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MASTER'S THESIS

HV ELECTRICAL SUBSTATION ANALYSIS WITH WEB-BASED SUBSTATION DESIGN AND MODERNIZATION INTERFACE

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Carried out
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TASK

For the implementation of master's thesis

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1	Master thesis theme:	HV Electrical Substation Analysis with Web-Based Substation Design and Modernization Interface	
	Тема работы:	Анализ высоковольтного оборудования подстанции с разработкой Веб-приложения для задач модернизации	
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3	Initial data of work:		
	Conventional Substation 500/220 kV Scheme with Specified Equipment		
4	Contents of the work (list of issues to be developed):		
	• Conventional Substation Design Analysis • Modernization Of 500 kV Switchgear • Comparative analysis of conventional and modernized 500 kV switchgears • Web design of the scientific calculation interface by PHP		
5	List of graphic material (with mandatory drawings):		
	Scheme of modernized 500 kV switchgear		

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Abstract

86 pages, 30 pictures, 18 tables, 1 application, 1 scientific paper

KEYWORDS: SUBSTATION, SWITCHYARD, DISCONNECTING CIRCUIT BREAKER, OPTIC CURRENT AND VOLTAGE TRANSFORMERS, MODERNIZATION, WEB DESIGN, PHP, JAVASCRIPT, HTML

In this study, based on the global problems and expectations, the future of the substation design-modernization industry, the possibilities provided by digital engineering solutions, and the modernization procedure of a 500kV HV conventional switchyard have been analysed according to the referred principles. In addition, as a practical implementation of the thesis and as an alternative solution to the future demands of the substation industry, a web-based calculation interface is programmed to lead the substation design and modernization procedure effectually for students, engineers, transmission and distribution corporations, and substation equipment manufacturers. The analysis and the project also include key points of the web-based engineering solutions, the advantages of the substation design-modernization interface, and as a pioneer usage of the system, technical and economic aspects of the 500 kV conventional switchyard modernization process. The key points affecting the effectiveness of the proposed solutions, a brief description of the circuit solution, and its main advantages are highlighted.

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Introduction

The future of power engineering is shaped according to some main factors, such as: the unstoppable population of the world, globalizing technology, increasing energy demands, growing industrial needs, and the aidless planet trying to provide all important elements while carrying all the pollution that is created meantime. Between each of those factors, there is a complicated net of connections that may light the way of possible improvements to lead the design and development procedure more efficiently.

The relevance of the master's thesis topic is determined by the fact that since electrical power is one of the major parts of today's energy, and recognizing electrical substations as important nodes of electrical power systems and strengthening the connections between “primary principles of substation design and modernization procedures” might further some of the solutions of future energy needs. In the presence of global environmental problems triggered by increasing energy consumption and greenhouse gas emissions, states have started to act to reduce greenhouse gas emissions, with the encouragements about a series of policy measures to combat climate change. Encouragingly, the share of renewable energy generation globally recorded its fastest-ever increase. That continues the strong growth seen in recent years. Over the past five years, renewable generation has accounted for around 60% of the accretion in global power generation, with wind and solar power more than doubling [1]. Not only but also, grid businesses, the core business of the electricity industry, actively respond to climate change, establish energy conservation and emission reduction efforts, and promote the development of a low-carbon economy in the power industry [2]. Thanks to the policies that encourage a levelling of the net load curve, electricity costs and greenhouse gas emissions may reduce by maximizing the use of variable renewable energy. Such policies can also optimize and modernize existing generation, transmission, and distribution capacity, easing grid reinforcement [3].

According to scientific studies of IEA, modernizing grids offers a great and sensible opportunity to upgrade the elements at the same time. Over the next ten years, about one-fifth of electricity grids worldwide need to be replaced, with around 16 million km of existing distribution lines and 1.5 million km of transmission lines [4]. Since substations act as nodes between various power system elements such as transmission lines, distribution lines, transformers, generators, and loads [5], it is clear that substation design and modernization will take a very considerable place in this development-oriented atmosphere of future electrics. Concerning these various social, technical, economic, environmental aspects, potential of digital solutions (such as web-based substation design and modernization interface) and following improvements on the primary principles of substation modernization procedures will lead the sector to faster, safer, and cleaner results by understanding the scientific backgrounds of the designing basics, intensifying the abilities of the substation market, strengthen business to business connections and accelerating the planning, building or modernizing processes to a smarter level.

Corresponding to the purpose of the research, the high voltage switchgear of a conventional 500/220 kV substation was investigated within the scope of equipment cost analyses, digital substation technologies, future of the substation industry, and modernization applications. As the subject of the research, possible ways of modernizing the switchgear with different calculation methods are compared. In this regard, the tasks of the research were defined as:

1. Analysing the current state of the conventional substation design, its components, advantages, and disadvantages.
2. To choose the optimal technological, ecological and economical way for modernization of high voltage switchyard.
3. Creating a web-based interface to identify possibilities, as part of innovative substation engineering solutions compared to conventional methods.

The scientific novelty of the research was verified by the multidimensional analysis of the current situation in substation design and equipment selection, where the modernization of high-voltage switchgear is proposed, including cutting-edge switching devices and metering converters. Moreover, the practical significance of the work is complemented by the possibility of applying the obtained research both to solving the practical problems of updating substation components and for further research in this direction. Considering the validation of the work and the application of its results, the main topics presented in the thesis were used to develop a website that can generate a report to make the online design of a substation very practical. In addition, the report of the proceedings of an international conference was published and indexed in the Russian scientific database.

CHAPTER 1. SUBSTATIONS AS A PART OF ELECTRICAL POWER SYSTEMS

First of all, understanding electrical networks, transmission lines, and distribution lines take great importance in substation design. Because, as mentioned, substations serve as nodes between different lines and while the substation calculations are being made, the electrical inputs and outputs of the substation are actively included in the calculations. Of course, electrical transmission and distribution systems have their own computational techniques, but a substation designer must stick to basic principles. In this study, the basic features of transmission and distribution systems are considered both in manual calculations and in the design of the web-based calculation interface as a part of the practical implementation.

1.1 Basic Information About Electrical Power Systems

1.1.1 Evolution of Electricity Generation and Substations

While the existence of energy in many different forms is an advantage in a sense, the difficulty and inefficiency of storing energy, increase the importance of power plant enterprises, electricity generation, transmission, and distribution lines. In this context, various processes and technologies are involved in the generation and transmission of electrical energy to consumers. The most important of these processes is the production of electrical energy using other energy sources. Considering this order of priority, energy resources are listed as primary and secondary. Primary energy sources come in many forms, including nuclear energy, fossil energy, and renewable energy sources to be converted into secondary energy as electricity for the to consumers. Primary sources are called "primary" because they can be described as the initial portion (or raw material) of energy. They can then be converted to other sources such as electricity or fuel oil.

According to BP's research [1], the results demonstrate the importance of understanding the world's energy mix, given the share of global electricity production by type of fuel. As seen below (Fig. 1.1), coal and natural gas, as two fossil sources, exert a significant influence on the share of global electricity generation. Due to conventional technology and habits; coal and natural gas are preferred for decades for electricity generation [6]. However, the effects of CO2 emissions and greenhouse gases necessitate possible energy reforms. These reforms lead the sector to different solutions such as renewable sources or cogeneration systems to increase efficiency. Besides cogeneration systems, considering conventional power plants as the main energy suppliers, such as thermal power plants, the location of the power plant is defined according to the location of the demand and/or the route of the raw material [7]. If the power plant is not able to be located close to the raw material, probably it is located near a port or the easiest route of the raw material. On the other hand, renewable sources may be located in several locations according to the type of energy production. Of course, to achieve better results, the location should be defined according to the efficiency analysis. Still, the variety of renewable sources, their technology, and their acceleration may create significant effects on the substation industry. Furthermore, according to carbonbrief.org article from 2020 [8], “Electricity generated from coal has plateaued since 2014, so considering the huge investment and operating costs of power plants and renewable sources of energy mix graphs, the system runs fewer hours. This fact erodes coal’s bottom line. That is to say, it would now be cheaper to build new wind and solar than to keep running half of existing coal plants.” After 2 years of exploitation, it is possible to see that erosion. On the other hand, the increase in renewables is both the reason and the result. Either, a good start to the revolution of renewables and substation technology.

The next table (Fig. 1.2) shows the electricity consumption of Europe and part of the Asia by fuel type. According to the table darker tones represents more CO2 emissions than others. Next, share of global electricity generation by fuel type graph follows the electricitymap.org’ interface.

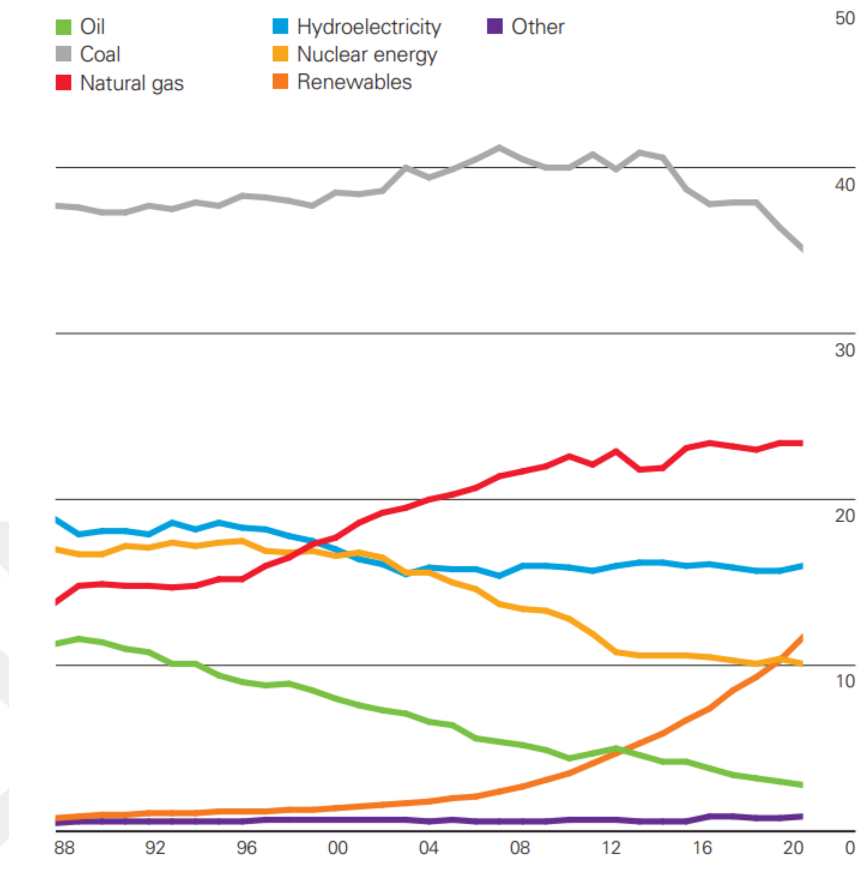


Fig. 1.1. Global share of renewables by fuel type

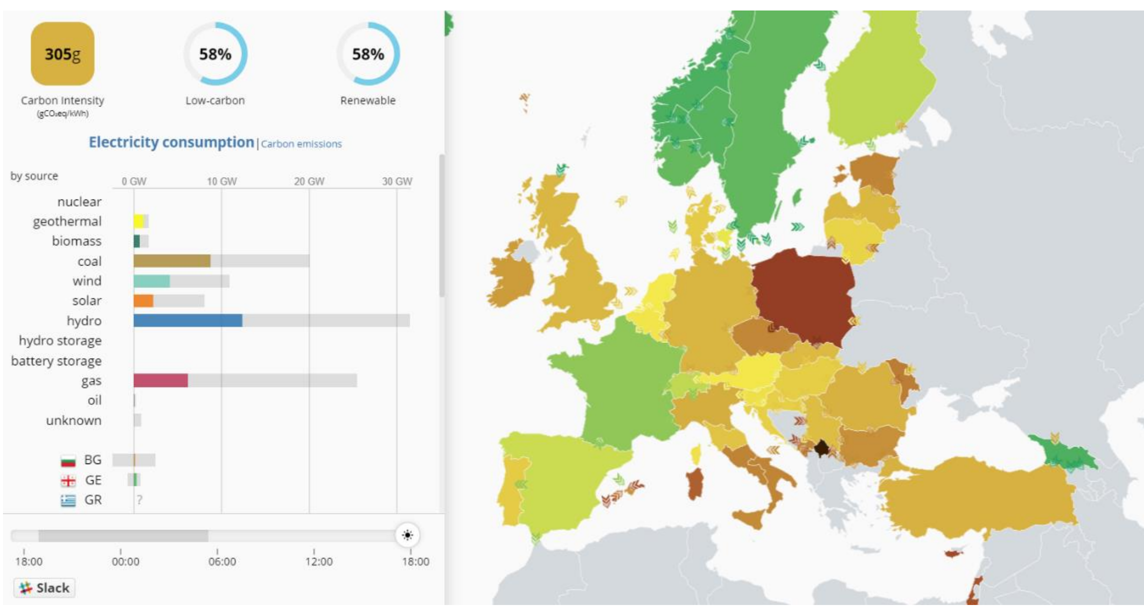


Fig. 1.2. Electricity consumption – CO2 Emission

1.1.2 Required Characteristics of an Electrical Network

Electricity transmission and distribution networks should be suitable for the uninterrupted and reliable transmission and distribution of electricity from generation to consumption. In ideal conditions, interruptions can be minimized when installation and maintenance are carried out periodically. However, in order for it to be reset, technical and practical applications must be done carefully. In fact, it is very difficult to provide uninterrupted electricity to consumers even during maintenance, but it is possible. In all of these processes, substation design is one of the most important considerations. Because substations generally provide flexibility, security, and sustainability to the networks they are located in. In order to achieve this, substation and network designs are of great importance.

There is a concept called metal fatigue in mechanical systems. With the effect of periodic stress on the same system, after a while, the metal deforms when it is well below the calculated fracture values. In order to prevent this, the factor of safety is taken into account in mechanical systems. Thanks to this safety factor, the system is used under a certain amount of its own limit and long-term problems are prevented. The maximum load that the system can carry is not applied to the system as much as possible in electrical networks, just like in mechanics. Problems are more likely to occur in a system operating at full capacity.

In this context, consumer categories are also taken into account in the design of the substation. The failures that will occur in the network should be foreseen, and the negative consequences should not affect the consumers.

- All consumers at the beginning of the line, in the middle of the line, and at the end of the line in distribution networks should be able to use electrical energy with the same characteristics (constant voltage and frequency). In order to achieve this, losses of power and changing power demand should be taken into account.

- Electricity networks must be able to respond to changing conditions and forces at any time. Therefore, power balance calculations should be made carefully and production should be kept at a certain level according to the instantaneously changing demand. Power balance calculations are one of the first steps in the design of the substation. So much so that the energy should be supplied not only to different voltage levels but also to different power characteristics at the same voltage value.

As seen, in electrical systems, the harmony between the different layers, which are connected to each other by strong technical and practical bonds, has huge importance. Although the amount and characteristics of the electricity used are different in residential, industrial and national areas, all of them are in connected to each other.

1.2 Design - Modernization Parameters and Standardizations

According to IEEE standards, substation means a specific area or a group of equipment, including transformers, circuit breakers, disconnectors, and buses, to switch power circuits for safe transmission, transformation, and distribution of electrical energy between sections [9].

1.2.1 Consumer Categories

Consumer Categories represent the power quality classifications created according to the specific demands and expectations of the consumers. Because each power system concerning consumers, goals uninterrupted power. Of course, maintenance purposes and different kinds of faults may cause interruptions. However, defining the possible problems of consumers that should be exposed to the results of any interruptions and designing the system according to the sustainable limits may lead both consumers and providers to better results. In this regard, according to different policies and standardizations, some categories are defined. As an example, and part of the project in Russia the three categories of power consumers are specified (Fig. 1.4).

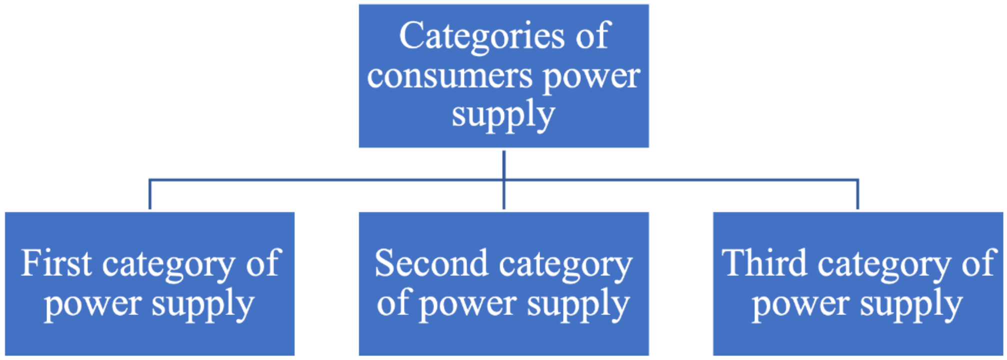


Fig. 1.3. Consumer categories

1st Category: Interruption of power supply may entail danger to human life, a threat to the security of the state, significant property damage, breakdown of complex technological process, etc [10]. Two independent mutually redundant power sources are obligatory for the 1st category of consumers with a power supply interruption in case of one of the power sources failure can be allowed only for the time of automatic switching. In addition, one special group of consumers is distinguished, the uninterrupted operation of which is necessary for an accident-free shutdown of production in order to prevent threats to human life, explosions, fires and damage to expensive basic equipment (three independent mutually redundant power sources are obligatory).

2nd Category: Interruption in work may lead to significant reduction of manufactured goods quality, or it may affect the normal life of a large number of citizens. This category is recommended to be supplied by electricity from two independent mutually redundant sources. Interruptions of the power supply are allowed for the time of switching or a period of time does not exceed 1 day in some cases.

