are multiple of 3 and are generated by single-phase loads overload
- Overloads, vibration and aging of generators, transformers and electrical motors.

## 7.2 Economic consequences of harmonic disturbances

Harmonics have significant economic consequences:

- Overloading in the distribution network can lead to higher levels of energy consumption and losses increase
- Distortion of the current curve shape can cause false triggering of circuit breakers, which can lead to the shutdown of the production process.

THD is a measurement of declination caused by harmonics. It is shown in percentage according to the size of curve's change: the less the percentage is, the more looks a curve as an ideal sinus curve.

A quantity expressing the degree of nonlinear distortion of the signal, equal to the RMS value of all higher harmonics of the signal to the value of the first harmonic:

$$THD_U = \frac{\sqrt{U_2^2 + U_3^2 + U_4^2 + ... + U_n^2}}{U_1} \tag{1.14}$$

Where $U_2$, $U_3$, … $U_n$ - are the RMS voltages of the n-th harmonic and $U_1$ – is the RMS voltage by fundamental frequency.

$$THD_I = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + ... + I_n^2}}{I_1} \tag{1.15}$$

Where $I_2$, $I_3$, … $I_n$ - are the RMS currents of the n-th harmonic and $I_1$ – is the RMS current by fundamental frequency.

Important notes:

1. The first harmonic is also called basic or fundamental, for a conventional network it is a 50Hz harmonic.
2. In the datasheet values of the UPS, stabilizers, and other equipment, this parameter is usually indicated.
3. THD is used mainly to measure the distortion of the shape of the input or output current and is denoted as current THD or THDI. Also for voltage: THD voltage or THDU.

## 7.3 Typical values of THD

- 0 % — the waveform is an ideal sinusoid;
- 3 % — the waveform is different from the sinusoidal, but the distortion is invisible for the eye;
- 5 % — deviation of the waveform from sinusoidal visible for the eye on an oscillogram;
- 10 % — standard level of distortion;
- 12 % — perfectly symmetrical triangular signal;
- 22 % — A "typical" signal of a trapezoidal or stepped form;
- 48 % — perfectly symmetrical square wave (meander);
- 80 % — ideal sawtooth signal.

# 8 The dynamic analysis in Simulink

The model for this master thesis is presented as an assembly of the follow main parts: inverter, filter, cable, load and feedback control loop on the figure 20. It is assumed that the source voltage is AC, has approximately straight sinusoidal shape and has a rectifier after, which is further connected to the batteries. It is assumed as well, that the batteries have enough capacity for to support the required voltage (400 V). The modelling starts right after batteries. N-conductor is presented in the model as zero, neutral point of UPS capacitive part of filter (which is star-connected). This assumption is made for convenience, because having a neutral conductor makes the solution much more complex (referring to cables features for example).

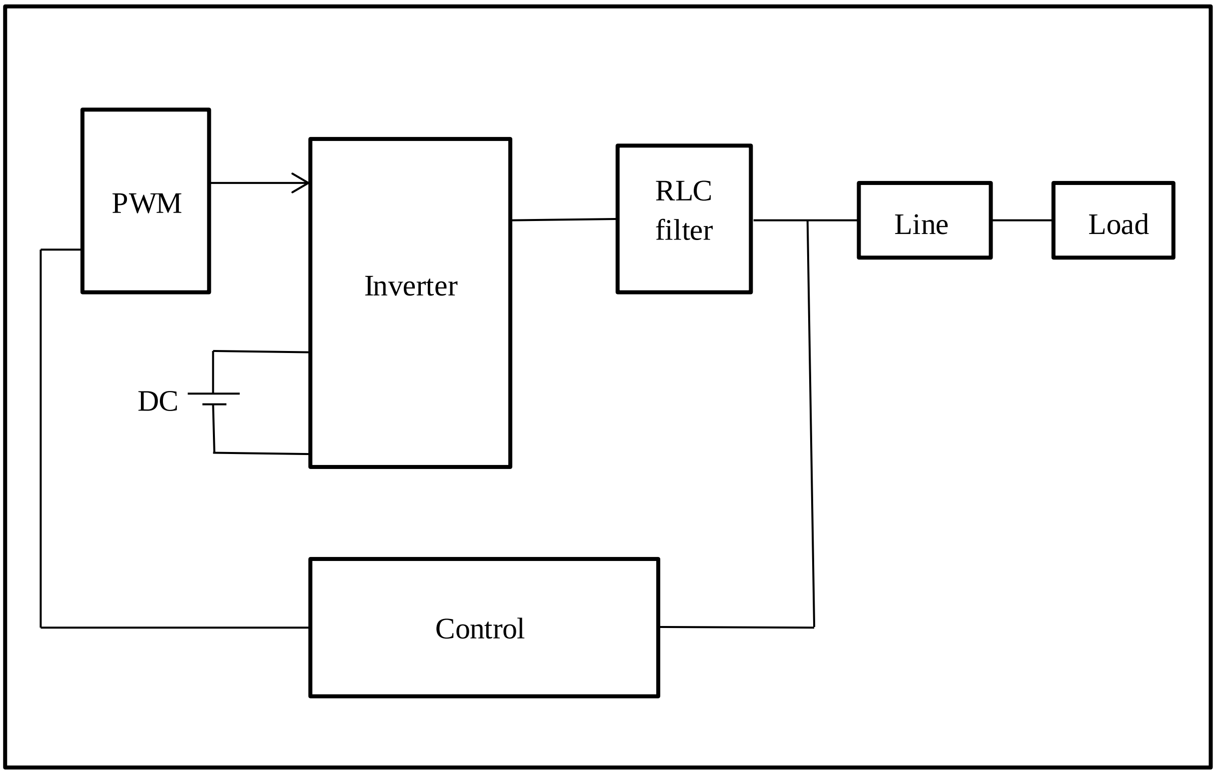


*Figure 20- Schema of the system*

## 8.1 PWM

PWM – pulse-width modulation is the process of controlling the power supplied to the load by changing the duty cycle of pulses at a constant frequency. Pulse-width modulator generates pulses for three-phase inverter. On the figure 21 it is presented pulses generated by modulator in accordance with the pulse-width modulation strategy of the model:

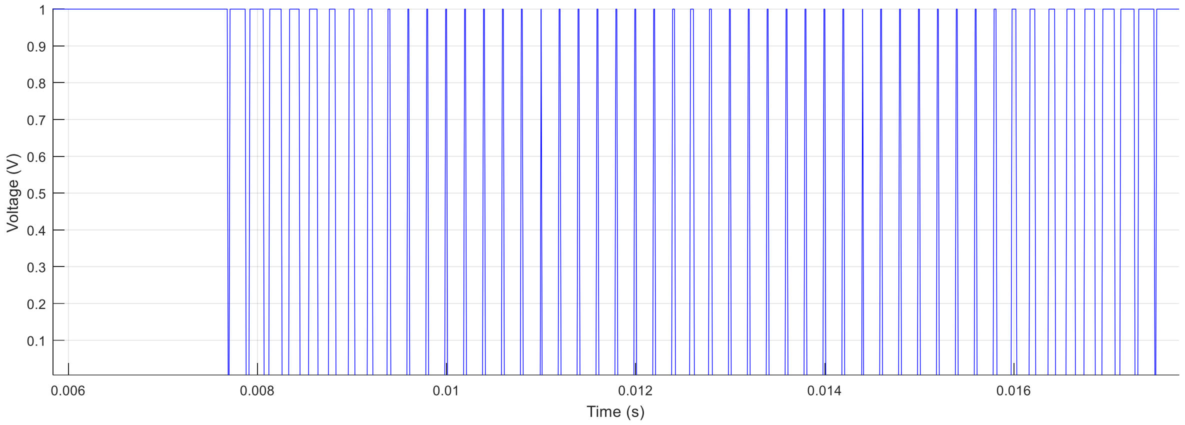


*Figure 21 - Pulses generated by modulator for 3-phase inverter*

## 8.2 Inverter

Inverter presents a part of UPS and follows after diode rectifier with C-filter, which converts current from network to DC. In this thesis network and rectifier are not presented in the model, because it is assumed, that frequency and voltage meet the requirements of FOL and losses of rectifier are negligible. The following figure 22 presents inverter as a part of the system:

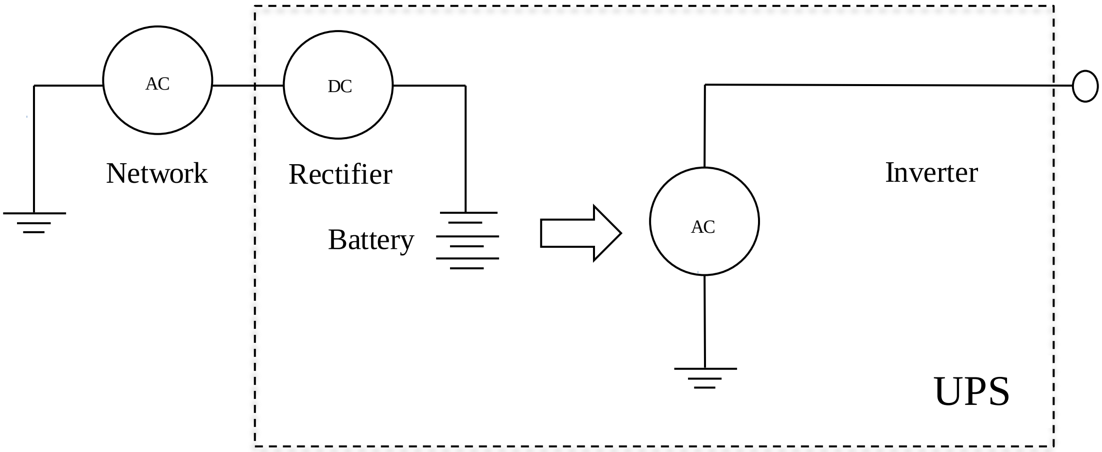


*Figure 22 – Phase equivalent scheme for UPS without filter*

The figure 23 shows IGBT/Diodes bridge which was chosen as inverter for the model.

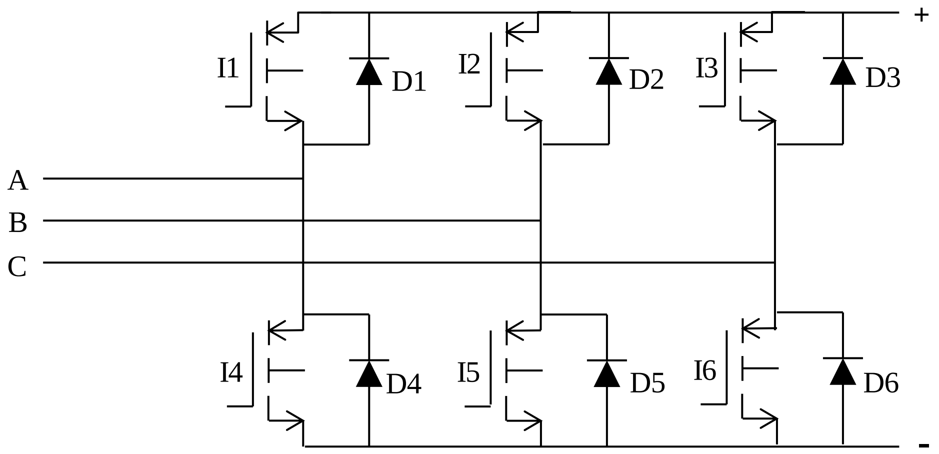


*Figure 23 – IGBT/Diode bridge*

It consists of power electronic devices (diodes) and forced-commutated devices (IGBT).

