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Short-circuit analysis of the onsite electric power system at Ringhals unit 4

Master of Science Thesis in the Master Degree Programme Electric Power Engineering

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Performed at Ringhals AB
Gothenburg, Sweden, 2010

VATTENFALL

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ABSTRACT

Because of an upcoming modernization of the electric system in unit 3 and 4 at Ringhals AB, new short-circuit current calculations have to be made. This report focuses on the development of a model of the electric power system in a nuclear power plant in order to perform short-circuit current calculations. In this model, different components can be exchanged in order to investigate future adjustments in the system.

The IEC 60909-0 standard is used in order to calculate various types of short-circuit currents for the power system. The usage of the standard IEC 60909-0 is in some cases quite conservative, which is positive when calculating currents for a system of this type. For the standard IEC 60909-0, some correction factors are introduced. The factor K_T is used for correction of the impedance of the transformers and K_G is used for the correction of the generator impedance. For the voltage, two factors are introduced to increase/decrease the voltage at the fault location. The power system is divided into several different voltage levels, where calculations are made for short circuits on the 6,6 kV and 500 V levels. Nine different cases are set up in order to evaluate the system, so that the maximum and minimum currents can be determined.

The different currents examined appear when a balanced three-phase fault occurs. The calculated currents are the maximum initial short-circuit current, the peak short-circuit current, and the maximum and minimum steady-state short-circuit currents. Among the cases that have been examined, the real case that gives the highest maximum initial current is case 3 for all buses. In the same case, the highest peak current and maximum steady-state current appear. The lowest minimum steady-state current is found in case 8 for the buses H4x-y6 and VHC4x, and in case 9 for the buses D4x-y6 and DHC4x.

In the performed sensitivity analysis, the new calculations have been compared to previous results. The deviations are small for all cases, which means that the new calculations have been performed with great satisfaction.

Keywords: short-circuit current, electric power system, IEC 60909-0, initial short-circuit current, steady-state short-circuit current, peak short-circuit current, per unit calculations, nuclear power plant.

SAMMANFATTNING

På grund av kommande moderniseringar av elsystemen i reaktorerna Ringhals 3 och 4, måste nya kortslutningsberäkningar tas fram. Denna rapport fokuserar på utvecklingen av en modell för det kraftelektriska systemet i ett kärnkraftverk för att kunna utföra kortslutningsberäkningar. I denna modell kan olika komponenter bytas ut för att undersöka framtida förändringar i systemet.

Den internationella standarden IEC 60909-0 används för att beräkna de olika typer av kortslutningsströmmar som uppkommer i systemet. Standarden IEC 60909-0 kan i vissa avseenden ge något konservativa resultat, vilket är fördelaktigt för beräkningar i denna typ av system. För denna standard introduceras ett flertal olika korrektionsfaktorer. Faktorn K_T används för att korrigera impedansen i systemets transformatorer och faktorn K_G används för att korrigera generatorernas impedans. För beräkningsspänningen introduceras två olika faktorer för att öka/minska spänningen i felstället. Elkraftsystemet är indelat i ett flertal olika spänningsnivåer, där beräkningar görs för kortslutningar på 6,6 kV- och 500 V- nivåerna. Nio olika typer av fall sätts upp för att utvärdera systemet, så att de största och minsta strömmarna kan bestämmas.
De olika strömmar som har undersökts uppstår när det sker ett symmetriskt trefas-fel. De beräknade strömmarna är den sub-transienta kortslutningsströmmen, stötströmmen, samt den största och minsta stationära kortslutningsströmmen. Bland de fall som har undersökts är fall 3 det verkliga fall som ger de största sub-transienta strömmarna för samtliga skenor. Samma fall ger även den största stötströmmen och den största maximala stationära kortslutningsströmmen. Den minsta minimala stationära kortslutningsströmmen återfinns i fall 8 för skenorna H4x-y6 och VHC4x och i fall 9 för skenorna D4x-y6 och DHC4x.

I den utförda känslighetsanalysen har de nya beräkningarna jämförts med tidigare resultat. Avvikelserna är små i samtliga jämförelser, vilket innebär att de nya kortslutningsberäkningarna är tillfredsställande.

Rapporten är skriven på engelska.

ACKNOWLEDGEMENTS

At first I would like to thank my supervisor at Ringhals AB, Sofia Johansson, for giving me the opportunity to perform the Thesis Work at Ringhals AB and for great help and assistance. I would also like to give many special thanks to Magnus Knutsson and Klas Sjöberg at RAB for help and support during the work. Other people that have been of great help is Jonas Olsson (Gothia Power AB), Joakim Karlsson (ÅF Consult AB) and others at the division, RTAE, at Ringhals AB. Sara Athley needs thanks for priceless support throughout the work.

Finally I would like to thank my examiner at Chalmers University of Technology, Tuan A. Le.

ABBREVIATIONS

AC	Alternating Current
CSP	ChloroSulphonated Polyethylene (Hypalon)
DC	Direct Current
IEC	International Electrotechnical Commission
I_k	Steady-state short-circuit current
I_k''	Initial short-circuit current
I_p	Peak short-circuit current
I_{th}	Thermal short-circuit current
R	Resistance
RCP	Reactor Cooling Pump
SCC	Short-circuit current calculation
Sub	Subsystem
SvK	Svenska Kraftnät
V	Volt
W	Watt
X	Reactance
XLPE	Cross-linked PolyEthylene

CONTENTS

1 INTRODUCTION

1.1 Background

At a nuclear power plant, the work of upgrading and changing components in the system is an ongoing project. RTAE (Ringhals Teknik process och Anläggningsteknik El och I&C) will carry out a concept study for a modernization of the onsite power system switchgear and for a renewed electric manoeuvre for the control room at Ringhals 3 and 4. Analogue components will be exchanged in order to give room to digital ones. The electric system has gone through some smaller changes, by replacement of components, since it was first constructed. The calculations at hand were made when the system were under construction. New calculations will consequently be made to ascertain that the old calculations are still valid. Short circuit calculations have to be carried out so that data is accessible, when new equipment is going to be dimensioned, when developing the new system. The calculations are also important for the compatibility of different components and for the function and dimensioning of the settings and coordination of the protection system for the onsite power system.

1.2 Purpose

Because of an upcoming modernization of the electric system in the units Ringhals 3 and 4, new short-circuit current calculations have to be made and old calculations have to be examined.

The main purpose of the report is to carry out new calculations in order to secure the existing system’s reliability and to investigate the differences between new and old calculations. Included in this task is to develop a model where parts can be exchanged in order to evaluate the suitability of new parts in the system. The new calculations are performed according to the standard IEC 60909-0, first edition.

1.3 Delimitations

The calculations are supposed to cover both systems in Ringhals 3 and 4 (R3 & R4). Since the systems are very similar, a limitation is set to carry out all calculations for R4, not for R3. R4 is chosen because of its approaching power upgrade where the thermal power will increase with 18,6% to 3300 MW [14]. New calculations and safety analyses are conditions for the upgrade to be carried out in a secure way.

The onsite electric system of Ringhals 4 is divided into four different subsystems.

Calculations are limited down to 500 VAC levels “DHC” and “VHC” for all the four subsystems. For sub A, calculations are made for all the different levels more thoroughly. The subsystems are similar and because of this a limitation of this work is to analyze one subsystem in detail. The actual system with the existing components at the date 2009-10-02 is analyzed. For motors on the DHC level, all contribution are taken from Peter Angbergs compilation of motors [C5], where an equivalent impedance for all motors has been calculated. The impedance of the cables connecting the motors to the bus, DHC4x, is neglected. For the VHC-level, VHC41 has been thoroughly examined and the equivalent impedance of this bus has been used as a model for the other buses on the VHC level.

2 THEORETICAL BACKGROUND

2.1 Short-circuit current calculations

Among the most important tasks, when planning and operating power systems, are the short-circuit current calculations (SCCs). Faults, i.e. short-circuits, can be minimized in the system through planning and design, and well-performed maintenance and operation of the system, but cannot be totally avoided. Protection settings and coordination and dimensioning of switchgear require accurate and detailed SCCs because switches and breakers have to be designed to switch off short-circuits in a safe way and in short time. Another problem with short circuits is that currents that go through earth can induce voltages that are disturbing objects in the neighboring area, for example pipelines, fences and other metallic objects. Short-circuits can cause mechanical oscillations in generators which can lead to oscillations in the power in the system, causing problems of stability in the power transfer. In the worst case this can lead to a blackout of the system. One last area to consider is that the installed equipment must be able to withstand the thermal and mechanical effects of short-circuit currents [1][2].

The methods of SCCs have been developed and improved to better meet the requirements from the industry. Nowadays there are a number of different SCCs methods to be used in different cases. Mainly the enhancements have been to, take into account the impact of AC and DC decay resulting from rotating machines. These enhancements vary from simple corrections of sequence impedances to more complex calculations of sub-transient and transient impedances and short-circuit time constants for rotating machines [1].

2.1.1 IEC 60909-0

One of the more conservative method-compilations is the standard IEC 60909-0 [4], first edition. This standard is commonly used in Europe and is the standard to use according to ELSÄK FS 2004:1, when calculating SCCs at Ringhals. ELSÄK FS 2004:1 has been replaced by ELSÄK 2008:1 but in this standard, the connection to the standard IEC 60909-0 does not exist. Since the IEC 60909-0 has been used earlier according to ELSÄK FS 2004:1, it is considered appropriate to still use this standard when calculating short-circuit currents.

The standard used is very similar to the method of fixed impedance decaying short-circuit calculation, FIC. The most important difference is the use of voltage correction factors and impedance factors in the IEC standard. This will increase the voltage magnitude of the voltage source applied to the passive network, which will lead to an increase in current by a certain percentage. The currents will always be higher when using the IEC 60909-0 standard, which sometimes leads to more conservative results. However, this is advantageous when dealing with circuits that have a very high level of safety as in a nuclear power generating system. In IEC 60909-0 all the impedances of rotating machines are constant. The constant impedances for synchronous machines are calculated by use of the sub-transient impedances and corresponding impedance correction factors. When calculating the constant impedances for asynchronous machines, the locked rotor impedance values are used [1][4].

2.1.2 Maximum short-circuit current

When creating the design for the rating of equipment and what it can withstand, the main criterion is the maximum short-circuit current. It will limit the equipment as to how much thermal and electromagnetic (mechanical) effects it can resist without breaking. Maximum short-circuit current calculations are carried out for the design of substation earth electrode systems.

A detailed knowledge of the circuit is required so that the estimation of the maximum short-circuit current is accurate, without resulting in an unnecessary high rating of the equipment which leads to too high economic costs [2][3].

When calculating maximum short-circuit currents with IEC 60909-0 a few different conditions have to be introduced:

- A voltage factor c_{max} will be applied for the maximum calculation.
- The configuration that gives the maximum contributions from power plants and network feeders, which leads to the highest short-circuit current at the short circuit location, should be used.
- When external networks are to be represented by the equivalent impedance, the minimum equivalent impedance shall be used which corresponds to the maximum short-circuit current contribution from the feeders.

- In the most cases, motors are included in the calculations. The resistances of all the lines in the system are introduced at a temperature of 20°C [4].

2.1.3 Minimum short-circuit current

The minimum short-circuit current is needed when designing for protection systems and relay-settings to ensure accurate and coordinated relay operation. As well as for the maximum short-circuit current a detailed calculation of the currents has to be performed. When planning the safety margins of the protection of the system, it is important that none of the breakers trip for the highest operating current in the circuit as well as they have to be switched off for any short-circuit event [2][3].

When calculating minimum short-circuit currents with IEC 60909-0 a few different conditions have to be met:

- A voltage factor c_{min} is applied for the minimum calculation.
- The system configuration that leads to the minimum short-circuit current at the location of the fault has to be chosen.
- All motors can be neglected.

- Lines are introduced at a higher temperature [4].

2.1.4 Symmetrical three-phase faults

The symmetrical or balanced fault occurs when all the three different phases are connected, or shorted to ground. The duration of a fault can be divided into three different areas:

- The *sub-transient* period which occurs directly at the fault location. It lasts only for a couple of cycles.
- The *transient* period which occurs for tens of cycles.
- The *steady-state* period which will last for a longer time, for instance until there is a change in the system like if a line is failing or if a circuit breaker is opened [5]. See figure 1 for the different states and currents.

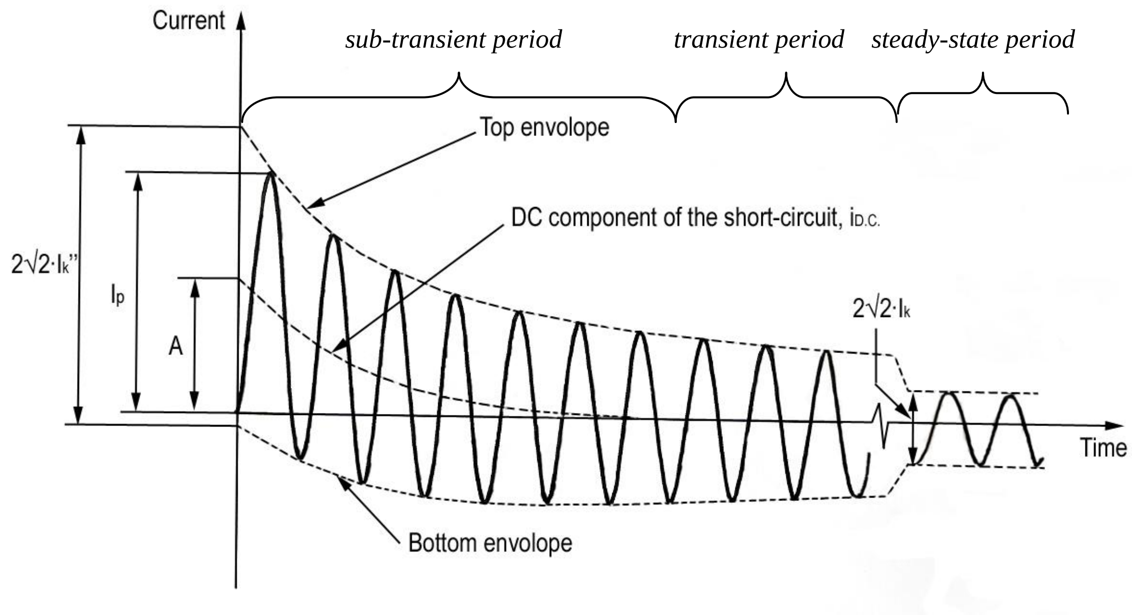

Figure 1. *Short-circuit currents with a decaying A.C.-component and different states during the short-circuit.*

2.1.4.1 Initial short-circuit current, I_k"

The highest initial short-circuit current will for this type of system, an impedance earthed neutral system, occur when there is a three-phase fault, see fig 10. in IEC 60909-0. The initial short-circuit current is the root mean square value of the initial AC component of the short-circuit current. I_k'' is used for maximum short-circuit current calculations. For a three-phase short-circuit the initial short-circuit current, I_k'' is calculated according to equation (1).

$$I_k'' = \frac{c_{\max} \cdot U_n}{\sqrt{3} \cdot Z_k} = \frac{c_{\max} \cdot U_n}{\sqrt{3} \cdot \sqrt{R_k^{\,2} + X_k^{\,2}}} \qquad (1)$$

$c_{\max} \cdot U_n / \sqrt{3}$ is the equivalent voltage source at the fault location and Z_k is the short-circuit impedance. To get the total current at a fault location I_k'' is calculated as the phasor sum of the individual partial short-circuit currents at the location.

When deciding the maximum voltage factor, c_{max}, table 1 in IEC 60909-0 is used. A highest value for c_{max} of 1,1 is used with one exception. That is that $c_{max}*U_n$ should not exceed the highest allowed voltage in the power system. In that case the factor c_{max} is set to the value $U_{n,max}/U_n$.

2.1.4.2 Steady-state short-circuit current, I_k

When the steady-state current, I_k, is calculated, the answer will be less accurate than for the initial short-circuit current, I_k'' [4]. I_k will be the value of the short-circuit current when several cycles have passed, according to figure 1.

For the calculation of the maximum steady-state short-circuit current, it is assumed that synchronous machines are set at the maximum excitation, see equation (2).

$$I_{k\max} = \lambda_{\max} \cdot I_{rG} \tag{2}$$

The value of $\lambda_{\max}$ can be decided from figures 18 and 19 in the standard IEC 60909-0. For the impedance values used for generators during this state, see section 3.2.4.

For the minimum steady-state current, the value of the steady-state short-circuit current for the synchronous machines is used to calculate the corresponding equivalent impedance. For more information on the impedance values used for the calculation of the minimum steady-state current, see section 3.2.4.
All asynchronous motors are neglected for these types of calculations [4].

2.1.4.3 Peak short-circuit current, I_p

The peak current is the largest momentary value of the short-circuit current. The peak short-circuit current is only calculated for the maximum short-circuit current. For a three-phase balanced fault the contribution of the peak short-circuit current from one branch can be calculated according to equation (3).

$$I_p = \kappa \cdot \sqrt{2} \cdot I_k'' \tag{3}$$

κ is a function of the R/X ratio and can be calculated with equation (4).

$$\kappa = 1.02 + 0.98 \cdot e^{-\frac{3 \cdot R}{X}} \tag{4}$$

At a fault location F, the total amount of I_p is the sum of the absolute value of all the partial short-circuit currents.

$$i_p = \sum_i i_{pi} \tag{5}$$

When the ratio R/X remains smaller than 0,3 in all branches, the R/X ratio of the equivalent impedance at the fault location can be used for the calculation of κ [4].

