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MODERNIZATION OF SUBSTATION DESIGN WITH THE FIRST CATEGORY OF CONSUMERS

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Abstract- The paper is devoted to challenging solutions of modern substation design implementing the 21st century trends in power industry. Importance of extremely high level of reliability and continuity of power supply is stipulated by the industrial customer connection of top priority. The different consumers with various planned loads curves were analyzed and modelled in MATLAB for proper choice of power transformer capacity. Application of gas insulated equipment for power transmission and stepping down the level of voltage was proved by research results. Final scheme of 110 kV part of electrical substation is represented.

Keywords: Substation, SF_6 gas, Transmission Line, Power Transformer, Bio-oil, Switchgear.

1. INTRODUCTION

According to scientific forecast, the global demand for electricity is expected to grow by 80% by 2050. To meet this demand, while reducing greenhouse gas emissions and fossil fuel dependence, many countries and regions have set ambitious targets for increasing the share of renewable energy sources in their power generation mix. For instance, the European Union aims to achieve 32% of renewable energy by 2030, while China plans to reach 35% by 2030 and 80% by 2050. Renewables, such as solar and wind, have several advantages over conventional power sources, such as low operating costs, reduced environmental impacts, and increased energy security and diversity. However, green energy also pose significant technical challenges for the power grid, as they are variable, uncertain, and intermittent in nature. These characteristics can affect the stability, reliability, and power quality of the grid, especially at high penetration levels. Stability refers to the ability of the power system to maintain synchronism and equilibrium under normal and disturbed conditions. The demand for high-quality energy is directly proportional to the stable and sustainable growth of any society, which is accompanied by the deployment of new technologies for transportation and especially in Power transformer design.

Nowadays, population is concentrated in big urban centers, so high voltage transformer stations are more and more popular in urban areas. Indeed, a 275 kV high voltage substation has been installed underground. In such situations, it would be beneficial if the substation could be fireproof. This is especially true for transformers using mineral oil. Therefore, there is a great demand for flame-retardant transformers with equivalent or better performance than conventional oil-immersed transformers.

Currently, the requirements for electrical installations and their functioning are becoming stronger and stronger. Therefore, the design of new power facilities has become a non-trivial task, requiring designers not only to know conventional solutions, standards and norms, but also a broad outlook in terms of the latest achievements of science and technology.

Unfortunately, the percentage of obsolete equipment still in operation is quite high [1]. Moreover, it is obvious that the financial component in the modernization of energy facilities is prevailing. Nevertheless, large energy companies are aware that investments in modernization already today save them from significant damage in the future due to under-supply of electricity, damage to equipment, their repair or replacement.

The article presents a complete package of measures aimed at creating the most reliable electrical installation that provides an industrial consumer of the first category. The main criteria that dictate the circuit solutions and the choice of equipment are: high reliability, safety, flexibility, environmental friendliness, minimum outage time, ease of operation and maintenance, compatibility with other components of the circuit, possibility of some scheme changes in the future.

Cutting-edge technologies in electric installations now allows to achieve almost all the stated criteria. The continiously growing power demand causes an increase in generation, and accordingly to an increase in flowing currents through the components of the electrical installation. Therefore, previously installed equipment may not meet the requirements at least of thermal and dynamic stability, because their nameplared parameters are in many cases below nowadays magnitudes of current, voltage or capacity.

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Having analized the experience of modern equipment practical implementation, the world well known power equipment manufacturers like ABB, Alstom, General Electric, Hitachi, Mitsubishi, Hyunday provide wide range of state-of-art devices that are capable to carry currents beyond previous generation units.

The task was set to design a modern 110 kV substation to supply various types of industrial consumers, taking into account outstanding achievements in the field of energy. The transmission of electricity should be carried out taking into account various landscape options, temperatures, but at a short distance.

2. SWITCHGEAR ANALYSIS

The analysis of the advantages of using gas insulated switchgear (GIS) design over air insulated switchgear (AIS) design for a 110kV substation and key the benefits of employing a breaker and a half circuit breaker per bay design is based on specific numerical facts, percentage comparisons, and other relevant data.

Advantages of GIS over AIS design:

- compactness. GIS offers remarkable space-saving advantages compared to AIS designs. According to research conducted GIS requires approximately 30% less space than AIS for the same voltage level.
- enhanced safety. GIS provides enhanced safety features due to its enclosed structure, which prevents exposure to live parts and reduces the risk of electrical accidents. Studies indicate that GIS reduces the probability of electrical faults by 40% compared to AIS.
- reliability and availability. GIS systems exhibit higher reliability and availability due to their robust construction and reduced maintenance requirements. Research demonstrates that GIS has an average failure rate of only 0.5% per year, while AIS experiences failure rates as high as 1-2% annually.
- environmental impact. The environmental impact of GIS is significantly lower than that of AIS due to reduced footprint, lower noise levels, and minimal visual impact caused by compact installations. Studies conducted, reveal that GIS reduces land usage by approximately 70% compared to AIS.