### 8.2.1 Diodes

The diode is the simplest two-electrode element, which conductivity depends on the direction of the current flow. The diode is considered to be opened, when it is applied a forward voltage to diode. The diode has a small resistance and through it flows direct current. In case, when the reverse voltage is applied to the diode, it is considered to be closed. This means that the reverse current is small, and in many cases is even zero.

Diodes are being used for:

1. Rectifying alternating current;
2. Stabilization of voltage;
3. As radiation detectors (photodiodes);
4. To create optical radiation (LEDs);
   etc.

### 8.2.2 Comparison of MOSFET and IGBT

**MOSFET:**

- MOSFET is controlled by voltage;  
- Less sensitive to temperature drop (than bipolar transistor);  
- A wide range of currents (from 0.5 to 100 A);  
- Presence of high switching frequency (up to 500 kHz);  
- Operating voltage up to 1000 V for large linear and load changes, heavy duty cycles and low output power;  
- MOSFET is easy to control.

MOSFETs are commonly used in impulse power supplies with operating frequencies above 200 kHz, as well as in charging devices for accumulative batteries.

**IGBT:**

- Small losses in the open state at high currents and stresses;
- Switching characteristics and conductivity are identical to bipolar transistor;
- IGBT is controlled by voltage;
- IGBT-transistors are used for voltages greater than 1000 V, high temperatures (above 100 ° C) and high output power (more than 5 kW).
- IGBT-transistors are used in motor control circuits (with an operating frequency of less than 20 kHz), uninterruptible power supplies, and also in welding machines.

The main criteria to select transistors are operating current and voltage. The choice of the transistor should be made with a margin of voltage to prevent its failure - that is why it has been chosen IGBT for modelling.

**IGBT/Diodes**

It is necessary to have both – diodes and IGBT in inverter, because diodes make possible for current to pass if it is needed. It protects transistors against overvoltages, which might be destroying for them. The transistors receive control signals from a control circuit.

## 8.3 Filter

Passive low-pass filter (LPF) – this device suppresses the frequency of the curve above the cutoff frequency of this filter.

The suppression of harmonics high-frequency components of the curve frequencies leads to the suppression of the curve details. The LPF always smooths the curve and brings each own filter delay.

In my model, the low-pass filter is used to improve the curve by delivering interference at frequencies higher than the upper limit of the curve bandwidth. The resonance frequency has to be much higher than fundamental frequency and much lower than thyristors switch frequency.

Circuit diagram on the next figure 24 shows how filter is integrated into the system, where n – is the neutral point, accessible through a fourth connector:

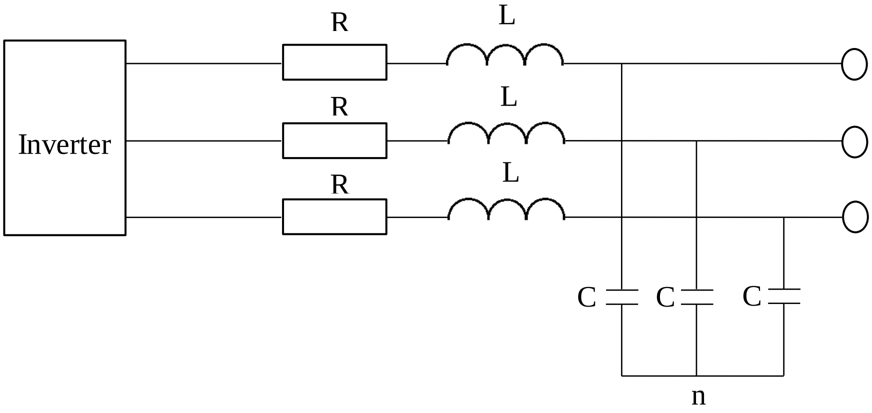


*Figure 24 – Circuit diagram of UPS filter*

Parameters, chosen empirically and according to the real possible values of filter:

*Table 5 - Filter parameters*

| | |
|---|---|
| R (resistance) | 0.1 Ω |
| L (inductance) | 2.1e-3 H |
| C (capacitance) | 10 μF |

$$Q_C = \frac{U^2}{X_C} = \frac{U^2}{\frac{1}{2\pi f \cdot C}} \tag{1.16}$$

Where Q<sub>C</sub> is reactive power, X<sub>C</sub> – capacitive reactance in Ohms, f – net frequency in Hertz and C – capacitance in Farads.

Capacitance was chosen as well, according to the typical values of capacitors for UPS - 10μF:

$$Q_C = U^2 \cdot 2\pi f \cdot C = 400^2 \cdot 2\pi \cdot 50 \cdot 10^{-6} = 502,66\,\text{VAr} \tag{1.17}$$

Where Q<sub>C</sub> is negative, since power is capacitive.

## 8.4 THD in the model

Further it is taken a look over the output signals from UPS to the load - current and voltage. These signals are considered in the stable statement, in the «healthy» net.

### 8.4.1 Load current

The current has a significant distortion in curves caused of the type of load – pure resistive.

The FFT allows defining this distortion in accordance to frequency, which is shown on the figure below:

*Figure 25 - Current signal, 5 cycles*

For this analysis fundamental frequency was chosen 50 Hz and maximum frequency to show – 1000 Hz, 5 cycles of the current signal (phase a).

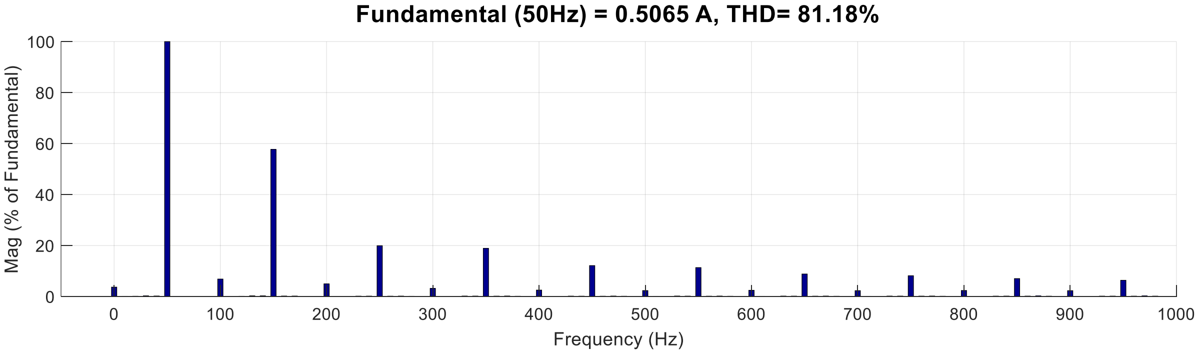


*Figure 26 - FFT current analysis*

As it is possible to see from the figure and data, THD is quite big – it is almost sawtooth signal (80%) instead of sinusoidal (3-10%). The biggest distortion is produced of the harmonics which are odd, compared to the fundamental (it means, harmonics of 3, 5, etc. orders – 150 Hz, 250 Hz, etc. accordingly).

### 8.4.2 Load voltage

For this analysis fundamental and maximum frequencies were chosen the same as for current. It was chosen 15 cycles of the voltage signal (phase a).

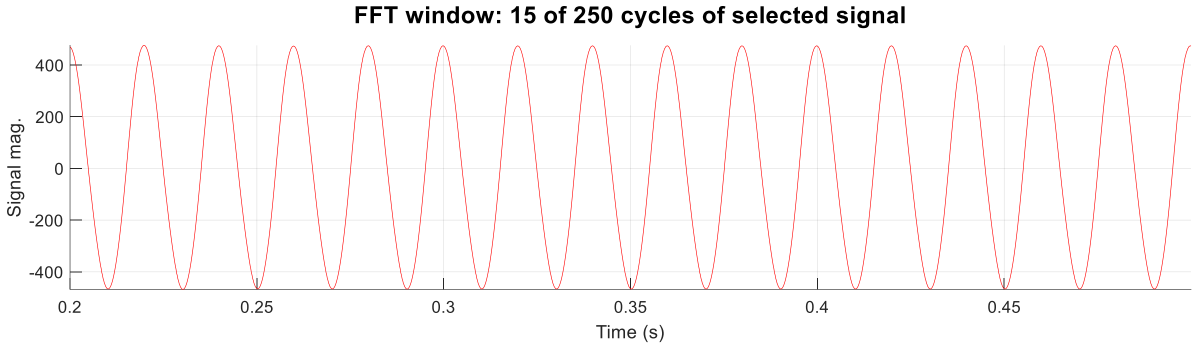


*Figure 27 - Voltage signal, 15 cycles*

As it is easy to see from the figure 27, the signal becomes stable in a very short period of the time, which shows a high quality of the voltage.

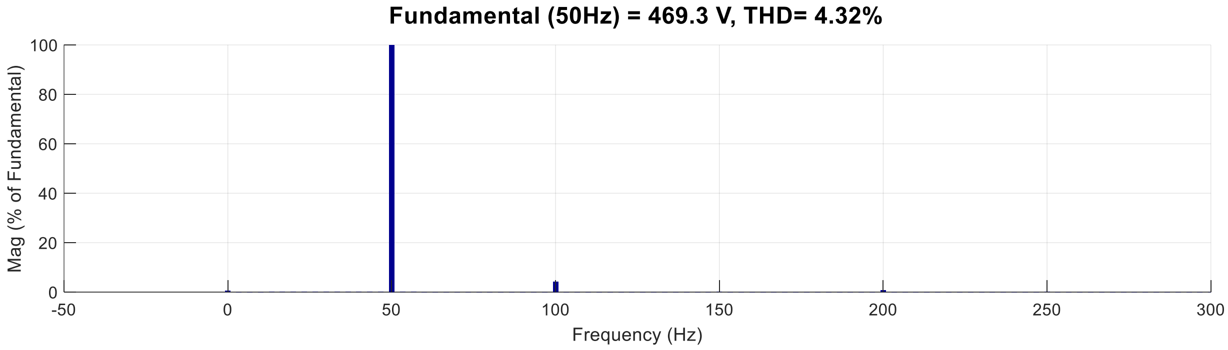


*Figure 28 - FFT voltage analysis*

THD is a bit over 4% - that means that the deviation of voltage curve waveform from sinusoidal is visible for the eye on an oscillogram. But it is still in frames of standard level of distortion.

## 8.5 Line

Cable taken for computation as a prototype of line is IFSI 4x50/16 AL, length – 300 m. This is a cable, which is being used nowadays for construction of tunnels backup systems, supplied directly from 400 TN-C-S net. The regular length for the tunnel of 1km UPS-supply is in average 280 m. This cable can be used in all types of rooms, including outdoors. It is one of the main distributive cables, which has the following parameters:

*Table 6 - Cable’s parameters, computed for 300 m length*

| | |
|---|---|
| R (resistance) | 0,1923 Ω |
| $X_L$ (reactance) | 0,030324 Ω |
| C (capacitance) | 0,15 μF |

Knowing reactance, it is possible to compute inductance:

$$L = \frac{X_L}{2\pi f} = \frac{0,030324}{2\pi \cdot 50} = 0,96 \cdot 10^{-4} H \tag{1.18}$$

Where f – net frequency, $X_L$ - reactance.

