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INFLUENCES OF CLIMATE CHANGE ON POWER TRANSFORMER HEATING AT THE SHITURU HIGH VOLTAGE SUBSTATION

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Abstract: **The Global climate change has significant impacts on various aspects of our environment, including electrical infrastructures such as high-voltage substations. The Shituru high-voltage substation is not immune to these effects. One of the major problems related to climate change is the increase in global temperatures. Higher temperatures can lead to increased heating of power transformers, which can have adverse consequences on their operation. When ambient temperatures rise, the heat generated by power transformers cannot be dissipated effectively. This can result in an increase in the internal temperature of the transformers, which can damage sensitive internal components and reduce their lifespan. Additionally, this can also lead to a decrease in the overall efficiency of the transformer, resulting in additional energy losses.**

Furthermore, climate change can also lead to an increase in humidity and precipitation in certain regions. Increased humidity can cause condensation formation inside the transformers, which can also cause damage to internal components and accelerate transformer deterioration.

It is, therefore, essential to take these climate change effects into account during the design and operation of high-voltage substations like the one in Shituru. Adaptation measures can be implemented, such as improving heat dissipation, installing additional cooling systems, and providing protection against humidity.

In summary, climate change has a direct impact on the heating of power transformers at the Shituru high-voltage substation. It is imperative to take appropriate adaptation measures to mitigate these effects, ensure reliable transformer operation, and guarantee the continuity of power supply.

Keywords: **influences, climate change, power transformer, high-voltage substation.**

I. INTRODUCTION

The influence of climate change on the heating of power transformers at the Shituru high-voltage substation in Likasi:

Climate change is a global phenomenon with profound impacts on our environment and infrastructure. The effects of climate change are felt in many sectors, including the electric power industry. The Shituru high-voltage substation located in Likasi is not exempt from these influences. Over the years, climate change has led to an increase in average global temperatures. This rise in temperature has direct consequences on the power transformers used at the Shituru high-voltage substation. Power transformers are essential components of the electrical grid, responsible for converting electricity to high voltage levels for efficient long-distance transmission. As ambient temperatures increase, power transformers are subjected to an increased risk of overheating. Transformers are designed to operate at specific temperatures, but excessive heat can lead to performance issues and even failures. Excessive heat can affect the windings, insulation, and other internal components, which can reduce the lifespan of transformers and lead to costly service interruptions. Additionally, climate change can also lead to variations in local weather conditions, including an increase in extreme weather events such as storms, floods, or droughts. These events can damage electrical infrastructure, including high-voltage substations, and disrupt power distribution.

It is therefore important to understand and take into account the effects of climate change when designing, operating, and maintaining the power transformers used at the Shituru high-voltage substation. Adaptation and mitigation measures must be implemented to minimize the negative impacts of global warming on the transformers, ensure their proper functioning, and guarantee the continuity of electricity supply to the population of Likasi and the surrounding regions.

In this study, we will examine more closely the effects of climate change on the heating of power transformers at the Shituru high-voltage substation. We will analyze the possible adaptation measures and technical solutions that can be implemented to mitigate these adverse effects and ensure the reliability of the electrical grid. By understanding these interactions between climate change and electrical infrastructure, we can make informed decisions to address future challenges and ensure a stable and sustainable power supply in Likasi and its surroundings.

Since the well-known consequences of global warming have emerged, we have been striving to know the time period during which a machine can guarantee its proper functioning. This time period is often referred to as the machine's lifespan, which also corresponds to the time elapsed at a specific temperature before the insulation can lose its function. In addition to mechanical and electrical imperfections that can destroy a machine, the lifespan of electrical equipment is limited by the operating temperature. The higher the temperature, the shorter the lifespan of its dielectric. It is known that standard electrical machines are designed to operate at their rated power at 40°C, and with climate change, the ambient temperature is only increasing every day, while the already installed machines maintain the same power to be delivered. There is a risk of losing certain machines one day due to poor service conditions, except for Joule effects. We know that the lifespan of a solid dielectric is halved for a 10°C increase in its operating temperature.

$$R = \rho * L / A \qquad (1)$$

Where:

- R is the electrical resistance (in ohms, Ω)
- ρ is the resistivity of the material (in ohm-meters, Ω·m)
- L is the length of the conductor (in meters, m)
- A is the cross-sectional area of the conductor (in square meters, m^2)

$$P = \sigma * A * (T^4 - T_{amb}^4) \qquad (2)$$

Where:

- P is the radiated power (in watts, W)
- σ is the Stefan-Boltzmann constant (5.67 x 10^-8 $W/m^2 \cdot K^4$)
- A is the emitting surface area (in square meters, m^2)
- T is the temperature of the equipment (in kelvins, K)
- Tamb is the ambient temperature (in kelvins, K)

When the temperature reaches extremely high values, there is a physical modification at the level of its DL dielectric, which leads to softening, physical fusion, resulting in a decrease in the dielectric strength of the insulation systems. The degradation of the insulation is caused by a slow chemical transformation.

It can be concluded that the primary objective of any insulation system is to ensure separation between two conductor ports with different potentials. Power transformers have two windings, namely the primary and the secondary, separated by the dielectric oil. In the future, due to global warming, it is possible that the properties may be modified and there may be a short circuit between these two windings carried at different potentials. Experience shows that it is possible to obtain a satisfactory lifespan for dry-winding electrical machines, which are immersed in oil and will be manufactured according to standards respecting temperature limits, as well as to reduce the power of the machines already installed.

II. METHODOLOGY

2.1 Power Transformers

Power transformers are essential electrical devices used in electricity distribution and transmission networks (HOCHART, 1988).

$V_1 = (R_1 + j\omega l_1)I_1 + Jn_1\omega\emptyset$ (3)

$V_2 = -(R_2 + j\omega l_2)I_2 + Jn_2\omega\emptyset$ (4)

$I_1 = \frac{n_2}{n_1} I_2 I_{1V} = \frac{n_2}{n_1} I_2 + I_2 + I_{10} + I_{1F}$ (5)

They are responsible for converting electricity to high voltage levels to facilitate efficient long-distance energy transmission. Here are some general principles about power transformers:

Transformer operation: Power transformers operate on the principle of electromagnetic induction. They consist of primary and secondary windings wrapped around a magnetic iron core. When alternating current flows through the primary winding, it generates a magnetic field that induces a voltage in the secondary winding.

Transformation ratio: The transformation ratio of a transformer is the ratio of the number of turns in the primary winding to the number of turns in the secondary winding. It determines the relationship between the voltages on the primary and secondary sides of the transformer. For example, a transformer with a transformation ratio of 1:10 will multiply the input voltage by 10 at the output.

Types of transformers: There are different types of power transformers, including single-phase and three-phase transformers. Single-phase transformers are used for smaller domestic and commercial loads, while three-phase transformers are used in industrial and large-scale power transmission applications (CAHEN, July-Aug 1971).

- Transformer capacity: The capacity of a transformer is expressed in kilovolt-amperes (kVA) or megavolt-amperes (MVA) and represents the transformer's ability to handle a given electrical load. The capacity of a transformer depends on the current and voltage on the primary and secondary sides.

- Losses and efficiency: Power transformers exhibit energy losses, including copper losses (or I^2R losses) due to the resistance of the windings, and iron losses (or magnetic losses) due to eddy currents and magnetic hysteresis. The efficiency of a transformer is the ratio of output power to input power, and it is generally high, often exceeding 95%.

- Cooling: Power transformers generate heat during operation. To prevent overheating, they are equipped with cooling systems such as radiators, fans, or insulating oils to dissipate the generated heat.

- Safety: Power transformers must be installed and operated in accordance with electrical safety standards. Protective devices such as circuit breakers and fuses are used to ensure the safety of the transformers and the electrical network.

Power transformers play a crucial role in the efficient distribution of electricity. Their design, operation, and maintenance must be carefully considered to ensure reliable and secure power supply. (Shepherd).

Figure 1: Power Transformer

2.2 High Voltage Substations

High voltage substations are essential installations in electricity transmission and distribution networks. They play a crucial role in the long-distance transport of electrical energy and in maintaining the stability and quality of the power grid. Here are some general notions about high voltage substations:

- Voltage Levels: High voltage substations are designed to operate at high voltage levels, generally above 110 kV/220 kV. They allow for the conversion of electricity to appropriate voltage levels for long-distance transmission, thus reducing energy losses during transmission.