3rd Category: May include shops, office buildings, domestic consumers, etc. The period in which the power supply of consumers 3 category of reliability can be stopped — not more than 24 hours and not more than 72 hours per year in total.

1.2.2 Main Requirements for the Substation Design

1. Reliable and high-quality uninterrupted power supply to consumers.
2. Implementation of advanced or cutting-edge design and environmentally safe solutions.
3. High level of quality of construction and installation works.
4. Economic efficiency - reduction of capital investments due to the use of optimized design solutions, reduction of occupied footprint, reduction of operating costs.
5. Optimal loading of power (auto)transformers.
6. The possibility of expanding the substation in the future.
7. Energy efficiency requirements in terms of the technologies and materials used to ensure the rational consumption of energy resources both during the construction (reconstruction) of buildings, structures, and during their operation.

1.2.3 Required Initial Data for the Substation Design

1. The location of the substation: in terms of the impact of climate, the contamination of external insulation, seismic conditions, thunderstorm activity, etc.
2. Loads with their voltages and categories of consumers.
3. The number, installed capacity and rated voltage of power (auto) transformers.
4. Levels and limits of voltage regulation on substation buses.
5. The number of connected lines with a voltage of 6 kV and above and their loads.
6. Recommendations on the schemes of the substation.
7. The redundancy of auxiliary system supply (independent sources).
8. Neutral grounding of power transformers.
9. The number and capacity of surge arresters in 110 kV and above networks.
10. Calculated values of single-phase and three-phase short-circuit currents and measures of their limitation.
11. Recommendations for the ferro resonance prevention and for high-frequency switching over voltages limiting on electrical equipment in the 110 kV and above [11].

1.2.4 Substation Elements

1.2.4.1 Power Transformers – Auto Transformers

Transformers are electrical machines that change the voltage and current values of electrical energy according to the demand without changing the frequency. Transformers increase the voltage value produced in the power plants and reduce it in the step-down substations located near or inside the city centers. Power transformers are manufactured as two-winding transformer, with split low voltage windings transformer, three-winding transformer, and autotransformer [10]. Transformers are main elements of substations. An auto transformer is used in the thesis project, due to the following advantages. Transformers where some or all of the primary winding is used as a secondary winding and both windings are under the influence of the same magnetic field are called auto transformers. As we know, normal transformers had primary and secondary windings. However, auto transformers have only one winding. This winding acts as both primary and secondary. Voltage conversion is done through this winding. Since the primary and secondary circuits of auto transformers are the same winding, they are on the same magnetic circuit. The magnetic field formed in the primary part is directly transmitted to the secondary part. Thus, leakage fluxes are considerably reduced and their efficiency is increased. Auto Transformer does not change the frequency. Increases or decreases current and voltage. If it lowers the current, it increases the voltage; if it lowers the voltage, it increases the current. It transfers power to the extent of its efficiency (e.g. 95%, 97%). The input power is roughly equivalent to the output power. So, it doesn't raise or lower the power. Only 3-5% loss occurs in terms of efficiency. This does not mean that transformers have a power reduction feature. These losses occur as heat energy and require cooling processes. Since the working principle is different from normal transformers, less iron and copper are used. This provides the transformer's lightness, cheapness and high efficiency. Also, the regulation of auto transformers is better than two-winding transformers. It is highly preferred in high voltage systems [12].

1.2.4.2 Control and Protection Elements

Circuit breakers and disconnectors are used as control elements that perform operations such as opening and closing of power lines in medium voltage and high voltage systems in switchyards. Although these two control elements basically do the opening and closing work, they show great differences in their structures, the place they are used and the way they are used. On the other hand, protection elements are circuit elements that protect or inform against heat and other negative effects caused by high fault currents and voltages in high voltage switchgear facilities and power transmission lines. The protection elements used in high voltage power transmission lines and substations are as follows:

Ø Fuses
Ø Surge Arresters
Ø Bird Repellents
Ø Circuit Breakers
Ø Disconnectors
Ø Protection conductor
Ø Grounding
Ø Protective Relaying

Fuses: It prevents the occurrence of larger faults by preventing the reflection of the fault occurring at any point of the high voltage networks to other parts by the protection element above the faulty operating element.
Surge arresters: They prevent the effects of excessive and harmful high voltage shocks that occur as a result of accidents such as line faults, lightning strikes and breaker tripping in high voltage facilities. In addition, it is a device that prevents the destructive effect of walking waves that occur in transmission lines. It is the element that is connected between the conductors and the ground in the circuit and protects all kinds of electrical devices against temporary over voltages.

Bird Repellents: It is not desirable to see birds make a nest on the upper part of the connection point of the insulators on the sleepers located on the poles carrying the high voltage energy lines. For this reason, a U or V shaped asparagus material is mounted in this part of the sleepers for the birds to be placed, and it is tied with a galvanized thin binding wire crosswise. Otherwise, bird droppings cause a ground fault by short-circuiting the insulators. Bird repellents are highly recommended and necessary, given the fact that today the annual cost of bird cleaning and repair is around $300,000 in total for substations worldwide [13].

Circuit Breakers: It is the device for breaking the load current and short circuit currents in high voltage and high current switches. It is a device that opens and closes in short circuits and under load in high voltage transmission lines. Breakers can be three-phase or single-phase controlled. They are switches that can open and close quickly and safely under load, that is, when current is drawn from the circuit at medium and high voltages. It is produced internally and externally. Breakers are manufactured in different types according to the environment in which the arc is extinguished. These are:

1) Air blast circuit breaker (obsolete)

2) Oil circuit breaker (MOCB – up to 35 kV, BOCB – up to 220 kV)

3) Vacuum circuit breaker (up to 110 kV – around the world, up to 35 kV – in Russia)

4) SF6 circuit breaker (up to 1000 kV)

Gas breakers are mostly used in medium and high voltage substations. The main reason for this is the rapid interruption of the arc that occurs during opening and closing and the absence of a fire hazard. Circuit breakers are also classified as follows based on the voltage level of the installation. In the project high voltage circuit breakers (> 72 kV) were applied according to initial data.

Disconnectors: Opens and closes in medium and high voltage systems when unloaded. The opening and closing process is visible. It is also used in grounding the circuit. Disconnectors are carefully chosen according to the power characteristics of the system. There are several types of disconnectors. These types differ according to the usage, footprint, reliability, safety and voltage level.

Protection Conductors: They are braided steel conductors and they function to attract lightning that may fall on energy transmission lines and transfer them to the ground. The protection wire is drawn on the top of the poles above the overhead lines by connecting with small insulators manufactured for the protection wire.

Groundings: Making a conductive connection between a point of the operating current circuit or the non-current conductive parts of the facility and the ground is called grounding. It is obtained by embedding copper or galvanized rods or sheets in pits dug near the building and near transmission lines. The grounding circuit ensures that in case of failure in electrical installations, short-circuit currents pass through in a way that will not be dangerous for human life.

Protective Relaying: There may be various faults in substations and energy transmission lines. These faults can be caused by short circuits, undesired high voltages, etc. High and medium voltage facilities must be protected in order to prevent damage that may occur as a result of faults. Relays used to notify faults in energy transmission lines and substations are called protection relays. It notifies the relays of faults via audible or illuminated circuit elements. Others open circuits according to the sizes they set without notification. It is used together with relays, circuit breakers, and notification systems to prevent faults in the networks effectively and economically.

1.2.4.3 Insulators

Network materials used in energy transmission overhead lines, which are used to fix the poles, to carry the conductors and to isolate the earth and the pole against the conductors. In substations, insulators are used for carrying conductors and also for fixing connections. Insulators are made of porcelain, glass, epoxy resin with high resistance to electric current and resistant to high temperatures.

1.2.4.4 Instrument Transformers

Measuring instruments cannot be directly connected to the network in order to measure the desired values at high voltage. It is difficult to provide insulation at suitable values for high voltage and to manufacture a device of appropriate size. Therefore, measuring instruments and protection relays need an auxiliary element to connect them to the circuit. Elements that keep current and voltage values at desired values are called measurement transformers. Measurement transformers are divided into two as current and voltage transformers.

Current Transformer: It is a measurement transformer that reduces the primary current at a certain rate and the phase difference between the primary current is approximately zero degrees. The circuit is connected in series.

Voltage Transformer: It is a transformer that reduces the high voltage at the desired rate and the phase difference between the primary and secondary voltages is approximately zero degrees. The voltage transformer is connected in parallel with the circuit.

1.2.4.5 Conductors and Cables:

Measurement control cables: small cross-section, suitable for normal operating conditions are used for signal communications. If it is to be operated under heavy operating conditions, cables manufactured with oil resistant and special outer sheaths are used. Fine stranded copper conductor is used.

Underground conductor connections cables: Underground copper cables are generally used as protothen-x insulated cables with copper and aluminum conductors. Protothen-x insulated cables are preferred for medium and high voltages. It is produced from high molecular pure polyethylene with organic peroxide additive.

Cables used in electricity transmission and distribution: The conductor to be used in high voltage overhead line connections should both carry energy and be mechanically durable. The following criteria are taken into account when grouping the conductors to be used according to voltages.

1.2.4.6 Measuring Instruments

The measuring instruments used in the substation are connected to each feeder separately and used to record the required values and inform the responsible table in the substation. The measuring instruments used are fed by current and voltage transformers. These measuring instruments are located on the panel inside the substation and also on the panels next to the required device when necessary. The measuring instruments used in the substation are Ammeter, Voltmeter, Wattmeter, Cosine meter, Active counter, Reactive counter, Oil pressure for transformer, Distance relay, Buchholz relay, Differential relay and many other types of relays.

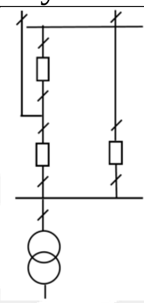
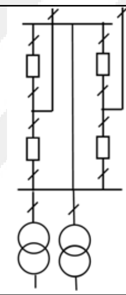
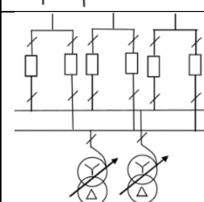
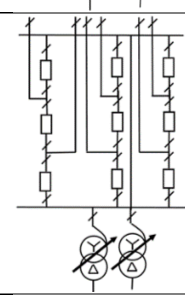
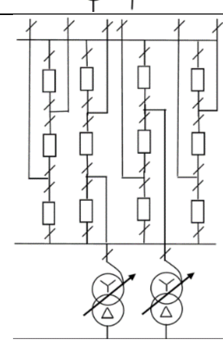
The measuring instruments used can be used numerically as well as pointers. In addition, in newly established substations, it is preferred that the measuring instruments are more recording features [14].

Generally, the way of designing or modernizing the substation is mostly about the major elements such as autotransformers, disconnectors, and circuit breakers. However, it is also required to define and compare the different solutions for measuring and controlling systems considering the switchgear scheme layouts (Table 1.1Table 1.1).

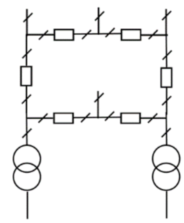
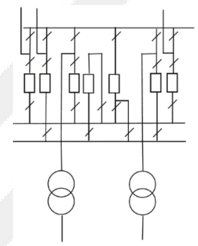
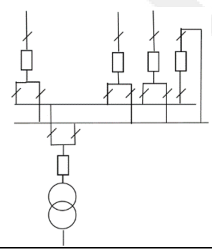
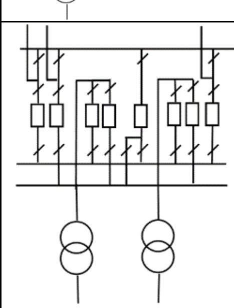
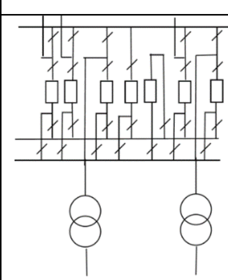
1.2.4.7 Switchgear Scheme Layouts

Table 1.1

Switchgear Scheme Layouts

Name of the scheme	Voltage, kV	Number of bays	Switchgear Scheme Layout	Recommendation
1	750 kV 500 kV And For Special Applications 330 kV	3		As the first stage of more complicated scheme
2		4		As the first stage of more complicated scheme
3		3-4 lines+2AT		100% redundancy of transmission lines connection
4		5 -10 lines+2AT		When it is required to connect transmission line by two circuit breakers
5		6-10 lines+2AT		High reliability requirements

Continuation of Table 1.2

Name of the scheme	Voltage, kV	Number of bays	Switchgear Scheme Layout	Recommendation
6	330 kV 1-5+	6 (4 lines+2 transformers)		
7	220 kV	5 and more		When the 100% continuity of power supply is required (no interruption)
8		5 and more		Power supply interruption is possible for switching time
9		5 and more		When the 100% continuity of power supply is required (no interruption) and extremely high requirements to power transformers operation
10		5-15		When the 100% continuity of power supply is required (no interruption)

1.3 Substation Technology and Costing

The usage of technologies in electrical installations creates a significant improvement, in terms of increasing reliability, safety, operational flexibility, and finally economic efficiency. Nevertheless, when using cutting-edge equipment in the designs of switching devices, instrument transformers, and conductors, the expected effect involves huge economical costs [15].

During the construction of a new substation, the greatest costs are associated with the construction of equipment. Moreover, for air-insulated substations with a high level of voltage like 500 kV, the construction cost will be about 63% of the total cost. For indoor substations, the percentage will be even higher, reaching 68% [16]. The planning a substation to been build or modernize with non-conventional equipment creates significantly useful results. Especially, considering the less footprint of the non-conventional instrument transformers and disconnecting circuit breakers (which may be up to 90%), the price of land allocation for the substation can be decreased successfully as a major part of investments. The decreased footprint will lead the design or modernization process to more advantages. The amount of the reduction for construction and installation will reach up to 25% of total construction for conventional substation components.

Considering the switchyard of 500 kV substation only, the share of equipment cost is defined as about 72%. The resting 28% percentage of the cost comprises only the construction cost. By comparing this value with the construction percentages of the total substation and considering the first or previous construction expenses of the conventional substation as an evident loss, modernization of the switchyard only will become an affordable, sensible, and leading option. That, leading the investments to cover the equipment itself firstly, will keep the price-performance ratio of the modernization at a sensible level. Therefore, to increase the efficiency and reliability of existing substations, it is advisable to modernize the facility, besides building a new one.

On the other hand, the economic analysis findings outlined that, in some cases, the construction of a new substation may be more profitable than updating an existing one. According to various estimates, the deterioration of the equipment of Russian substations today averages 50%. Considering the total expenses, rebuilding the substation might create more reliable and sustainable results. Whereas, a partial reconstruction of the existing substation with a moderate degree of deterioration in general, is more than appropriate in the current economic conditions. Also, since the replacement of technically and physically obsolete equipment is necessary during each reconstruction, the increase in the reliability and the continuity of the power supply, make the procedure certainly preferable. In the light of the given information and findings, besides comparing rebuilding and modernizing, focusing on the modernization costing analysis might help define the details of future plans for substations.

As a primary goal of power systems, all inlets, outlets, and intermediate steps of a substation should be operated according to the limitations defined according to the policies, demand expectations, capacity characteristics, and the system's physical situation. Furthermore, as well as all common forms of industrial energy, electricity might be dangerous in case of running out of control. Even with an optimistic view, any possible failure may interrupt the system and create indirect problems. Each failure should be predicted and compensated precisely to prevent an accident or interruption. Such as all power systems, to keep the substation safe and under control, the design of secondary systems such as measuring and controlling systems requires significant attention. The industry of instrument transformers (IT) as a fundamental member of measuring and controlling systems provides the safe, reliable, and inventive solutions for modern needs. Nevertheless, considering the costings and estimating the share of instrument transformers in all substation investments will be defined as 1-3%. Surprisingly, besides the high costs of other equipment with the higher technology, new generation instrument transformers provide new technology at less cost.

In addition, the modern technology of non-conventional equipment will make the process more sensible based on reduced costs for maintenance, reduction of utilization costs, refusing the copper cables, elimination of the analogue-digital converters, and modernized controls over the system's working factors. Taking into account all of these, the possibility to increase the speed of operation of protective relaying will be higher and the differential protection will operate with higher level of sensitivity.

Moreover, in accordance with the IEC 61850 standard (International Electrotechnical Commission), self-diagnostics of the DCB plus FOCS solutions; will make the simultaneous control of the circuit breaker, isolator, and current transformer possible to increase the reliability and create high accuracy. In this regard, in the case of open secondary circuits, personnel safety will become more reliable.

As in all engineering fields, the cost-performance relationship should be kept at a reasonable level in the design or modernization of the substation. Fortunately, there is serious competition among manufacturers and it is possible to find better solutions in the purchasing process. Because especially for the secondary equipment such as fiber optic cables, optical sensors, and data cables, more items will be needed. For example, for a 500 kV switchyard three fiber optic cables will be required in general. These will be for protective relaying, backup protection, commercial accounting, and other measurements [17].

Up-to-date and rather obsolete technologies may bring some risks due to practical experiments or fatigue. However, with new technology, it is much easier to define and solve possible problems. For example, according to the experience of optic IT at the "Tobol" 500 kV substation, there was a malfunction of optic sensors about phase shift in measured currents compared to conventional IT [18]. The problem has been defined and solved. In addition, in "Tobol" 500 kV substation there are 10 SF6 circuit breakers and 25 free-standing center break disconnectors. Changing them for DCB may be sensible but the mentioned parameters about costing and performance should be considered deeply and following the certain policies in its modernization processes.

According to the Russian Power Grids Company "Rosseti" requirements, one of the largest electricity grid companies in the world, the payback period for digitalization is recommended to be limited by 10 years. At the same time, despite their higher costs, pursuing eco-friendly solutions, provides better results for nature because SF6 IT is not environmentally friendly for sure. Also, the operating costs of monitoring gas leakage, the danger of opening secondary circuits at the CT, maintenance, utilization costs, construction costs, the need for an ADC for compliance with the IEC61850 standard, large weight, and size make them less efficient than non-conventional instrument transformers [19].