## 8.6 Vector control

### 8.6.1 Clarke and Park transformations in the backup system with the pure resistive load

The analysis of a three-phase AC system uses both - Clarke and Park transformation matrix:

$$M_{CP} = M_C \cdot M_P = \begin{bmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{bmatrix} \cdot \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \Rightarrow \tag{1.19}$$

Where $M_{CP}$ is Clarke-Park transforming matrix; $M_C$ is Clarke transforming matrix and $M_P$ – Park transforming matrix.

$$\Rightarrow M_{CP} = \frac{2}{3} \cdot \begin{bmatrix} \sin\vartheta & \sin\left(\vartheta - \frac{2\pi}{3}\right) & \sin\left(\vartheta + \frac{2\pi}{3}\right) \\ \cos\vartheta & \cos\left(\vartheta - \frac{2\pi}{3}\right) & \cos\left(\vartheta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{1.20}$$

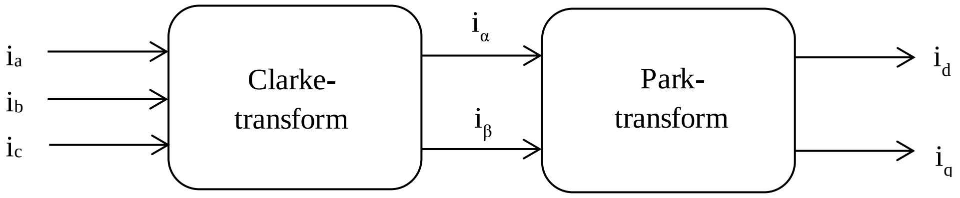


*Figure 29 - Clarke-Park transform*

According to the block-scheme of Clarke-Park transform, shown on the figure 29, equation 1.21 of current transform follows as:

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3} \cdot \begin{bmatrix} \sin\vartheta & \sin\left(\vartheta - \frac{2\pi}{3}\right) & \sin\left(\vartheta + \frac{2\pi}{3}\right) \\ \cos\vartheta & \cos\left(\vartheta - \frac{2\pi}{3}\right) & \cos\left(\vartheta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{1.21}$$

The transformation back to the AC-signal is achieved by inverse matrix:

$$M_{CP}^{-1} = \begin{bmatrix} \sin\vartheta & \cos\vartheta & 1 \\ \sin\left(\vartheta - \frac{2\pi}{3}\right) & \cos\left(\vartheta - \frac{2\pi}{3}\right) & 1 \\ \sin\left(\vartheta + \frac{2\pi}{3}\right) & \cos\left(\vartheta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \tag{1.22}$$

Thereby:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \sin\vartheta & \cos\vartheta & 1 \\ \sin\left(\vartheta - \frac{2\pi}{3}\right) & \cos\left(\vartheta - \frac{2\pi}{3}\right) & 1 \\ \sin\left(\vartheta + \frac{2\pi}{3}\right) & \cos\left(\vartheta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} \tag{1.23}$$

The very important moment to use this transformation is that the signal which is coming to be regulated by PID-regulator has to be even, without ripples. Otherwise PID-regulator would not be able to change the signal in accordance to the reference.

In this thesis the challenge of this transformation consists in the type of load, which is presented as pure resistive. It is an approximation, because in the real system the load is almost always presented as a mix of non-linear and linear. Each kind of load gives perturbations of the current, which causes ripples. In case of mixed load these perturbations from different types of load are cancelling each other, what gives even curve without ripples on the input of transformation. Current curves of pure resistive load are shown on the figure 30 below:

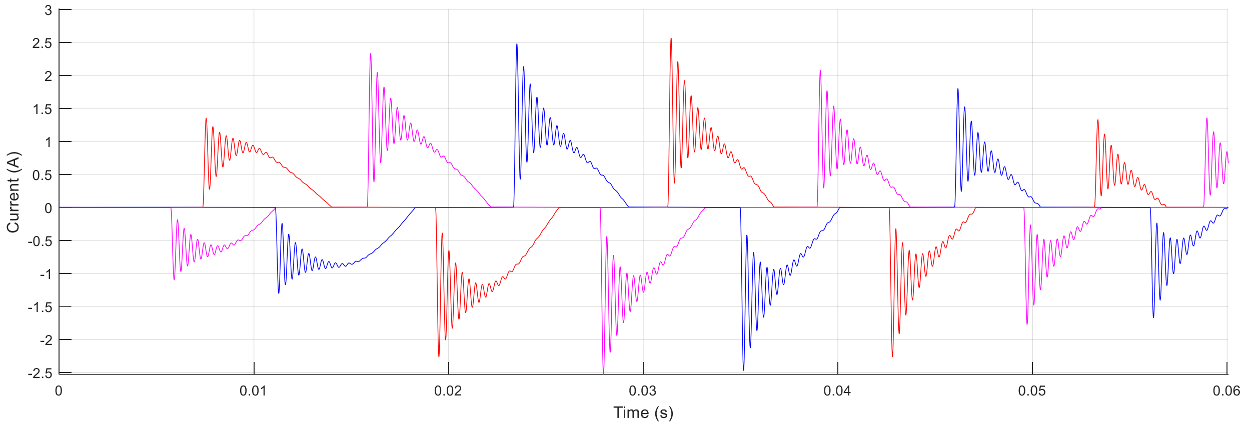


*Figure 30 - Ripples caused by perturbation of the line current curves (1st phase – purple; 2nd phase – blue; 3rd phase – red)*

Sometimes it is not possible to control the system, using one feedback control only – that is why it is being used an alternative type of ordinary control, which is called cascade control. The most important point about cascade control is that the compensation for process disturbance is better so that deviation is smaller.

Therefore in case of using only one type of load there are different ways how to avoid this situation or correct the signal. There are as well different ways how to correct the signal, which means might be used for to align it: it could be a single filter, presented in Simulink modeling as a Transfer function block or more challenging system using different methods of compensation. The following filter equation was used in the model to reduce ripples and correct the current and the voltage curve:

$$H(s)=\frac{1}{Ts+1} \tag{1.24}$$

Where T is a time constant.

It is not a goal of this thesis to research the best possible way of such compensation, that is why it was used the simplest solution - a single filter, presented in the modelling as transfer function with paramenters selected empirically. For current loop T was chosen equal to 1 and for voltage – equal to 10. Both coefficients are quite high and are not used in the real system. But in the model it has been made some simplifications which may cause such a deviation in the control loops.

In the control loops it was used PID-controller, which is being used the most often.

### 8.6.2 PID-controller

PID-controller function is shown in the following equation:

$$R(s)=K+\frac{1}{T_i s}+T_d s \tag{1.25}$$

Where K – is a proportional coefficient, $\frac{1}{T_i s}$ - is the integral part with $T_i$ – time constant and $T_d s$ - the derivative part with $T_d$ – derivate time.

The proportional component produces an output signal that counteracts the deviation of the controlled value from the set value observed at a given moment in time. The integral part is used to eliminate a static error, which does not let the real value to become equal to the set value. The derivative component is proportional to the rate of change in the deviation of the controlled quantity and is designed to counter deviations from the target value that are predicted in the future.

In this thesis was used PI-controller, because the time of modeling is quite small and the derivative part is not necessary. In the tables below are shown coefficients chosen for current and voltage PI-controllers.

*Table 7 – PI-parameters for controller in current loop*

| | |
|---|---|
| P | 1.5 |
| I | 100 |

*Table 8 – PI-parameters for controller in voltage loop*

| | |
|---|---|
| P | 12 |
| I | 100 |

Integral parameter is chosen much higher compared to proportional one, because of the small time of simulation. It can be easily changed to the smaller one by extending the simulation time.

Block-scheme for PI-controller looks as it is shown on figures 31 and 32 – for d-component and q-component. They were considered separately, because the control block-scheme for d-component will include voltage and current controls, while scheme for q-component consists of current control only. It is explained that the reference value for q-component $I_{ref}$ has to be 0.

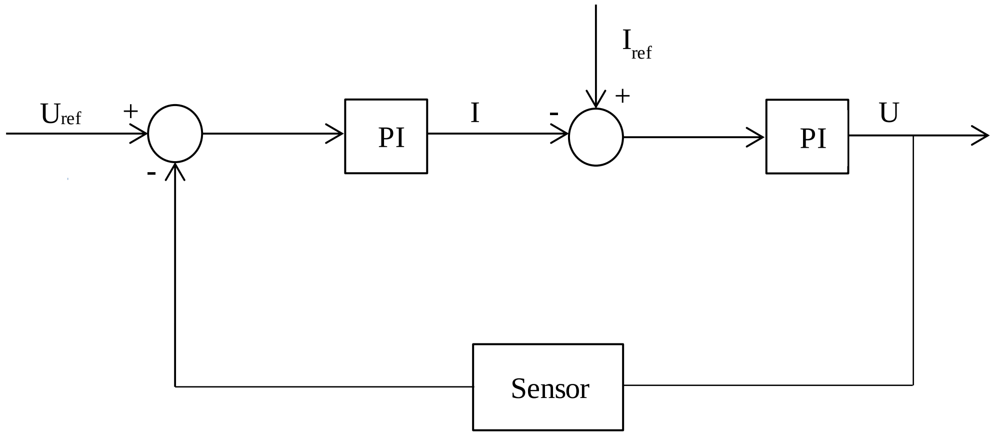


*Figure 31 – Block-scheme for d-component, cascade control*

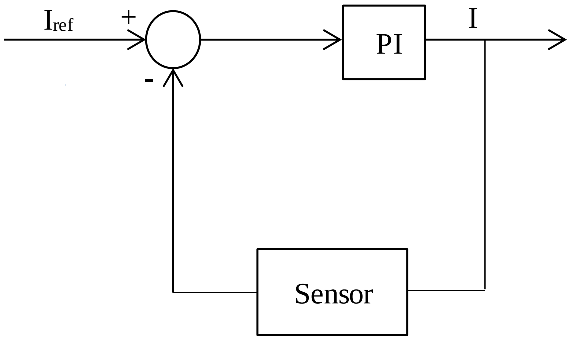


*Figure 32 – Block-scheme for q-component, current control*

It is important to notice, that compensation is causing the changes of the original signal, seen from the regulators side, that's why it should be paid attention to the angle control of the rotational system (the reference value of θ). Using as before, empirical way, it was computed, that the value of θ for abc/dq0 transform and inverse transform will be $\frac{3\pi}{4}$ rad.

Figures 33 and 34 shown below present ripples in d-q-curves, caused by overharmony. Figures 35 and 36 display the same d-q-curves after using filter, and it proves that filter solves the ripple-problem.

