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Directional Zone Selectivity in Low Voltage Networks

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MASTER'S THESIS

Name	Ståle Norenes
Subject	ELECTRIC POWER ENGINEERING
Title (Norw.)	**Retningsbestemt soneselektivitet i lavspentnett**
Title (English)	**Directional Zone Selectivity in Low Voltage Networks**

Background

In low voltage networks, radial network structures with circuit breakers in series are a common way to deal with the challenge of selectivity. This is an easy and well-known technique that works well for both short circuit and overload protection. In some situations it is desirable to use a ring or meshed network structure. This requires another way of thinking, as well as circuit breakers with other characteristics like bus communication and delay possibility to obtain the necessary selectivity.

Traditionally, protection in radial low voltage networks is carried out by the use of time-current based selectivity, which is challenging to use in ring and meshed networks. ABB has introduced a circuit breaker series offering directional zone selectivity, which should be a possible selectivity method to use in ring and meshed networks.

The candidate shall simulate different low voltage networks where time-current selectivity and directional zone selectivity can be used. Further research should look into how directional zone selectivity can be implemented in low voltage networks and in what manner this method can be used.

The candidate must:

- Simulate and analyze low voltage networks with the use of directional zone selectivity.
- Consider different aspects of the use of directional zone selectivity

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PREFACE

This thesis is the final work of the two-year Master's program in Electric Power Engineering for the Department of Electric Engineering at Faculty of Information Technology, Mathematics and Electrical Engineering at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway.

I would like thank my supervisor and co-supervisor, Associate Professor Eilif Hugo Hansen and Magne Holdhus in ABB AS division Low Voltage Products, for their patience, understanding and involvement. Both have played an important role and willingly answered questions and given motivation during the period for this Master's thesis. Thank you for your time and for sharing your knowledge.

I would also like to thank Alexander Klose and Anette Kyvik for proofreading the thesis, and my fellow students in Trondheim for a fabulous period of study.

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Ståle Norenes

ABSTRACT

In low voltage networks, radial network structure with circuit breakers in series and time-current selectivity are quite common to deal with the challenge of selectivity. This is an easy and well-known technique that works well for both short circuit and overload protection. In some electric installations it can be desirable to use ring or meshed network structures and in these situations the traditional time-current selectivity is not particularly suitable to use. ABB has developed the Emax 2 circuit breaker series communicating over bus or Ethernet which uses directional zone selectivity. This is a method that should be possible to use in both ring and meshed networks to achieve selectivity.

The objective in this thesis was to simulate and analyze low voltage networks with directional zone selectivity and to consider different aspects of this selectivity technique. As a part of this the communication ability for those circuit breakers was reviewed to find possible solutions for remote control in overload situations.

For this thesis, simulations of a hypothetical radial, ring and meshed network were performed. The traditional time-current selectivity method was used for the radial network, while directional zone selectivity was used as the selectivity method in the ring and the meshed network. Simulations of a hypothetical grid installation formed as a ring network in sparsely populated area with overhead lines and double feeding source were also performed.

Simulations showed that it was possible to achieve selectivity in ring and meshed networks with the use of directional zone selectivity. When these network types and directional zone selectivity were combined, higher reliability in the installation was achieved. Because of the circuit breakers' characteristic, it was most appropriate to use directional zone selectivity in the main distribution system of an electric installation or in the grid.

To plan and design an installation with directional zone selectivity was experienced as more demanding compared to the traditional time-current selectivity. The complexity of the directional zone selectivity was increased with an increasing number of circuit breakers and the size of the electric installation. Currently there are few facilities that use directional zone selectivity, which means that experience with this selectivity method is limited.

It is concluded that directional zone selectivity can be a possible solution for future use in low voltage networks, both for electric installations and in the grid. It is especially suitable for use in large electric installations at the main distribution level for electric power when ring or

meshed network structures are being considered. The communication ability adds a new dimension for control of low voltage networks where an external control device can be used for remote load shedding in overload situations, remotely read out of measurements from the circuit breakers or be programmed with advanced customized functions.

SAMMENDRAG

I lavspenningsnettet er det vanlig å bruke radielle nettstrukturer med effektbrytere i serie og tid-strøm selektivitet for å oppnå selektivitet. Dette er en enkel og velkjent metode som fungerer godt, både i kortslutnings- og overstrømsområde til vernene. I noen elektriske installasjoner kan det være ønskelig å anvende ring eller masket nettstruktur, og i slike situasjoner er ikke tid-strøm selektivitet egent bruk på samme måte. ABB har utviklet effektbryter serien Emax 2 som kommuniserer over bus eller Ethernet og som bruker retningsbestemt soneselektivitet. Denne metoden skal kunne benyttes både i ring og masket nett for å oppnå selektivitet.

Målet i denne masteroppgaven var å simulere og analysere ulike lavspentnett hvor en brukte retningsbestemt soneselektivitet og vurdere ulike aspekter ved denne selektivitetsteknikken. Det ble også sett på hvordan kommunikasjonsmuligheter i disse effektbryterne kunne brukes for å løse eventuelle overbelastningssituasjoner ved fjernstyrt inn- og utkobling av laster.

Det ble utført simuleringer i et tenkt radielt, ring og masket nett. Tradisjonell tid-strøm selektivitet ble anvendt i det radielle nettet, mens retningsbestemt soneselektivitet ble brukt i ring og maske nettet. Det ble også utført simuleringer i et tenkt lavspent distribusjonsnett med luftlinjer koblet i ring og med mating fra to sider.

Simuleringene viste at det var mulig å oppnå selektivitet i både ring og masket nett ved bruk av retningsbestemt soneselektivitet. Når disse topologiene og retningsbestemt soneselektivitet ble kombinert, oppnådde en høyere leveringspålitelighet ved feil i installasjonen. På grunn av effektbryternes egenskaper og design var det mest aktuelt å bruke retningsbestemt soneselektivitet i hoveddistribusjons-systemet i en installasjon eller i det lavspente distribusjonsnettet.

Planlegging og design av installasjoner med retningsbestemt soneselektivitet ble opplevd som mer krevende i forhold til den tradisjonelle tid-strøm selektivitetsmetoden. Kompleksiteten med retningsbestemt soneselektivitet økte med et økende antall effektbrytere og størrelsen på den elektriske installasjonen. Det er foreløpig få anlegg hvor retningsbestemt soneselektivitet er brukt, noe som betyr at det er begrenset erfaringer med denne metoden.

Det konkluderes med at retningsbestemt soneselektivitet kan være en mulig løsning for fremtidig bruk i lavspentnett, både i elektriske installasjoner og i fordelingsnettet. Det er spesielt godt egnet i store elektriske installasjoner på hovedfordelingsnivå når ring eller

masket nett vurderes brukt. Kommunikasjonsmulighetene til effektbryterne tilfører en ny dimensjon for kontroll i lavspente nettverk. En ekstern kontroll enhet kan brukes til fjernstyrt last på/avslag i overbelastningssituasjoner, fjernavlesing av måledata fra effektbryterne eller programmeres med avanserte tilpassede funksjoner.

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1 INTRODUCTION

In low voltage networks, radial network structures with circuit breakers in series are a common way to deal with the challenge of selectivity. This is an easy and well-known technique that works well for both short circuit and overload protection. In some situations it is desirable to use a ring or meshed network structure. This requires another way of thinking, as well as circuit breakers with other characteristics like bus communication and delay possibility, to obtain the necessary selectivity.

Traditionally, protection in radial low voltage networks is carried out by the use of time-current based selectivity, which is challenging to use in ring and meshed networks. ABB has introduced a circuit breaker series offering directional zone selectivity, which should be a possible selectivity method to use in ring and meshed networks.

This thesis will look into different low voltage networks with radial, ring and meshed structures where traditional time-current selectivity and directional zone selectivity will be used. The objective will be held against how directional zone selectivity can be used in low voltage networks, and how these circuit breakers with communication ability can be set to cooperate with an external control device to achieve higher control in low voltage installations.

2 TOPOLOGIES FOR LOW VOLTAGE NETWORKS

2.1 GENERAL

There are many solutions and types of topologies when it comes to how to build up an electrical installation. During the planning phase, different topologies must be evaluated and the most techno-economical solution should be chosen. Important points to consider in selection of the correct type of topology can be [1, 2]:

- Type of building
- Range of use and structure of the building
- Local conditions
- Regulations from authorities or requirements from utility company

Together with the specification and needs for the customer like [1, 2]:

- Load type, dimension and localization
- Voltage level and type of distributing system
- Internal generation, UPS and safety supply

This makes the basis for the correct selection of the topology for the installation. This chapter will briefly introduce different topologies with their respective pros and cons.

2.2 RADIAL NETWORK

The radial network is one of the most common topologies in low voltage networks. It is widely used in building installations, the low voltage grid, industry, hospitals etc. and the topology is based upon a structure where the main distribution board is at the highest level in the hierarchy followed by sub-distribution boards and general loads. There are many opportunities in how to build up a radial network. It is easy to achieve good selectivity in this kind of network because the fuses or circuit breakers are in series, making it easy to split up the protection in different order of size by looking into the fuses' or circuit breakers' time-current characteristics. By selecting different time-current characteristics for the different levels in the hierarchy, a reliable installation is achieved [1, 2].

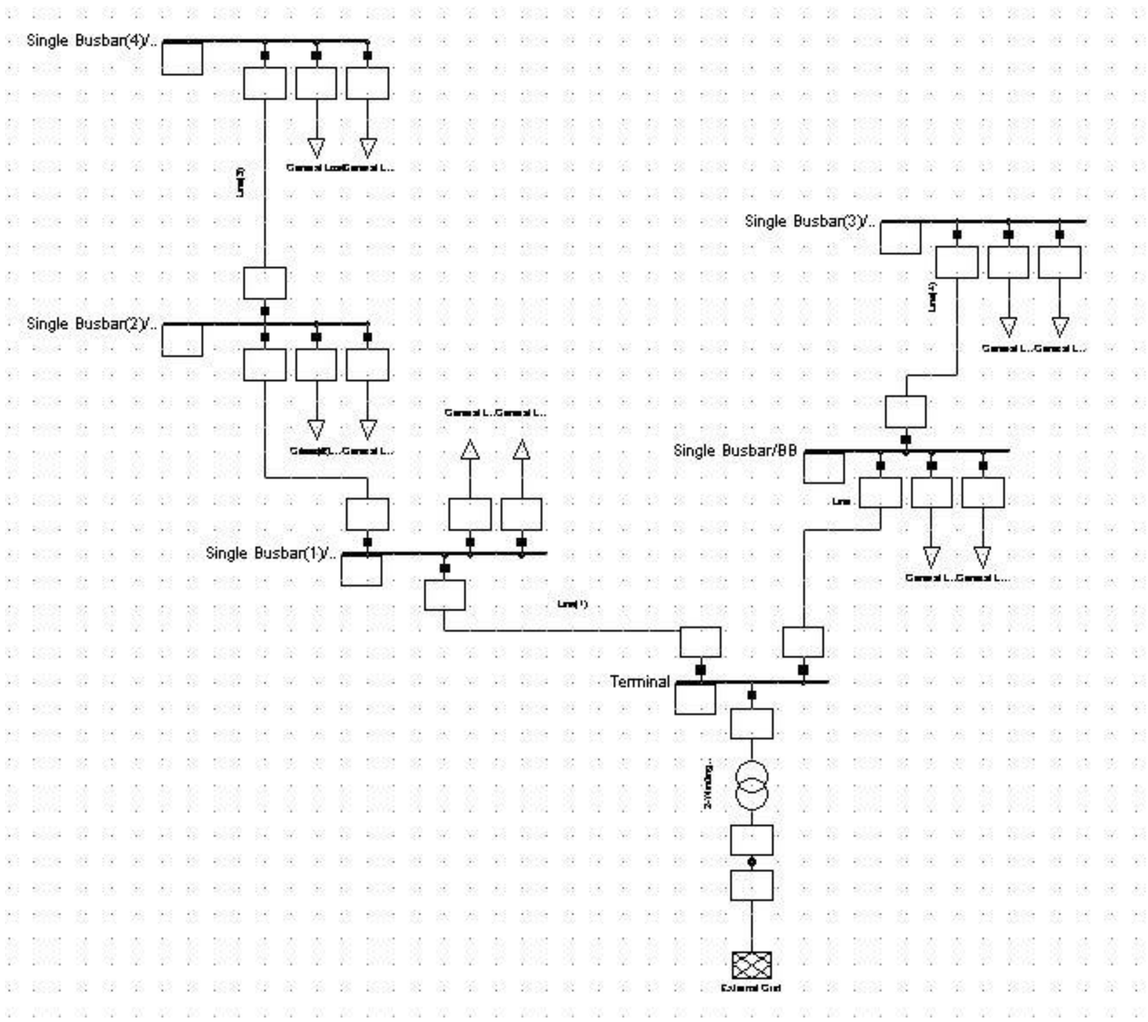

Figure 1 - Example of a radial network

2.3 RING NETWORK

Ring network is a system topology more used at higher voltage levels in for example the high voltage distribution systems. This kind of topology has some benefits compared to a radial network. Under normal conditions it gives higher regularity in the supply of power and more opportunities because of many switching possibilities. The load on the different cables or bus bars will also split up and contribute to a lesser load on each of the cables or busways and lower voltage drop in the whole system. When a fault occurs, this kind of network has the ability to reverse or send the power flow in a different direction to achieve a minimum of interruption on the total system. Drawbacks with this system are complicated relay solutions and control systems, more cabling and circuit breakers which increases the total investment cost [2, 3].

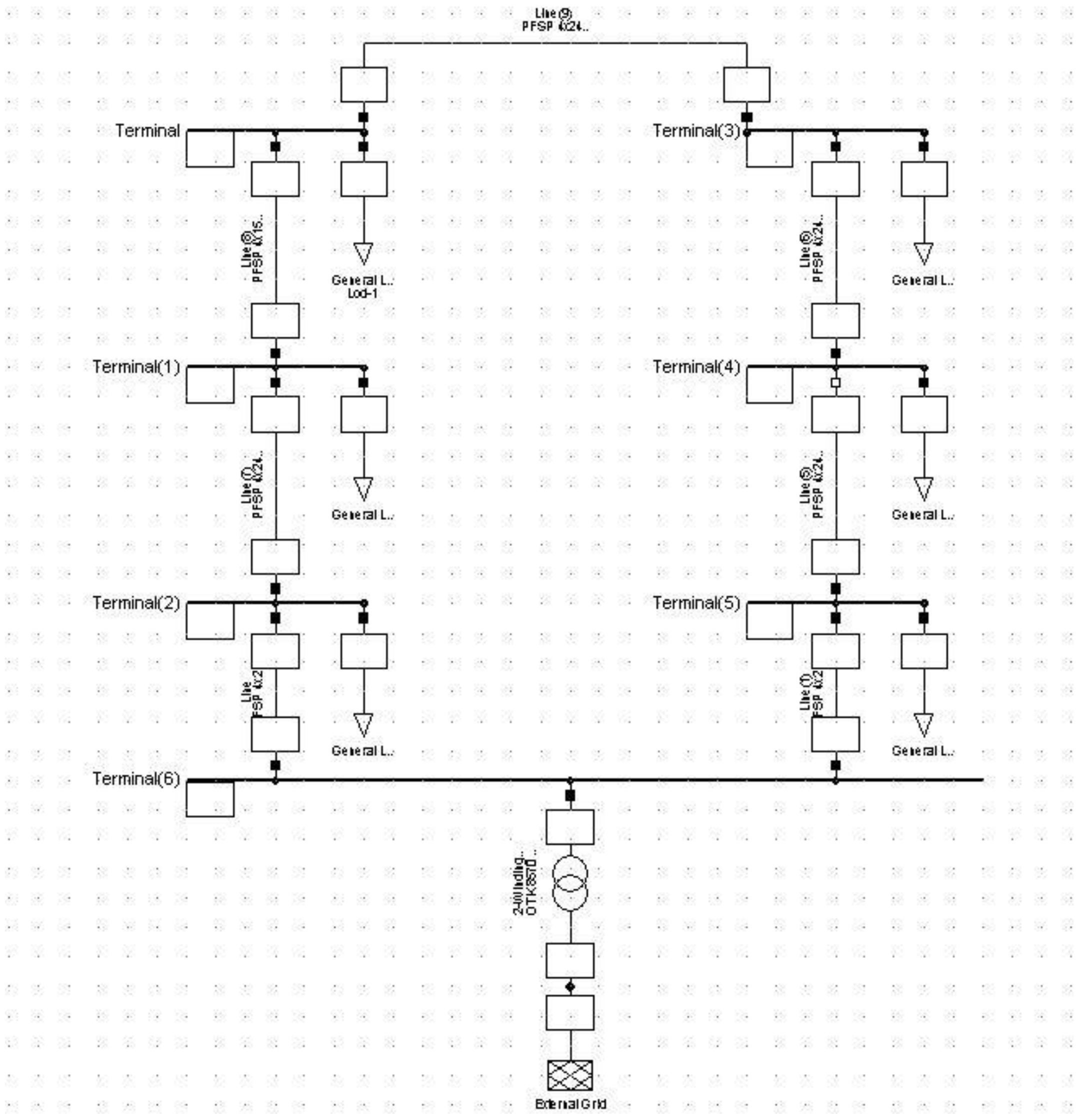

Figure 2 - Example of a ring network

2.4 MESHED NETWORK

The meshed network topology is a development of the ring network where additional connections between the main distribution board or sub-distribution boards in addition to the ring connection are included. It can be seen as a network consisting of many rings connected together into one network and it can be a good network for use in larger electrical installation and in the low voltage distribution network. Meshed networks have great advantage since it is possible to build a network with low losses, low voltage drop and good current distribution, but because of all the connections and routes in the network, protection of the network is challenging [1-3].

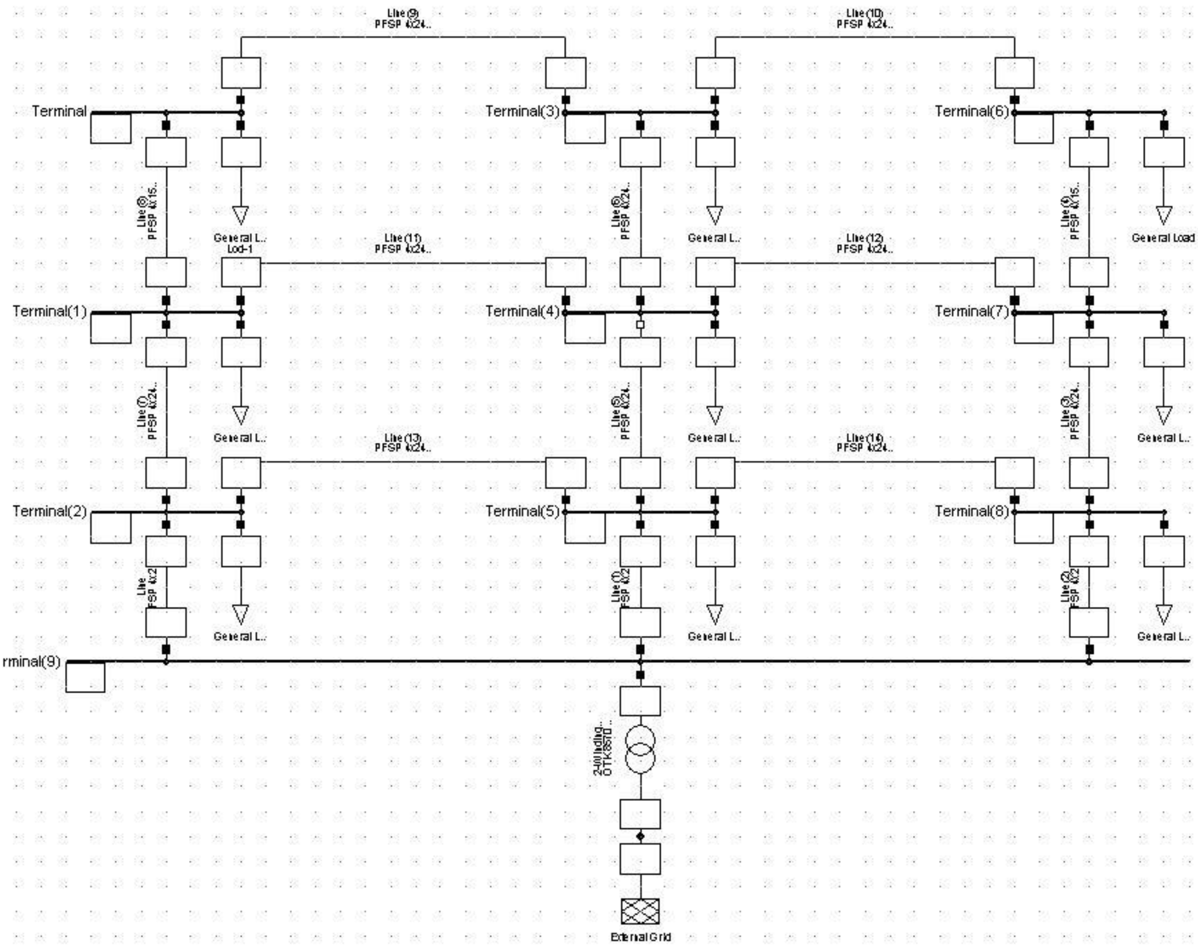

Figure 3 - Example of a meshed network

3 Protection and Selectivity Techniques

3.1 Protection and Selectivity in Electric Installations

A protection system in electrical installations is necessary to guarantee correct functional service, reduce problems caused by abnormal situations, minimize the consequences of faults and repairs and ensure safety for personnel [4, 5].

Some of the most important tasks for a good designed protection system are to perceive what happens and where, and it should be able to discern different situations in different locations to avoid unwanted trips. When there is a fault the most important task is to act rapidly to limit the damage of the system, and secure the power supply for the rest of the installation [5].

The protection device has three main tasks to handle: protection against overload, short circuits and personnel safety. Overload is typically a current from I_n for the protection device up to 8-10 times the I_n, while short circuits are a current typically > 8-10 times the I_n for the device. Personnel safety is achieved by the opportunity to disconnect and separate the installation with the protection device to make sure parts or the whole system is without voltage [4, 5].

Selectivity of protection is in the IEC standard defined as “the ability of a protection to identify the faulty section and/or phase(s) of a power system” [6]. Selectivity can be divided into two categories; total selectivity and partial selectivity. Total selectivity is when the protection device nearest the fault carries out the protection without making other devices trip. Partial selectivity is when the protection device nearest the fault can protect up to a given level of a short circuit or overcurrent but needs backup protection from a device higher in the protection hierarchy to disconnect the fault [5]. If a protection system has good selectivity it is able to isolate the faulty item only and at the same time guarantee stability for the rest of the installation by leaving healthy circuits intact. It should be sensitive as well to detect the smallest faults and when any fault occurs it should operate with as high speed as possible to minimize damage and ensure personnel safety [4].

There are several techniques to get the necessary selectivity where different requirements decide which technique is most suitable in the particular situation. This chapter will later review different techniques for selectivity.

3.2 TIME-CURRENT SELECTIVITY IN THE OVERLOAD ZONE

To protect against overloads, it is normal to use a thermal release or a similar function for electronic releases. An overload trip characteristic looks into the currents' size and when it exceeds the I_n of the protection device it starts to influence the thermal release function. The more the current increases, the trip time of the device decreases. This kind of technique is called time-current selectivity. Selectivity of protection devices in series is set by looking into the time-current plot and making sure that the plots are not entangled [5].

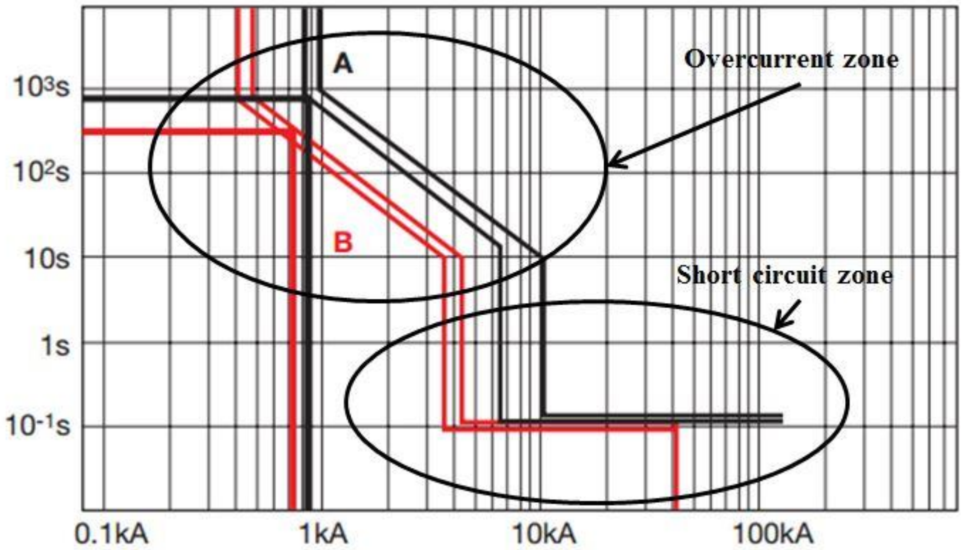

Figure 4 - Time-current selectivity in the overload zone [5]

3.3 CURRENT AND TIME SELECTIVITY IN THE SHORT CIRCUIT ZONE

Current selectivity is one of the most used types of techniques in low voltage networks and is based upon the difference in the short circuit current due to the distance from the power source. Close to the source the short circuit current will be high and it will decrease when the distance increases because of the impedance in cables and busways. By choosing different circuit breakers with different instantaneous protection current values it is possible to achieve the correct selectivity. The most standard way to study this kind of selectivity is to look into the circuit breakers' time-current plot [5].