1.4 Forecasts about the Future of Global Substation Industry

According to the report published by Global Market Insights in 2020, Digital Substation commercial volume, which was 96 billion USD in 2020, is expected to exceed 130 billion USD in 7 years. This 7-year increase expectation paves the way for digitalization in the substation market. So much so, that the CAGR (compound annual growth rate) is over 6%. Improved product specifications will positively impact technological developments in line with the growing demand for reliable and secure electrical infrastructure in commercial, utility, industrial, and residential establishments. Additionally, government regulatory policies and updates to standard product configurations for installers and end-users will provide a positive business outlook. The continued trend toward electrification adoption across off-grid networks and renewable electricity infrastructure will positively impact technological improvements. The energy R&D sector is expected to experience a significant increase due to the increasing demand for efficient transmission and distribution control systems. With the lack of efficient electricity networks in developing countries, efforts to expand the existing infrastructure are increasing at a level that meets expectations.

The positive trend of end-users towards substation installation to provide uninterrupted power supply and the increase in power grid life expectancy will further strengthen the industry dynamics. In addition to the report, when the worldwide pandemic in 2019 is taken into account, it can be understood that the expected increases in the use of renewable energy resources and in the substation market are in a mutualistic relationship [20]. Last but not least, the analysis divided it into different branches as in the table below and focused on all branches separately. This scheme (Fig. 1.4) proves the importance of substation equipment.

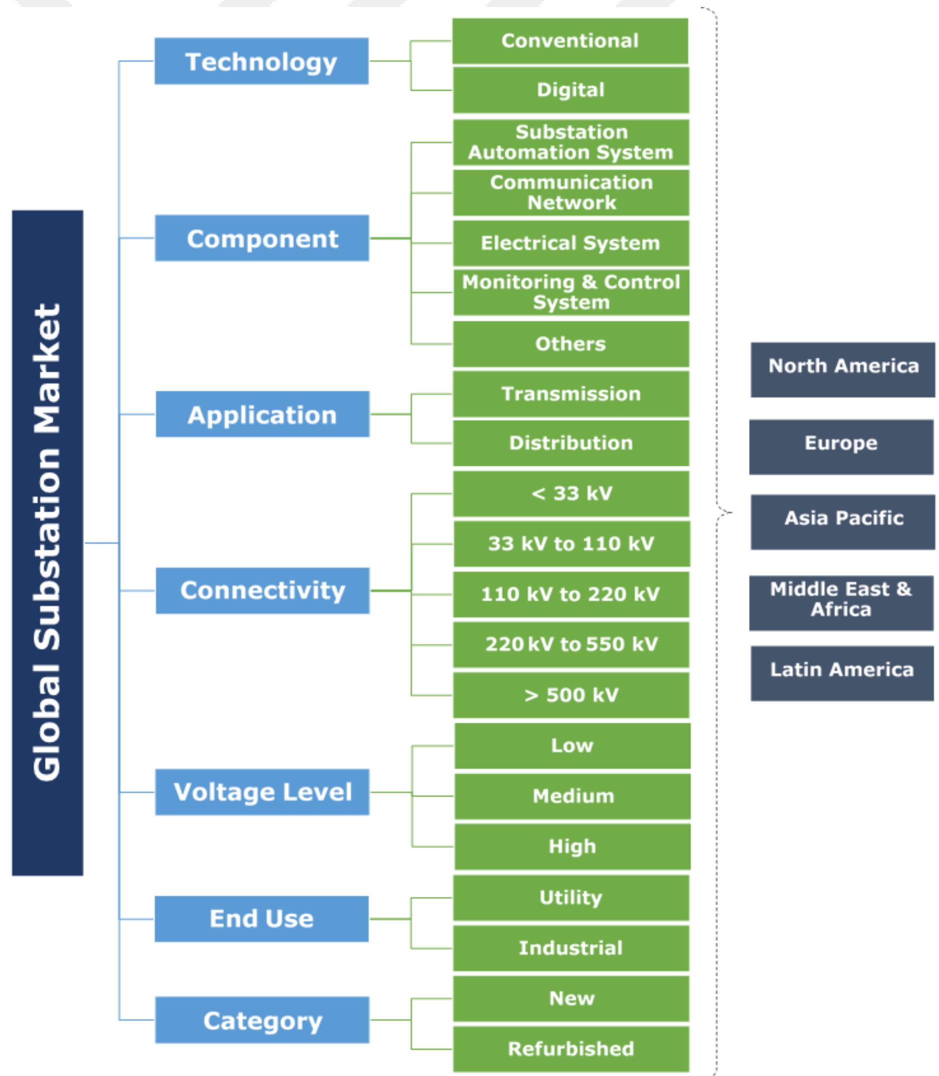


Fig. 1.4. Scheme of the Substation Market Analysis

CHAPTER 2. ONLINE SUBSTATION DESIGN AND MODERNIZATION TOOL

A website with an interface that leads the users;

- to enter the initial data of the electrical power system,
- to see the basic principles of substation design or modernization,
- to define the required values for each element,
- to choose the elements according to the required values,
- to define the approximate cost, lifetime, efficiency, reliability and scheme layout,
- to compare and analyse the different effects of the combinations of the elements,
- to generate the report that includes all useful information regarding the designing or modernization procedure.

2.1 Goals of the project

- Creating a connection between manufacturers of substation elements and the substation builders such as companies and/or engineers.
- Clarifying the calculation methods of the substation design procedures for the manufacturers, designers, engineers, students and teachers.
- Creating better market experience for manufacturer companies, designer/builder companies and customers.
- Minimizing the possible faults and defining better results by calculating all the values according to the algorithm based on scientific formulations and accurate database parameters.
- Generating reports, scientific graphs, costings and analytics for manufacturer companies, designer/builder companies, consumers and scientists.
- Improving itself by saving the data of user preferences and habits to create business intelligence analysis.

2.2 The basic working principle of the interface

- User opens the webpage substationdesigner.com
- User choses one of the following primary options

  - Substation Design
    - Interface asks user to enter the initial data about the source, load and scheme. (Such as voltage level, busbar layout and so on).
    - Interface asks about priorities, such as reliability, flexibility and costing.
    - Interface shows suggestions suitable to the initial parameters, for each element, one by one.
    - Interface generates a report with the explanations, comparisons, utilities, dimensions of occupancy, minimum frequency of maintenance, possible improvements, costing and busbar layout, etc.

  - Substation Modernization
    - Interface asks user to define the element to modernize.
    - Interface asks user to enter the initial data about the source, load, scheme layout and all nameplate parameters of existing elements.
    - Interface asks about priorities, such as reliability, flexibility and costing.
    - Interface shows products as suggestions suitable to the initial parameters, for the elements, one by one.
    - Interface generates a report with the explanations, comparisons, utilities, dimensions of occupancy, minimum frequency of maintenance, possible improvements, costing and footprint reduction.

2.3 Scientific usage of the interface

- Interface clarifies the basics of the substation design procedures for the students as future power engineers and for the instructors as guides.
- Interface generates reports, comparisons scientific graphs and analytics for scientists.
- Interface improves itself by saving the data of user preferences and habits to create business intelligence analysis.

2.4 Industrial usage of the interface

Thanks to the interface,

- A substation designer company or engineer will have a chance to choose the elements easily and accurately according to the parameters without making complicating calculations.
- A manufacturer of any substation elements will be able to target its products only by entering the parameters into the system.

2.5 Branding (substationdesigner.com)

Fig. 2.1. Logo design of substationdesigner.com

Logo design with an elegant font type with futuristic colour palette. (Fig. 2.1,Fig. 3.15)

Font Type: Montserrat Bold

Main Color HEX Code: 4F5B67

CHAPTER 3. PRACTICAL IMPLEMENTATION

The practical implementation consists of three parts:

In the first part, key points of substation switchgear modernization are examined according to main factors and different scenarios are compared for the modernization of 500 kV HV Electric Substations via dcbsubstations.com developed by Hitachi, which can be an example of digital solutions in substation design and modernization processes. As a digital solution, there was no need for manual calculations in the analysis made on dcbsubstations.com. So much so that these calculations can be done by the interface itself.

In the second part, the principles and calculations are shown step by step with detailed explanations and are implemented for both the existing modernization procedure and arithmetical design of the following substation design interface.

In the third part, an interface that can be used for a similar purpose with the interface developed by Hitachi, but can make the necessary calculations not only with disconnector circuit breakers but also in the selection of all substation equipment with a single button, has been designed and the same modernization calculations have been made through this substationdesigner.com interface.

In order to make a comparison with substationdesigner.com, which is still under construction, the modernization process was first discussed with the analyses obtained from dcbsubstations.com.

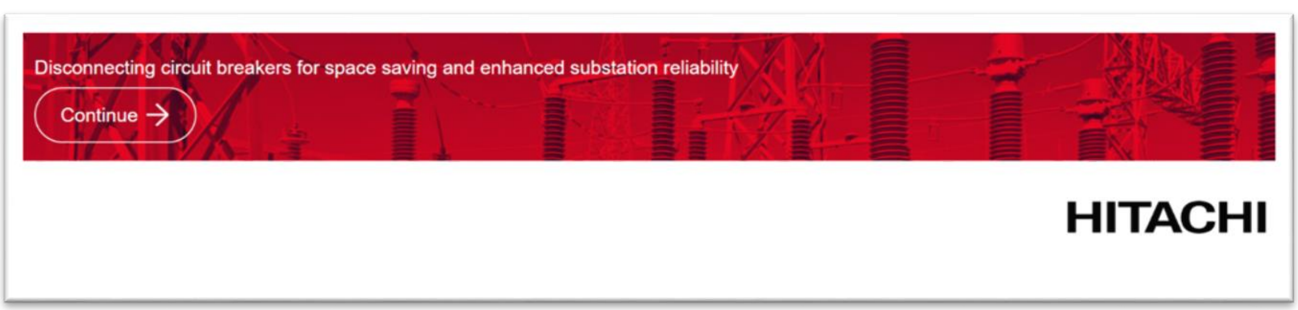


Fig. 3.1. The welcome page of the dcbsubstations.com

3.1 Modernization of 500 kV Switchgear by DCB Solutions

In modern big cities all around the world there are severe problems of both reducing the switchgears footprints of power stations and substations, and increasing the reliability of their functioning. Various approaches to solving these problems are proposed and implemented:

- replacement of conventional air insulated substations with underground constructures when it is required;
- replacement of conventional switching devices with more advanced designs;
- replacement of conventional measuring current and voltage transformers with state-of-the-art equipment.

Substation construction is a complex and responsible technical process that requires rigorous design and engineering preparation, compliance with regulations, safety and reliability requirements. When choosing a place for construction, the terrain and conditions for overhead transmission lines routing have to be studied in details. In mountainous and hilly areas, the work becomes more complicated.

As mentioned before, during the construction of a substation, the greatest costs are associated with equipment. If we consider only the 500 kV switchgear, then the share of equipment costs will be 72%. To increase the reliability of existing substations, it is advisable to modernize the facility. Replacement of technically and physically obsolete equipment is necessary during each reconstruction, thereby increasing the reliability and continuity of power supply. According to various estimates, the deterioration of the equipment of Russian substations today averages 50%. The economic analysis findings outlined that the construction of a new substation may in some cases be more profitable than updating an existing one. However, a partial reconstruction of the existing substation with a moderate degree of deterioration is more than appropriate in the current economic conditions [21].

It is proposed to retrofit the 500 kV switchyard at the existing substation (Figure 4.2.) with the replacement of air blast circuit breakers and free-standing horizontal center break disconnectors with modern disconnecting circuit breakers (DCB), as well as the replacement of measuring oil-filled transformers with modern optical current and voltage sensors [22]. Initially, the 500 kV switchyard was arranged according to a scheme with two circuit breakers per three connections. Six single-phase autotransformers ASOFAF-167000/500/220 and six transmission lines are connected to the switchyard. Air blast circuit breakers VVBK-500, disconnectors RNDZ-500, measuring transformers of current TFZM-500B and voltage NKF-500 are installed at the switchyard. A fragment of a 500 kV switchgear is shown in Figure 4.3.

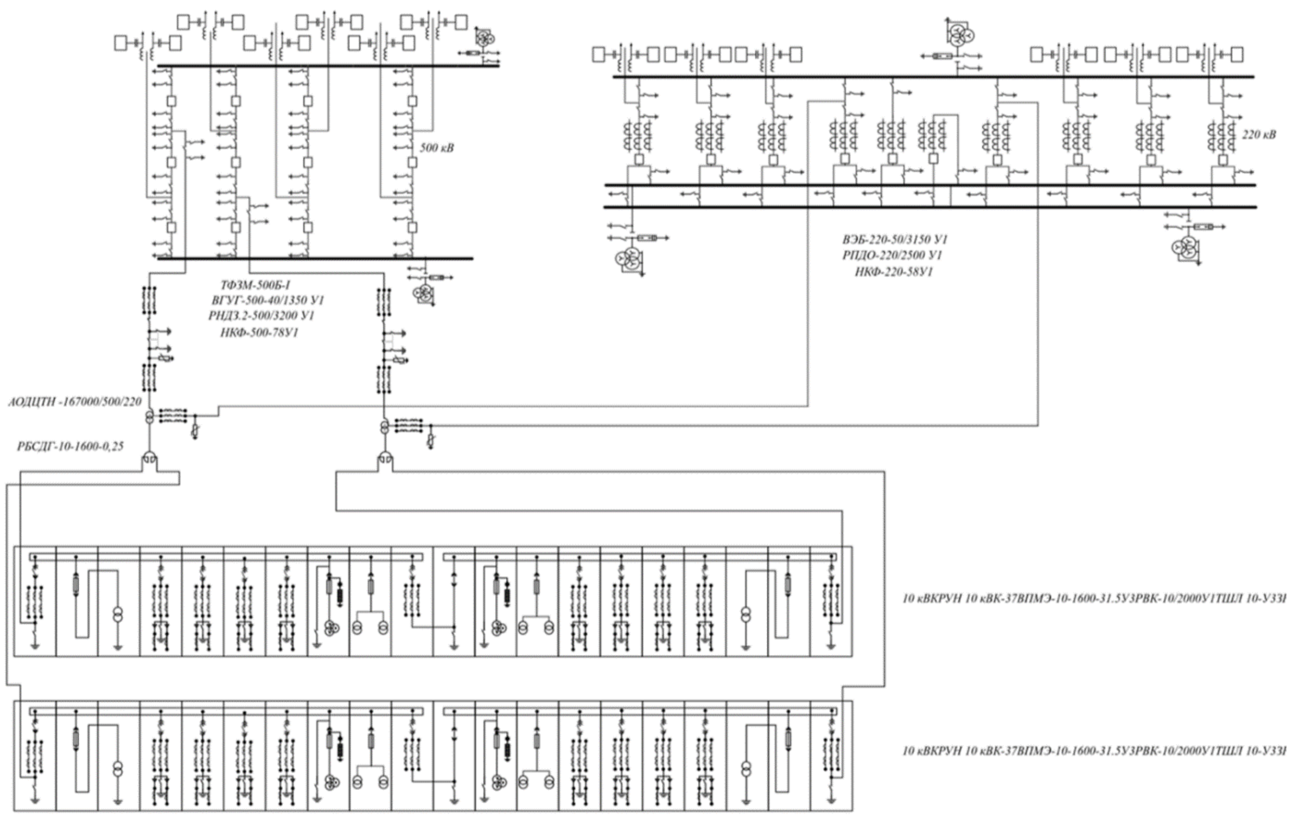


Fig. 3.2. Initial scheme of 500/220 kV substation

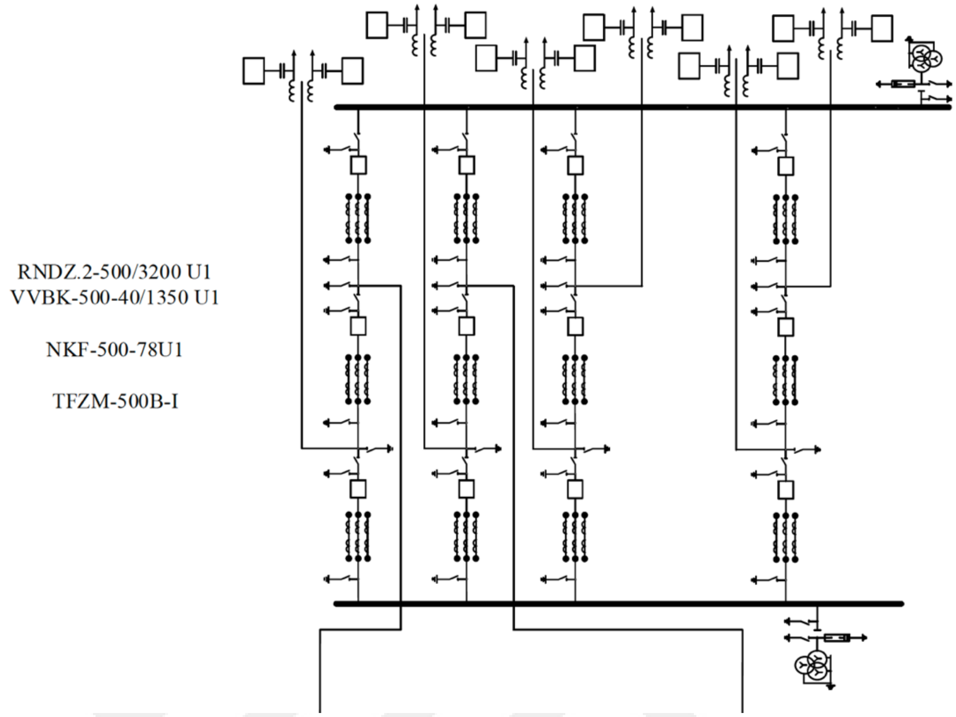


Fig. 3.3. Switchyard 500 kV before modernization

For 500 kV switchgear modernization was selected:

- disconnecting circuit breakers VGT-UETM 500 Russia,
- optic current and voltage sensors for 500 kV by Profotek, Russia.