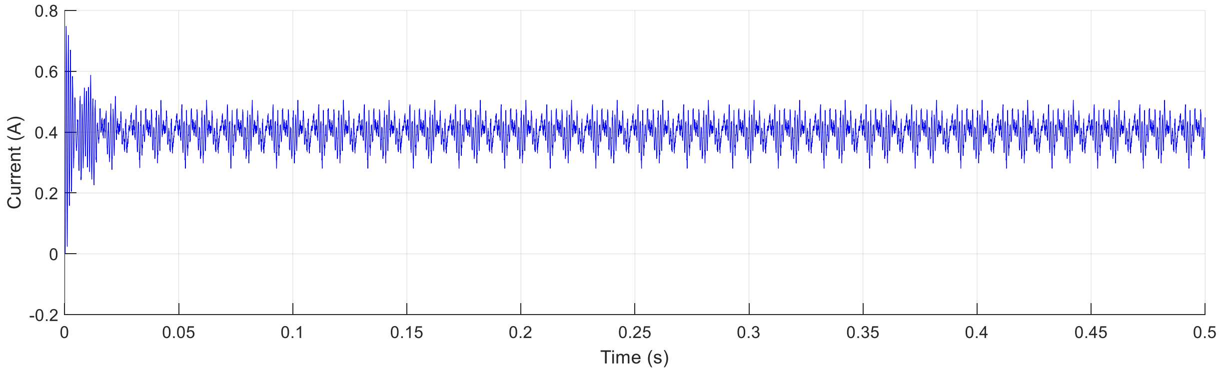


*Figure 33 – d-signal without filter*

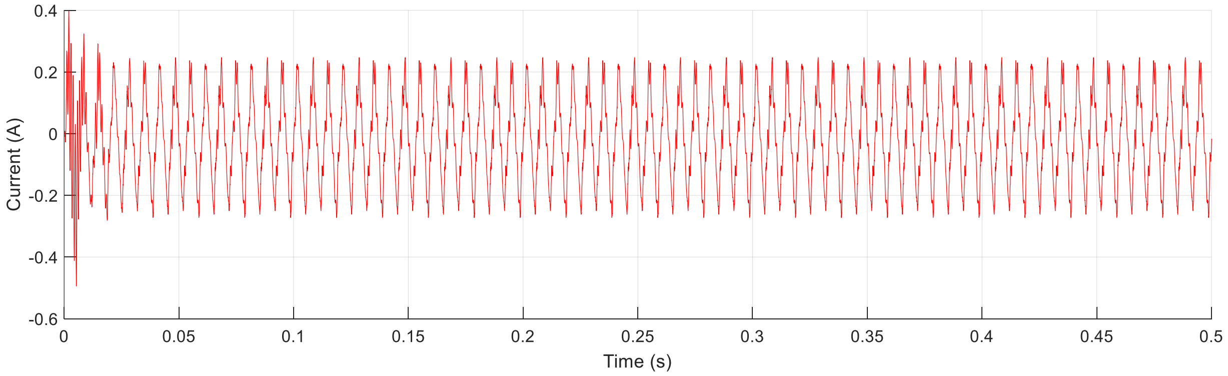


*Figure 34 – q-signal without filter*

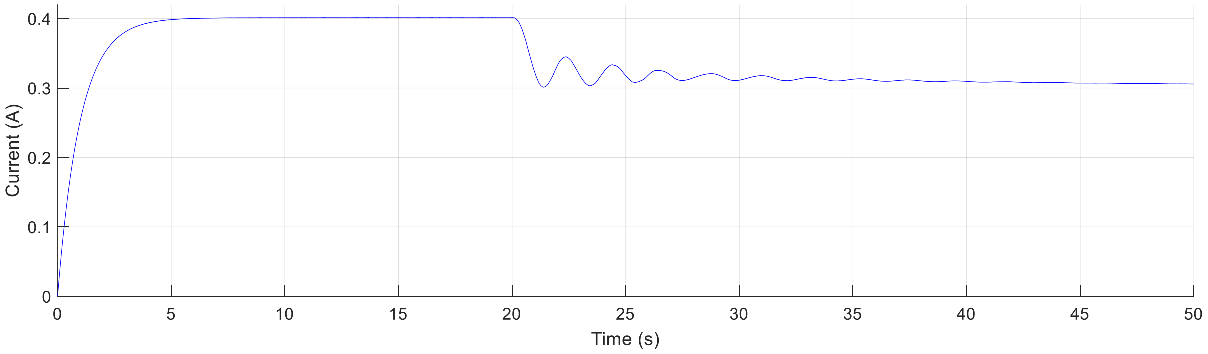


*Figure 35 – d-signal with filter*

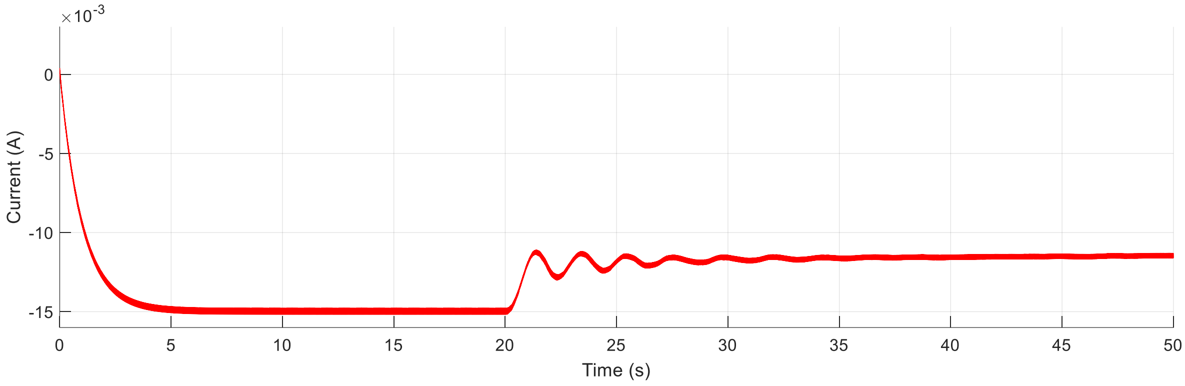


*Figure 36 – q-signal with filter*

System shows quite good regulating response, what means that cascade control works.

## 8.7 Load

As it was mentioned above, the load is pure resistive and is presented in the model as resistive unit connected to the net trough the diode bridge, which is shown on the figure 37 below:

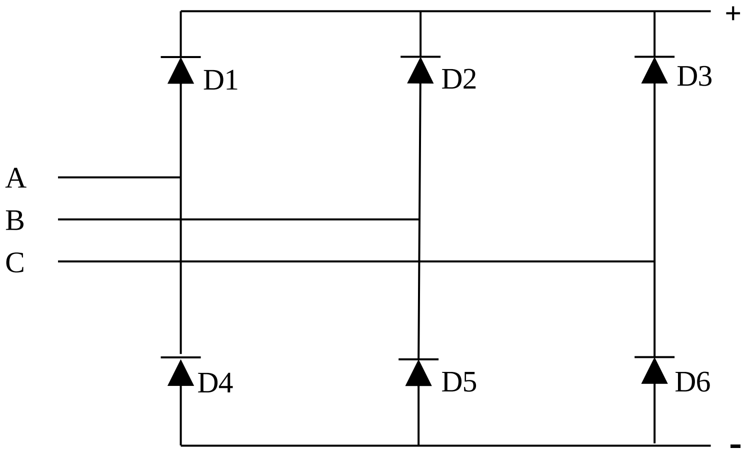


*Figure 37 – Diode bridge*

In Simulink the load-block of every phase looks as it is shown on the figure 37:

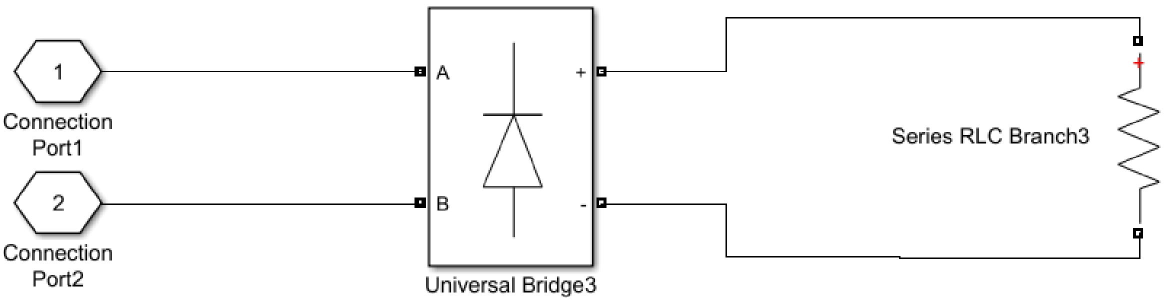


*Figure 38 – Simulink block of load (the common structure for every phase)*

The load for every phase might be computed by the following equation:

$$R_f = \frac{U_f^{\,2} \cdot 3}{P_N} \tag{1.26}$$

Where $R_f$ – phase resistance, $U_f$ – phase voltage, $P_N$ – nominal power.

## 8.8 2-phase minimum fault

The actual question is the smallest value of short circuit current, so that the protective system is available to react on it on the right time. As it was written before, the smallest 2-phase fault might be smaller than the smallest 1-phase fault. That is why it is necessary to take into account these 2-phase-fault computations. The initial data for these computations were taken on the 1 km distance from the UPS. For the simplicity of computation it was taken the cable IFSI 4x50/16 Al, which has the following parameters:

*Table 9- Cable's parameters*

| | |
|---|---|
| R (resistance) | 0.641 Ω/km |
| $X_L$ (reactance) | 0.19978 Ω/km |
| C (capacitance) | 0.5µF/km |

Active rated power is taken 7,9 kW (according to the original data).

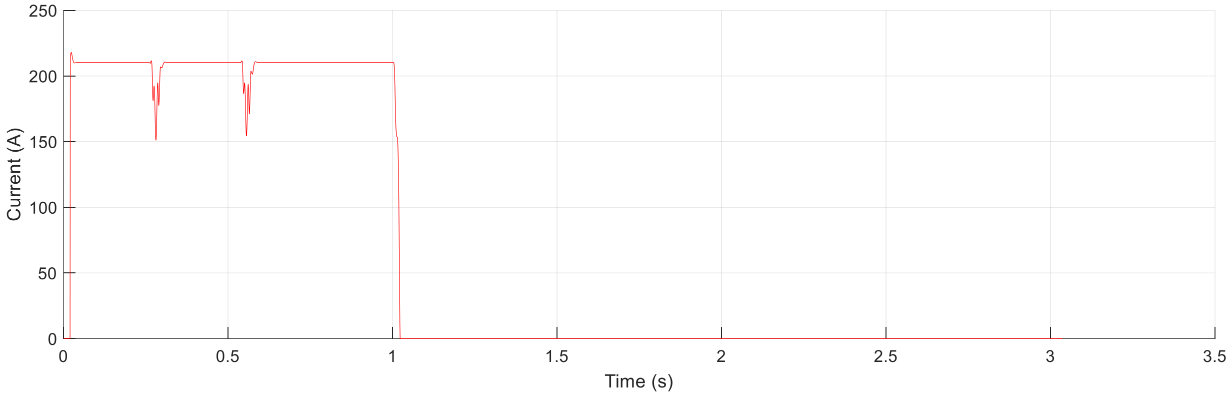


*Figure 39 – 2-phase fault, phases a and b*

The value from the figure 39, which current is being kept during its stable period (phases a and b) is approximately 210 A.

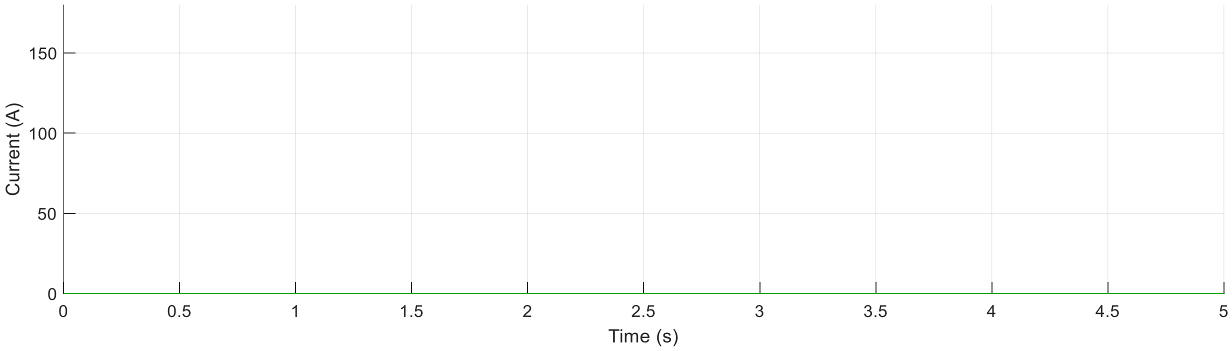


*Figure 40- 2-phase fault, phase c*

As it is easy to see from the Figure 40, the current on the 3rd phase is equal to 0 – what confirms the theory.