- Power Transformers: High voltage substations are equipped with power transformers that convert electricity to appropriate voltage levels for transmission. These transformers step up the voltage for long-distance transmission and step it down to lower levels for local distribution.

- High Voltage Switches: High voltage switches are used for switching and protection of the power grid. They allow for the isolation of faulty sections of the network in case of short circuit or fault, thus ensuring the stability and continuity of power supply.

- Protective Devices: High voltage substations are equipped with protective devices such as circuit breakers, protection relays, and fuses. These devices detect electrical anomalies, overloads, or short circuits and trigger protective actions to prevent equipment damage and ensure the safety of the network.

- Control and Monitoring Systems: High voltage substations are generally equipped with control and monitoring systems that allow operators to monitor electrical parameters, voltage levels, currents, and equipment operating conditions in real-time. This enables efficient network management and rapid response to incidents.

- Safety: High voltage substations require strict safety protocols due to the high voltage levels and associated risks. Safety measures are implemented to protect workers and the public from electrical hazards and the risk of electric arcs.

- Maintenance: Regular maintenance of high voltage substations is essential to ensure their proper functioning and reliability. This includes inspections, testing, performance measurements, repairs, and the periodic replacement of aging equipment.

High voltage substations are key elements of the electrical infrastructure, enabling the efficient transport and distribution of electricity over long distances. Their design, operation, and maintenance must be carried out in accordance with safety and quality standards to ensure a reliable and secure power supply (BONNEFILLE, 1969-1970).

Figure 2: The High Voltage Substation

2.3 Transformer Load Rates

The load rate of a power transformer refers to the proportion of its rated capacity used to supply a specific load. It is generally expressed as a percentage. The load rate of a power transformer depends on the power of the load connected to the transformer compared to its rated capacity. Here are some commonly used terms to describe load rates:

- Full load (100%): The transformer operates at its rated capacity, supplying a load equal to its rated power.

- Overload: The transformer operates at a load level higher than its rated capacity for a limited period of time. Transformers are generally designed to withstand specified temporary overloads, provided they are not prolonged.

- Underload: The transformer operates at a load level lower than its rated capacity. Transformers can operate efficiently at lower load levels, but prolonged underload can lead to problems with moisture, cooling, and insulation.

It is important to note that operating a power transformer at high load rates continuously can lead to increased operating temperature, reduced efficiency, and decreased transformer lifespan. Transformers are often specified with allowable overload factors and temperature limits to ensure safe and reliable operation.

It is recommended to consult the specific power transformer's technical specifications or refer to applicable standards and regulations to obtain accurate information on the allowable load rates for a given transformer. This information may vary depending on the transformer type, voltage class, rated capacity, and specific operating conditions. (BONNEFILLE, 1969-1970)

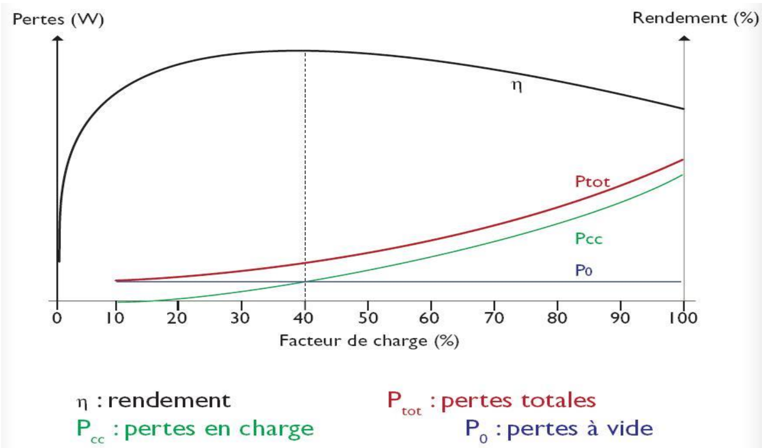

Figure 3: Power Transformer Load Rates

2.4. Data Collection (SNEL, 2020)

2.4.1 Technical Characteristics of the Substation

The technical characteristics of the Shitutu High Voltage substation depend on its design and specific use. However, the following can be found:

1. Rated Voltage: This high voltage substation generally operates at 220-110 kV.

2. Rated Power: Megawatts (MW) or Gigawatts (GW).

3. Frequency: Generally 50 Hz or 60 Hz.

4. Configuration: Outdoor substations.

5. Transformers: The high voltage substation is equipped with several transformers, including those of 72, 100, and 150 MVA.