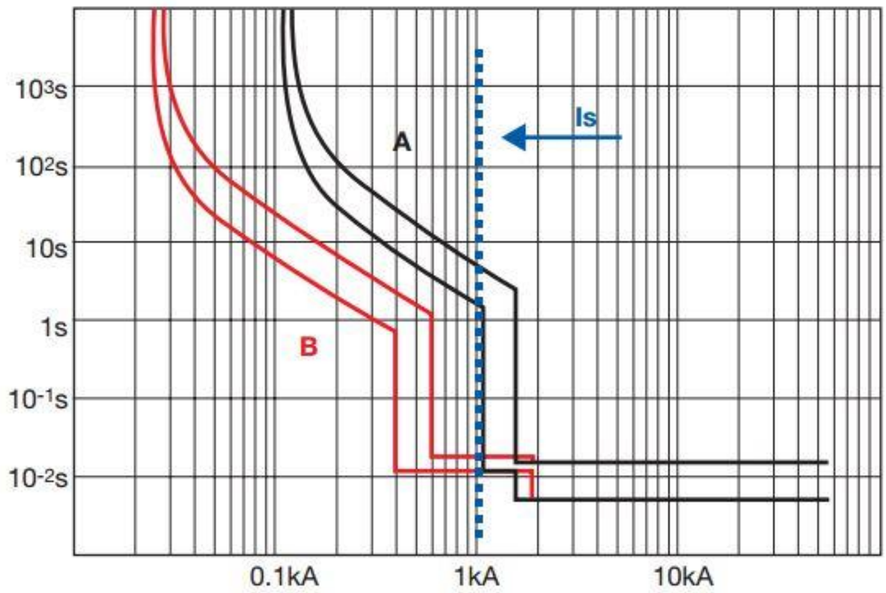

Figure 5 - Current selectivity in the short circuit zone [5]

An evolution of the current selectivity resulted in the time selectivity. It is based on the same principle as the current selectivity with the difference in the short circuit current according to the length from the source. The main difference from current selectivity is the added time or delay for each of the devices. When the circuit breaker sees a short circuit current it waits a specific time or delays before it starts the trip action. This technique's strategy is to increase the trip delay as one gets closer to the source and gives the device nearest the fault or at the correct hierarchy level the opportunity to trip first [5].

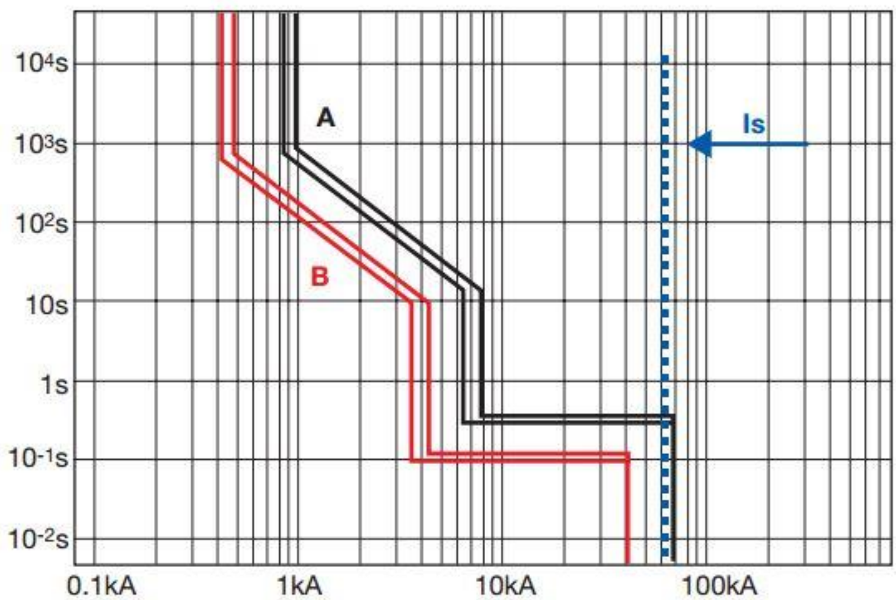

Figure 6 - Time selectivity in the short circuit zone [5]

3.4 ZONE SELECTIVITY

This kind of selectivity is based on coordination between installed protection devices. By a dialogue between all the devices, either via a supervision system or by blocking signals, it is decided which one of the devices should trip first. The communication between the devices makes it possible to identify the faulty zone and disconnect it from power source. One of the greatest benefits compared with traditional coordination between protection devices is that there is no need for intentional delay as one move towards the power source. It is only necessary to include a little time delay to make sure the processing of the signals from the devices can be understood and communicated to other parts of the system. This makes it possible to reduce the trip time to a minimum, reduce the damage caused by the fault, reduce the thermal and dynamic stresses and give a high number of selectivity levels. The disadvantage is the requirement of auxiliary power supply for each device, higher cost and more complexity. This type of selectivity is suitable for radial networks, and if the directional protection is added it can be suitable for ring and meshed networks as well [5].

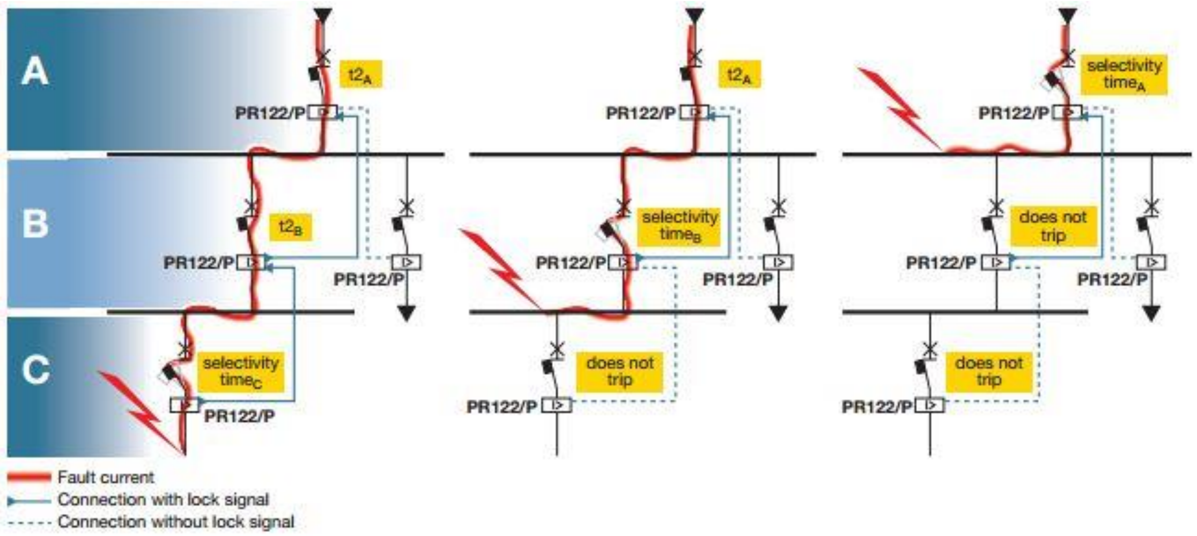

Figure 7 - Zone selectivity principle diagram [5]

3.5 Directional Zone Selectivity

Directional zone selectivity is an extra opportunity offered in circuit breakers with electronic release. By a combination of the zone selectivity and directional protection, the directional zone selectivity is made possible. The advantage of circuit breakers offering directional zone selectivity is that they can identify the fault currents direction by use of internal voltage and current measurements. This makes it possible for the circuit breaker to trip in different times accordingly to block signals and the direction of the fault current. The directional zone function makes this circuit breaker especially good for ring and meshed networks, networks with more than one power supply and bus tie systems. An auxiliary power supply is required to operate the directional zone selectivity function[5, 7].

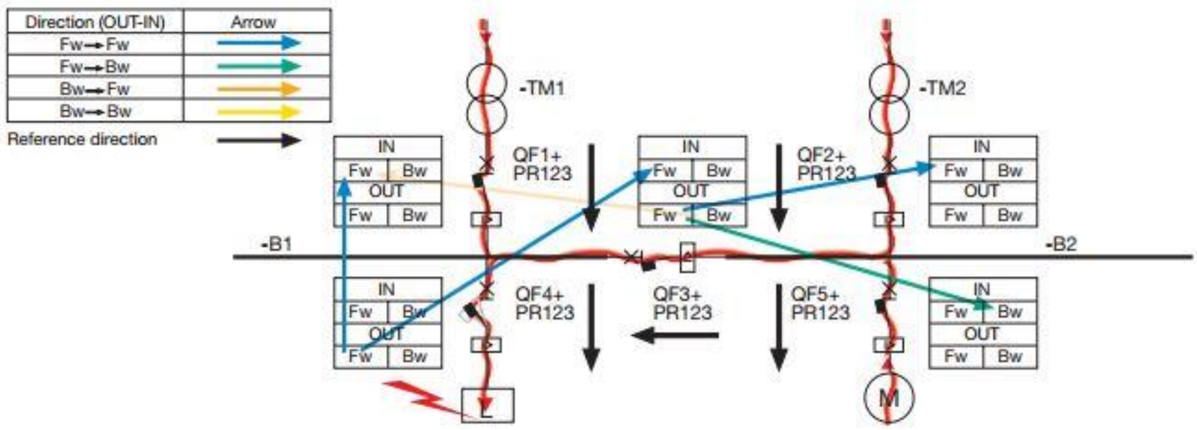

Figure 8 - Directional zone selectivity [5]

3.6 CRITERIA FOR LOW VOLTAGE PROTECTION

In the international IEC standards for electrical installations there are serval requirements for circuit breakers and the design of the network for how to deal with short circuits and overload situations. This chapter will give a brief overview of the most general requirements based on the Norwegian standard for low voltage installations NEK 400:2014 [8].

The general descriptions for protection against electrical shock are found in section 410 in NEK 400:2014. This section describes how the interaction between devices and equipment has to be in order to prevent humans and pets from electrical shock. The definition of electrical shock is, according to 203.1, "physiological effect resulting from an electric current passing through a human or animal body" while the definition for protection against electrical shock is per definition as described in 203.2, "provision of measures reducing the risk of electric shock".

In sections 411, 412, 413 and 415 in NEK 400:2014 different protection methods are described, but there will only be a brief introduction to section 411 which is the most relevant protection method for the networks discussed later in this thesis. In addition there will also be a brief introduction to sections 433 and 434, which describe requirements for short circuit and overload protection. Supplementary information about requirements and rules can be found by reading NEK 400:2014.

Section 411 gives requirements and rules about automatic disconnection of the power supply. All the equipment in an installation must be grounded to protective earth potential as specified for the different distribution system and all circuits must have a protective conductor in connection with the earth bus. A circuit breaker must disconnect if a fault occurs in the system, for consumers circuits ≤ 32 A, within a given time described in Table 41A in NEK 400:2014 partly quoted under in Table 1.

Table 1 – Maximum disconnection time for circuit breakers [8]

System	120 V< $U_o \leq 230$ V [s]	230 V < $U_0 \leq 400$ V [s]	$U_0 > 400$ V [s]
	AC	AC	AC
TN	0.4	0.2	0.1
IT	0.4	0.3	0.04
TT	0.2	0.07	0.1

A disconnection time up to 5 s is allowed for TN systems and up to 1 s for TT systems if the circuit is a part of the main distribution system and as long as it not a consumer circuit ≤ 32 A [8].

3.6.1 *Overload Protection*

According to 433 in NEK 400:2014 there are two main requirements for the characteristics of a protection device that protects against overload current:

$$I_b \leq I_n \leq I_z \qquad \textbf{Eq. 3.1}$$

$$I_2 \leq 1.45\, I_z \qquad \textbf{Eq. 3.2}$$

I_b = designing load current

I_z = current-carrying capacity for cable in normal situations

I_n = nominal current for the circuit breaker

I_2 = current that guarantees disconnection of the circuit breaker within a definite time, the value is given by the manufacturer

The rule is mainly to use an overload protecting device in front of every change in; cross section, method of installation etc. that changes the current-carrying capacity. It allows one overload protection device for parallel connected conductors, and there are not any special regulations for the use of ring networks as long as the main rules are followed.

3.6.2 *Short Circuit Protection*

According to 434 in NEK 400:2014, the short circuit current must be determined for relevant positions either via calculations or measurements. Protection devices against short circuit normally must be placed before each conductor and give protection for the whole length, but if special rules are followed the short circuit protection device can be excluded or placed in another way.

The short circuit protection device must normally be able to disconnect the highest short circuit current that can arise where it is installed if special rules are not followed. The protection device must protect cables and conductors from being damaged by temperature due to a short circuit and disconnect before allowed temperature for the insulation is reached. This can be fulfilled by following the equation [8]:

$$I^2 t \leq k^2 S^2, t < 0.1\ s \qquad \textbf{Eq. 3.3}$$

$$t = \frac{k^2 S^2}{I^2}, 0.1\ s < t < 5\ s \qquad \textbf{Eq. 3.4}$$

t = duration in seconds

S = cross section in mm^2

I = RMS value of the short circuit current in amp

k = specific material constant

The first equation says that the energy let through the protection device during a short circuit, I^2t, must be smaller than the cables k^2S^2, which is the indicator for the energy needed to warm up the cable to the temperature limit. The equation is valid when the protection device uses less than 0.1 s to disconnect the short circuit. The value for I^2t is given by the manufacture of the protection device [8].

The second equation returns the time it takes to warm up the cable from the highest allowed working temperature to the temperature limit when there is a short circuit and gives a time in seconds which tells the necessary speed of operation for the protection device [8].

4 DISTRIBUTION NETWORKS AND FAULT CURRENT CALCULATION

4.1 IT NETWORK

Characteristic for this network type is the system earthing where the transformers' neutral point is isolated with large impedance from earth and exposed-conductive-parts in the electric installation is earthed independent from system earth. Normally the system operates with 230 V line voltages and connected single phase loads are connected between two of the phases. Because of the system earthing, the fault currents by earth faults will be small since the return path for the fault current is through the systems capacitances against earth. IT-network is often considered used when disconnection of the power supply are critical since this network type can, due to the low contact voltage, be operated with one standing earth fault[1, 9, 10].

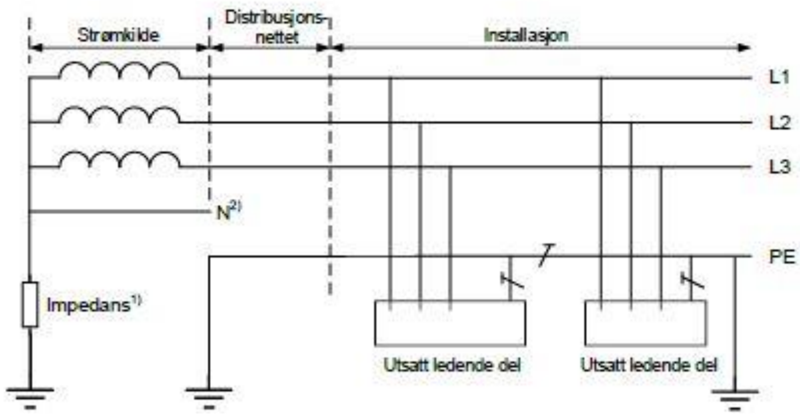

Figure 9 - IT-network [9]

4.2 TN-C-S NETWORK

Characteristic for this network is the transformers directly earthed neutral point and exposed-conductive-parts in the electric installation are earthed and in direct connection with system earth. In the utility company's distribution network, the network is operated with common earth and neutral conductor as a TN-C network. In the transition between the utility company and the customers, earth and neutral conductors are split and then operated as a TN-S network. Normally the network is operated with 400 V line voltages and 230 V is available by connecting single phase loads between one phase and neutral. This network structure is the most used in Europe and the use of this network is also increasing in Norway. The system is directly earthed and the transformers neutral is in connection with exposed-conductive-parts in the electric installation, this causes a low impedance connection resulting in large short circuit currents by earth faults [1, 9, 10].

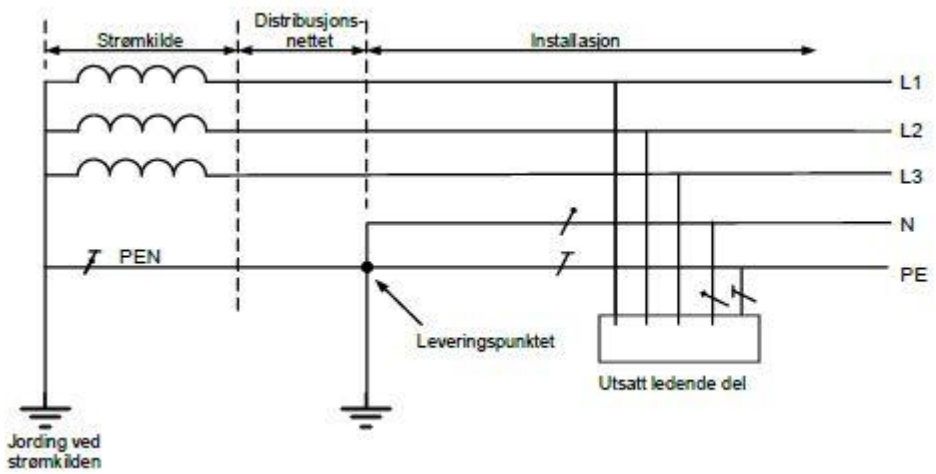

Figure 10 - TN-C-S network [9]

4.3 FAULT SITUATIONS

When the short circuit current must be calculated there are in general two values of special interest [10, 11]:

- The largest short circuit current noted as I_{k3pmax}. This is the largest short circuit current that can arise when a 3-phase symmetrical short circuit occurs. This is in general the value which determines the breaking capacity or rating for the electrical equipment used in installations.
- The smallest short circuit current noted as I_{k2pmin} for IT-networks and I_{k1pmin} for TN-networks or with the common term as just I_{kmin}. This is in general the value deciding circuit breakers or other protection unit settings.

4.3.1 3-PHASE SHORT CIRCUIT

This is a short circuit where all of the three phases are included and the fault current floats in all phases. This fault can occur in all network types as long it is a 3-phase system [9, 10].

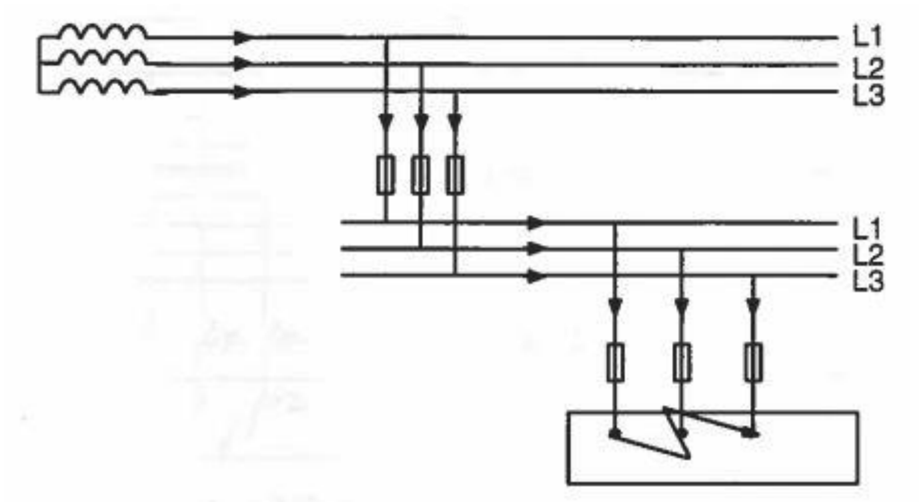

Figure 11 - 3-phase short circuit [9]

4.3.2 2-PHASE SHORT CIRCUIT

This is a short circuit between two phases where the fault current floats in both of the affected phases. This type of short circuit can arise in both IT- and TN-networks [9, 10].

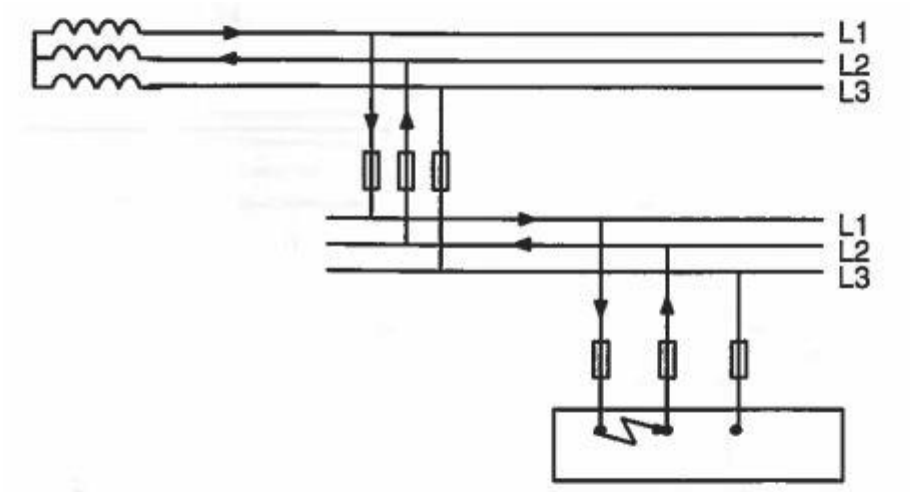

Figure 12 - 2-phase short circuit [9]

4.3.3 1-PHASE SHORT CIRCUIT BETWEEN PHASE AND NEUTRAL

A short circuit that arises between the phase and the neutral conductor where the short circuit current is mainly determined by the conductors and the neutral conductor cross section and length. This fault arises in TN-networks only [9, 10].

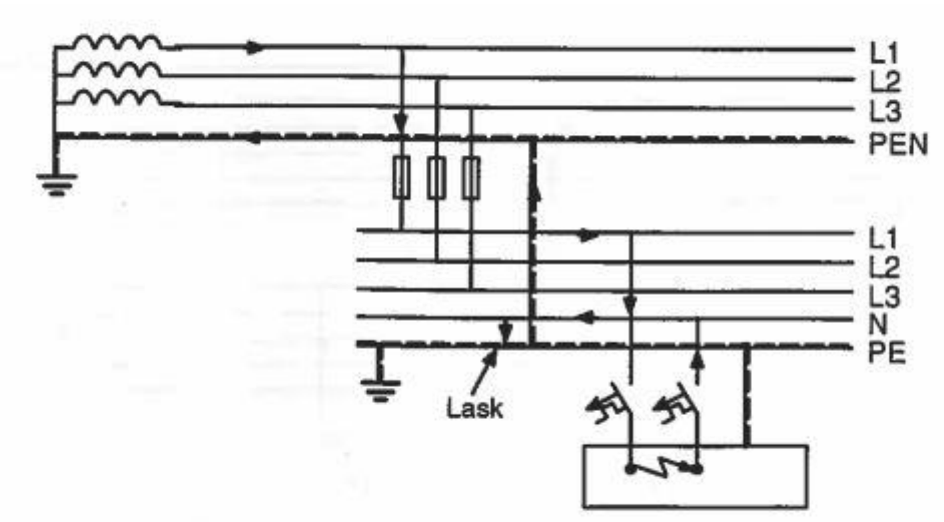

Figure 13 - 1-phase to neutral short circuit in a TN-network [9]

4.3.4 1-PHASE SHORT CIRCUIT BETWEEN PHASE AND EARTH

This is a short circuit between one of the phases and earth and can occur in both IT- and TN-networks. In an IT-network the systems capacitances against earth will be the main path for the short circuit current while in the TN-network the earth conductor is the return path for the short circuit current [9, 10].