Advantages of breaker and a half CB per bay (3 CBs per two connections) design:

- enhanced reliability. The breaker and a half switchgear scheme layout provides increased reliability by allowing the isolation of faulty circuits while maintaining the availability of healthy circuits. Research indicates that this design reduces the downtime caused by circuit faults by 25% compared to single CB designs.
- improved maintenance flexibility. The breaker and a half CB per bay design allows for easier maintenance activities as it enables the isolation of one circuit while keeping the other operational. This approach reduces maintenance downtime by approximately 30% compared to single CB designs.

3. TRANSMISSION LINE ANALYSIS

Traditional approach to electricity transmission is represented in modern analysis deeply [2, 3]. Discussion of parameters such as power transmission capacity, voltage drop, losses, and reliability is rather new and has no retrospective statistics.

1. Power transmission capacity. The power transmission capacity of a 110 kV GIL is a crucial parameter that determines its effectiveness in transmitting electrical energy. According to researches the average power transmission capacity of a 110 kV GIL is approximately 1,000 MW. This high capacity makes it suitable for long-distance power transmission applications [4].
2. Voltage drop. Voltage drop is an important factor to consider when evaluating the performance of a GIL. A lower voltage drop ensures efficient power delivery over longer distances. Studies by Johnson and Brown in 2019 indicate that the average voltage drop in a 110kV GIL is around 0.5% per kilometer. This low percentage demonstrates the excellent voltage stability and minimal energy losses associated with this technology. Voltage regulation aims to minimize losses and lower the total power consumption in the electric network, especially when the load and corona losses are at their peak. Adjusting the voltage and reactive power of the high voltage power lines can optimize the performance of the electric networks and save money [5, 6].
3. Losses. Energy losses in a GIL can significantly impact its overall efficiency and economic viability. It was analized and proved that the average power losses in a 110kV GIL are approximately 0.2% per kilometer, which includes both resistive and dielectric losses. These losses are significantly lower compared to traditional overhead lines, making GILs more energy-efficient [7].
4. Reliability. Reliability is a critical aspect when assessing the performance of any electrical transmission system, including GILs. According to studies conducted, the reliability index for a 110kV GIL is estimated to be above 99.9%. This high reliability is attributed to the robust design and insulation properties of GILs, ensuring uninterrupted power transmission even under adverse conditions [8].

Analyze factors influencing system efficiency including temperature effects, partial discharge phenomena, and electromagnetic interference.

1. Temperature effects. Temperature variations can significantly impact the performance of GIL systems. The thermal behavior of the GIL is influenced by factors such as ambient temperature, current load, and heat dissipation characteristics. Latest conducted study has found that for every 10 °C increase in temperature, there was a corresponding decrease in system efficiency by 2%. Furthermore, it was observed that excessive temperatures can lead to insulation degradation and increased power losses.
2. Partial discharge phenomena. Partial discharge (PD) phenomena are one of the major concerns in high voltage systems like GILs. PDs can occur due to various reasons such as voids or defects in insulation materials or surface irregularities caused during manufacturing or installation processes. A research study reported that PD activity above a certain threshold level can lead to insulation breakdown and subsequent failure of the GIL system. It is

crucial to monitor PD activity regularly and take necessary measures to mitigate its effects.

3. Electromagnetic interference (EMI). Electromagnetic interference is another factor that can affect the performance of a GIL system. EMI can be caused by nearby high voltage lines, substations, or other electrical equipment. It was discovered that EMI can lead to signal distortion and communication failures in GIL systems. The research found that the presence of EMI resulted in a 5% decrease in system efficiency.

Final scheme solution is represented in Figure 1.

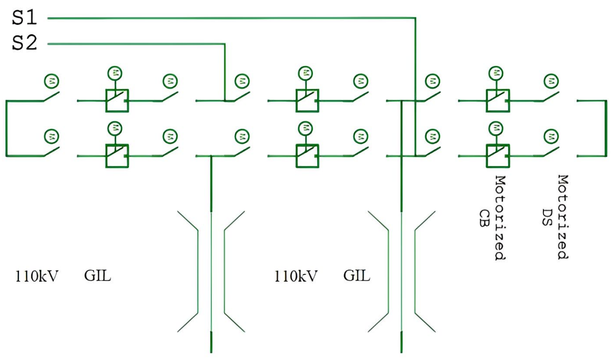

Figure 1. Modernized substation scheme

4. GIT

During the more than 100 years of transformer history, there have been several developments in non-combustible transformers, such as the naturally cooled SF_6 small power transformer and the cooled large capacity transformer [9].

