UNIVERSITY OF WEST BOHEMIA IN PILSEN

Faculty of Electrical Engineering
Department of Power Engineering

MASTER'S THESIS

TEPLATOR SMR´s electrical equipment design

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ZADÁNÍ DIPLOMOVÉ PRÁCE

(projektu, uměleckého díla, uměleckého výkonu)

Jméno a příjmení:	**Bc. Jan ULLMANN**
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Studijní program:	**N0713A060013 Výkonové systémy a elektroenergetika**
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Zásady pro vypracování

1. Popište zařízení TEPLATOR s ohledem na klíčové systémy vyžadující napájení elektrickou energií.
2. Definujte normativní a legislativní požadavky na systémy napájení vlastní spotřeby jaderných zařízení.
3. Rozdělte zařízení podle úrovně zajištění napájení vlastní spotřeby a popište sítě SZN.
4. Navrhněte a popište koncepci systému napájení vlastní spotřeby TEPLATORu.

Rozsah diplomové práce: **40-60**
Rozsah grafických prací:
Forma zpracování diplomové práce: **elektronická**

Seznam doporučené literatury:

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Abstract

The submitted master's thesis deals with the overall design of the electrical part of the SMR TEPLATOR. The first part of the thesis describes critical systems requiring electrical power. Subsequently, the thesis presents the requirements for the design of nuclear facilities. It then addresses legislative and normative requirements for the power supply systems of nuclear facilities' own consumption. The thesis presents the power supply system of the Temelín NPP and CANDU reactor as a model for the subsequent design of the TEPLATOR power supply system, specially targeted to individual categories according to the importance of power supply in terms of uninterruptible power supply. The last part of the thesis focuses on designing and describing the concept of the own consumption power supply system. The emphasis in the master's thesis is placed on the system for connecting the most critical equipment in the SMR TEPLATOR technology, both in terms of sizing supply cables to equipment and the overall connection of the nuclear facility to the power grid. The thesis also focuses on controlling the voltage drop on the transformer during the start-up of the largest motor and motor group.

Keywords

Nuclear power, small modular reactors, self-consumption power plants, emergency power supply system

Abstrakt

Předkládaná diplomová práce se zabývá celkovým návrhem elektrické části SMR TEPLATOR. V první části práce jsou popsány klíčové systémy vyžadující napájení elektrickou energií. Následně práce představuje požadavky na projekt jaderného zařízení. Dále se zabývá legislativními a normativními požadavky na systémy napájení vlastní spotřeby jaderných zařízení. V práci je prezentován systém zajištěného napájení jaderné elektrárny Temelín a reaktoru CANDU jako vzor pro následný návrh systému zajištěného napájení zařízení TEPLATOR. Poslední část práce je zaměřena na samotný návrh a popis koncepce systému napájení vlastní spotřeby. V diplomové práci je kladen důraz na systém připojení nejdůležitějších zařízení v technologii SMR TEPLATOR jak k dimenzování přívodního napájecích vodičů k spotřebičů, ale i v celkovému připojení jaderného zařízení k elektrizační soustavě. Práce se svým návrhem také zabývá kontrolou na pokles napětí natransformátoru při rozběhu největšího motoru a skupiny motorů.

Klíčová slova

Jaderná energetika, malé modulární reaktory, vlastní spotřeba elektráren, systém napájení vlastní spotřeby

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Contents

List of Symbols

c	Voltage factor	
f	Frequency	Hz
I_{th}	Thermally equivalent short-time current	A
I_k''	Short-circuit current	A
I_k	Inrush current of motors	%
K	Coefficient respecting the type of insulation	-
K_{TR}	Correction factor of transformer	-
M	Torque	Nm
m	DC Heat dissipation factor	-
n	AC Heat dissipation factor	-
P	Real Power	W
ΔP_{kTR}	Short-circuit losses of transformer	W
Δu	Voltage drop	%
R	Resistance	Ω
R_{km}	Cable resistance per kilometre	Ω/km
S_p	Apparent Power	VA
S_{min}	Minimum cross-section of cable	mm^2
S_k''	Short-circuit power	VA
t_k	Short-circuit time	sec
U	Voltage	V
$u_{\text{kTR\%}}$	Short-circuit voltage of transformer	%
$X_{k\text{net}}$	Reactance	Ω
X_{km}	Cable reactance per kilometre	Ω/km
Z	Impedance	Ω
β	Diversity factor	-
$\cos\varphi$	Power factor	-
η_m	Efficiency of motors	-
η_s	Efficiency of the power supply system	-
γ	Load	-
κ	Peak factor	-

List of abreviations

AC	Alternating current
ČSN	Czech technical standard (Česká státní norma)
DC	Direct current
DG(s)	Diesel generator(s)
EDG	Emergency diesel generator
HP	High-pressure
HV/LV	High voltage / Low voltage
IAEA	International Atomic Energy Agency
I&C	Information and control systems
LP	Low-pressure
NPP	Nuclear power plant
SMR(s)	Small modular reactor(s)
TR	Transformer
ÚJV	Nuclear Research Institute (Ústav jaderného výzkumu)

Introduction

Nowadays, topics such as energy, renewables, and the transition away from fossil fuel sources of electricity and heat are very relevant. Nuclear energy is and will be one of the primary sources in the energy mix. However, by moving away from fossil fuels, the availability of heating networks in Central and Eastern Europe will have to switch to another source, as cities are now heated by coal-fired sources. The situation is being addressed temporarily by individual countries with gas-fired power stations. Nuclear energy is also playing its part in this transformation since nuclear power plants are already powering the Czech Republic's electricity network and the heating supply system. The SMR TEPLATOR project is dedicated to maintaining district heating. It is a small modular reactor designed exclusively for heat supply.

At the moment, the TEPLATOR prototype is in the development stage. In the development so far, the designers have focused mainly on the nuclear part of the whole plant, which is the keystone for the subsequent development of the whole project. Thanks to the fact that SMR TEPLATOR is developed in cooperation with the Faculty of Electrical Engineering of the University of West Bohemia in Pilsen, the diploma thesis on the electrical part is created at this faculty. Because the prototype only counts on heat supply, it will not have its generator, which usually in power plants supplies its consumption, making this system original. However, its structure may be similar to research reactors, which usually have a lower heat output.

The thesis aims to show and describe the legislative and normative requirements for nuclear facilities in the Czech Republic based on the atomic law and recommendations from the IAEA for the electrical part of nuclear facilities. Part of the design of the electrical part is the need to define the different categories of electrical equipment according to their importance in terms of nuclear safety or the need to maintain an uninterrupted power supply; this design is part of the practical part of the thesis. After defining the normative and legislative requirements and designing the categories of equipment, the actual design of the electrical part is part of the work. Whether it is the connection to the power grid or the choice of the number and size of individual transformers. However, the cross sections and types of cables that will be considered in the thesis will also be designed. Various tests for voltage drops within the start-up of the largest motors will also be part of the control of the design of the electrical part. Emergency power sources such as diesel generators and batteries will also be designed in the thesis.

In its conclusion, this thesis shows the design of the structured electrical part and its first design. This thesis can be subsequently used in the further development of the electrical schematic.

1 SMR

1.1 Small Modular Reactors introduction

The concept of the TEPLATOR nuclear reactor falls into the Small Modular Reactors (SMRs) category. Small Modular Reactors are currently a very attractive and often discussed topic in academic circles, as well as in the media and industry. According to the definition of the International Atomic Energy Agency (IAEA), a small reactor is a nuclear facility with a power output of up to (approximately) 300 MW(e) per module. The modularity of these reactors is understood in various ways. Some manufacturers associate this term with the prefabrication of modules and the possibility of assembling them in a manufacturing plant, as opposed to large nuclear power plants where the assembly of individual parts of the plant is done on-site. Other manufacturers/developers see modularity as the ability to produce SMRs through serial production, thereby reducing procurement/investment costs. However, this fact sometimes clashes with some SMR prototypes, which are scaled-down versions of already existing large reactors. Currently, only two small modular reactors are in operation: the Russian (Akademic Lomonosov – KLT-40S) and the Chinese reactor (HTR-PM). CNP300 and PHWR-220 are small reactors that are also already in operation but are not categorized as modular. [1, 2, 3, 4]

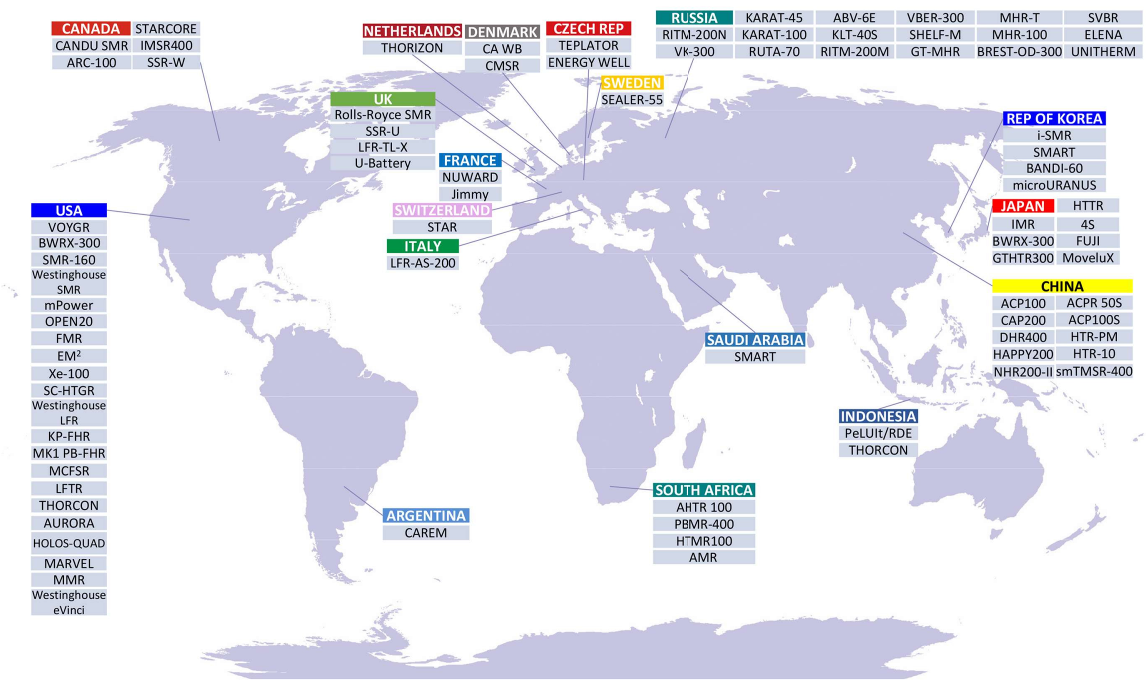

Fig. 1.1 Global Map of SMR Technology Development [2]

Currently, SMR development is underway in 17 different countries, with work on over 80 different SMR designs. SMR development is primarily conducted by nuclear states (such as the USA, France, and South Korea), which already have significant experience in nuclear reactor development. Flagship companies developing small modular reactors include EDF, Westinghouse, and Rolls Royce SMR. Among the most advanced prototypes are NUWARD by EDF, BWRX-300 by GE-Hitachi Nuclear Energy, and AP300 by Westinghouse or SMART from KHNP. Most SMR reactor prototypes are pressurized water reactor (PWR) types, moderated and cooled by light water, with enriched uranium oxide used as fuel. Due to the high pressure, PWR reactors are the smallest in size, which is advantageous for designing small modular reactors. PWR reactors are controlled using control rods in the pressure vessel's upper part. Several research teams in the Czech Republic are also involved in SMR development. Specifically, six developed concepts of small reactors exist in the Czech Republic. A pressurized water reactor with a power of 50 MWt, named DAVID SMR, is being developed by Witkowitz Atomica and Czechatom. Four small modular reactor concepts are being developed by the ÚJV group in Řež, including the Allegro reactor, Energy Well, and HeFASTo. The newest concept from the ÚJV group is a pressurized water reactor with a power of 100 MWt. Part of the development in the Czech Republic is also the prototype SMR TEPLATOR, which could provide a solution for heating after the closure of aging coal power plants in the Czech Republic and globally.

1.2 TEPLATOR

The innovative concept of the SMR TEPLATOR nuclear reactor is considered an original solution for district and industrial heating. A unique feature of this concept is that it allows for using spent fuel from large nuclear power plants (VVER-440); although this is not a necessary condition, fresh fuel can also be used. Another specification, unlike other small modular reactors, is that the concept exclusively focuses on heat production, not cogeneration. Spent fuel from the fuel cycle in VVER-440 reactors may appear in various states; the reusable fuel will be the one that has not reached its regulatory and design limitations. Spent fuel can be taken directly from the spent fuel pool or intermediate storage. In the case of using spent fuel, there is no need to produce new fuel. Another advantage of using spent fuel is its cost. In the Czech Republic, and potentially throughout Europe, there is a huge supply of more than 60,000 of these fuel assemblies, which is a significant motivation to utilize them. Fuel reprocessing has been used worldwide for decades; however, in the case of TEPLATOR, there would be no re-enrichment of uranium and additional reprocessing process needed. The advantage of using spent fuel lies in its already approved license, although it will operate in TEPLATOR in a different geometry and under other conditions. It will generate heat under much lower conditions than in large nuclear power plants. Licensing for using spent fuel can be quite problematic, so as I mentioned earlier, it's not a necessary condition for the project.

Since no one has attempted to license a nuclear reactor with a similar design yet, this unique construction will initially be tested on the TEPLATOR DEMO unit. Subsequently, there could be an increase in power. The heavy water reactor TEPLATOR DEMO has a thermal output of 50 MW with 55 spent fuel assemblies from VVER-440 in the active zone. The outlet temperature of the fluid from the active zone is 192°C, with the entire unit operating at 2 MPa pressure. The final outlet temperature for district heating will vary depending on the

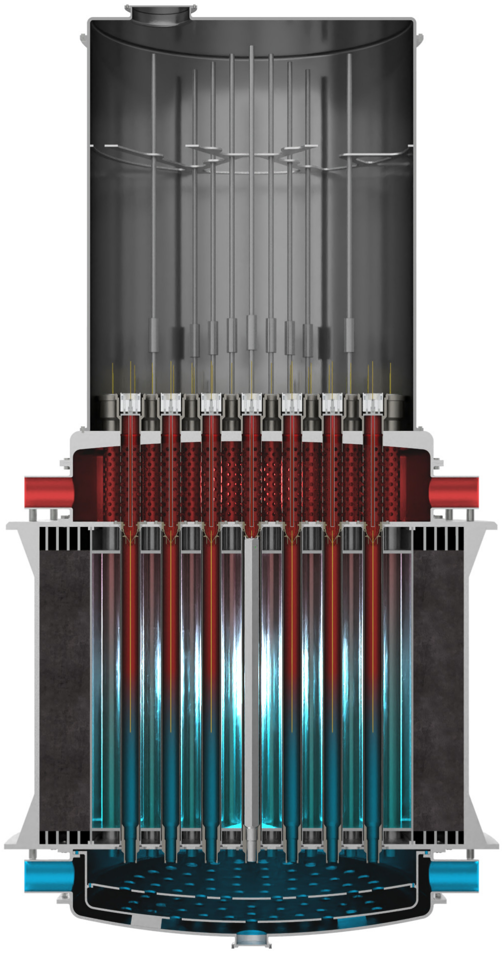

Fig. 1.2 TEPLATOR CORE

configuration for the specific location and pressure. The design itself considers one heat exchanger and two main circulation pumps. TEPLATOR, therefore, relies on forced convection; in the case of natural convection, the overall equipment would be more significant and less compact, which is why forced circulation is used for DEMO. The available articles regarding the SMR TEPLATOR technology are of older date, therefore the most up-to-date parameters and configurations received from the project designer are mentioned here. The information is therefore composed of articles, but also of information received from the designer to keep the thesis itself up to date.

TEPLATOR DEMO operates with three circuits. The reactor core in the primary circuit is the heat source; it is followed by a tubular heat exchanger, which transfers energy to the intermediate circuit. Another exchanger separates the last circuit again, and this heat can already be utilized for district or industrial heating.

The intermediate circuit, or the accumulator circuit, serves three main functions. The accumulator is used to smooth out peaks in heat demand during morning and evening hours. This function replaces the adjustability of the nuclear facility itself, which is not primarily designed for regulation, so accumulation is used here. The second function of the accumulator is the ability to deliver excess heat to the accumulator in case of an unexpected need for a safe reactor shutdown. In case of a breach or fault in the steam pipe, the function of the accumulator can be utilized again; this is the third function of the heat accumulator. Due to the prototype's pressure on compactness and spatial arrangement requirements, horizontal heat exchanger was selected. [5]

Fig. 1.3 TEPLATOR facility - Architectural design

2 Electrical parts of the nuclear facility

The electrical connection of a nuclear facility to the power grid, whether it involves a direct connection to the grid or systems for providing power to essential equipment, is crucial for its operation. For instance, to meet the necessary requirements for the external electrical system of a nuclear power plant (NPP), the Dukovany NPP has backup power from the 110 kV grid, designed as a dual-unit system. Additionally, energy from the generator is exported to the 400 kV transmission system. In the event of a loss of normal power supply, the NPP switches to the preferred power supply. If this normal/preferred power supply fails, the systems switch to an emergency/safety power supply system and rely on emergency sources such as diesel generators and battery banks. Critical to the power supply of nuclear facilities are not only the transmission lines leading directly to the plant but also the corresponding substations, which must meet the requirements for supplying nuclear facilities (e.g., dual/triple busbars, etc.). It's important to ensure that normal and preferred power systems are supplied from various geographically and directionally diverse sources in the transmission system. This includes using hydroelectric power plants for backup power or starting up from a blackout. At Dukovany NPP, this is achieved through the Dalešice Power Station (with a capacity of 4x112.5 MW) and the ability to receive power within 60 minutes (via the 110 kV line) from the Vranov Hydro Power Plant. The external power grid demands all these measures of the nuclear facility. [6]

As mentioned above, nuclear power plants place extreme emphasis on the reliability of backup power systems. These reliability factors directly influence the safety of operating nuclear facilities. Various systems for measurement or power supply are commonly employed in nuclear power plants, with the primary objective of these measures being to enhance the reliability and safety of nuclear facilities.

2.1 Qualification of equipment in an NPP

The individual equipment and power systems are classified in nuclear power plants. The importance of the individual equipment and its associated power supply (in terms of various redundancies, etc.) is closely related. The qualification of individual equipment will be the focus of this chapter.

2.1.1 Class 1E

Electrical systems and equipment classified in Class 1E are important for emergency shutdown of the reactor, isolation of the containment from releasing radioactive materials outside the containment, and cooling of the reactor and containment. They are also closely related to removing residual heat from the reactor or containment to prevent significant release of radioactive materials from the reactor system. Power systems for 1E class equipment consist of an AC power system, a DC power system, and an I&C power system. If the normal or preferred power supply fails, the power is replaced by Class 1E standby power systems. Class 1E systems must also meet various qualification tests and checks to ensure the safe operation of the entire nuclear power plant. [7]

2.1.2 Non-class 1E

These are other equipment that may not qualify due to their function. Therefore, much fewer requirements are placed on their reliability, but also on their power supplies.