The modernized switchyard is represented at Figure 4.4.

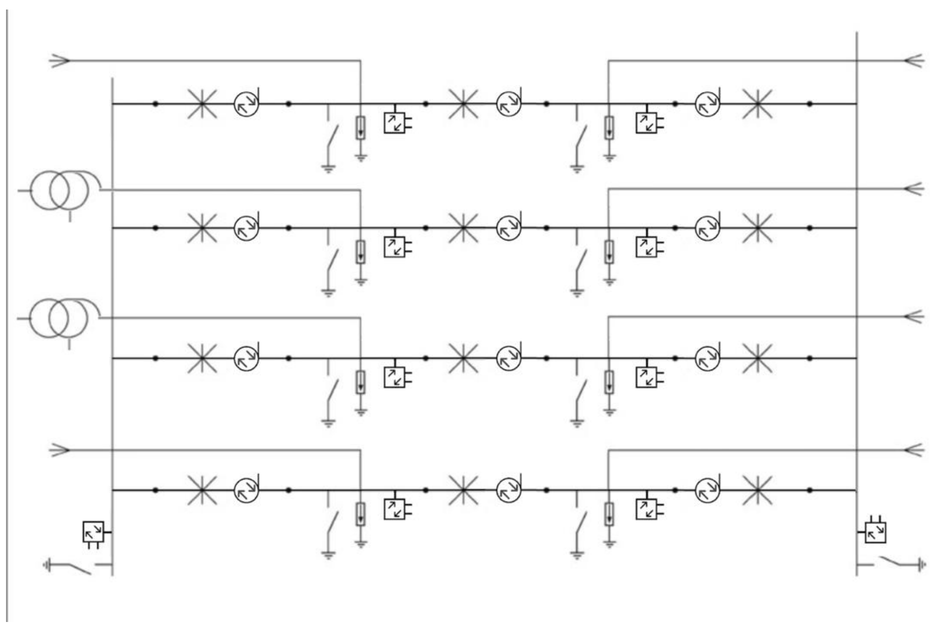


Fig. 3.4. Switchyard 500 kV after modernization

There are 6 lines and 2 autotransformers as the HV bays 500 kV. Therefore, there are 8 bays in total. The main scheme of switchgear layout of the substation is selected taking into account the future development of electric networks of the power system. Basic requirements for switchgear scheme layout:

a) the scheme must provide the reliable power source to consumers in all operating modes;

b) the scheme should ensure the reliable transit of power through the substation;

c) the scheme should be simple, economical and provide automatics for restoring power to consumers in a post-emergency mode without the personnel involvement;

d) the scheme should allow the step-by-step development without significant reconstructions and interruptions in consumer supply;

e) the number of simultaneously tripping switches within one switchgear should be no more than two in case of line fault and no more than four in case of the transformer fault. According to aforesaid the 3/2 scheme is chosen for the 500 kV switchgear.

3.1.1 Conventional 3/2 Circuit Breaker vs 3/2 Disconnecting Circuit Breaker

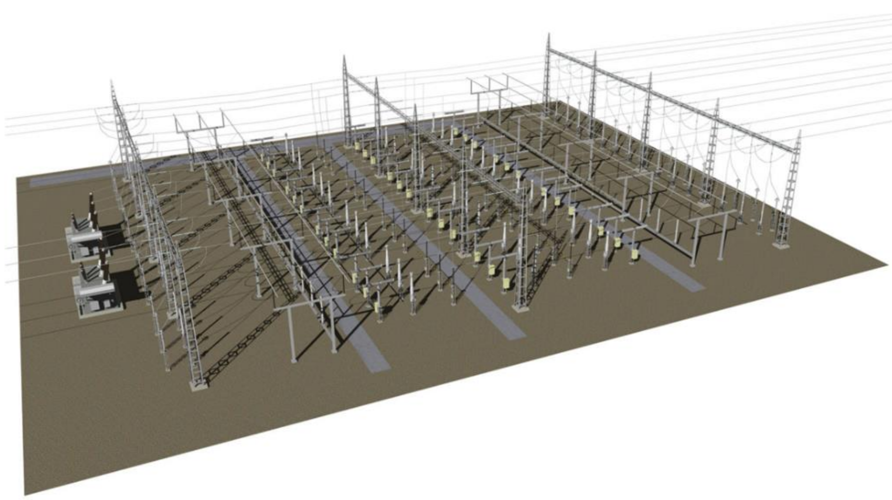


Fig. 3.5. 3D image of DCB solution (with 3/2 DCB)

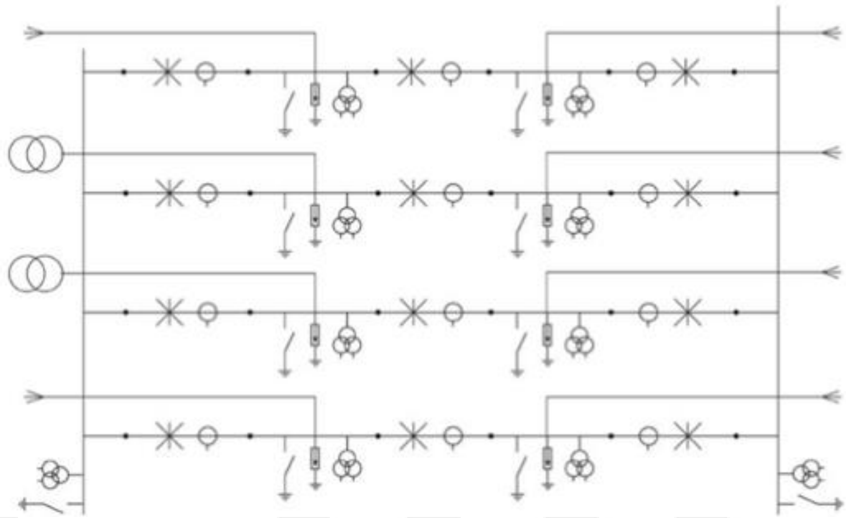


Fig. 3.6. Single line diagram of ring bus scheme

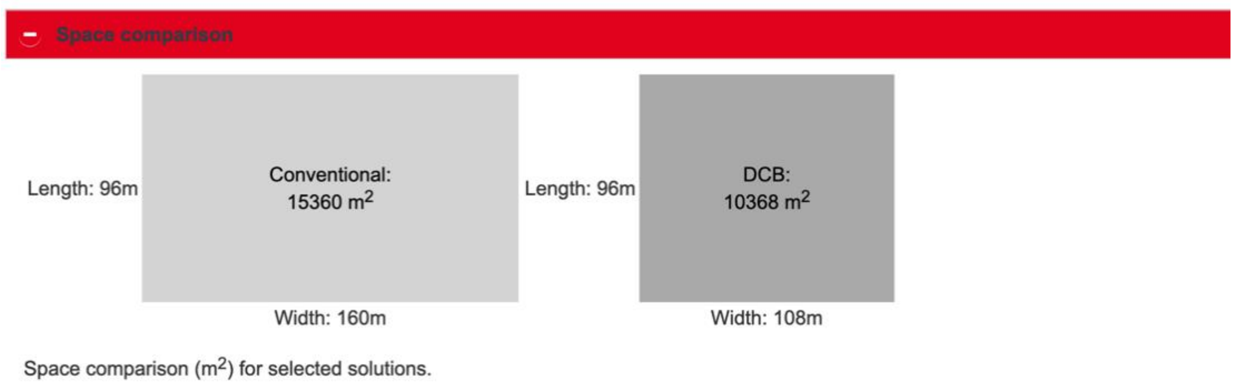


Fig. 3.7. Space Comparison (with 3/2 DCB)

To compare the footprint of the substation before and after reconstruction, an online simulator of ABB Hitachi companies was used [23], which allows to pre-evaluate the effect of replacing both the components of the switchyard and the switchgear layout itself. The integration of DCB in substation make it possible to reduce footprint of 500 kV switchyard for about 32% with realization 1½ CB per one connection. It would be possible to reduce switchyard footprint up to 90% in ring layout arrangement.

3.1.2 Conventional 3/2 Circuit Breaker vs DCB Ring bus

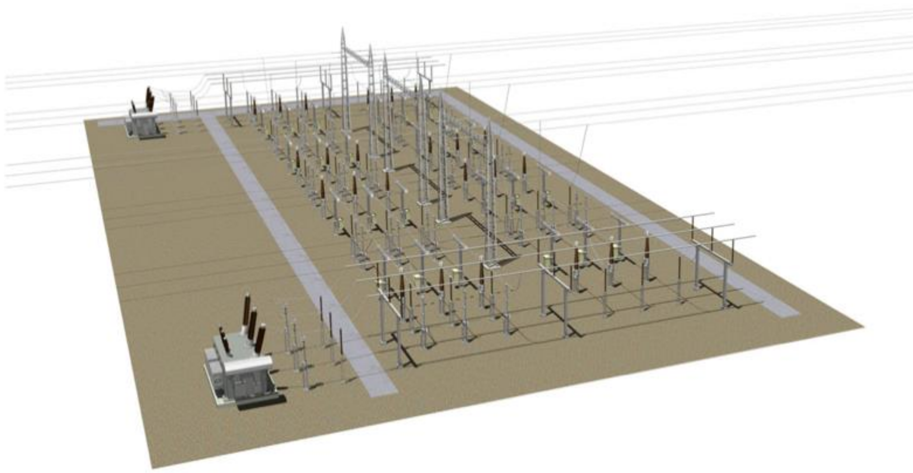


Fig. 3.8. 3D image of DCB solution (with DCB Ringbus)

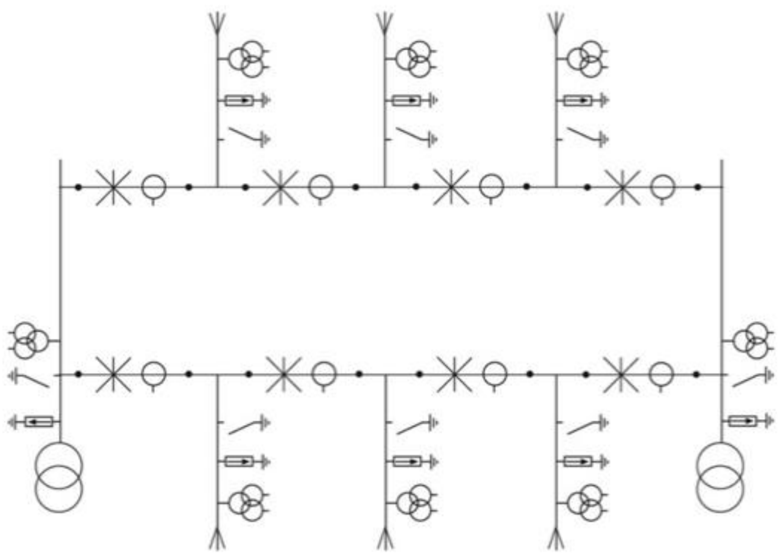


Fig. 3.9. Single line diagram of ring bus scheme

But flexibility of the ring scheme is less compared to 1½ CB per one connection, especially taking into account the quantity of bays. In addition, reliability of the scheme was increased because of refusing free standing disconnectors as component with high tendency to fail and consequently low reliability indexes.

Application of optic CT and VT follows the tendency of power industry digitalization nowadays. These cutting-edge devices are capable to withstand extremely high dynamic and thermal currents, temperatures; eco-friendly; less weight and size compare to free standing SF6 instrument transformers [17, 18].

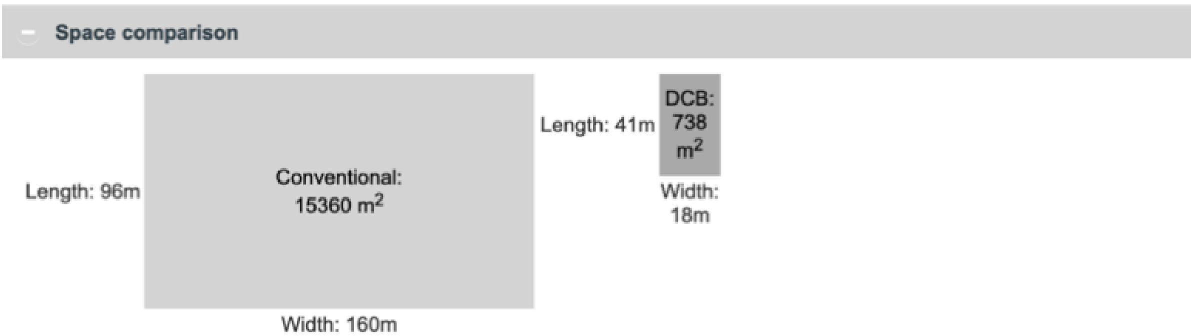


Fig. 3.10. Space Comparison (with DCB Ringbus)

Lastly, as seen below the conventional (Fig. 3.11) and non-conventional (Fig. 3.12) instrument transformers are compared according to the sizing.

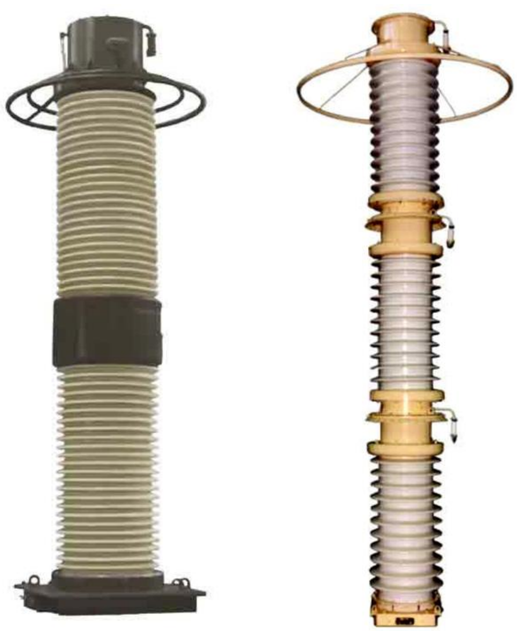


Fig. 3.11. Conventional CT and PT

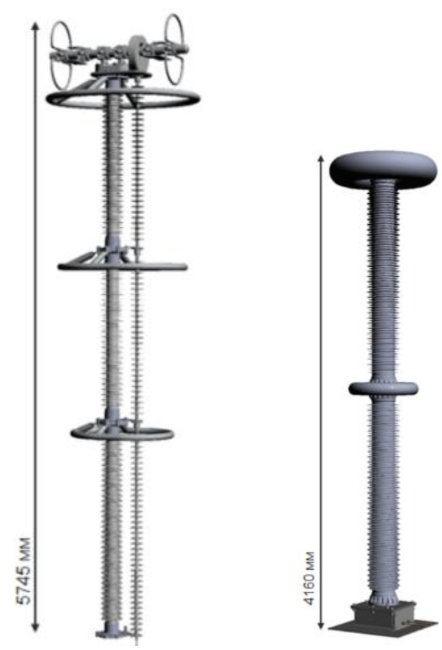


Fig. 3.12. Non-conventional CT and PT

Table 3.1

Comparison of conventional and non-conventional IT sizing

Type of instrument transfomer	Heigh, meters	Weight, kg
TFZM-500	5.930	4920
NKF-500	6.080	2150
Optic CT 500 kV by Profotek	5.745	390
Electronic VT 500 kV by Profotek	4.160	390

Table 3.2

Cost comparison of fiber optic instrument transformers
compare to conventional IT

Manufacturer	Country	Price increase
Profotek -optic CT -optic PT	Russia	 280% 150%
NXTPhase -optic CT -optic PT	Canada	 380% 180%
Nari-Relays -optic CT -optic PT	China	 300% 135%

Considering the equipment costs according to the catalogue prices of the leading manufacturers; it is seen that Profotek's optical sensors are 50-70% more expensive than conventional ITs. But integration the optic sensors in the scheme, may be achieved the total costs reduction for optic current transformer about 15% and for voltage transformer about 20%. Based on this information, the importance of extensive research activities before the design or modernization procedure becomes even more important.

3.1.3 Reliability and Cost Comparison of 500 kV Switchyard Components

Table 3.3

Table Reliability indexes of 500 kV switchgear switching devices

500 kV sw/gear component	Failure rate, 1/year	Mean recovering time, hours	Rate of planned maintenance, 1/year	Time of planned maintenance, hours
ABCB	0.15	60	0.2	133
Isolator	0.01	14	0.166	31
DCB	0.03	18	0.08	42

Conventional solution with disconnectors the maintenance interval – once in 5 years

DCB solution, the maintenance interval – once in 15 years

TFZM-500 recalibration interval - 4 years

NKF-500 recalibration interval - 4 years

Optic CT recalibration interval - 8 years

Electronic VT recalibration interval - 8 years

The use of DCBs and NCITs can essentially reduce the footprint of a substation. In addition, the number of materials like steel, copper, insulation and in some cases oil, are also significantly reduced leading to an eco-friendly substation [5].