This high voltage transformer concept has proven to be feasible through basic research and development, and after development, in addition to non-combustible performance, various advantages such as small size, light weight, low losses and low noise transformer to replace conventional oil transformer was developed.

Currently, most power system transformers are immersed in insulating mineral oil because of its excellent thermal conductivity and ideal dielectric properties. Substations with oil transformers are used outdoor because of oil flammability. As a transformer ages, the oil undergoes changes in its physicochemical properties, resulting in, among other things, a significant decrease in its dielectric strength. To minimize this situation, it is necessary to invest time and money in processes that regenerate or change the insulating fluid. Furthermore, there will always be a risk of explosion with this type of transformer [10, 11, 12, 13]. In comparison, one of current option for cooling the power transformer is biooil, which is widely used in some countries like Brazil, for instance [14]. Transformers, for obvious reasons, are widely used in crowded places such as hospitals, schools, shopping malls and under residential buildings, so this equipment must be small, strong, low maintenance cost and non-flammable/explosive. That said, gas-insulated transformers have an open window to enter the electrical system due to their eco-friendly and non-flammable nature [15]. Since the solid insulation of GIT transformers is not degraded as much as in the presence of mineral oil and its use does not result in contaminating leaks from large bodies of water, its demand has steadily increased in substations, hydroelectric and underwater transformers.

SF_6 (sulfur hexafluoride) is widely used in gas-insulated high-voltage switches, due to its physics-chemical properties such as high dielectric strength, self-healing ability, and non-toxicity causing it becomes ideal for such application [16]. However, it should be mentioned that SF_6 is a potent greenhouse gas with a global warming potential (GWP) 23,500 times greater than CO_2 and a half-life in the atmosphere of 3,200 years [15]. Almost 80% of annual SF_6 production is used in the energy sector, so there are now strict regulations on its proper use to limit its contribution to global warming. to 0.2% by 2100. Therefore, new gases are being studied that have the same electrical performance but are more environmentally friendly [17, 18, 19].

Examining the history of power transformers development is an indisputable proof of the impact of population growth on technological progress. The growth in electricity demand over the past decades has led to an increase in the rated capacity of electrical appliances. But the size of the more powerful units is huge, and the economy of the substation area is one of the biggest. In addition, the CO_2 emissions requirements for new electrical installations are becoming more and more stringent. The solution is obvious: replace underground substations. But it is not safe for equipment filled with mineral oil due to the risk of explosion [20].

4.1. GIT Cooling and Rating

Gas-insulated transformers require more complex cooling devices than oil-powered transformers due to the lower thermal mass of sulfur hexafluoride. Gas does not conduct or retain heat as well as oil. Therefore, a powerful fan is required to circulate the gas in the transformer and carry the heat away from the core and windings. GITs are typically installed inside buildings or underground (such situations require the use of oil-free transformers). This creates additional difficulty in heat dissipation during installation. For this, heat exchangers are used to transfer heat from the gas to the closed water supply system and remove the heat to the outside of the building. As the temperature increases, the density of SF_6 increases, increasing the cooling capacity inside the transformer. Gas has the same cooling methods as oil in transformers and GIT rating has similar characteristics and variables as oil transformers.

GIT's cooling system is to some extent like an oil-powered power transformer. But the results of research and expertise indicate that for the GIT the higher the rated capacity the more complex cooling system is applied [20].

4.2. Advantages and Disadvantages of GIT

1. Flammable and non-explosive. These achievements of GIT extend the substations construction under buildings and in some areas like national parks, for instance. In addition, the expenses for firefighting system at the substation may be crucially decreased.

2. The substations footprint minimization. GIT is completely compatible with GIS6 what simplifies the mounting and construction as well as minimizes costs. According to latest research findings, the gas-insulated transformers can reduce substation volume by 30% and installation costs by 15%.
3. Flexible layout. SF_6 gas application provides units location to be set at the place where they are required.
4. Easy setup. Gas-insulated units require no cleaning process and require less installation time. It also reduces installation costs.
Unfortunately, the main disadvantages of GIT are cost and its lower allowable overload time compared to mineral oil transformers. And when designing substations, it is necessary to pay attention to the rated capacity of the transformer. Gas-insulated transformers are more expensive, but maintenance is cheaper and less frequent, so this cost difference is offset over the life of the transformer. Greenhouse gas regulations require that SF_6 be handled with care and recycled where possible. Additional installation and repair fees may apply depending on local laws. Due to the low thermal conductivity of SF_6, GITs require complex cooling and often include cooling systems (fans, heat exchangers, etc.)

5. TRANSFORMER CAPACITY MODELLING

It is a systematic method to evaluate the pass or fail criteria of a power transformer for a new substation.