2.2 Power Supplies

In the following section of the thesis, I would like to focus on the electrical power system within the nuclear facility, which is crucial for ensuring safe and reliable operation. Systems and equipment necessary for the power plant operation are powered by its own consumption. In most cogeneration power plants, auxiliary transformers powered directly from the unit generator are utilized. In case of a normal power outage for one's own consumption, an external transmission grid or other sources within the power plants may be used. The power supply for individual equipment in own consumption is ensured through multiple switchboards and power supply systems, which are backed up using substitutional or redundant principles. From the perspective of power supply, own consumption has at its disposal:

2.2.1 AC Power Systems

– Normal Power Supply

It concerns auxiliary transformers with voltage regulation under load, which are powered directly from the turbogenerators or the 400 kV grid. This principle is ensured by the same system in both Czech NPPs (Dukovany NPP and Temelín NPP).

– Preferred Power Supply

Reserve auxiliary transformers with voltage regulation are intended to ensure the supply of electrical energy for own consumption in the event of a malfunction of the normal power supply. A reserve power supply is usually provided from the grid via a reserve transformer. In the case of the Dukovany NPP, a reserve transformer (one transformer for two units) can supply power to shut down one unit in the event of a loss of normal power supply. Additionally, the grid, through the reserve transformer, is tasked with bringing the power plant to a complete halt under normal and abnormal conditions. The preferred power supply is not a Class 1E system. [6]

2.2.2 DC Power Systems

The DC power system contains the power supply and distribution required to power both Class 1E DC loads and the I&C of individual elements for Class 1E DC power systems. Each power system should have its battery feeder, its battery, and multiple battery feeders may be used. [8, 9]

2.2.3 Standby power supply

These are sources that ensure the shutdown of the nuclear facility in case of failure of both the normal and preferred power sources. These sources power all devices safety-related and safety systems. Standby sources include diesel generators, battery banks, and uninterruptible power supplies (in case of operation in rectifier/inverter mode). These sources are sized according to the requirements of the powered loads, and their functionality is independent of the status of normal, preferred sources or the external transmission grid. For example, in the Dukovany NPP, each unit has three redundant standby power supplies. [8, 9]

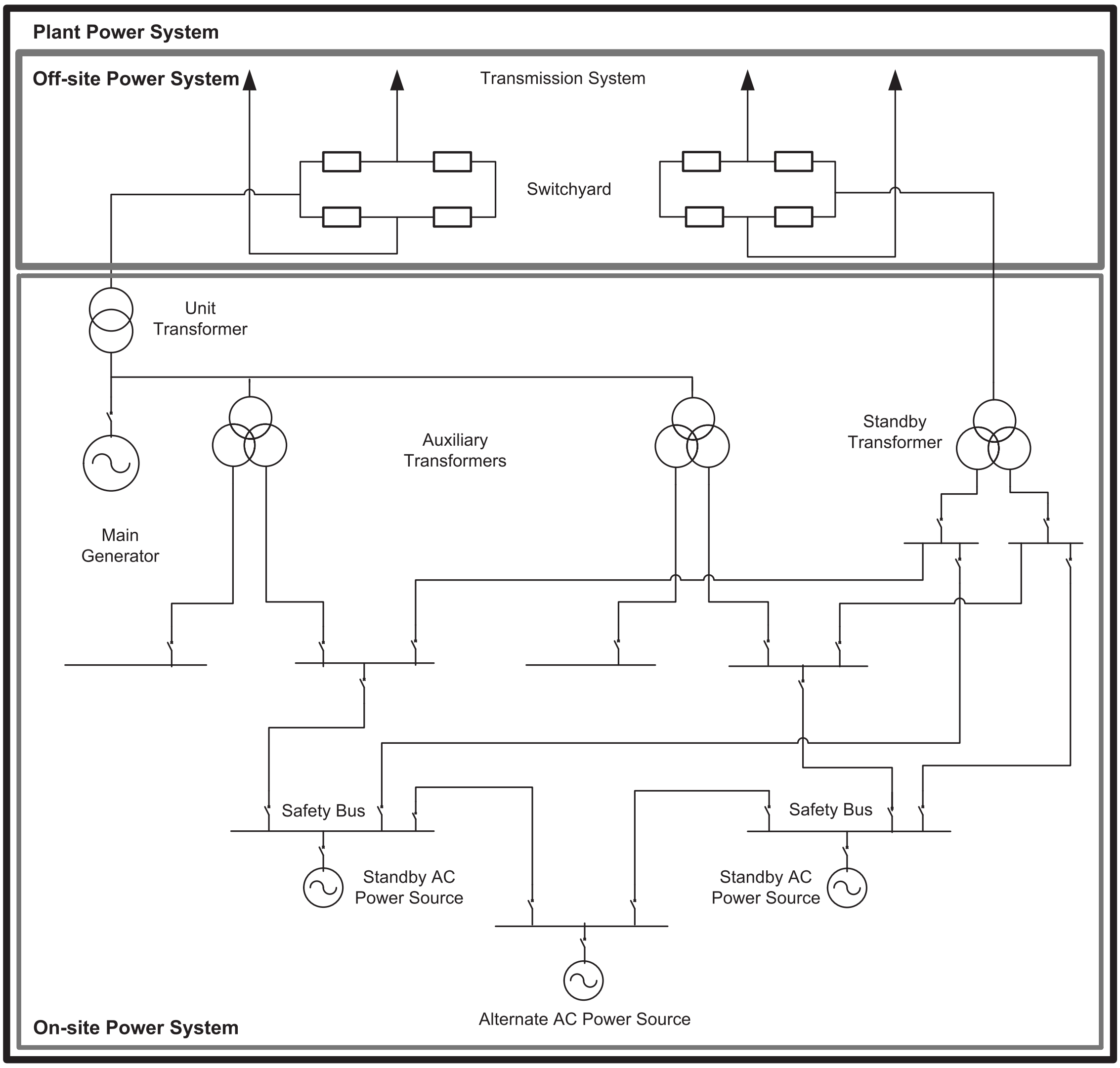

Fig. 2.1 Plant Power System [9]

2.3 Summary and practical example

– Nuclear safety equipment

Equipment vital for nuclear safety is supplied by the standby power supply in case a normal/preferred power supply fails. These systems are dimensioned by protected power supply networks and standby sources. During normal (fault-free) operation, the safety-related and safety systems are powered by normal or preferred sources. In the event of a normal power loss, the relevant system is disconnected from normal power and switches to the preferred power supply. The system utilizes battery banks, which immediately supply electrical energy to critical equipment if a continuous power supply is required.

In the case of Dukovany NPP, conditions for switching from normal to preferred power occur when the voltage in the system drops below 25 % of the Un for 2.5 seconds or below 70 % of the Un for 6 seconds. A drop in frequency below 47 Hz for 6 s also triggers the switch to preferred power. Diesel generators immediately start in the event of such a drop in the external power transmission grid, and they can be loaded after a 10-second interval from the start command.

– Non-Nuclear safety equipment

Equipment not crucial for nuclear safety (systems not involved in reactor emergency cooling, non-1E Class equipment) is powered by normal sources. In the event of a power supply loss, they automatically switch to the preferred power supply.

In nuclear power plants, it is essential to ensure that all power sources are physically, electrically, and fire-separated. To ensure electrical isolation, normal sources are powered from the 400 kV grid, while preferred sources are from the 110 kV grid. In the case of non-cogeneration smaller nuclear facilities, this can be ensured by two independent 22 kV distribution networks. [6]

3 Normative and legislative requirements for SMR TEPLATOR

For the definition of normative and legislative requirements, the thesis is mainly based on Decree No. 329/2017 Coll, which deals with the requirements for nuclear facilities in their design. The second decree used here is the standard CSN 34 1610, which deals with the design of industrial plants. Thus, the following chapters will form the theoretical basis for the subsequent practical work.

3.1 Requirements for Nuclear Facility Design (based on Decree No. 329/2017 Coll)

In the Czech Republic, The State Office for Nuclear Safety (SÚJB) is responsible for the state administration in the use of nuclear energy and ionizing radiation, as well as in the field of nuclear, chemical, and biological weapons. In the context of this work, SÚJB's responsibilities primarily include permitting activities according to the Atomic Law, which encompasses the placement and operation of nuclear facilities. Additionally, SÚJB is involved in approving documentation related to nuclear safety assurance and plays a role in professional collaboration with the International Atomic Energy Agency and other organizations.

Part of the regulations for the construction or design of a nuclear facility is Decree No. 329/2017 Coll., which defines requirements for the design of nuclear facilities. It primarily outlines the content of documentation for permitted activities. Furthermore, the decree specifies safety functions that nuclear facilities must fulfill, categorizing them based on their importance for nuclear safety. It also contains specific requirements for the design of nuclear facilities as stipulated by Atomic Law.

The fundamental rule of fulfilling the principles of safe use of nuclear energy involves utilizing safety objectives to prevent accident conditions and to mitigate the consequences of accident conditions, should they occur. One of the safety objectives also includes considering the impact of human factors on the operation of nuclear facilities, including radiation protection, monitoring radiation situations, and securing and influencing human performance through the characteristics of the nuclear facility.

Another rule is to ensure compliance with the conditions and requirements in the area of safeguards of the International Atomic Energy Agency, stemming from international treaties. Furthermore, nuclear facilities must meet technical requirements for ensuring independent power supply. [10]

3.1.1 Electrical Power Supply Systems

The following chapters, 3.1.1 to 3.1.3, are based on Decree No. 329/2017 Coll. on Requirements for the Design of Nuclear Facilities.

According to the decree, in the case of electrical power supply systems, it is necessary to ensure independent sources of electrical power that, to a reasonably feasible extent, prevent the possibility of failure of electrical power supply systems, structures, and components affecting nuclear safety. It is essential to ensure that the systems can fulfill their functions concerning nuclear safety, and backup systems must be independent.

Ensuring its reliability and capacity to meet the project limits in operational conditions is necessary regarding the electrical power source. As part of the electrical power supply, it is required to address the situation where there is a malfunction of the electrical transmission grid outside the nuclear facility so that it does not affect either the normal or preferred power supply of the nuclear facility and so that the system is capable of meeting safety requirements. The standby power supply is a critical component of the nuclear facility project. It must be fast, accessible, reliable, independent, and testable during operation. Its sizing must allow for delivering the required power for the necessary duration to ensure reliable situation fulfillment. It is also essential to anticipate a situation where the standby power supply loses external power. In this extreme situation, a gradual connection of individual appliances is used, taking into account their importance for nuclear safety, to prevent overloading of the standby power source due to the gradual activation of all appliances.

As part of this gradual activation of individual appliances, it is necessary to define for each nuclear facility which devices, components, and structures must be continuously powered from batteries/DG, considering their critical function for maintaining nuclear safety. Electrical power supply systems must be equipped with monitoring and information systems that provide information about the status of individual components directly to the operators. Safety and protective components also include devices capable of clearly detecting and localizing faults in the electrical power supply or its components. [10]

3.1.2 Energy Conversion System

The decree also addresses the energy conversion system, particularly specifying requirements for the secondary circuit of the nuclear facility with an emphasis on nuclear reactor cooling. A vital aspect of the energy conversion system is ensuring the safe separation of the primary and secondary circuits to prevent the penetration of radioactive material into the secondary circuit outside the hermetic space both in operational states and in the event of accident conditions. The nuclear facility project must specify requirements for ensuring safety functions, including protecting all components and structures of nuclear safety against internal events. The energy conversion system from the primary to the secondary circuit must also include design measures for monitoring the level of release of radioactive substances. This monitoring must be ensured through additional functions that, in the event of a release of radioactive substances, prevent their further progression through the system. The goal is to prevent a radiation incident or radiation accident. [10]

3.1.3 Control Room and Control Systems

The nuclear facility project must also include the design of the main control room, which must enable safe access for workers and ensure their health safety. Protection against the effects of internal events must be provided. Furthermore, it is necessary to ensure such a user interface that considers human factors and ergonomic requirements, enabling the transmission of information about the operation of the nuclear facility, including automatic system changes or manual interventions. It is essential to maintain the ability to perform activities by internal regulations. Additionally, the nuclear facility project must include emergency control room facilities if evacuation from the main control room becomes necessary. [10]

3.1.4 Defense-in-Depth

The necessity of applying the defense-in-depth principle in the design of nuclear facilities and other activities related to nuclear safety, including managerial, organizational, and operational tasks, is crucial. Defense-in-depth implies that the project and the design process must incorporate an adequate number of independent layers of protective measures. These layers ensure that in case one layer fails, the occurrence is detected and compensated for by another layer. Effective prevention must be ensured to a practically feasible extent in the event of failure of one layer due to the failure of another barrier or the compromise of the integrity of physical barriers. Defense-in-depth must be implemented through physical barriers to prevent the release of fission products. These barriers may consist of the structural material of nuclear fuel with high chemical stability and retention capability to prevent the escape of fission products beyond the designated area. The defense-in-depth system also involves using technical and organizational measures to protect and maintain physical barriers, which directly safeguard employees, the population, and the environment. [11]

3.2 Electrical power supply design of an industrial plant

The power supply design must meet the requirements mentioned above for nuclear equipment. Still, the design of the electrical components is based on the same principle as the design of other industrial plants. Therefore, designing electrical power supplies for industrial plants is subsequently used.

3.2.1 Dimensioning of Appliances in Own Consumption

The following chapter is based on the standard ČSN 34 1610 concerning heavy-current distribution systems in industrial plants. [12]

The size of the own consumption resources/transformers (normal and standby power supplies) is determined based on the total output of all appliances, considering the diversity factor, which is defined by the relation:

$$\beta = \frac{P_{\max}}{P_i} \tag{3.1}$$

$P_{\max}$ represents the value of the maximum possible power demand, and P_i denotes the installed power. The coefficient β can also be determined using the equation:

$$\beta = \frac{k_s \cdot k_z}{\eta_m \cdot \eta_s} \tag{3.2}$$

Where k_s is the diversity factor (simultaneity factor), which expresses the ratio of the rated powers of appliances simultaneously in operation to the installed power of all appliances. Subsequently, k_z or the utilization factor indicates the ratio of the actual power consumed by appliances simultaneously in operation to their rated power. The formula also includes the efficiency of motors under the given utilization and the efficiency of the power supply system from the considered point to the appliance. The resulting calculated load can be determined precisely from the rated installed power P_i and the assumed diversity factor β using the formula:

$$I_p = \frac{P_i}{\sqrt{3} \cdot U_s \cdot \cos\varphi} \tag{3.3}$$

In terms of sizing conductors used in the design and implementation of equipment, the focus is primarily on the current load of the conductors. This load is determined by maintaining the permissible operating temperature and the type of protection. In this sizing process, emphasis is placed on maintaining conductor cross-sectional sizes within economical limits, ensuring the mechanical strength of the conductors, and keeping voltage drop within specified limits. Additionally, the resistance of conductors to dynamic and thermal effects of short-circuit currents is crucial. The economy of the cross-sectional area of individual conductors is evaluated according to formulas and diagrams. The mechanical strength of the conductors is another criterion that is examined. The entire distribution system is assessed based on voltage drop, monitoring whether the voltage at the appliance terminals remains within specified limits. For motor, lighting, and thermal appliances, the voltage at the terminals, anywhere along the route, must not exceed 105 % of the rated voltage over the long term. At minimum load or no-load operation, the measured value must not exceed 110 % of the rated voltage of the distribution system.

For motor appliances, which operate continuously and are loaded with calculated load, the voltage drop during the passage of rated current must not exceed 5 % of the system's rated voltage. For the voltage at the terminals of other appliances, the voltage drop may be critical, for example, when disconnecting relay windings. For this reason, relays, electromagnetic contactors, and other devices powered by motor circuits must be maintained within certain limits, and voltage drop must not exceed these limits even during transient states, such as starting a larger motor, etc.

Several scenarios must be considered during the overall power plant consumption and distribution system dimensioning. One extreme case is the start-up of the largest drive and the start-up of a self-starting group of drives. This scenario involves significant loading of the distribution system due to the starting current draw of the largest motor, which can be 3-5 times higher than the motor's rated current, requiring careful monitoring of voltage drop. The voltage should not drop below 85 % of U_n and must not fall below 80 %. During self-starting, the limit value at the bus is 65 % of U_n. The standby power source is often dimensioned similarly to the normal power source. In a nuclear facility, ensuring that the standby power source can handle normal operation and emergency shutdown of the reactor unit is essential. When restarting systems, priorities are determined based on their importance, specifying which appliances will be restored primarily and which can be started in the second phase. These groups and the schedule for starting individual devices, appliances, or groups of appliances are specified in each nuclear facility's regulations. [13]

3.2.2 Selection of Individual Equipment for On-site Power Supply

In a nuclear power plant, the main appliances are very similar to those in conventional power plants, but much greater emphasis is placed on the reliability of individual devices. These appliances include various cooling pumps, oil cooling systems, alternator cooling, valve actuators, measurement, control, security, information technology, elevators, cranes, and lighting. Among the largest devices in nuclear power plants are the main circulation pumps (core cooling pumps), which ensure coolant circulation in pressurized water reactors. Synchronous electric machines drive turbo-compressors in the primary circuit of gas-cooled nuclear power plants. Pressurizer maintain a constant coolant pressure and prevent boiling.

Additionally, some appliances ensure nuclear safety and control nuclear and thermal parameters, including protection systems, transport systems, and reactor control. Other important appliances include drives for spent fuel transport, high-performance ventilation systems, and more. When selecting individual appliances, examining several critical equipment parameters is crucial. The central component of most appliances in the power plant is the motor. Therefore, it is essential to carefully study the torque characteristics of the machines to have detailed information about the behavior of the appliance, for example, during start-up or voltage changes at the buses. [13]

3.2.3 Selection of Electric Motors for Equipment Drives

Special requirements are placed on drives for own consumption. Given the need to maintain the functionality of critical equipment even in emergency situations, it is essential to ensure optimal reliability, cost-effectiveness, and maintainability in demanding environments with high temperatures and similar influences.

Requirements for motors for own consumption:

- **Torque Characteristics:** The motor should have torque characteristics enabling smooth starting, which is influenced by the square-law relationship between torque and voltage (due to the dependence of torque on the square of the voltage, denoted as $\mathrm{M} \approx \mathrm{U}^2$
- **Ability to Withstand Heavy Starts:** The motor should endure up to three prolonged heavy starts in cold conditions.
- **Ability to Start the Heated Machine Twice:** The motor should start the heated machine twice at around 120 °C
- **Reliability:** The motor should generally exhibit high reliability, even during frequent startups.
- **Inrush current:** The inrush current should not exceed 5.5 times the rated current to prevent significant voltage drop during the gradual start-up of the motor group, especially on a weak grid.
- **Operation at reduced voltage:** The motor should operate at a reduced voltage of 70 % of rated voltage and rated load for 15 minutes.