2.1.4.4 Thermal equivalent short-circuit current, I_{th}

Short-circuit currents that are flowing in the system create thermal effects due to heating on equipment and conductors. The joule integral is a measure of the energy generated in the system by the short-circuit current. It is measured by the value $I_{th}^2 * T_k$, where T_k is the short-circuit current duration [3][4]. I_{th} is given by equation (6).

$$I_{th} = I_k'' \cdot \sqrt{m+n} \tag{6}$$

The factor *m* is the value of the time-dependent heat effect of the d.c. component of the short-circuit current. It is calculated by using equation (7), where κ can be found in equation (4) and T_k is the duration of the short-circuit current.

$$m = \frac{1}{100 \cdot T_k \cdot \ln(\kappa - 1)} \cdot (e^{200 \cdot T_k \cdot \ln(\kappa - 1)} - 1) \tag{7}$$

The factor *n* is the time-dependent heat effect of the AC component of the short-circuit current. It is found by using figure 22 in IEC 60909-0. Here, the relation between the initial short-circuit current and the steady-state current, I_k'' / I_k, needs to be known. The duration of the fault time is often set to 1 second, but another time constant can sometimes be of interest. No value of I_{th} is therefore presented in this report, but the relation I_k'' / I_k is presented in the results for each bus, so it can be used for further calculation of I_{th}.

2.2 Description of the onsite power system at Ringhals AB unit 4

The onsite power system is the name of the electrical components and switchgears in the system, which is supporting the process system components with electric power.

2.2.1 The structure of the onsite power system

The onsite power system is divided into two parts, which are independent from each other. These two parts are physically separated and individually fed from different transformers, LT410 and LT420, see figure 2. The two parts are called part A and part B respectively. The risk of fire to spread is smaller since it will get isolated to one part.

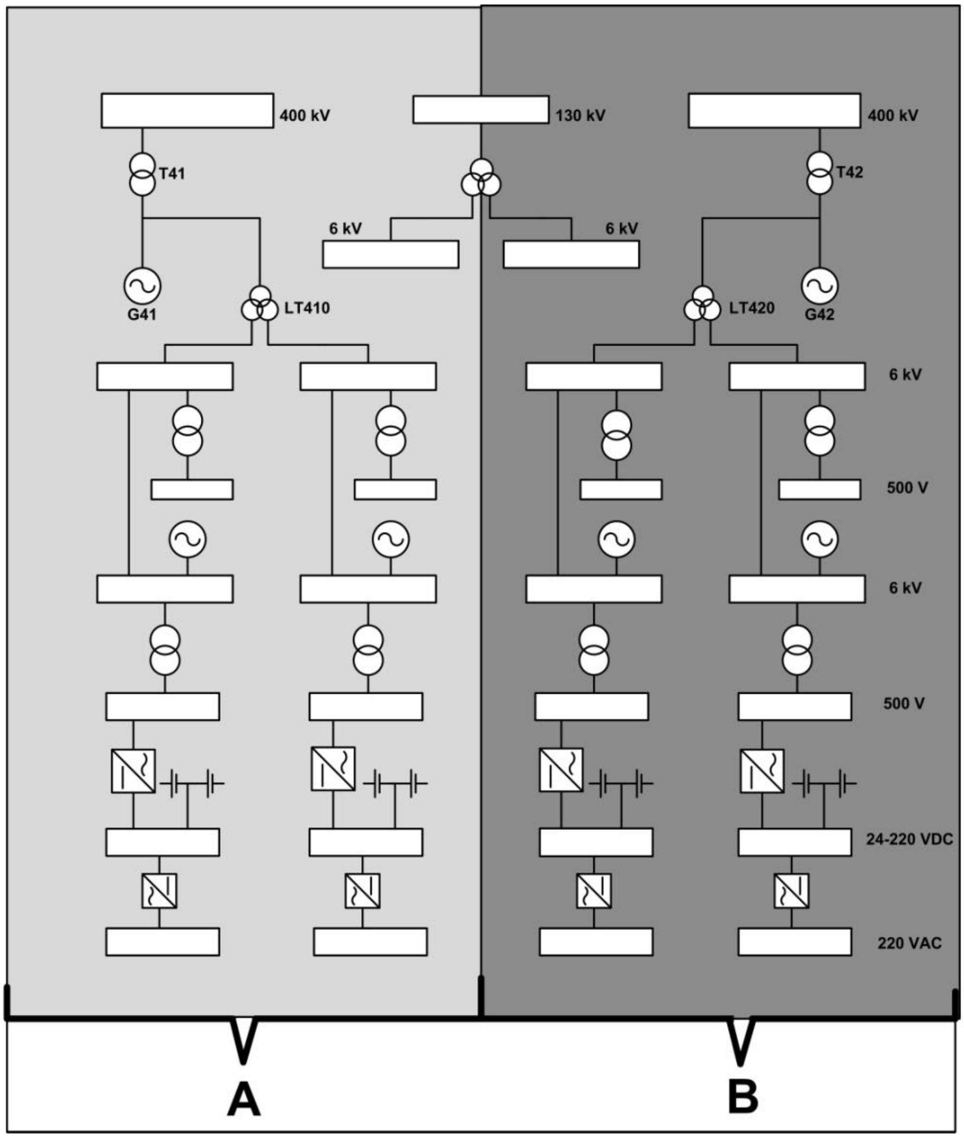

Figure 2. *Part A and part B of the onsite power system*

The system is further divided into four different subsystems(subs), sub A, B, C and D, see figure 3. The different subs can be interconnected to each other, but they are not connected during normal operation. The division into four different subs is motivated by the fact that the subs are physically isolated from each other. Each sub will get a better voltage regulation because the ratio between the short-circuit power and the installed power will be larger and the size of each single switchgear station will be limited.

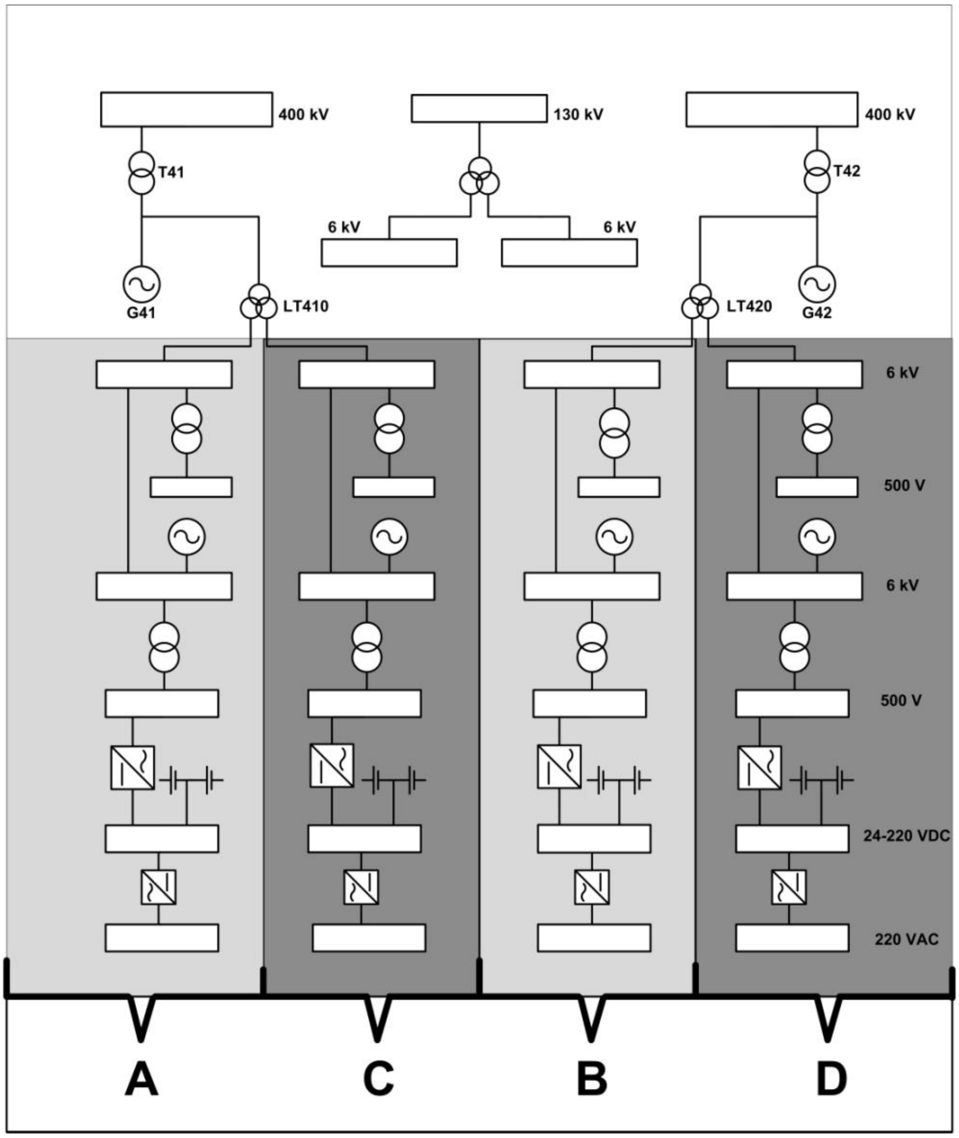

Figure 3. *Four different subsystems of the onsite power system, A, C, B and D.*

2.2.2 Three different safety levels

To increase the level of security, every subsystem, described in 2.2.1, is divided into three different levels of safety. They are called the non-safety related, the safety related (diesel secured) and the battery secured system, see figure 4.

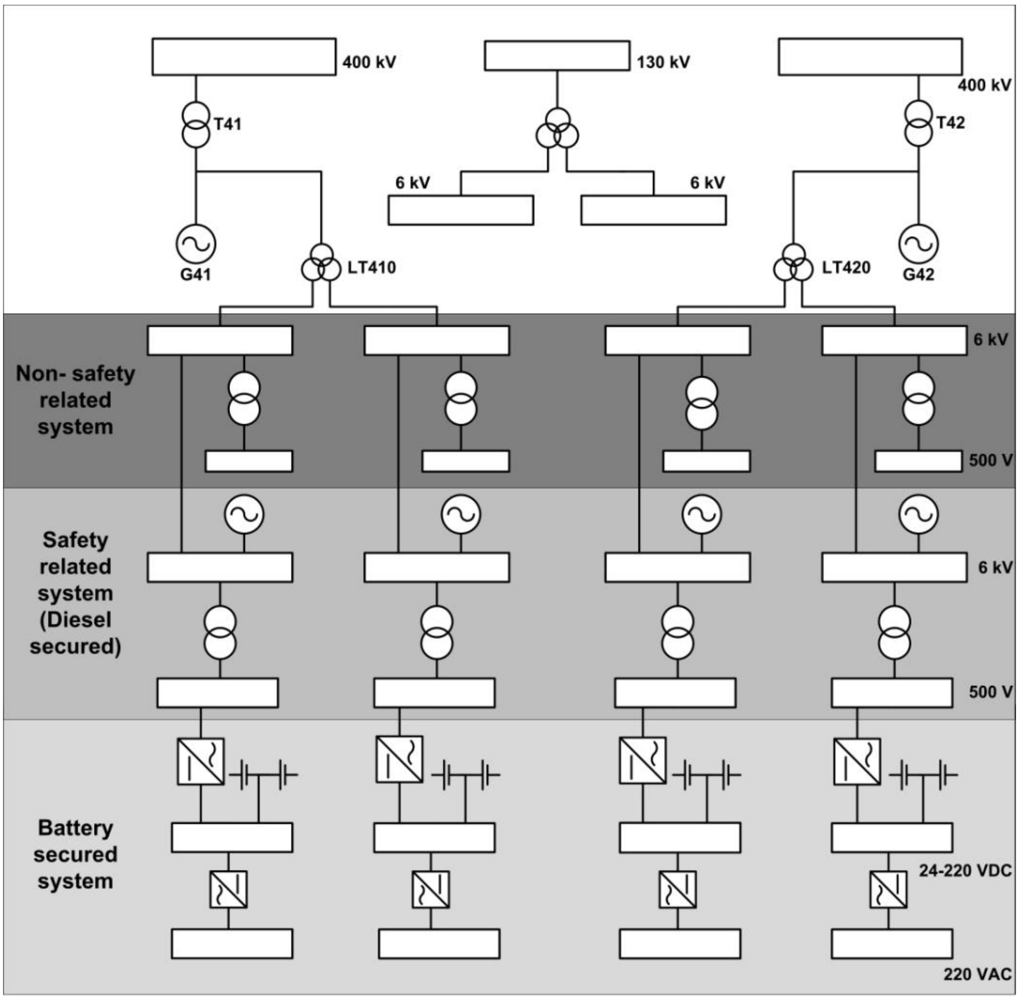

Figure 4. *Three different safety levels of the system*

2.2.3 Voltage levels of the onsite power system

The onsite power system is designed so that it is divided into two different parts, one that has back up from diesel-generators, which is called the safety related system and one that has not got this back up, the non-safety related system [6].

2.2.3.1 6 kV non-safety related system

The 6 kV non-safety related system is feeding non-safety related objects. This system is providing the turbine’s 6 kV objects and the RCPs (Reactor Cooling Pumps), with power. Buses for this system is the buses H94-A6 and H94-B6 which are connected with the 130 kV grid via T94. For connections with the 400 kV grid via LT410/LT420 the buses are called H41-A6 and H43-C6 for sub A and C and H42-B6 and H44-D6 for sub B and D.

2.2.3.2 500 V non-safety related system

The 500 V non-safety related system is feeding objects that are non-safety related. The function of the system is to feed 500 V drives for pumps and vents with power from the 6 kV non-safety related system, through transformers 6,8/0,525 kV. The names of the buses for the level are VHC41, VHC42, VHC43, and VHC44 for sub A, B, C, and D.

2.2.3.3 6 kV safety related system

The 6 kV safety related system is feeding the 6 kV safety related objects as well as the 500 V safety related system. The transformers connected are two 6,8/0,525 kV transformers that are numb connected in parallel, with a common circuit breaker on each side. The reason for this design is that in this way, there is low transformer impedance, which gives a low voltage drop over the transformer. The objects are connected so when the turbo-generators are activated, each generator is feeding its own objects. The buses in this level are called D41-A6, D42-B6, D43-C6, and D44-D6 that corresponds to sub A, B, C, and D.

2.2.3.4 500 V safety related system

The 500 V safety related system is feeding objects that are safety related and objects that are important to a safe shutdown of the reactor. The buses are called DHC41, DHC42, DHC43, and DHC44 for sub A, B, C, and D.

2.2.3.5 The AC-DC converter system

The DC system consists of DC converters and batteries. The DC system provides instrument and control equipment, relays, magnet vents, inverters and the turbine’s emergency oil pumps with power so that they can fulfill their assignments undependably of the status on the AC-side of the onsite power system.

At a normal operation the loads are fed via DC converters. If the DC-converters are lost, the batteries take over the feeding without any interruption. The capacity of the batteries is enough for at least one hour running without the DC converters. The DC system consists of different voltage levels, 220, 110, 48, ±24 and 24 V. For every voltage bus there are normally two DC-converters connected in parallel (for the 48 V system there is only one). The ±24 V system consists of two separate batteries that are connected to a joint center.

2.2.3.6 The DC-AC inverter system

The inverter system has the task of providing instruments, control equipment, emergency lights and computers with steady alternating voltage undependably of the status of the onsite power system. Four one-phased AC converters are fed from 110 V DC.

2.2.4 Different types of transformers in the power system

A transformer is a static device that can transfer electrical energy, without changing the frequency, from one circuit to another by electromagnetic induction. In a power system, there are a number of different types of transformers [11].

2.2.4.1 Generator transformers

At a generating station, the power is stepped up by a transformer to a higher voltage for the energy to be transmitted over a larger distance. In this system the generators T41 and T42 are generator transformers with a voltage ratio of 22,6 kV through 438,5 kV [11][C2].

2.2.4.2 Unit auxiliary transformers

These transformers are step-down transformers with the primary directly connected to a generating station, the generators G41 and G42, with voltages of 21,5 kV. The secondary is connected to the buses H4x-y6 in order to supply different types of auxiliary equipment in the generating station, with a voltage of 6,8 kV, i.e. the voltage ratio is 21,5 kV / 6,8 kV. The transformers of this type in the system are LT410 and LT420 [11][C2].

2.2.4.3 Station transformer

The station transformer (start-up transformer) is required to supply the auxiliary equipment during the setting up of the station generator and during the start-up operation. The primary is connected to the 130 kV grid, with a voltage of 145 kV, while the primary side has a voltage of 6,8 V. The station transformer in the system is called T94 [11][C2].

2.2.4.4 Service transformers

The service transformers are the transformers that supply 500 V level with power from the 6,6 kV level. These transformers are of dry-type and are self-cooled, with a secondary voltage of 525 V. The voltage ratio for these transformers is 6,8 kV / 525 V. The transformers in the system of this type are LT4xy and DT4xP [C2]. In each case-description the transformers are called LT1, LT2, DT1, and DT2. The real names of the transformers are: LT411, LT412, DT410P and DT410Q for sub A, LT421, LT422, DT420P and DT420Q for sub B, LT431, LT432, DT430P and DT430Q for sub C, and LT441, LT442, DT440P and DT440Q for sub D.

2.3 Cable impedance

When calculating short-circuit currents the impedance of the cables is of great importance since it affects the value of the short-circuit currents. The impedance consists of two different parts, one real part, the resistance of the conductor R, and one imaginary part, the inductive reactance X_L, see equation (8) The capacitive reactance is so small that it can be neglected [4][7].

$$Z_L = R_L + jX_{L,L} \quad [\Omega] \tag{8}$$

The cables in the system are specified according to the Swedish standard SS 424 17 01, fifth edition, where a letter code define the cables.
The letter code is made up in the following way:

- The first letter describes the material of the conductor.
- The second letter describes the material of the insulation.
- The third letter describes the material of the screen and/or sheath.
- The fourth letter describes a construction detail or a way of usage.
- The fifth letter describes a construction detail or a way of usage.

For instance is FKKJ a common cable in the system. The letter code implies that the cable has a conductor of copper (class 2), an isolation of PVC, a sheath of PVC and that the cable may be stationed in the ground [8].

2.3.1 Cable resistance

For cables up to 1 kV the resistance values for FKKJ- and EKKJ- cables are found in the standard SS 424 14 05, second edition, table 1. Since the resistance is not affected by the design voltage level of the cable, the values in the standard SS 424 14 05 can also be used for all the cables in the system since all the cables have a conductor made of copper. Another way of finding the resistance at 20°C is by using equation (9).

$$R_{L,20} = \frac{\sigma_{L,20}}{A} \ [\Omega / km] \qquad (9)$$

In this equation the resistance of the cable at 20°C is found. $\sigma_{L,20}$ is the resistivity of the conductor material at 20°C $[\Omega \cdot mm^2 / km]$. A is the nominal cross-section of the conductor $[mm^2]$.