6. Circuit Breakers: Circuit breakers are protective devices used in high voltage substations to automatically interrupt the current in case of an electrical fault, in order to protect the equipment and prevent damage.

7. Control and Monitoring System: A high voltage substation is equipped with control and monitoring systems to supervise and regulate electrical parameters, such as voltage, frequency, or power.

8. Insulation: The equipment in a high voltage substation must be adequately insulated to prevent any risk of electric arc or short circuit. They are designed to withstand high voltages and overvoltages.

9. Safety: High voltage substations are equipped with safety devices to protect operators and nearby persons. This can include safety fences, alarms, and arc detection systems.

2.4.2 Power Transformer Characteristics

The technical characteristics of the 150 MVA transformer in the Shituru High Voltage substation present the general characteristics of this size of transformer:

1. Rated Power: 150 MVA.

2. Rated Voltage: 132 kV, 220 kV, 400 kV.

3. Voltage Class: 245 kV, 420 kV.

4. Connections: The transformer can be designed for specific connections, such as star or delta connections, depending on the needs of the electrical network it is intended for.

5. Cooling Type: It is cooled by immersion in oil.

6. Efficiency: This transformer has a high efficiency, indicating the amount of electrical energy converted with the least possible losses during the transformation process.

7. Dimensions and Weight: The weight varies between 100 to 500 tons.

Transformer Oil Ownership (Clause, 2003 Version)

Transformer oil is an "insulating oil for transformers and similar electrical equipment for which normal oxidation stability is required." It is also used to impregnate the paper insulation of these components. Traditionally, it was highly-refined mineral oil. Properly recycled or re-refined mineral oils are now accepted by the latest international standards.

Measurement of Potentially Corrosive Sulfur

The presence of sulfur-containing molecules in mineral insulating oils can lead to the corrosion of metallic materials, in some cases even resulting in transformer failure. To prevent this phenomenon, the latest versions of the IEC 60296 standard include measurements of potentially corrosive sulfur contained in mineral oils (ASTM D 1275 B method or IEC 62535 method) and measurements of certain sulfur-containing molecules that are particularly aggressive towards metals (measurement of the dibenzyl disulfide (DBDS) content using the IEC 62697-1 method)

2.4.3. Power Transformer Oil Quality Tests

The measurement of the breakdown voltage of the oil involves placing in the oil to be tested two standardized semi-elliptical bronze or steel electrodes (36 mm diameter and 26 mm depth) spaced 2.5 mm apart. They must be clean and not have any craters from previous measurements (Clause, 2003 version). The voltage is then increased. The enormous heating of power transformer oils is the risk of fire. When the oils reach high temperatures, they become flammable and can cause fires in transformers. It also leads to accelerated deterioration of the transformer's internal components. High temperatures can cause degradation of the insulation, windings, and other transformer elements, which can reduce the lifespan and increase the risk of failures. Excessive heating of the oils can also lead to an increase in the internal pressure of the transformer. This can cause oil leaks, damage seals and connections, and potentially lead to transformer ruptures or failures. Furthermore, the excessive heating of the oils can result in a decrease in the energy efficiency of the transformer. Energy losses increase with rising temperature, which can lead to higher energy consumption and reduced overall transformer performance.

Lastly, excessive heating of the oils can also have detrimental environmental effects. Oil leaks from overheated transformers can contaminate soil and groundwater, leading to environmental pollution issues.