– **Maximum torque:** The motor's maximum torque should be at least twice the rated torque M_n.

These and other specific requirements are only met by squirrel-cage asynchronous motors. DC motors and AC commutator motors have better speed regulation capabilities but do not meet reliability standards, especially in conventional power plants. Nuclear facilities prioritize reliability; hence, squirrel-cage asynchronous motors are predominantly utilized. For high-power turbo compressors in NPP, synchronous machines are preferred due to their higher efficiency and power factor. [13]

3.2.4 Voltage level for motors

When selecting electric motors for NPP, several key factors must be considered. For drives with a power rating up to 250 kW, a supply voltage of 380 (400) V is typically preferred, while for drives exceeding 300 kW, the higher voltage level of 6 kV is utilized. The choice of motor power is guided by the rule of 1.1 to 1.15 times the power of the driven equipment, which includes a reserve for smooth operation and start-up time. The start-up time of electric motors, a critical parameter, has two main aspects. The inrush current remains constant throughout the start-up period, and the nature of the load influences the start-up time itself. Operational losses are taken into account when considering their impact on overall performance. However, when using higher voltage levels (6 kV), caution must be exercised regarding overvoltage while switching small inductive currents. [13]

3.2.5 Transformers in Power Plants

Transformers in power plants are divided into two main groups. The first group comprises the main transformers connecting the alternator to the grid. Transformers for internal consumption supply power to internal electrical appliances either from the alternator or an external grid (as in the case of the TEPLATOR prototype).

4 Components – TEPLATOR

The following chapter will describe the individual parts of the SMR TEPLATOR prototype, which are very important for the operation of the device and for the design of individual electrical power supplies for these devices in the next part of the thesis.

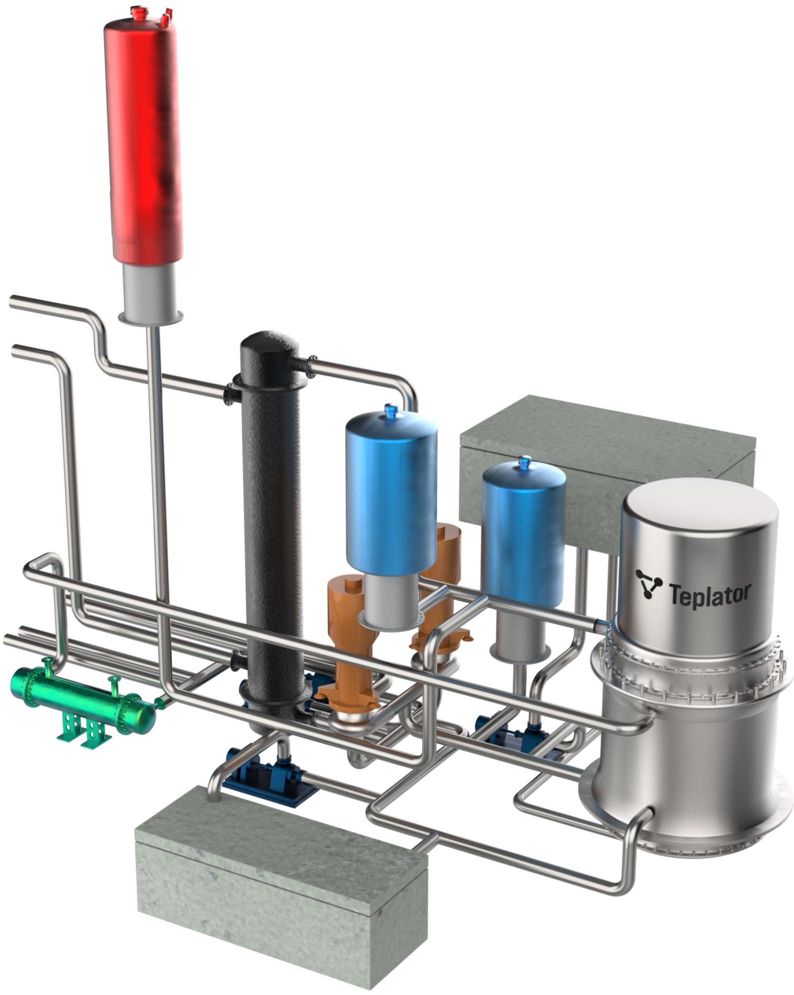

Fig. 4.1 TEPLATOR Technology

4.1 Reactor coolant pumps

In the SMR TEPLATOR prototype, the pressure gradient is utilized to move the coolant through the primary loop of the power plant. These pumps are critical components in nuclear power plants, as they significantly impact operational reliability despite not being readily accessible. Their reliability is critical, and in case of a malfunction, it is essential to shut down the entire circuit to which the pump belongs if there are shut-off valves in that circuit. Mechanical rotary pumps are commonly used in liquid-cooled reactors, particularly in radial or vertical configurations. Given the low head and high coolant flow, single-stage pumps are preferred. After consultation with the TEPLATOR designer, only two main circulation pumps are planned for the entire system.

4.2 Emergency Cooling Pumps

Each nuclear power plant has its emergency core cooling system in case the main pumps provide a loss of normal and preferred power supply. These emergency pumps enable continued circulation and removal of residual heat from the core in the event of an emergency cooling situation. In case of normal power and preferred supply failure, the standby power system powers the emergency cooling pumps (from DG).

4.3 Spray system

In the event of a leak in the primary circuit, the spray system reduces the pressure. The main advantage of pressure reduction in the containment is to reduce the risk of release of radioactive material from the containment. The second advantage is reducing the speed of possible spread of radioactive material from the containment envelope due to the pressure reduction. In the case of Temelín NPP, when the primary pipe breaks, the medium starts to enter the containment; we want to cool the containment quickly and reduce the pressure; this is how we understand the function of the spray system.

4.4 Pressurizer

In the event of a change or fluctuation in the nuclear power plant's power output, there is a corresponding temperature change. Changes in temperature in the primary circuit also result in fluctuations in the density, volume, and pressure of the coolant. Primarily due to pressure changes, or instead changes in volume, the primary circuit undergoes varying stresses. These changes can be corrected by the pressurizer. In the event of a pressure drop, electric heaters at the bottom of the pressurizer are activated, increasing the volume of steam in the upper part of the pressurizer and consequently increasing the pressure in the primary circuit. Conversely, in the event of a pressure increase, the shower system is activated in the upper part of the pressurizer. If there is a failure to activate the shower system, pressure is released through the relief valve or safety valves. Steam is then vented through the safety valves into the bubbler tank, where it condenses. The pressurizer also includes actuating elements for the primary circuit pressure regulator. The pressurizer, especially its gas space, must be designed to maintain coolant pressure within prescribed limits during regular operation when adjustments occur. Electric heaters on Temelín NPP consist of 28 units with a total power of 2520 kW, while there are 108 units on Dukovany NPP with a total power of 1620 kW. [14]

4.5 Instrumentation and Control System (I&C)

The control system is tasked with ensuring the operation of the nuclear facility by ensuring safety and technical and economic conditions. During any nuclear reactor operation (startup, shutdown, post-shutdown checks), the control system must maintain these conditions. Nuclear facilities have unique demands for adhering to safety and reliability conditions. The regulatory system is responsible for maintaining prescribed physical parameters within certain limits. The measurement and control system ensures the acquisition of many physical and technological parameters through measurement systems. Various measurable quantities exist (temperature, pressure, flow rate, level). For example, reactor power can be measured in various ways, such as neutron flux inside and outside the reactor or through flow rate and temperature difference of the coolant at the inlet and outlet of the reactor. Essential parameters are not measured using only one method based on one physical principle but employ independent physical/measurement principles. Control and monitoring systems for reactivity measurement (ExCore, InCore) and post-accident monitoring systems are powered by batteries (to achieve uninterrupted power supply). [14, 6]

4.6 Main Control Room

Given the need for maximum reliability and cost-effective operation of power plant units, coupled with the minimization of the number of operators, the concept of control and its associated location plays a crucial role. In the control room, equipment for measuring, controlling, regulating, and signaling various states is concentrated. An essential part of designing the control room is its layout and architectural design, which significantly influences the creation of the best user interface for operators. The comprehensive automation of power plants results in many monitored parameters and devices for measurement, signaling, protection, control, and regulation. The complexity and multitude of different control systems lead to expanding automation elements. Even with the development of predictive models and artificial intelligence for calculations, it is almost unrealistic to expect operators to analyze situations quickly. [13]

4.7 Measuring Instrumentation

Automation in I&C is increasingly prevalent across the technological industry, including nuclear power plants. Sensors and measuring instruments serve as input devices into the control loop. They generate an electrical signal at their output corresponding to the measured quantity. Most measuring devices require power for their operation. The most common measured variables include flow rate, pressure, temperature, and neutron flux. Subsequently, the signal travels along a transmission path (typically standardized to a current signal of 4-20 mA or a voltage signal of 0-5 V). Since the output from the sensor is analog, an analog-to-digital (A/D) converter is needed before connecting it to the controller.

In the context of measuring and controlling nuclear power plants, it is essential to ensure diversification (two identical safety functions that are independent of each other and structurally different), redundancy (one device operates in direct control mode while the other serves as a backup, ready to take over control immediately), and mutual independence of systems.

4.8 Moderator Circuit Pumps

Moderator circuit pumps play a crucial role in the functionality of nuclear reactors as they ensure the proper circulation of the moderator through the reactor core, which is essential for maintaining a constant and controlled fission reaction. Like most pumps in nuclear facilities, circulating pumps maintain a continuous flow. Moderator circuit pumps are specific to certain reactor types, such as VVER reactors in the Temelín and Dukovany Nuclear Power Plants. They are also utilized, for example, in CANDU reactors.

4.9 Drive Units of Control Elements

The principle of reactor power regulation and control of the fission reaction is accomplished through two systems. The first involves inserting fixed absorbers (control rods) or injecting boron as a liquid absorber. Reactivity regulation during rapid manipulations is achieved using the control rod system. Boron regulation changes more over the reactor's lifecycle timeframe.

4.9.1 Control Rods

The control rod system is crucial for reactor operation, especially during power changes, and it ensures both preventive and emergency reactor protection. In the case of the VVER-1000 nuclear reactor, the system comprises 61 control rods with 61 to 121 linear step drives, depending on the reactor type, which can operate independently or simultaneously. [15]

4.9.2 Boron Regulation System

The boron regulation system is designed to compensate for slow reactivity changes. Part of this regulation involves maintaining the reactor in a critical state during transient events associated with xenon poisoning. Boron regulation also operates during reactor startup and shutdown. This regulation is also used during refueling operations or various maintenance activities on the reactor to achieve the required subcriticality. The combination of the control rod system and the boron regulation system increases the reactor's power maneuvering capability. [15]

4.10 Diesel-generator

It is a diesel fuel engine and a synchronous generator. Each diesel generator is equipped with operational and storage tanks. The prevailing backup power source in nuclear power plants is diesel generators (emergency diesel generator EDG). The sizing and requirements of diesel generators are set according to the size of the load to be powered and the time within which they must be fully operational to ensure power supply, for example, within 10 seconds. Especially after the Fukushima accident, great emphasis is placed on resistance to external influences, and the use of mobile diesel generators is increasing. The DG includes its I&C for all wait-to-start, start-up, and load measurement states. DG also includes its cooling systems, etc.

4.11 Battery

Batteries are a key part of the electrical distribution system in a nuclear power plant. Together with the DG, they form the emergency power supply. Especially batteries are used to achieve uninterrupted power supply for the most important equipment in a nuclear installation. These batteries are powered through rectifiers under normal conditions, and their charge must be maximum. If the normal and preferred power supply fails, the batteries immediately take over power to the selected equipment. The batteries perform the power supply function mainly when the DG is being started (usually 10 s). Batteries must be sized to meet the criteria for supplying power to the selected devices for a specified period.

4.12 Ventilation Systems

The main task of ventilation systems in nuclear facilities is maintaining the necessary conditions for safe and reliable equipment operation. Simultaneously, ventilation systems are responsible for maintaining conditions for the workforce (maintaining proper temperature, humidity, airflow, air cleanliness, and circulation). Additionally, the ventilation system must maintain a certain level of radioactivity inside the nuclear facility to prevent the spontaneous penetration of radioactive elements into the surrounding area of the power plant. Part of the ventilation system also includes maintaining so-called ventilation zones, where the system maintains pressure differentials between these zones to ensure airflow from uncontrolled zones to controlled ones. The ventilation system is closely related to the fire safety of the entire nuclear power plant. It is, therefore, a very complex system that goes beyond the scope of this thesis. [16]

4.13 Summary of devices

All of the devices considered in this work were obtained/discussed with the designers of the TEPLATOR prototype, mainly regarding all the essential pumps and their electrical power. I&C equipment was obtained from dataPartnert Ltd., and some I&C systems were also consulted with the TEPLATOR designers. Considered sizes of individual devices correspond to the latest SMR TEPLATOR design

Tab. 4.1 Main electrical equipment

Device	Power (kW)
Reactor coolant pump	2x250
Emergency core cooling injection pumps	3x40
Containment spray pumps	3x20
Moderator circulating pump	2x15
Secondary pumps	2x150
Sum (Pumps)	1010

Tab. 4.2 I&C equipment

Systems	Device	Power (kW)
Protection system	Emergency Protection Subsystem	3.4
	Neutron Flux Measurement Subsystem	1.8
	In-Core Monitoring Subsystem	2
Power system	Subsystem for receiving and processing reactor shutdown orders	2
	24x Control Rod Control Subsystem	2
	Power Supply for Valves and Drives	200
Control system	Reactor Power Control and Limiting Protection Control Subsystem	3
	Control Rod Control Subsystem	2
	Reactor Protection System Control Subsystem Channel	33
Others	Information system	10
	Support systems	3
	Emergency monitoring system (PAMS)	1
	Main control room	4
	Emergency control room	3
Sums I&C		270.2
Total Sums (Pumps + I&C)		1280.2
Consider Total Power		1300

5 TEPLATOR divisions design

5.1 Categories of power systems in Nuclear Power Plants

Specifying the different equipment categories for all nuclear facilities is necessary. These categories are closely related to the power supply system and their backup in case of failure. In a nuclear power plant, we divide the equipment into those related to nuclear safety and those not related to nuclear safety. We further divide them into equipment that allows a power failure, equipment that allows an outage for, for example, only a few seconds, or equipment that does not need power recovery because it is not related to nuclear safety or its failure does not result in high economic losses. For the following proposal of the individual categories/divisions, the solution for the division of equipment in the CANDU reactor system will be presented first, followed by the Temelín NPP.

5.2 CANDU NPP divisions

Power sources in CANDU reactors are divided into four categories according to the tolerance allowed for loss of power supply. For most nuclear plants, the equipment that requires uninterrupted power is the lowest in overall power demand, as these are I&C systems or other instrumentation and control of critical equipment. As the time of possible interruption increases, the power load increases; for example, the largest equipment in a nuclear power plant, such as the main circulation pumps, tend to be in Category IV, as they are replaced by emergency pumps in the event of a power failure. A representation of this trend can be seen in the figure. [17]

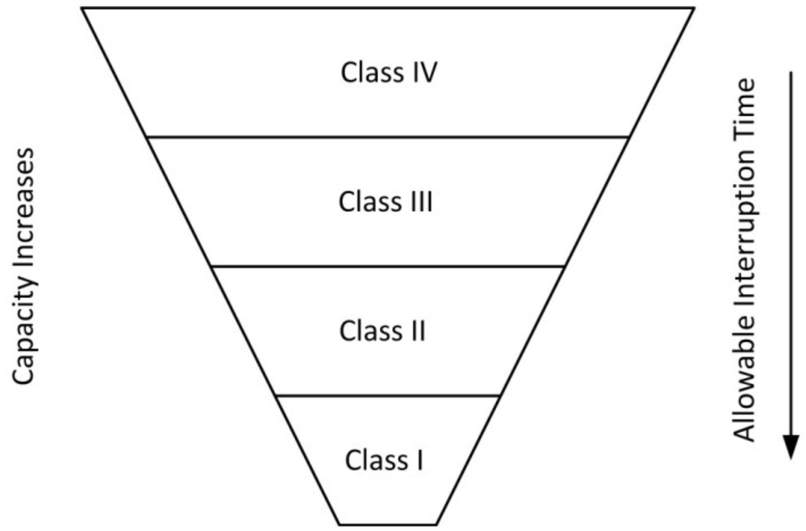

Fig. 5.1 CANDU Classes [17]

The categories and their allowable power failure durations are in the table below this text.

Tab. 5.1 CANDU NPP Class of power

Class of power	System load characteristics
Class I	Power can never be interrupted under postulated conditions
Class II	Power can be interrupted up to 4 milliseconds
Class III	Power can be interrupted for up to 5 minutes
Class IV	Power can be interrupted indefinitely

5.2.1 Class I

Class I supply is used for equipment for which the supply cannot be interrupted. Uninterruptible power is achieved by using battery banks. During normal operation, the batteries are connected to the normal power supply (via a rectifier), and their charge level is always maintained. Therefore, the batteries are always fully charged during normal operation and ready to take over the most critical nuclear safety equipment supply. The batteries in the CANDU system can power a critical load of 60 minutes, depending on the application of the individual plant and mainly on the nuclear safety requirements. These are DC devices, so they don't need a DC to AC conversion using an inverter.

5.2.2 Class II

These are very important devices but not DC in character; they are at 120 and 600V AC voltage levels. In normal operation, these devices are powered from Class I sources, where inverters are used to transition from DC to AC. If inverters are not available for any reason, these devices are powered from Class III. Namely, these devices are Digital control computers, Emergency lighting, and Reactor regulation instrumentation.

5.2.3 Class III

The equipment being considered for Class III has a much larger power capacity than Class II AC equipment, so it is not suitable to be powered from inverters during normal operation. Diesel generators power these devices in the event of a failure of the normal and preferred power supply. The period these systems are not powered is between the loss of normal/preferred power supply and the full start-up of the emergency DG. When the normal power supply is available, electrical power is used from Class IV. Emergency core coolant injection pumps, Firewater pumps, Class I power rectifiers, and Shutdown system cooling pumps are mainly considered for this class.