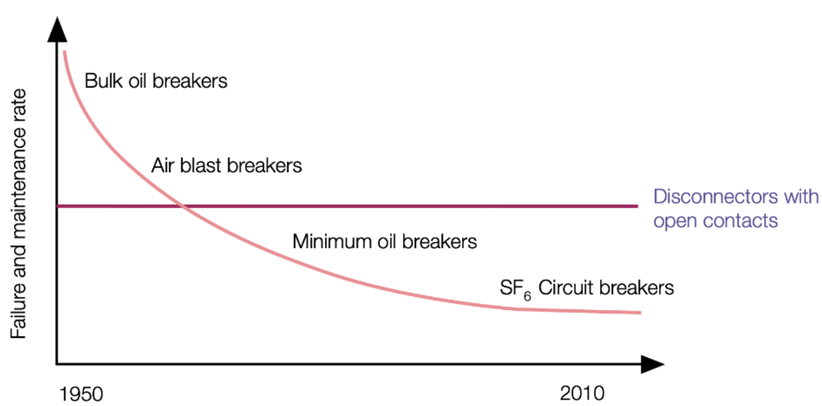


Fig. 3.13. The reliability of switching devices during 60 years

Table 3.4

Table Comparison between ABCB and DCB solution for breaker and a half switchgear scheme 500 kV

	ABCB solution			DCB solution		
	cost, $	number	Total, $	cost, $	number	Total, $
Circuit breaker	111.400	12	1,336.800	185.000	12	2,220.000
Isolator (3 phase)	11.000	32	35.200	0	0	0
Foundation	10.000	56	560.000	10.000	32	320.000
Total			1,932.000			2,540.000

Table 3.5

Table Cost comparison of ABCB and DCB switchgear solution for breaker and a half switchgear scheme 500 kV

	ABCB cost, $	DCB cost, $
Equipment	1,932.000	2,540.000
Failure and maintenance	308.000	154.000
Busbar and connections	1,226.000	1,226.000
Civil work	8.340.000	10,020.000
Design	4,940.000	6,130.000
Total	16,746.000	20,070.000

3.2 Manual Solutions of the Calculations

3.2.1 Source and Load

In the present case, as seen in Fig. 3.14 and Table 3.6, the substation to be modernized has a source with two parts as System 1 and System 2, with 500 kV voltage value. Each of the sources has an apparent power value as Sr1 and Sr2 with the unit of MVA. Apparent power refers to the total current and voltage in the electrical circuit. The term is preferred in descriptions of total electrical power in installations and captures both real and reactive power in an electrical circuit. It is the common value used in main electrical installations such as transformers and generators. In addition, Xs1 and Xs2 represent the reactance values with a per-unit definition, as a method to lead the calculation procedure clearly [21, 22]. Afterward, there are two overhead lines with different length values mentioned as lw1 and lw2.

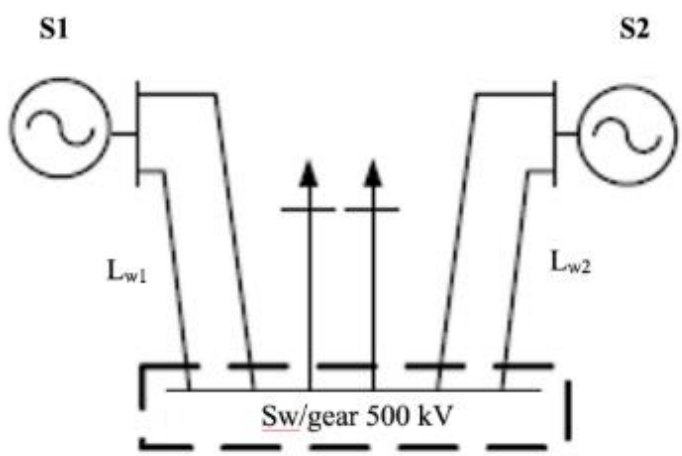


Fig. 3.14. The principal scheme of 500 kV substation switchyard

Table 3.6

Sources with Impedance Value

Uhv	System S1		System S2		OHL	
	Sr1	Xs1	Sr2	Xs2	lw1	lw2
500	8000	0.8	9500	0.9	240	80
kV	MVA	Per Unit	MVA	Per Unit	km	km

Table 3.7

Loads with Medium and Low Voltage Steps

Voltage Level	U	n*p	r_sim	cosφ	t_max
MV	220	6*60	0.87	0.92	7500
LV	10	4*14	0.8	0.9	5000
Units	kv	n*MV	-	-	hours

Looking at Table 3.7 and considering loads, there are two different voltage values for low and medium voltage applications as 220 kV and 10 kV. Each of the loads demands electricity with different specific power characteristics, according to maximum individual demand capacity(n*p), demand factor(r_sim), power factor (cosφ), and maximum demanding period (t_max).

3.2.2 Calculations

At the very beginning, according to initial data, the power balance should be defined for MV and LV. Power balance, which is the relation of the different kinds of loads, is determined according to the alignment of the voltage and current waves. Briefly, the resultant vector created by active and reactive power represents apparent power [24].

3.2.2.1 Active Power Demand at MV and LV:

(3.1)

$$P_{MV} = r_{sim} \times \sum N_{MV} \times P_{MV} = 0{,}87 \times (6 \times 60) = 313.2\ MW,$$

(3.2)

$$P_{LV} = r_{sim} \times \sum N_{MV} \times P_{LV} = 0{,}8 \times (14 \times 4) = 44.8\ MW$$

Multiplying the demand capacity(n*p), the demand factor(r_sim), and the power factor (cosφ) all equals active power demand. Using the formulation above active power demand for MV is defined as 313.2 MW. When the parameters of the LV are applied to the same formula, the active power demand for LV is defined as 44.8 MW.

3.2.2.2 Apparent Power Demand at MV and LV

(3.3)

$$S_{MV} = \frac{P_{MV}}{cos\ \varphi} = \frac{312.2}{0.92} = 340.435\ MVA$$

(3.4)

$$S_{LV} = \frac{P_{LV}}{cos\ \varphi} = \frac{44.8}{0.9} = 49.78\ MVA$$

Dividing active power by the power factor using the formulation above, the apparent power demand for MV is defined as 340.435 MVA. Using the same formulation with the parameters of the LV, the apparent power demand for LV is defined as 49.78 MVA.

3.2.2.3 Reactive Power Demand at MV and LV

$$Q_{MV} = S_{MV} \times sin\,\varphi = 340.435 \times 0.392 = 133.422\ MVAr \tag{3.5}$$

$$Q_{LV} = S_{LV} \times sin\,\varphi = 49.78 \times 0.436 = 21.7\ MVAr \tag{3.6}$$

Converting the power factor from cosine to sin and multiplying sinφ with active power, the apparent power demand for MV is defined as 133.422 MVAr. Using the same formulation with the parameters of the LV, the apparent power demand for LV is defined as 21.7 MVAr. Later on, the total active, reactive and apparent power is defined as follows.

3.2.2.4 Total Active, Reactive and Apparent Power Demand of External Consumers

Active $$\Sigma_P = P_{MV} + P_{LV} = 313.2 + 44.8 = 358\ MW \tag{3.7}$$

Reactive $$\Sigma_Q = Q_{MV} + Q_{LV} = 133.42 + 21.7 = 155.12\ MVAr \tag{3.8}$$

Apparent $$\Sigma_S = \sqrt{{\Sigma_Q}^2 + {\Sigma_P}^2} = \sqrt{358^2 + 155.12^2} = 390.16\ MVA \tag{3.9}$$

As mentioned above, to find the total apparent power demand the resultant vector is created by active and reactive components [9]. Hereupon, with the help of initial values and calculations, auto-transformer, circuit breaker, disconnector, current transformer, potential transformer, busbar layout, conductor and lastly switchgear will be defined.

3.2.2.5 Apparent Capacity of Auto-Transformer with Possible Overload

During the calculations above, the demand characteristics are emphasized. Furthermore, possible interruptions should be taken into consideration earlier to improve the power quality by preventing the interruptions. A power quality categorization limits the instant capacity, to avoid interruptions, and not to tire the system.

As seen in Table 3.8, each category has a specific factor as a multiplier to keep the system functioning by levelling down the capacity. Assuming the location as an industrial area according to the consumer preferences, the interruptions should be as few as possible. For this purpose, the 1st category is chosen and the Rated Apparent Power is defined as 273.11 MVA.

Table 3.8

Recommended Ratio for Transformer Load according to the consumer categories and number of power transformers $\mathbf{n_{pt}}$ [Chapter 2.2, p.12]

Parameter	*1st category of consumer*	*2nd category of consumer*	*3rd category of consumer*
Ratio of transformer loading in normal conditions $\boldsymbol{r_{tr}}$ *and* $\boldsymbol{n_{pt}}$	0.65 - 0.7 With at least 2 transformers. (selected)	0.7 - 0.8 With 2 transformers.	0.9 - 0.95 • Traditionally with 1 transformer, • for some special purposes 2 transformers

(3.10)

$$S_{Rated(Nominal)} = R_{tr-max} \times \Sigma_S \times \frac{1}{n_{pt} - 1} =$$

$$= 0.7 \times 390.16 \times \frac{1}{2-1} = 273.11\ MVA$$

Since it is required to deal with the high and medium voltage sections, the fundamental parameters are defined as the system's total apparent power value (ΣS), UHV, and UMV values. However, it is not always possible to find a 3-phase autotransformer suitable for our system, and it can be costly to build it specially. To overcome this situation, it has been used 3 of single-phase autotransformers connected in parallel. For redundancy and taking into account the first category of consumers, the two 3-phase autotransformers will arrange connections between three levels of voltages at the substation. Suggested autotransformer for substation design or modernization purposes was chosen from the catalogue in Appendixes (Table A1) and nameplate parameters of selected AT are in the Table 3.9.

$\boldsymbol{AT's\ Rated\ Apparent\ Power}$;

should be higher than $273.11\ MVA$ *(for 1 of 3-phase AT)*

(3.11)

should be higher than $\frac{273.11}{3}$ = 91.03 MVA *(for 3 of single-phase AT)*

ASOFAF-167000/500/220-M1

A	Auto Transformer
S	Single Phase
OFAF	Oil Forced Air Forced
167000	Rated Power (kVA)
500	Primary Voltage (Inlet)
220	Secondary Voltage (Outlet)
M1	For medium climate and for the installations with height above sea level below 1000 m.

Table 3.9

Selected Autotransformer

Type	Rated power, MVA		Rated voltage, kV			Weight, tons				(L)x (B)x (H), мм
	Auto transformer	LV wind.	HV	MV	LV	total	oil	Oil to add	transp	
ASOFAF-167000/ 500/ 220- M1	167	50	500 / √3	230 / √3	10,5; 11,0;38,5	161	39	9,7	126	9050x7000x11620 7290x3370x4300
		6			10,5; 11,0	166	42	10,1	130	9050x7000x11150 7300x3338x4300

Therefore, it is proposed to retrofit the 500 kV switchyard at the existing substation with the replacement of measuring elements of oil-filled transformers with modern optical current and voltage sensors, as well as the replacement of air blast circuit breakers and free-standing horizontal center break disconnectors with modern disconnecting circuit breakers (DCB).

Furthermore, to define the essential characteristics and ranges of the intended elements, according to the rated voltage value, mid rated and maximum voltage values should be chosen according to

Table 3.10 for the following calculations.

$$S_B = 1000\ MVA$$

Table 3.10

The scale of rated, mid rated and maximum voltage values

$\boldsymbol{U_r}$, kV	3	6	10	20	35	110	150	220	330	500	750
$\boldsymbol{U_{mid\ r}}$, kV	3.15	6.3	10.15	21	37	115	154	230	340	515	770

$\boldsymbol{U_{max}}$, kV	3.6	7.2	12	24	40.5	126	172	252	363	525	787

$$U_{mid-rated} = U_{MR} = 515kV$$

$$I_B = \frac{S_B}{\sqrt{3} \cdot U_{MR}} = \frac{1000}{\sqrt{3} \cdot 515} = 1.12kA \tag{3.12}$$

The following calculations are based on the source initials. Values are from Table 3.6.

$$U_{HV} = 500kV \quad U_{MV} = 220kV \quad U_{LV} = 10kV \tag{3.13}$$

$$X_{S1_{pu}} = X_{source1} \times \frac{S_B}{S_{R1}} = 0.8 \times \frac{1000}{8000} = 0.1\ pu \tag{3.14}$$

$$X_{S2_{pu}} = X_{Source2} \times \frac{S_B}{S_{R2}} = 0.9 \times \frac{1000}{9500} = 0.095\ pu$$

Table 3.11

Midrange reactance values per km of transmission lines

$X_{l\,pu}$ (Ω/km)		
220 kV	330 kV	500 kV
0.32	0.32	0.3

According to Table 3.11, reactance values for the specific voltage value should be defined. In the current situation the reactance value for the system is defined as 0.3. At the end of calculations periodical current at zero time is defined as 12.76 kA. This value also represents rated short-circuit thermal withstanding current. ($\boldsymbol{I_{B0}}$)

$$X_{L1_{pu}} = \frac{X_{SP} \times l_1}{2} \times \frac{S_B}{U_{MR}^2} = \frac{0.3 \times 240}{2} \times \frac{1000}{515^2} = 0.135\,pu \tag{3.15}$$

$$X_{L2_{pu}} = \frac{X_{SP} \times l_2}{2} \times \frac{S_B}{U_{MR}^2} = \frac{0.3 \times 80}{2} \times \frac{1000}{515^2} = 0.045\,pu \tag{3.16}$$

$$X_1 = X_{S1_{pu}} + X_{L1_{pu}} = 0.1 + 0.135 = 0.236\,pu \tag{3.17}$$

$$X_2 = X_{S2_{pu}} + X_{L2_{pu}} = 0.095 + 0.045 = 0.14\,pu \tag{3.18}$$

$$X_{pu}^{K1} = \frac{X_1 \times X_2}{X_1 + X_2} = \frac{0.236 \times 0.14}{0.236 + 0.14} = 0.087\,pu \tag{3.19}$$

$$I_{p0}^{K1} = I_{B0} = I_B^{HV} \times \frac{1}{X_{pu}^{K1}} = 1.12 \times \frac{1}{0.087} = 12.76\,kA \tag{3.20}$$

The short-circuit voltage Uk% of the AT is the voltage when it is supplied to one of the windings of the transformer with the other winding shorted, a current equal to the rated flows through it. The short circuit voltage is determined by the voltage drop in the transformer; it characterizes the total impedance of the transformer windings. In three-winding transformers and autotransformers, the short-circuit voltage is determined for any pair of its windings with the third winding open. Thus, three short-circuit voltage values are given in the catalogues.

The transformers are with star and delta configuration. In this regard following calculations should be applied

$$X_{AT\%}^{H} = 0.5 \cdot \left(U_{\frac{S}{c}\%}^{HV-LV} + U_{\frac{S}{c}\%}^{HV-MV} - U_{\frac{S}{c}\%}^{MV-LV} \right)$$
$$= 0.5 \cdot (35 + 11 - 21.5) = 12.25\% \tag{3.21}$$

$$X_{AT\%}^{M} = 0.5 \cdot \left(U_{\frac{S}{c}\%}^{HV-MV} + U_{\frac{S}{c}\%}^{MV-LV} - U_{\frac{S}{c}\%}^{HV-LV} \right)$$
$$= 0.5 \cdot (11 + 21.5 - 35) = -1.25\% = 0\% \tag{3.22}$$

$$X_{AT\%}^{L} = 0.5 \cdot \left(U_{\frac{S}{c}\%}^{LV-MV} + U_{\frac{S}{c}\%}^{LV-HV} - U_{\frac{S}{c}\%}^{HV-MV} \right)$$
$$= 0.5 \cdot (35 + 21.5 - 11) = 22.75\% \tag{3.23}$$

$$X_{AT\,pu}^{L} = \frac{X_{AT\%}^{H}}{100} \cdot \frac{S_B}{S_{ATR}} = \frac{12.25}{100} \cdot \frac{1000}{167} = 0.734\,pu \tag{3.24}$$

$$X_{AT*}^{M} = 0$$

$$X_{AT\,pu}^{L} = \frac{X_{AT\%}^{L}}{100} \cdot \frac{S_B}{S_{ATR}} = \frac{22.75}{100} \cdot \frac{1000}{167} = 1.362\,pu \tag{3.25}$$

After the calculations, desired equipment to be modernized should be defined according to comparison between calculated parameters and nameplate parameters. All should be able to withstand the physical and electrical effects of the system. In this regard, all effects are compared by the nameplate parameters according to the calculations to prove the safety, sustainability, and reliability of the chosen element.

Essentially, installed voltage (U_{inst}),, installed current (I_{inst}), rated short-circuit thermal withstanding current (I_{B0}), Rated peak withstanding current (I_p) and Thermal withstanding (β_{th}) values should be compared with the help of following table.

To define installed current, the calculation to be applied is:

$$I_{inst} = \frac{S_{HV}}{2 \cdot \sqrt{3} \cdot U_{HV}} = \frac{390.16}{2 \cdot \sqrt{3} \cdot 500} = 0.225kA \tag{3.26}$$

For the following calculations, Time of aperiodic short circuit current decreasing value (T_a) and ratio of peak short circuit current (k_p) are chosen according to with the help of following table.