Active and reactive power is presented on figures 41 and 42:

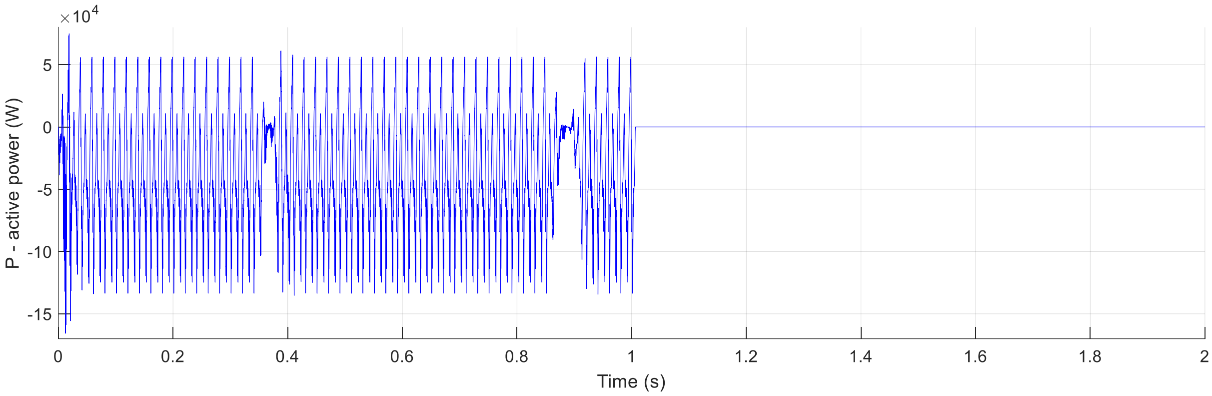


*Figure 41 – Active power*

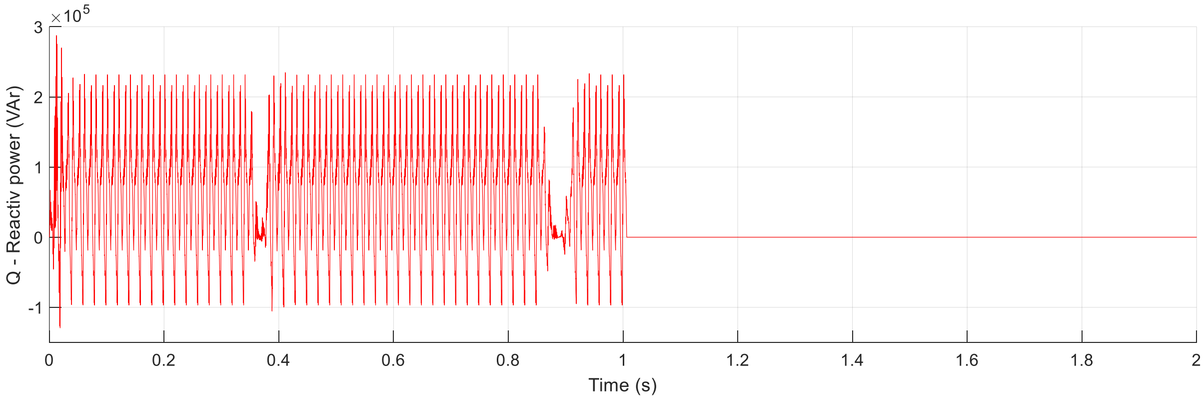


*Figure 42 – Reactive power*

Down-jumps on the figure 39 are caused by PI-controller, which tries to control the system even after fault. The figures below 43 and 44 shows the reaction of PI-controller in current and voltage control loop:

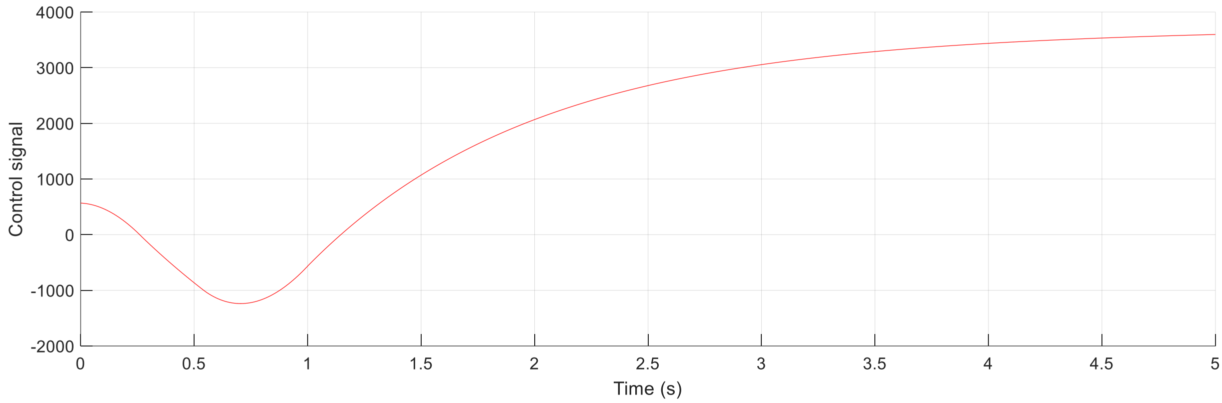


*Figure 43 – PI-controller, current control loop*

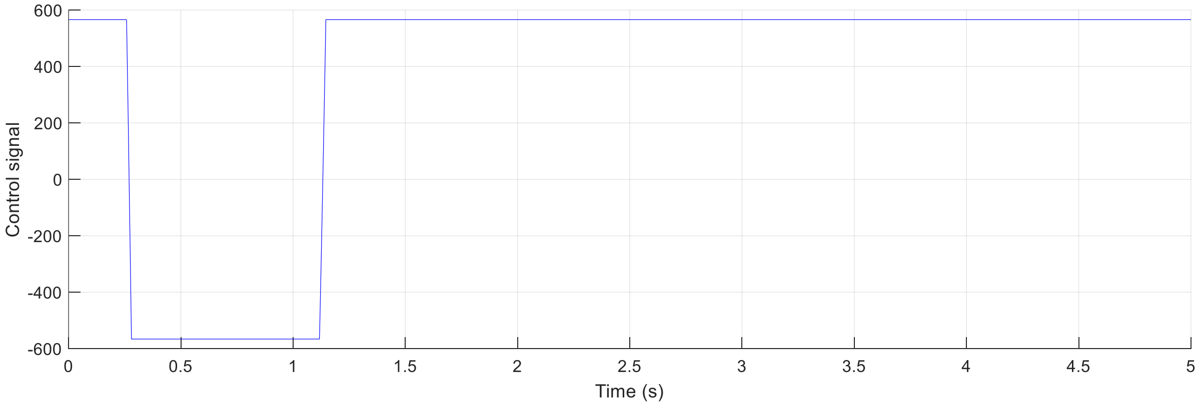


*Figure 44 – PI-controller, voltage control loop*

On these figures control signal means the weights, which are the proportional and integral gain parameters.

The real UPS does not cause such jumps in the system because of its own balanced parameters and more complicated construction than it was presented in the model.

## 8.9 Single-phase minimum fault

In the TN-net it is necessary to compute both – the minimum 2-phase fault and the minimum single-phase fault for to compare the results and decide which of them is the smallest.

The figures 43, 44 and 45 below show the results of single-phase minimum fault:

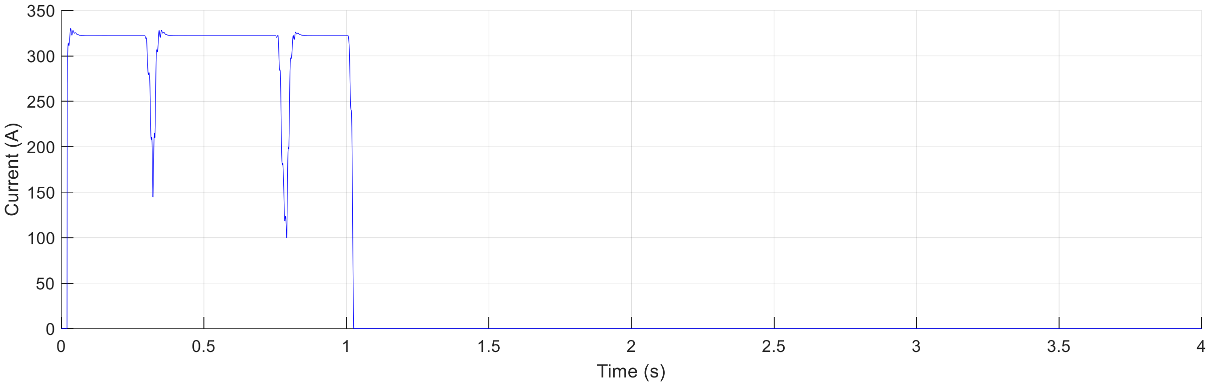


*Figure 45 – Single-phase fault, phase a*

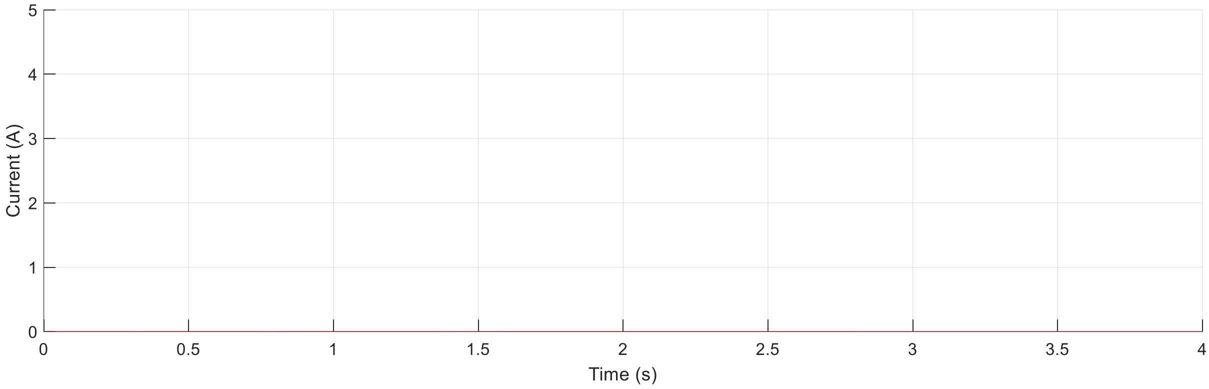


*Figure 46 - Single-phase fault, phase b*

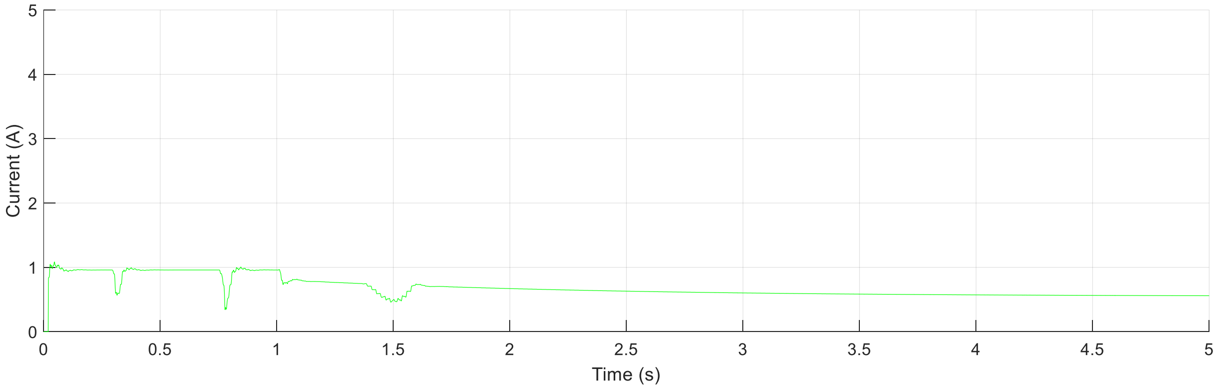


*Figure 47 - Single-phase fault, phase c*

The single-phase fault minimum value from the figure 45 (phase a) is approximately 322 A, which is more than the result from the 2-phase simulation (210 A). That means that the minimum value which should be taken in account by choosing the protective system for UPS, modelled in this thesis, and evaluating its sensitivity is 210 A. The jumps on the figure 45 are caused by the same, as by 2-phase short circuit – the trial of PI-controller to hold the system in accordance with the reference values.