5.2.4 Class IV

Class IV is used for devices that allow complete power interruption. These devices are not closely related to nuclear or personal safety. During normal operation, power is supplied from the main generator of the individual unit. Alternatively, a station service transformer (preferred power supply) may be used for Class IV power. During normal operation of the nuclear power plant, the Class IV power supply is used to power the entire plant. However, in the event of a loss of Class IV power, additional backup supplies will be used to shut down and cool down the reactor safely. Possible considerations for Class IV powered equipment are Condenser cooling water pumps, Heating and ventilation equipment, Normal lighting systems, and Main boiler feed pumps. [17]

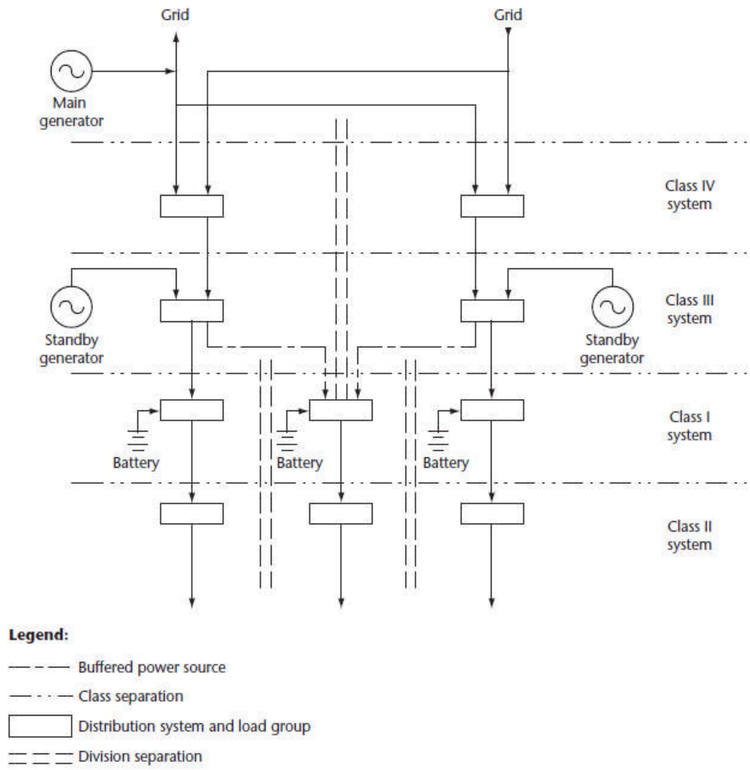

Fig. 5.2 CANDU power system [17]

5.3 Temelín NPP

For the first unit of Temelín NPP, the normal power supply is provided by four switchboards at 6 kV. These distribution switchboards supply the main circulation pumps, hotwell pumps, and cooling water pumps. From the units' 6 kV distribution switchboards, there are feeds through 6/0.4 kV transformers to section switchboards at 0.4 kV, which are the basis of the normal power supply for equipment and secondary distributions of the primary and secondary circuits. Additionally, there are DC power distribution lines for the main control room, measuring systems, and various movable equipment.

The emergency power supply of Category I and II consists of three identical and independent systems, which ensure nuclear safety with a 200 % reserve during the emergency shutdown and cooling phase of the unit. The only emergency power source at the 6 kV level are diesel generators (3x6.3 MW). Rectifiers are supplied from the 0.4 kV distribution switchboards, which serve as sources for Category I. Battery banks provide the emergency power source for Category I.

5.3.1 III Category

This category includes equipment that is not involved in reactor emergency cooling. They do not require power after its interruption, following reactor protection actuation. The restoration of power will only occur after the restoration of normal or preferred sources. These devices have no backup power supply in case the normal and preferred power system fails. For example, these may be core cooling pumps.

5.3.2 II Category

Equipment is involved in reactor emergency cooling, allowing for power loss from 10 seconds to 10 minutes. The time when equipment is not powered is calculated from the start of the interruption until the connection of standby sources (DG). They are powered by diesel generators (standby source), but during the start-up of DGs, they are without power. This mainly includes emergency cooling pumps, shower systems, etc. At the 6 kV level, this primarily concerns emergency cooling pumps, potentially HP (High-pressure) boron injection pumps, and LP (Low-pressure) shower pumps. At the 400 V level, it involves HP boron injection pumps.

5.3.3 I Category

Equipment is involved in reactor emergency cooling but does not allow for power interruptions (maximum fraction of seconds). This equipment is of the highest degree of importance. Power is provided to the connection of diesel generators by battery backup and standby sources. Voltage is 400 V AC and 220 V DC. These include systems responsible for controlling important valves, such as rapid-closure valves or steam release stations to the atmosphere, and reactor I&C systems at the 400 V level. Furthermore, at the DC power supply level, they include impulse valves on the steam lines in the reactor containment or I&C of the reactor containment.

5.3.4 III/II Category

Equipment does not contribute to the emergency cooling of the reactor core and allows for power interruptions ranging from 10 seconds to 10 minutes. Similarly to equipment in III/I, they ensure personnel safety and valuable equipment but do not require a continuous power supply. These include turbine bypass systems and upstream normal pumps. The supply is provided at the 400 V level. At the 6 kV level, it also contains normal replenishment pumps and auxiliary electronic load banks.

5.3.5 III/I Category

It is not involved in emergency unit cool-downs, is not related to nuclear safety, and does not allow power interruptions (fractions of seconds maximum). However, they ensure the safety of persons and expensive equipment. Therefore, they require a continuous power supply. These are the I&C turbine-hall systems, primary circuit systems without effect on emergency aftercooling, and the integrated reactor room IT system. There are three independent safety/emergency power supply divisions in the Temelín NPP system. In the table, we can see them for category I and II systems.

Tab. 5.2 Category of devices with voltage levels and associated equipment

Category	Voltage level (kV)	Device/equipment	Division
III	6 (AC) 0,4 (AC)	Feeder cooling pump (from River) Main pumps Pumps of cooling system for selected equipment	Normal/Preferred power supply
II I	6 (AC) 0,4 (AC) 0,4 (AC) 0,220 (DC)	HP boron injection pumps and LP shower pumps HP boron injection pumps Impulse valves, I&C of the reactor containment Impulse valves, I&C of the reactor containment	Divisions 1, 2, 3
III/II III/I	6 (AC) 0,4 (AC) 0,220 (DC)	Normal replenishment pumps Turbine governor I&C turbine-hall systems	Divisions 4, 5

5.3.6 Equipment of each division

Each of the divisions (1, 2, 3) is made up of:

- Emergency DG 6.3 kV, 6.3 MW,
- 6 kV bus (Safety power supply)
- 0.4 kV Bus and 6/0.4 kV Transformer
- Rectifiers, batteries, inverters for powering sensitive devices

DG loading is determined by a schedule based on automated sequential starting, according to fixed schedules, without operator intervention. The cable systems of divisions 1, 2, and 3 are independent of each other, thus guaranteeing the functional and space independence of 90 min of these systems. During normal operation (when powered by a normal or preferred power supply), the batteries are constantly powered/recharged. When the normal and preferred power supply fails, power is supplied to the rectifiers from the diesel generators. Each subsystem (division) has its battery, rectifier, and inverter.

The emergency sources for divisions 4 and 5 are common DG, common to two units (ETE1 and ETE2). For both divisions (4,5), one working common diesel generator for both units is sufficient.

5.3.7 Battery power supplies

Divisions 1, 2 and 3 contain thyristor rectifiers (220 V, 800 A), battery banks (220 V, 1600 Ah), and two transistor inverters (220/380 V AC, 170 kVA). These systems power the most important control and safety systems and emergency lighting.

Division 4 contains two subsystems that are fed from a common DG. Each subsystem contains a thyristor rectifier (220 V, 1000 A), a battery bank (220 V, 2000 Ah), and an inverter (220/380 V AC, 170 kVA). These two subsystems back each other up (100 % + 100 %), and the appliances are powered from both subsystems.

Division 5 contains two subsystems that are fed from a common DG. Each of the subsystems contains two thyristor rectifiers (220 V, 800 A), a battery bank (220 V, 2400 Ah), and an inverter (220/380 V AC, 170 kVA). Similar to the subsystems of Division 4, Division 5 also backs each other up 100 %.

In addition to these emergency battery sources, the ETE contains batteries in the reactor control cluster drive system (110 V, 1200 Ah) that stabilize the system during short-term voltage drops. Two 24 V 600 Ah batteries continuously monitor the rods falling to the down position. [18]

5.4 TEPLATOR (Design of divisions)

The same categories as for the Temelín nuclear power plant are considered for the TEPLATOR facility. The IAEA Safety Standards (Safety Classification of Structures, Systems, and Components in Nuclear Power Plants) should be used as a guide for determining the categories and power systems for individual facilities in the final design of the power systems for a nuclear facility. My thesis mainly focuses on the basic classifications of main equipment that are significant for the design. The final electrical design itself will be much more complex. Unfortunately, not all the equipment and safety requirements of the small modular reactor are specified. Therefore, the categories of individual equipment considered are only for the basic appliances that are currently available.

Tab. 5.3 Categories/Divisions and voltage levels for individual equipment (TEPLATOR)

Category	Voltage level (kV)	Device/equipment	Division
III	6 (AC)	Core cooling pumps, Secondary pumps, Non-safety related systems, Administrative building	Normal/preferred power supply
II	0,4 (AC)	Emergency cooling pumps, shower system, dosimetry, part I&C	Divisions 1, 2
I	0,4 (AC) 0,220 (DC)	I&C, DG self-consumption, armatures, valves, emergency lightning, etc	Divisions 1, 2

5.4.1 I. Category

This category does not allow interruption of the electrical power supply, so batteries provide a permanent backup. Whether it is a direct connection to the battery via DC distribution or an AC load that is connected to the battery via an inverter. These include all instrumentation of the reactor control systems, measuring and control systems, and IT systems (important parts regarding nuclear safety and reactor operation). This includes the unit and emergency control room. It is also about the DG consumption (for the control and starting mechanism of the system) and all the necessary control systems for the different armatures and valves. For simplicity, I consider all I&C in Category I. In practice, this will be different because only some I&C is closely related to reactor operation but involves processes unrelated to nuclear safety or the requirements placed on the nuclear facility during a power supply failure. Category III/I equipment at Temelín NPP, which are not related to nuclear safety but may cause significant economic and human losses (damage to equipment, etc.) due to power supply failure. These devices are also included in Category I. The information available is based on nuclear cogeneration plants, which operate with much larger amounts of radioactive material and significantly larger thermal power than 50 MW thermal. Therefore, this section listing the individual plants is simplified because the requirements for the I&C and their uninterruptible power supply are unclear when writing.

5.4.2 II. Category

Devices that belong to category II are devices that allow, also due to nuclear safety, a power interruption for a while before the diesel generator starts to run at rated speed. Also to be considered in this category is that the diesel generator must be loaded sequentially due to the inrush current of all motors. Therefore, some equipment may take longer to start up than the backup power (DG). In this situation, it is necessary to determine how and in what order each device will be started up due to its nuclear safety urgency and its inrush currents. Maintaining a certain voltage drop level during the individual devices' start-up is necessary. This category includes emergency cooling pumps, shower system, reactor building crane, dosimetry, part of normal lighting, part I&C.

5.4.3 III. Category

This device will not maintain a continuous power supply even if the normal and preferred power supply fails. For category III equipment, the main circulation pumps and the pumps of the secondary circuit are considered (meant for heat removal from the secondary circuit). These secondary pumps are not related to nuclear safety, as the construction of a cooling tower is considered to remove residual heat during reactor cool-down if necessary. This tower will be dry and passive, according to information from the designers it is not clear at the moment how this solution will be designed, therefore the thesis does not include any pump on the passive tower part. At the moment, a solution other than the tower is being considered by the designers. Thus, if the normal and preferred power supply fails, power will not be restored to the secondary pumps. Similarly, the main circulation pumps, since their function in the event of a loss of the normal and preferred power supply, will be replaced by the emergency pumps, which the standby power supply will supply. This category also includes non-nuclear safety related equipment, common systems, administrative rooms, etc.

Therefore, these pumps will be powered from the main 22/6 kV transformers.

During normal operation, when normal/preferred power is available, the entire plant will be powered through Category III, whether it will be a constant charging of the batteries through the rectifiers (so that the batteries are fully charged and available at all times), but also devices that fall under category II.

6 Theoretical approach for designing the electrical parts

6.1 Selection of the voltage level of the power supply network

The most common voltage level that supplies industrial plants is 22kV. This distribution network is commonly used to supply power to power plant systems and industrial operations with voltage levels of 6 and 10kV (for example through transformer 22/6 kV). High-voltage networks are operated without a conductive connection of the neutral point in a star-connected system, or this neutral point is connected by resistance, Peterson-coil grounding. The grounding method does not significantly affect normal operation, but the behavior and switching method are substantially different in case of a fault.

Most commonly, in cable networks, we utilize resistance grounding. Faults in cable networks are typically permanent and are immediately disconnected. In the case of overhead lines, such as connections to industrial plants, overhead lines with a Peterson coil are likely to be chosen. In case of a single-phase fault during operation with a Peterson coil, the system can continue operating (for a limited period). Due to the connection of HV/LV transformers, this fault does not propagate into the low-voltage network, as even with a ground connection, the interphase voltages remain unchanged.

Typically, the consumption of power plant units is operated as isolated networks (the neutral point of transformers is not grounded). In contrast, shared consumptions are usually operated indirectly and grounded through reactance. The choice of individual operations for high-voltage networks depends on several criteria, such as the total capacitive current of the system (which determines the necessity of using a reactance), the level of fault current (residual current in case of ground connection), or steady-state fault voltages, and finally, safety considerations regarding the magnitude of touch and step voltages. [19]

6.2 Sizing of Transformers

Regarding the sizing of the main transformers, SMR TEPLATOR should be seen as an industrial plant. It is not a cogeneration plant where the nuclear/fossil/gas plant has its electric generator. TEPLATOR is considered in the thesis as an industrial plant in terms of electricity connection from the grid, but this plant will have to meet all the relevant requirements in terms of nuclear safety. However, its transformer is not taken as a power plant unit transformer. After a generator, the transformers are subject to different conditions for sizing and operation.

For the actual sizing of the transformer, we must consider the power that we want to supply with the transformer. From the perspective of the design of transformers for the power supply of SMR TEPLATOR, the conditions are considered so that one transformer can power the entire plant. For the sizing of the transformer, it is also necessary to take into account the power factor of the entire power plant; the final size of the transformer is determined by the equation:

$$S_p = \frac{P_c \cdot \beta}{\cos\varphi} \tag{6.1}$$

Therefore, each transformer must be able to supply the entire plant, but splitting the load between two or more transformers can reduce the load on each transformer. An operation with a split load between two transformers is expected during normal operation, but they will not work in parallel and only redistribute the load. Using the power required to be transmitted by the transformer divided by the power size of the transformer, we can find out how much the transformer is loaded and, alternatively, how two transformers are loaded for the same load.

$$\gamma = \frac{S_p}{S_{TR}} \tag{6.2}$$

$$\gamma_2 = \frac{S_p}{2 \cdot S_{TR}} \tag{6.3}$$

From the selection of individual transformers, the basic parameters for the following calculation are transformer power, short-circuit voltage, and short-circuit losses.

6.3 Sizing of Cables

My thesis also focuses on designing the size of the cable cross-section and insulation of the individual cables that are considered. The design of the cable mainly depends on its application and the conditions to which it will be exposed during its operation. For my simplified calculation, I base it mainly on the current I expect the cable to transmit. Then, using individual sub-calculations, I check the design of this cable against the dynamic and thermal effects of the largest possible short-circuit currents; this calculation and the size adjustments of the conductors will be mentioned later in my work.

6.4 Calculation of short-circuit currents

All electrical systems must be designed and, more importantly, sized to withstand the worst conditions during operation. Therefore, it is necessary to calculate the worst-case short-circuit scenarios for correct and sufficient oversizing of equipment, cables, substations, etc.

However, minimum short-circuit currents must also be considered for sizing protection and safety elements in the power system. In this case, $c_{\min}$ the minimum short-circuit current effects because we want to be sure that the safety and protection equipment can also respond to these conditions. However, my work only deals with designing cables for an electrical system, so I will continue to describe and use only the worst-case conditions for a short circuit to occur (maximum short-circuit currents). The design of protection and safety systems is not the subject of this thesis.

Short-circuit calculations are an integral part of designing the power supply for electrical equipment. Therefore, in the following chapter, I will focus on short-circuit calculations when powering industrial equipment

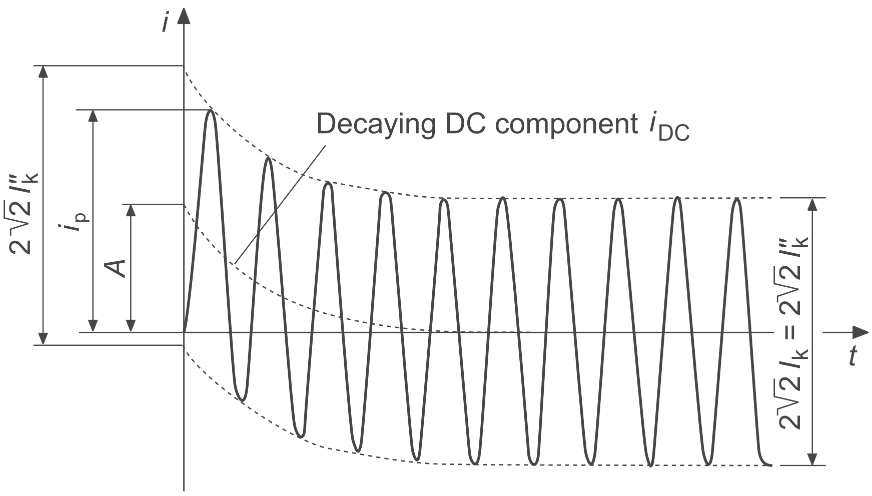

Fig. 6.1 Time curve of short-circuit currents [20]

such as the SMR TEPLATOR. A short-circuit current arises from an unwanted conductive connection between circuit parts with different potentials. The short-circuit current flows from the power supply (from sources, from network feeder) towards the fault location through the voltage source impedances and supply lines to the fault location. The short-circuit current is significantly greater than the normal operating current, resulting in thermal and mechanical effects.

Electrical protections cannot detect these faults as quickly, so it's necessary to size electrical equipment for these abnormal short-circuit currents. To allow for over-sizing these devices, it is necessary to know at least approximately the magnitude and time profile of the short-circuit current for the given power supply, hence the need for calculation. The most used method for calculation is the equivalent voltage source method at the fault location (based on the Thevenin theorem, IEC 60909). All network feeders and the synchronous and asynchronous machines are replaced in the calculation by their impedance. All line capacitances and the parallel admittances of non-rotating loads, except those of the zero-sequence system, are neglected. [20]

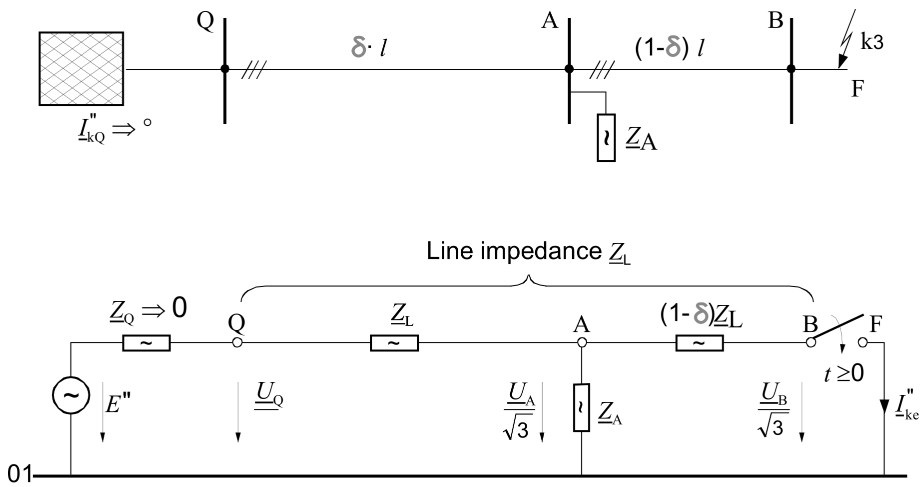

Fig. 6.2 AC model and Equivalent circuit diagram [21]

The dynamic effects of short-circuit currents arise from the magnetic fields' interaction with adjacent conductors carrying current. The magnitudes of the forces are determined by the maximum value of the first amplitude of the short-circuit current, defined as the peak short-circuit current. These dynamic forces result in significant movement of individual conductors, so it is necessary to consider these forces when designing windings, mounting elements, etc.