Table 3.12

Magnitudes of time of aperiodic s/c current decaying and ratio of peak s/c current

Components of power system	T_a, s	k_p
Turbogenerators with installed capacity, MW 12-60 100-1000	 0.16-0.25 0.4-0.54	 1.94-1.955 1.975-1.98
G-T units 60 MW with rated generator voltage, kV 6.3 10	 0.2 0.15	 1.95 1.935
G-T units with rated G capacity, MW 100-200 300 500 800	 0.26 0.32 0.35 0.3	 1.965 1.97 1.973 1.967
Power system connected to buses (as s/c point) through OHL with level of voltage, kV 35 110-150 220-330 500-750	 0.02 0.02-0.03 0.03-0.04 0.06-0.08	 1.608 1.608-1.717 1.717-1.78 1.85-1.895
Power system connected to buses 6-10 kV (as s/c point) through power transformer with capacity, MVA 80 and higher 32-80 5.6-32	 0.06-0.15 0.05-0.1 0.02-0.05	 1.85-1.935 1.82-1.904 1.6-1.82
Circuits protected by reactor with rated current, A 1000 and higher 630 and less	 0.23 0.1	 1.956 1.904
Distributed network 6-10 kV	0.01	1.369

To define rated peak withstanding current (I_p), the calculation to be applied is:

$$I_p = \sqrt{2} \cdot I_{B0} \cdot k_p = \sqrt{2} \cdot 12.76 \cdot 1.85 = 33.395\ kA \tag{3.27}$$

For further short circuit current calculations the preliminary choice of CB is required. In accordance with initial scheme parameters the disconnecting circuit breaker VGT UETM 500 of Russian manufacturer was selected. (Table A2).
Lastly, to define the thermal withstanding, the calculation to be applied is:

$$\beta_{th} = I_{B0}^2 \cdot (t_{CB} + t_{PR\,min} + T_a + t_{AR}) \tag{3.28}$$

$$t_{CB} = 0.02 \qquad t_{PR\,min} = 0.01 \qquad T_a = 0.06 \qquad t_{AR} = 0.21$$

$$12.76^2 \cdot (0.02 + 0.01 + 0.06 + 0.21) = 48.878\ kA^2 \cdot s$$

t_{CB} CB opening time (nameplate parameter from the catalogue)
$t_{PR\,min}$ Minimal time of protective relaying. Depends on the protected equipment.
t_{AR} Auto-reclosure time, sec (defined as 0.21 as a design preference)

Finally, all the calculations are collected in the following part as a reference point of equipment selection (Table 3.13).

3.2.3 Equipment Selection

Table 3.13

Calculation Results

Calculated Parameters and Values	Nameplate	
Installed – Rated Voltage		
U_{inst}	500 kV	U_R
Installed – Rated Current		
I_{inst}	0.225 kA	I_R
Rated Short Circuit Thermal Withstanding Current (Breaking Current)		
I_{B0}	12.764 kA	I_{TH}
Rated Peak Withstanding Current (Making Current)		
I_{peak}	33.395 kA	I_S
Thermal Withstanding (VGT UETM 500)		
$\beta_{th} = I_{B0}^2 \cdot (t_{CB} + t_{PR\,min} + T_a + t_{AR})$ =48.878 $kA^2 \cdot s$	$\beta_{th} = I_{th}^2 \cdot t_{th}$ t_{th} =1 sec t_{th} =3 sec	

In the case of modernizing the substation, creating different variations according to the calculations will be sensible to compare different parameters. The first variation is named Variant 0 which is representing the existing conventional equipment. Initially, Air blast circuit breakers VVBK-500, disconnectors RNDZ-500, measuring transformers of current TFZM-500B and voltage NKF-500 are installed at the switchyard as mentioned

Calculated Parameters and Values			Name Plate	Air Blast Circuit Breaker VVBK 500	Disconnectors RNDZ 500	CT TFZM 500B	PT NKF 500	Unit
Installed – Rated Voltage								
U_{inst}	500	kV	U_R	500	500	500	500	kV
…								
Variant 0								

before. Mentioned equipment are called as Variant 0 (Variant Zero

Table 3.14).

Variant Zero Table 3.14

After short circuit current calculations, the circuit breakers, disconnectors, and instrument transformers should be finally selected according to the calculated values. In the table below, some recommended equipment can be seen in accordance with the calculated values. These parts of equipment can be considered as alternative solutions in the design or modernization processes. However, they are presented here as examples and references. Only calculations are taken into account in this section and a reference point is established for the analyses that follow, assuming an optimal design goal. Because for the practical application of this equipment, their prices, availabilities and other physical properties must be taken into account. For example, although NXVCT and FOCS are productions of the today's cutting-edge technology, it may not be preferred due to its rather high price. When the table below (Table 3.15) is re-examined in the light of the evaluations mentioned in section 4.1, it is understood that the fourth variant is the most suitable equipment group for the modernization process.

The nameplate parameters of the selected instrument transformers are in Appendixes – for optic current transformers (Table A3) and for electronic voltage transformers (Table A4). The connection of cutting-edge current and voltage transformers to the process bus is illustrated at Figure A1 and Figure A2 respectively.

Table 3.15

Calculated Parameters and Values		Nameplate	DCB HPL 362-550B2 by ABB	DCB VGT UETM 500 Russia	NXVCT 500	FOCS FS-550 by ABB	Optic CT 500 kV by Profotek (EFOCT)	Electronic VT 500 kV by Profotek (EVT)	Unit
Installed – Rated Voltage									
$\boldsymbol{U_{inst}}$	500 kV	U_R	362 – 550	500	500	550	500	500	kV
Installed – Rated Current									
$\boldsymbol{I_{inst}}$	0.225 kA	I_R	4	31.5	1 – 4	2	0.2 – 40	-	kA
Rated Short Circuit Thermal Withstanding Current (Breaking Current)									
$\boldsymbol{I_{B0}}$	12.764 kA	I_{TH}	63	40 (3s)	63	63 (1s) / 40 (3s)	-	-	kA
Rated Peak Withstanding Current (Making Current)									
$\boldsymbol{I_{peak}}$	33.395 kA	I_S		100	170	164	400	-	kA
Thermal Withstanding (VGT UETM 500)									
$\boldsymbol{\beta_{th} = I_{B0}^2 \cdot (t_b^R + T_a)}$ =48.878		$\beta_{th} = I_{th}^2 \cdot t_{th}$							
		t_{th} =1 sec	3969		3969	3969			$kA^2 \cdot s$
		t_{th} =3 sec	11907	4800	11907	4800			$kA^2 \cdot s$

Variant 1							
Variant 2							
Variant 3							
Variant 4							Selected

3.3 Web-based Calculation Interface - substationdesigner.com (beta)

Fig. 3.15. Interface - The welcome page of the website.

The web design part consists of different layers such as frontend and backend development. There are design requirements for both frontend (visible) and backend (hidden) development. Because in order to create an interface that leads the users to enter the initial data with flexible options, the frontend part was developed with a basic visual structure. HTML frameworks were used to accelerate the backend of the interface and to create a clean, sensible, and efficient look at the frontend of the interface. In this regard, it was one of the challenging part to show the possibilities of the interface to the user. At this point, JavaScript was used to animate some parts of the interface providing ergonomic usage with collapsible elements, alerts and warnings. At the same time PHP coding was effective and sensible while creating the calculations and tables during backend development. In addition, an excel file containing the same calculations was used to create a reference point for the calculation algorithms created using PHP coding (Fig. 3.16).

3.3.1 Initial Data

Uhv	System S1		System S2		OHL	
	S_{r1}	X	S_{r2}	X	l_{w1}	l_{w2}
500	8000	0.8	9500	0.9	240	80
kV	MVA	Per Unit	MVA	Per Unit	km	km

	Load				
Voltage Level	U	n*p	r_{sim}	$\cos\varphi$	T_{max}
MV	220	360	0.87	0.92	7500
LV	10	56	0.8	0.9	5000
Units	kv	n*MV	-	-	hours

Fig. 3.16. Excel - The part of the excel file showing initial data.

As seen below (Fig. 3.17), the interface welcomes the user to the form with checkboxes showing that it is possible to choose one to three sources and one or two loads while entering the initial data of the system. Especially in this part, the backend development of the interface was created with several arrangements to let the interface answer different options such as single source - single load or single source - two loads.

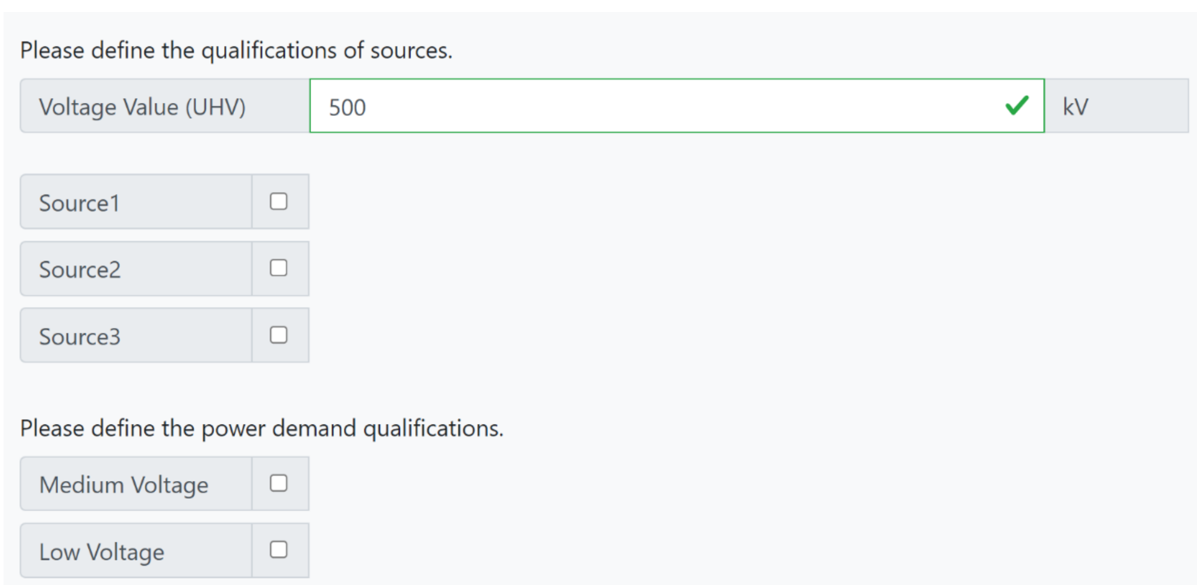


Fig. 3.17. Interface - Initials of the sources and loads.

According to the case of the practical implementation, there are two sources and two loads of the system. After enabling checkboxes, the hidden parts become visible and lead the user to enter the data (Fig. 3.18). For the user, it is required to enter the initial data consisting of Apparent Power, Reactance Value, and Overhead Line Length.

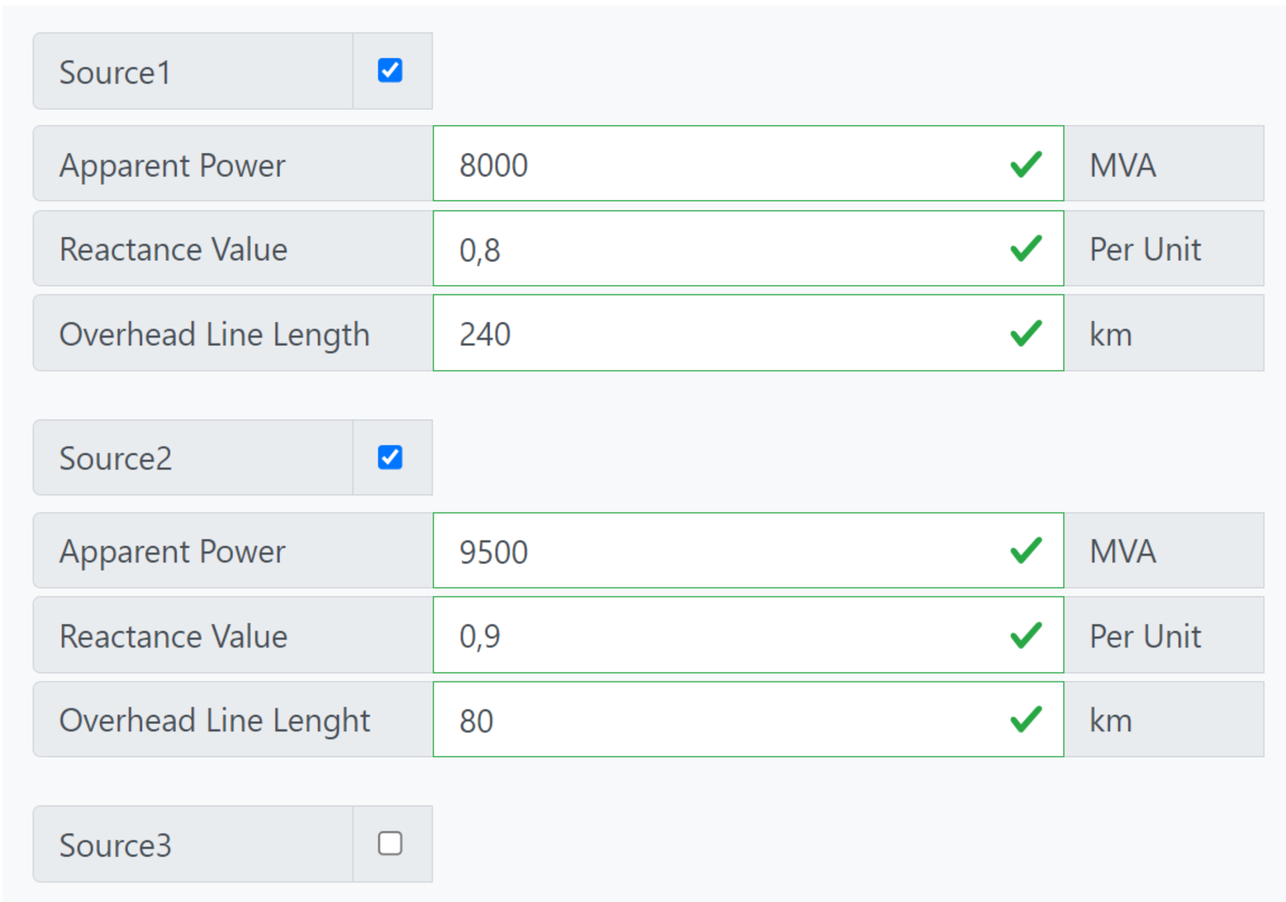


Fig. 3.18. Interface - Sources

After entering the initial data of the sources, the interface leads the user to add at least one load. (Fig. 3.19) In this part, it is required to enter the initial data consisting of Voltage, Active Power Demand, r_sim, Power Factor and Operating Hours for both medium and low voltage demands.

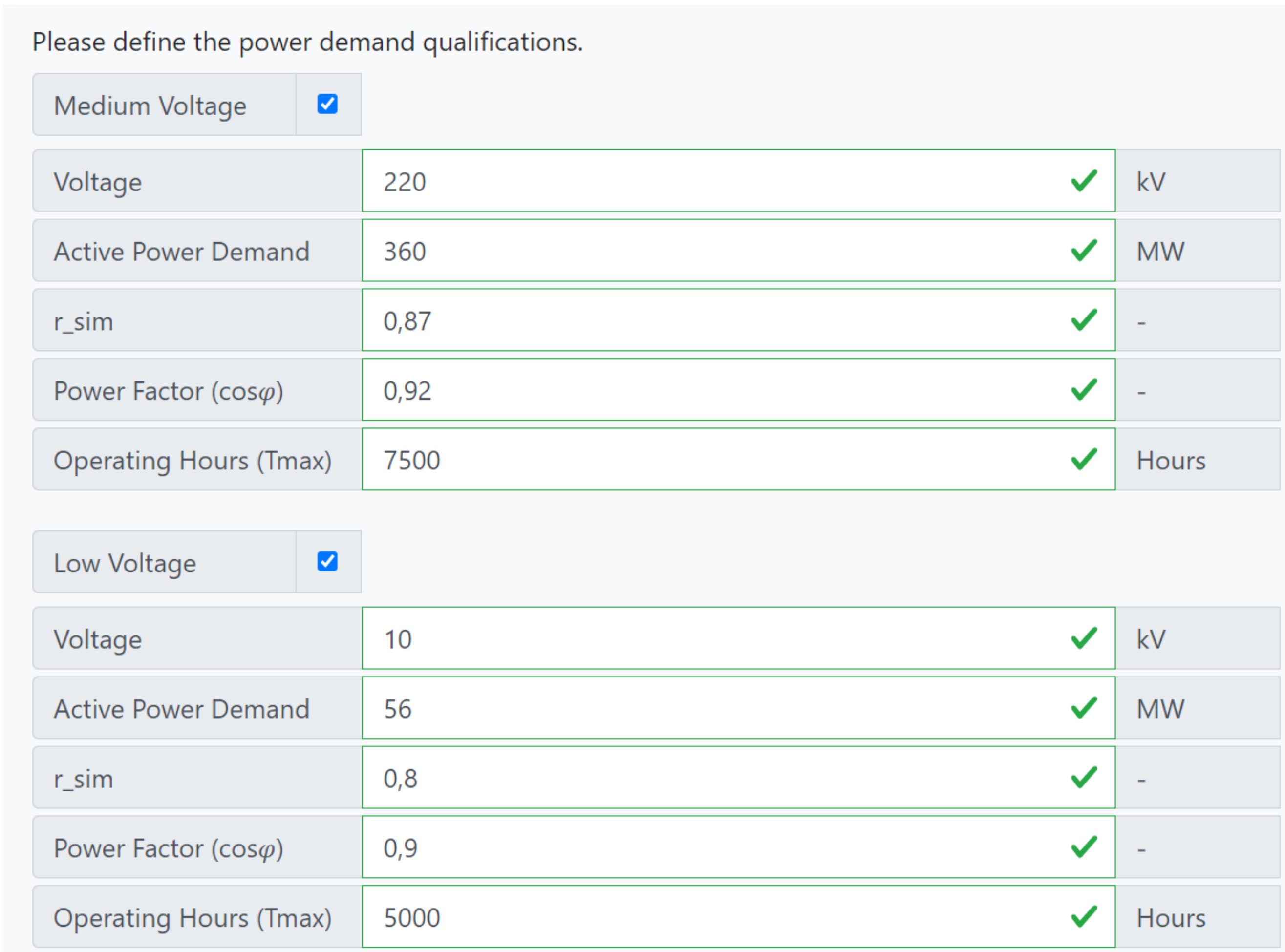


Fig. 3.19. Interface – Loads

After the definition of the loads and sources, the interface leads the user to define the consumer categories. The importance of the consumer categories in the substation design methodology is mentioned in the part 2.1.1. As seen below (Fig. 3.20), radio buttons are added to lead the user chose one of the selections. The selection of categories also shows the range, algorithmic selection of the transformer load ratio, and a number of 3-phase power transformers. In addition, in the case of special applications with high accuracy required, the interface is able to accept a user-defined ratio by providing a number input in case of selection of design preference.