## 8.10 3-phase maximum fault

The figure 48 below shows 3-phase short circuit current, which, according to the theory, is much higher, than 2-phase short circuit:

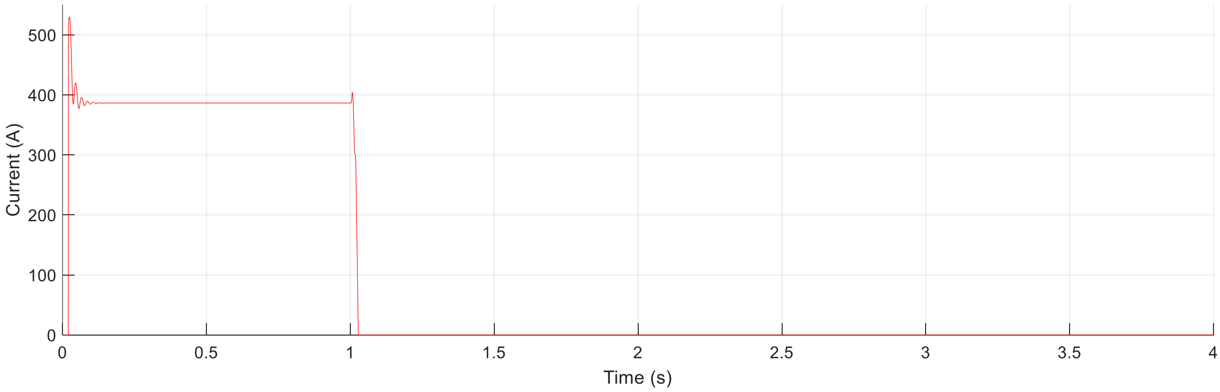


*Figure 48 – 3-phase short circuit current for all the 3 phases*

Maximum value is 386 A. UPS controls voltage – and thereby current, that is why the maximum value of the current is almost never achievable. It is the only one situation, when this current can become very high and can present a serious danger - when the ByPass manual controller of UPS connects system directly to the net.

There are no jumps on this figure 48, because of the measurements, which are taken for 3-phase maximum short circuit current right after UPS - it means, before the including of control loops into the system.

# 9 Alternative ways to protect the system

The new system of backup power supply is already in use. Therefore there are already in use some alternative approved ways of protection. Statens Vegvesen specified them in Håndbok N601 [5]:

- NEK 400-4-41, chapter 412 Double insulation or reinforced insulation
- NEK 400-4-41, chapter 413 Electrical separation
- NEK 400-4-41, chapter 414 Extra low voltage SELV/PELV(SELV – Separated or Safety Extra-Low Voltage – system is electrically separated from other systems and from earth; PELV – Protected Extra-Low Voltage – the system meets all the demands to SELV, but is not electrically separated from earth)
- Duplex Supply / Redundant Supply

Each of these solutions has each own challenges, which cannot assure the 100% safety. Most of them make system be more complex, expensive and less controllable. For example, the use the isolating transformer right after ByPass requires double isolation, which is needed for all the equipment and cables. Technical cupboards that are supposed to be placed by every SOS-station (except the SOS-station placed close to the technical rooms in tunnel and pitheads) have to be double isolated as well. The double isolation is not that common used nowadays, what makes the market of double isolated cables and technical cupboards very limited. The equipment which cannot be double isolated has to be provided by each own breaker or SELV/PELV.

# 10 Conclusion

In this work it was performed the risk assessment, which consists in that the TN-net might provide huge currents and might cause destroying consequences, if the protective system is chosen wrong.

It was defined the key-criterias for a reliable backup power system, which include type of protection, its dimensioning, selectivity and the simulating instruments to achieve them. It was shown, that UPS can control by itself only those currents, which cause a big voltage jump – but the currents which are lower and present danger, have to be controlled separately, using special equipment such as circuit breakers and fuses.

It was explained, why selectivity is so important and were given examples to prove it.

It was presented the model in accordance to the investigated system and simulated different cases (single-phase minimum, 2-phase minimum and 3-phase maximum short circuit) in accordance to the goal of research.

The results of this simulation match the theory described above and are theoretically founded.

This work and presented results are not the final stage of work and can be developed further, using different methods of modelling, coming up new modeling tools and taking in account more details, which determine the accuracy of research. Thus, the following steps can be taken:

- loads and cables impedance can be presented more detailed using FEBDOK modelling

- protective system can be simulated using FEBDOK data base for breakers and fuses

- Simulink model can include more protective elements, taking in account the features of load

- it should be taken into account more details of cables type, loads, breakers, some specific features of the exact tunnel to compute the costs according to the safety requirements of the conversion to the new power supply system.

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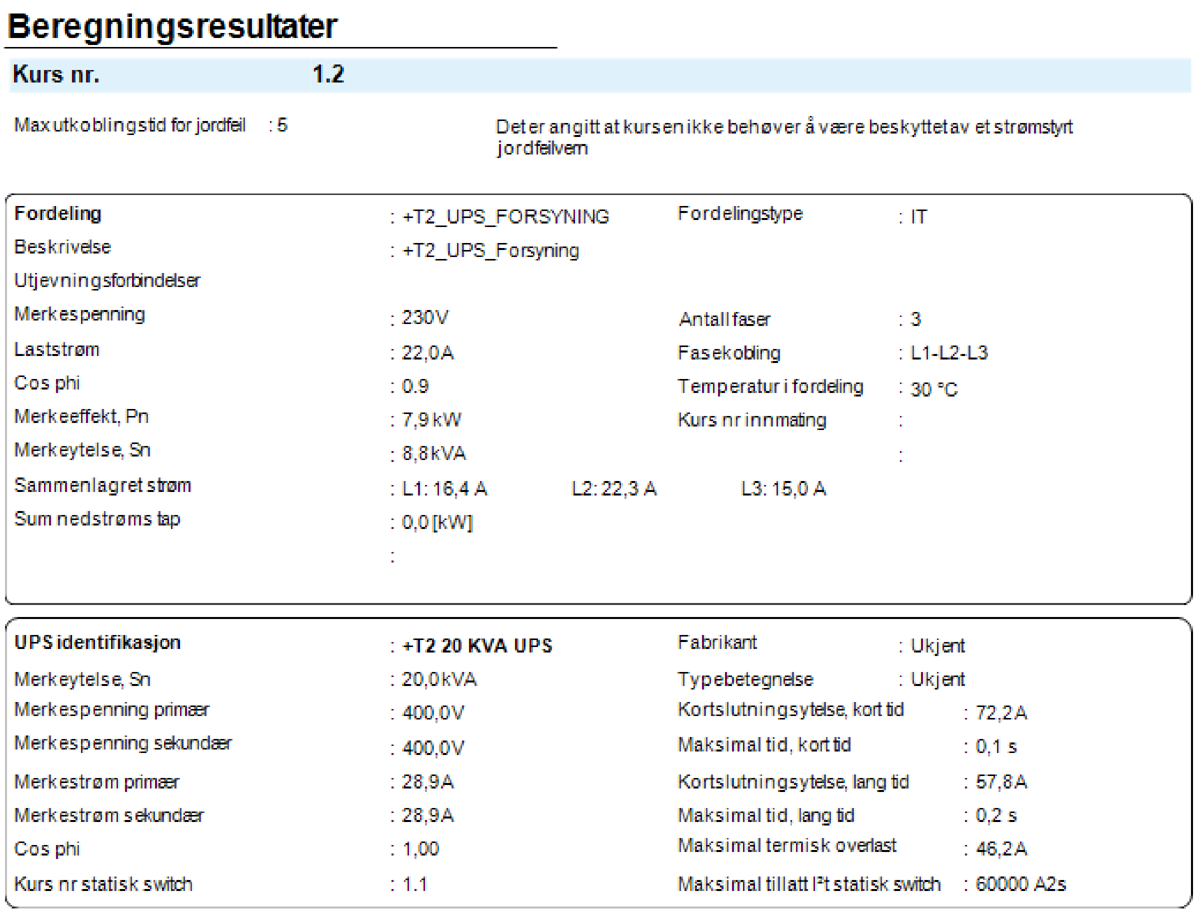
# Appendix

## Appendix A – Hamnøytunnelen, FEBDOK, main load circuit



### Beregningsresultater

**Kurs nr.** **1.2**

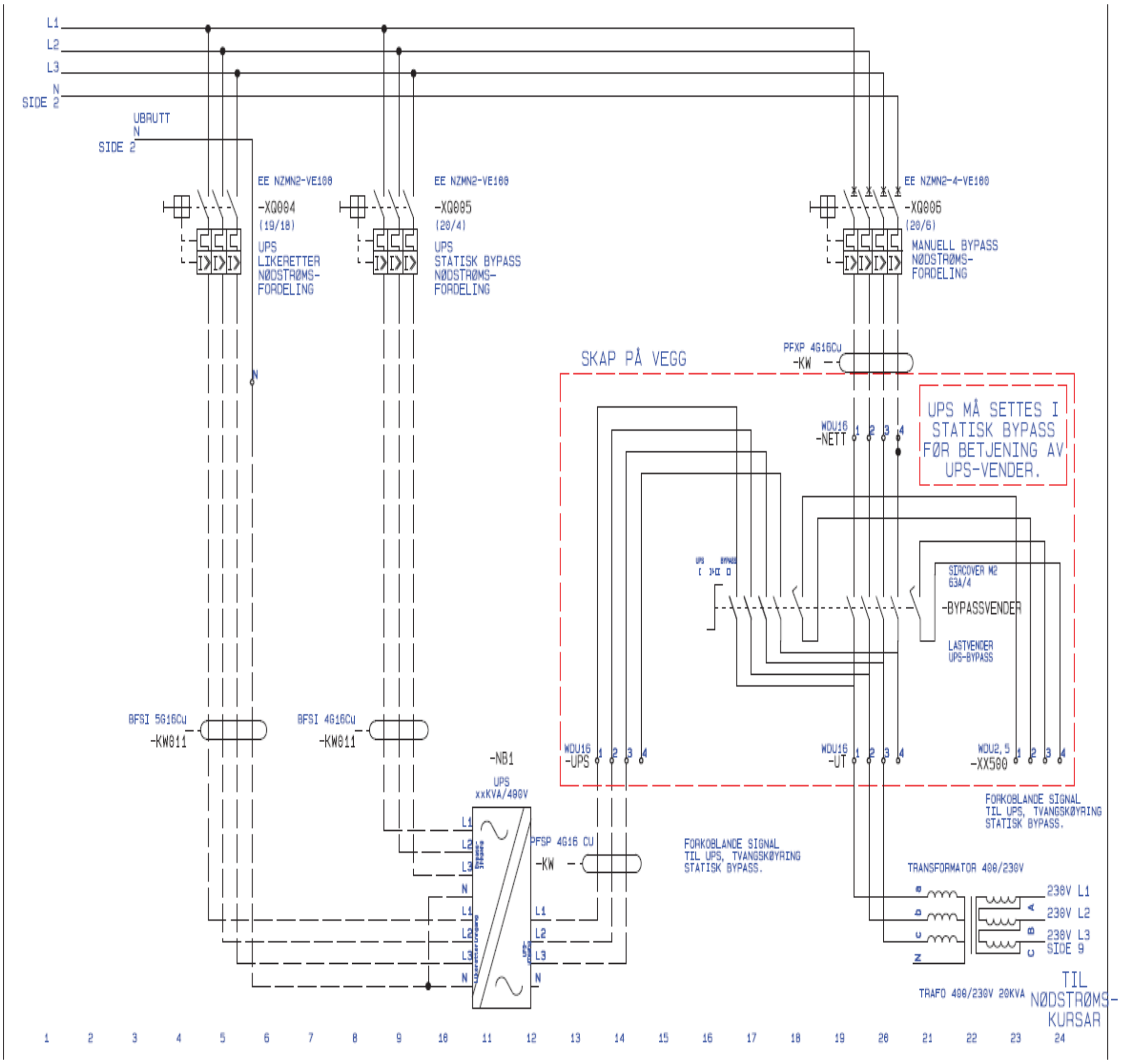
Max utkoblingstid for jordfeil : 5

Det er angitt at kursen ikke behøver å være beskyttet av et strømstyrt jordfeilvern