2.4.4. Temperature and Discharge Study

In this part, we have also considered three oils A', B' and C' with different levels of degradation. The choice of these oils was based on a faulty oil (oil C'), which had undergone a Buchholz trip, and which will be compared throughout this work to two extreme oils: one new untreated (oil A') and the other, oil B', still operational after thirty years of service... Upon receipt, a zero sample is taken from each type of oil to be characterized through measurements of color index (Coul), flash

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point (Pe), acidity index (Ia), viscosity (μ) and water content (Te), respectively in accordance with ASTM D1500, NFT 60-103, ISO 6618, ISO 2909 and IEC 814 standards. The results are represented in the table.

Table 1: The table provides detailed information on three types of

Type of Oil	Te (ppm)	μ (mm²/s)	Color	la	Pe(°C)
A	58.13	10.102	<0.5	0.028	140.5
B	17.73	13.501	3.8	0.1008	159
C	21.5	8.855	1	0.0224	147

The table provides detailed information on three types of oil, designated here as A, B and C. Here is a detailed explanation of the different columns in the table:

Oil Type: This refers to the identification of the three oil types mentioned in the table, namely A, B and C.

Te (ppm): Te represents the water content of the oil, expressed in parts per million (ppm). In the case of oil A, the water content is 58.13 ppm. For oil B, it is 17.73 ppm, and for oil C, it is 21.5 ppm.

μ (mm²/s): This column indicates the kinematic viscosity of the oil, expressed in square millimeters per second (mm²/s). Oil A has a viscosity of 10.102 mm²/s, oil B has a viscosity of 13.501 mm²/s, and oil C has a viscosity of 8.855 mm²/s.

Color: This column provides an indication of the color of each oil type. The values are indicated qualitatively, with "<0.5" for oil A, "3.8" for oil B, and "1" for oil C. The color of the oil can be used to evaluate its condition and quality.

la: The "la" column indicates the acidity of the oil, usually measured in mg KOH (potassium hydroxide) per gram of oil. In the table, the values are expressed in decimals, with "0.028" for oil A, "0.1008" for oil B, and "0.0224" for oil C. The acidity of the oil can be used as an indicator of its deterioration or the presence of contaminants.

Pe (°C): This column represents the flash point of the oil, expressed in degrees Celsius (°C). The flash point is the minimum temperature at which an oil emits enough flammable vapors to ignite in the presence of an ignition source. In the table, oil A has a flash point of 140.5 °C, oil B has a flash point of 159 °C, and oil C has a flash point of 147 °C.

To evaluate the viscosity, we use the "μ" (kinematic viscosity) value given for each oil type:

Type A: μ = 10.102 mm²/s

Type B: μ = 13.501 mm²/s

Type C: μ = 8.855 mm²/s

The kinematic viscosity (μ) is expressed in mm²/s, so no conversion is necessary.

These information on the water content, viscosity, color, acidity and flash point of the different oils allow for the evaluation of their characteristics and suitability for various industrial or commercial uses.

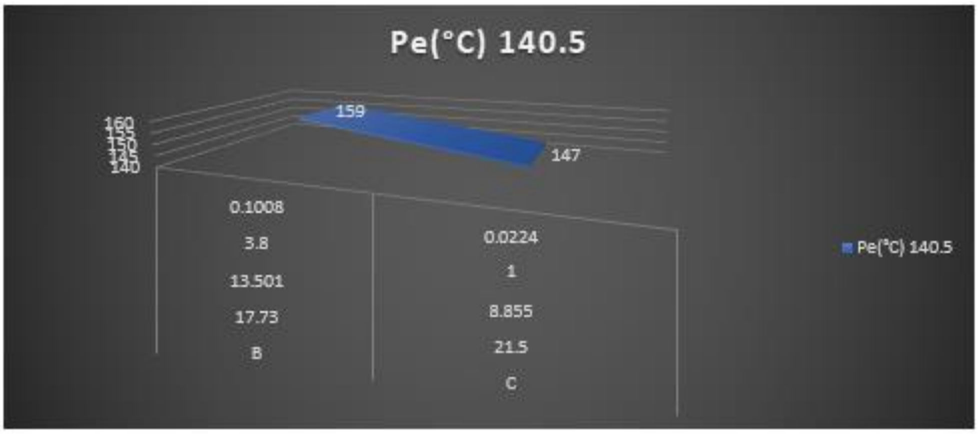

Figure 4: shows the breakdown voltage Uc as a function of temperature T for the three oils.