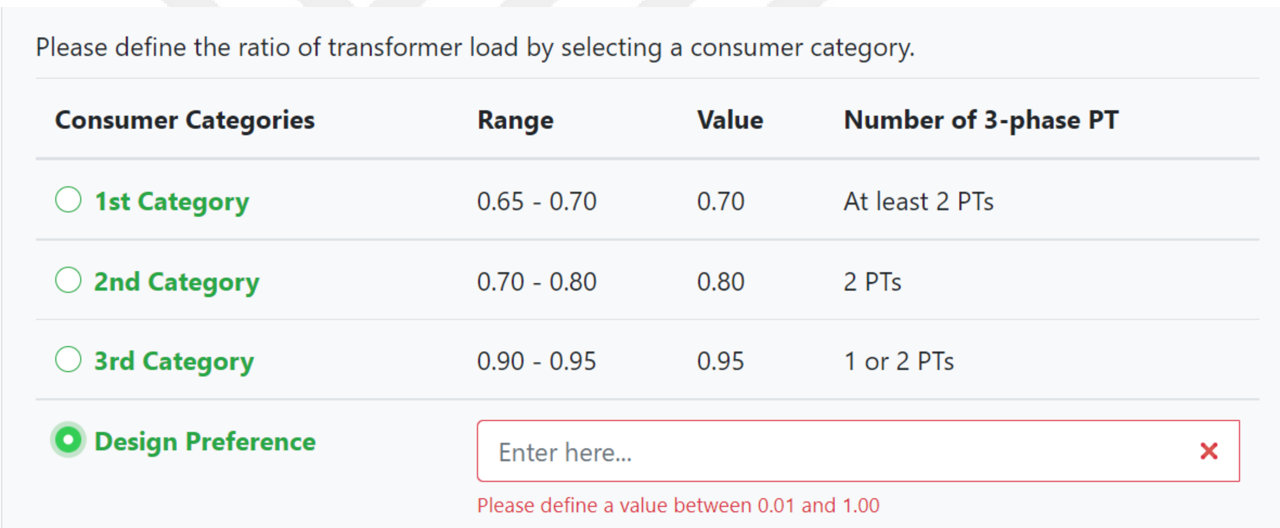


Fig. 3.20. Interface - Consumer categories

Then, in the following part, the interface shows the algorithmic definition of mid-rated and maximum voltage values by rated voltage (Fig. 3.21). In this part, for special applications and each particular voltage value a graph and a special algorithm were created to define the mid-rated voltage value automatically by following the linear line of the defined values (Fig. 3.22).

Algorithmic definition of rated, mid rated and maximum voltage values.

U rated (kV)	**3**	**6**	**10**	**20**	**35**	**110**	**150**	**220**	**330**	**500**	**750**
U mid-rated (kV)	3.15	6.3	10.15	21	37	115	154	230	340	515	770
U max (kV)	3.6	7.2	12	24	40.5	126	172	252	363	525	787

Fig. 3.21. Interface - Definition of U mid rated

U rated	U mid-rated	Ratio
3	3.15	1.05
6	6.3	1.05
10	10.5	1.05
20	21	1.05
35	37	1.057
110	115	1.045
150	154	1.027
220	230	1.045
330	340	1.03
500	515	1.03
750	770	1.027

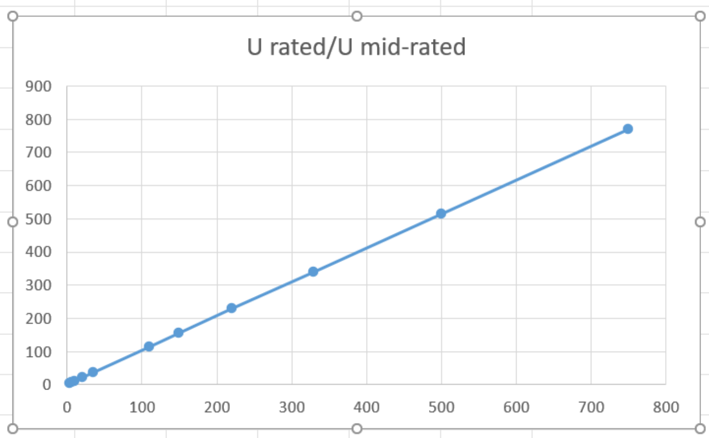


Fig. 3.22. Excel – Definition of U mid rated

In the last part of the form which is collecting the initial data, it is required to enter the S Basis value and the number of 3-ph transformers. Also, the interface shows the algorithmic definition of the specific reactance value by voltage level. In this part, it is also possible to enter a user-defined XSP value for special applications by clicking the checkbox. As a final requirement, the voltage value for the periodical current at zero time should be defined. It is the last part before the submission button (Fig. 3.23).

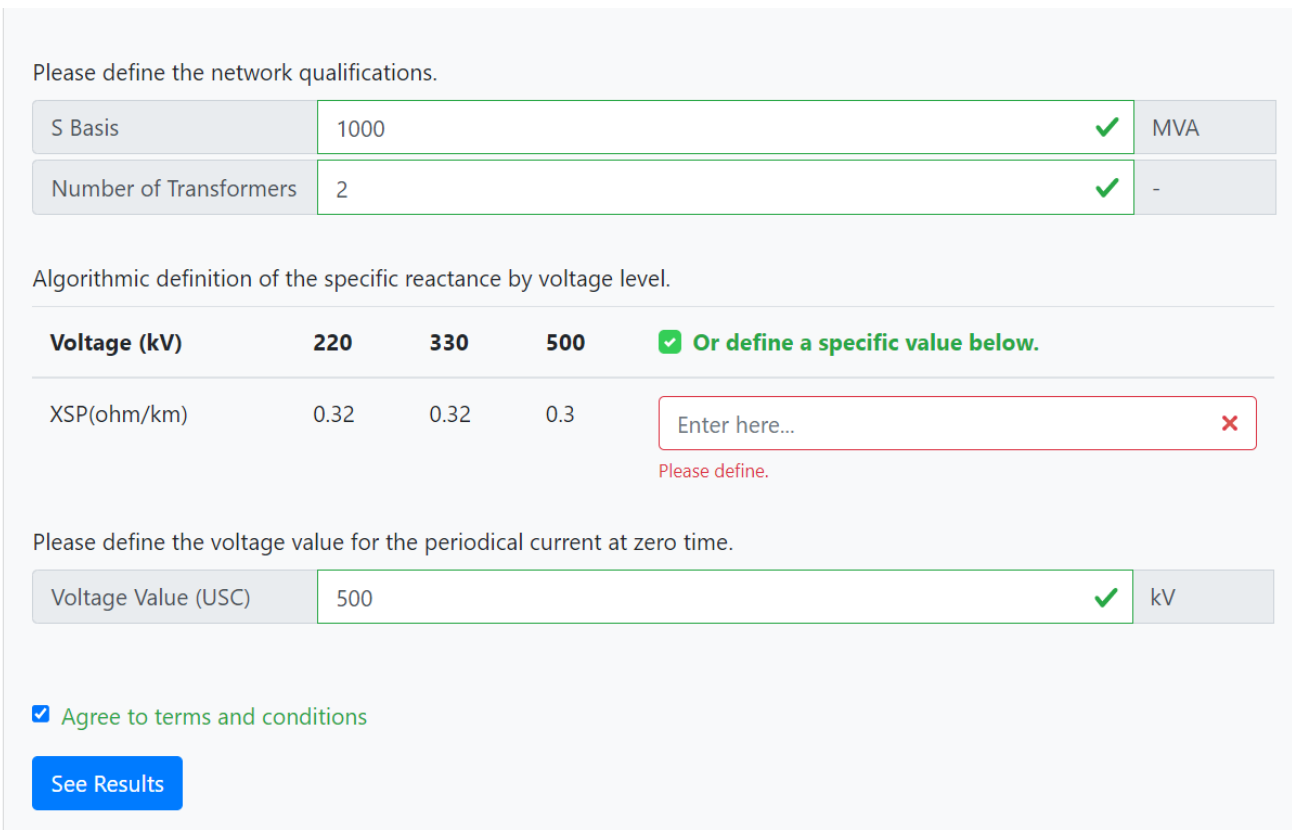


Fig. 3.23. Interface - Network Calculations

If all the required values are entered into the system according to the definitions, the submission button leads the user to the following part which gives a chance to the user to check and verify the entered values (Fig. 3.24).

In the following part it is possible to see and verify the initial data before obtaining the results (Table 3.16).

Sources

Initial Voltage	500	kV		

Parameter	**Source1**	**Source2**	**Source3**	**Unit**
Apparent Power	8000	9500		MVA
Reactance Value	0.8	0.9		Per Unit
Overhead Line Length	240	80		km

Loads

Parameter	**MV**	**LV**	**Unit**
Voltage	220	10	kV
Active Power Demand	360	56	MW
R_sim	0.87	0.8	-
Power Factor (cosφ)	0.92	0.9	-
Operating Hours (Tmax)	7500	5000	hours

Network Initials

Transformer Load Ratio	0.7	-
S Basis	1000	MVA
U Midrated	515	kV
Number of Transformers	2	-
Specific Resistance	0.30	ohm/km

Fig. 3.24. Interface – Verification of the initial data

3.3.2 Reporting

Table 3.16

Reporting the results for 500 kV switchgear with suggested values.

Results				
#	Variable	Value	Unit	Explanation
Medium Voltage Demand				
MV	P	313.2	MW	Active Power Demand at MV
MV	S	340.4347826087	MVA	Apparent Power Demand at MV
MV	Q	133.42264129386	MVar	Reactive Power Demand at MV
Low Voltage Power Demand				
LV	P	44.8	MW	Active Power Demand at LV
LV	S	49.777777777778	MVA	Apparent Power Demand at LV
LV	Q	21.697630296736	MVar	Reactive Power Demand at LV

Total Active Power Demand

MV	P	313.2	MW	Active Power Demand at MV
LV	P	44.8	MW	Active Power Demand at LV
HV	P	358	MW	Active Power Demand at HV

Total Reactive Power Demand

MV	Q	133.42264129386	MVar	Reactive Power Demand at MV
LV	Q	21.697630296736	MVar	Reactive Power Demand at LV
HV	Q	155.1202715906	MVar	Reactive Power Demand at HV

Total Power Demand at HV

HV	P	358	MW	Total Active Power Demand at HV
HV	Q	155.1202715906	MVar	Total Reactive Power Demand at HV
HV	S	390.1618877573	MVA	Total Apparent Power Demand at HV

Transformer Selection Parameters

I Installed	0.22526007092421	kA	Installed Current

>>>Minimum Rated Apparent Power of Power Transformer at HV

S Rated	273.11332143011	MVA	1 Power Transformer - three-phase
S Rated (3ph)	91.037773810037	MVA	3 Power Transformers - all single-phase

Network Calculations

S BASIS	1000	MVA	Accepted Basis Apparent Power
U Mid Rated	515	kV	Basis Voltage Level at s/c Point
I BASIS	1.1210684838634	kA	Basis Current at s/c Point

Per Unit Specific Reactance

XSP	0.30	ohm/km	Midrange Specific Reactance of Transmission Line

Source1 Reactance Values

XS1 PU	0.1	Per Unit	Reactance of Source1
XL1 PU	0.13573381091526	Per Unit	Reactance of OHL 1
X1	0.23573381091526	Per Unit	Equivalent Reactance 1

Source2 Reactance Values

XS2 PU	0.094736842105263	Per Unit	Reactance of Source2
XL2 PU	0.04524460363842	Per Unit	Reactance of OHL 2
X2	0.13998144574368	Per Unit	Equivalent Reactance 2

Total Reactance

XK1 PU	0.087828106731744	Per Unit	Equivalent scheme reactance for s/c point 1

Periodical Current at Zero Time

USC	500	kV	Voltage at short circuit point
UPU	1	Per Unit	Voltage per unit at short circuit point
IK1P0	12.764347605573	kA	Periodical Current at Zero Time

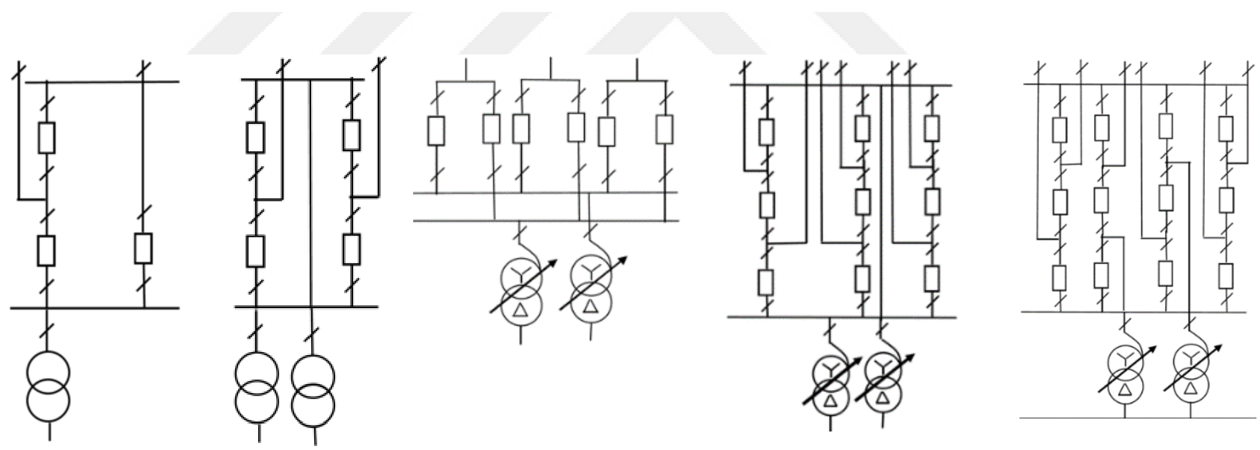
Short Circuit Algorithmic Parameters

	Ur (kV)	Ta (s)	kp
	110 - 220	0.02	1.608
	220 - 330	0.03	1.717
	330 - 500	0.04	1.78
>>	500 - 750	0.06	1.85
	750 +	0.08	1.895

Calculated Values for Switchyard Equipment Selection

Parameter	Value	Unit	Explanation
U Ins	500	kV	Installed – Rated Voltage
I Ins	0.22526007092421	kA	Installed – Rated Current
I B0	12.764347605573	kA	Breaking Current
I Peak	33.395299972495	kA	Making Current
B Th	48.87857093877	kA^2 * s	SC Thermal Withstanding (for VGT UETM 500)

Possible Variations of Switchyard Scheme Layouts for 500 kV



Three bays ring Scheme	Four bays ring Scheme	Transformers-buses scheme with two CB per each line	Transformers-buses scheme with breaker and a half line connection	Breaker and a half Scheme

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St. Petersburg, Russia - 2020

In order to confirm the accuracy of the data obtained in the last part of the report generated from the interface, a comparison can be made with the calculation data, excel data and data of the interface (Table 3.17).

Table 3.17

Comparison between different methods of calculations

Parameter	Calculated by Interface's Algorithm	Calculated by Hand	Calculated by Excel File	Unit
U Ins	500	500	500	kV
I Ins	0.22526007092421	0.225	0.22526007	kA
I B0	12.764347605573	12.764	12.7643476	kA
I Peak	33.395299972495	33.4	33.3953	kA
B Th	48.87857093877	48.88	48.8785709	kA^2 *
S Rated	273.11332143011	273.2	273.11332	MVA
Error Rate	0	0.031727149	0.0000004102	%

3.3.3 Backend Development

Backend development consists of very complicated design elements. In this part, only the calculation methods coded by PHP will be explained.

Variables:

$involt	Initial Voltage Value
$sources1	Activation the checkbox of Source 1
$inappv1	Apparent Power of Source 1
$inreacv1	Reactance Value of Source 1
$inohl1	OHL Line Length of Source 1

Other variables of the sources follows as $sources2, $inapp2 and so on.

$loads1	Activation the checkbox of Load 1
$lovo1	Voltage Value of Load 1
$loapd1	Active Power Demand of Load 1
$lorsim1	R_sim value of Load 1
$lopofac1	Power Factor ($\cos\varphi$) of Load 1
$lotmax1	Operating Hours (Tmax)

Other variables of the loads follows as $loads2, $lovo2 and so on.

Additional Entries

$locat	Consumer category
$catuser	User defined consumer category
$nesbasis	S Basis
$umidrat	U Mid-rated
$npt	Number of Power Transformers
$userxsp	User defined specific reactance value
$Nevozero	Voltage value for the periodical current at zero time

Definition of Power Demands

$pmv=$loapd1 * $lorsim1;	Active Power Demand at MV
$smv=$pmv / $lopofac1;	Apparent Power Demand at MV
$sinf1=sin (acos ($lopofac1));	Cosine – Sine conversion
$qmv=$smv * $sinf1;	Reactive Power Demand at MV

Same equations repeats for Low Voltage Power Demand.