Another undesirable effect of short-circuit currents is the thermal impact on the conductors through which the short-circuit current flows and their immediate surroundings. Thermal losses are proportional to the square of the current passing through them. This heating can exceed the allowable operating temperature and accelerate insulation degradation in various circuit parts. Additionally, exceeding a certain threshold temperature can lead to the melting of insulation and generating explosive gases, which are highly undesirable in electrical circuits.
For sizing equipment, it is necessary to determine the maximum short-circuit current, for which the following conditions need to be considered:

- Use the maximum voltage factor $c_{\max}$
- Select the system configuration and maximum contributions from power plants and network feeders to lead to the maximum value of the short-circuit current at the fault location.
- Use impedance correction factors (for transformers, etc.).
- Include motors as needed.
- The resistance of the conductors must be considered at a temperature of 120 °C.

The impact of motors (rotating machines at the time of short circuit) can be neglected when the sum of the motors' rated currents does not exceed 1 % of the short-circuit current calculated without the participation of these motors or the motors are involved in the short-circuit through 2 transformers.

6.4.1 Calculation

When creating an equivalent circuit for calculating short-circuit current using an equivalent voltage source, the schema consists of individual impedance respecting various parts of the circuit, such as the power supply system, feeders, lines, transformers, generators, etc.

Formulas for the individual components of the equivalent circuit:

– Distribution network:

$$Z_{knet} = c \cdot \left(\frac{U_n^2}{S_k''} \right) = c \cdot \frac{U_n}{\sqrt{3} \cdot I_k''} \tag{6.4}$$

U_n is the transformer's rated voltage and, S_k'' is the network short-circuit power (or I_k'' network short-circuit current). Both reactance and resistance can be calculated from the total impedance using the equations mentioned below.

$$X_{\text{knet}} = 0.995 \cdot Z_{\text{knet}} \tag{6.5}$$

$$R_{\text{knet}} = 0.1 \cdot X_{\text{knet}} \tag{6.6}$$

– Transformer:

$$Z_{\text{TR}} = \frac{u_{\text{kTR\%}}}{100} \cdot \frac{U_{\text{nTR}}^2}{S_{\text{nTR}}} \tag{6.7}$$

Parameter $u_{k\%}$ is short-circuit voltage, and S_n is rated as apparent power. Resistivity can be calculated using short-circuit losses and transformer power using the formula. The reactance is calculated using the Pythagorean theorem.

$$R_{\text{TR}} = \Delta P_{\text{kTR}} \cdot \frac{U_{\text{nTR}}^2}{S_{\text{nTR}}} \tag{6.8}$$

$$X_{\text{TR}} = \sqrt{Z_{\text{TR}}^2 - R_{\text{TR}}^2} \tag{6.9}$$

Impedance correction factor K_T when calculating the short-circuit impedances of network transformers:

$$Z_{\text{TRK}} = K_{\text{TR}} \cdot Z_{\text{TR}} \tag{6.10}$$

$$K_{\text{TR}} = \frac{0.95 \cdot c_{\text{max}}}{1 + 0.6 \cdot x_{\text{TR}}} \tag{6.11}$$

$$x_{\text{TR}} = X_{\text{TR}} \cdot \frac{U_{\text{nTR}}^2}{S_{\text{nTR}}} \tag{6.12}$$

– Cables:

The cable parameters needed to calculate can be obtained using IEC TR 60609-2 or from manufacturers' data sheets. This work considers PVC cables at 6 kV and 0.4 kV. In a real design, LOCA cables or cables with increased oxygen index must be considered in certain places to guarantee a non-propagating fire test by standards IEC 332.3A. The parameters of these cables are difficult to trace, and the requirements for using each cable type are beyond the scope of this thesis. The cables in the diagram are negligible for calculating short-circuit currents, so normal PVC cables for industrial use were used. For the calculation, the data-sheet values for resistivity and reactance per kilometer are considered; by multiplying the cable length, we get the real resistivity/reactance of the cable in the circuit diagram.

$$R_V = R_{\text{km}} \cdot d_V \tag{6.13}$$

$$X_V = X_{\text{km}} \cdot d_V \tag{6.14}$$

Subsequently, knowing the values of individual impedances, it is necessary to construct an equivalent circuit using series and parallel combinations according to the actual connection.

With this equivalent circuit, we can calculate the total impedance and determine the short-circuit current using the formula:

$$I_k'' = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_{cc}} \tag{6.15}$$

The short-circuit capability of cables is determined by their maximum permissible insulation temperature, expressed in terms of the conductor temperature during a short circuit. The maximum permissible temperature is considered at a maximum short circuit duration of 5 s. To evaluate the effect of short-circuit currents, a thermally equivalent short-time current is used, which is calculated using the heat dissipation factors m and n, taking into account the thermal effect of the DC and AC components of the short-circuit current.
The subsequent equation is of the following form:

$$I_{th} = I_k'' \cdot \sqrt{m+n} \tag{6.16}$$

For calculating the far-from-generator short-circuit of the heat dissipation of AC component n, we can consider $n = 1$. However, for the heat dissipation of DC component m, we need to find the peak factor κ.

$$\kappa = 1.02 + 0.98e^{-\frac{3R}{X}} \tag{6.17}$$

When calculating the peak factor, the R/X ratio of the short-circuit impedance at a particular point of the short circuit is considered. Subsequently, to calculate the heat dissipation of the DC component m is calculated using the formula (a certain value is always considered for the short-circuit time t_k, to maintain selectivity).

$$m = \frac{1}{2 \cdot f \cdot t_k \ln(\kappa - 1)} \cdot \left[e^{(4 \cdot f \cdot t_k)\ln(\kappa-1)} - 1 \right] \tag{6.18}$$

From the obtained thermally equivalent short-time current, the smallest possible cross-section of the cable is then calculated, taking into account its insulation type and short-circuit breaking time; using the relation, this cross-section must then be compared with the calculated one.

$$S_{\text{min}} = \frac{I_{\text{th}} \cdot \sqrt{t_k}}{K} < S_{\text{cable}} \tag{6.19}$$

In addition, when designing cables, the requirements for acceptable voltage drops are often considered; this is important, especially for devices with much longer cable feeders; in the configuration under consideration, there are no significant voltage drops due to the short distances of the individual devices. That is why they are not described in this work. [21, 22, 23]

7 Practical design

In the following chapter, the thesis focuses on the specific design of the individual components of the SMR TEPLATOR power supply. The main focus will be the concept of the entire electrical power supply of the plant itself. Subsequently, the thesis will focus on the design of the size of the individual transformers and on the sizing of the individual cables that will be used to power the main equipment in the nuclear facility (not only the cross-sections of the individual wires will be considered, but also their control for short-circuit currents). The following calculations refer specifically to the sizing of the individual transformers. At the end of the calculations, we find a complete table of the transformers included in the design.

7.1 Simplified Scheme

Regarding the main operational, normal power supply, a high-voltage level of 22kV is chosen.

The design of the electrical part consists of 2 main transformers and one reserve transformer. Subsequently, the busbars SECTION A and B are powered. If necessary, a connection between the sections is proposed from the reserve supply. The 6kV appliances (Main pumps and Secondary pumps) are fed from Sections A and B.

Subsequently, the 6/0.4 kV transformers are fed from both sections and are connected to the dieselsections where the emergency DGs are also connected. Again, the same topology is chosen, so 2 main transformers TR4 and TR6 are chosen, with TR5 being the standby transformer. These transformers are connected together with the DGs to the 0.4 kV busbars. From these busbars, similar to the main pumps and secondary pumps, the individual devices from each section of EPS1 or EPS2 are always connected to provide backup.

Each EPS1 and EPS2 busbar also has its own rectifier that feeds the battery and through a downstream inverter or direct connection, the equipment that requires uninterrupted supply is powered. The system is designed so that only one 22/6 kV main transformer and a 6/0.4 kV main transformer through one EPS can supply the entire load. However, in normal operation the consumption is designed to be split (not in parallel) between both main transformers.

The individual loads are distinguished by colour. For a more detailed view and description of each part of the diagram, an appendix is attached. This diagram is only for the purpose of showing how the electrical parts are systematically designed and which parts are subsequently sized, checked.

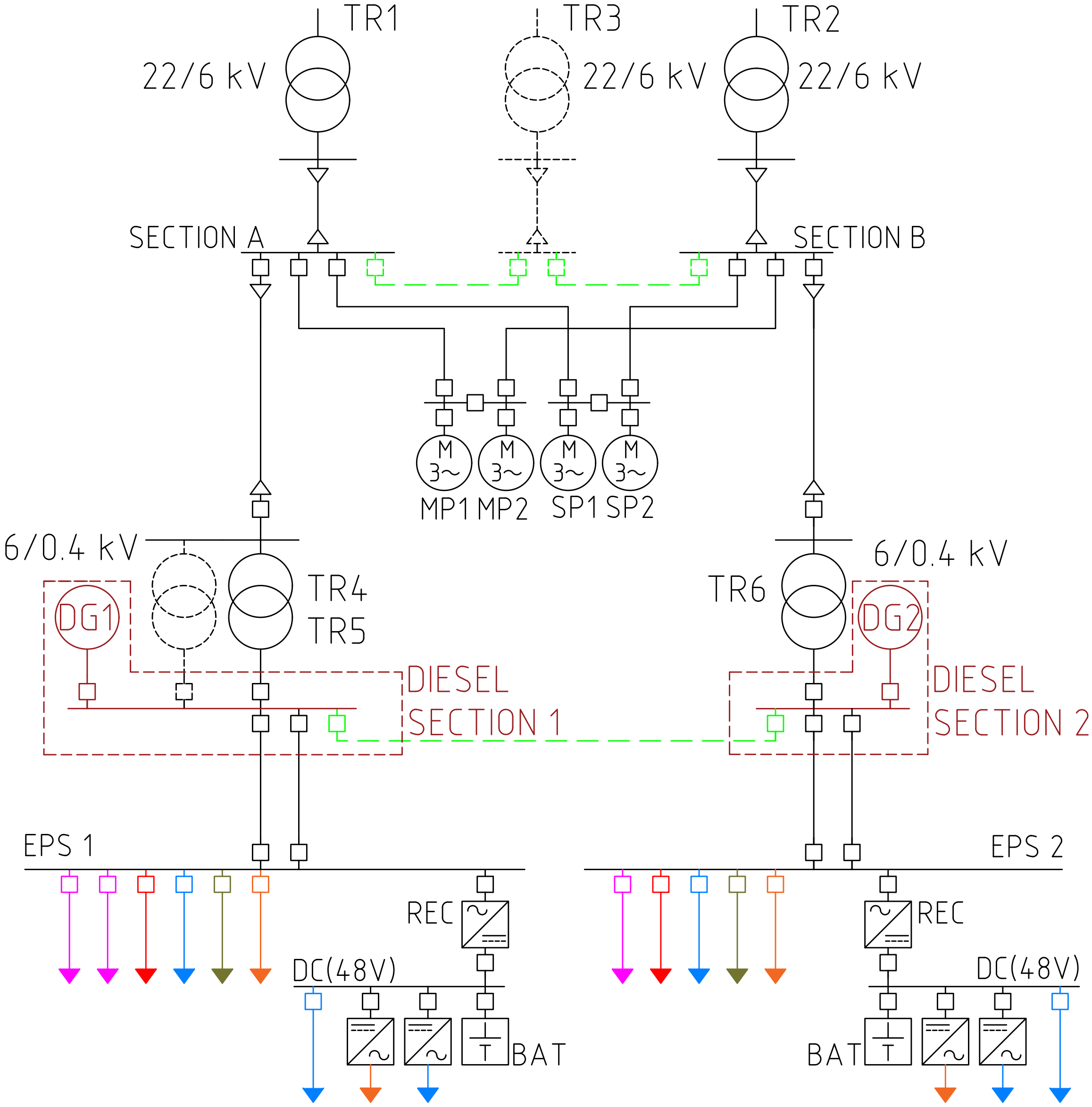

Fig. 7.1 TEPLATOR - Practical design

7.2 Voltage level – Main pumps and Secondary pumps

A voltage level of 6 kV was selected to supply the main and secondary pumps. Their power load is exactly 250 kW (for the main pumps) for one piece, which is the level for a 0.4 kV supply. However, because of the large current load on the individual busbars, these largest pumps are considered at the 6 kV level. The advantage of placing these pumps at the 6 kV level is that their supply is not restored during an interruption, so emergency power sources are only at the 0.4 kV level.

7.3 Transformers – 22/6 kV, 6/0.4 kV

When designing the individual transformers, the possibility of operating the entire plant through one main transformer was taken into account. In the actual design of the whole power supply system, we can notice that the system contains exactly three transformers 22/6 kV. Two main transformers (2 MVA) are considered as normal power supply. In case of a long-term failure of one of the main transformers, a reserve transformer (1.6 MVA) can be used if necessary when operating with one main transformer. The whole scheme is also designed so that the reserve transformer can also power the whole plant if needed.

Example of transformer dimension calculation:

$$S_{pTR1} = \frac{P_c \cdot \beta}{\cos\varphi} = \frac{1300 \cdot 10^3 \cdot 0.78}{0.75} = 1.352 \text{ MVA} \tag{7.1}$$

$$S_{TR1} = 2 \text{ MVA} \tag{7.2}$$

$$\gamma_{TR1} = \frac{S_{pTR1}}{S_{TR1}} = \frac{1.352}{2} = 0.676 \tag{7.3}$$

$$\gamma_{2xTR1} = \frac{S_{pTR1}}{2 \cdot S_{TR1}} = \frac{1.352}{2 \cdot 2} = 0.338 \tag{7.4}$$

For TR1, 2 MVA power was chosen because of the possibility of powering the entire plant with just one transformer. Also, its power was increased to control the start-up of the largest device in the plant. Considering that the total consumption will be fed from TR1 alone, the percentage load on this transformer is 67.6 %. When the power consumption is split between two 2 MVA transformers, the percentage load is 33.8 %. It is the percentage load of approximately 30 % of one transformer that is expected in normal reactor operation. The same process was chosen for the calculation of 6/0.4 kV transformers. Their load is reduced just by the main pumps and secondary pumps.

Tab. 7.1 Transformers

	Calculated power (MVA)	Considered power (MVA)	1xTR (%)	2xTR (%)	u_k (%)	P_k (kW)
TR1, TR2	1.352	2	0.676	0.338	6	22
TR3	1.352	1.6	0.845	0.376	6	17
TR4, TR5, TR6	0.520	0.63	0.825	0.413	4	6.5

However, the entire scheme is designed so that the two transformers do not operate in parallel. There will always be power splitting in operation, but the transformers cannot operate in parallel. If parallel operation were allowed, the short circuit ratios would fundamentally change. Parallel operation is not allowed; therefore, it is not considered in the short circuit current calculations.

7.4 Cables – Sizing and short-circuit control

The next step was to design the individual cables that would be installed to power the individual devices. When designing the cable size, the expected current through the cable (with load reflection) was first considered. Subsequently, this cable was checked for the effects of short circuit currents. The worst-case scenario was considered for calculating short circuit currents, and motor allowances were respected when necessary. The detailed calculation of each cable is described and outlined in detail in the matlab-calculation appendix. A model calculation for cable L1 will be shown in the following sections. Matlab was used to calculate the short circuit currents, and a script was created to calculate the individual cables for the chosen configuration. The validation mechanism is provided by the program DNCalc. The results of the individual calculations or the deviations between the Matlab and DNCalc calculations are shown in the table. The calculation should have addressed the checks for voltage drop since the longest cable runs are 150 m, so the question of voltage drop on the lines, still respecting the cable lines, is irrelevant for this application. The voltage drop across the transformer was considered for the test of starting the largest motor (main pump); this calculation is also outlined later in this chapter.

7.4.1 Example of calculation for cable L1

Calculation of the expected current through cable L1

$$I_{pL1} = \frac{P_c \cdot \beta}{\sqrt{3} \cdot U_n \cdot \cos\varphi} = \frac{1.3 \cdot 10^6 \cdot 0.78}{\sqrt{3} \cdot 6 \cdot 10^3 \cdot 0.75} = 130.1\,\mathrm{A} \tag{7.5}$$

$$I_{nL1} = \frac{I_{pL1}}{k_1 \cdot k_2} = \frac{130.1}{1 \cdot 1} = 130.1\,\mathrm{A} \tag{7.6}$$

To find the nominal current, coefficients must be used to respect the specified conditions. For PVC conductors stored in air, when the ambient temperature is 30 °C, and the maximum permissible operating temperature is 60 °C, it is possible to consider the coefficient $k_1 = 1$. The second coefficient takes into account the load capacity of the cable depending on the method of laying and fixing the cable. For the application of this work, cable gratings are considered where cables are stored loosely. Therefore, the coefficient is also $k_2 = 1$, and both coefficients are chosen according to ČSN 33 2000-5-523.

For the calculation of short-circuit currents, a calculation method using the equivalent voltage source at the point of short-circuit was chosen based on Thevenin's theorem (IEC 60909). The worst-case short-circuit calculation scheme for cable L1 includes the distribution network and transformer TR1.