The values given in the table of the standard SS 424 14 05 are a bit larger than the ones calculated using equation (9). This depends on the increasing losses, which appear, when wires are put close to each other. These additive losses are small compared to the DC losses and thus gives equation (9) an sufficient approximation. The resistance value at 20°C is used when calculating maximum short-circuit currents according to IEC 60909-0 [4]. When calculating minimum short-circuit currents the value of the resistance has to be introduced at a higher temperature since the resistance is increasing with increased temperature [4]. The temperature dependence is more or less linear and the new resistance value can be calculated with equation (10), when the resistance at 20°C is known.

$$R_{L,\Theta} = R_{L,20} \cdot (1 + \alpha_{20}(\Theta - 20)) \ [\Omega / km] \qquad (10)$$

Θ is the new temperature in °C and α_{20} is the temperature coefficient at 20°C for the conductor material. (α_{20} for copper is 0,00393°C^{-1}) [7].

For the cables in the system there are different maximum temperature allowed when a short-circuit occurs. The temperature depends on the material of the insulation, according to the standard SS 424 14 07, sixth edition. The different temperature values are shown in table 1 for a short-circuit that lasts for maximum 5 seconds [8].

Table 1. *The maximum allowed end temperature for the different cables.*

Type of cable	Nominal voltage [kV]	Maximum allowed end temperature of the conductor [°C]
XLPE-insulated cable (PEX)	12-24	250 [8]
XLPE-insulated cable (PEX)	1	250 [8]
PVC-insulated cable	1	150 [8]
CSP-insulated cable (Hypalon)	1	250 [9][10]
PO-insulated cable (HFFR)	1	150[1]

2.3.2 Cable reactance

A cable consists of both inductive and capacitive reactance. The inductive reactance acts is series with the conductor resistance. The capacitive reactance acts between the conductor and earth, and between the conductors. It is so small compared to the inductive reactance so it can be neglected. The inductance is affected by how the cables are arranged, for instance in trefoil, and the material of the isolation. To find the inductance in a trefoil arrangement for three uniform one-phase cables, equation (11) is used, see figure 5 [7].

$L_R = L_S = L_T = L$

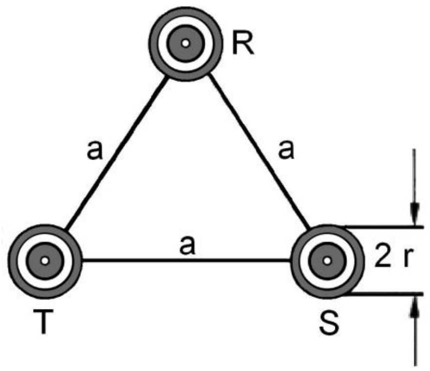

Figure 5. *Three one-phase cables arranged in trefoil formation.*

[1] Aron Adamsson, Nexans, Telephone conversation 2009-11-30.

$$L = 0{,}05 + 0{,}2 \cdot \ln\left(\frac{a}{r}\right) \ [mH/km] \qquad (11)$$

Equation (11) [7] gives a good approximation but the inductance should be measured if a more accurate value is wanted since the isolation material also affects the inductance. To find the inductive reactance the inductance is used according to equation (12) [7].

$$X_L = \omega \cdot L \cdot 10^{-3} \ [\Omega/km] \qquad (12)$$

Where $\omega = 2 \cdot \pi \cdot f$

f = The frequency in Hz

L = The inductance in mH/km

In the standard SS 424 14 05, table 1, the inductive reactance can be found for cables of type EKKJ and FKKJ. For cables with XLPE-insulation a data sheet from Nexans is used [15]. For cables in the system with insulation of hypalon, the inductance is found from a data sheet from ASEA Kabel [Appendix D] and the inductive reactance is calculated by using equation (12).

According to Adamsson[2] the reactance is the same for cables with insulation of Polyolefin (PO) and PVC. Therefore reactance values from SS 424 14 05, table 1 are used for cables with PO-insulation. The inductive reactance is, as earlier mentioned, depending on the number of conductors in the cable. In the standard SS 424 14 05, table 1, the values are specified for a three-core cable. For a four-core cable in the system, the reactance for a three-core cable can be used, according to Adamsson[2].

2.4 Synchronous generators

The three-phase current in the stator winding of a synchronous generator generates an electromagnetic field. This field will rotate as fast as the rotor and its field. The machine terminal voltage, V_t can be obtained from the armature voltage, V_a, by realizing that the stator winding has a small resistance, R_L, and a leakage reactance, X_L. This is a result of the flux produced by the stator. X_m is the equivalent reactance produced by the magnetic conditions inside the machine. The sum of the reactances X_L and X_m is often considered as the synchronous reactance, X_S, shown in the equivalent circuit of the synchronous machine, see figure 6 [12].

[2] Aron Adamsson, Nexans, Telephone conversation 2009-11-12.

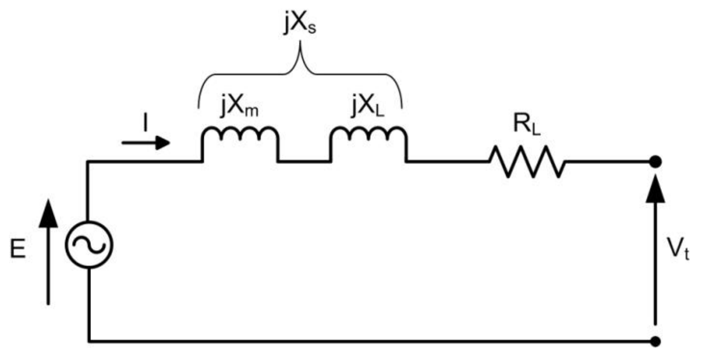

Figure 6. *Equivalent circuit of a round-rotor synchronous generator.*

The phasor equation of the synchronous machine is:

$$\underline{E} = \underline{V}_t + \underline{I}(R_L + j\,X_s) \qquad (13)$$

,where the value of R_L often is neglected in most power system calculations [12].

When a short-circuit occurs, the current will be different throughout the fault and will eventually fade out to a constant value as mentioned in section 2.1.4. The different areas are shown in figure 7.

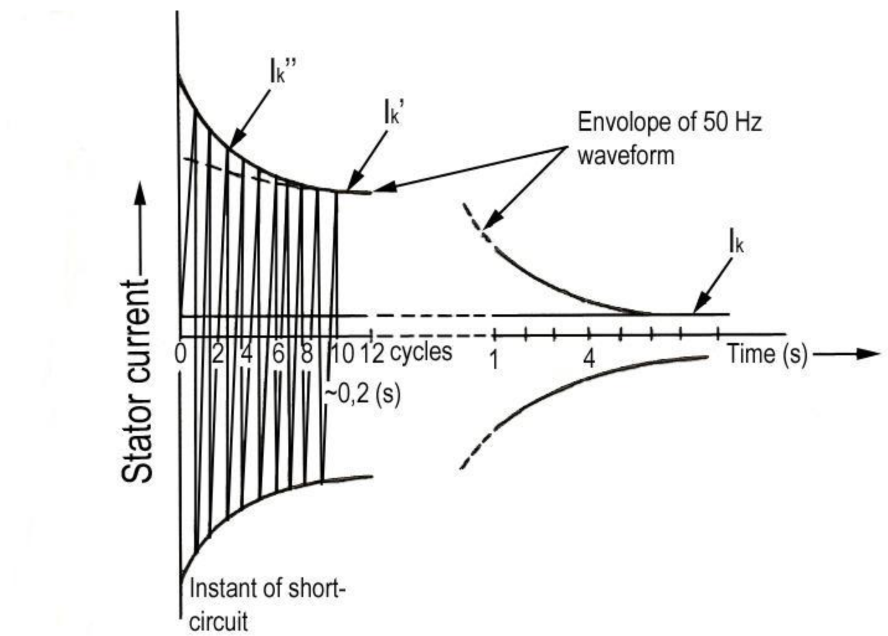

Figure 7. *Different areas in the short-circuit current of a generator.*

To describe the different conditions, two new reactances are needed to represent the generator. The initial condition requires the subtransient reactance, *X'',* and the subsequent condition requires the transient reactance, *X'*. The synchronous reactance, X_s, mentioned earlier, represents the final state that will be reached after several cycles. If *E* is the no-load phase voltage of the generator, *X''* and *X'* can be found from the following equations:

$$X'' = \frac{E}{I_k''} \qquad (14) \qquad\qquad X' = \frac{E}{I_k'} \qquad (15)$$

If the machine is loaded the voltage applied to the equivalent reactance, E in equations (14) and (15) has to be modified due to the initial load-drop. For example, the voltage behind the sub-transient reactance for the loaded generator will be:

$$\underline{E''} = \underline{V} + i\,\underline{I_L} \cdot X'' \qquad (16)$$

,where $\underline{I_L}$ is the current through the load and $\underline{V}$ the voltage over the load [12].

When calculating short-circuit currents with IEC 60909-0, the generator impedance has to be corrected because the equivalent voltage source, $cU_n/\sqrt{3}$, is used instead of the subtransient voltage source, E'', as described above. For calculation of the correction factor see section 3.3.4.

2.5 Asynchronous motors

To find the impedance of the asynchronous motors, the rating of the motors is used, combined with equation (17) below.

$$Z_M = \frac{1}{I_{LR}/I_{rM}} \cdot \frac{U_{rM}}{\sqrt{3} \cdot I_{rM}} = \frac{1}{I_{LR}/I_{rM}} \cdot \frac{U_{rM}^{\;2}}{S_{rM}} \qquad (17)$$

U_{rM} is the rated voltage of the motor, S_{rM} is the rated apparent power of the motor and can be found from the relation $S_{rM} = P_{rM} / (\eta_{rM} \cos\varphi_{rM})$ [4].

I_{LR}/I_{rM} is the ratio of the locked rotor current to the rated current of the motor. An approximation of this relation can be found in the TBE 103 [C9]. According to TBE, the relation is 5 times for motors larger than 1 kV and 7 times for motors smaller than 1 kV.

Since the relation between the resistance and the reactance is not known, the following relations can be used, according to IEC 60909-0, with sufficient accuracy:

$R_M / X_M = 0{,}1 \quad , with\, X_M = 0{,}995 \cdot Z_M$ for medium-voltage motors with powers/pair of poles ≥ 1 MW.

$R_M / X_M = 0{,}15 \quad , with\, X_M = 0{,}989 \cdot Z_M$ for medium-voltage motors with powers/pair of poles < 1 MW.

$R_M / X_M = 0{,}42 \quad , with\, X_M = 0{,}922 \cdot Z_M$ for low-voltage motors groups.

In the relations above, the impedance of the motors Z_M can be calculated with equation (17).

3 MODELING & SIMULATION

3.1 Different cases

The different cases analyzed are a number of network configurations that are of interest to investigate (cf. each case). The cases are set-up as theoretical alternatives and not necessarily as real allowed network configurations. Sub A or sub A and sub B have been made examples of how the connections are made, for all figures corresponding to the different cases. For calculations regarding sub C and D, for instance, the feeding generator is G42 and not G41 as shown in figure 8. For cases when the subs are in some way connected, via H94-A6/H94-B6, it is always with the corresponding sub (A to B and C to D). See Appendix A for a detailed description of the complete system.

Nine different cases are set up, where each case has a specific objective which is important to examine.

3.1.1 Case 1

Case 1 is set up at normal operation, with contribution from the 400 kV grid and from the generators G41 and G42 respectively. The diesel generator for the calculated sub is presumed to be synchronized, and connected to the system. It is connected because a fault can appear during the procedure when a diesel generator is connected to the system, as diesel generators are regularly tested and could be connected during a fault. See figure 8. for further description.

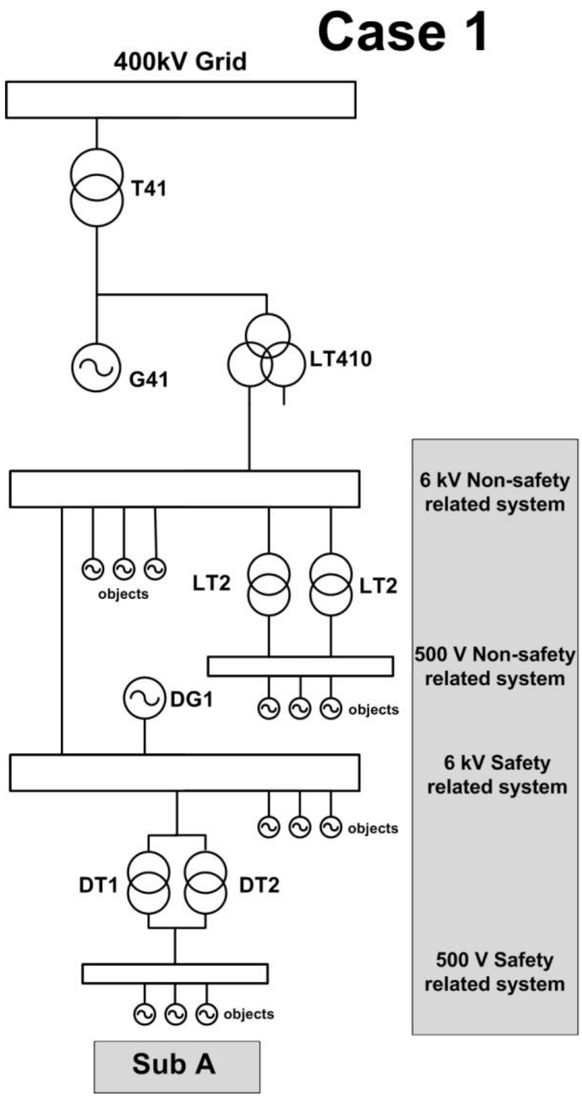

Figure 8. *Description of Case 1, used for calculations of SCCs on sub A.*

For calculation of the maximum sub-transient short-circuit current, I_k'', the system is connected as shown in figure 8. The maximum SSC contribution of the 400 kV grid is used as calculated in section 3.3.5.1. For synchronous machines the sub-transient value of the reactance is used. The factor c_{max} is set to 1,08 for buses H4x-y6/D4x-y6 and to 1,1 for DHC4x/VHC4x, as the voltage of the generators G41 and G42 has a maximum variation of 21,5 kV ±5 %. See section 3.2.1 for a more detailed description of this issue.

When calculating the maximum steady-state short-circuit current, I_k, all asynchronous motors are neglected, according to section 2.1.4.2. For the synchronous generators in the system another value for the reactance is used, see section 3.2.4.

The calculation of minimum steady-state currents for this case is of no interest.

3.1.2 Case 2

For the second case the system is set up during a fast-bus transfer. The 6,6 kV ordinary net can be supplied either from the unit auxiliary transformer, LT410 or LT420 respectively, or via the start-up transformer, T94. The changeover could be made either by manual command or by automatic command. During the manual command, the energy supply changeover from the auxiliary transformer to the start-up transformer is carried out, the system appears to be supplied from both transformers for a very short time. During this fast-bus transfer, two subs are connected to the bus H94-A6 or to bus H94-B6 respectively. Short-circuit current contribution comes from both the 400kV and the 130 kV net as well as from the generators G41 or G42 respectively. As two subs are connected they both contribute to the equivalent impedance. No diesel generators are connected in this case, since there is a small probability of the fast-bus transfer to occur when a diesel generator is connected. See figure 9 for further description [C2].

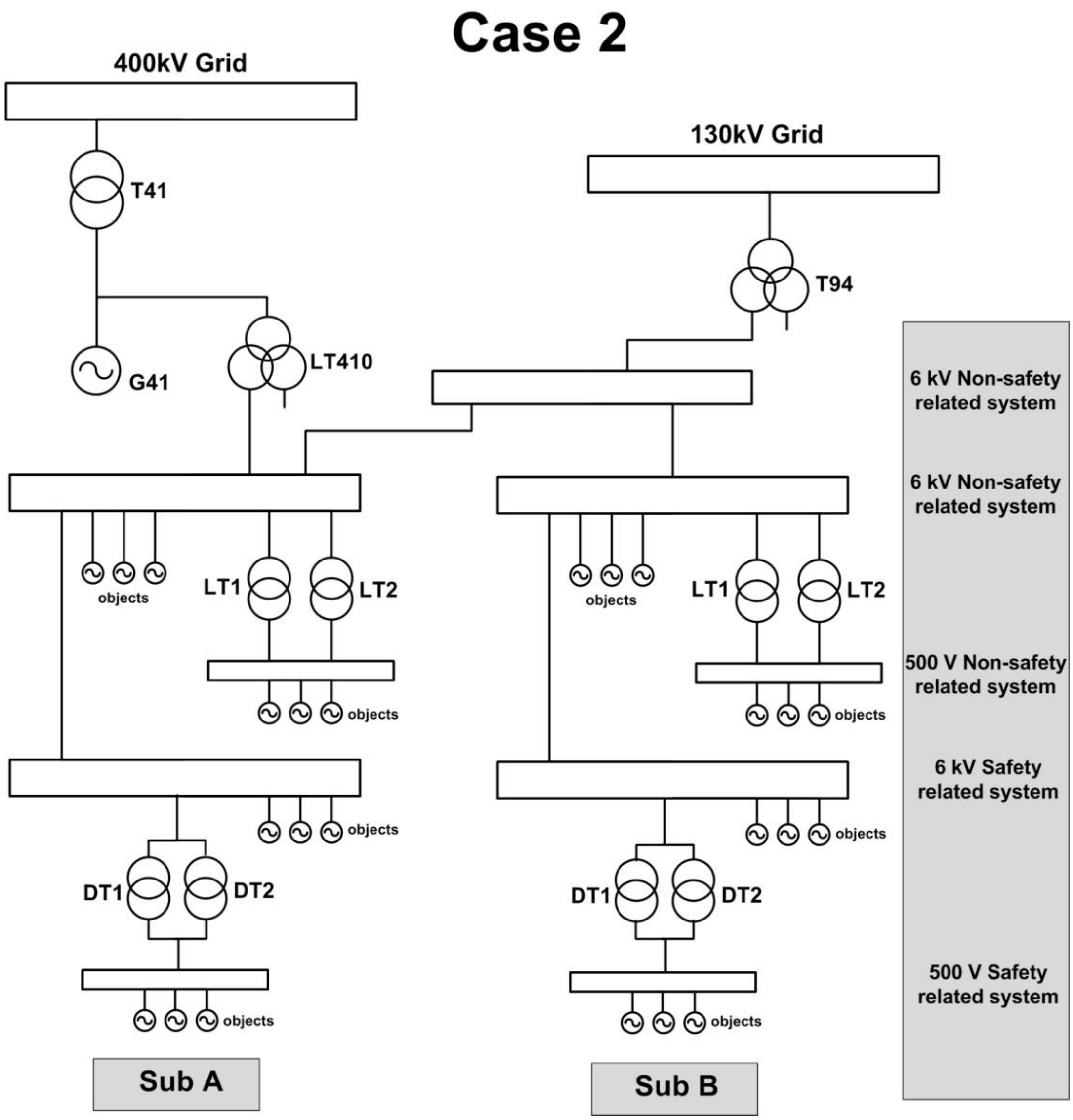

Figure 9. *Schematic description of case 2, for sub A.*

For calculation of the maximum sub-transient short-circuit current, I_k'', the system is connected as shown in figure 9. The maximum contribution from the 400 kV grid as well as from the 130 kV grid is used as calculated in section 3.3.5. For synchronous machines the sub-transient value of the reactance is used. The factor c_{max} is set to 1,03 for the buses H4x-y6/D4x-y6 because the voltage on the bus H4x-y6 has to be held between ±1,03*U before a changeover takes place. This is because of that the voltage is held between 6,6 and 6,78 kV on the bus H94-A6 due to the transformer T94 [C8]. This will lead to a voltage factor for the DHC4x/VHC4x-buses of 1,05, see section 3.2.1.