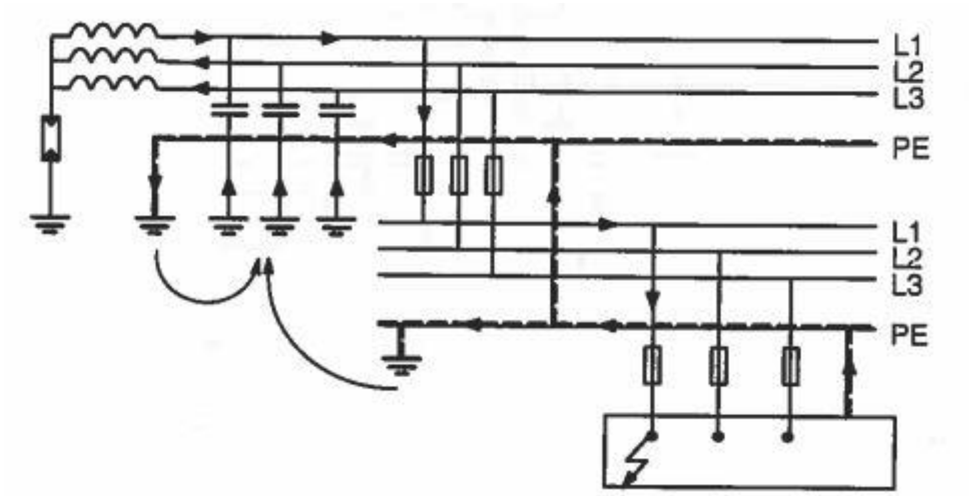

Figure 14 - 1-phase short circuit between phase and earth [9]

4.3.5 OTHER FAULTS THAT CAN OCCUR

In addition are there other faults that can occur in both network system [9, 10]:

- 2-phase short circuit against earth
- Double short circuit against earth at different places in the same transformer circuit
- Short circuit between neutral and earth
- Fracture in the neutral conductor

These failures are not the most common ones and are not a part of the main parameters for setting and choosing circuit breakers.

4.4 DETERMINING THE SHORT CIRCUIT CURRENT

When short circuit currents are to be determined, the method described in the international standard EN 60909-0 is used. This standard is accepted for calculation of short circuit currents in low voltage three phase AC systems with a system frequency at 50 or 60 Hz where the main focus is to determine I_{k3pmax} and I_{kmin} [10, 11].

When the short circuit currents are to be determined, the standard makes some assumptions where the main assumptions are [10, 11]:

- When a short circuit arises there is no change in the type of the short circuit during the situation that is going to be simulated / calculated
- The network involved in the short circuit is always the same and is not changing
- Transformers tap changers are in the main position
- Arc resistance is neglected
- Line capacitances, shunt admittances and non-rotating loads are neglected except for calculations in zero sequence

The standard uses a method with symmetrical components for calculating the short circuit currents. It is done by putting in an equivalent voltage source at the fault location as the only active voltage source. In addition all components are represented with an internal impedance, which is an impedance that is transformed to the correct voltage level for the calculation [10, 11].

The symmetrical system is divided into three components which are [10, 11]:

- Positive sequence
- Negative sequence
- Zero sequence

If the symmetrical system is derived it will lead to the formulas for the different short circuit currents representative for the different fault situations [1, 9-11]:

Three phase short circuit: $$I_{k3pmax} = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_k}$$ **[Eq. 4.1]**

Two phase short circuit: $$I_{k2pmin} = \frac{c \cdot U_n}{Z_+ + Z_-}$$ **[Eq. 4.2]**

Single phase short circuit: $$I_{k1pmin} = \frac{c \cdot U_n}{Z_+ + Z_- + Z_N}$$ **[Eq. 4.3]**

Single phase short circuit to earth: $$I_{k1pmin} = -\frac{c \cdot \sqrt{3} \cdot U_n}{Z_+ + Z_- + Z_0}$$ **[Eq. 4.4]**

In the formulas factor “c” has been used. This is a voltage factor defined in the standard as a voltage deviation that can occur in a low voltage system. The factor is either a 5 or 10 % factor used in the calculation for the smallest and largest short circuit current [1, 10, 11].

Table 2 - Voltage factor [11]

Nominal voltage	Voltage factor “c” for calculating	
	Largest short circuit current	Smallest short circuit current
Low voltage 100 -1000 V	1.05	0.95
Medium voltage >1 – 35 kV	1.10	1.00
High voltage >35 kV	1.10	1.00

5 ABB SACE Emax 2 Series

The ABB SACE Emax series of air circuit breakers was introduced to the market some years ago and the second generation has been introduced as the ABB SACE Emax 2 offering new opportunities for efficiency and control for low voltage networks. The circuit breaker is delivered in four different sizes covering nominal currents from 100 to 6300 A with breaking capacity from 42 to 200 kA depending on the configuration. As long as the sizing of the circuit breakers is the same it is possible to increase or decrease the nominal current of the circuit breaker just by changing the I_n module without changing it completely. By changing the rating plug of the smallest version it is possible to get I_n down to 100 A. The same principle is given to the rest of the features in the Emax 2 series; by just adding modules or plugs to the breaker it is possible to outfit it with communication, measurement, actuators etc. [12].

The series is divided into two main versions which are the Ekip Touch and the Ekip Hi-Touch version. Hi-Touch is delivered with an advanced network analyzer which monitors phenomena like voltage dips and harmonics without any additional equipment. The Hi-Touch version is also the only version offering the opportunity for directional zone selectivity. There are two versions designed especially for generator protection, called Ekip Touch G and Ekip Hi-Touch G. These versions have in addition dedicated generator protection functionality to take care of, for example, over and under frequencies, voltage unbalance, under and over voltage, start-up function and etc. [12].

Figure 15 - ABB SACE Emax 2 Touch [13]

5.1 BLOCKING AND SIGNALING

The Emax 2 Hi-Touch series can use zone and directional zone selectivity. Both selectivity techniques are based upon communication of blocking signals to other devices in the system by signaling through hard wiring, bus or Ethernet communication. The difference between zone and directional zone selectivity is the directional functionality which can identify the direction of the fault current compared with the reference direction set for the circuit breaker [5, 7].

The directional zone selectivity is based upon sending out blocking signals in the system either in the forward or backward direction. Circuit breakers first discovering the fault will start disconnecting and do this within the set selectivity time and at the same time send out blocking signals in either a forward or backward direction to the rest of the circuit breakers in the network. If the first circuit breaker for some reason fails, blocked circuit breakers will disconnect after a given time delay in accordance with the blocking signal. Thanks to this communication possibility, directional zone selectivity is a possible technique for use in low voltage ring and meshed networks and systems with more than one power source. The fastest possible breaking speed for the Emax 2 series, selectivity time also noted as t7, is 130 ms, but if needed is adjustable up to 500 ms [5, 7].

The physical blocking signal from the circuit breaker is a 0 - 24 V high / low signal. When a 24 V signal is given, the blocking is high or on, and when there is 0 V no blocking signal is sent out of the circuit breaker. This is the same for both forward and backward blocking signals [14].

5.1.1 CRITERIA FOR CORRECT FUNCTION OF DIRECTIONAL ZONE SELECTIVITY

To be able to use the directional zone selectivity functionality in the circuit breakers, some criteria must be met [5]:

- Function S, I and G in the circuit breaker must be deactivated or set in a way to not interrupt the D protection
- The circuit breakers must be fitted with a 24 V auxiliary power supply
- There must be a circuit breaker of high touch version since this is the only version supporting directional zone selectivity in this series

Anywhere the circuit breaker is placed in the network, it must always be able to break the largest fault current and therefore must it satisfy [5]:

$$I_{cw} \geq I_{kmax} \qquad \textbf{Eq. 5.1}$$

The triggering current for the directional zone selectivity must satisfy the following equation to make sure circuit breakers are triggered during a fault situation [5]:

$$I_7 < I_{kmin} \qquad \textbf{Eq. 5.2}$$

The setting for the delay because of an incoming blocking signal must be set in accordance with [5]:

$$t7 > selectivty\ time + 70\ ms \qquad \textbf{Eq. 5.3}$$

This time setting is an absolute minimum and the recommendation from ABB experts is to follow [14]:

$$t7 > selectivty\ time + 100\ ms \qquad \textbf{Eq. 5.4}$$

5.2 COMMUNICATION AND CONTROL

The Emax 2 series can communicate in protocols using field bus or Ethernet network by adding a module called Ekip Com. Circuit breakers fitted with the Ekip Com module can send signals to other circuit breakers and information to control equipment based on SCADA, PLC or PC. The communication makes it possible to change the parameters and read out alarms and measurements from the circuit breakers[15].

If the circuit breaker is fitted with Ekip Com Actuator, opening and closing coil and motor for recharging of the closing spring it is possible to remotely operate it over the control system. In some situations in which it is desirable to have high reliability, for example in hospitals or industrial plants, then an extra communication module called Ekip Com Redundant can be added to the circuit breaker to give redundancy in the communication [15].

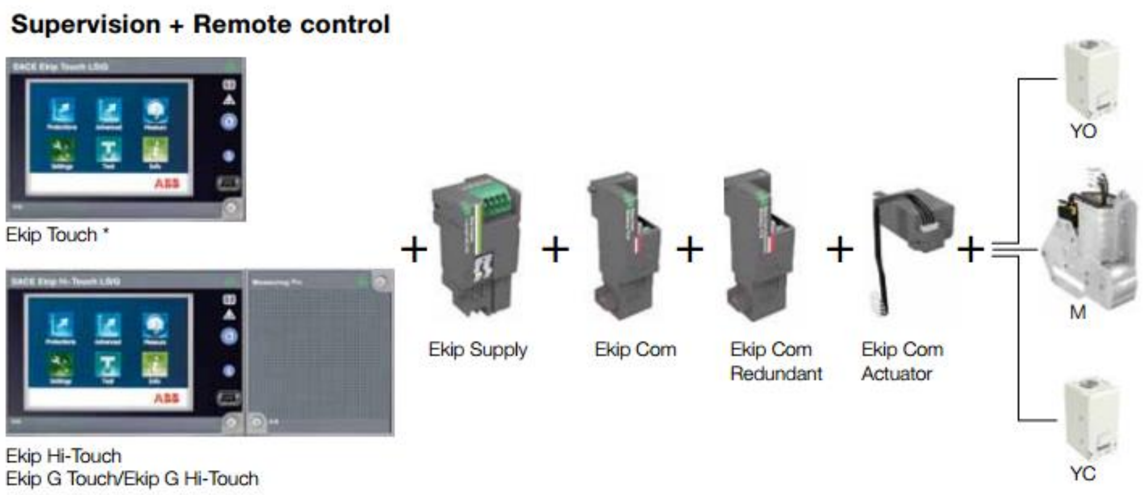

Figure 16 - Overview possible Ekip modules and remote control units [15]

5.2.1 TCP / IP COMMUNICATION

In industrial Ethernet two common protocols are the Modbus TCP and the IEC 61850. The IEC 61850 protocol is becoming more and more used in the control of electrical systems because it is designed specially with characteristics related to electrical power control. The Emax 2 series is the first low voltage circuit breaker from ABB classified as an Intelligent Electronic Device according to the standard IEC 61850. Since the Emax 2 series fulfills the IEC 61850 it can use TCP/IP telegrams over Ethernet for communication and control instead for hard-wired signals. This reduces the complexity of the signal wiring and makes it possible to communicate with other devices fulfilling the IEC 61850.

An advantage if the IEC 61850 protocol is used for communication is how the protocol can give higher priority to selected signals. During normal operation it is not necessary to transfer signals fast, but in a fault situation it is important to transfer signals with as low delay as possible. The IEC 61850 protocol handles this with event driven communication by splitting it into vertical and horizontal communication. Horizontal communication or GOOSE messaging, enables rapid transmitting of signals between different devices [15].

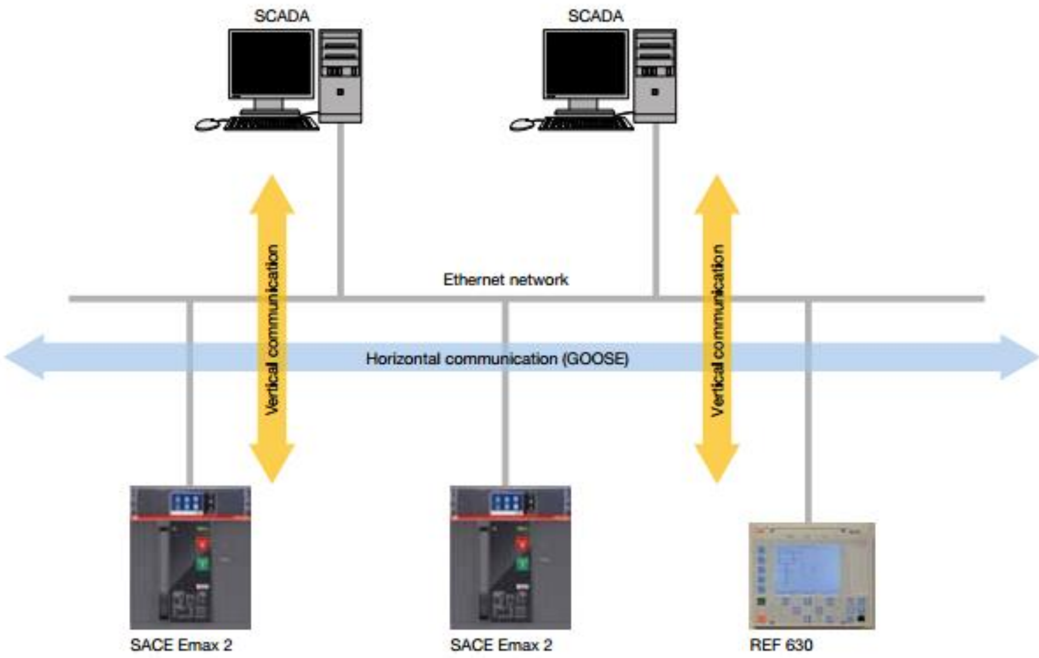

Figure 17 - Communication possibilities for the Emax 2 series [15]

All circuit breakers and the control system are simply connected together via Ethernet switches and standard Cat6 Ethernet cables with RJ 45 connectors. The maximum length from the circuit breaker to the switch is 100 m, but it is possible to use fiber optics to extend the range. It is not necessary to have an external control or supervision system connected to the circuit breakers, the circuit breakers can simply be connected together and communicate with each other after a preprogrammed mode of operation [14, 15].

Circuit breakers fitted with any Ekip Com module need in addition the Ekip Supply module to deliver 24 V for supplying Ekip Com and Ekip Actuator with auxiliary power for correct operation. If the external supply of power is missing or out of function the circuit breaker will operate as a normal circuit breaker without any of the special features like communication, remote control, zone selectivity function or directional zone selectivity functionality[14, 15].

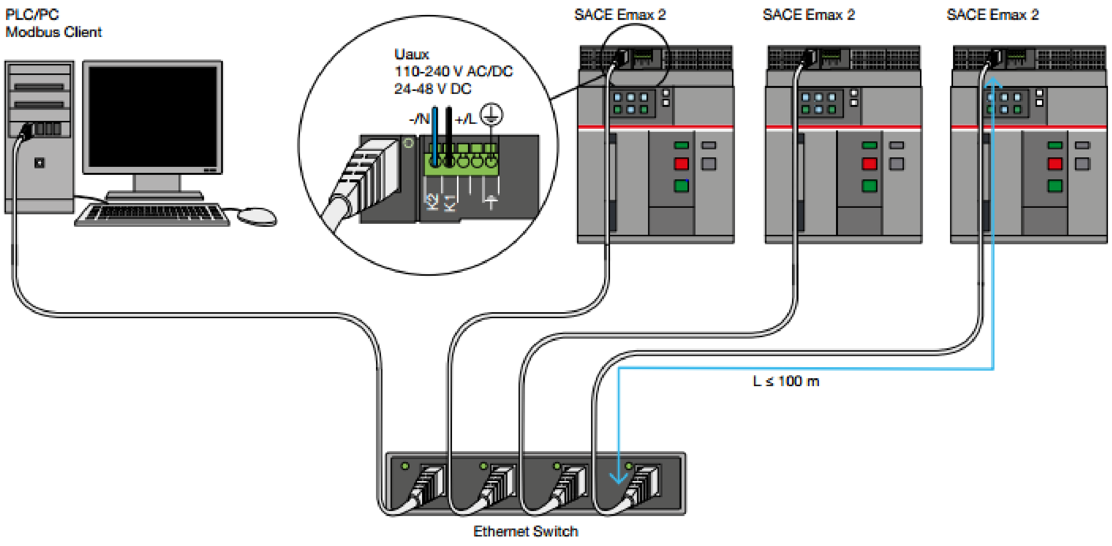

Figure 18 - TCP/IP cabling between Emax 2 series and supervision / control system [15]

6 SIMULATIONS OF LOW VOLTAGE NETWORKS

6.1 GENERAL

This part of the thesis will look into and simulate four low voltage networks, one radial network, two ring networks where one of them is double fed, and one meshed network. The radial network is the basis for one of the ring networks and the meshed network. By adding extra cables, the radial network is redesigned into a ring and a meshed network structure. The radial network will be simulated and analyzed with traditional time and current selectivity, while the ring and the meshed network will use directional zone selectivity as selectivity method. Solutions for how to handle short circuit and overload protection in ring and meshed networks with directional zone selectivity will be central. The simulations will be based on a 230/400 V TN-S network since this is the most used network structure in new large electric installations and the most used network type for that purpose in Europe.

Directional zone selectivity is offered by the Emax 2 circuit breaker and load switch series from ABB and all considerations are based upon the use of these devices. There are in addition many other possibilities offered by the use of these circuit breakers that can make a difference in the way of thinking and planning of low voltage installations. Some of these functions will be looked into and possible solutions for how to implement them in the big picture will be introduced.

The radial, ring and meshed networks simulated first in this chapter are a hypothetical part of the main distribution system in an electric installation. The reason for this is the Emax 2 series properties where the smallest nominal current is 100 A. The circuit breakers are delivered for 3-phase only which excludes them to be used for single phase consumer loads.

In the analyzing part of this thesis there are used two simulation programs which are DIgSILENT PowerFactory v 15.1 (PowerFactory) and ABB DOC v 2.0.0.0085 (DOC). PowerFactory is used for the power flow analysis where the program uses the Newton-Raphson method with power equations for solving the different power flow cases. In addition PowerFactory is used for static calculation of short circuit currents according to the IEC 60909 standard “Short circuits currents in three-phase a.c. systems”. DOC is used for selectivity analysis while time-current plots used further in this thesis are constructed in DOCs integrated functionality called “Curve”.

6.2 RADIAL NETWORK

6.2.1 DESCRIPTION OF THE RADIAL NETWORK

A radial network was designed and can be seen in Figure 19. The radial network has two risers with three sub-distribution boards connected to each of the two rising cables. In front of the network is a transformer of 1250 kVA, which is connected to a grid known as "stiff." The total demand in the system is 900 kW distributed out to six sub-distribution boards as described in Appendix B. The network is designed as a TN-S 230/400 V system with separate neutral and earth conductor. Interlinking cables between the sub-distribution boards are designed with PFSP 4x240/70 mm^2 AL cables according to the cable plan (see Appendix A). Figure 19 shows the power flow in the network in normal operation, which is the basis for all calculations and analysis.

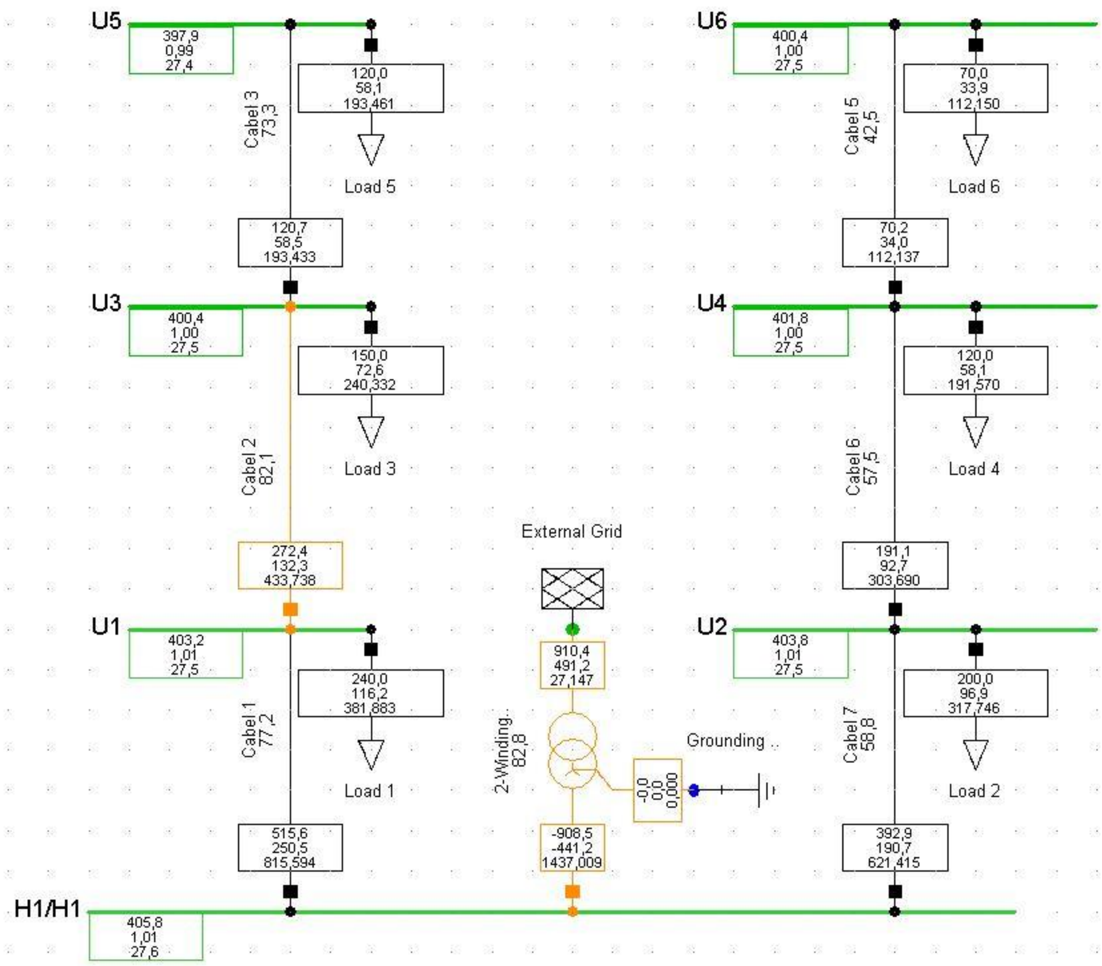

Figure 19 - Radial network

6.2.2 *Radial Network: Short Circuit and Overload Protection*

The minimum and maximum short circuit currents seen by each circuit breaker have been identified and can be seen in Table 3.

Table 3 - Short circuit currents seen by the circuit breakers

	Circuit breaker						
	H1:1 [kA]	H1:2 [kA]	H1:3 [kA]	U1:1 [kA]	U2:1 [kA]	U3:1 [kA]	U4:1 [kA]
I_{k1pmin}	31.54	24.05	24.05	14.62	14.62	7.76	7.76
I_{k3pmax}	28.38	28.38	28.38	24.95	24.95	19.28	19.28

The cable plan is the basis for setting the nominal current for the circuit breakers. Nominal current for the circuit breakers are set in accordance with the current-carrying capacity for each of the interlinking cables. All of the circuit breakers have the L functionality for overload protection and the I functionality for instantaneous short circuit protection activated. Settings for the circuit breakers can be seen in Table 4.

Table 4 - Settings and nominal current for the circuit breakers

Circuit breaker	I_n plug [A]	Y x I_n	Set I_n [A]	Delay L [s]	Setting I [x I_n]
H1:1	2000	0.725	1450	15	8.5
H1:2	1000	1	1000	10	8.5
H1:3	1000	1	1000	10	8.5
U1:1	630	0.835	526	10	7
U2:1	630	0.835	526	10	7
U3:1	400	0.65	260	10	5
U4:1	400	0.65	260	10	5

The settings for the circuit breakers are used to construct time-current and break-through energy plots for the system that can be seen in Figure 20 and Figure 21. In these plots the green area represents the main circuit breaker H1:1, the blue area represents H1:2 and H1:3, the red area represents U1:1 and U2:1 and the black area represents U3:1 and U4:1. The cable's critical level is shown in the plot and is the same color as the circuit breaker protecting it. A plot analysis shows that all cables are protected against overload and short circuits, and this network fulfills the requirements mentioned in chapter 3.6. Time-current selectivity is used as selectivity method in the overload zone while current selectivity with time delay is used as selectivity method in the short circuit zone. None of the curves in the plots are entangling each other, which means that selectivity is achieved and wanted function is obtained.