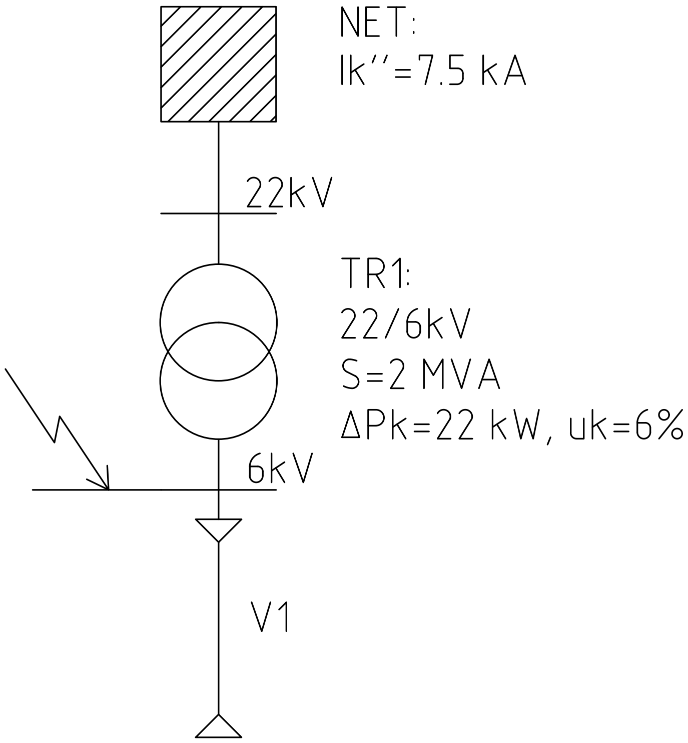

Fig. 7.2 Scheme Short-circuit L1

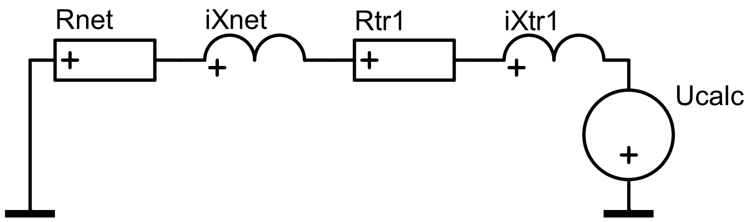

Fig. 7.3 Equivalent scheme L1

First, the individual parameters of the alternative scheme are calculated, i.e., the resistance and reactance of the distribution network and the transformer. Subsequently, the sum of the individual parameters is performed, and using the Pythagorean theorem, we conclude the total impedance of the scheme for a given configuration. The short-circuit current I_k'' at the fault location can be calculated using this impedance.

– Distribution network:

$$Z_{\text{net}} = c \cdot \frac{U_n^2}{S_k''} = c \cdot \frac{U_n^2}{\sqrt{3} \cdot U_n \cdot I_k''} = \frac{1.1 \cdot (22 \cdot 10^3)^2}{\sqrt{3} \cdot 22 \cdot 10^3 \cdot 7.5 \cdot 10^3} \cdot \left(\frac{6 \cdot 10^3}{22 \cdot 10^3}\right)^2 = 0.1386\,\Omega \qquad (7.7)$$

$$X_{\text{net}} = 0.995 \cdot Z_{\text{net}} = 0.995 \cdot 0.1386 = 0.1379\,\Omega \qquad (7.8)$$

$$R_{\text{net}} = 0.1 \cdot Z_{\text{net}} = 0.1 \cdot 0.1379 = 0.01379\,\Omega \qquad (7.9)$$

– Transformer:

$$Z_{\mathrm{TR1}} = \frac{u_{\mathrm{tr1\%}}}{100} \cdot \frac{U_{\mathrm{nTR1}}^2}{S_{\mathrm{nTR1}}} = \frac{6}{100} \cdot \frac{(6 \cdot 10^3)^2}{2 \cdot 10^6} = 1.08\,\Omega \tag{7.10}$$

$$R_{\mathrm{TR1}} = \Delta P_{\mathrm{kTR1}} \cdot \frac{U_{\mathrm{nTR1}}^2}{S_{\mathrm{nTR1}}} = 22 \cdot 10^3 \cdot \frac{(6 \cdot 10^3)^2}{(2 \cdot 10^6)^2} = 0.198\,\Omega \tag{7.11}$$

$$X_{\mathrm{TR1}} = \sqrt{Z_{\mathrm{TR1}}^2 - R_{\mathrm{TR1}}^2} = \sqrt{1.08^2 - 0.198^2} = 1.062\,\Omega \tag{7.12}$$

Correction factor K_t for transformer:

$$x_{\mathrm{TR1}} = \frac{X_{\mathrm{TR1}}}{\left(\frac{U_{\mathrm{nTR1}}^2}{S_{\mathrm{nTR1}}}\right)} = \frac{1.062}{\left(\frac{(6 \cdot 10^3)^2}{2 \cdot 10^6}\right)} = 0.059 \tag{7.13}$$

$$K_{\mathrm{TR1}} = \frac{0.95 \cdot c_{\mathrm{max}}}{1 + 0.6 \cdot x_{\mathrm{TR1}}} = \frac{0.95 \cdot 1.1}{1 + 0.6 \cdot 0.059} = 1.0093 \tag{7.14}$$

$$R_{\mathrm{TR1K}} = K_{\mathrm{TR1}} \cdot R_{\mathrm{TR1}} = 1.0093 \cdot 0.198 = 0.1998\,\Omega \tag{7.15}$$

$$X_{\mathrm{TR1K}} = K_{\mathrm{TR1}} \cdot X_{\mathrm{TR1}} = 1.0093 \cdot 1.062 = 1.0715\,\Omega \tag{7.16}$$

$$\overline{Z_{\mathrm{TR1K}}} = R_{\mathrm{TR1K}} + jX_{\mathrm{TR1K}} = (0.1998 + j1.0715)\,\Omega \tag{7.17}$$

– Total impedance:

$$\overline{Z_c} = R_{\mathrm{net}} + jX_{\mathrm{net}} + R_{\mathrm{TR1K}} + jX_{\mathrm{TR1K}} = \tag{7.18}$$

$$\overline{Z_c} = 0.01379 + j0.1379 + 0.1998 + j1.0715 = (0.2136 + j1.2094)\,\Omega \tag{7.19}$$

$$Z_c = \sqrt{R_c^2 + X_c^2} = \sqrt{0.2136^2 + 1.2094^2} = 1.2281\,\Omega \tag{7.20}$$

– Short-circuit current (L1):

$$I_k'' = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_c} = \frac{1.1 \cdot 6 \cdot 10^3}{\sqrt{3} \cdot 1.2281} = 3.103\,\mathrm{kA} \tag{7.21}$$

– Peak factor κ :

$$\kappa_1 = 1.02 + 0.98 e^{-\frac{3 \cdot R_c}{X_c}} = 1.02 + 0.98 e^{-\frac{3 \cdot 0.2136}{1.2094}} = 1.5969 \tag{7.22}$$

– Heat dissipation of the DC component:

$$m = \frac{1}{2 \cdot f \cdot t_k \cdot \ln(\kappa - 1)} \cdot \left[e^{(4 \cdot f \cdot t_k \cdot \ln(\kappa - 1))} - 1\right] = \tag{7.23}$$

$$m = \frac{1}{(2 \cdot 50 \cdot 0.5 \cdot \ln(1.5969 - 1))} \cdot \left[e^{(4 \cdot 50 \cdot 0.5 \cdot \ln(1.5969 - 1))} - 1\right] \tag{7.24}$$

$$m = 0.0388 \tag{7.25}$$

– Heat dissipation of the AC component $n = 1$

– Thermally equivalent short-time current:

$$I_{\text{th}} = I_k'' \cdot \sqrt{(m+n)} = 3.103 \cdot \sqrt{(0.0388+1)} = 3.163\,\text{kA} \tag{7.26}$$

– Smallest possible cross-section of the cable:

$$S_{\text{min}} = \frac{I_{\text{th}} \cdot \sqrt{t_k}}{K} = \frac{3.163 \cdot 10^3 \cdot \sqrt{0.5}}{76} = 29.4\,\text{mm}^2 \tag{7.27}$$

– Cable L1 selection according to short-circuit current control and expected current load:

  – 6-AYKCY 3X95/16 (nominal current: 168 A, R=0.378 Ω/km, X=0.082 Ω/km)

7.4.2 Summary of cables

All other cables that were designed are summarized in the table. For certain cables that met the conditions, the short-circuit currents were also calculated with the contribution of large motors, as these motors can contribute to the short-circuit currents.

Tab. 7.2 Cables

Cables	Matlab		DNCalc	Deviation	Nominal current	Control for short-circuit current	Nominal cross section	Considered cable type
Variable (unit)	Z_k (Ω)	Ik'' (kA)	Ik'' (kA)	Dev (%)	I_p (A)	S_{min} (mm^2)	S (mm^2)	X-AYK(C)Y
L1, L1.1	1.228	3.10	3.15	1.61	130.01	29.42	150	6-AYKCY
L1.2	1.363	2.54	2.57	1.18	130.01	24.02	150	6-AYKCY
L2, L2.1	1.158	3.28	3.32	1.22	64.15	27.89	35	6-AYKCY
L3, L3.1	1.108	3.43	3.47	1.17	38.49	29.17	35	6-AYKCY
L4, L4.1, L4.2	1.040	3.66	3.69	0.82	64.15	31.09	50	6-AYKCY
L5, L5.1, L5.2	0.020	17.23	17.52	1.68	76.98	127.00	150	1-AYKY
L6, L6.1	0.020	17.79	18.08	1.63	57.74	131.19	150	1-AYKY
L7, L7.1	0.019	18.13	18.42	1.60	115.47	133.69	150	1-AYKY

7.4.3 Diagram of the control model in DNCalc

Using DNCalc, I created a validation scheme that considers the same configuration as the Matlab calculation. This figure illustrates the schematic that is considered, so that the transformers, the individual cables of the calculated cross section and the individual electrical loads are included. In the diagram, the different voltage levels are separated by colour. The individual short-circuit currents for different configurations were then calculated in this program to validate the results obtained from the Matlab calculation.

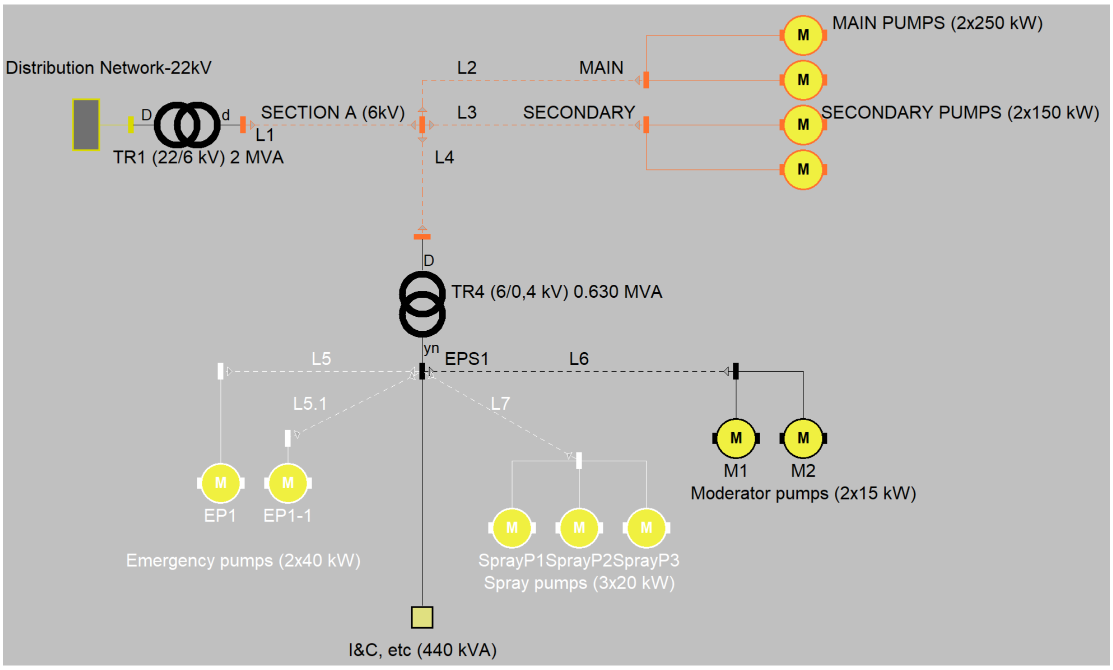

Fig. 7.4 DNCalc model

7.5 Control for starting the largest motor/group of motors

Another common control of a power plant's self-consumption is to start the largest motor. The purpose of this test is to determine the ability of the distribution system in the self-consumption of the power plant to maintain the required voltage drop limit when the starting current of the largest motor in the plant is applied. This test is mainly related to the transformer power and it short-circuit voltage. For the purpose of demonstrating this test, the starting of the main pump was considered when the whole plant was supplied from one transformer (2 MVA).

7.5.1 Start-up control variant 1

The first variant assumes that one main pump is started up and the remaining plant load is replaced by a substitute impedance, calculated based on the remaining power and power factor.

– Impedance 1 Main pump:

$$S_{\text{mainPump}} = \frac{P_{\text{mainPump}}}{\eta \cdot \cos\varphi} = \frac{250}{0.94 \cdot 0.75} = 354.61\,\text{kVA} \tag{7.28}$$

$$Z_{\text{mainPump}} = \frac{1}{i_k} \cdot \frac{U_{nMP}^2}{S_{nMP}} = \frac{1}{5} \cdot \frac{(6 \cdot 10^3)^2}{354.61 \cdot 10^3} = 20.303\,\Omega \tag{7.29}$$

$$\begin{aligned} \overline{Z}_{\text{mainPump}} &= \left(\frac{R_m}{X_m} + j\right) \cdot \frac{Z_{\text{mainPump}}}{\sqrt{1 + \left(\frac{R_m}{X_m}\right)^2}} = \\ &= (0.15 + j) \cdot \frac{20.303}{\sqrt{1 + \left(\frac{0.15}{1}\right)^2}} = \end{aligned} \tag{7.30}$$

$$\overline{Z}_{\text{mainPump}} = (3.01 + j20.08)\,\Omega \tag{7.31}$$

– Impedance others:

$$P_{\text{others}} = P_C - P_{\text{mainPump}} = 1300 - 250 = 1050\,\text{kW} \tag{7.32}$$

$$Q_{\text{others}} = P_{\text{others}} \cdot \tan(\arccos(\cos\varphi)) = 1050 \cdot \tan(\arccos(0.75)) = 926.01\,\text{kVAr} \tag{7.33}$$

$$\overline{Z}_{\text{others}} = \frac{U^2}{P_{\text{others}} - jQ_{\text{others}}} = \frac{(6 \cdot 10^3)^2}{(1050 - j926.01) \cdot 10^3} = (19.29 + j17.01)\,\Omega \tag{7.34}$$

– Total impedance:

$$\overline{Z}_1 = \left(\frac{1}{\overline{Z}_{\text{mainPump}}} + \frac{1}{\overline{Z}_{\text{others}}}\right)^{-1} = \left(\frac{1}{3.01 + j20.08} + \frac{1}{19.29 + j17.01}\right)^{-1} = \tag{7.35}$$

$$\overline{Z}_1 = (5.31 + j10.83)\,\Omega \tag{7.36}$$

$$Z_1 = \sqrt{R_1^2 + X_1^2} = \sqrt{5.31^2 + 10.83^2} = 12.07\,\Omega \tag{7.37}$$

$$\overline{Z}_{\text{net+tr1+L1}} = R_{\text{net}} + jX_{\text{net}} + R_{\text{TR1K}} + jX_{\text{TR1K}} + R_{\text{L1}} + jX_{\text{L1}} \tag{7.38}$$

$$= 0.0138 + j0.1379 + 0.1998 + j1.0715 + 0.0567 + j0.0123$$

$$= (0.2703 + j1.2217)\,\Omega \tag{7.39}$$

$$Z_{\text{net+tr1+L1}} = \sqrt{R_{\text{net+tr1+L1}}^2 + X_{\text{net+tr1+L1}}^2} = \sqrt{0.2703^2 + 1.2217^2} = 1.2513\,\Omega \tag{7.40}$$

– Voltage drop:

$$\Delta u = \frac{1 \cdot Z_1}{Z_{\text{net+tr1+L1}} + Z_1} = \frac{1 \cdot 12.07}{1.2513 + 12.07} = 0.91 \tag{7.41}$$

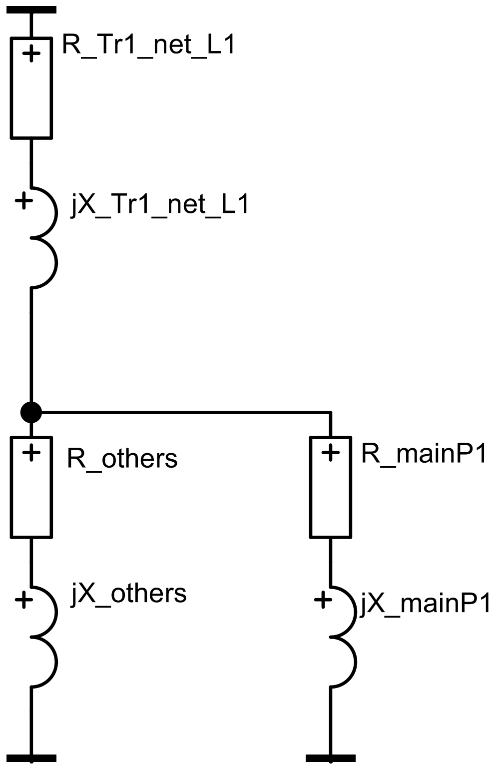

Fig. 7.5 Scheme variant 1

For the largest motor to start, the voltage should not drop below 85 %, the chosen topology meets the condition.

7.5.2 Start-up control variant 2

The second option is to start up all the motors simultaneously (main, secondary, and moderator pumps) and account for the I&C load simultaneously. So, the impedance replaces all the motors, and the other parallel line is the line leading to the moderator pumps and I&C..