When calculating the maximum steady-state current, the asynchronous machines are neglected. For all synchronous generators, the impedance values are changed to those mentioned in section 3.2.4.

For the calculation of the minimum steady-state current, this is not a case of interest.

3.1.3 Case 3

This case is very similar to case 2. The only difference compared to case 2 is that the diesel generator for the calculated sub is presumed to be synchronized and connected to the system. For a detailed description see figure 10.

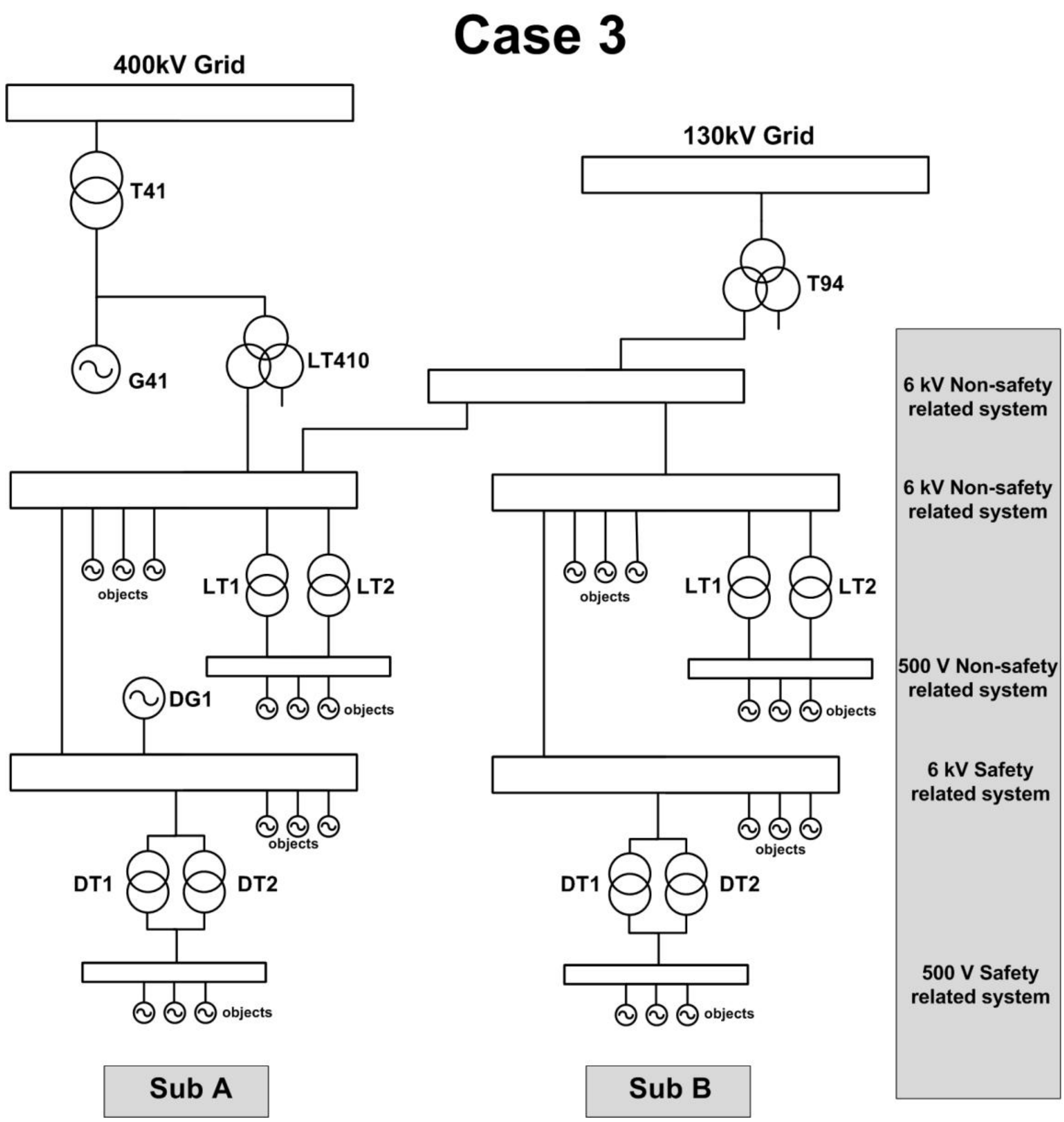

Figure 10. *Description of case 3, used for calculating SCCs on sub A.*

For calculation of the maximum sub-transient short-circuit current, I_k'', the system is connected as shown in figure 10. The maximum contribution of the 400 kV grid as well as for the 130 kV grid is used as calculated in section 3.3.5. For synchronous machines, the sub-transient value of the reactance is used. The factor c_{max} is set to 1,03 for H4x-y6/D4x-y6 and to 1,05 for DHC4x/VHC4x in line with the same reasoning as for case 2.

For the calculation of the steady-state current, the same corrections are made as for case 2.

The minimum steady-state current is not calculated for this case.

3.1.4 Case 4

In the fourth case, the condition after a fast-bus transfer is set up. The energy is supplied via the start-up transformer, T94. Two subs are assumed to be connected and the diesel generator for the calculated sub is synchronized and connected. See figure 11 for further description.

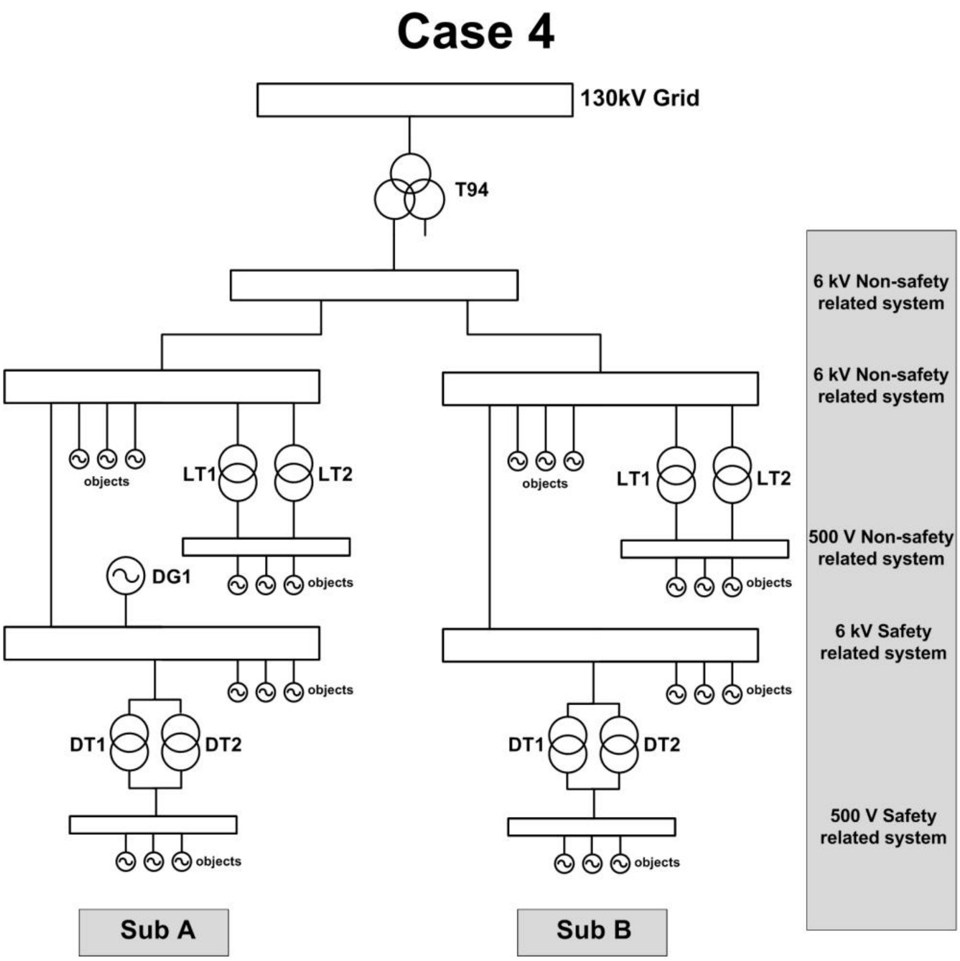

Figure 11. *Description of case 4 for calculations on sub A.*

For the calculation of I_k'', the system is connected as in figure 11. The maximum contribution from the 130 kV grid is used. All asynchronous motors and the diesel generator for the calculated sub are connected. The case which is shown is for calculations on buses in sub A. For sub B, the diesel generator DG420 is connected instead of DG410 and so on for the different buses. The factor c_{max} is set to 1,03 for the 6 kV-level and to 1,05 for the 500 V-level because of the tap-changer on T94., see section 3.2.1.

When calculating the maximum steady-state short-circuit current, I_k, all rotating objects are neglected. The contribution from the diesel generator is in form of the transient reactance, see section 3.2.4.

The calculation of the minimum I_k is not of interest for this case.

3.1.5 Case 5

In the fifth case the feeding of a sub from the opposite 21,5 kV generator via the 400kV bus is examined. There is no contribution from the corresponding generator nor from the 400 kV grid. No diesel generator is connected for this case.

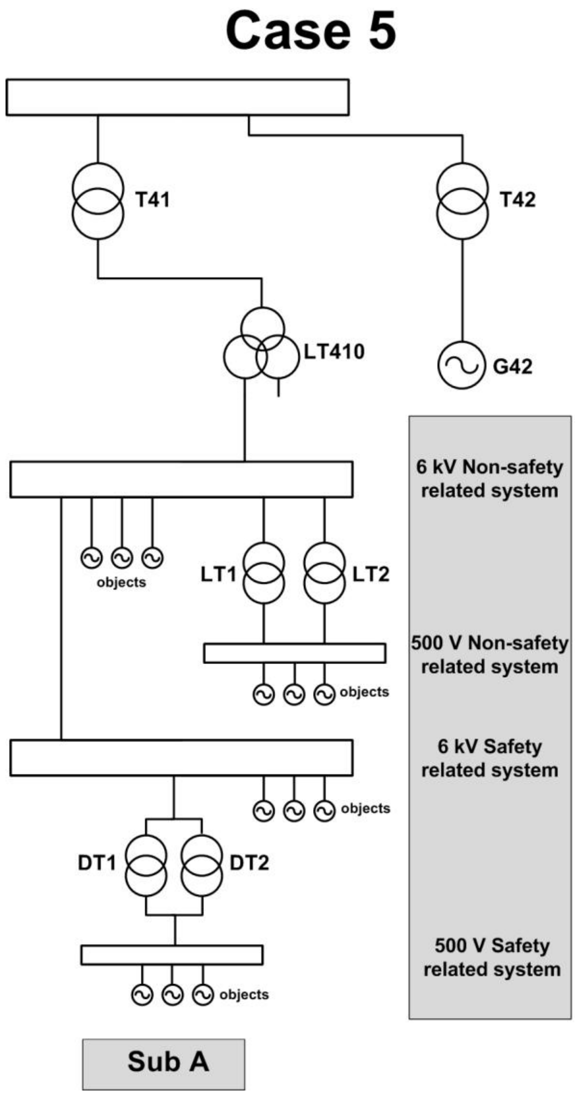

Figure 12. *Description of case 5 for calculations on sub A.*

When calculating I_k'' all components shown in figure 12. are connected. The sub-transient reactance value for the generator G41/G42 is used. All asynchronous motors are included in the calculations. The voltage factor c_{max} is set to 1,08 for H4x-y6/D4x-y6 and to 1,1 for DHC4x/VHC4x, since the generator is included in this case and the same aspect as in case 1 is considered, namely that the voltage will be limited according to the generators maximum divergence allowed.

When the maximum steady-state short-circuit current, $I_{k,max}$, is calculated all motors are disregarded and the transient reactance value of the generator G41/G42 is used.

For calculation of the minimum steady-state short-circuit current, the resistance values for all cables are calculated at the maximum temperature allowed at the end of the short-circuit, see section 2.3.1. No motors are included and the reactance value for the generator G41/G42 is the same as for $I_{k,max}$. The factor c_{min} is chosen to 0,95 for calculations on all 500 V buses and to 1,0 for calculations on the 6,6 kV buses. This is all according to the standard IEC 60909-0, table 1, which shows the value of the factor to use. This value depends on, at which voltage level the calculations are performed [4].

3.1.6 Case 6

For the sixth case a direct "house-load" operation is examined. A lost connection to the 400 kV grid is assumed and the sub will be supplied by the 21,5 kV generator, G41 or G42. There is no contribution from the transformer T41/T42. One sub is connected and no diesel generator is synchronized and connected to the system.

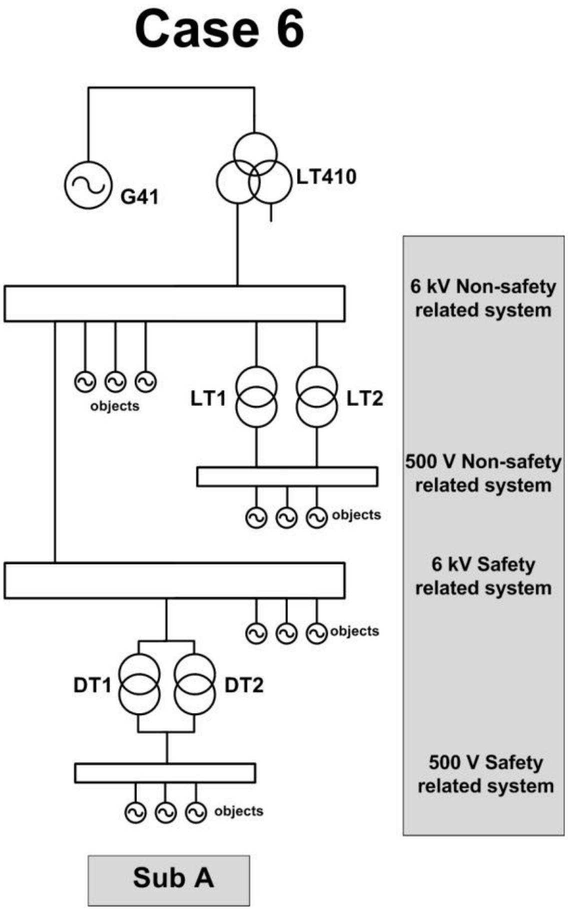

Figure 13. *Description of case 6 when calculating short-circuit currents on sub A.*

For calculation of the initial short-circuit current the system is modeled as shown in figure 13. The factor c_{max} is chosen to 1,08 for the 6,6 kV-level and to 1,1 for the 500 V-level, for the same reasons as in case 1.

When the maximum steady-state current is calculated, all motors are put aside and the transient reactance of the generator G41/G42 is used.

For calculation of $I_{k,min}$, the resistance values for all cables are calculated at the maximum allowed temperature at the end of the short-circuit, see section 2.3.1. All motors are neglected and the reactance value for the generator G41/G42 is the same as for $I_{k,max}$. The factor c_{min} is chosen to 0,95 for the calculations on the 500 V level and to 1,0 for calculations on the 6,6 kV level

3.1.7 Case 7

Case 7 is very similar to case 3, i.e. two subs are connected to bus H94-A6/H94-B6 and the diesel generator is synchronized and connected to the sub. The difference is that the contribution from the 400 kV and the 130 kV grids are considered to be infinite. In this way the transformers T4x and T94 will limit the current and maximum contributions possible from these sources are examined.