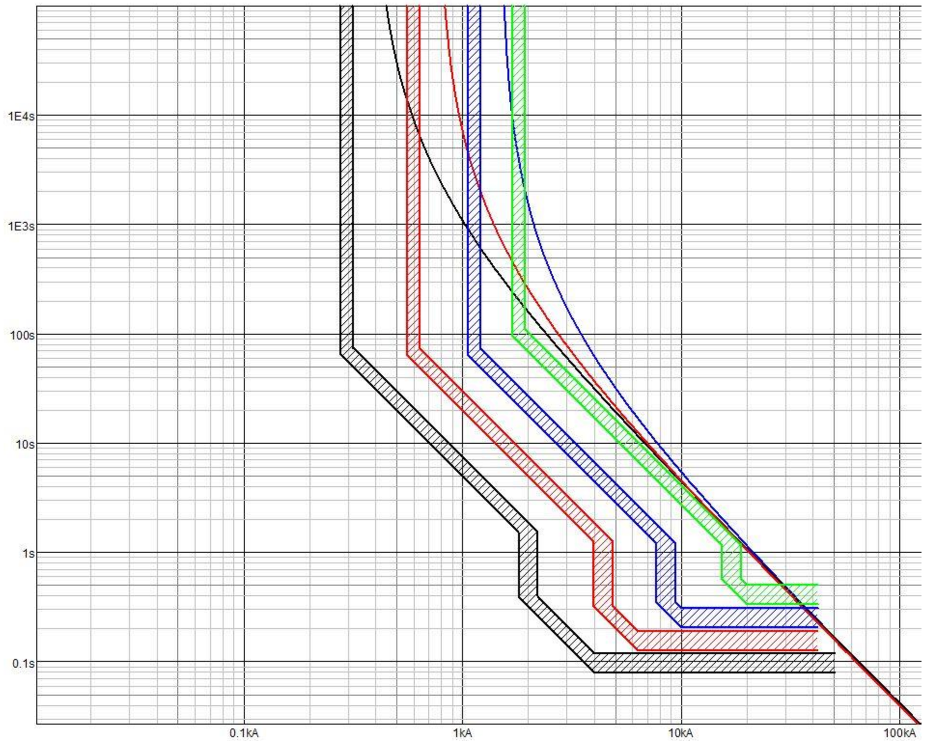

Figure 20 – Time-current plot for the radial network

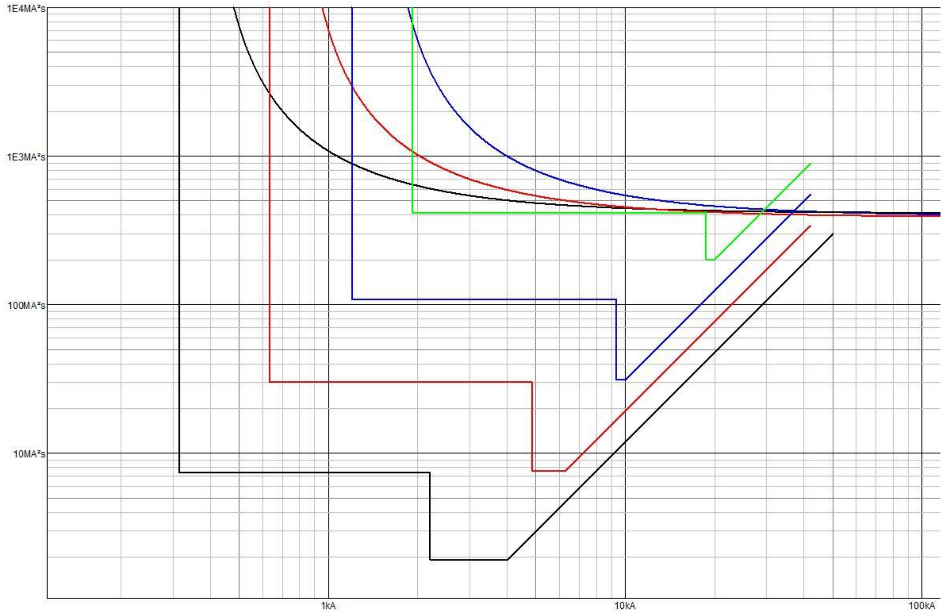

Figure 21 – Break-through energy plot for the radial network

6.3 RING NETWORK

6.3.1 DESCRIPTION OF THE RING NETWORK

The radial network has in this sub chapter been redesigned by adding cable 4 to connect the two riser cables together to form a ring network. Demand, cable lengths, transformer and network system are the same as in the radial network. Some of the interlinking cables have more cables in parallel due to the challenge of getting high enough short circuit currents in some of the fault situations. Cable plan and lengths, system description and power flow for different situations can be found in Appendix B.

The ring network can be seen in Figure 22 and may represent the main distribution network in a hospital, small industrial plant or an office building. Figure 22 shows the ring network in normal operation, which is the basis for all calculations and analysis.

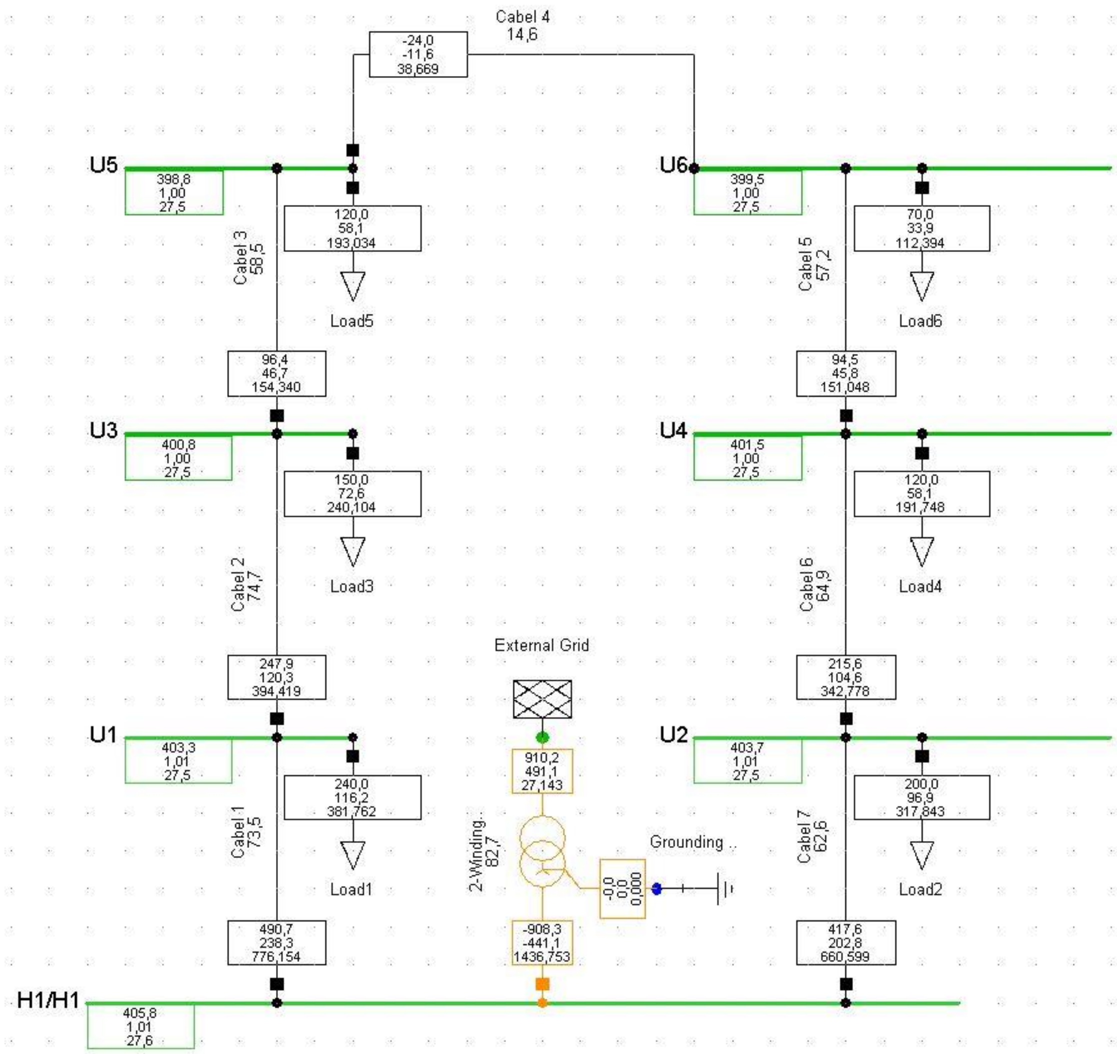

Figure 22 - Ring network

6.3.2 *SHORT CIRCUIT PROTECTION IN THE RING NETWORK*

A traditional method to obtain necessary selectivity was used in the radial network; time-current plots were looked into, making sure that the curves weren't entangled. When a ring network is designed with directional zone selectivity, this traditional method alone doesn't suffice. A blocking and signaling plan must also be set up to make sure that the network has necessary selectivity.

When dealing with directional zone selectivity, the need for operating reliability must be determined. In the simulated ring network a reliability that never causes more than one load to be disconnected has been chosen; this presumes that there is only one fault, and the fault doesn't occur in the main distribution board H1. This solution gives an acceptable risk of loss of power without using too many circuit breakers and is sufficient for the majority of installations.

Directional zone selectivity is based on communication between the circuit breakers in the network. The Emax 2 devices can communicate either via bus or Ethernet depending at the chosen technology. The circuit breakers used in the simulations are fitted with add-on equipment needed to operate over Ethernet, be remotely operated and have the possibility for remote reading of measurements.

The first step is to set up a plan for the directional zone selectivity to identify possible places where faults can occur and then set up a table for wanted circuit breaker behavior in those situations. This table should include an overview of the fault position, which circuit breakers that must trip instantly and which circuit breakers that must be blocked.

Table 5 - Fault locations and circuit breaker behavior in the ring network

Fault location, zone in (x)	Circuit breaker to trip instantly / selectivity time	Circuit breakers to be blocked / time threshold
H1(1)	H1:1	None
U1 or cable 1 (2)	H1:2 and U1:1	H1:1, H1:3, U2:1, U3:1, U4:1, U5:1
U2 or cable 7 (3)	H1:3 and U2:1	H1:1, H1:2, U1:1, U3:1, U4:1, U5:1
U3 or cable 2 (4)	U1:1 and U3:1	H1:1, H1:2, H1:3, U2:1, U4:1, U5:1
U4 or cable 6 (5)	U2:1 and U4:1	H1:1, H1:2, H1:3, U1:1, U3:1, U5:1
U5 or cable 3 (6)	U3:1 and U5:1	H1:1, H1:2, H1:3, U1:1, U2:1, U4:1
U6, cable 4 or cable 5 (7)	U4:1 and U5:1	H1:1, H1:2, H1:3, U1:1, U2:1, U3:1

Even if Ethernet is used for communication and signaling, it is possible and useful to design a graphic that shows how the signals transfer between the circuit breakers. This graphic gives an understanding of the basic principles for directional zone selectivity. The graphic can be seen in Figure 23 where the green arrows represent forward signals, the red arrows represent backward signals and the black lines represent the cable system. Each box indicates the circuit breaker with its given name. The black arrow inside each box represents the set power flow direction for each circuit breaker.

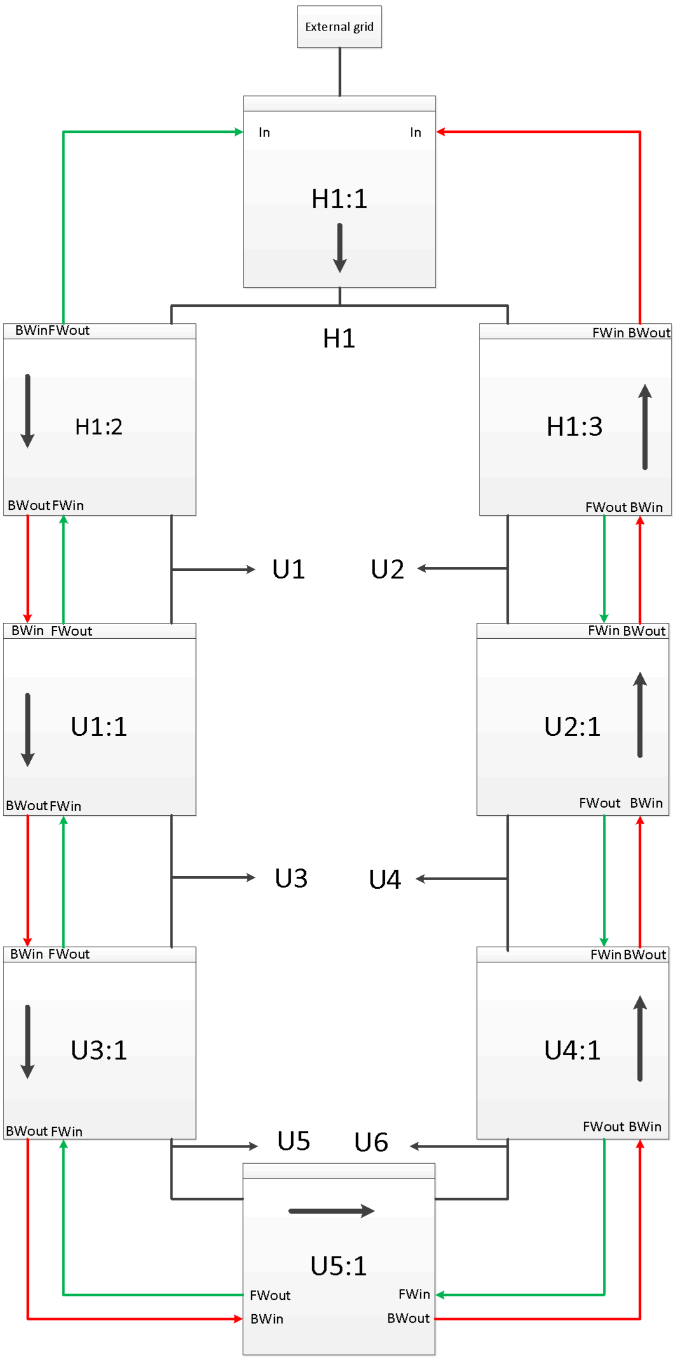

Figure 23 - Ring network communication graphic

The communication graphic can be used as the basis for setting up Table 6. This table indicates whether a circuit breaker sends or receives a blocking signal. The table also shows in which direction the signal is transferred compared with the set direction for the circuit breaker as indicated with black arrows in Figure 23. Table 6 gives a good overview of the signaling and makes it easy to see if all circuit breakers are involved in all fault situations, which is necessary to avoid unwanted tripping other places in the network.

Table 6 - Blocking scheme with direction indication for ring network

			OUT														
			H1:1	H1:2		H1:3		U1:1		U2:1		U3:1		U4:1		U5:1	
			Out	FW	BW	FW	BW	FW	BW	FW	BW	FW	BW	FW	BW	FW	BW
	H1:1	In		X			X	X	X	X	X	X	X	X	X	X	X
	H1:2	FW						X		X		X		X		X	
		BW															
	H1:3	FW															
		BW							X		X		X		X		X
	U1:1	FW								X		X		X		X	
		BW															
IN	U2:1	FW															
		BW							X				X		X		X
	U3:1	FW								X				X		X	
		BW							X								
	U4:1	FW								X							
		BW							X				X				X
	U5:1	FW								X				X			
		BW							X				X				
Fault in zone				1	Only H1:1 will operate with a fault in zone 1												
Fault in zone				2	X												
Fault in zone				3	X												
Fault in zone				4	X												
Fault in zone				5	X												
Fault in zone				6	X												
Fault in zone				7	X												

To identify short circuit currents is an important part of the selectivity analysis both in traditional selectivity techniques and for directional zone selectivity. The simulated system is divided into 7 different zones where short circuits either will arise in one of the bus bars or in the cable system. Since this is a ring-connected network, the short circuit will get contribution from both connections to the main distribution board H1. This makes the analysis of short circuit currents a little more complex compared to a traditional radial network. I_{k1pmin} is simulated in all buses and cables where short circuit in the cable is simulated as a short circuit that occurs in the middle of the cables length. In comparison, I_{k3pmax} is only simulated at the buses. In Table B10 in Appendix B a complete list for all the short circuits can be found. An excerpt of the results from the short circuit analysis can be seen in Table 7.

Table 7 – Minimum and maximum I_{k1pmin} and I_{k3pmax} seen by the circuit breakers in the system

Short circuit current seen by the circuit breaker			
	Min I_{k1pmin} [kA]	Max I_{k1pmin} [kA]	I_{k3pmax} [kA]
H1:1	13.88	31.54	28.38
H1:2	1.07	26.77	28.38
H1:3	1.07	26.77	28.38
U1:1	1.07	16.85	23.27
U2:1	1.07	16.85	23.27
U3:1	1.07	10.64	16.18
U4:1	1.07	10.64	16.18
U5:1	1.07	6.94	11.76

The results from the short circuit analysis show a minimum short circuit current I_{k1pmin} = 1.07 kA for all circuits breakers expect for H1:1. The smallest I_{k1pmin} occurs when a single phase short circuit to ground appears in either cable 1 or 7. Depending on the situation and the fault position, the short circuit current differs for all the circuit breakers. It is however enough to evaluate the minimum I_{k1pmin} value which is the basis for setting the I7 triggering current for the directional zone selectivity, and the I_{k3pmax} or I_{k1pmin} maximum value which is the basis for selecting the circuit breakers breaking capacity.

Short circuit currents are the basis for programming the circuit breakers protecting functionality correctly. The circuit breakers used in this ring network have three protection functions against short circuits:

- Directional zone protection, D, with triggering current I7
- Delayed short circuit / zone protection, S, with triggering current I2 and a possible delay up to 0.8 seconds
- Instantaneous short circuit, I, with triggering current I3

If the D protection is in use, the S and I protection must be deactivated or they have to be adjusted not to interfere with the D protection. Below follows a review of all the different faults explaining choices taken for the different circuit breakers. Table 8 gives an overview of the settings for each circuit breaker.

Fault in H1, zone 1

If a fault occurs in H1, the circuit breaker intended to disconnect is H1:1. This circuit breaker should only disconnect with fault in bus bar H1. If other faults occur in the network, it should work as a backup for the rest of the circuit breakers. In this circuit breaker the directional zone selectivity is deactivated while the instant short circuit I and the delayed short circuit S are activated. The S protection must have a 450 ms delay not to interrupt the directional zone selectivity in the others circuit breakers. The triggering current has been set to 10 kA, securing that the S protection is activated during all short circuits. If a fault arises in bus bar H1, the I protection will be activated. This protection must have a triggering current higher than the largest short circuit current resulting from a fault in cable 1 or 7, which is 27.84 kA. Therefore, the I protection is given a triggering current at 28.5 kA to secure correct operation.

Fault in cable 1 or U1, zone 2

H1:2 and U1:1 are the circuit breakers protecting zone 2, and they must disconnect within selectivity time which is set to 250 ms when a fault occurs in either cable 1 or bus bar U1. H1:2 will see a fault in the forward direction and activate forward blocking signals while U1:1 will see a fault in the backward direction and activate backward blocking signals.

If the fault arises in cable 1, the backward blocked circuit breakers see the smallest short circuit current at 1.07 kA. The triggering current I7 for the directional zone selectivity must therefore be set under 1.07 kA. As a result, I7 has been set to 0.95 kA for all circuit breakers in the sub-distribution board. I7 for H1:2 have to be 1.7 kA since 0.95 kA is lower than the circuit breakers nominal current.

Fault in cable 2 or U3, zone 4

U1:1 and U3:1 are the circuit breakers protecting zone 4. They will disconnect within selectivity time set to 250 ms. U1:1 will activate forward blocking signals while U3:1 will activate backward blocking signals.

Fault in cable 3 or U5, zone 6

U3:1 and U5:1 are the circuit breakers protecting zone 6. They will disconnect within selectivity time set to 250 ms. U3:1 will activate forward blocking signals while U5:1 will activate backward blocking signals.

Fault in cable 4 or 5 or U6, zone 7

U5:1 and U4:1 are the circuit breakers protecting zone 7. They will disconnect within selectivity time set to 250 ms. U5:1 will activate forward blocking signals while U4:1 will activate backward blocking signals. When a short circuit occurs in cable 4, the H1:1 sees the smallest short circuit current at 13.88 kA, which then will be the maximum triggering current for the H1:1s S protection. The triggering current for the S protection must therefore be set to 10 kA to secure H1:1 to be activated in any fault case.

Fault in cable 6 or U4, zone 5

U5:1 and U4:1 are the circuit breakers protecting zone 5. They will disconnect within selectivity time set to 250 ms. U5:1 will activate forward blocking signals while U4:1 will activate backward blocking signals.

Fault in cable 7 or U2, zone 3

U2:1 and H1:3 are the circuit breakers protecting zone 3. They will disconnect within selectivity time set to 250 ms. U2:1 will activate forward blocking signals while H1:3 will activate backward blocking signals. If a fault arises in cable 7, the smallest short circuit current at 1.07 kA will occur, but this time for the circuit breakers in the backward direction for U2:1.

This gives the following overview of the circuit breakers settings and chosen protecting method for different parts in the network:

Table 8 - Settings for the circuit breakers

Protection function	S		D				I
Circuit breaker	I2	t2	I7	t7FW	t7BW	ST	I3
H1:1	10 kA	450 ms	OFF	OFF	OFF	OFF	28.5 kA
H1:2	OFF	OFF	1.7 kA	350 ms	350 ms	250 ms	OFF
H1:3	OFF	OFF	1.7 kA	350 ms	350 ms	250 ms	OFF
U1:1	OFF	OFF	0.95 kA	350 ms	350 ms	250 ms	OFF
U2:1	OFF	OFF	0.95 kA	350 ms	350 ms	250 ms	OFF
U3:1	OFF	OFF	0.95 kA	350 ms	350 ms	250 ms	OFF
U4:1	OFF	OFF	0.95 kA	350 ms	350 ms	250 ms	OFF
U5:1	OFF	OFF	0.95 kA	350 ms	350 ms	250 ms	OFF

The triggering current I7 has to be set in accordance with requirement $I7 < I_{kmin}$. I_{kmin} for all circuit breakers in the system simulated to be 1.07 kA. Therefore, the I7 triggering current has been set to 0.95 kA for all circuit breakers in the sub-distribution boards to fulfill the requirement, but not for H1:2 and H1:3. The reason for this is the nominal current for those two circuit breakers, which is as high as 1050 A. If I7 of those circuit breakers had been set to 0.95 kA they could have been triggered in a normal situation.

Since 0.95 kA is under the circuit breakers' nominal current their triggering current for I7 must be set higher and the requirement $I7 < I_{kmin}$ is no longer met, but can be defended in this particular situation which now will be explained. If a fault occurs in the middle of cable 1, H1:3 will see a fault current at 1.07 kA and with a set I7 = 1.7 kA it will not be triggered. In the direction of the fault current of 1.07 kA are four other circuit breakers with I7 = 0.95 kA that will be triggered. This means that if U1:1 fails, four other circuit breakers will be a backup in the backward direction and the need for H1:3 to be triggered is extremely low. Therefore, it may be allowed in this particular situation to set I7 = 1.7 kA for circuit breaker H1:2 and H1:3 without this affecting the selectivity in the ring network.

One of the requirements when directional zone selectivity is in use is to ensure that other connected devices on the load side are placed outside the directional zone selectivity range of protection. This can be fulfilled by adjusting the selectivity time to ensure time-current selectivity with circuit breakers at the load side. Since the requirement according to Table 1 is instantaneous disconnection within 0.2 s for consumer courses, the selectivity time has been set to 0.25 s. This will guarantee that circuit breakers at the load side of the installation trip first, though the circuit breakers in the main distribution part also get triggered. A more detailed analysis for this requirement is given in chapter 6.3.5.

From the settings it can be seen that all circuit breakers have the same selectivity time at 250 ms. This is one of the main advantages of the use of directional zone selectivity, especially in larger networks: the fault will be disconnected at the same time all over in the main distribution network, independent of the circuit breakers' place in the hierarchy.

Another requirement to be checked is the short withstand current for the circuit breakers. The minimum short withstand current delivered for this circuit breaker series is
I_{cw} = 42 kA, while I_{kmax} = 31.54 kA. The requirement $I_{cw} \geq I_{kmax}$ is checked and approved.

To be sure cables are not damaged during a short circuit, the breakthrough energy of the circuit breakers must be checked against the cable`s limit. This can be checked by calculating the critical time for the adiabatic heating of the cables. The largest short circuit current in the sub-distribution boards is used and the short circuit current is assumed distributed equally to parallel connected cables. This results in Table 9 which shows the necessary breaking time.