– Impedance I&C:

$$S_{\text{I\&C}} = 440\,\text{kVA} \tag{7.42}$$

$$P_{\text{I\&C}} = S_{\text{I\&C}} \cdot \cos\varphi = 440 \cdot 0.75 = 330\,\text{kW} \tag{7.43}$$

$$Q_{\text{I\&C}} = P_{\text{I\&C}} \cdot \tan(\arccos(\cos\varphi)) = 330 \cdot \tan(\arccos(0.75)) = 291.03\,\text{kVAr} \tag{7.44}$$

$$\overline{Z}_{\text{I\&C}} = \frac{U^2}{P_{\text{I\&C}} - jQ_{\text{I\&C}}} = \frac{(0.4 \cdot 10^3)^2}{(330 - j291.03) \cdot 10^3} = (0.273 + j0.241)\,\Omega \tag{7.45}$$

– Impedance others pumps:

$$S_{\text{others\_pumps}} = \frac{P_{\text{others\_pumps}}}{\eta \cdot \cos\varphi} = \frac{550}{0.94 \cdot 0.75} = 780.14\,\text{kVA} \tag{7.46}$$

$$Z_{\text{others\_pumps}} = \frac{1}{i_k} \cdot \frac{(U_{nOP}^2)}{S_{nOP}} = \frac{1}{5} \cdot \frac{(6 \cdot 10^3)^2}{(780.14 \cdot 10^3)} = 9.23\,\Omega \tag{7.47}$$

$$\overline{Z}_{\text{others\_pumps}} = \left(\frac{R_m}{X_m} + j\right) \cdot \frac{Z_{\text{others\_pumps}}}{\sqrt{1 + \left(\frac{R_m}{X_m}\right)^2}} = (0.15 + j) \cdot \frac{9.23}{\sqrt{1 + 0.15^2}} = \tag{7.48}$$

$$\overline{Z}_{\text{others\_pumps}} = (1.37 + j9.13)\,\Omega \tag{7.49}$$

$$\overline{Z}_{\text{MOD+I\&C(6kV)}} = \left(\frac{1}{\overline{Z}_{\text{MOD}} + \overline{Z}_{L6}} + \frac{1}{\overline{Z}_{\text{I\&C}}}\right)^{-1} \cdot \left(\frac{6 \cdot 10^3}{0.4 \cdot 10^3}\right)^2 + \overline{Z}_{\text{TR4}} + \overline{Z}_{L4} \tag{7.50}$$

$$= \left(\frac{1}{0.11 + j0.74 + 0.008 + j0.0023} + \frac{1}{0.273 + j0.241}\right)^{-1} \cdot \left(\frac{6 \cdot 10^3}{0.4 \cdot 10^3}\right)^2 + 0.602 + j2.255 + 0.022 + j0.003 =$$

$$\overline{Z}_{\text{MOD+I\&C(6kV)}} = (34.85 + j49.36)\Omega \tag{7.51}$$

$$\overline{Z}_2 = \left(\frac{1}{\overline{Z}_{\text{others\_pumps}} + \overline{Z}_{\text{MOD+I\&C(6kV)}} + \overline{Z}_{\text{mainPump}}}\right)^{-1} = \tag{7.52}$$

$$= \left(\frac{1}{1.37 + j9.13 + 34.85 + j49.36 + 3.01 + j20.08}\right)^{-1} =$$

$$\overline{Z}_2 = (1.106 + j5.69)\Omega \tag{7.53}$$

$$Z_2 = \sqrt{R_2^2 + X_2^2} = \sqrt{1.106^2 + 5.69^2} = 5.8\,\Omega \tag{7.54}$$

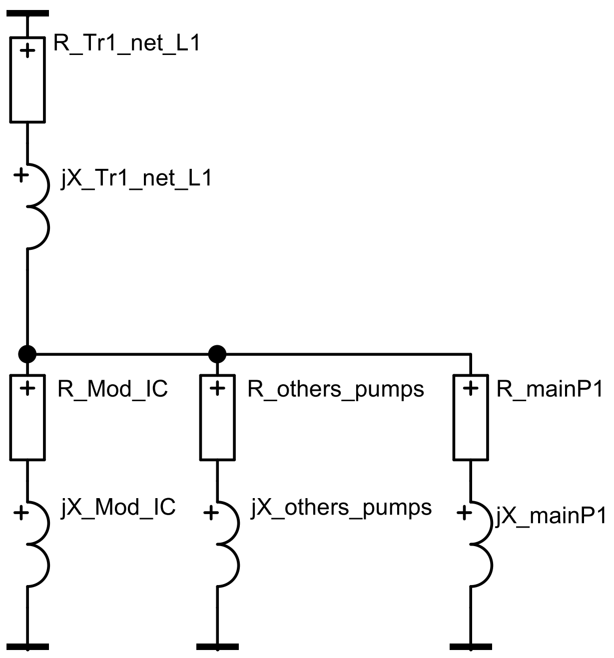

Fig. 7.6 Scheme variant 2

– Voltage drop:

$$\Delta u_2 = \frac{1 \cdot Z_2}{Z_{\text{net+tr1+L1}} + Z_2} = \frac{1 \cdot 5.8}{1.2463 + 5.8} = 0.823 \tag{7.55}$$

For self-running motors, the voltage drop should not fall below 65 %; just like the first control, the second control of the selected topology makes the voltage drop without problems.

In real operation, the power consumption of individual transformers will be split. When the largest motors start up, it is the momentary load and especially the network parameters that determine whether it has a high short-circuit capacity. Another factor contributing to the magnitude of the loss is also the transformer parameter such as short-circuit voltage. Due to the load distribution and the influence of a proper optimization of the order and control of the individual starts, significantly smaller voltage drops are achieved than in this control example. For example, it is not assumed that we run all motors simultaneously without any control (staggered start-up using frequency converters, etc.), all these aspects result in a reduction of the motor starting current and thus a reduction of the voltage drop.

7.6 Diesel generators

The sizing of emergency diesel generators depends on how much power they will need to supply. The design considers two diesel generators installed in the diesel section just behind the 6/0.4 kV transformers. The diesel generators considered for the chosen configuration must supply the same load as that considered for the 6/0,4 kV transformers. For simplicity, the design is therefore based on the load of the transformers with the addition of the reserve superstructure. The diesel generators under consideration are designed for a size of 2x440 kVA for each section. Further, these generators are not tested as they are beyond the scope of this thesis. However, their location is by legislative and regulatory requirements. For defense in depth, two DGs are considered for the whole system (each for its division), and both DGs are capable of supplying the entire consumption should a fault occur at one of the divisions (either at the busbar or directly at the DG).

7.6.1 Specific DG selection

There are different configurations of diesel generator sections in nuclear power plants. The option chosen for this thesis is the mobile diesel generators used in Temelín NPP - in the TEPLATOR diagram, we notice that each section has its diesel generator section. The DG1 section will contain just two D440 diesel generators. Each generator has an output of 440 kVA and 352 kW. The output current of each DG is approximately 600 A, so with only two DGs running, we already have 1200 A available for the most important equipment. The generator has mechanical driven fan. The generators are already used in the nuclear industry, but the chosen configuration of a larger number of diesel generators can help handle the sequential load attachment. The diesel generators are engine-brand DOOSAN, which has many years of experience supplying equipment to the nuclear industry.Thus, a total of four D440 diesel generators are designed for the TEPLATOR configuration. [24]

Fig. 7.7 Diesel generator SDMO D440 [24]

7.7 Battery

The design of the batteries is crucial for the whole electrical design. In the design presented in this thesis, EPS 1 and EPS 2 are equipped with batteries that, either directly or through an inverter, power the most important equipment in the nuclear facility.

Parameters required for the design of the batteries:

- Power demand

For the design of batteries for the emergency power supply of nuclear facilities, the size of the load we want to power depends mainly. In case of SMR TEPLATOR it will be division 1, 2 namely I&C, self-consumption DG, armatures, valves, emergency lighting, etc.

- Longer-term/Short-term

If emergency batteries are required to start the motors, this must be considered when selecting the type of batteries. For the configuration that has been proposed in this thesis, there is no starting motor using batteries. The starting of the pumps is considered to be powered by diesel generators. Therefore, for the design, we can consider batteries without the inability to manage the starting currents in a short time. It will be more of a matter of maintaining the most important instrumental and control systems before the DG start-up occurs.

– Power period

The period of time for which batteries are required to power the most important equipment depends on the requirements of the Atomic Energy Act. Determining these values depends on the configuration and a much more complex analysis than this thesis. The most common time ranges required in nuclear power plants are from 0.5 to 72 hours.

– Voltage level

Individual station batteries could also be divided into different voltage levels, for example 24, 48 V. This choice will mainly depend on the final configuration of the individual devices and their parameters.

7.7.1 Specific Battery selection

For our configuration, one battery choice is 2V lead acid cells with a fan. The advantage of these cells is that they are very simple and low maintenance (just top up the acid if needed), another advantage of this type of battery is durability. For the configuration I chose HOPPECKE, which supplies the GroE series batteries (marking according to HOPPECKE ”grid — power V X, or for higher starting currents power V M). The overall design of the battery section will also require dimensioning of the individual rectifiers and inverters according to the selected batteries. [25]

Fig. 7.8 Battery - Power V M [25]

Conclusion

The design of the electrical parts of nuclear power plants will be very important in developing small modular reactors. Nowadays, when many countries are developing small modular reactors, the design of the electrical part of the SMR TEPLATOR is still quite special because in the normal design of the electrical supply of the individual equipment in the self-consumption, the alternator of the unit itself is the normal power source, for the most part, it is the cogeneration units. This thesis aimed to introduce the SMR TEPLATOR nuclear reactor and mainly design the electrical part of the power supply of the individual equipment. TEPLATOR can offer to sustain district heating even after the shutdown of fossil power plants. The design also included defining and categorizing the equipment and the individual power supplies, either in terms of the importance of the power supply concerning nuclear safety or the allowed period when the equipment can be without power. Batteries were designed for devices with uninterrupted power supplies. The CANDU and Temelin NPP nuclear facilities were used to design and divide each facility into groups/divisions. Thus, in the thesis, divisions of appliances are designed according to the importance of uninterrupted power supply and devices that are considered only for normal or preferred power supply.

The thesis presents the normative and legislative requirements for nuclear facilities, as no easing of the requirements for small modular reactors is foreseen. The normative and legislative requirements are very important for the actual design and the fulfillment of the main objective of this thesis. Therefore, the power supply design includes just three supply options from the 22 kV distribution network, which include two main transformers and one reserve transformer in case one of the main transformers is out of service for a long time. The transformers are sized to supply the entire load associated with all reactor operating conditions. The electrical design also included the electrical location and sizing of the two emergency diesel generators, which are positioned in such a way that they can provide the total nuclear reactor power for shutdown in the event of one failure. For the design of the transformers and the individual cables, data obtained from TEPLATOR's main designer were used, mainly regarding the power sizing of the individual devices, which were taken into account at the time of the creation of the work to make the design itself as up-to-date as possible. Unfortunately, this is still a prototype reactor, so only some of the systems and their electrical ratings have been finalized. That is why, for example, the individual cables that lead to the equipment, which still need to be defined, are not calculated.

The detailed electrical design would need much more information about the individual devices to complete the design. Only some systems have been designed at the time of the thesis, so the design needs to be more detailed. I have incorporated the available information in the thesis and created an electrical design. During the design of the individual cables, I approached the design as an industrial plant power supply design, so the relevant standards for cable design and its controls are used. The control for short circuit currents was created for all the cables I considered for the electrical supply. For cable design, the worst-case configuration was always considered to achieve the highest possible short circuit currents, which included contributions from pumps if necessary. The whole procedure of the individual calculations is incorporated in a mathematical script in Matlab, part of the thesis. Part of the verification of these results included the DNCalc program, which formed the backbone for checking the results of either short circuit currents or the resulting short circuit impedances. During the manually created procedure calculation, a maximum of 2 % deviation was not exceeded for calculating short-circuit currents for individual cables compared to DNCalc.

Part of the design of the electrical part of the SMR Teplator was also checking for voltage drop on the main transformer when starting the largest engine and when starting a group of engines. The design of the main transformers passed this test so that when the largest motors are started, the transformers will maintain the required voltage, even in a configuration where one transformer supplies the entire electrical load of the appliances associated with the operation of the nuclear reactor. The transformers under consideration for their normal operating condition consider power sharing. Thus, the consumption will be split between the two main transformers, which will never operate in parallel (they will only redistribute the consumption using a switch configuration). The design also includes a diagram where the overall power system is described, thus providing visual support for the orientation of the electrical supply. In the thesis, the schematics are used as visual support in the examples of the individual calculations.

Several simplifications were used as part of the cable design due to the scope of the thesis, which was not part of the assignment. For example, the cable design considers PVC cables placed separately on gratings. The thesis does not address their placement (one placement method for all cables is considered), which could change the potential coefficients for individual cables. For example, LOCA cables can be used for important cables that feed devices in the primary circuit. Still, unfortunately, the design of these cables did not find the values of resistances and reactances of these LOCA cables, so the simplification and use of PVC cables were used. In calculating the individual short circuit ratios, the impedances of the cables did not have a major influence due to their lengths, the main influence being the transformers, the distribution network, or the large pumps. When the design of the individual cable types is completed, the values of resistances and reactances in the script can be adjusted (respecting the parameters of the LOCA cables). Still, the resulting currents will not be fundamentally different. The requirements' final definition may result in reducing the backup systems, such as transformers, backup power to individual devices, or the cross-sectional size of individual cables. When the prototype is finalized, the design must be consulted with the entity that will license this type of reactor for the first time, as nuclear equipment of similar power output is not currently used for heating only. Therefore, the final requirements for the electrical systems will also have to be discussed. For example, the safety functions of the individual pumps and the subsequent sizing of the emergency batteries and diesel generators. This is completely beyond the scope of this thesis—the thesis aimed to design the SMR TEPLATOR's electrical supply in its current state of development.

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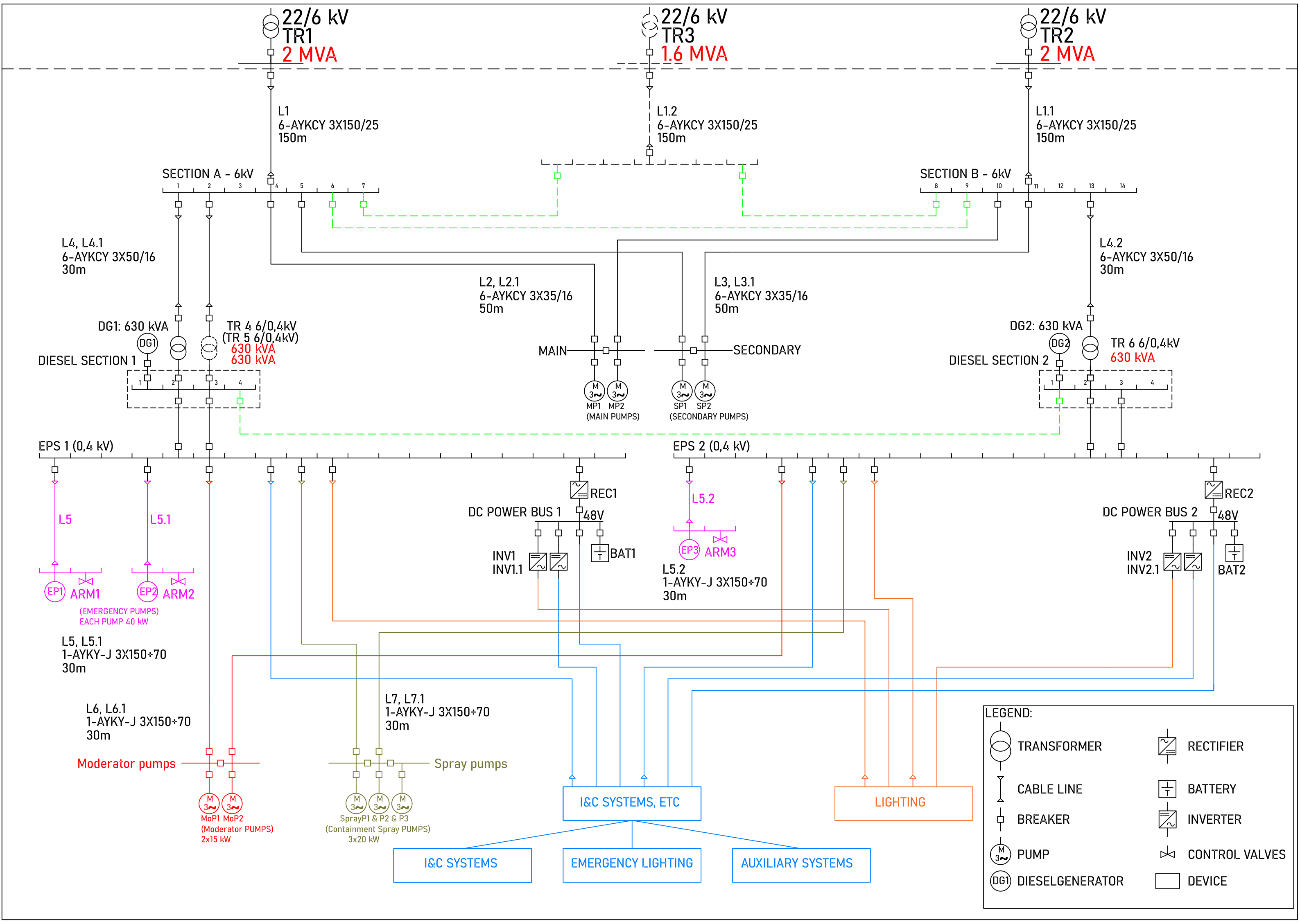
List of Figures

List of Tables

List of Appendices

Appendix A Diagram TEPLATOR



22/6 kV
TR1
2 MVA
22/6 kV
TR3
1.6 MVA
22/6 kV
TR2
2 MVA
L1
6-AYKCY 3X150/25
150m
L1.2
6-AYKCY 3X150/25
150m
L1.1
6-AYKCY 3X150/25
150m
SECTION A - 6kV
SECTION B - 6kV
L4, L4.1
6-AYKCY 3X50/16
30m
L4.2
6-AYKCY 3X50/16
30m
L2, L2.1
6-AYKCY 3X35/16
50m
L3, L3.1
6-AYKCY 3X35/16
50m
DG1: 630 kVA
TR 4 6/0,4kV
(TR 5 6/0,4kV)
630 kVA
630 kVA
DIESEL SECTION 1
MAIN
SECONDARY
MP1 MP2
(MAIN PUMPS)
SP1 SP2
(SECONDARY PUMPS)
DG2: 630 kVA
TR 6 6/0,4kV
630 kVA
DIESEL SECTION 2
EPS 1 (0,4 kV)
EPS 2 (0,4 kV)
REC1
DC POWER BUS 1
48V
BAT1
INV1
INV1.1
L5.2
EP3 ARM3
L5.2
1-AYKY-J 3X150÷70
30m
REC2
DC POWER BUS 2
48V
INV2
INV2.1
BAT2
L5
L5.1
EP1 ARM1
EP2 ARM2
(EMERGENCY PUMPS)
EACH PUMP 40 kW
L5, L5.1
1-AYKY-J 3X150÷70
30m
L6, L6.1
1-AYKY-J 3X150÷70
30m
L7, L7.1
1-AYKY-J 3X150÷70
30m
Moderator pumps
MoP1 MoP2
(Moderator PUMPS)
2x15 kW
Spray pumps
SprayP1 & P2 & P3
(Containment Spray PUMPS)
3x20 kW
I&C SYSTEMS, ETC
LIGHTING
I&C SYSTEMS
EMERGENCY LIGHTING
AUXILIARY SYSTEMS
LEGEND:
TRANSFORMER
RECTIFIER
CABLE LINE
BATTERY
BREAKER
INVERTER
PUMP
CONTROL VALVES
DG1 DIESELGENERATOR
DEVICE