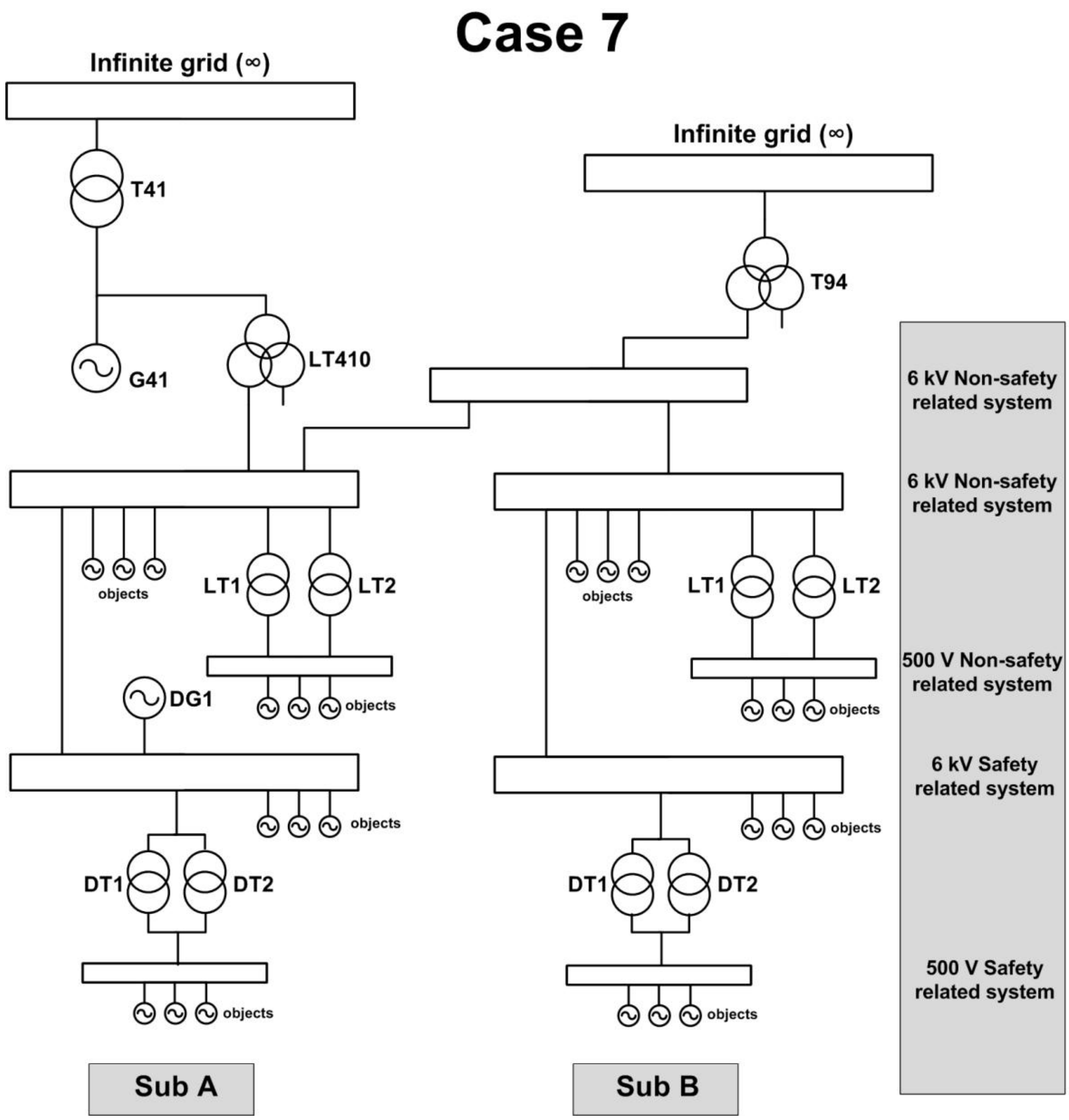

Figure 14. *Description of case 7 for calculations on sub A.*

The maximum initial short-circuit current is calculated in the same way as for case 3. The factor c_{max} is chosen to 1,03 for the buses H41-y6/D4x-y6 and to 1,05 for the buses DHC4x/VHC4x, since the voltage cannot diverge more than this if a fast-bus transfer is going to take place, see section 3.2.1. When calculating $I_{k,max}$ no motors are included and the transient reactance value for the generator G41/G42 is used. For the diesel generator, transient reactance is used.

Calculation of the minimum steady-state current is of no interest for this case.

3.1.8 Case 8

Case 8 is similar to case 4 in the way that they both include a single feeding from the 130 kV grid in both cases. The differences are firstly that the diesel generator is not connected for case 8 and secondly that only one sub is connected to bus H94-A6/H94-B6. The most interesting part to investigate in case 8 is the minimum steady-state current since the contributions are as small as they could be for the H4x-y6 and VHC4x buses.

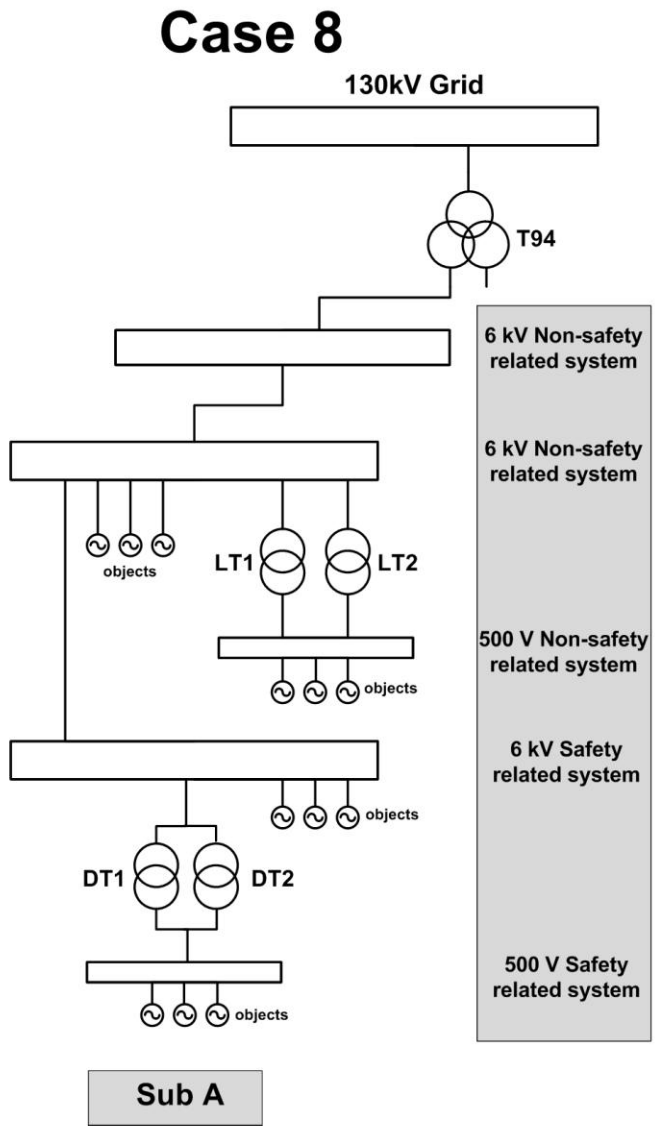

Figure 15. *Description of case 8 when calculating short-circuit currents on sub A.*

When calculating I_k'', the system is built up as shown in figure 15. The factor c_{max} is determined to 1,03 for the 6 kV-level and to 1,05 for the 500 V-level in line with the previous argumentation, as for case 3 and 7. For maximum calculations, the maximum contribution from the 130 kV grid is used as calculated in section 3.3.5. For calculations of the maximum steady-state short-circuit current, all motors are disregarded. The maximum current is calculated because it can be of interest to examine the differences between the maximum and minimum current for the same case.

When calculating the minimum steady-state current, the minimum contribution from the 130 kV grid is used, see section 3.3.5.4. No asynchronous motors are included. The resistance values for all cables are calculated at the maximum temperature allowed at the end of the short-circuit, see section 2.3.1.

The factor c_{min} is set to 0,95 for the 500 V levels and to 1,0 for the 6,6 kV levels.

3.1.9 Case 9

Case 9 is a minimum case only, for the buses D4x-y6 and DHC4x. The case is examined because it represents the safety-related net. In this case, the system is assumed to be fed only from the diesel generator, DG4x0.

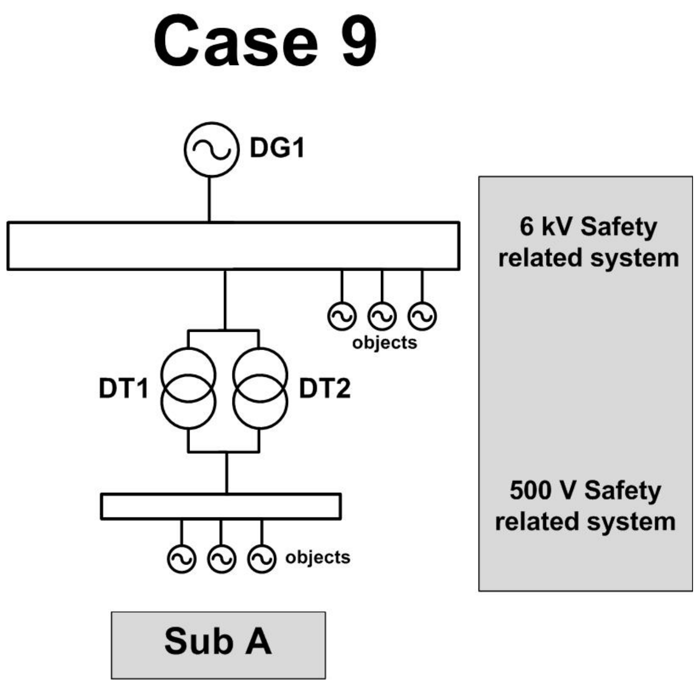

Figure 16. *Description of case9 when calculating short circuit currents on the buses D4x-y6 and DHC4x.*

When calculating the minimum steady-state short-circuit current, the reactance of the diesel generator according to section 3.2.4 is used. All motors are disregarded for this case. For all cables in the system, the resistance value is calculated at the maximum temperature allowed at the end of the short-circuit, see section 2.3.1.

3.2 Data collection

In this section, some of the data used for the short-circuit calculations are described in more detail. The maximum and minimum voltage factors are presented and also how data is developed for the power cables.

3.2.1 The voltage factor c_{max}

The factor will be different depending on which case the calculations are made for and the different c_{max} values are collected in table 2. A more detailed description of why the voltage factor is different is presented below.

For the cases 1, 5 and 6 the generator G41/G42 decides the maximum voltage factor, since it will limit the deviation for the nominal voltage to maximum 5%. These 5% will lead to a voltage on the other buses according to table 3.

Table 2. *Voltage factor c_{max} for cases 1,5 and 6.*

Voltage level	**Equation for the "new" voltage**	**Voltage factor c_{max}**
UnMV (21,5 kV)	21500 * 1,05 = 22575 V	---
UnLV (6,6 kV)	22575*(6800/21500) = 7140 V	7140/6600 = 1,08
UnLLV (500 V)	7140*(525/6800) = 551,25 V	551,25/500 = 1,1

For the cases 2, 3 and 7 the tap-changer on the transformer T94 will automatically hold the voltage between 6,6 and 6,78 kV before a changeover takes place [C8]. This leads to a voltage factor on the 6,6 kV level of 6,78/6,6 = 1,03.

For the 500 V-level, the voltage factor, c_{max}, will be: 1,03*6600*(525/6800) = 525 $\Rightarrow$ 525/500 = 1,05.

For cases 4 and 8, the voltage factor will be 1,03 for the 6 kV -level, since the tap-changer on T94 will hold the voltage within this limit, and 1,05 for the 500 V-level. If no component in the system had been limiting the voltage, the maximum voltage factor had been set to 1,1 according to IEC60909-0.

Case 9 is a minimum case only, which is why no maximum voltage factor is calculated.

Table 3. *Voltage factor c_{max} that corresponds to each case for the buses.*

Case	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**	**9.**
c_{max} for bus:									
H4x-y6/D4x-y6	1,08	1,03	1,03	1,03	1,08	1,08	1,03	1,03	-
DHC4x/VHC4x	1,1	1,05	1,05	1,05	1,1	1,1	1,05	1,05	-

3.2.2 The voltage factor c_{min}

The voltage factor c_{min} depends on the voltage level, where the fault is calculated.
For voltages larger than 1 kV, the minimum voltage factor is set to 1,0 and for voltages smaller than 1 kV, c_{min} is 0,95 [4].

3.2.3 Data for power cables in the system

To be able to find the impedances of the cables in the system, a thorough search in the Ringhals cable database (R4 Kabeldatabas) was carried out. In the database, the two connected points of the cable are specified, as well as the dimensions of the cable and the letter code according to the Swedish standard SS 424 17 01, fifth edition. For the calculations of the impedance values, see section 2.3.

3.2.4 Generator reactances for the different short-circuit current calculations

For the calculation of the initial short-circuit current, the saturated sub-transient value of the reactance, x_d'', is used for both the generators G41/ G42 and for DG4x0. This value is used with respect to the correction factor, K_G, calculated in section 3.3.4.

When calculating the steady-state short-circuit current, the generators are set at maximum excitation, because this will lead to the highest steady-state current contribution.

For the calculation of the maximum contribution from generators G41/G42 the maximum excitation has not been examined. A conservative assumption is to use the transient saturated reactance, x_d', which can be found in the datasheet for G42 [C11]. This value shall not be corrected with the factor K_G according to IEC 609009-0 [4].

In line with the previous assumption, the transient reactance for the generators DG4x0 is used for the calculation of the maximum steady-state current. The usage of the transient reactance will lead to a short-circuit current that will be approximately 6,2 times larger than the rated current. This current value will then be calculated into a corresponding impedance at the level of the fault voltage.

Since the magnetization for the generators DG4x0 has not been investigated, the saturated transient reactance is used for the calculation of the minimum steady-state current.

For the generators G41 and G42, the saturated transient reactance is used for the minimum short-circuit current calculations since the magnitude of G41/G42 is not of great importance. This is because the contribution always will be in series with LT4x0 and its contribution will be dominant for all cases.

3.2.5 Data for asynchronous motors

The ratings for the motors on VHC41 have been found in the database Ellista R3/R4 [C10] and in FSAR-R4 [C2]. Since the equivalent impedance for the different subs is similar, according to section 4.2.1. in the sensitivity analysis, the same equivalent impedance as for VHC41 has been used for the other buses on VHC4x. For the motors on buses DHC4x, Peter Angberg’s compilation of electric motors in *Belastningsprofiler dieselgeneratorer R34,* has been used [C5]. For these motors, no impedance of the cables connecting them to D4x-y6 has been used. This is a conservative assumption, but as the sensitivity analysis shows in section 4.2.2, it has a small impact on the results for the other buses.

All ratings for the motors on the buses H4x-y6 and D4x-y6 have been found in FSAR-R4 [C2].

3.3 Preparatory calculations

When the standard IEC 60909-0 is used, some preparatory calculations have to be made before calculating short-circuit currents. For the transformers in the system, a factor K_T is calculated and for the synchronous generators a factor K_G.

3.3.1 The introduction of IEC 60909-0 for calculation of the impedance for transformers

There are two different kinds of transformers in the system, two-winding transformers (T41, T42, LT4xy and DT4xP) and three-winding transformers (LT410, LT420 and T94).

3.3.1.1 Two-winding transformers

The short-circuit impedance of two-winding transformers can be calculated from the rated data of the transformer and with the following equations [4]:

$$\underline{Z_T} = R_T + jX_T \qquad (18)$$

$$Z_T = \frac{u_{kr}}{100\%} \cdot \frac{U_{rT}^2}{S_{rT}} \qquad (19)$$

$$R_T = \frac{u_{Rr}}{100\%} \cdot \frac{U_{rT}^2}{S_{rT}} = \frac{P_{krT}}{3 \cdot I_{rT}^{\;2}} \qquad (20)$$

$$X_T = \sqrt{Z_T^2 - R_T^2} \qquad (21)$$

,where U_{rT} is the rated voltage of the transformer.
S_{rT} is the apparent power of the transformer.
u_{kr} is the short-circuit voltage at rated current in percent.
u_{Rr} is the rated resistive component of the short-circuit voltage in percent.
P_{krT} is the total loss of the transformer in the windings at rated current.

For the generator transformers, the data is collected from test reports where both the u_{kr} and u_{Rr} values are specified. R_T can be calculated with equation (20) and Z_T with equation (19). X_T is found by using equation (21) and $\underline{Z_T}$ is then given by equation (18), and corrected according to section 3.3.2, for further use in the short-circuit current calculations.

For the service transformers, the value of u_{kr} alone, is specified. To find the value of R_T, it has to be calculated according to equation (20). Equation (18) gives the value of $\underline{Z_T}$.

3.3.1.2 Three-winding transformers

For three-winding transformers the impedances can be found in a similar way. Also, in this case, the data from the rating plate is used to perform the following equation, where the impedance between side A and B is calculated (referred to the A side):

$$\underline{Z}_{AB} = \left(\frac{u_{RrAB}}{100\%} + j\frac{u_{XrAB}}{100\%}\right) \cdot \frac{U_{rTA}^2}{S_{rTAB}} \qquad (22)$$

$$u_{Xr} = \sqrt{u_{kr}^2 - u_{Rr}^2} \qquad (23)$$

,where u_{RrAB} is the rated resistive component between sides A and B in percent.
u_{XrAB} is the rated reactive component between sides A and B in percent, which can be calculated in the same way as in equation (23).

U_{rTA} is the voltage on the A side of the transformer.
S_{rTAB} is the apparent power between sides A and B.

Impedance between the other sides, A and C and B and C, can be calculated similarly to equation (22).

For the unit auxiliary transformers, all the data is retrieved in test reports, where both the u_{kr} and u_{Rr} values are specified. u_{Xr} can be calculated with equation (23). $\underline{Z}_T$ is given by equation (22), and corrected according to section 3.3.2, for further use in the short-circuit current calculations.

For the station transformer T94, the value for u_{kr} is specified in a test report for the similar transformer T93 for station 3. These transformers are very similar, so the same value can be used for T94 as well[3]. The value for u_{Rr} is not specified but can be calculated according to equation (20), since the total loss of the transformers in the windings, P_{krT}, has been specified in the test protocol. The transformer impedance has to be corrected with a factor K_T, prior to usage in the short-circuit current calculations, see section 3.2.1.

[3] Owe Samuelsson, RAB-PRRUTU, Telephone conversation 2009-12-08.

3.3.2 Calculation of the correction factor K_T for two- and three-winding network transformers

A transformer that is connecting two or more different networks is called a network transformer. The impedance for these transformers is to be corrected which means that different tap-positions do not need to be considered. To calculate this correction factor K_T, for two winding transformers, equation (24) is used.

$$K_T = 0,95 \cdot \frac{c_{max}}{1 + 0,6 x_T} \tag{24}$$

,where x_T is the relative reactance of the transformer $x_T = X_T / (U_{rT}^2 / S_{rT})$ and c_{max} depends on which case is examined, see section 3.1, *Different cases*.