Table 9 - Necessary braking time for protecting the cables against overheating

	I_{kmax} [kA]	Cables in parallel	I_{kmax} per cable [kA]	k	Cable cross section [mm^2]	k^2S^2 [MA^2s] per cable	Necessary breaking time [s]
Cable 1	27.84	4	6.96	76	240	332.70	6.87
Cable 2	19.91	2	9.96	76	240	332.70	3.36
Cable 3	15.36	2	7.68	76	240	332.70	5.64
Cable 4	13.88	2	6.94	76	240	332.70	6.91
Cable 5	15.36	2	7.68	76	240	332.70	5.64
Cable 6	19.91	2	9.96	76	240	332.70	3.36
Cable 7	27.84	4	6.96	76	240	332.70	6.87

The range for the necessary breaking times is from 3.36 s to 6.87 s, and all of the circuit breakers in the ring will break within 0.25 s and in a worst case scenario within 0.35 s. The requirements for breaking time and breakthrough energy are met.

In Eq. 3.4 used for calculating the necessary breaking time, a condition is set that is only valid up to 5 s. This is because the equation expects the heating of the cable within the first 5 s of a short circuit to be adiabatic and after 5 s some of the heat will be released into the environment. The equation may be used after 5 s as well since the adiabatic process is a worse condition compared to the situation if some of the heat is released into the environment. The only change with using it for more than 5 s is the breaking time will be lower, but in this situation is this does not cause any problems. The circuit breakers will still be able to protect the cables against overheating in a short circuit situation.

6.3.3 Overload Protection in the Ring Network

In addition to protecting against short circuits the protection system must take care of overload situations. All the circuit breakers have the L functionality activated, which is the functionality that analyzes and handles overload situations.

An important task for the overload protection is to keep the temperature of cables or bus bars to an acceptable level and make sure there is no damage during an overload. The circuit breakers' L functionality has to be set in accordance with the cable or bus bar current-carrying capacity, which is the basis for setting the circuit breakers nominal current. From the cable plan in Appendix B the type, numbers and lengths of cables in parallel can be seen and this makes the basis for calculating the nominal current for each of the circuit breakers.

For simplicity's sake, the current-carrying capacity for one PFSP 4x240/70 mm^2 AL cable is set to 264 A. The calculation of the cables' current-carrying capacity can be found in Appendix B and the circuit breakers' nominal current is set under the current-carrying capacity for the cable it is going to protect, which is the basis for Table 10. The rating of H1:1 is decided by the needed value for the I protection which is maximum 15 x I_n of the circuit breaker, therefore H1:1 is given a 2000 A nominal current plug to reach a triggering current for I1 = 28.5 kA.

Table 10 - Nominal current for the circuit breakers in the ring network

Nominal current for the circuit breakers				
	$I_{n\ plug}$ [A]	Y x I_n	I_n [A]	$I_{cable\ max}$ [A]
H1:1	2000	0.8	1600	--
H1:2	1250	0.84	1050	1056
H1:3	1250	0.84	1050	1056
U1:1	630	0.835	526	528
U2:1	630	0.835	526	528
U3:1	630	0.835	526	528
U4:1	630	0.835	526	528
U5:1	630	0.835	526	528

The I_n plug column in Table 10 represents the nearest available standard nominal current plug for the circuit breaker. The circuit breakers' nominal current can be adjusted down by an internal scaling factor to reach the desired nominal current that fits the cable-carrying capacity. The scaling factor is represented in the Y x I_n column and the final setting for the nominal current is found in the I_n column. Cable-carrying capacity for cables connected to the circuit breakers are indicated in the $I_{cable\ max}$ column.

In Figure 24 the time current plot for the L functionality can be seen where the green shaded area represents the main circuit breaker H1:1, blue represents H1:2 and H1:3, and red represents circuit breakers in all sub-distribution boards. The same colors in the single lines are the cable`s critical level. The colors of these lines must be seen in accordance with the respective colors for the circuit breakers. These diagrams represent only the time current plot for the L protection, except for the main circuit breaker H1:1 where the delayed short circuit protection S and instant short circuit protection I are included. It is not possible to include the D protection in the time current plots in DOC, which is the reason why the plots end like they do.

The circuit breakers have been set up with a delay in the L protection to make it possible to respond in overload situations. A minimum three-second delay is standard for these circuit breakers, which can be adjusted up to 144 s if needed. This delay gives opportunities to tune the total demand for the system by load shedding by connecting a PLC / SCADA controller into the communication line together with the circuit breakers.

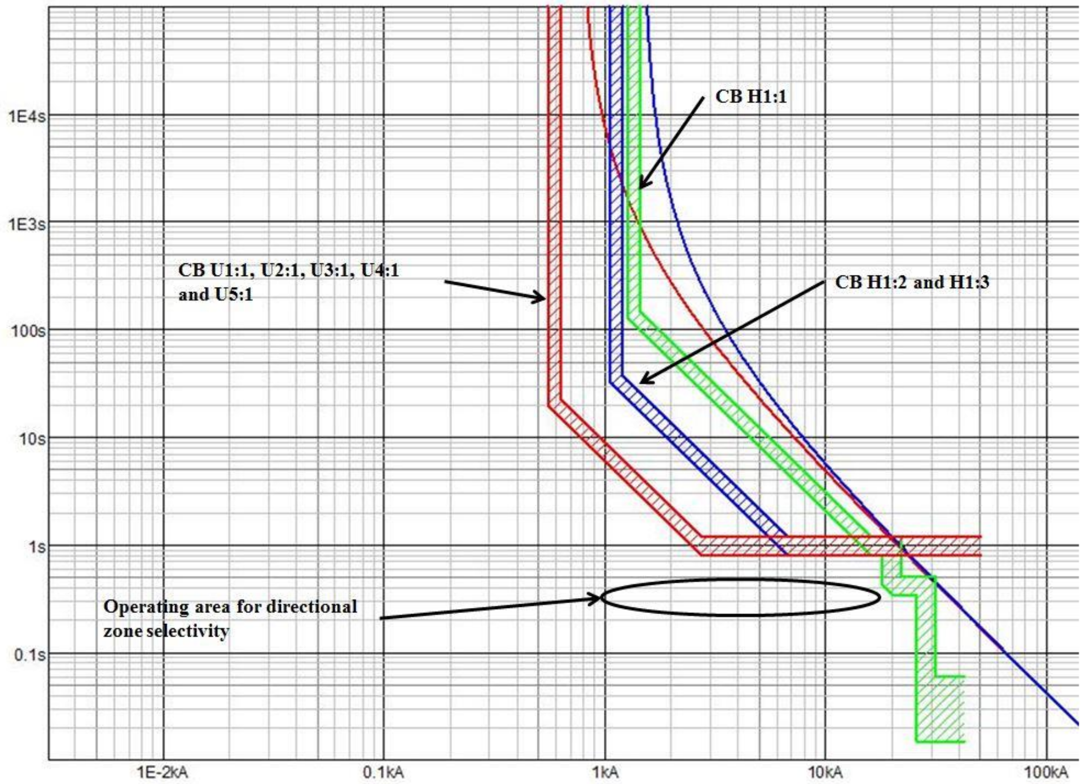

Figure 24 - Time current plot for ring network

6.3.4 *OVERLOAD MANAGEMENT IN THE RING NETWORK*

In the ring network one of the advantages is the reliability because of the possibility to send power flow in two directions if a fault occurs or if maintenance is needed. If one zone is out of service, the ring connection will be split up and the system will instead work as a two-radial system. The challenge when the ring network is split up is that cables or busways in the network may become overloaded. In addition, the networks' design and state may cause the overload protection to trip in other parts of the network, potentially causing unwanted situations in an already extraordinary situation.

When ring networks are considered, there must be a plan for how to operate the network if the ring is split up in order to avoid several parts of the network blacking out because of overloading. In this kind of situation there are two main possibilities which can solve this issue:

- By over-dimension cables or busways to always handle one disconnected zone
- By splitting up into priority and non-priority loads in the sub-distribution boards and disconnect non-priority loads when needed

Over dimension of cables or busways

This solution requires an analysis of the power flow in the different fault situations that can be found in Appendix B. This type of solution must aim at getting all the cables under 100 % loading factor during any type of situation. The power flow tables in Appendix B indicate overload for some cables in the network in two out of six situations when one zone falls out of service. Simulation of the different situations with overloaded cables results in Table 11 and the use of 100 m extra PFSP cable if none of the cables should be more than 100 % loaded.

Table 11 - Extra cables needed for over dimension of the cable system to secure no more than 100 % loading factor

Cabel number	Cabels in paralell orignaly	Extra cables needed	New number of cabels in parallel
Cabel 1	4	0	5
Cabel 2	2	1	3
Cabel 3	2	0	2
Cabel 4	2	0	2
Cabel 5	2	0	2
Cabel 6	2	1	3
Cabel 7	4	0	4

Sort out in non-priority loads and remote operation with PLC / SCADA

This solution is based on the communication possibility offered by the circuit breakers and load switches in the Emax 2 series. The solution requires a PLC / SCADA system to be connected into the system to take care of the necessary disconnections if a zone falls out of service. In the sub-distribution boards the loads must be sorted out in priority and non-priority loads where the non-priority loads need a controllable circuit breaker or load switch of the Emax 2 type for remote operation.

Both load switches and circuit breakers fitted with the correct add-on equipment can send out signals for their different stat in the particular moment and in order to be remotely operated. When a zone falls out of service the circuit breakers protecting the zone will activate high signals for open contacts and activate inputs in the PLC / SCADA controller. The PLC / SCADA controller can in these situations be programmed to send an opening signal to load switches in front of the non-priority loads to reduce the total demand and decrease the cables' load factor. In larger networks it might be more desirable to only disconnect some of the non-priority loads depending on which zone falls out of service. It is then possible to route different signals in the PLC / SCADA into different logical blocks based on which zone falling out of service, and only send opening signal to some of the non-priority loads.

In the simulated ring network the overload situation can be solved by splitting up the loads into priority and non-priority categories. This network has two situations resulting in overloaded cables where action is needed from a PLC / SCADA controller. Table 12 gives an overview of how the loads can be separated into the different categories.

Table 12 - Overview priority and non-priority loads

Sub distributing board	Total demand [kW]	Factor for non-priority load	Priority load [kW]	Non-priority load [kW]
U1	240	0.35	156	84
U2	200	0.35	130	70
U3	150	0.50	75	75
U4	120	0.50	60	60
U5	120	0.55	54	66
U6	70	0.55	31.5	38.5

As mentioned, there are two situations requiring action from the PLC / SCADA system; the least favorable situation occurs when zone 2 falls out of service. Cable 6 will then have a loading factor of 132.3 % and if the current passing through, 699 A, is compared with the red curve in the time current plot in Figure 24, a minimum disconnection time for circuit breaker U2:1 at 11.5 second is observed. To avoid U2:1 from disconnecting due to overloading, the PLC / SCADA must be able to have finished disconnecting non-priory loads within 11.5 seconds. If the control system fails, U2:1 will open between 8 and 12 seconds, resulting in loss of power for sub-distribution boards U3, U4, U5 and U6.

The most favorable effort is always to minimize the number of non-priory loads being disconnected. By analyzing fault situations where different zones are out of service, Table 13 can be constructed to show which non-priority loads that have to be disconnected to ensure a network that does not have overload.

Table 13 - Disconnecting plan for non-priority loads

Fault or maintenance in	Disconnect non-priority load in
Zone 1	No action required
Zone 2	U3 and U4
Zone 3	U3 and U4
Zone 4	No action required
Zone 5	No action required
Zone 6	No action required
Zone 7	No action required

From Table 13 it can be seen that only U3 and U4 need to be disconnected during the situations where overloading occurs. This means that only those two sub-distribution boards need to have installed a remotely operated load switch, and to have split up the load in two categories. It is important to remember that this is just one example of a solution, and other solutions to prevent overloading are also possible. In Appendix D figures with power flow in the different situations before and after disconnection of the non-priory loads can be found for situations with fault or maintenance in zone 2 and 3.

The suggested solution will in this situation disconnect the non-priority loads as fast as possible after an open signal from the circuit breakers is received. With the use of a PLC / SCADA it will be possible to extract measurement data from each of the circuit breakers. If this information is used in a good way it cannot be ignored that real time measurement can be used as a part of the evaluation of when to disconnect non-priority loads. This can be a smart solution since the demand in electrical installations varies with time.

Measurement inputs can then be implemented in the PLC / SCADA system and can be compared to a limit for each circuit breaker; non-priority loads will be disconnected when the limit is passed. It can also be possible to evaluate the situation over a short period of time by delaying the overload protection functionality as long as it can be documented that cables are not damaged during that time.

With the use of a PLC / SCADA controller a lot of special features can be added for control and analysis in a low voltage network where imagination and customer need are the only limits.

6.3.5 *Selectivity between the Ring and the Network Lower in the Hierarchy*

One of the requirements for correct function of directional zone selectivity is to achieve time-current selectivity with circuit breakers on the load side in the installation. At the same time, the circuit breakers at the load side must be set in a way that allows them to operate with both open and closed ring.

To prove this selectivity, a time-current plot must be set up that takes into account circuit breakers in the whole network. As an example, sub-distribution board U2 has been expanded and connected to a motor load and an area distributor with two loads.

There are two important considerations:

- Circuit breakers on the load side must disconnect short circuit faults with good time margin to the selectivity time set for the circuit breakers dealing with the directional zone selectivity in the ring network
- The time-current plot for circuit breakers on the load side must not entangle with the time-current plot for circuit breakers taking part in the ring.

If these two considerations are taken into account, the time-current plot for the ring network and the expansion of the sub-distribution board may look like this:

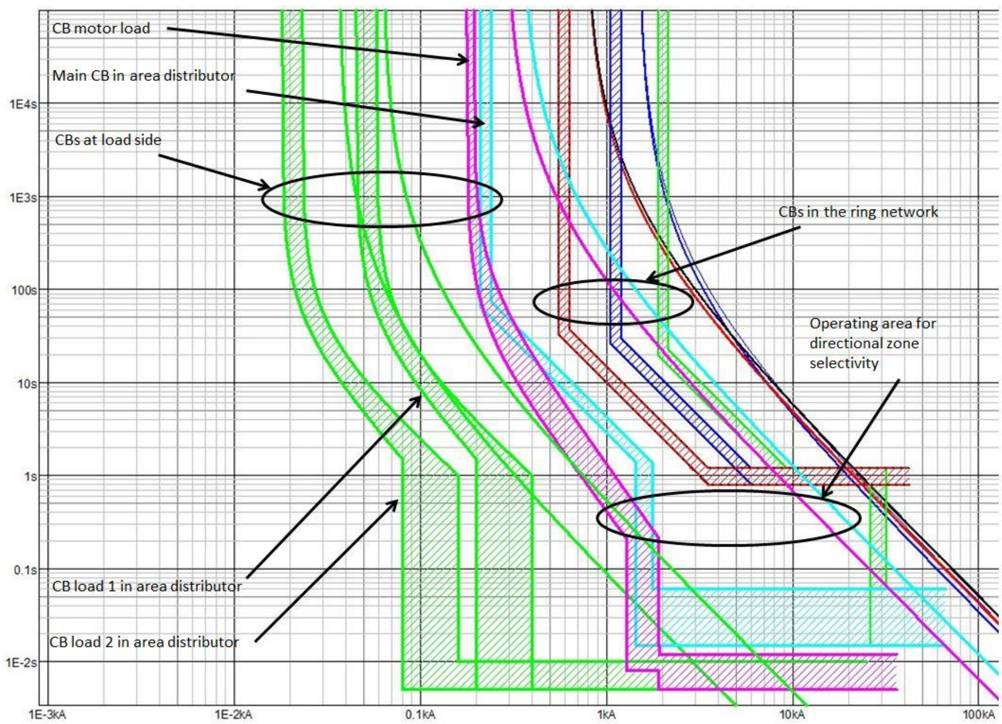

Figure 25 - Time-current plot with expanded U2, ring network

Figure 25 shows that the time-current plot of the load side does not entangle the circuit breakers in the ring network - with one exception. That exception is the main circuit breaker protecting the cable to the area distributor which entangles the H1:1 circuit breaker, but this is not a problem since I_{kmax} seen by the main circuit breaker in the area distributor is smaller than the set triggering current for H1:1.

Some of the circuit breakers in the ring network will in different situations be triggered when a short circuit arises on the load side, which is the reason the selectivity time in the ring network is set to 0.25 s. Even if some of the circuit breakers in the ring network see a short circuit current high enough to trigger, when there is a short circuit on the load side, the circuit breaker on the load side will disconnect the fault within 0.1 s and the ring network will be unaffected.

From the time-current plot is it clear that the overload area for the directional zone selectivity is unaffected by the load-side circuit breakers. The load-side circuit breakers will always disconnect an overload before the circuit breakers in the ring network when the overload happens on the load side regardless of whether the ring is open or closed.

This simulation shows that selectivity is possible to achieve between the ring network and the load-side circuit breakers when the installation is expanded on the load side.

6.4 MESHED NETWORK

6.4.1 DESCRIPTION OF THE MESHED NETWORK

The ring network is further developed by adding cable 8 and 9 making it into a meshed network. The general network design is still the same as in the radial and ring network, but due to challenges with getting high enough short circuit currents it was necessary to change the cable plan. The cable plan and other network descriptions for the meshed network can be found in Appendix C. Figure 26 shows the meshed network in normal operations, which are the basis for all calculations and analysis.

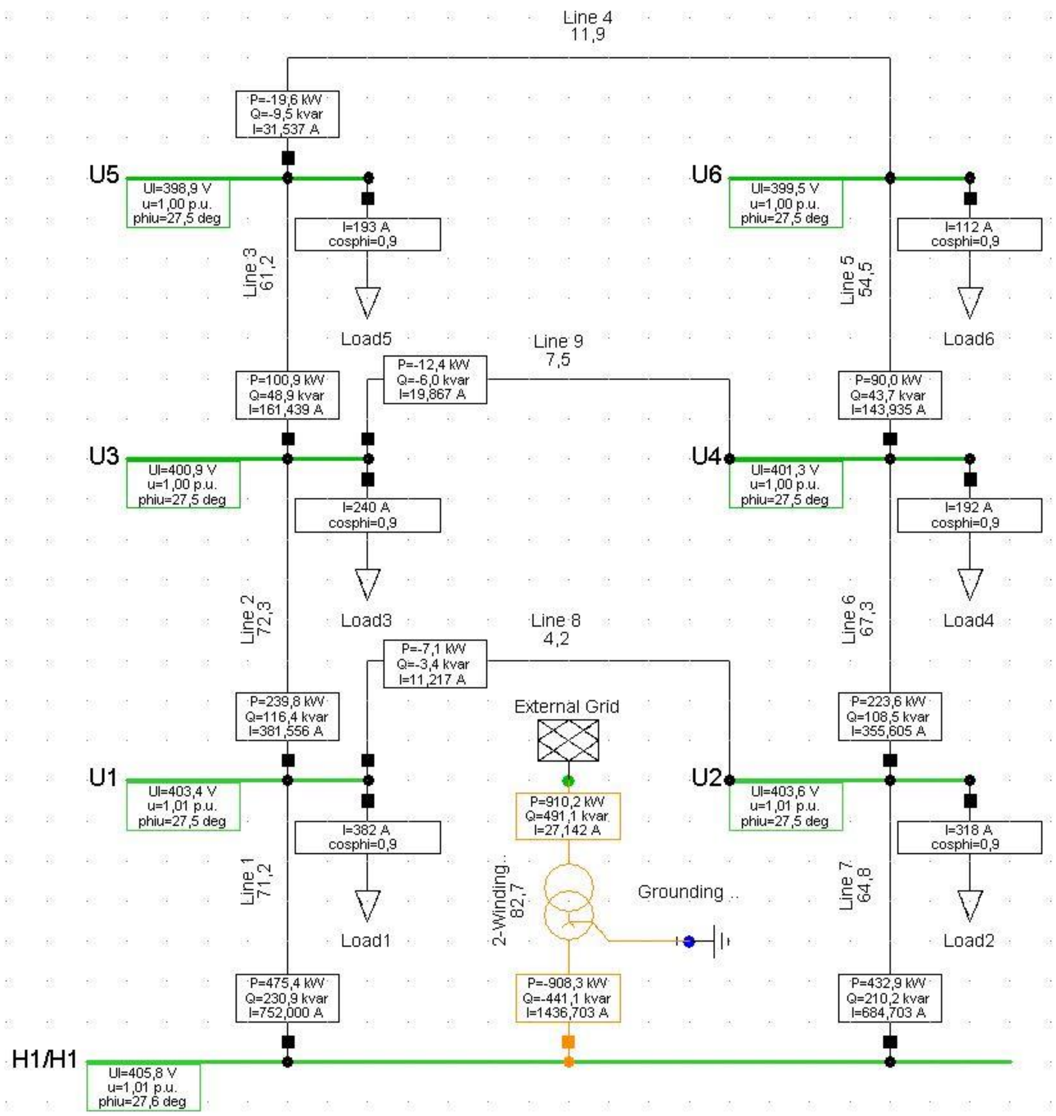

Figure 26 - Meshed network

6.4.2 *Short Circuit Protection in the Meshed Network*

One may apply the same method of thinking when designing the meshed networks' circuit breaker structure as when designing the ring network, only with awareness. The greatest change in the meshed network is how the short circuit currents behave because of all the new possible routes by just adding cable 8 and 9. This requires deeper analysis to make sure all the circuit breakers will behave as intended to secure the network in short circuit situations.

In the meshed network cable 8 and 9 must be secured with a circuit breaker in both ends. This is necessary because in a situation where a short circuit occurs in either cable 8 or 9, the short circuit current will be concentrated in one of these cables and the rest of the network lower in the hierarchy will not see a short circuit current. To be able to isolate a cable fault in cable 8 or 9 those cables must be secured with two circuit breakers instead of one. Since the network lower in the hierarchy does not see a short circuit current if a fault occurs in cable 8 or 9, it is enough in those situations to only block circuit breakers higher in the hierarchy.

The desired circuit breaker behavior for the rest of the network is still quite equal to the ring network and an overview of circuit breaker behavior can be seen in Table 14 while the communication graphic for signaling between the circuit breakers can be seen in Figure 27.