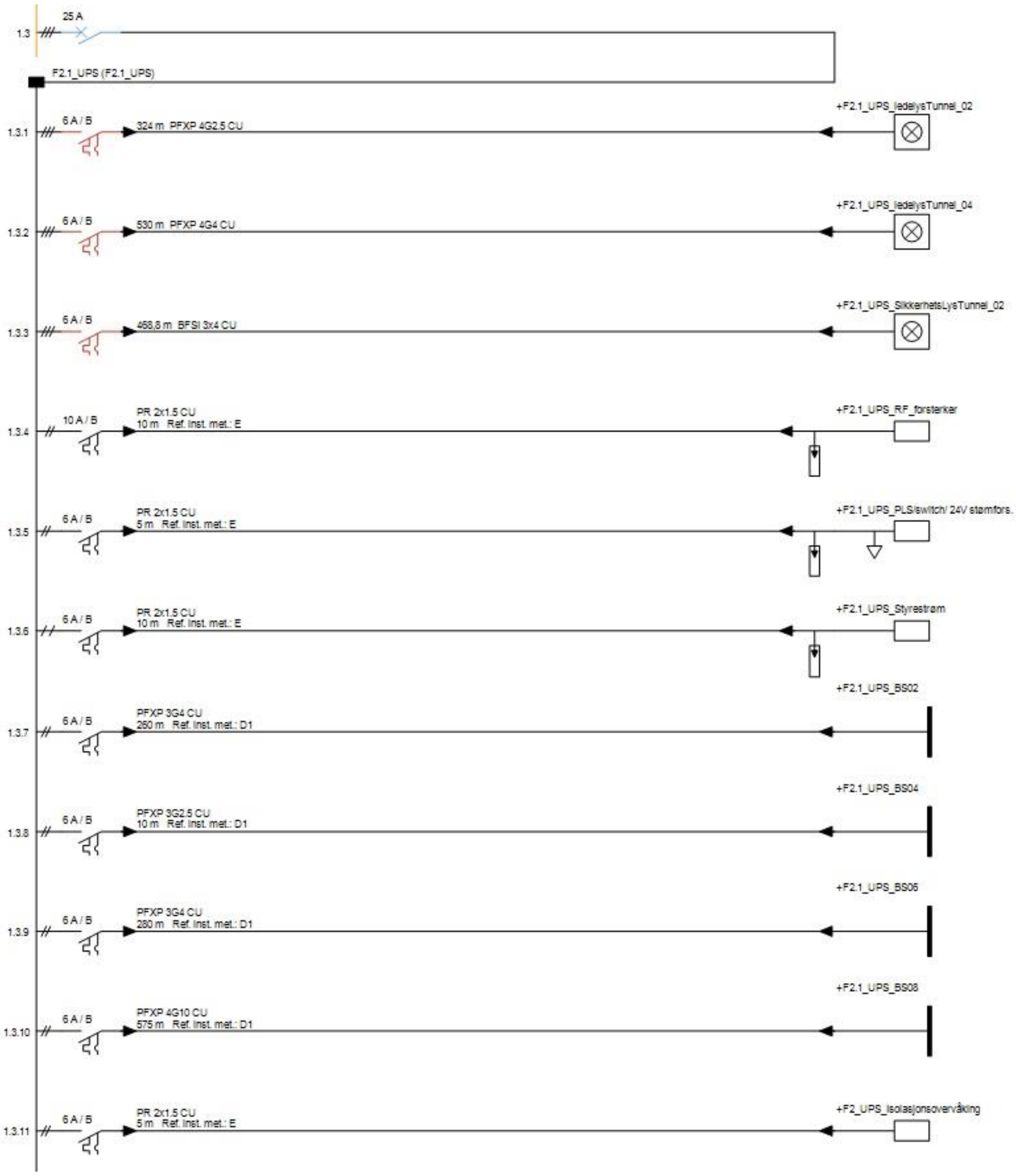
| | | | |
|---|---|---|---|
| **Fordeling** | : +T2_UPS_FORSYNING | Fordelingstype | : IT |
| Beskrivelse | : +T2_UPS_Forsyning | | |
| Utjevningsforbindelser | | | |
| Merkespenning | : 230V | Antall faser | : 3 |
| Laststrøm | : 22,0A | Fasekobling | : L1-L2-L3 |
| Cos phi | : 0.9 | Temperatur i fordeling | : 30 °C |
| Merkeeffekt, Pn | : 7,9 kW | Kurs nr innmating | : |
| Merkeytelse, Sn | : 8,8 kVA | | : |
| Sammenlagret strøm | : L1: 16,4 A | L2: 22,3 A | L3: 15,0 A |
| Sum nedstrøms tap | : 0,0 [kW] | | |
| | : | | |

| | | | |
|---|---|---|---|
| **UPS identifikasjon** | : **+T2 20 KVA UPS** | Fabrikant | : Ukjent |
| Merkeytelse, Sn | : 20,0 kVA | Typebetegnelse | : Ukjent |
| Merkespenning primær | : 400,0V | Kortslutningsytelse, kort tid | : 72,2A |
| Merkespenning sekundær | : 400,0V | Maksimal tid, kort tid | : 0,1 s |
| Merkestrøm primær | : 28,9A | Kortslutningsytelse, lang tid | : 57,8A |
| Merkestrøm sekundær | : 28,9A | Maksimal tid, lang tid | : 0,2 s |
| Cos phi | : 1,00 | Maksimal termisk overlast | : 46,2A |
| Kurs nr statisk switch | : 1.1 | Maksimal tillatt I$^2$t statisk switch | : 60000 A2s |

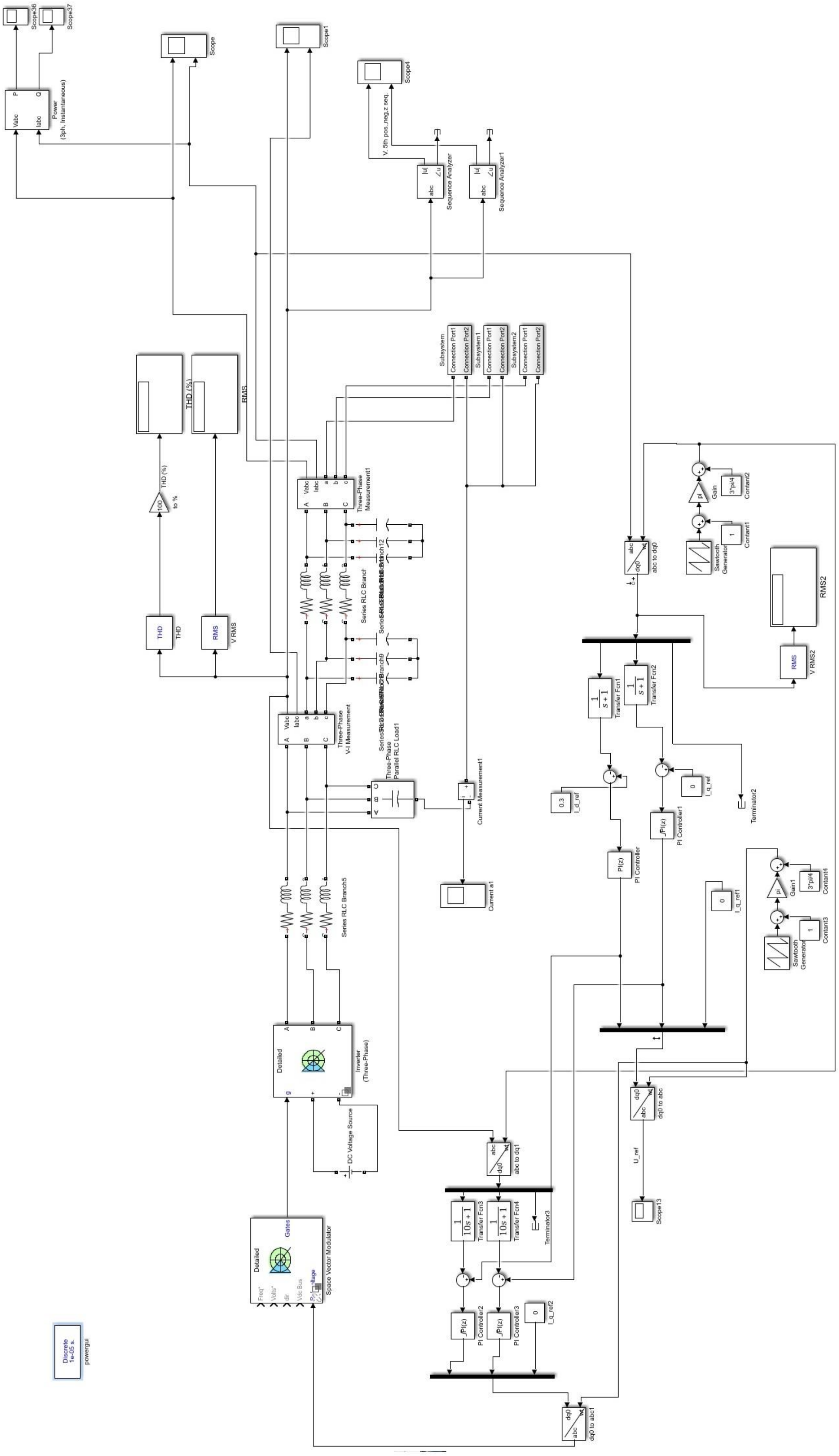
# Appendix B - Tunnel's emergency power plant, Statens Vegvesen



# Appendix C – Load of the backup power system, FEBDOK, Hamnøytunnelen



# Appendix D – Simulink model, healthy net



# Appendix E – Description of the most important elements in Simulink model

Space Vector Modulator – responsible to provide input pulses for invertor and which follows PWM – strategy. The block “Switching time calculator” sets the width of pulses.

DC Voltage Source – 590 V (to get 400 RMS, paying attention to voltage losses)

3-phase inverter – consists of 6 forced-commutated devices - IGBT. They are controllable switches. The IGBT has a high impedance gate, which requires only a small amount of energy to switch the device. IGBT has a small on-state voltage even in devices with large blocking voltage ratings. IGBT can be used in many applications of power electronics, especially in control drivers with PWM for servo motors and 3-phase asynchrony engines, which require wide dynamic control diapason and a low level of electromagnetic noise. IGBT devices are mostly used in UPS inverter parts, because of their fast reaction on the control and the possibility to vary between working modes «on-off».

RLC filter – passive low-pass filter (LPF).

THD – the block THD computes the total value of distortion factor (THD) of the periodic signals as

$$THD = \frac{\sqrt{I_{rms}^2 - I_1^2}}{I_1^2}$$

where $I_{rms}$ is RMS value of the input signal $I_1$ is RMS of its first harmonic.

Suggested simple hyperbolic voltage THD upper and lower bound approximations for single- and three-phase inverters are valid for arbitrary modulation indices and equidistant level counts with a practical accuracy of 5%–10% of voltage THD and may serve as reliable initial reference values for practical measurements and calculations, often making numerical voltage THD calculations unnecessary.