For three-winding transformers the correction factor for the corresponding winding is calculated according to equation (25) and similar for the other windings, AC and BC.

$$K_{T,AB} = 0,95 \cdot \frac{c_{max}}{1 + 0,6 x_{T,AB}} \tag{25}$$

The correction factor is multiplied with the transformer impedance value calculated by equation (22). It will lead to: $\underline{Z_{TK}} = K_T \cdot \underline{Z_T}$, where $\underline{Z_T} = R_T + i\, X_T$. [4.]

The factor is not introduced for unit transformers of power station units, i.e. the transformers T41 and T42, since they do not have any tap-changers [4].

3.3.3 Calculation of the resistance value, R_G, for synchronous generators

For the generator G42 the saturated sub-transient reactance and the value of the saturated transient reactance are used for the short-circuit calculations and are found in the data sheet of the generator [C7]. For the generator G41, the data is retrieved from the station circuit-diagram for R4 and from the selectivity plan for the system, [C3]. For the diesel generators, the data is collected from [C2] and [C3].

The resistance value of the generator is needed because the relation between R and X has to be known for the calculation of the peak current, see section 2.1.4.3. To calculate the resistance of the generators G41 and G42, the time constant T_a is used, which is found in the data sheet for G42. The same time constant is used for G41. The resistance is calculated according to equation (26) [C7].

$$R_G = \frac{x_d'' \cdot (U_{rG}{}^2 / S_{rG})}{2\pi \cdot f \cdot T_a} \tag{26}$$

The resistance for the diesel generators, DG4x0 is calculated according to IEC 60909-0, where a fictitious resistance can be found for further calculations of the peak current with the following relation:

$R_{Gf} = 0{,}07 \cdot X_d''$, for generators with $U_{rG} > 1$ kV and $S_{rG} < 100$ MVA

3.3.4 Calculation of the correction factor, K_G, for synchronous generators

For calculation of the initial short-circuit current a correction factor K_G has to be introduced because the equivalent voltage source, $c_{\max} \cdot U_n / \sqrt{3}$, is used instead of the sub-transient voltage *E''* behind the sub-transient reactance of the generator, for the bus where the fault is calculated, see figure 17. With help of equation (27), the correction factor can be calculated.

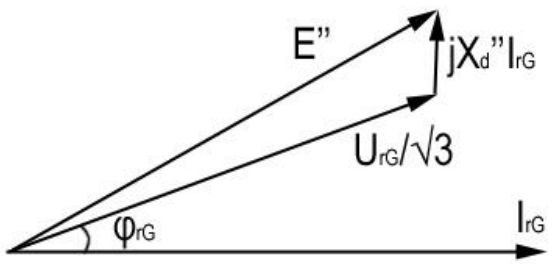

Figure 17. *Phasor diagram of a synchronous generator at rated conditions.*

$$K_G = \frac{U_n}{U_{rG}} \cdot \frac{c_{\max}}{1 + x_d'' \cdot \sin(\varphi_{rG})} \tag{27}$$

The factor c_{max} depends on which case is examined. φ_{rG} is the rated power factor of the generator and x_d'' is the sub-transient reactance of the generator. The values are specified in the data sheet of the generator.

This leads to the corrected impedance of the generator:

$$\underline{Z_{GK}} = K_G \cdot \underline{Z_G} = K_G \cdot (R_G + i\,X_d'') \tag{28}$$

3.3.5 Calculations for the 400 kV and the 130 kV grid

For the 400 kV grid there is only one interesting case to examine and that is the maximum short-circuit contribution. Since there will be much lower currents for the cases when the 400 kV grid is not connected, it is of no interest to examine the minimum contribution from the 400 kV grid. Data is collected from calculations made by Svenska Kraftnät (SvK), which can be found in [C6].

For the 130 kV grid it is of interest to examine both the maximum and the minimum contribution. Data for the maximum calculations are collected from calculations made by SvK, found in Appendix C. For the minimum case, data from [C1] is used.

3.3.5.1 Maximum short-circuit current contribution from the 400 kV grid

When there is a balanced three-phase fault on the 400 kV bus, the maximum current contribution is 13756 A at 419,99 kV. The impedance angle is –87.35°. [C6]. This will lead to the following equations according to IEC 60909-0:

$$Z_{Q,400} = \frac{U_{nQ}}{\sqrt{3} \times I''_{kQ}} = \frac{419{,}99 \cdot 10^3}{\sqrt{3} \times 13756} = 17{,}627\ \Omega \qquad (29)$$

$$\frac{X_Q}{R_Q} = \tan(87{,}37°) = 21{,}77 \qquad (30)$$

$$X_{Q,400} = \frac{Z_{Q,400}}{\sqrt{1 + (R_Q / X_Q)^2}} = \frac{17{,}627}{\sqrt{1 + (1/21{,}77)^2}} = 17{,}609\ \Omega \qquad (31)$$

(18) and (19) $\Rightarrow$

$$R_{Q,400} = \frac{Z_{Q,400}}{\sqrt{1 + (X_Q / R_Q)^2}} = \frac{17{,}29}{\sqrt{1 + 21{,}77^2}} = 0{,}809\ \Omega \qquad (32)$$

$$\bar{Z}_{Q,400} = R_{Q,400} + i\ X_{Q,400} = 0{,}809 + i\,17{,}609\ \Omega \qquad (33)$$

The impedance, $\bar{Z}_{Q,400}$, will then be changed to per unit values so that all impedances can be easily processed, see section 3.4.3. for per unit calculations.

3.3.5.2 Minimum short-circuit current contribution from the 400 kV grid

The minimum short-circuit current contribution is of no interest for the 400 kV grid, since the contribution for the cases concerning the 130 kV grid will be much lower. These cases (case 4, 8 and 9) are therefore those which are critical to examine.

3.3.5.3 Maximum short-circuit current contribution from the 130 kV grid

For a balanced three-phase fault the current contribution from the 130 kV grid will be 20,932 kA, with the impedance angle -86,93° at 139,2 kV. [Appendix C]. This will lead to the following impedance:

$$Z_{Q,130} = \frac{U_{nQ}}{\sqrt{3} \times I''_{kQ}} = \frac{139{,}2 \cdot 10^3}{\sqrt{3} \times 20932} = 3{,}839\,\Omega \tag{34}$$

$$\frac{X_Q}{R_Q} = \tan(86{,}93°) = 18{,}645 \tag{35}$$

$$X_{Q,130} = \frac{Z_{Q,130}}{\sqrt{1 + (R_Q / X_Q)^2}} = \frac{3{,}839}{\sqrt{1 + (1/18{,}645)^2}} = 3{,}833\,\Omega \tag{36}$$

(23) and (24) $\Rightarrow$

$$R_{Q,130} = \frac{Z_{Q,130}}{\sqrt{1 + (X_Q / R_Q)^2}} = \frac{3{,}839}{\sqrt{1 + 18{,}645^2}} = 0{,}206\,\Omega \tag{37}$$

$$\bar{Z}_{Q,130} = R_{Q,130} + i\, X_{Q,130} = 0{,}206 + i\, 3{,}833\,\Omega \tag{38}$$

The impedance, $\bar{Z}_{Q,130}$, will then be changed to per unit values so that all impedances can be easily processed, see section 3.4.3. for per unit calculations.

3.3.5.4 Minimum short-circuit current contribution from the 130 kV grid

When calculating the minimum short-circuit contribution from the 130 kV grid the same model as in the report *“Ringhals 1 – Kortslutningsberäkningar i 6 kV och 500 V huvudställverk och underfördelningar”* will be used [C1]. Here, the smallest contribution possible is considered. It will appear when there is only one gas turbine from Lahall gas powerplant feeding the grid. According to the report, the minimum short-circuit power is 266 MVA in this case, with a corresponding voltage of 142 kV. When calculating the minimum steady-state short-circuit current, the impedance can be considered to the purely reactive. This will lead to the equation:

$$X_{Q,130,\min} = \frac{{U_{n,130}}^2}{S_{k,\min}} = \frac{(142 \cdot 10^3)^2}{266 \cdot 10^6} = 75{,}805\,\Omega \qquad (39)$$

Per unit values for the minimum impedance, $X_{Q,130,\min}$, will then be used so that all impedances can be easily processed, see section 3.4.3. for per unit calculations.

3.4 Method of calculation

The method of the calculation is in line with the standard IEC 60909-0, as mentioned earlier. The software that has been used is *Microsoft Excel*. The main reason for choosing this software is that all the data have to be processed and here it can provide a good overview of these preparatory calculations. Another reason is that *Excel* easily handles imaginary data and also that it makes it easy to collect data from different sheets. The raw data has been added into different sheets, were some of the data have been processed according to IEC 60909-0, see section 3.2 and 3.3. The pure calculations have been performed in another sheet of the document were all the data concerning the case set up, has been inserted from the other sheets. Each case that is set up has one document for each voltage level and type of current that is calculated.

3.4.1 Calculation of the impedance contributions for further calculation of SCC and the usage of per unit values

When using the standard IEC 60909-0, an equivalent impedance has to be found in order to be able to calculate the short circuit current. In a more complicated system there are different voltage levels that need to be considered before impedances are added. As an explanation of how the calculations have been performed, case 1 is employed as an example. The initial short-circuit current for a three-phase balanced fault on bus H41-A6 will be calculated in the example.

3.4.2 Base data

At first, the different impedance values have to be set under the same base. The base voltage that is used is set at the fault location and the other levels are calculated from the base level, taking into account the voltage ratio of the transformers. A common power base for all voltage levels is used and this gives an impedance base, Z_{base} , for each voltage level. See table 4. for calculations of the different levels**.**

Table 4. *Base data used for short-circuit calculations*

Unity	**Equation**	**Base data used in calculations**
Sb	1,0*E+09 (fixed)	1,0E+09
UbHV	UbMV*(438,5/22,6)	437,27877E+03
UbMV	UbLV*(21,5/6,8)	22,53706E+03
UbLV	CMAX*Un= 1,08*6,6	7,128E+03
UbLLV	UbLV*(0,525/6,8)	550,32353
ZbHV	$UbHV^2/Sb$	191,21272
ZbMV	$UbMV^2/Sb$	0,50792
ZbLV	$UbLV^2/Sb$	0,050808
ZbLLV	$UbLLV^2/Sb$	0,00030286

3.4.3 Per unit calculations

To find the per unit value of an object, the impedance value, in ohms, is divided with the impedance base value at that specific voltage level. For instance, the reactance value for the generator G41 is found by equation (40). Note that this calculation only accounts for the reactive part of the impedance and that no compensation is done here (see section 3.2.4 for more information regarding this subject).

$$X''_{d,G41} = \frac{x''_{d,G41} \cdot (U_n^2 / S_n)}{ZbMV} = \frac{0{,}25 \cdot (21{,}5^2 / 577)}{0{,}507919} = 0{,}376306 \ p.u. \qquad (40)$$

In the same way the other impedances in the system are transformed into per unit values.

When all impedances have been converted into per unit values, the equivalent impedance can be calculated. For case 1 the contribution from the 400 kV grid, via the transformer LT410, is shown.

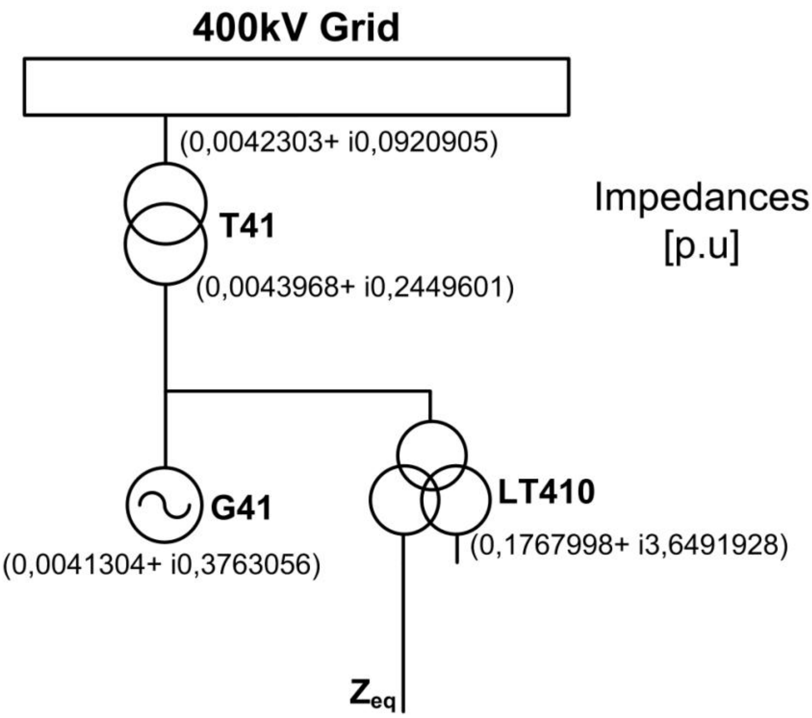

Figure 18. *Part of case 1 for calculation of the equivalent impedance.*

3.4.4 Calculation of the equivalent impedance

As shown in figure 18, the objective is to find the equivalent impedance. Some of the impedances will act in series with each other and others will act in parallel. If two contributions act in series, they will simply be added to each other and the sum will be the equivalent impedance, see equation (41). For impedances that act in parallel, the equivalent impedance is found by using equation (42). To be able to find the equivalent impedance, calculations have to be performed in steps, see table 5.

For impedances in series: $$\underline{Z}_1 + \underline{Z}_2 + \ldots + \underline{Z}_n = \underline{Z}_{eq} \qquad (41)$$

For impedances in parallel: $$\frac{1}{\underline{Z}_1} + \frac{1}{\underline{Z}_2} + \ldots + \frac{1}{\underline{Z}_n} = \frac{1}{\underline{Z}_{eq}} \qquad (42)$$

Table 5. *Working procedure for calculation of the equivalent impedance.*

Equivalent sum	**Contribution and performed action**
0,00860000+i0,33705634	400kV Grid + T41
$\frac{(0{,}00860000 + i0{,}33705634) \cdot (0{,}00413041 + i0{,}37630565)}{(0{,}00860000 + i0{,}33705634) + (0{,}00413041 + i0{,}37630565)} =$ $= 0{,}00331505 + i0{,}17780839$	(400kV Grid + T41) // G41
$(0{,}00331505 + i0{,}17780839) + (0{,}17679978 + i3{,}64919275) =$ $= 0{,}18011483 + i3{,}82700115 = Z_{eq,1}$	((400kV Grid + T41) // G41) + LT410

The equivalent impedance is used for calculating the initial short-circuit current contribution from this branch according to equation (43).

$$I''_{k,eq1} = \frac{c_{\max} \cdot U_n}{\sqrt{3} \cdot \left|Z_{eq,1}\right|} = 21{,}15\ kA \qquad (43)$$

The factor c_{max} is 1,08 for the bus where the fault occurs, and U_n equals 6,6 kV.

Asynchronous motors that are connected to the bus are all connected in parallel. Since the relation between R and X does not differ much between the motors, an equivalent impedance for the motors can be calculated according to equation (42). See figure 19. for a simplified picture of the system.

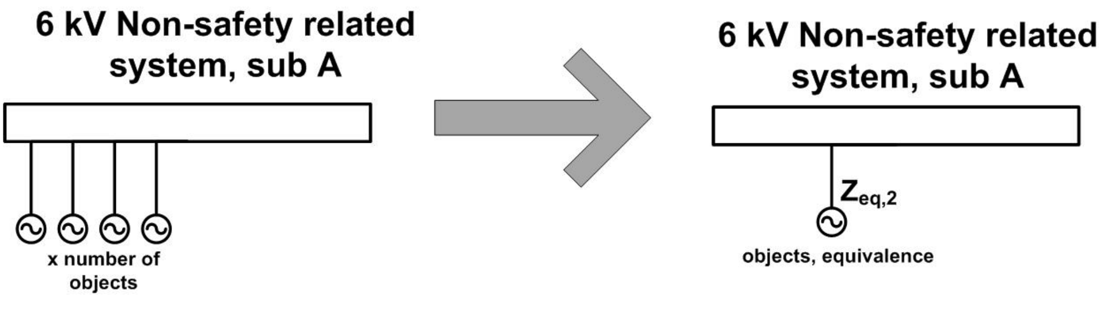

Figure 19. *The equivalent impedance of the asynchronous motors.*

The rest of the contributions are calculated in line with the same reasoning as above which leads to the final simplified circuit, see figure 20. The equivalent impedance contribution $Z_{eq,\,4}$ comes from the bus D41-A6.

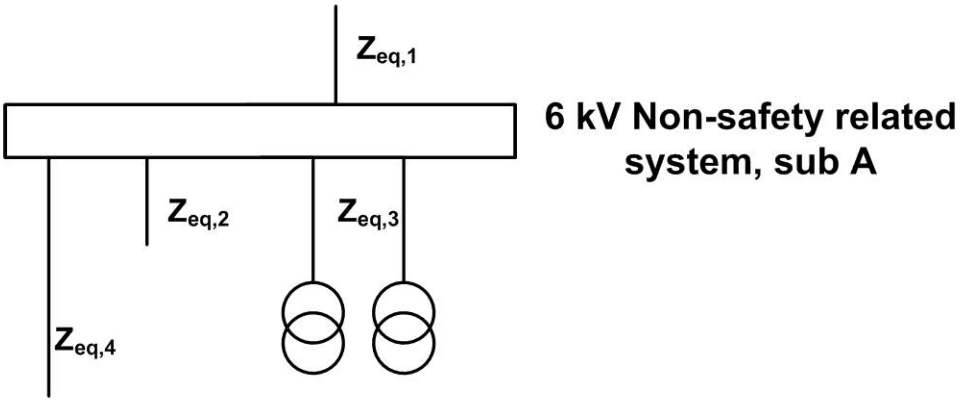

Figure 20. *The equivalent impedances of the system for case 1 on H41-A6.*

3.4.5 Calculation of the current contribution

According to equation (43), each impedance contribution will lead to a short-circuit current and the sum of all these currents is the total equivalent initial short-circuit current. See figure 21 and equation (44).