Table 14 - Circuit breaker behavior in the meshed network

Fault location, fault zone in (x)	Circuit breakers to trip instantly / selectivity time	Circuit breakers to be blocked / time threshold
H1(1)	H1:1	None
U1 or cable 1 (2)	H1:2, U1:1 and U1:2	H1:1, H1:3, U2:1, U2:2, U3:1, U3:2, U4:1, U4:2, U5:1
U2 or cable 7 (3)	H1:3, U2:1 and U2:2	H1:1, H1:2, U1:1, U1:2, U3:1, U3:2, U4:1, U4:2 U5:1
U3 or cable 2 (4)	U1:1, U3:1 and U3:2	H1:1, H1:2, H1:3, U1:2, U2:1, U2:2, U4:1, U4:2, U5:1
U4 or cable 6 (5)	U2:1, U4:1 and U4:2	H1:1, H1:2, H1:3, U1:1, U1:2, U2:2, U3:1, U3:2, U5:1
U5 or cable 3 (6)	U3:1, U5:1	H1:1, H1:2, H1:3, U1:1, U1:2, U2:1, U2:2, U3:2, U4:1, U4:2
U6, cable 4 or cable 5 (7)	U4:1 and U5:1	H1:1, H1:2, H1:3, U1:1, U1:2, U2:1, U2:2, U3:1, U3:2, U4:2
Cable 8 (8)	U1:2 and U2:2	H1:1, H1:2, H1:3
Cable 9 (9)	U3:2 and U4:2	H1:1, H1:2, H1;3, U1:1, U2:1

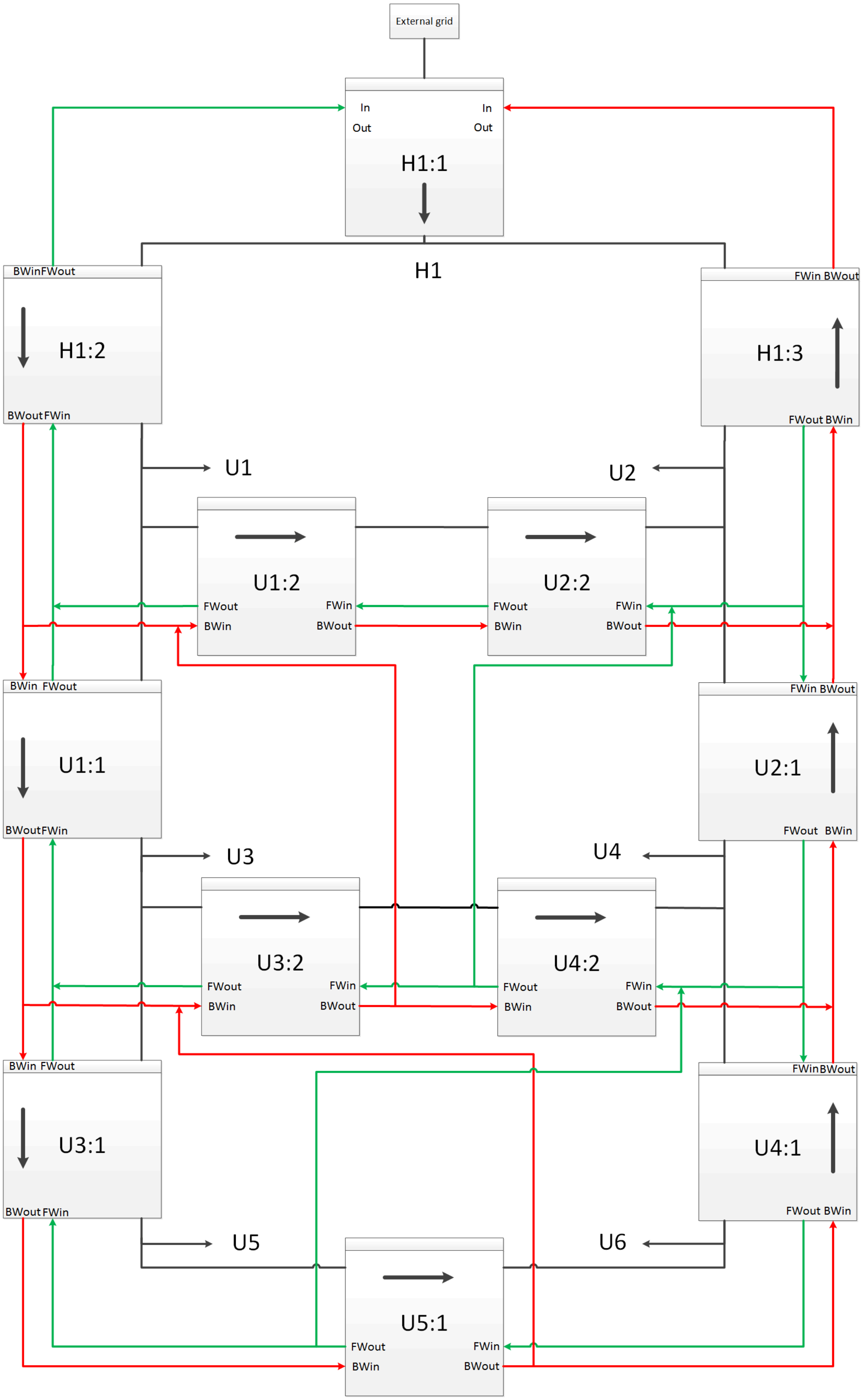

Figure 27 - Meshed network communication graphic

An analysis of Figure 27 and Table 14 results in Table 15, which indicates the signaling between the circuit breakers in the different fault situations.

Table 15 - Blocking scheme with direction indication for meshed network

			OUT																						
			H1:1	H1:2		H1:3		U1:1		U1:2		U2:1		U2:2		U3:1		U3:2		U4:1		U4:2		U5:1	
			Out	FW	BW	FW	BW	FW	BW	FW	BW	FW	BW	FW	BW	FW	BW	FW	BW	FW	BW	FW	BW	FW	BW
IN	H1:1	In		X			X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
	H1:2	FW						X		X		X		X		X		X		X		X		X	
		BW																							
	H1:3	FW																							
		BW							X		X		X		X		X		X		X		X		X
	U1:1	FW										X				X		X		X		X		X	
		BW																							
	U1:2	FW												X								X		X	
		BW																	X						X
	U2:1	FW																			X				
		BW							X								X		X				X		X
	U2:2	FW																				X		X	
		BW									X								X						X
	U3:1	FW										X								X				X	
		BW							X																
	U3:2	FW										X										X			
		BW							X																X
	U4:1	FW										X													
		BW							X								X								X
	U4:2	FW										X												X	
		BW							X										X						X
	U5:1	FW										X								X					
		BW							X								X								
Fault zone				1	Only H1:1 will operate with a fault in zone 1																				
Fault zone				2	X																				
Fault zone				3	X																				
Fault zone				4	X																				
Fault zone				5	X																				
Fault zone				6	X																				
Fault zone				7	X																				
Fault zone				8	X																				
Fault zone				9	X																				

The short circuit current seen by each circuit breaker in different situations has to be identified for the correct setting of the circuit breakers' triggering current. An analysis of possible faults in the meshed network gives short circuit currents presented in Table C12 in Appendix C with an excerpt presented in Table 16. Compared to the ring network the minimum I_{k1pmin} seen by the circuit breakers in the meshed network is not that constant, but varies more because of several routes for the short circuit current.

In some situations some of the circuit breakers in the meshed network will see 0 A as short circuit current. Since 0 A not is a possible setting for the triggering current I7 for the directional zone selectivity, those values are excluded from Table 16.

Table 16 - Short circuit current seen by the circuit breakers in the meshed network

Short circuit current seen by the circuit breaker			
	Minimum I_{k1pmin} [kA]	Maximum I_{k1pmin} [kA]	I_{k3pmax}
H1:1	14.88	31.54	28.38
H1:2	2.82	31.41	28.38
H1:3	2.82	31.41	28.38
U1:1	1.42	18.03	25.58
U1:2	0.37	9.20	25.58
U2:1	1.42	18.03	25.58
U2:2	0.37	9.20	25.58
U3:1	0.66	13.21	22.94
U3:2	0.77	7.86	22.94
U4:1	0.66	13.21	22.94
U4:2	0.77	7.86	22.94
U5:1	0.66	7.44	20.04

One of the requirements for the protection system can now be checked with the basis in Table 16, which is the short withstanding current for the circuit breakers. The minimum short withstand current delivered for this circuit breaker series is I_{cw} = 42 kA, while I_{kmax} = 31.54 kA. The requirement $I_{cw} \geq I_{kmax}$ is checked and approved for all circuit breakers.

The different fault situations can now be evaluated and special situations requiring special treatment can be found. All circuit breakers have the D protection for directional zone selectivity activated except for H1:1 which instead uses the S protection for delayed short circuit and the I protection for instantaneous short circuit. With basis in the determined short circuit currents in Table C12 in Appendix C an overview for the circuit breaker setting can be made.

Table 17 - Settings for the circuit breakers in the meshed network with time threshold

Protection function	S		D				I
Circuit breaker	I2	t2	I7	t7FW	t7BW	ST	I3
H1:1	10 kA	450 ms	OFF	OFF	OFF	OFF	29 kA
H1:2	OFF	OFF	2.5 kA	350 ms	350 ms	250 ms	OFF
H1:3	OFF	OFF	2.5 kA	350 ms	350 ms	250 ms	OFF
U1:1	OFF	OFF	1.3 kA	350 ms	350 ms	250 ms	OFF
U1:2	OFF	OFF	0.35 kA	350 ms	350 ms	250 ms	OFF
U2:1	OFF	OFF	1.3 kA	350 ms	350 ms	250 ms	OFF
U2:2	OFF	OFF	0.35 kA	350 ms	350 ms	250 ms	OFF
U3:1	OFF	OFF	0.6 kA	350 ms	350 ms	250 ms	OFF
U3:2	OFF	OFF	0.6 kA	350 ms	350 ms	250 ms	OFF
U4:1	OFF	OFF	0.6 kA	350 ms	350 ms	250 ms	OFF
U4:2	OFF	OFF	0.6 kA	350 ms	350 ms	250 ms	OFF
U5:1	OFF	OFF	0.6 kA	350 ms	350 ms	250 ms	OFF

The first and one of the central requirements for directional zone selectivity is to identify the triggering current I7 and make sure it fulfills the term I7 < I_{kmin}. It is desirable that all circuit breakers get their directional zone selectivity activated in all short circuit situations. In the meshed network this requirement is achieved by looking into Table 16 and set I7 lower than their minimum I_{kmin}. The set triggering current I7 for all of the circuit breakers can be found in Table 17.

Another requirement when dealing with directional zone selectivity is to ensure that other connected devices on the load side are placed outside the directional zone selectivity range of protection. This can be fulfilled by adjusting the selectivity time to make sure there is time-current selectivity with circuit breakers on the load side. Since the requirement according to Table 1 is instantaneous disconnection within 0.2 s for consumer courses, the selectivity time has been set to 0.25 s. This will guarantee that the circuit breakers on the load side of the installation trip first even if the circuit breakers in the meshed network get triggered. A more detailed analysis for this requirement is given in chapter 6.4.5.

To avoid cables being damaged during a short circuit, the breakthrough energy of the circuit breakers must be checked against the cables’ limit. This can be checked by calculating the critical time for the adiabatic heating for the cables. The largest short circuit current in the sub-distribution board is used and it is assumed that the short circuit current is distributed equally to parallel connected cables. This results in Table 18, which shows the necessary breaking time for the circuit breaker to avoid damage of the cable.

Table 18 - Breakthrough energy and necessary breaking time

	I_{kmax} [kA]	Cables in parallel	I_{kmax} per cable [kA]	k	Cable cross section [mm^2]	k^2S^2 [MA^{2}s] per cable	Necessary breaking time [s]
Cable 1	27.84	4	6.96	76	240	332.70	6.87
Cable 2	19.91	2	9.96	76	240	332.70	3.36
Cable 3	15.36	2	7.68	76	240	332.70	5.64
Cable 4	13.88	2	6.94	76	240	332.70	6.91
Cable 5	15.36	2	7.68	76	240	332.70	5.64
Cable 6	19.91	2	9.96	76	240	332.70	3.36
Cable 7	27.84	4	6.96	76	240	332.70	6.87
Cable 8	25.58	1	25.58	76	240	332.70	0.51
Cable 9	22.94	1	22.94	76	240	332.70	0.63

6.4.3 *Overload Protection in the Meshed Network*

The nominal currents for the circuit breakers have to be set to construct the time-current plot for the meshed network. The nominal current for the circuit breakers is set just beyond the current-carrying capacity for the protected cable.

Table 19 - Nominal currents for the circuit breakers in the meshed network

Nominal current setting for the circuit breakers				
	In plug [A]	Y x In	In [A]	$I_{cable\ max}$ [A]
H1:1	2000	0.8	1600	--
H1:2	1250	0.84	1050	1056
H1:3	1250	0.84	1050	1056
U1:1	800	0.97	776	792
U1:2	250	1	250	264
U2:1	800	0.97	776	792
U2:2	250	1	250	264
U3:1	630	0.64	403	528
U3:2	250	1	250	264
U4:1	630	0.64	403	528
U4:2	250	1	250	264
U5:1	630	0.64	403	528

The setting for the nominal currents is the basis for the construction of the time-current plot representing the L functionality for overload situations. The time current-plot for the meshed network is shown in Figure 28 where the green area represents H1:1, the blue area represents H1:2 and H1:3, the red area represents U1:1 and U2:1, the black area represents U3:1, U4:1 and U5:1, and the magenta area represents the circuit breakers for the meshed connections U1:2, U2:2, U3:2 and U4:2.

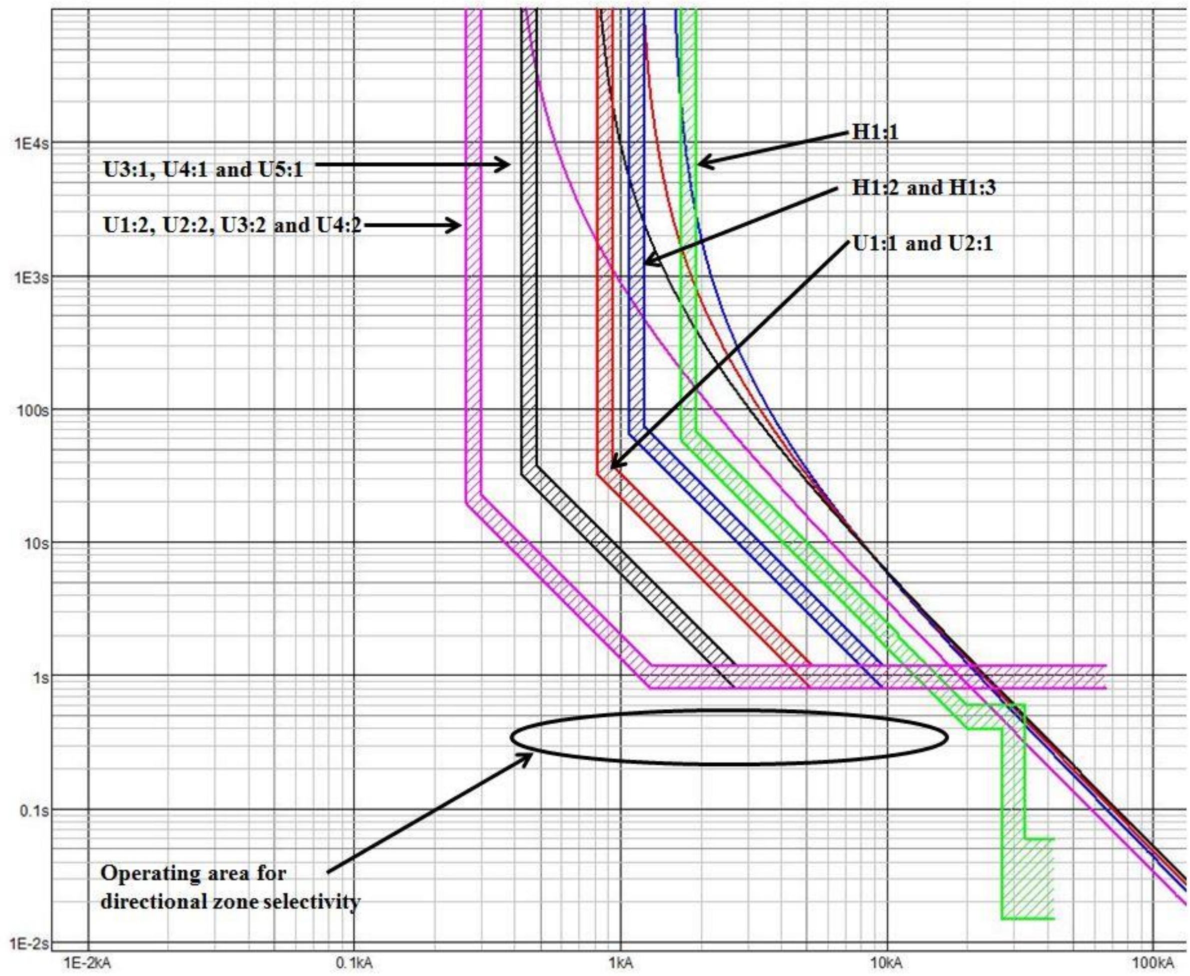

Figure 28 - Time current plot LLL-LL for meshed network

6.4.4 *OVERLOAD MANAGEMENT IN THE MESHED NETWORK*

As in the ring network, overloading can occur in parts of the meshed network if one zone falls out of service because of a fault or if one zone is taken out of service for maintenance reasons. During the design of the meshed network it was challenging to set up the interlinking cable system to get high enough short circuit currents in all the different fault situations since the short circuit current had more possible routes through the network. To get the short circuit currents high enough, it was necessary to have more cabling. Together with the two extra connections in cable 8 and 9 this resulted in a system that can handle one zone out of service without need for other actions like, for example, disconnection of non-priority loads. A specific solution for how to deal with this problem is therefore not given. All the power flow tables to prove no overload situations in this meshed network can be found in Appendix C.

Even if this is not a challenge in the meshed network simulated in this thesis, it can be challenging in other situations because of faults or maintenance in parts of a network. Therefore it can still be desirable to put in a PLC / SCADA device in the communication line to remotely control the circuit breakers, monitor measurements or program the PLC / SCADA controller to deal with automatic remote control in special situations. The same principle as described in chapter 6.3.4 for how to implement automatic remote control can still be used.

6.4.5 Selectivity between the Meshed Network and Load-Side Network

There must be proved selectivity between circuit breakers participating in the meshed network and against the load-side circuit breakers. This can be proved with the same method as for the ring network by setting up a time-current plot including circuit breakers on the load side and in the meshed network.

The same sub-distribution board U2 has been expanded with the same added loads, one motor load and one area distributor with two connected courses.

The two considerations mentioned for the ring network are still valid for the meshed network:

- Circuit breakers on the load side must disconnect short circuit with good time margin to the selectivity time set for the circuit breakers dealing with the directional zone selectivity in the meshed network
- The time-current plot for circuit breakers on the load side must not entangle with the time-current plot for circuit breakers taking part in the meshed network.

This result for the time-current plot can be found in Figure 29:

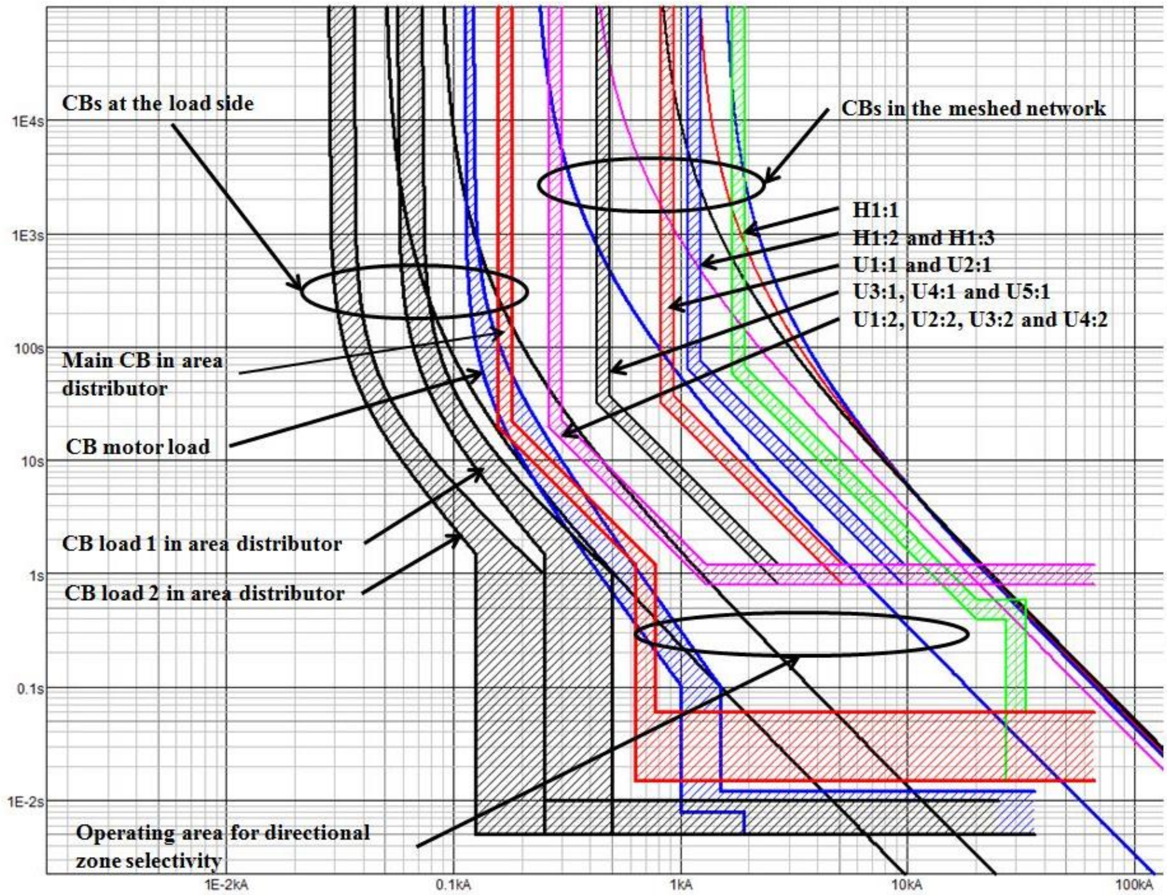

Figure 29 - Time-current plot with expanded U2, meshed network

6.5 Ring Network with Directional Zone Selectivity in a Double Feed Low Voltage Distribution Network

Traditional low voltage distribution networks are mainly constructed as radial networks and the use of live ring networks is not common by utility companies. The reason live ring networks aren't more widely used might be because of difficulties in how to deal with the selectivity. This is a situation where directional zone selectivity and ring network can be an innovative solution compared to the traditional radial structure in situations where high reliability or double fed systems are an opportunity.

In Norway, the use of overhead lines in the low voltage distribution system is a common solution in sparsely populated areas. During winter storms and other heavy weather conditions this kind of distribution system is vulnerable to damage and highly exposed to irregular power delivery. In some situations it might be possible to combine two radial networks into one ring network with two sources feeding the ring. An opportunity is then to rebuild the relay system with directional zone selectivity and increase the reliability for the network. An example of this kind of network will be given further in this chapter.

The following assumptions must be taken to not make the problem difficult to simulate:

- Transformers will not be overloaded in any situation
- The circuit breakers are put into a coupling or a transformer house for protection from weather conditions
- Communications between the circuit breakers is possible even if the distance is long

The simulated situation can be imagined as a little local grid in a sparsely populated area in Norway. It consists of overhead lines connecting two transformers and four areas of power consumption together in one ring network. The high voltage grid is considered as stiff which gives high values for the short circuit current on the secondary side of the transformers. There are in total 34 houses where each has a demand of 16 kW, the total demand in the network is 544 kW. Line 1, 3 and 4 consist of three parallel connected EX 1x3x95 mm^2 overhead lines while line 4 has four in parallel which is needed to achieve an acceptable voltage drop in every situation. The network is designed as an IT system with nominal voltage at 230 V and can be seen graphically in Figure 30.

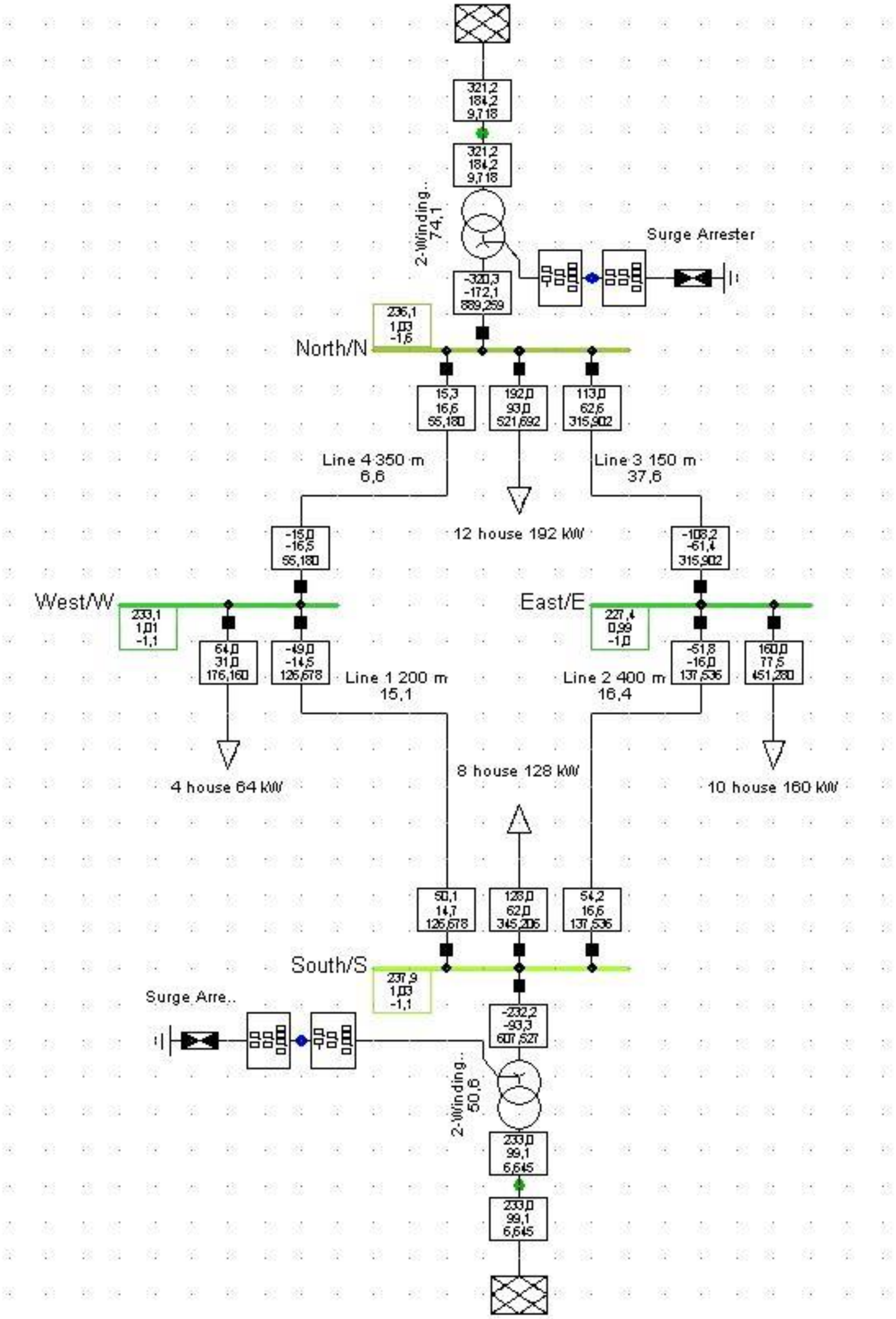

Figure 30 - Ring network in a local low voltage distribution network

6.5.1 *Short Circuit Protection with Directional Zone Selectivity*

In this network the suggested solution is to use a minimum number of the Emax 2 circuit breakers that make it possible to set up a rational protection with directional zone selectivity. The minimum number of circuit breakers needed is six. If six are used, in the worst case, only one zone will be affected in a fault situation if the circuit breakers are put into the ring network at strategic places. In Figure 31 the strategic placement of the six circuit breakers is marked with red. If higher reliability is desirable it is possible to increase the number of circuit breakers up to eight. If both red and green circuit breakers are in use the system will be redundant and if a line falls out of service, all the loads will still have a power supply via one of the directions in the ring network. Later in this analysis the solution with red marked circuit breaker will be used.