RMS – calculates it over a running window of one cycle of the specified fundamental frequency; that is, for the last T s, T=1/*f*, *f* is the fundamental frequency.

Sequence analyzer - The Sequence Analyzer block outputs the magnitude and phase of the positive-, negative-, and zero-sequence components of a set of three-phase signal. Index 1 means the positive sequence, 2 - the negative sequence and 0 - the zero sequence. The signals can optionally contain harmonics. The three sequence components of a three-phase signal (voltages $V_1$ $V_2$ $V_0$ or currents $I_1$ $I_2$ $I_0$) are computed as follows:

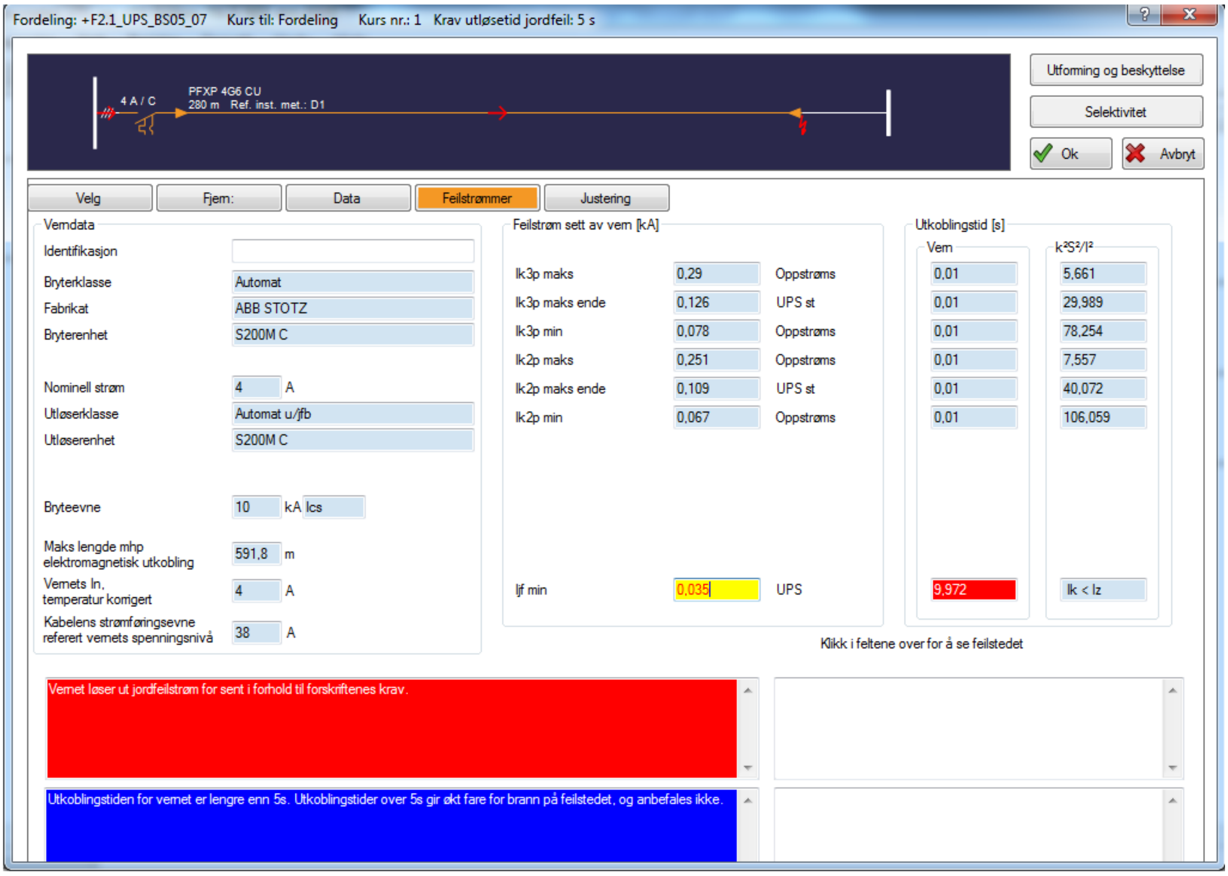
$$V_1=1/3(V_a+a\cdot V_b+a^2\cdot Vc)$$

$$V_2=1/3(V_a+a^2\cdot V_b+a\cdot Vc)$$

$$V_0=1/3(V_a+V_b+Vc)$$

$V_a$,$V_b$,$V_c$=three voltage phasors at the specified frequency $a=e^{j2\pi/3}=1\angle 120^\circ$ complex operator.

# Appendix F - FEBDOK, system warning, caused by unsatisfactory protection



Fordeling: +F2.1_UPS_BS05_07 Kurs til: Fordeling Kurs nr.: 1 Krav utløsetid jordfeil: 5 s

Verndata

| | |
|---|---|
| Identifikasjon | |
| Bryterklasse | Automat |
| Fabrikat | ABB STOTZ |
| Bryterenhet | S200M C |
| Nominell strøm | 4 A |
| Utløserklasse | Automat u/jfb |
| Utløserenhet | S200M C |
| Bryteevne | 10 kA Ics |
| Maks lengde mhp elektromagnetisk utkobling | 591,8 m |
| Vernets In, temperatur korrigert | 4 A |
| Kabelens strømføringsevne referert vernets spenningsnivå | 38 A |

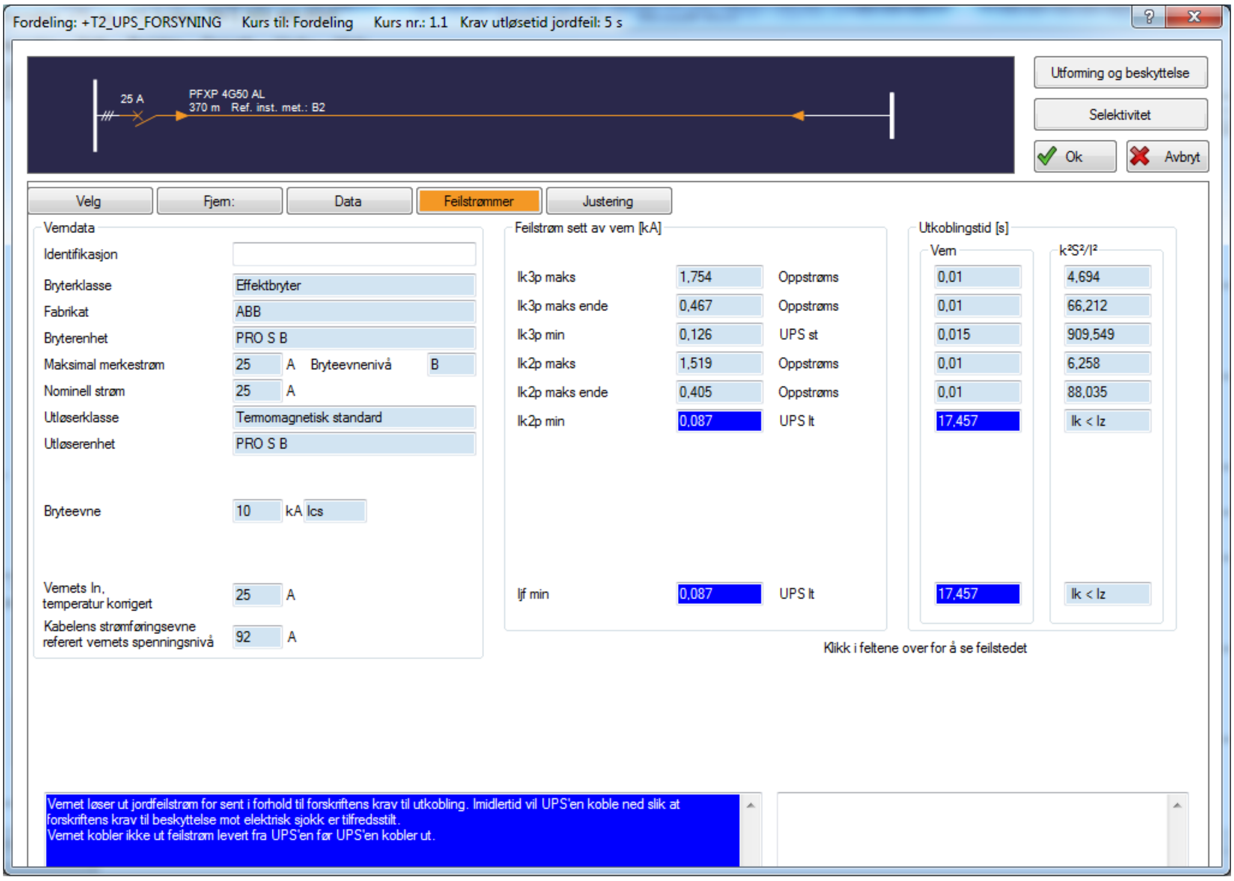
| Feilstrøm sett av vern [kA] | | | Utkoblingstid [s] | |
|---|---|---|---|---|
| | | | Vern | k²S²/I² |
| Ik3p maks | 0,29 | Oppstrøms | 0,01 | 5,661 |
| Ik3p maks ende | 0,126 | UPS st | 0,01 | 29,989 |
| Ik3p min | 0,078 | Oppstrøms | 0,01 | 78,254 |
| Ik2p maks | 0,251 | Oppstrøms | 0,01 | 7,557 |
| Ik2p maks ende | 0,109 | UPS st | 0,01 | 40,072 |
| Ik2p min | 0,067 | Oppstrøms | 0,01 | 106,059 |
| Ijf min | 0,035 | UPS | 9,972 | Ik < Iz |

Klikk i feltene over for å se feilstedet

Vernet løser ut jordfeilstrøm for sent i forhold til forskriftenes krav.

Utkoblingstiden for vernet er lengre enn 5s. Utkoblingstider over 5s gir økt fare for brann på feilstedet, og anbefales ikke.

# Appendix G - FEBDOK, system warning, caused by low protection



Fordeling: +T2_UPS_FORSYNING Kurs til: Fordeling Kurs nr.: 1.1 Krav utløsetid jordfeil: 5 s

Verndata

| | |
|---|---|
| Identifikasjon | |
| Bryterklasse | Effektbryter |
| Fabrikat | ABB |
| Bryterenhet | PRO S B |
| Maksimal merkestrøm | 25 A Bryteevnenivå B |
| Nominell strøm | 25 A |
| Utløserklasse | Termomagnetisk standard |
| Utløserenhet | PRO S B |
| Bryteevne | 10 kA Ics |
| Vernets In, temperatur korrigert | 25 A |
| Kabelens strømføringsevne referert vernets spenningsnivå | 92 A |

| Feilstrøm sett av vern [kA] | | | Utkoblingstid [s] Vern | k²S²/I² |
|---|---|---|---|---|
| Ik3p maks | 1,754 | Oppstrøms | 0,01 | 4,694 |
| Ik3p maks ende | 0,467 | Oppstrøms | 0,01 | 66,212 |
| Ik3p min | 0,126 | UPS st | 0,015 | 909,549 |
| Ik2p maks | 1,519 | Oppstrøms | 0,01 | 6,258 |
| Ik2p maks ende | 0,405 | Oppstrøms | 0,01 | 88,035 |
| Ik2p min | 0,087 | UPS lt | 17,457 | Ik < Iz |
| Ijf min | 0,087 | UPS lt | 17,457 | Ik < Iz |

Vernet løser ut jordfeilstrøm for sent i forhold til forskriftens krav til utkobling. Imidlertid vil UPS'en koble ned slik at forskriftens krav til beskyttelse mot elektrisk sjokk er tilfredsstilt.
Vernet kobler ikke ut feilstrøm levert fra UPS'en før UPS'en kobler ut.