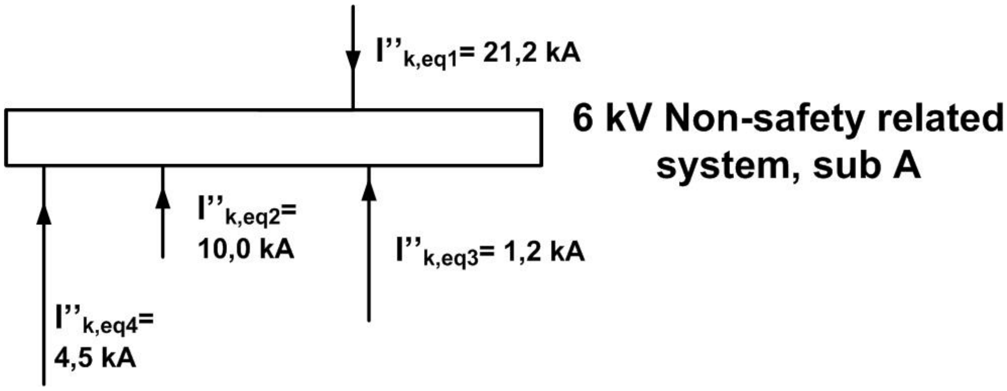

Figure 21. *The different current contributions of the system for case 1 on H41-A6.*

$$
\begin{aligned}
I''_{k,total} &= \sum I''_{k,eq} = I_{k,eq1} + I_{k,eq2} + I_{k,eq3} + I_{k,eq4} = \\
&= (21{,}2 + 10{,}0 + 1{,}2 + 4{,}5)kA = 36{,}9\ kA
\end{aligned} \qquad (44)
$$

Since the R/X relation does not exceed 0.3, the partial absolute value contributions are summarized [4]. The same procedure is used for all the different cases which are studied. For calculation of the different currents, the different regulations in IEC 60909-0 are used, see section 2.1.4.

4 RESULTS

4.1 Short-circuit calculations results for the different buses

Four different types of short circuit currents are calculated for all buses. The different cases examined are set up so that each bus can have a worst case scenario with the maximum and minimum short-circuit currents affecting each bus. The buses examined are H4x-y6, D4x-y6, VHC4x and DHC4x. The detailed results for all different cases are presented in Appendix B.

4.1.1 Results for buses H4x-y6

For the buses H41-A6, H42-B6, H43-C6 and H44-D6, the case in which the maximum initial short-circuit current is as large as possible is in case 7. Since this is a fictitious case, the actual "theoretical real" case that corresponds to the maximum I_k'', is case 3. As the peak current depends on I_k'', the maximum case for these currents is case 3 as well.

For the maximum steady-state current, the results are the same as for the initial SCC, i.e. case 3 is the case with the highest currents.

For the minimum steady-state current case 8 is the case with the lowest currents.

When calculating the thermal short circuit current, the relation between I_k'' and I_{kmax} is needed and therefore presented here as well. The results for the different currents on the buses are shown in table 6, where the maximum currents are from case 3 and the minimum currents from case 8.

Table 6. *Calculated currents for the buses H41-A6, H42-B6, H43-C6 and H44-D6.*

Type of current or relation	**Bus** **H41-A6**	**H42-B6**	**H43-C6**	**H44-D6**
I_k'' [kA]	67,3	67,0	66,9	66,5
I_p [kA]	169,7	168,9	168,2	167,4
$I_{k,max}$ [kA]	41,5	41,3	41,9	41,5
$I_{k,min}$ [kA]	10,4	10,4	10,5	10,5
I_k''/ $I_{k,max}$	1,62	1,62	1,60	1,60

4.1.2 Results for buses D4x-y6

For the following buses D41-A6, D42-B6, D43-C6 and D44-D6, the case where the highest currents are found is case 7. For the same reasons as mentioned previously, the maximum real case is case 3.

For the minimum steady-state current, case 9 is the case with the lowest currents since the safety related system can be supplied solely from the diesel generator DG4x0.
For further calculation of the thermal short-circuit current, the factor I_k''/I_{kmax} is presented. The results for the, highest or lowest, different currents on the buses D4x-y6 are shown in table 7, where the maximum currents are from case 3 and the minimum currents are from case 9.

Table 7. *Calculated currents for the buses D41-A6, D42-B6, D43-C6 and D44-D6.*

Type of current or relation	**Bus** D41-A6	**D42-B6**	**D43-C6**	**D44-D6**
I_k'' [kA]	60,8	60,6	60,5	59,8
I_p [kA]	138,9	138,5	138,3	136,3
$I_{k,max}$ [kA]	38,9	38,8	39,3	38,8
$I_{k,min}$ [kA]	1,3	1,3	1,3	1,3
$I_k''/ I_{k,max}$	1,56	1,56	1,54	1,54

4.1.3 Results for buses VHC4x

The maximum initial short-circuit current and the maximum peak current for the buses VHC41, VHC42, VHC43 and VHC44 are found in case 3. But the variations are not that large between the different cases, since the magnitude of the current mainly depends on the transformers LT4x1/LT4x2,

For the maximum steady-state voltage, the critical case is case 7, but in line with the previous reasoning, case 3 is the real case with the highest values.

The case with the minimum I_k is case 8. For further calculation of the thermal short-circuit current, the relation I_k''/I_{kmax} is shown. The different currents are listed in table 8, where the value from the maximum/minimum real case is expressed (case 3/case 8).

Table 8. *Calculated currents for VHC41, VHC42, VHC43 and VHC44.*

Type of current or relation	**Bus** VHC41	**VHC42**	**VHC43**	**VHC44**
I_k'' [kA]	72,9	72,9	72,9	72,9
I_p [kA]	160,7	160,7	160,6	160,6
$I_{k,max}$ [kA]	49,4	49,4	49,5	49,5
$I_{k,min}$ [kA]	34,1	34,1	34,1	34,1
$I_k''/ I_{k,max}$	1,48	1,48	1,47	1,47

4.1.4 Results for buses DHC4x

For the maximum I_k'' and for I_p on the buses DHC41, DHC42, DHC43 and DHC44, the maximum currents appear for case 7 but the critical real case will be case 3.

For the maximum steady-state current, the decisive case is the same as for I_k'' and I_p.

The minimum I_k is found for case 9, when the safety related system is fed singularly by the diesel generator.

The relation I_k''/I_{kmax} is also presented so that the thermal short circuit current can be easily calculated. Results are shown in table 9. for the buses DHC4x, where the maximum values comes from case 3 and the minimum currents from case 9.

Table 9. *Calculated currents for the buses DHC41, DHC42, DHC43 and DHC44.*

Type of current or relation	Bus DHC41	DHC42	DHC43	DHC44
I_k'' [kA]	59,8	60,9	61,7	62,4
I_p [kA]	129,4	132,0	133,9	135,5
$I_{k,max}$ [kA]	49,0	49,0	49,0	49,0
$I_{k,min}$ [kA]	14,4	14,5	14,5	14,5
$I_k''/ I_{k,max}$	1,22	1,24	1,26	1,27

4.2 Sensitivity analysis

It is of interest to vary a number of different factors in order to see how much they affect the final result. For example, the impedance of the objects of VHC4x is varied and the effect of including the impedance of the cables that connects these motors to the bus is examined. The new calculations are also compared with previous calculations to see that the new results are of the right magnitude, for a discussion of the results from sensitivity analysis, see chapter 5, *Conclusion & discussion*.

4.2.1 Variation of the impedance of the objects on VHC4x

The impedance of the object on bus VHC41 is varied in order to examine how much it affects the other buses in the same sub. VHC41 is set as an example and the same results are presumed for the other subs. The case that is examined is case 3 because this is the most critical case. Results are shown in table 10.

Table 10. *Variance of the impedance of the object on VHC41 in order to examine the deviations of the maximum initial SCC on different buses compared to the normal case.*

Variation	I_k'' on Bus (deviation in %) H41-A6 [kA]	D41-A6 [kA]	DHC41 [kA]	VHC41 [kA]
$Z_{VHC41,objects}$ (normal case)	67,3	60,8	59,8	72,9
$Z_{VHC41,objects}$*10	65,2 (-3,1%)	59,2 (-2,6%)	59,8 (-0,2%)	53,6 (-26,5%)
$Z_{VHC41,objects}$/10	71,7 (+6,5%)	64,2 (+5,6%)	59,9 (+0,2%)	266,2 (+333%)
$Z_{VHC41,objects}$*2	66,3 (-1,5%)	60,0 (-1,3%)	59,8 (-0,1%)	62,2 (-14,6%)
$Z_{VHC41,objects}$/2	68,6(+1,9%)	61,9(+1,8%)	59,8 (0%)	94,4(+30,2%)

4.2.2 Effect of the cables connecting motors on bus VHC41

When the equivalent impedance for the objects on VHC41 is calculated, each cable is added to the motor, which is connected to the bus. A Thevenin equivalent impedance is calculated where all these objects are connected in parallel. Here, the contributions of the cables for the short-circuit are examined for case 3, sub A. Results are presented in table 11.

Table 11. *The effect of the impedance contributions from cables connecting motors on bus VHC41 for SCC on different buses.*

Variation	I_k'' on Bus (deviation in %) H41-A6 [kA]	D41-A6 [kA]	DHC41 [kA]	VHC41 [kA]
Contribution from cables incl.	66,5	59,8	59,8	72,9
No cable impedance	66,5(+0,1%)	59,9(+0,2%)	59,8 (+0%)	74,3 (+1,9%)

4.2.3 Comparison between the infinite and the existing systems i.e. case 7 and case 3

Cases 7 and 3 are more or less the same. However, for case 7, infinite 130 kV and 400 kV grids are considered. In table 12., the deviations are shown for the maximum initial short-circuit current since case 7 and case 3 are the cases that provide the maximum values.

Table 12. *Comparison between case 7 and 3 for I_k'' for sub A.*

I_k'' on Bus (deviation in %)	H41-A6 [kA]	D41-A6 [kA]	DHC41 [kA]	VHC41 [kA]
Case 7	68,2	61,5	59,8	73,0
Case 3	67,3	60,8	59,8	72,9
Difference	0,95 (1,4%)	0,77 (1,2%)	0,04 (0%)	0,04 (0%)

4.2.4 Comparison of the short-circuit currents to previous calculations

In 1978, some simplified short-circuit calculations were done. When performing these calculations, the standard IEC 60909-0 was not used, but the results could be of some guidance to see that the new calculations are of the right magnitude. The calculations can be found in [C3]. The old calculations were set up for a special case, which is similar to case 1 in this report, except that there is no contribution from the 400 kV grid via T41, nor from D41-A6 in the old case. The old calculations only concerned the minimum steady-state current, which is why this is the type of current to compare. For the new calculations, the steady state current is calculated according to IEC 60909-0 for the same case as in the old calculations. An $I_{k,\,min}$ value for the new calculation with the voltage factor set to 1,0 is also performed. As the cable impedances are not considered in the old calculations, new calculations have been performed where the cable impedances have been disregarded. To compare the different cases, a new calculation has been performed with the old method in [C3], but with the new data inserted, i.e. with respect taken to the cable impedance and the factor c_{min}. See table 13 for results and comparison regarding the different calculations.

Table 13. *Comparison between new and old calculations for bus VHC41.*

$S_{k, min}$ on Bus VHC41 [MVA](deviation from old results)	
Old results	39,5
New calculation (according to IEC 60909-0)	37,3 (-5,5%)
New calculation (at 100 % voltage)	39,3 (-0,6%)
New calculation (without cable impedance, c_{min} according to IEC 60909-0)	37,5 (-5,1%)
New calculation (without cable impedance at 100 % voltage, i.e. same as old calculation)	39,5 (0%)

4.2.5 Comparison of the new calculations to the results found in the report "R4 Förstudierapport - Elmatning till PRZ-värmare"

In the report *R4 Förstudierapport - FREJ - Elmatning till PRZ-värmare,* short circuit power for R4 is calculated [C4]. As the new generator data for G41 are considered in these calculations (with a nominal power of 677 MVA) cases regarding G42 need to be examined since the generator is of the same magnitude in both calculations, i.e. cases regarding sub B and D. The type of current that can be compared in the two different calculations is the maximum steady-state current. For calculations in [C4], voltage values for $U_{6\ kV}$ of 6,8 kV and $U_{0,5\ kV}$ of 515 V are used for the maximum case. The maximum case that is set up is similar to case 3 in this report, with some modifications. For case 3, two subs are connected to the H94-x6 bus. For the calculations in [C4], only one sub is connected. Calculations are only performed for buses DHC42 and VHC44, which means that it will be these two results that are compared. The transient reactance is used for all generators. For a comparison between the different current values on the buses see table 14.

Table 14. *Comparison between new calculations and results from [C4].*

$I_{k, max}$ when a fault occur on Bus:	DHC42 [kA]	VHC44 [kA]
New calculations (Case 3 with adaptations)	49,1	49,4
Results from [C4]	43,4/(√3*0,515)=48,7	43,7/(√3*0,515)=49,0
Difference (in % compared to the new calculations)	-0,8%	-0,8%

4.2.6 Comparison between calculations with IEC 60909-0 and the software PowerWorld

The calculated short-circuit currents for bus A in case 6 have been compared with results from calculations performed with the software PowerWorld.

4.2.6.1 Background and method for the PowerWorld Simulator

PowerWorld Simulator 14 Evaluation is a power system design package. The core of the simulator is a robust Power Flow Solution engine. The base package contains all the tools necessary to perform various analyses, for example short-circuit analysis [13].

For the fault analysis, a specific pre-fault profile option is available that is called Flat IEC-909. For this option, the voltage factor c_{max} can be used, which will increase the voltage in the fault location in the same way as for IEC 60909-0.

In the following calculations, the power flows for the specific set-ups are calculated using the Newton-Raphson method (Single solution – Full Newton). For this solution, the fault analysis is performed. The pre-fault profile chosen, is the Flat IEC-909, for a 3 phase balanced fault at the bus where the fault is calculated.

4.2.6.2 Modelling

To be able to do some type of comparison between the two different methods, the same cases have to be compared. Case 6 has been chosen, see section 3.1.6, to make this comparison, and the short-circuit current that has been calculated is the maximum steady-state current, $I_{k,max}$.

For the calculation of the fault current on each bus, a specific set-up is needed. For the different bus configurations, see figures (22) and (23) below.

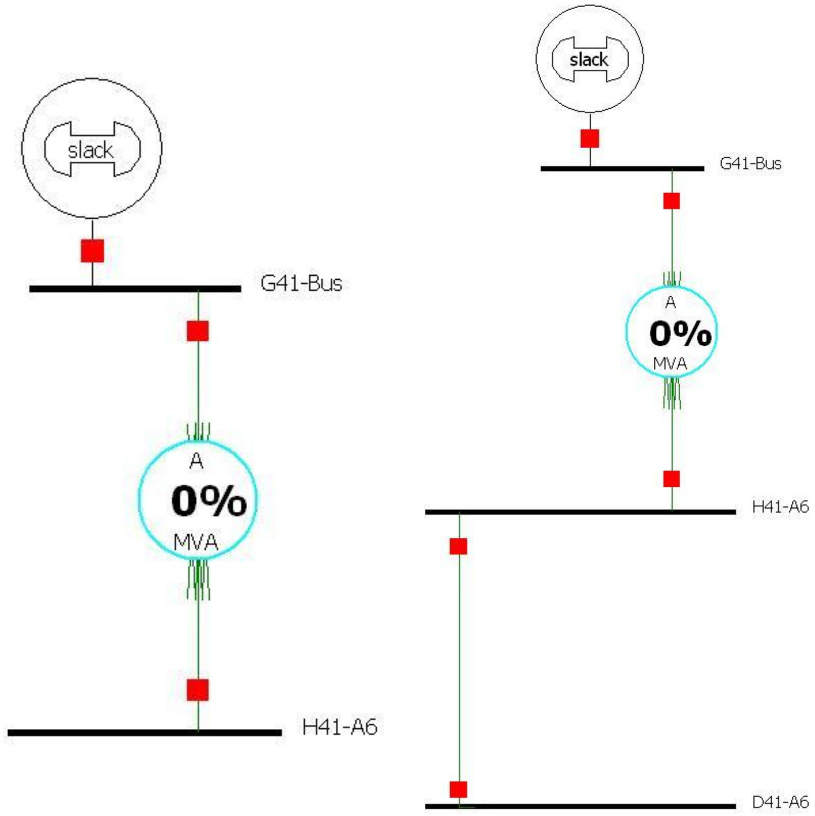

Figure 22. *The set-ups for calculating SCC on H41-A6 and D41-A6 respectively.*

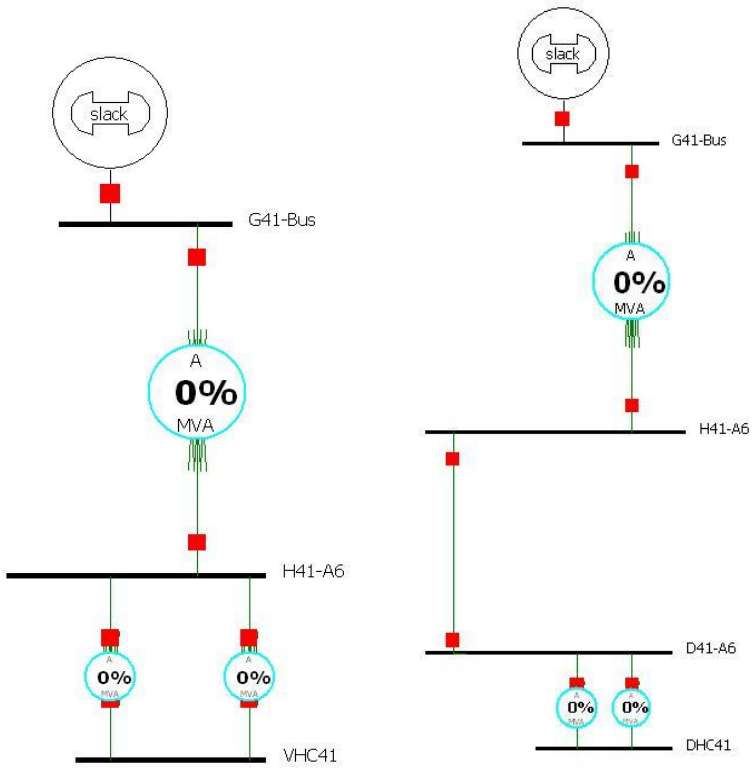

Figure 23. *The set-up for calculations on VHC41 and DHC41 respectively.*

For all specific setups, the same voltage and impedance values have been used, as for the calculations performed with IEC 60909-0.