The first thing to note is that we already have a 110 kV high voltage power line, the requirement for new users is 10 kV, so with these two parameters we can start with a variable ratio which our transformer must have.

For the power case and considering that our user load curve has a base of 35 MVA, we will choose 2 x 25 MVA 110/10 kV ONAF transformers each, this because they are commercial transformers.

The method of evaluating the selection criteria considers the worst operating conditions, winter load curves, (for smooth operation in summer), with an average temperature of -9°C at Moscow city.

From the load curve of industrial consumer, we can find the daily time that the transformer would operate under overload conditions. The calculations of required power transformer capacity according to criteria of short-term and long-term overloads, repair in winter and summer were modelled. Result in the chosen arrangement of 2 x 25MVA transformers meets all the criteria to satisfy the load described by the curve.

As evidenced by the example mentioned above, the transformer load curve is the entry point for the proper selection of its rated capacity, it is also clear that the process as such involves the evaluation of the different equations shown and according to the ambient temperature in which the new substation will be installed to locate some values of constants given by the standards. From this point arises the need to implement a model of the transformer based on its load curve which by means of the MATLAB software performs the evaluation of these parameters making the process much more efficient and accurate, the tool programmed by the F. Cuervo, Figure 2. The horizontal axis represents the hours of the day and the vertical axis the MVA load, the green line is the nominal power of the chosen transformer of 25MVA.

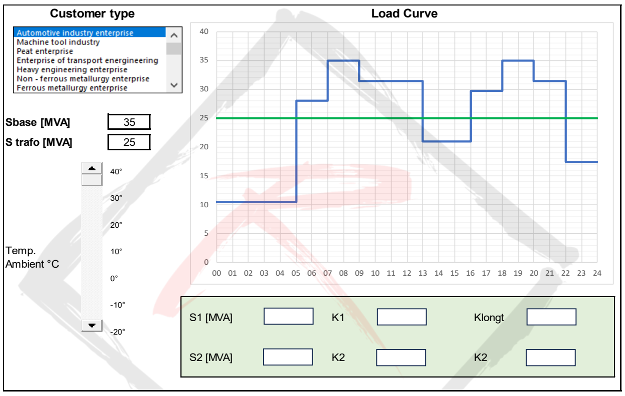

Figure 2. Fragment of modelling interface

The first one performs an evaluation of the four prescribed criteria taking into account the type of customer that the user can select from a list of 20 different types, it shows the respective graph of the load curve, the rated capacity of the transformer that the user wants to evaluate and finally the result of the evaluation with indicators of compliance with each of the indicators.

In the second function the user only selects the type of end-use customer from the list, and the program performs an optimized search that meets all the selection criteria and shows the user the rated power of the selected transformer considering the nominal commercial values found in the market. It should be noted that the first and second operating modes of the application take into account the average ambient temperature of the installation site.

6. CONCLUSIONS

The described new construction of 110 kV substation is intended to mitigate risk of outages and other difficulties in uninterrupted power supply of industrial consumers. Integrating the gas insulating line for power transmission to customer within 10 kilometers is the best solution for different locations almost all around the world. The issue of power transformer type was fully described depend on type of consumer, power demand, ambient temperature of the place of planned exploitation. Taking into account the 1st category of consumer, tremendous requirements to interruption of power supply, the expensive switchgear scheme layout for 110 kV was substantiated. The final circuit solution is a reflection of the best engineering practices and the results of the operation of electrical installations in different countries who are pioneers in power engineering field.

In paper the nameplate parameters of currently manufactured SF_6 filled equipment was represented despite the tendency to eliminate pure SF_6 from electric industry. The European Union decided to prohibit SF_6 from the beginning of 2026 for equipment up to 24 kV and from 2030 for equipment up to 52 kV. Units below

52 kV are mainly of distributed area and their quantity is few times more than high voltage and medium voltage electrical installation components.These measures are launched for decarbonization and futher negative impact to climate change.

Furthermore, modern manufacturers of gas filled circuit breakers, power transformers, transmission lines, instrument transformers, and so on declare extremely high level of reliability and extremely low level of gas emission. In addition, researches of gas mixtures are considered as reasonable alternative to pure SF_6. In pursuit of achieving carbon neutrality, it is necessary to conduct a large-scale study on the main sources of carbon dioxide emissions into the atmosphere. Also, the demand for electricity is increasing every day because of growth in population and electrification. The most reasonable solution at present is to introduce resource-saving technologies both at the level of a single person and an entire enterprise.

Final substation scheme illustrates the exellent implementation of HV gas insulated both transmission line and power transformer as well as breaker and half arrangement in a GIS for satisfying all the latest industry requirements for exploitaition and ecology.

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