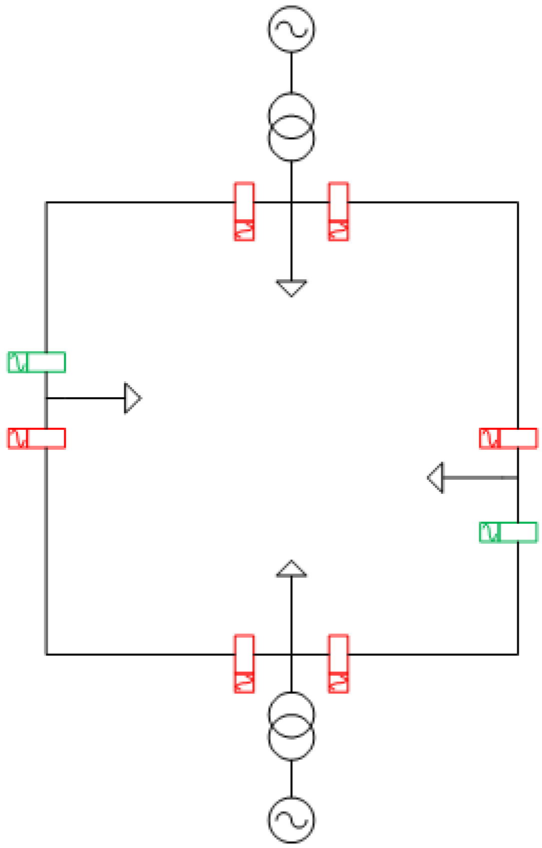

Figure 31 - Ring network with 4 or 8 circuit breakers depending on desired reliability

In Figure 31 only the Emax 2 circuit breakers are marked, but there will also be a need for protection in connection with the transformers, this is done by normal fuses that have a melting curve with slow characteristics to prevent them from melting before the circuit breakers have done their necessary disconnections. The following Table 20 shows the short circuits' currents seen by the circuit breakers and is the basis for the setting of I7 for the directional zone selectivity.

Table 20 - Short circuit currents

Circuit breaker	I_{k2pmin}	I_{k3pmax}
North R	1.422	12.96
North L	1.422	6.60
South R	1.422	5.86
South L	1.422	10.50
West	1.422	3.50
East	1.422	4.10

Depending on the corridor for the fault, west or east corridor, the short circuit current will be smaller than I_{k2pmin} noted in Table 20, but in a situation where a fault happens in the west corridor, the short circuit current seen by the circuit breakers in the east corridor is very low and within the current-carrying capacity for the lines. The circuit breakers have to be set to see and disconnect short circuits in their respective corridor, if a fault occurs in the other corridor they will receive a block signal, but never be triggered for further action. Instead the fuse in the transformer will be a backup if something goes wrong with the disconnection of some of the circuit breakers. The short circuit currents give the basis for the settings for the circuit breakers shown in Table 21.

Table 21 - Circuit breaker settings

Protection function	S		D				I
Circuit breaker	I2	t2	I7	t7FW	t7BW	ST	I3
North R	OFF	OFF	1.1 kA	350 ms	350 ms	250 ms	OFF
North L	OFF	OFF	1.1 kA	350 ms	350 ms	250 ms	OFF
South R	OFF	OFF	1.1 kA	350 ms	350 ms	250 ms	OFF
South L	OFF	OFF	1.1 kA	350 ms	350 ms	250 ms	OFF
West	OFF	OFF	1.1 kA	350 ms	350 ms	250 ms	OFF
East	OFF	OFF	1.1 kA	350 ms	350 ms	250 ms	OFF

6.5.2 *OVERLOAD PROTECTION*

There is need for an overload protection in this network even if the lines are over dimensioned because of the need for higher cross section to get the voltage drop down to an acceptable level. Instead the highest possible current flowing in the lines depending on the situation can be found and be used to define the circuit breakers' nominal current.

Table 22 - Nominal current for circuit breakers

Circuit breaker	I_{max} [A]	I_n plug [A]	Y x I_n	I_n [A]	Color in time-current plot	Tripping delay [s]
North R	461	630	0.80	504	Blue	10
North L	183	200	0.95	190	Black	10
South R	490	630	0.80	504	Blue	10
South L	177	200	0.95	190	Black	10
East	137	200	0.75	150	Red	10
West	183	200	0.95	190	Black	10

The I_n set for the circuit breakers is far away from the real current-carrying capacity for the lines, and there will never be a problem with overloading, but if the power outage over the line is increased it will result in a higher voltage drop which isn`t acceptable and therefore the current through the lines must be controlled. These I_n settings give the circuit breakers the time-current plot for overloading shown in Figure 32. The circuit breakers have been given a delay of 10 s for the overload protection L functionality. This means when a triggering signal is given for overload the circuit breaker will wait another 10 s before it responds by opening.

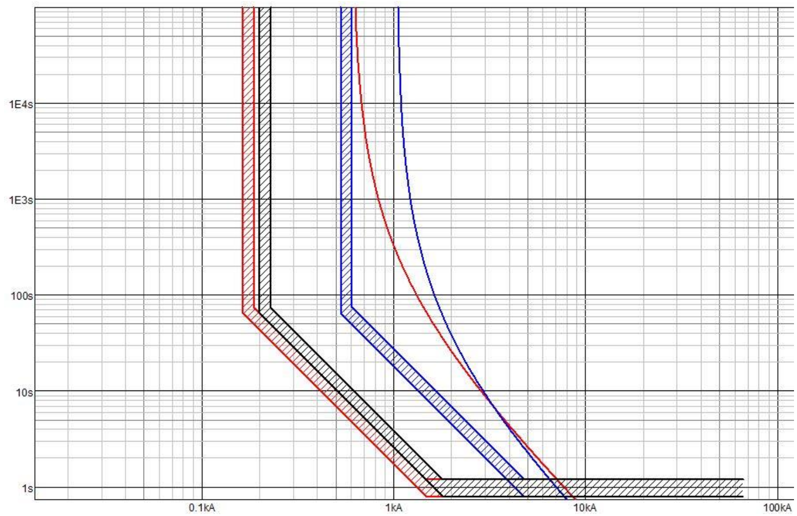

Figure 32 - Time current plot for overload situations

7 Discussion

7.1 Directional Zone Selectivity, Non-Radial Networks and Communication

This thesis has considered the use of circuit breakers with directional zone selectivity in non-radial network structures for low voltage networks. Non-radial network structures are networks with ring or meshed structure. ABB has developed circuit breakers with directional zone selectivity which enables selectivity to be achieved in non-radial networks. Simulations have been completed where directional zone selectivity has been used to present future oriented possibilities with the use of non-radial network structures in low voltage networks.

There are currently few installations and experiences using directional zone selectivity in low voltage networks, and the simulations conducted in this thesis originated therefore in hypothetical low voltage installations. Circuit breakers with directional zone selectivity are currently used by ABB in a few installations, mainly in ships and then mostly as bus tie breakers.

However, there are opportunities to use this selectivity method in low voltage installations and especially in connection with ring and meshed networks. On the basis of the circuit breakers' design and nature the usage will be primarily targeted at large electrical installations such as hospitals, industry and large office buildings where it can be actual and advantageous to use ring and meshed networks. It will in such cases be most appropriate to use directional zone selectivity just at the main distribution level in the installation to ensure high reliability.

Experiences made during simulations with the combination of non-radial networks and circuit breakers with directional zone selectivity are generally good, but projecting an installation with non-radial networks and directional zone selectivity were more demanding compared to the traditional method of radial networks and time-current selectivity. Part of the reason for this may be the use of two lesser known methods of how to design and plan an electric installation.

Lesser known methods are, for example, the use of ring or meshed networks and directional zone selectivity where the size of the installation to be planned is an important factor. Complexity in terms of size depends on the number of circuit breakers and how cooperation between these should be, and the size of the electric installation or grid. Since few installations have this solution, experiences are limited which may increase the experience of a more demanding engineering and design. A future increase in the use of non-radial networks and directional zone selectivity can change this.

With the fact that planning is more demanding and the increased complexity of such an installation, directional zone selectivity can’t be seen as an immediate successor to the traditional methods, but would be most appropriate for use in electric installations that require something extra in terms of reliability or other advanced functionality offered by the circuit breakers in the Emax 2 series.

There have been no studies of the economical aspect of investment in circuit breakers with directional zone selectivity versus conventional circuit breakers, but ABB's experience makes clear that circuit breakers with directional zone selectivity and other advanced functionality are more costly than conventional ones. This is a factor which reinforces the impression of a most appropriate use for installations requiring higher reliability or that need one or more of the advanced integrated features that can be found in the Emax 2 series.

There are also benefits to using directional zone selectivity. A major advantage is the increased ability to use non-radial networks in low voltage networks. By using non-radial networks, advantages like lower losses, lower voltage drop and increased reliability in fault situation can be achieved, benefits that previously were more or less reserved for the high voltage grid.

However, possibly one of the largest benefits is not related to the selectivity technique itself. This benefit or opportunity is the Emax 2 circuit breakers’ ability to communicate with an external control device via bus or Ethernet if they are fitted with the Ekip Com module. This allows control and management of low voltage installations at a completely different level compared to the traditional systems with conventional circuit breakers.

If this communication option is used correctly a control system can be configured to control switching of loads in the installation in for example an overload situation which is shown in the simulations. The circuit breakers are also fitted with a measurement unit and if measurement information is communicated to a control system, this creates many opportunities for advanced control functions to be implemented in low voltage networks.

In order to get the directional zone selectivity and communication ability to work properly, an auxiliary power supply module must be added in all circuit breakers. This auxiliary power supply needs in addition a power source. For correct function of the directional zone, selectivity and the communicating ability must one have an industrial Ethernet or bus connecting all the circuit breakers and devices together via Ethernet cables. This is necessary to get it all to work, but is a slight disadvantage and contributes both to additional sources for faults, more equipment necessary and higher investment costs.

7.2 Transferability to Reality

All simulations that were performed were based on hypothetical low voltage networks and none of them exist in real life. This gives an uncertainty in how transferable these networks are to a real life situation and if the method for directional zone selectivity can be directly transferred to a real project.

The simulated radial, ring and meshed networks mentioned as a possible hospital or industry installation can to certain extent be compared to a real installation. The total demand is reasonable and the design with risers is a design method used in many buildings. Overall there is just one design parameter in those networks which can be slightly unrealistic: the distances used for the interconnecting cables between the sub-distribution boards, which are set to 50 m and 75 m for the ring and meshed connections.

In a real situation 50 m between two sub-distribution boards located on each floor in the same riser will often be a bit long. This also reflects the challenging part in the simulations of the networks where it was hard to get high enough short circuit currents in any fault situation. This long length has probably affected the result of the simulations mostly in connection by not getting the full effect of the non-radial networks since more cables had to be used. If shorter interconnections had been used it would have been possible to optimize the cables' cross section more in accordance with the maximal load current instead of increasing the cross section to get high enough short circuit currents.

When it comes to the directional zone selectivity, the simulations show a method for how to implement this in low voltage networks. Based on the experience with the design and the simulations, no special challenges are identified as long as one excludes factors that increase the complexity in the design as mentioned earlier. This means that as long the requirement for directional zone selectivity is followed, the process can be as follows:

- Identify the needed level for reliability which regulates the total amount of circuit breakers in the ring or meshed network

- Identify fault locations and circuit breaker behavior
- Identify signaling and blocking between the circuit breakers
- Determine I_{kmin} for all fault situations
- Evaluate I_{kmin} for correct setting of the directional zone selectivity in each circuit breaker and make sure all circuit breakers can handle I_{kmax}. Set the selectivity time high enough to avoid triggering before load side circuit breakers
- Set the overload functionality L to not entangle in the overload zone with load side circuit breakers

If this is used as a basis there should not be any problem with implementing directional zone selectivity in low voltage networks when ring or meshed structures are used.

7.3 Directional Zone Selectivity for Utility Companies

This thesis discussed an example of a hypothetical grid with overhead lines intended to be a part of a low voltage distribution network for a utility company. This example was given to highlight the opportunity for use of directional zone selectivity in the grid. Many types of grid installations with overhead lines are exposed to heavy weather conditions and long interruptions occur more frequently, which causes many customers to lose their power for longer periods of time. Since much of the low voltage grid in addition is radial and fitted with a limited amount of fuses, a small tree that has fallen over the overhead lines can cause large areas to lose power.

The example given in this thesis shows it is possible to use directional zone selectivity in combination with ring networks in the low voltage grid. The reliability will be increased and if it in addition is double fed, the low voltage grid can be redundant, fulfilling the same criteria as used in the high voltage grid, n-1. The ability to use directional zone selectivity is not only present using overhead lines, but also in cable facilities since the principles of design of directional zone selectivity are equal for both purposes.

Utility companies in Norway must plan their grid infrastructure in accordance with socioeconomic policies. This has not been a part of this thesis and it cannot be concluded that the investment cost for such a grid installation does not need to be socioeconomically profitable.

Future development in the wider use of distributed generation among customers such as photovoltaic plants can force another way of thinking in the protection of infrastructure in the low voltage grid where it may be desirable to have communication between the circuit breakers protecting the photovoltaic plant and the utility company. In such a context, the use of circuit breakers with directional zone selectively may become a feasible option.

7.4 Manufacturers of Similar System

All simulations performed were based on the use of the ABB SACE Emax 2 circuit breakers. This is an air circuit breaker offering directional zone selectivity and a lot of other functionality to be implemented with the use of bus or Ethernet communication. Even if this is the only circuit breaker series mentioned, it doesn’t mean it is the only one available in the market with the same or a similar technology.

Siemens offers an air circuit breaker with a similar technology called Zone Selective Interlocking which is based on bus communication. Their technology is not studied in depth, but the main functionality seems to be missing the directional part. The zone selective functionality itself seems like being much the same for both products. Whether their technology is possible to use in non-radial low voltage networks has not been studied.

Eaton offers zone selectivity without the directional functionality making it possible to operate radial networks with faster disconnecting times. It seems like their zone selectivity functionality is mostly meant for use in radial networks and will probably not be suitable for use with non-radial network structures.

Many manufacturers deliver systems with bus communication between the circuit breakers. In most cases this is for use with zone selectivity and for sending of blocking signals, but systems offering remote operation and remote state reading for open / closed circuit breakers have been found. Based on available information, it seems like ABB is delivering one of the most advanced bus communicating circuit breakers on the market today.

8 CONCLUSION

The thesis objectives have been to simulate different low voltage networks with directional zone selectivity and to consider different aspects of the use of this selectivity technique, which also includes a brief introduction to this type of circuit breakers' possibility for communication and control. Simulations of radial, ring and meshed networks were performed where the ring and meshed networks were simulated with the use of directional zone selectivity. Techniques for how to handle overload situations have been considered and other possibilities as a result of the communication possibilities between the circuit breakers and a control system have been mentioned.

Examples and simulations showed that directional zone selectivity worked well as selectivity method for low voltage networks and this technique is suitable for use in both electrical installations and in the low voltage grid. Characteristics of the circuit breakers that offered directional zone selectivity were the most suitable method for electric installations of a certain size and then mainly for use in the main distribution systems.

Directional zone selectivity is particularly suitable when combined with non-radial networks which give increased reliability in security of power supply. As a method and way of thinking, this selectivity technique seems reasonable and it should be transferable to other devices and systems.

A control device could be put into the communication line between the circuit breakers offering directional zone selectivity. This could be used to control low voltage installations in overload situations by for example load shedding, and this provides many other opportunities for advanced analysis and control for low voltage networks.

The use of directional zone selectivity and communication features offered within the same circuit breaker can therefore be a possible solution for future use in low voltage networks when ring or meshed networks are considered both in electric installations and in the grid.

There are still topics in the field of directional zone selectivity and with communicating circuit breakers that can be studied more in depth; suggestions for further work follow in chapter 9.

9 Suggestion for Further Work

Suggestions for further work within the topic directional zone selectivity and for communicating circuit breakers:

- A possibility is to do a laboratory test of the circuit breakers where directional zone selectivity is an option. This could have focused on the use of directional zone selectivity for use in building installations and industry where non-radial networks can be an option. The test setup and the testing could be based on the simulated networks in this thesis to get more practical experience with the use of directional zone selectivity.
- The circuit breakers offer possibilities with bus communication and control. A study looking into how low voltage installations can be controlled by the use of a PLC / SCADA device. How can the measurement data from each circuit breaker be used to control the electric installation, can this for example be implemented in a large bus system? How much can really be controlled and to what extent does this create new opportunities?

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11 APPENDIX

Appendix A - Radial Network 1

Appendix B - Ring Network 3

Appendix C - Meshed Network 9

Appendix D - Disconnection of Non-Priority Loads 15

APPENDIX A - RADIAL NETWORK

General system description:

Voltage: 400 V

Distribution system: TN-C-S

Transformer: 1250 kVA

Cabel data: PFSP 4 x 240 / 120 mm^2 AL cabel, capacity 264 A per cable

The capasity used for the cabels is calculated with the basis from [8]. The cables are layed with metode E, in air on cabel ladders. Accordingly to Tabel 52 B 11 and corrcetion factor for more than one cable on the ladder set to 0.8 from Tabel 52 B 17 in [8] got each cabel a calculated I_z = 264 A. The same I_z is used for all cabels of simplicity reason.

Table A1 - Cable plan in the radial network

Cabel number	Length [m]	Cabels in paralell	Total cabel capasity [A]
Cabel 1	50	4	1056
Cabel 2	50	2	528
Cabel 3	50	1	264
Cabel 7	50	4	1056
Cabel 6	50	2	528
Cabel 5	50	1	264

Table A 2 - Power demand

Load	Demand [kW]
Load 1	240
Load 2	200
Load 3	150
Load 4	120
Load 5	120
Load 6	70
Total demand	900

APPENDIX B - RING NETWORK

General system description:

Voltage: 400 V

Distribution system: TN-C-S

Transformer: 1250 kVA

Cabel data: PFSP 4 x 240 / 120 mm^2 AL cabel, capacity 264 A per cable

The capasity used for the cabels is calculated with the basis from [8]. The cables are layed with metode E, in air on cabel ladders. Accordingly to Tabel 52 B 11 and corrcetion factor for more than one cable on the ladder set to 0.8 from Tabel 52 B 17 in [8] got each cabel a calculated I_z = 264 A. The same I_z is used for all cabels of simplicity reason.

Table B1 - Cables plan for ring network

Cabel number	Cable length [m]	Cabels in paralell	Total cabel capasity [A]
Cabel 1	50	4	1056
Cabel 2	50	2	528
Cabel 3	50	2	528
Cabel 4	75	2	528
Cabel 5	50	2	528
Cabel 6	50	2	528
Cabel 7	50	4	1056

Table B2 - Demand in the ring network

Load	Demand [kW]
Load 1	240
Load 2	200
Load 3	150
Load 4	120
Load 5	120
Load 6	70
Total demand	900

Table B3 - Power flow under normal operation

Node	P [kW]	Q[kvar]	I [A]	Loding on cabel(s) [%]
H1 to U1	484.6	156.1	719	68.1
H1 to U2	422.4	138.5	628	59.5
U1 to U3	242.1	78.1	361	68.4
U2 to U4	220.5	65.0	326	61.8
U3 to U5	90.9	40.1	142	26.9
U4 to U6	99.5	34.4	150	28.5
U6 to U5	29.3	18.1	49	9.3

Table B4 - Power flow with fault in cable 1 or U1

Node	P [kW]	Q[kvar]	I [A]	Loding on cabel(s) [%]
H1 to U1	0	0	0	0
H1 to U2	674.7	223.2	1000	94.7
U1 to U3	0	0	0	0
U2 to U4	470.0	147.9	699	132.3
U5 to U3	150.0	37.2	226	42.9
U4 to U6	345.5	115.0	522	98.8
U6 to U5	270.4	95.6	419	79.3

Table B5 - Power flow with fault in cable 2 or U3

Node	P [kW]	Q[kvar]	I [A]	Loding on cabel(s) [%]
H1 to U1	240.6	76.8	356	33.7
H1 to U2	516.2	180.5	771	73.0
U1 to U3	0	0	0	0
U2 to U4	313.4	106.4	469	88.9
U3 to U5	0	0	0	0
U4 to U6	191.3	75.1	294	55.6
U6 to U5	120.0	58.1	192	36.4

Table B6 - Power flow with fault in cable 3 or U5

Node	P [kW]	Q[kvar]	I [A]	Loding on cable(s) [%]
H1 to U1	392.0	114.9	575	54.5
H1 to U2	392.4	120.0	578	54.7
U1 to U3	150.4	37.5	219	41.5
U2 to U4	190.8	46.6	278	52.6
U3 to U5	0	0	0	0
U4 to U6	70.1	16.2	102	19.4
U6 to U5	0	0	0	0

Table B7 - Power flow with fault in cable 4, cable 5 or U6

Node	P [kW]	Q[kvar]	I [A]	Loding on cable(s) [%]
H1 to U1	72.6	174.8	767	72.6
H1 to U2	321.4	103.1	476	45.1
U1 to U3	271.9	96.5	410	77.6
U2 to U4	120.3	30.1	176	33.3
U3 to U5	120.3	58.3	191	36.2
U4 to U6	0	0	0	0
U6 to U5	0	0	0	0

Table B8 - Power flow with fault on cable 6 or U4

Node	P [kW]	Q[kvar]	I [A]	Loding on cable(s) [%]
H1 to U1	587.0	192.4	871	82.5
H1 to U2	200.4	72.6	301	28.5
U1 to U3	343.4	113.7	514	97.3
U2 to U4	0	0	0	0
U3 to U5	190.9	74.9	294	55.6
U4 to U6	0	0	0	0
U5 to U6	70.1	16.2	104	19.6

Table B9 - Power flow with fault in cable 7 or U2

Node	P [kW]	Q[kvar]	I [A]	Loding on cable(s) [%]
H1 to U1	713.3	226.4	1053	99.7
H1 to U2	0	0	0	0
U1 to U3	468.1	146.6	696	131.8
U2 to U4	0	0	0	0
U3 to U5	313.5	106.5	475	89.9
U6 to U4	120.0	29.9	180	34.2
U5 to U6	191.4	47.0	285	53.9

Table B10 - I_{k1pmin} and I_{k3pmax} [kA] seen by the circuit breakers in different fault situations

Fault in	Fault zone 1	Fault zone 2		Fault zone 3		Fault zone 4		Fault zone 5		Fault zone 6		Fault zone 7			
Fault at	Bus H1	Cable 1	Bus U1	Cable 7	Bus U2	Cable 2	Bus U3	Cable 6	Bus U4	Cable 3	Bus U5	Cable 4	Bus U6	Cable 5	Ik3pmax
H1:1	31.54	27.84	24.58	27.84	24.58	19.91	17.07	19.91	17.07	15.36	14.38	13.88	14.38	15.36	28.38
H1:2	0.00	26.77	22.69	1.07	1.89	16.85	13.13	3.06	3.94	10.64	8.85	6.94	5.53	4.73	28.38
H1:3	0.00	1.07	1.89	26.77	22.69	3.06	3.94	16.85	13.13	4.73	5.53	6.94	8.85	10.64	28.38
U1:1	0.00	1.07	1.89	1.07	1.89	16.85	13.13	3.06	3.94	10.64	8.85	6.94	5.53	4.73	23.27
U2:1	0.00	1.07	1.89	1.07	1.89	3.06	3.94	16.85	13.13	4.73	5.53	6.94	8.85	10.64	23.27
U3:1	0.00	1.07	1.89	1.07	1.89	3.06	3.94	3.06	3.94	10.64	8.85	6.94	5.53	4.73	16.18
U4:1	0.00	1.07	1.89	1.07	1.89	3.06	3.94	3.06	3.94	4.73	5.53	6.94	8.85	10.64	16.18
U5:1	0.00	1.07	1.89	1.07	1.89	3.06	3.94	3.06	3.94	4.73	5.53	6.94	5.53	4.73	11.76

APPENDIX C - MESHED NETWORK

General system description:

Voltage: 400 V

Distribution system: TN-C-S

Transformer: 1250 kVA

Cable data: PFSP 4x240/120 mm^2 AL cabel, capacity 264 A per cable

The capasity used for the cabels is calculated with the basis from [8]. The cables are layed with metode E, in air on cabel ladders. Accordingly to Tabel 52 B 11 and corrcetion factor for more than one cable on the ladder set to 0.8 from Tabel 52 B 17 in [8] got each cabel a calculated I_z = 264 A. The same I_z is used for all cabels of simplicity reason.