4.2.6.3 Comparison between the short-circuit currents for case 6

In table 15 below, the different currents from each method are presented, for calculation on the different buses for sub A in case 6. For the calculations, the same voltages have been used, as well as the same impedances. The voltage factor, c_{max}, is set to 1,08 for the buses D41-A6 and H41-A6 and to 1,1 for the buses VHC41 and DHC41.

Table 15. *Comparison between calculations performed with IEC 60909-0 and PowerWorld respectively, for the different buses of sub A for case 6.*

MAX I_k	**Bus [kA]**			
Type of calculation	**H41-A6**	**D41-A6**	**VHC41**	**DHC41**
IEC 60909-0	18,77	18,21	45,19	44,80
PW Flat IEC-909	18,64	18,11	45,45	45,26
Deviation (%)	-0,7%	-0,6%	+0,6%	+1,0%

As seen in table 15 above, the results are similar and the deviations are within a reasonable range. The deviations are a bit higher for the bus DHC41. It can be explained by the fact that the cable between H41-A6 and D41-A6 affects the results differently in the calculations.

5 CONCLUSION & DISCUSSION

In this report, the IEC 60909-0 standard is used in order to calculate various types of short circuit currents in a power system. The usage of the standard IEC 60909-0 is in some cases quite conservative and this is positive when calculating currents for a system of this type. The power system is divided into several different voltage levels, where calculations are made for short circuits on the 6,6 kV and 500 V levels. Nine different cases were set up in order to evaluate the system, so that the maximum and minimum currents could be found.

For the buses H4x-y6 and D4x-y6, the nominal voltage is 6,6 kV. The case that leads to maximum values for these buses is case 7, where an infinite grid is assumed. Since this is a fictional case, the maximum “real” case is case 3, which has the same set-up as case 7. The difference is that case 3 handles real data from SvK for the 130 kV and 400 kV grid. Since the contribution from VHC4x and DHC4x have small affect on the currents on H4x-y6 and D4x-y6 according to *Variation of the impedance of the objects on VHC4x*, these values mainly depend on the contributions from the 400 kV grid and the generator G41/G42 via LT4x0 and from the 130 kV grid via T94.
For case 1, the case where normal operation is assumed, the SSC deviate from the extreme setup in case 3, where the currents are almost twice as large, see Appendix B.

The buses VHC4x and DHC4x have a nominal voltage of 500 V. For VHC4x the critical maximum real case is case 3. If case 3 is compared to case 8, the actual minimum case, the results are similar. The transformers LT4xy are the crucial factors for the amount of current for both cases since the transformers will come in series with the underlying impedance. At normal operation, case 1, the SSC do not differ from the extreme setup in case 3 and the currents are almost of the same size, see Appendix B.

According to the results of the performed sensitivity analysis, the steady-state short circuit currents on the VHC4x buses are similar to earlier calculations in [C3]. One reason for the differences in the results is that no cable impedances have been taken into account in the old calculations. The contribution from these cables will act in series with the total impedance and the total current will be lower than in [C3]. The minimum voltage correction factor, c_{min}, will also decrease the currents for the new calculations. As seen in table 13, the currents differ 5,5% when the IEC standard is used compared to the old results. There are some simplifications in the old calculations, as only transformer ratios that are of the same magnitude as the bus voltage are considered. In the real case, the bus voltages are different from the transformation ratio, so that a new voltage has to be calculated from the voltage level where the fault occurs. When the new data is used to perform a calculation in the old way, the actual current will be the same according to table 13, this is when all the cables are disregarded and the voltage factor is set to 1.0.

For the initial short circuit currents, the values are very similar for the VHC4x level, since the same equivalent impedance is used for the different subs. If a more specific value of the initial short circuit current is needed, for VHC42, VHC43 and VHC44, a more detailed study, which has been performed for VHC41, is recommended. For the contribution of the current from VHC4x to the other buses, the sensitivity analysis regarding *Variation of the impedance of the object on VHC4x* shows that even large variations of the impedance have little impact on the other buses. For DHC4x, data from [C5] has been used. This data has been developed for Ringhals 3 but since the two units are very similar, the data has been used for Ringhals 4. In this data, some variations are to be found which are notable in the initial short circuit current calculations for DHC4x. Similar to VHC4x, a more detailed study should be performed if an exact value of maximum I_k'' is of great importance for DHC4x. The size of the impedance of the objects on DHC4x has little impact on the current value on the other buses in the system. In the sensitivity analysis performed for DHC42, the results of the steady state current in the new calculations and the results from [C4] are much alike, since the deviation is smaller than 1%, see table 14 in section 4.2.5.

For the motors on DHC4x, the impedance values of cables connecting them to the bus are disregarded. According to the analysis performed, the results in *Effect of the cables connecting motors on bus VHC41* show that the cables have little effect on the SCCs. However, if more detailed values for the results on DHC4x are needed, they could be of interest.

In the comparison between the calculations performed with IEC 60909-0 and PowerWorld, the results are essentially the same, according to section 4.2.6.3. The similarity of the results are not too surprising, as more or less the same method of calculation has been used. However, having performed calculations both manually and by using software, thereby gaining the same results, increases the reliability of the final results.

6 RECOMMENDATIONS AND FUTURE WORK

If more detailed values are needed for the buses DHC4x and VHC4x, a thorough analysis, as performed for VHC41, should be made. In the same way, it would be advantageous to have test protocols for the transformers LTxy and DT4x0P/Q, since these are the dominant factors for the buses VHC4x and DHC4x. Moreover, it would strengthen the results to perform measurements on the transformers, and use the data for the short-circuit current calculations. The magnetization of the synchronous generators in the system could also be examined in order to have less conservative results for the calculation of the steady-state short-circuit current.

Finally, the components in the models, developed in this report, could be exchanged in order to examine the magnitude of short-circuit currents in a new system.

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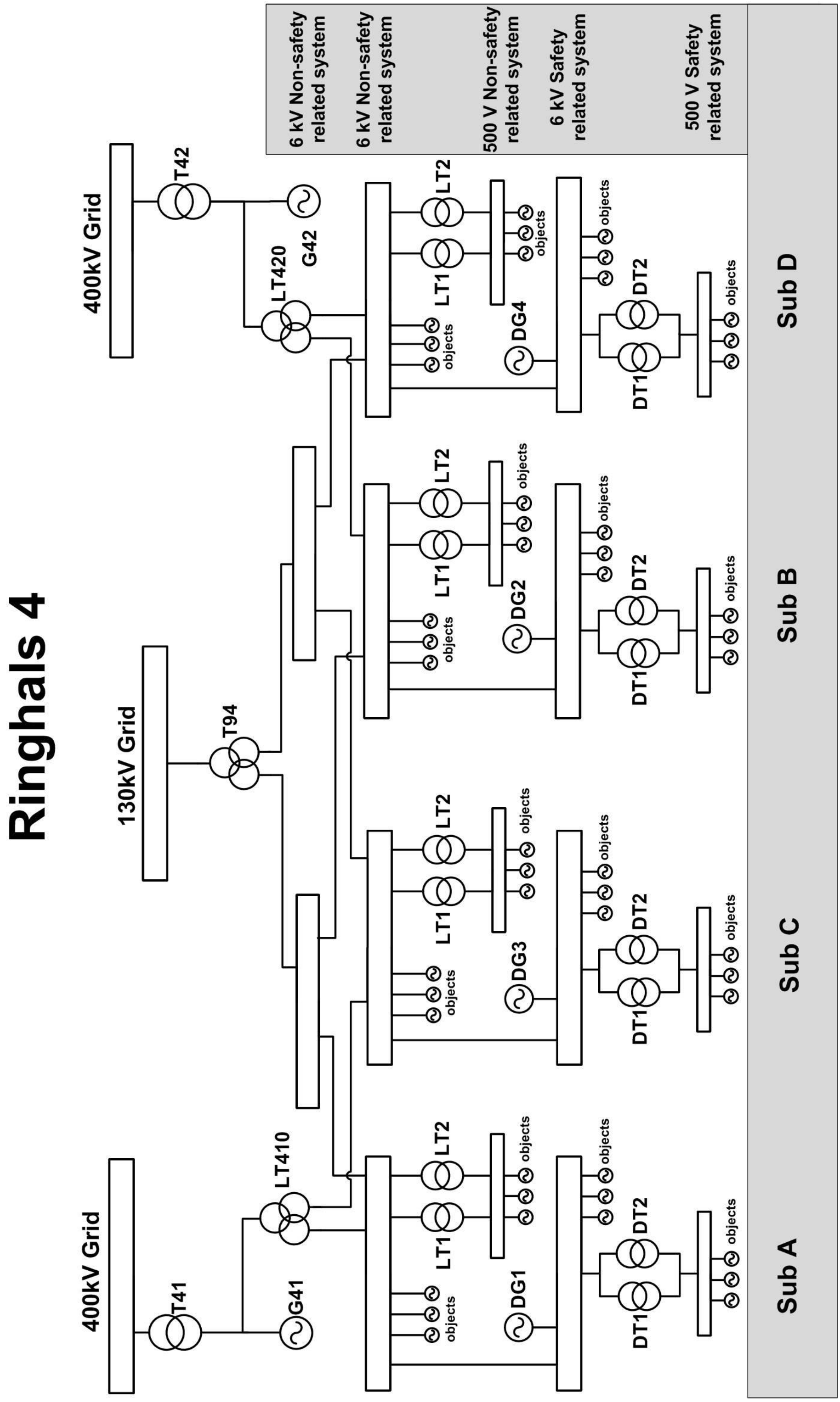
APPENDIX A



Ringhals 4
400kV Grid
130kV Grid
400kV Grid
T41
G41
LT410
T94
T42
LT420
G42
LT1
LT2
DT1
DT2
DG1
DG2
DG3
DG4
objects
Sub A
Sub C
Sub B
Sub D
6 kV Non-safety related system
6 kV Non-safety related system
500 V Non-safety related system
6 kV Safety related system
500 V Safety related system

APPENDIX B

Compilation of short-circuit currents (Real extreme values high-lighted)

Type of short-circuit current	Bus	Case 1.	2.	3.	4.	5.	6.	7.	8.	9.
MAX Ik'' [kA]	H41-A6	36,5	63,7	66,5	45,8	30,6	32,7	67,5	31,0	
	D41-A6	34,9	57,3	60,2	42,9	29,2	31,1	60,9	29,4	
	VHC41	71,4	72,7	72,9	71,4	70,4	70,7	72,9	69,4	
	DHC41	57,8	59,5	59,7	58,4	56,8	57,1	59,8	56,4	
	H42-B6	36,3	63,3	66,1	45,7	30,4	32,5	67,1	30,9	
	D42-B6	34,7	57,0	59,9	42,8	29,0	31,0	60,6	29,4	
	VHC42	71,3	72,7	72,9	71,5	70,3	70,7	72,9	69,4	
	DHC42	58,9	60,7	60,8	59,5	59,0	58,3	60,9	57,5	
	H43-C6	35,3	63,2	66,1	45,1	29,3	31,4	67,0	29,8	
	D43-C6	33,8	57,0	59,9	42,3	28,1	30,0	60,6	28,4	
	VHC43	71,2	72,7	72,9	71,4	70,1	70,5	72,9	69,1	
	DHC43	59,6	61,5	61,7	60,3	58,5	58,9	61,7	58,1	
	H44-D6	37,1	62,8	65,7	45,0	31,1	33,3	66,6	31,5	
	D44-D6	35,2	56,3	59,2	42,1	29,6	31,5	59,9	29,8	
	VHC44	71,5	72,7	72,8	71,4	70,4	70,8	72,9	69,5	
	DHC44	60,7	62,2	62,4	61,0	59,6	60,0	62,4	59,1	
MAX Ip [kA]	H41-A6	92,1	159,9	167,0	112,7	77,3	82,6	169,4	77,7	
	D41-A6	83,8	130,0	137,1	99,1	70,3	74,5	138,7	70,0	
	VHC41	157,7	160,3	160,6	157,5	155,7	156,5	160,7	153,4	
	DHC41	126,1	128,9	129,3	126,7	124,2	124,8	129,4	123,1	
	H42-B6	91,4	158,7	165,7	112,3	76,6	82,1	168,1	77,3	
	D42-B6	83,2	129,2	136,4	98,9	69,8	74,2	137,9	70,0	
	VHC42	157,6	160,3	160,6	157,6	155,6	456,4	160,6	153,5	
	DHC42	128,8	131,5	131,9	129,4	128,9	127,5	132,0	125,7	
	H43-C6	89,1	158,1	165,2	110,4	74,1	79,4	167,6	74,2	
	D43-C6	81,4	129,1	136,3	97,6	67,7	72,1	137,8	67,4	
	VHC43	157,3	160,2	160,5	157,4	155,1	156,0	160,6	152,9	
	DHC43	130,5	133,4	133,8	131,1	128,4	129,2	133,9	127,1	
	H44-D6	93,2	157,4	164,5	110,6	78,3	83,8	166,9	78,7	
	D44-D6	84,1	127,2	134,4	97,0	70,6	75,1	135,9	70,6	
	VHC44	157,8	160,2	160,5	157,4	155,8	156,6	160,6	153,7	
	DHC44	132,7	135,0	135,4	132,8	130,8	131,5	135,5	129,4	

Compilation of short-circuit currents (Real extreme values high-lighted)

Type of short-circuit current	Bus	Case 1.	2.	3.	4.	5.	6.	7.	8.	9.
MAX Ik [kA]	H41-A6	22,5		41,0	20,5	17,1		42,0	18,7	
	D41-A6	21,9		38,5	19,9	16,7		39,3	18,0	
	VHC41	46,1		49,4	45,3	43,9		49,7	44,5	
	DHC41	45,7		48,9	45,0	43,5		49,2	44,1	
	H42-B6	22,3		40,7	20,4	16,4		41,7	18,6	
	D42-B6	21,7		38,2	19,8	16,0		39,1	18,0	
	VHC42	46,0		49,4	45,3	44,0		49,7	44,5	
	DHC42	45,7		48,9	45,0	43,2		49,2	44,1	
	H43-C6	22,7		41,4	20,7	17,2		42,4	18,8	
	D43-C6	22,0		38,8	20,1	16,8		39,7	18,2	
	VHC43	46,1		49,4	45,4	44,9		49,8	44,6	
	DHC43	45,8		48,9	45,0	43,6		49,3	44,2	
	H44-D6	22,5		40,9	20,5	16,6		41,9	18,6	
	D44-D6	21,8		38,3	19,9	16,1		39,2	18,0	
	VHC44	46,1		49,4	45,3	43,6		49,7	44,5	
	DHC44	45,7		48,9	45,0	43,2		49,2	44,1	
MIN Ik [kA]	H41-A6					15,4	16,7		9,9	
(only calculated for	D41-A6					15,0	16,1		9,7	1,8
relevant cases)	VHC41					38,4	39,0		34,3	
	DHC41					38,0	38,6		34,1	15,1
	H42-B6					14,8	16,9		9,8	
	D42-B6					14,4	16,4		9,6	1,8
	VHC42					38,5	39,1		34,4	
	DHC42					37,7	38,7		34,1	15,1
	H43-C6					15,6	16,8		9,9	
	D43-C6					15,1	16,3		9,7	1,8
	VHC43					38,4	39,0		34,4	
	DHC43					38,1	38,6		34,2	15,1
	H44-D6					14,9	17,1		9,9	
	D44-D6					14,5	16,5		9,7	1,8
	VHC44					38,1	39,1		34,5	
	DHC44					37,7	38,7		34,2	15,1

APPENDIX C

The e-mail from SvK can not be shown here due to it is an intercompany secret.
Data from the mail can be seen in table AC1 below.

Table AC1. *Data from SvK for the 130 kV grid at a three-phase fault.*

I_{nk} [kA]	U_{nk} [kV]	Ψ_{nk}
20,932	139,2	-86,93°

For a balanced three-phase fault the current contribution from the 130 kV grid will be 20,932 kA, with the impedance angle -86,93° at 139,2 kV.

APPENDIX D

ASEA KABEL

Electrical data — Maximum values for conductor resistance, cable capacitance and inductance are given in the following tables.

Table 2

ESSJ, FSSJ, RSSJ

	Number of conductors and nominal area mm²	Maximum resistance of conductor at 20°C Ω/km	Maximum capacitance at 20°C µF/km	Inductance mH/km
RSSJ	3x2,5/2,5	7,79/		0,30
ESSJ	3x2,5/2,5	7,56/7,22	0,32	0,30
FSSJ	3x6/6	3,11/3,10	0,36	0,32
	3x16/16	1,16/1,11	0,46	0,29
	4x16/16	1,16/1,11	0,46	0,29
	3x35/16	0,529/1,11	0,64	0,26
	3x50/25	0,391/0,66	0,70	0,26
	4x70/35	0,270/0,514	0,75	0,24

FSSR

Number of conductors and nominal area mm²	Maximum resistance of conductor at 20°C Ω/km	Maximum capacitance at 20°C µF/km	Inductance mH/km
3x1	21,6	0,14	
4x1	21,6	0,14	
7x1	21,6	0,14	
14x1	21,6	0,14	
19x1	21,6	0,14	

FSFR

Number of conductors and nominal area mm²	Maximum resistance of conductor at 20°C Ω/km	Maximum capacitance at 20°C µF/km	Inductance mH/km
7x1	20,4	0,16	0,35
12x1	20,4	0,16	0,35
16x1	20,4	0,16	0,35
19x1	20,4	0,16	