$plv=$loapd2 * $lorsim2;	Active Power Demand at LV
$slv=$plv / $lopofac2;	Apparent Power Demand at LV
$sinf2=sin (acos ($lopofac2));	Cosine – Sine conversion
$qlv=$slv * $sinf2;	Reactive Power Demand at LV

$phv=$pmv + $plv;	Total Active Power Demand
$qhv=$qmv + $qlv;	Total Reactive Power Demand
$shv=hypot ($phv,$qhv);	Total Apparent Power Demand
	*“hypot” function represents: sqrt(x*x + y*y)*

```
$srated=$shv*$locat*(1/($npt-1));            S Rated
$ibhv=$nesbasis/(sqrt(3)*$umidrat);          I Basis HV
$iins=$shv/(2*(sqrt(3)*$involt));            Installed Current
```

Following part represents the calculation of Specific Reactance Value. As seen below, the value will be defined by algorithm or by user according to the checkbox.

```
if (isset($_POST["checkxsp"])){              $_POST – represents the inputs
$userxsp=$_POST["userxsp"];
}else if($involt>420){
$userxsp="0.30";}else{
$userxsp="0.32";};
```

To define U mid rated following algorithm was used
to make the system answer specific values.

```
if ($involt>=750){$umidrat=round(($involt*0.026)+$involt);}
else if($involt>=500){$umidrat=round((0.03*$involt)+$involt);}
else if($involt>=330){$umidrat=round((0.03*$involt)+$involt);}
else if($involt>=220){$umidrat=round((0.045*$involt)+$involt);}
else if($involt>=150){$umidrat=round((0.026*$involt)+$involt);}
else if($involt>=110){$umidrat=round((0.045*$involt)+$involt);}
else if($involt>=35){$umidrat=(round(0.057*$involt)+$involt);}
else if($involt>=1){$umidrat=(0.05*$involt)+$involt;};
```

Then, following part was created as the calculation of reactance values of source 1. As seen below, the calculation will happen if the checkbox of the source1 is checked. Same rule works for all sources.

```
if (isset($_POST["sources1"])){
$xs1pu=($inreacv1*$nesbasis)/$inappv1;
$xl1pu=(($userxsp*$inohl1)*(0.5)*($nesbasis/($umidrat*$umidrat)));
$x1=$xs1pu+$xl1pu;
$oneoverx1=1/$x1;
```

(To obtain the total reactance value easily.)

Then total reactance value is obtained as follows.

```
$xk1pu=1/($oneoverx1+$oneoverx2+$oneoverx3);
```

Breaking Current is defined as follows.

```
$ik1pz=$ibz=$ibhv*(1/$xk1pu);
```

Algorithmic definition of Ta and kp values are as follows.

```
if($involt>749){ $tas=0.08; $kp=1.895;
}else if($involt>499){$tas=0.06; $kp=1.85;
}else if($involt>329){$tas=0.04; $kp=1.78;
}else if($involt>219){$tas=0.03; $kp=1.717;
}else{$tas=0.02; $kp=1.608;};
```

	Range Ur, kV		TA,s	kp
	110	220	0.02	1.608
	220	330	0.03	1.717
	330	500	0.04	1.78
>>>>	500	750	0.06	1.85
	750	+	0.08	1.895

Fig. 3.25: CB time values from excel file

```
$ipeak=(sqrt(2) * $ibz*  $kp);
```

Definition of Making Current

```
$bth=($ibz * $ibz * ($tas + $tcb+ $ar));
```

SC Thermal Withstanding

In addition to the PHP based calculations, there are various elements coded by HTML such as tables, checkboxes, numeric inputs, and radio buttons. Last but not least, there are algorithmic loops coded by JavaScript to verify the entries and to have instant reactions such as alerts, warnings, dropdown lists, and collapsible elements. In total, only the form itself consists of 1500 rows of code as the main part of the interface.

CONCLUSION

Currently, the issue of modernization of electric power facilities is of great importance, because the deterioration of equipment at some electrical installations is 50% or more. In addition, the digitalization of the industry and compliance with the IEC 61850 standard is the exclusion of leaving the situation in its current position.

In the study, firstly, the traditional solutions of substation design and modernization processes were examined based on the analysis of the past and future of electrical power systems. At this point, the basic requirements, standards, and visions of power systems were summarized taking into account the climate change and the obligations caused by the delayed awareness of this global problem. In addition, the sectoral acceleration that came with the demands for the reduction of carbon dioxide emission and the increase in generating energy by renewable resources were highlighted. The future potential of the substation design as a part of the transmission and sub-transmission system was examined concerning the aforesaid information.

The contribution to the development of substation engineering by the traditional design approach and modernization process has been researched considering the leading companies' products in the power equipment manufacturing sector. Attention was drawn to the orientation of the companies towards visionary and innovative solutions. The digital technologies and design-oriented interfaces that form the basis of this sectoral orientation are of great importance. Therefore, the use, potential, and possible advantages of a unique interface design are explained as part of both practical implementation and analysis of non-conventional solutions.

The development process of the interface which started at the beginning of the master's thesis period and will continue to be developed is explained in the light of cross-sectoral intersections. As well as the examined design and modernization-oriented auxiliary resources are pointed out.

A practical implementation part has been created to put the research done up to this part and the online substation designer interface, which is an essential part of the master's thesis, into practice with a solid example. In the practical implementation part, firstly "Modernization of 500 kV Switchgear by DCB Solutions" was examined, and the necessity and advantages of the modernization process in traditional substations were explained. In the modernization study the requirements and standards of electrical power systems, substation design, and modernization processes were examined in detail and the different benefits of variations were compared in the light of information obtained from contemporary sources with actual prices, and reliability indexes. As a result of these comparisons, the importance of critical points such as footprint, reliability, and cost, should be considered in substation design and modernization processes, and the importance of digital technologies and design-oriented interfaces that contribute to sectoral acceleration has been proven.

The mathematical calculations that form the basis of the design and modernization processes, were represented in the first part of the practical implementation and applied to the online version. Different combinations of parameters in this section created different variations that appeal to a variety of priorities. At the same time, the compatibility of the variation determined in the first part of the practical implementation with the calculations that form the theoretical basis of the balance between source and load is verified.

In the last part of the practical implementation, the manual calculations made in the second part were recalculated by the online substation design and modernization interface explained in the third chapter. In this section, the structure and use of the interface created are explained in detail, and the improvements made to meet user expectations and provide ease of use are mentioned. In this regard, the results of the Excel calculations which form the basis of the coded web-based interface, manual calculations, and the calculations of the web-based interface, were compared and the accuracy rates were highlighted.

Finally, the past and future trends of substation systems, global expectations, and sectoral visions, have been examined in a narrowing circle from general to specific, the benefits of innovative solutions have been proven with practical application, and a new one can be added to the web-based substation applications. The theoretical and practical results of the thesis can be applied to substantiating the modernization of existing substation switchgear for various voltage levels and further research in this engineering area.

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Appendixes

Table A 1

AT technical parameters (all AT are with Tap Changer)

Тип	Rated power, MVA		Rated voltage, kV			Tap Changer
	AT	LV wind	HV	MV	LV	
ASOFAF-167000/500/330-M1	167	33	500/√3	330/√3	10,5; 38,5	LTC at MV side ±12%, ± 8 steps
ASOFAF-167000/500/220-M1	167	50	500/√3	230/√3	10,5; 11, 0; 38,5	LTC at MV side ±12%, ± 6 steps
		6			10,5; 11,0	
ASOFAF-267000/500/220-M1	267	67	500/√3	230/√3	10,5; 38,5	LTC at MV side ±12%, ± 8 steps
ASOFAF-133000/330/220-M1	133	33	330/√3	230/√3	10,5; 38,5	LTC at MV side ±12%, ± 6 steps
ATOFAF-200000/330/110-M1	200	20	330	115	10,5	LTC at MV side ±12%, ± 6 steps
		80			6,3; 6,6; 10,5; 11,0; 38,5	
ATOFAF-125000/220/110-M1	125	63	230	121	6,3; 6,6; 10,5; 11,0; 38,5	LTC at MV side ±12%, ± 6 steps
ATOFAF-200000/220/110-M1	200	80	230	121	6,3; 6,6; 38,5	LTC at MV side ±12%, ± 6 steps
		100			10,5; 11,0	
ATOFAF-250000/220/110-M1	250	100	230	121	10,5; 27,5; 38,5	LTC at MV side ±12%, ± 6 steps
		125			10,5; 11,0	
ATOFAF-63000/220/110-M1	63	32	230	121	6,3; 10,5; 11,0; 38,5	LTC at MV side ±12%, ± 8 steps
ATOFAF-250000/500/110-M1	250	100	500	121	10,5; 38,5	LTC at MV side -

Table A 2

Circuit breaker nameplate parameters

№	Наименование параметров	Норма					
		ВГТ-УЭТМ®-330 У1 (31,5кА или 40кА)	**ВГТ-УЭТМ®-330 ХЛ*** (31,5кА или 40кА)	**ВГТ-УЭТМ®-330 У1** (50кА)	**ВГТ-УЭТМ®-500 У1** (31,5кА или 40кА)	**ВГТ-УЭТМ®-500 ХЛ*** (31,5кА или 40кА)	**ВГТ-УЭТМ®-500 У1** (50кА)
1	Номинальное напряжение, кВ	330			500		
2	Наибольшее рабочее напряжение, кВ	363			525		
3	Номинальный ток, А	2000, 2500 , 3150, 4000		3150	2000, 2500, 3150, 4000		3150
4	Номинальный ток отключения, кА	31,5; 40		50	31,5; 40		50
5	Номинальное относительное содержание апериодической составляющей, %, не более	47					
6	Параметры сквозного тока короткого замыкания						
	наибольший пик, кА (ток электродинамической стойкости)	100		125	100		125
	среднеквадратичное значение тока за время его протекания, кА (ток термической стойкости)	40		50	40		50
	время протекания тока термической стойкости, с	3					
7	Параметры тока включения, кА						
	наибольший пик	100		125	100		125
	начальное действующее значение периодической составляющей	40		50	40		50
8	Коммутация емкостного тока (класс С1)						
	номинальный ток коммутации ненагруженной воздушной линии, А	315			500		
	номинальный ток коммутации кабельной линии, А	355			500		
	номинальный ток коммутации одиночной батареи конденсаторов, А	400			400		
9	Нормированный ток отключения шунтирующего реактора, А	315±63					
10	Минимальный ток отключения шунтирующего реактора, А	100±20					
11	Собственное время отключения, с	$0{,}020^{+0{,}005}_{-0{,}002}$					
12	Минимальная бестоковая пауза при АПВ, с, не более	0, 3					
13	Собственное время включения, с, не более	0,070		0,080	0,070		0,080
14	Разновременность работы полюсов, с, не более						
	при включении	0,005					
	при отключении	0,0033					
15	Масса выключателя со стойками базовой высоты (2032) и приводами, кг, не более	9200			10800		

Table A 3

Optic current transformer nameplate parameters

Параметр	Значение
Номинальное напряжение, кВ	0 – 750
Номинальный первичный ток, А	100 – 3 000
Цифровой выход*	МЭК 61850-9-2LE (дублированный Ethernet 100Base-FX с поддержкой протоколов PTP и PRP)
Аналоговый выход	1А
Класс точности • для измерений • для защиты	• 0.2s (цифровой и аналоговый выходы) • 5TPE (цифровой выход)
Частотный диапазон, Гц	• 0 – 9000 (оптический датчик) • 0 – 5000 (SV256), • 0 – 2000 (SV80)
Диапазон рабочих температур, °С • измерительный датчик • электронный блок	• -60 ... +60 • -10 ... +40
Расстояние между датчиком и электронным блоком, м	до 1 200
Габаритные размеры, мм: • измерительный датчик (высота) • электронный блок	• 1 837 (110 кВ), 2 961 (220 кВ) • 480 (длина) x 380 (ширина) x 135 (высота)
Масса, кг: • измерительный датчик • электронный блок	• 65 (110 кВ), 120 (220 кВ) • 11
Энергопотребление (на один электронный блок), Вт	50
Наличие свидетельства о внесении в ГРСИ	Да

* Возможно исполнение с аналоговым выходом 1А для коммерческого учета

Figure A 1

Scheme of CT connection to processing unit

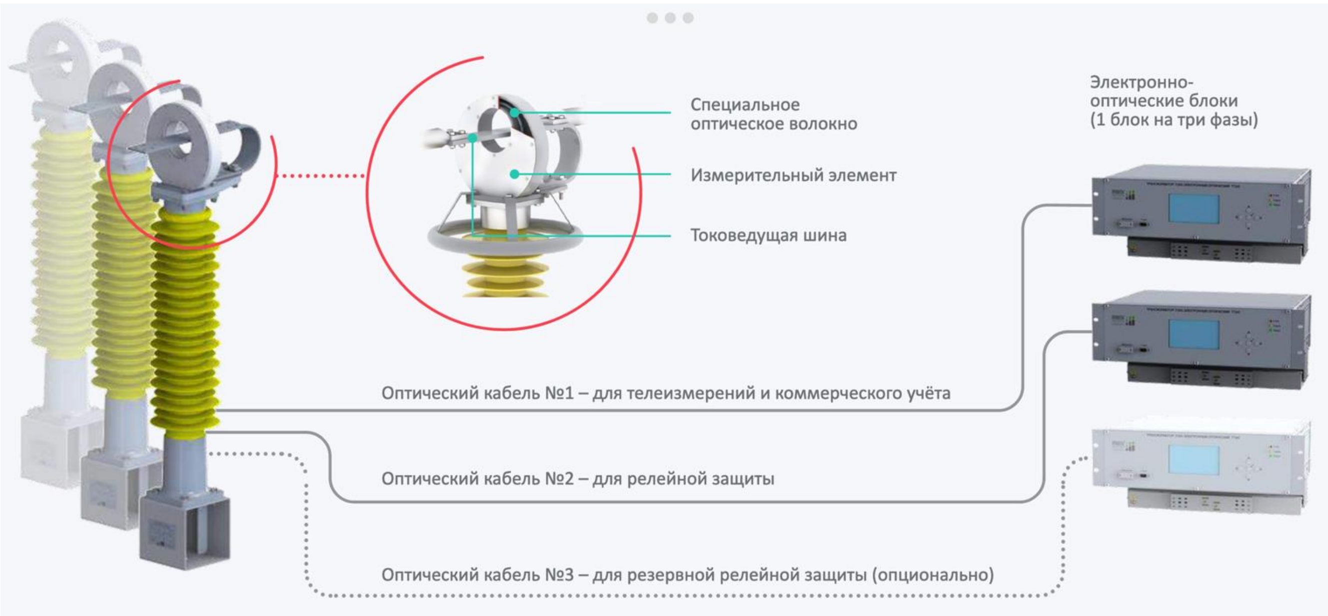


Table A 4

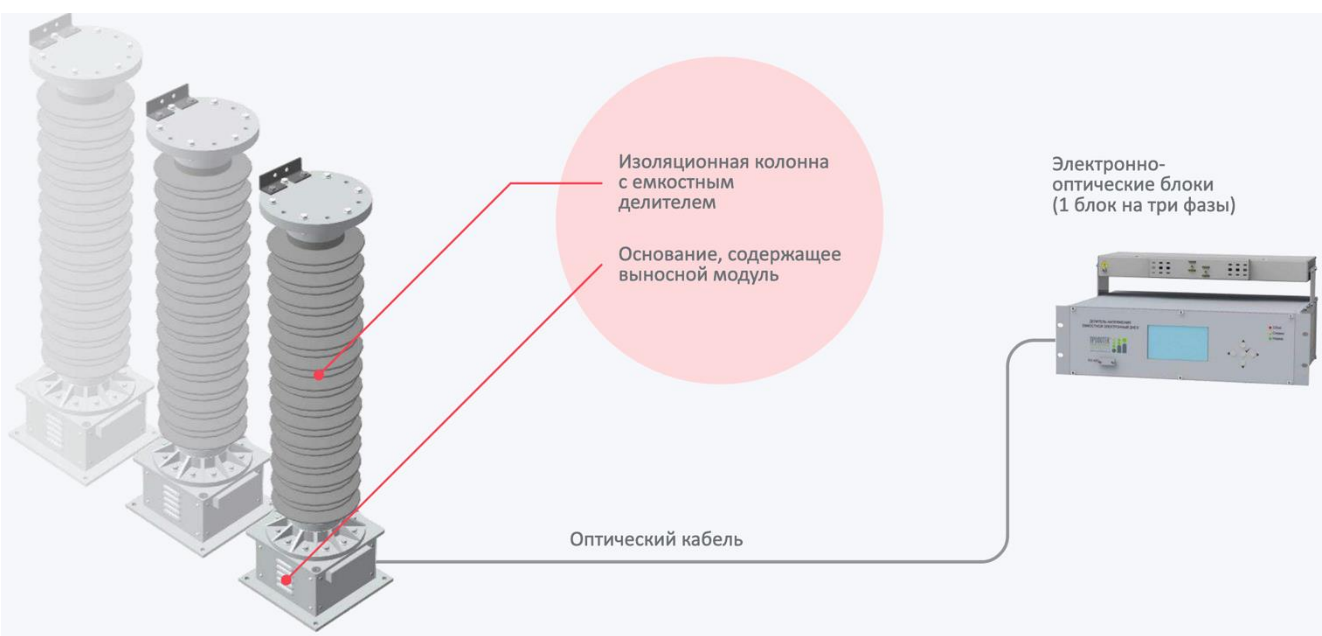
Electronic voltage transformer nameplate parameters

Параметр	Значение
Номинальное напряжение, кВ	110 – 220
Цифровой выход*	МЭК 61850-9-2LE (дублированный Ethernet 100 Base-FX с поддержкой протоколов PTP и PRP)
Класс точности (цифровой выход): • для измерений • для защиты	• 0.2 • 3P
Частотный диапазон, Гц	• 15 – 5 000 (для датчика напряжения) • 15 – 2 000 (SV80), • 15 – 5 000 (SV256)
Диапазон рабочих температур, °C • измерительный датчик • электронный блок	• -60 ... +60 • -10 ... +40
Расстояние между датчиком и электронным блоком, м	до 1 200
Габаритные размеры, мм: • измерительный датчик (высота) • электронный блок	• 1460 (110кВ), 2650 (220кВ) • 480 (длина) x 380 (ширина) x 135 (высота)
Масса, кг: • измерительный датчик • электронный блок	• 110 (110 кВ), 175 (220 кВ) • 8
Энергопотребление, Вт	50
Наличие свидетельства о внесении в ГРСИ	Да

* Возможно исполнение с аналоговым выходам (номинальное вторичное напряжение 100/√3)

Figure A 2

Scheme of VT connection to processing unit



End.