Table C1 - Cable plan for the meshed network

Cabel number	Cable length [m]	Cabels in paralell	Total cabel capasity [A]
Cabel 1	50	4	1056
Cabel 2	50	3	792
Cabel 3	50	2	528
Cabel 4	75	2	528
Cabel 5	50	2	528
Cabel 6	50	3	792
Cabel 7	50	4	1056
Cable 8	75	1	264
Cable 9	75	1	264

Table C2 - Demand in the meshed network

Load	Demand [kW]
Load 1	240
Load 2	200
Load 3	150
Load 4	120
Load 5	120
Load 6	70
Total demand	900

Table C 3 - Power flow in normal operation

Node	P [kW]	Q[kvar]	I [A]	Loding on cable(s) [%]
H1 to U1	473.7	169.0	711	67.4
H1 to U2	432.5	146.9	646	61.2
U1 to U3	238.1	78.2	356	45.0
U2 to U4	223.8	68.5	333	42.0
U3 to U5	97.3	39.0	150	28.3
U4 to U6	93.1	27.5	139	26.2
U6 to U5	22.9	19.2	43	8.1
U4 to U3	10.0	5.8	16	6.2
U2 to U1	6.8	3.6	11	4.2

Table C4 - Power flow with fault in connection to U1

Node	P [kW]	Q[kvar]	I [A]	Loding on cable(s) [%]
H1 to U1	0	0	0	0
H1 to U2	670.3	225.8	995	94.3
U1 to U3	0	0	0	0
U2 to U4	465.7	149.2	693	87.6
U5 to U3	12.4	3.0	18	3.5
U4 to U6	203.8	64.2	305	57.8
U6 to U5	132.4	55.1	207	39.1
U4 to U3	137.6	47.5	210	79.5
U2 to U1	0	0	0	0

Table C5 - Power flow with fault in connection to U2

Node	P [kW]	Q[kvar]	I [A]	Loding on cable(s) [%]
H1 to U1	710.1	244.9	1058	100.2
H1 to U2	0	0	0	0
U1 to U3	464.8	148.6	693	87.5
U2 to U4	0	0	0	0
U3 to U5	201.1	71.0	305	57.8
U6 to U4	10.0	4.0	16	3.0
U5 to U6	80.2	12.3	117	22.1
U3 to U4	110.7	31.2	165	62.3
U2 to U1	0	0	0	0

Table C6 - Power flow with fault in connection to U3

Node	P [kW]	Q[kvar]	I [A]	Loding on cable(s) [%]
H1 to U1	275.0	103.9	415	39.3
H1 to U2	480.9	167.4	718	68.0
U1 to U3	0	0	0	0
U2 to U4	312.6	102.8	467	58.9
U3 to U5	0	0	0	0
U4 to U6	191.3	67.1	289	54.7
U6 to U5	120.0	58.1	192	36.3
U4 to U3	0	0	0	0
U1 to U2	34.2	10.5	51	19.2

Table C7 - Power flow with fault in connection to U4

Node	P [kW]	Q[kvar]	I [A]	Loding on cable(s) [%]
H1 to U1	537.7	190.7	805	76.3
H1 to U2	248.7	90.6	374	35.4
U1 to U3	342.6	112.4	512	64.6
U2 to U4	0	0	0	0
U3 to U5	190.9	66.9	289	54.7
U4 to U6	0	0	0	0
U5 to U6	70.1	8.2	101	19.2
U4 to U3	0	0	0	0
U2 to U1	47.9	16.5	712	27.3

Table C8 - Power flow with fault in connection to U5

Node	P [kW]	Q[kvar]	I [A]	Loding on cable(s) [%]
H1 to U1	395.9	134.8	590	55.8
H1 to U2	388.1	121.7	573	54.3
U1 to U3	155.6	43.0	229	28.9
U2 to U4	185.3	45.0	270	34.1
U3 to U5	0	0	0	0
U4 to U6	70.1	8.2	100	19.0
U6 to U5	0	0	0	0
U3 to U4	5.3	-1.7	8	3.0
U2 to U1	1.3	2.2	4	1.4

Table C9 - Power flow with fault in connection to U6

Node	P [kW]	Q[kvar]	I [A]	Loding on cable(s) [%]
H1 to U1	464.2	175.2	701	66.4
H1 to U2	371.1	132	557	52.7
U1 to U3	237.3	87.9	360	45.4
U2 to U4	154.2	50.4	230	29.1
U3 to U5	120.3	58.3	191	36.1
U4 to U6	0	0	0	0
U6 to U5	0	0	0	0
U4 to U3	33.8	15.4	53	20.1
U2 to U1	15.4	7.1	24	9.2

Table C10 - Power flow with fault in connection to Cable 8

Node	P [kW]	Q[kvar]	I [A]	Loding on cable(s) [%]
H1 to U1	478.8	171.7	719	68.1
H1 to U2	427.4	144.2	638	60.4
U1 to U3	236.4	77.3	354	44.7
U2 to U4	225.5	69.4	335	42.3
U3 to U5	96.5	38.6	148	28.1
U4 to U6	93.9	27.9	140	26.5
U6 to U5	23.7	19.6	44	8.3
U4 to U3	10.9	6.3	18	6.8
U2 to U1	0	0	0	0

Table C11 - Power flow with fault in connection to Cable 9

Node	P [kW]	Q[kvar]	I [A]	Loding on cable(s) [%]
H1 to U1	478.4	171.8	719	68.1
H1 to U2	427.8	144.2	638	60.5
U1 to U3	244.4	81.9	367	46.3
U2 to U4	217.5	64.9	323	40.7
U3 to U5	93.6	36.9	144	27.2
U4 to U6	96.8	29.7	144	27.3
U6 to U5	26.6	21.4	49	9.2
U3 to U4	0	0	0	0
U2 to U1	8.4	4.6	14	5.1

Table C12 - I_{k1pmin} and I_{k3pmax} [kA] seen by the circuit breakers in different fault situations

Fault in	Fault zone 1	Fault zone 2		Fault zone 3		Fault zone 4		Fault zone 5		Fault zone 6		Fault zone 7			Fault zone 8	Fault zone 9	
Fault at	Bus H1	Cable 1	Bus U1	Cable 7	Bus U2	Cable 2	Bus U3	Cable 6	Bus U4	Cable 3	Bus U5	Cable 4	Bus U6	Cable 5	Cable 8	Cable 9	Ik3pmax
H1:1	31.54	28.08	25.46	28.08	25.46	22.31	20.28	22.31	20.28	17.28	15.67	14.88	15.67	17.28	18.40	15.72	28.38
H1:2	0.00	25.26	20.34	2.82	5.12	16.31	13.46	5.99	6.82	10.66	8.94	7.44	6.74	6.62	9.20	7.86	28.38
H1:3	0.00	2.82	5.12	25.26	20.34	5.99	6.82	16.31	13.46	6.62	6.74	7.44	8.94	10.66	9.20	7.86	28.38
U1:1	0.00	1.42	2.58	1.42	2.58	18.03	14.57	4.27	5.71	11.34	9.30	7.44	6.37	5.95	0.00	7.86	25.58
U2:1	0.00	1.42	2.58	1.42	2.58	4.27	5.71	18.03	14.57	5.95	6.37	7.44	9.30	11.34	0.00	7.86	25.58
U3:1	0.00	0.66	1.19	0.66	1.19	1.97	2.64	1.97	2.64	13.21	10.32	7.44	5.35	4.07	0.00	0.00	22.94
U4:1	0.00	0.66	1.19	0.66	1.19	1.97	2.64	1.97	2.64	4.07	5.35	7.44	10.32	13.21	0.00	0.00	22.94
U5:1	0.00	0.66	1.19	0.66	1.19	1.97	2.64	1.97	2.64	4.07	10.32	7.44	5.35	4.07	0.00	0.00	20.04
U1:2. U2:2	0.00	1.40	2.54	1.40	2.54	1.72	1.11	1.72	1.11	0.67	0.37	0.00	1.02	0.67	9.20	0.00	25.46
U3:2. U4:2	0.00	0.77	1.39	0.77	1.39	2.30	3.08	2.30	3.08	1.87	1.02	0.00	0.37	1.87	0.00	7.86	22.86

APPENDIX D - DISCONNECTION OF NON-PRIORITY LOADS

Fault or maintenance in zone 2:

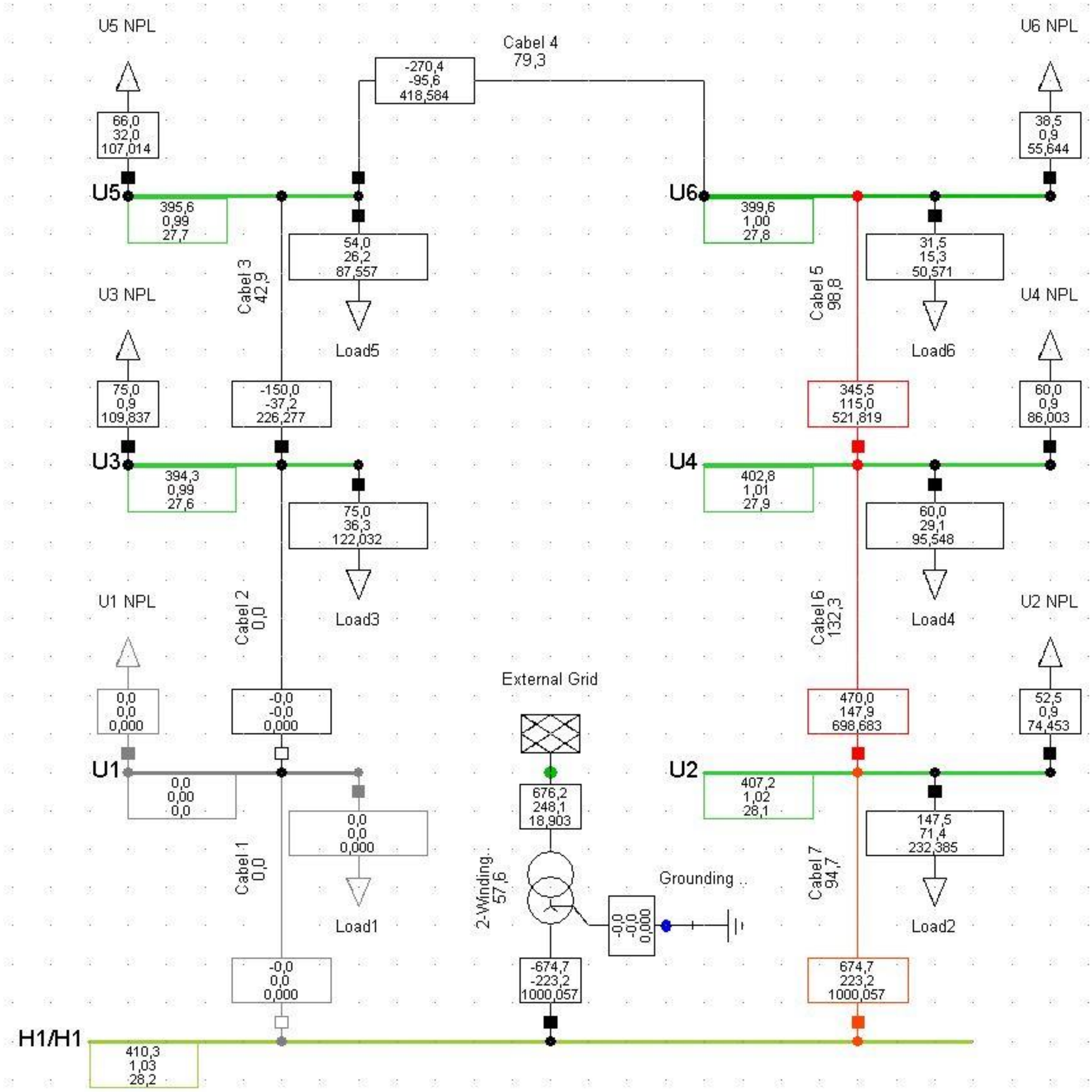

Figure D1 - Power flow with zone 2 out of service

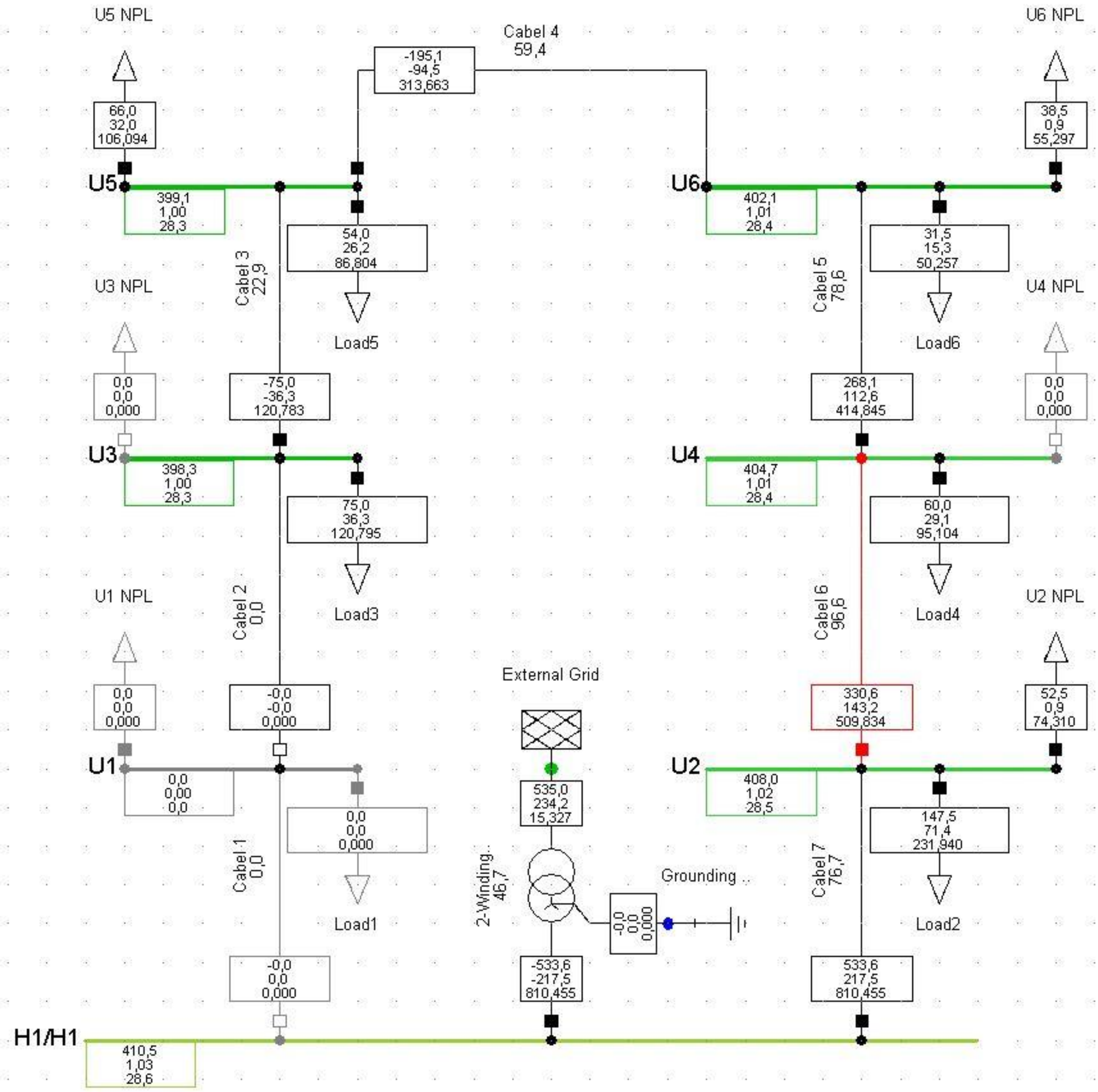

Figure D2 - Power flow with zone 2 out of service and necessary non-priority loads disconnected

Fault or maintenance in zone 3:

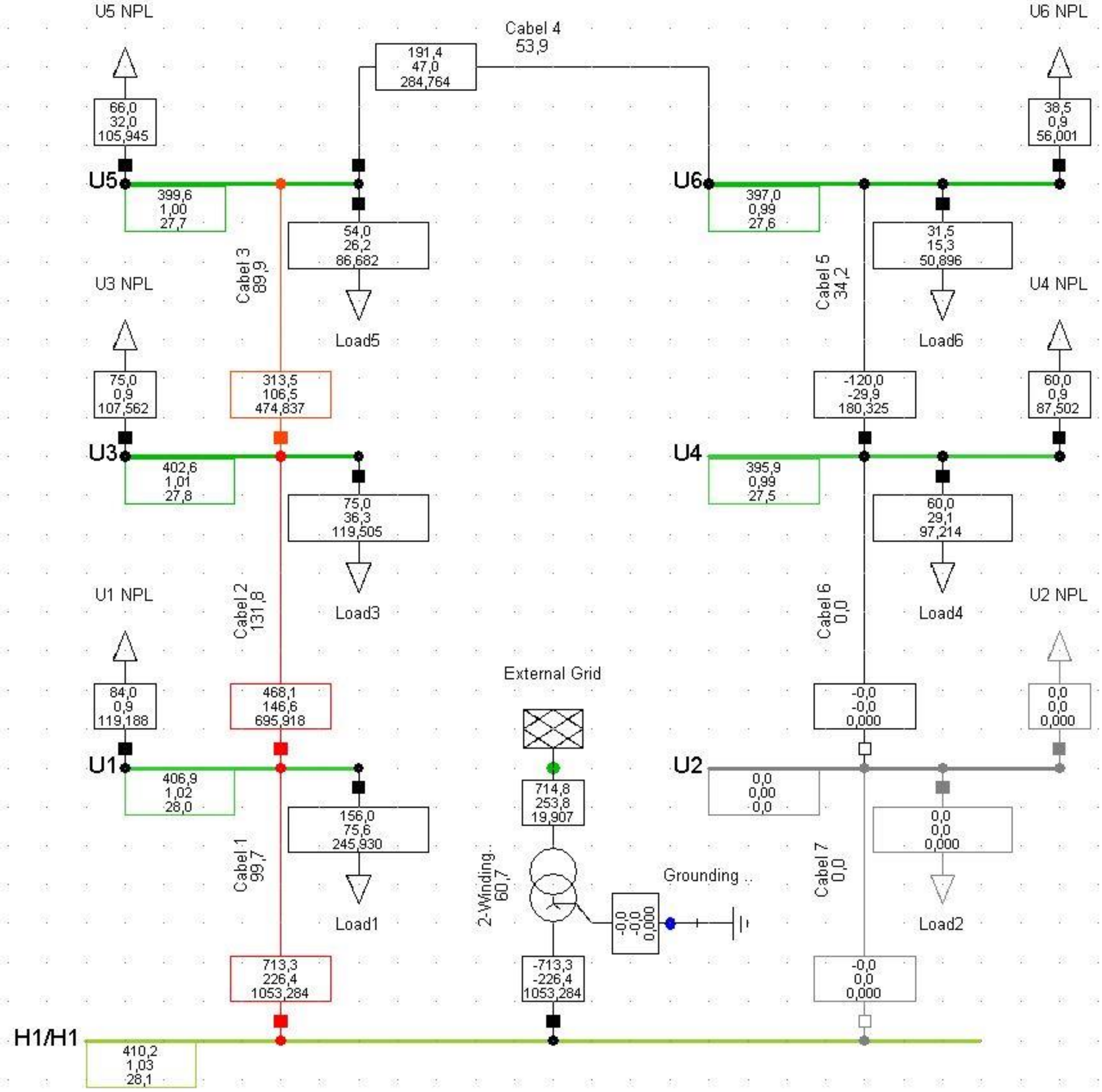

Figure D3 - Power flow with zone 3 out of service

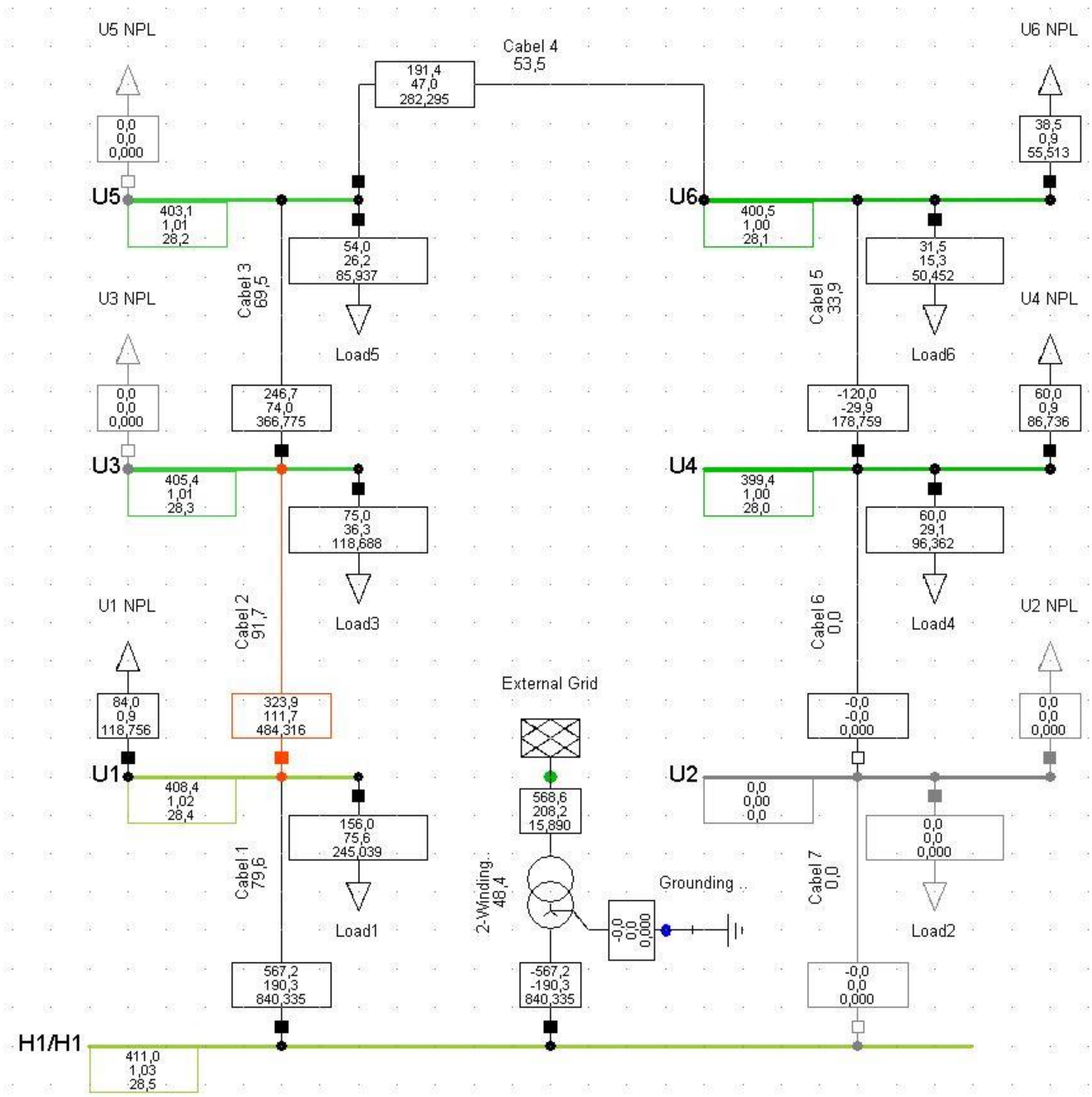

Figure D4 - Power flow with zone 3 out of service and necessary non-priority loads disconnected

With fault or maintenance in the remaining zones is there no need for disconnecting zones due to overloading.