Appendix B Matlab - Script

Code listing B.1 Matlab - Script

```
%TEPLATOR SMRs electrical equipment design
%DIPLOMA THESIS
%author: Ullmann Jan
Pc=1300*10^3;
% ČSN 341610
Beta=0.78;
CosFi=0.75; %power factor
SinFi=sin(acos(CosFi));
U1=6000; %Voltage level
U2=22000; %Voltage level

%TR1
Sp_TR1=Pc*Beta/CosFi;
%Considered power S_TR1=2 MVA
S_TR1=2*10^6;
delta_Pk_TR1=22*10^3; %datasheet
uk_tr1=6/100; %datasheet

%Power Load 1xTR(2 MVA for entire plant load)
load_TR1=Sp_TR1/S_TR1;

%Power Load  2xTR (2x2 MVA for plant load - normal operation, non-parallel)
load_2TR1=Sp_TR1/(2*S_TR1);

%TR3 (reserve TR)
S_TR3=1.6*10^6;
delta_Pk_TR3=17*10^3; %datasheet
uk_TR3=6/100; %datasheet
%Power Load 1xTR(1.6 MVA for entire plant load)
load_TR3=Sp_TR1/(S_TR3);

%Power Load TR1+TR2 (non-parallel)
load_TR3_TR1=Sp_TR1/(S_TR3+S_TR1);

%TR4, TR5, TR6
```

```
Pc_TR4=Pc-800*10^3; %Load for TR4 (Pc-Main pumps-Secondary pumps)
Sp_TR4=Pc_TR4*Beta/CosFi;
%Considered power S_TR4=0,63 MVA, also for others transformers 6/0,4 kV
S_TR4=630*10^3;
delta_Pk_TR4=6.5*10^3; %datasheet
uk_TR4=4/100; %datasheet

%Load 1xTR4(0,63 MVA for entire plant load without main pumps and
% secondary pumps)
load_TR4=Sp_TR4/S_TR4;
%Load 2xTR4(2x0,63 MVA for entire plant load without main pumps and
% secondary pumps, normal operation, non-parallel)
load_2TR4=Sp_TR4/(2*S_TR4);

%---------------------------------------------------------------------------
%Cable L1, and L1.1
d1=0.15; %150m, Lenght
%Current: Cable L1
Ip_L1=(Pc*Beta)/(CosFi*sqrt(3)*U1);

k1_L1=1;
k2_L1=1;
In_L1=Ip_L1/(k1_L1*k2_L1);
R_L1=0.239*d1;
X_L1=0.078*d1;
Z_L1=R_L1+X_L1*i;
Z_L1_abs=abs(Z_L1);
%Short-circuit curren control for L1
%Calculation
%The individual components of the scheme

%Distribution Network:
Ik_network=7.5*10^3;
Sk_network=sqrt(3)*U2*Ik_network;
c=1.1; %cmax
Z_network_abs=(c*U2^2/Sk_network)*(U1/U2)^2; %6kV
X_network=0.995*Z_network_abs;
R_network=0.1*X_network;
Z_network=R_network+X_network*i;
```

```
Z_network_abs=abs(Z_network);

%TR1:
Z_TR1_abs=uk_tr1*U1^2/S_TR1;
R_TR1=delta_Pk_TR1*U1^2/(S_TR1^2);
X_TR1=sqrt(Z_TR1_abs^2-R_TR1^2);

%Correction factor Kt for transformer
x_TR1_proportional=X_TR1/(U1^2/S_TR1);
k_TR1=0.95*c/(1+0.6*x_TR1_proportional);

%R_TR1 A X_TR1 with correction factor
R_TR1=k_TR1*R_TR1;
X_TR1=k_TR1*X_TR1;
Z_TR1=R_TR1+X_TR1*i;
Z_TR1_ABS=abs(Z_TR1);

%Total impedance (NETWORK + TR1)
Z_TR1_NET=Z_TR1+Z_network;
Z_TR1_NET_ABS=abs(Z_TR1_NET);

%Short-circuit current (L1)
Ik_TR1_NET=c*U1/sqrt(3)/Z_TR1_NET_ABS;

%Control for short-circuit current (L1)
R_X_L1=real(Z_TR1_NET)/imag(Z_TR1_NET);
kappa=1.02+0.98*exp(-3*R_X_L1);
f=50; %frequency 50 Hz
tk_L1=0.5;
m_L1=1/(2*f*tk_L1*log(kappa-1))*(exp((4*f*tk_L1)*log(kappa-1))-1);
n_L1=1; %far-from-generator short-circuit the heat dissipation
% of AC component n

K_L1=76; %6-AYKCY -> PVC -> K=76
S_L1_control=Ik_TR1_NET*sqrt(m_L1+n_L1)*sqrt(tk_L1)/K_L1;

%Control for voltage drop (L1)
delta_u1=(sqrt(3))*(R_L1*d1*Ip_L1*CosFi+X_L1*d1*Ip_L1*SinFi)/(U1)*100;
%-------------------------------------------------------------------------
```

```
%Cable L1.2
%TR3
Sp_TR3=Pc*Beta/CosFi;
%Considered power S_TR3=1.6 MVA
S_TR3=1.6*10^6;
delta_Pk_TR3=20*10^3; %datasheet
uk_TR3=6/100; %datasheet
%TR3:
Z_TR3_abs=uk_TR3*U1^2/S_TR3;
R_TR3=delta_Pk_TR3*U1^2/(S_TR3^2);
X_TR3=sqrt(Z_TR3_abs^2-R_TR3^2);

%Correction factor Kt for transformer
x_TR3_proportional=X_TR3/(U1^2/S_TR3);
k_TR3=0.95*c/(1+0.6*x_TR3_proportional);

%R_TR3 A X_TR3 with correction factor
R_TR3=k_TR3*R_TR3;
X_TR3=k_TR3*X_TR3;
Z_TR3=R_TR3+X_TR3*i;
Z_TR3_ABS=abs(Z_TR3);

%Total impedance (NETWORK + TR3)
Z_TR3_NET=Z_TR3+Z_network;
Z_TR3_NET_ABS=abs(Z_TR3_NET);

%Short-circuit current (L1.2)
Ik_TR3_NET=c*U1/sqrt(3)/Z_TR3_NET_ABS;

%Control for short-circuit current (L1.2)
R_X_L12=real(Z_TR3_NET)/imag(Z_TR3_NET);
kappa12=1.02+0.98*exp(-3*R_X_L12);
f=50; %frequency 50 Hz
tk_L12=0.5;
m_L12=1/(2*f*tk_L12*log(kappa12-1))*(exp((4*f*tk_L12)*log(kappa12-1))-1);
n_L12=1; %far-from-generator short-circuit the heat dissipation
% of AC component n

K_L12=76; %6-AYKCY -> PVC -> K=76
```

```
S_L12_control=Ik_TR3_NET*sqrt(m_L12+n_L12)*sqrt(tk_L12)/K_L12;

%---------------------------------------------------------------------------
%Cable L2, L2.1 - Main pumps (Core cooling pumps)
d2=0.05;
Pc_HCC=500*10^3; %Power of Main pumps
Ip_L2=Pc_HCC/(CosFi*sqrt(3)*U1);

R_L2=1.02*d2;
X_L2=0.094*d2;
Z_L2=R_L2+X_L2*i;



%Total impedance (NETWORK + TR1 + L1)
Z_TR1_NET_L1=Z_TR1_NET+Z_L1;
Z_TR1_NET_L1_ABS=abs(Z_TR1_NET_L1);
Ik_TR1_NET_L1=c*U1/sqrt(3)/Z_TR1_NET_L1_ABS;

%Control for short-circuit current (L2)
R_X_L2=real(Z_TR1_NET_L1)/imag(Z_TR1_NET_L1);
kappa_L2=1.02+0.98*exp(-3*R_X_L2);
tk_L2=0.4;
m_L2=1/(2*f*tk_L2*log(kappa_L2-1))*(exp((4*f*tk_L2)*log(kappa_L2-1))-1);
n_L2=1; %far-from-generator short-circuit the heat dissipation
% of AC component n

K_L2=76; %6-AYKCY -> PVC -> K=76
S_L2_control=Ik_TR1_NET_L1*sqrt(m_L2+n_L2)*sqrt(tk_L2)/K_L2;

%Kontrola na úbytek napětí pro L2
delta_u2=(sqrt(3))*(R_L2*d2*Ip_L2*CosFi+X_L2*d2*Ip_L2)/(U1)*100;

%---------------------------------------------------------------------------
%Cable L3, L3.1 - Secondary pumps
d3=0.05;
Pc_SEK=300*10^3; %Power of Secondary pumps
Ip_L3=Pc_SEK/(CosFi*sqrt(3)*U1);
R_L3=1.02*d3;
X_L3=0.094*d3;
```

```
Z_L3=R_L3+X_L3*i;

%Impedance Main Pumps
ik_HCC=5;
n_hcc=0.94;
S_HCC=Pc_HCC/n_hcc/CosFi;
Z_HCC_abs=1/ik_HCC*U1^2/S_HCC;
rm_xm=0.15;
Z_HCC=(rm_xm+i)*Z_HCC_abs/(sqrt(1+rm_xm^2));

%Impedance Secondary pumps
ik_SEK=5;
n_SEK=0.94;
S_SEK=Pc_SEK/n_SEK/CosFi;
Z_SEK_abs=1/ik_SEK*U1^2/S_SEK;
rm_xm=0.15;
Z_SEK=(rm_xm+i)*Z_SEK_abs/(sqrt(1+rm_xm^2));

%----------------------------------------------------------------------------
%Control of cable L3 at the contribution of the rotating main pumps

Z_control_L3=(Z_TR1_NET_L1*(Z_HCC+Z_L2))/(Z_TR1_NET_L1+Z_HCC+Z_L2);
Z_control_L3_abs=abs(Z_control_L3);
Ik_control_L3=c*U1/sqrt(3)/Z_control_L3_abs;

R_X_L3=real(Z_control_L3)/imag(Z_control_L3);
kappa_L3=1.02+0.98*exp(-3*R_X_L3);
tk_L3=0.4;
m_L3=1/(2*f*tk_L3*log(kappa_L3-1))*(exp((4*f*tk_L3)*log(kappa_L3-1))-1);
n_L3=1; %far-from-generator short-circuit the heat dissipation
% of AC component n

K_L3=76; %6-AYKCY -> PVC -> K=76
S_L3_control=Ik_control_L3*sqrt(m_L3+n_L3)*sqrt(tk_L3)/K_L3;

%----------------------------------------------------------------------------
%Control of cable L2 at the contribution of the rotating secondary pumps
Z_control_L2_MP=(Z_TR1_NET_L1*(Z_SEK+Z_L3))/(Z_TR1_NET_L1+Z_SEK+Z_L3);
Z_control_L2_MP_abs=abs(Z_control_L2_MP);
```

```
Ik_control_L2_MP=c*U1/sqrt(3)/Z_control_L2_MP_abs;

R_X_L2_MP=real(Z_control_L2_MP)/imag(Z_control_L2_MP);
kappa_L2_MP=1.02+0.98*exp(-3*R_X_L2_MP);
tk_L2_MP=0.4;
m_L2_MP=1/(2*f*tk_L2_MP*log(kappa_L2_MP-1))*(exp((4*f*tk_L2_MP) ...
    *log(kappa_L2_MP-1))-1);
n_L2_MP=1; %far-from-generator short-circuit the heat dissipation
% of AC component n

K_L2_MP=76; %6-AYKCY -> PVC -> K=76
S_L2_control_MP=Ik_control_L2_MP*sqrt(m_L2_MP+n_L2_MP)*sqrt(tk_L2_MP)...
/K_L2_MP;

%------------------------------------------------------------------------------
%Cable L4, L4.1
d4=0.03;
Ip_L4=Pc_TR4/(CosFi*sqrt(3)*U1);
R_L4=0.718*d4;
X_L4=0.088*d4;
Z_L4=R_L4+X_L4*i;

%------------------------------------------------------------------------------
%Control of cable L4 at the contribution of the rotating main pumps and
%secondary pumps

Z_control_L4=(1/Z_TR1_NET_L1+1/(Z_HCC+Z_L2)+1/(Z_SEK+Z_L3))^-1;
Z_control_L4_ABS=abs(Z_control_L4);
Ik_control_L4=c*U1/sqrt(3)/Z_control_L4_ABS;

R_X_L4=real(Z_control_L4)/imag(Z_control_L4);
kappa_L4=1.02+0.98*exp(-3*R_X_L4);
tk_L4=0.4;
m_L4=1/(2*f*tk_L4*log(kappa_L4-1))*(exp((4*f*tk_L4)*log(kappa_L4-1))-1);
n_L4=1; %far-from-generator short-circuit the heat dissipation
% of AC component n

K_L4=76; %6-AYKCY -> PVC -> K=76
S_L4_control=Ik_control_L4*sqrt(m_L4+n_L4)*sqrt(tk_L4)/K_L4;
```

```
%--------------------------------------------------------------------------
%Cable L5, L5.1 - Emergency pumps

Pc_EME=40000;
U3=400;
Ip_L5=Pc_EME/(CosFi*sqrt(3)*U3);

%TR4
Z_TR4=uk_TR4*U1^2/S_TR4;
R_TR4=delta_Pk_TR4*U1^2/(S_TR4^2);
X_TR4=sqrt(Z_TR4^2-R_TR4^2);

%Correction factor Kt for TR4
x_TR4_proportional=X_TR4/(U1^2/S_TR4);
k_TR4=0.95*c/(1+0.6*x_TR4_proportional);

%R_TR4 A X_TR4 with correction factor
R_TR4=k_TR4*R_TR4;
X_TR4=k_TR4*X_TR4;
Z_TR4=R_TR4+X_TR4*i;
Z_TR4_ABS=abs(Z_TR4);

%Impedance Moderator pumps
ik_MOD=5;
n_MOD=0.94;
Pc_MOD=30000;
S_MOD=Pc_MOD/n_MOD/CosFi;
Z_MOD_abs=1/ik_MOD*U3^2/S_MOD;
rm_xm=0.15;
Z_MOD=(rm_xm+i)*Z_MOD_abs/(sqrt(1+rm_xm^2));

%Control for short-circuit current (L5)
Z_L5=(Z_control_L4+Z_L4+Z_TR4)*(U3/U1)^2;
Z_control_L5=(1/Z_L5+1/Z_MOD)^-1;
Z_L5_ABS=abs(Z_control_L5);
Ik_control_L5=c*U3/sqrt(3)/Z_L5_ABS;

R_X_L5=real(Z_L5)/imag(Z_L5);
```

```
kappa_L5=1.02+0.98*exp(-3*R_X_L5);
tk_L5=0.3;
m_L5=1/(2*f*tk_L5*log(kappa_L5-1))*(exp((4*f*tk_L5)*log(kappa_L5-1))-1);
n_L5=1; %far-from-generator short-circuit the heat dissipation
% of AC component n

K_L5=76; %1-AYKY -> PVC -> K=76
S_L5_control=Ik_control_L5*sqrt(m_L5+n_L5)*sqrt(tk_L5)/K_L5;

%---------------------------------------------------
% Cable L6 - Moderator pumps

Pc_MOD=30000;
Ip_L6=Pc_MOD/(CosFi*sqrt(3)*U3);

%Impedance Emergency pump
ik_EME=5;
n_EME=0.94;
S_EME=Pc_EME/n_EME/CosFi;
Z_EME_abs=1/ik_EME*U3^2/S_EME;
rm_xm=0.15;
Z_EME=(rm_xm+i)*Z_EME_abs/(sqrt(1+rm_xm^2));

%Control of cable L6 at the contribution of the rotating main pumps and
%secondary pumps and emergency pumps
Z_control_L6=(1/Z_L5+1/Z_EME+1/Z_EME)^-1;
Z_control_L6_abs=abs(Z_control_L6);
Ik_control_L6=c*U3/sqrt(3)/Z_control_L6_abs;

R_X_L6=real(Z_control_L6)/imag(Z_control_L6);
kappa_L6=1.02+0.98*exp(-3*R_X_L6);
tk_L6=0.3;
m_L6=1/(2*f*tk_L6*log(kappa_L6-1))*(exp((4*f*tk_L6)*log(kappa_L6-1))-1);
n_L6=1; %far-from-generator short-circuit the heat dissipation
% of AC component n

K_L6=76; %1-AYKY -> PVC -> K=76
S_L6_control=Ik_control_L6*sqrt(m_L6+n_L6)*sqrt(tk_L6)/K_L6;
d6=0.03;
```

```
Z_L6=d6*0.258+d6*0.0782*i;
%----------------------------------------------------
% Cable L7 - Spray system
Pc_spray=60000;
U3=400;
Ip_L7=Pc_spray/(CosFi*sqrt(3)*U3);

%control with motors
Z_control_L7=(1/Z_control_L6+1/Z_MOD)^-1;
Z_control_L7_abs=abs(Z_control_L7);
Ik_control_L7=c*U3/sqrt(3)/Z_control_L7_abs;

R_X_L7=real(Z_control_L7)/imag(Z_control_L7);
kappa_L7=1.02+0.98*exp(-3*R_X_L7);
tk_L7=0.3;
m_L7=1/(2*f*tk_L7*log(kappa_L7-1))*(exp((4*f*tk_L7)*log(kappa_L7-1))-1);
n_L7=1; %far-from-generator short-circuit the heat dissipation
% of AC component n

K_L7=76; %1-AYKY -> PVC -> K=76
S_L7_control=Ik_control_L7*sqrt(m_L7+n_L7)*sqrt(tk_L7)/K_L7;

%---------------------------------------------------------
%Check to start-up the largest motor (Main pump - 250kW) - bus voltage drop

%Impedance 1xMain Pump
ik_HCC=5;
n_hcc=0.94;
S_HCC_startup=Pc_HCC/2/n_hcc/CosFi;
Z_HCC_abs_startup=1/ik_HCC*U1^2/S_HCC_startup;
rm_xm=0.15;
Z_HCC_startup=(rm_xm+i)*Z_HCC_abs_startup/(sqrt(1+rm_xm^2));
%one main pump impedance

%The other loads are considered without start-up, so only based on
% the rest of the power and power factor.
%Others
P_others=1050000;
Q_others=P_others*tan(acos(CosFi));
```

```
Z_others=U1^2/(P_others-Q_others*i);

Z_1=(1/Z_HCC_startup+1/Z_others)^-1;
Z_1_abs=abs(Z_1);

U_TR1=Z_1_abs/(Z_TR1_NET_L1_ABS+Z_1_abs);

%--------------------------------------------------------------------------
%Calculated with all motors starting up
%I&C
S_IC=440000;
P_IC=S_IC*CosFi;
Q_IC=P_IC*tan(acos(CosFi));
Z_IC=U3^2/(P_IC-Q_IC*i);

%Impedance Others pumps (Secondary+1xmain)
ik_HCC=5;
n_hcc=0.94;
Pc_others_pumps=(250+300)*10^3;
S_others_pumps=Pc_others_pumps/n_hcc/CosFi;
Z_others_pumps_abs=1/ik_HCC*U1^2/S_others_pumps;
rm_xm=0.15;
Z_others_pumps=(rm_xm+i)*Z_others_pumps_abs/(sqrt(1+rm_xm^2)); %others

%Impedance L4, TR4, moderator
Z_MOD_IC_400V=(1/(Z_MOD+Z_L6)+1/Z_IC)^-1;
Z_MOD_IC_6kV=Z_MOD_IC_400V*(U1/U3)^2;

Z_others2=Z_MOD_IC_6kV+Z_TR4+Z_L4;
Z_y=(1/Z_others_pumps+1/Z_HCC_startup+1/Z_others2)^-1;
Z_y_abs=abs(Z_y);
U_TR1_2=Z_y_abs/(Z_TR1_NET_L1_ABS+Z_y_abs);
```