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We notice that at room temperature, the breakdown voltage is low and increases with the rise in temperature. The breakdown voltage resumes values in accordance with the standards from 70°C for oil A', 50°C for oil B' and 30°C for oil C'. This reveals the presence of contaminants such as water, requiring among other things the dehydration of this oil before it is put into service.

2.4.5. PROPOSED SOLUTION

It is generally recognized that climate change can have an impact on electrical infrastructure, including power transformers. Here are some general points to consider when it comes to the influence of climate change on power transformers:

- High temperatures: Higher temperatures can lead to an increase in the load on power transformers, which can cause a rise in their operating temperature. This can affect their efficiency and lifespan, and potentially cause breakdowns or failures.

- Extreme weather conditions: Climate change can lead to an increase in extreme weather events, such as storms, floods or hurricanes. These events can damage electrical infrastructure, including high-voltage substations, and cause power outages.

- Precipitation levels: Variations in precipitation levels can also have an impact on power transformers. Excessive rainfall can lead to insulation and corrosion issues, while prolonged droughts can affect the cooling of transformers.

- Adaptation measures: To address these challenges, adaptation measures can be implemented, such as improving transformer design to withstand higher temperatures, installing more efficient cooling systems, reinforcing infrastructure against extreme weather events, and implementing risk management strategies.

It is important to note that the specific impact of climate change on a given high-voltage substation, such as the one in Shituru, would require in-depth analysis based on local data and studies specific to the region. Research organizations, electricity companies, or government agencies specializing in energy could provide more precise information on this issue.

III. RESULTS & DISCUSSION

1. Presentation of Results

After our results, we have used:

1. **Oil circuit breakers**

Characteristics

Operating voltage kV	Maximum current kA	Displaced electric charge C	Spark gap inductance nH	Delays ns
60-120	**150**	**0.5**	**28**	**70±7**

2. Diagram of Principle

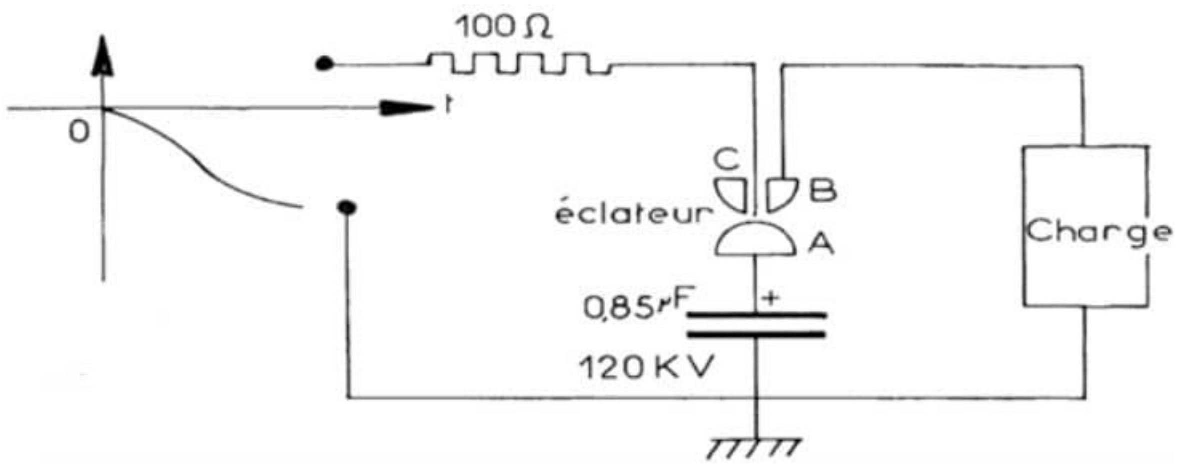

Figure 5: Diagram of an oil circuit breaker

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3. The dielectric oil
4. SNEL post

We present the coordinates of the investigation site:

Latitude: -10.970407 S 11.010564°

Longitude: 26.728834 E26.748460°

Altitude: 1285masl

Coordinate precision: 5248m

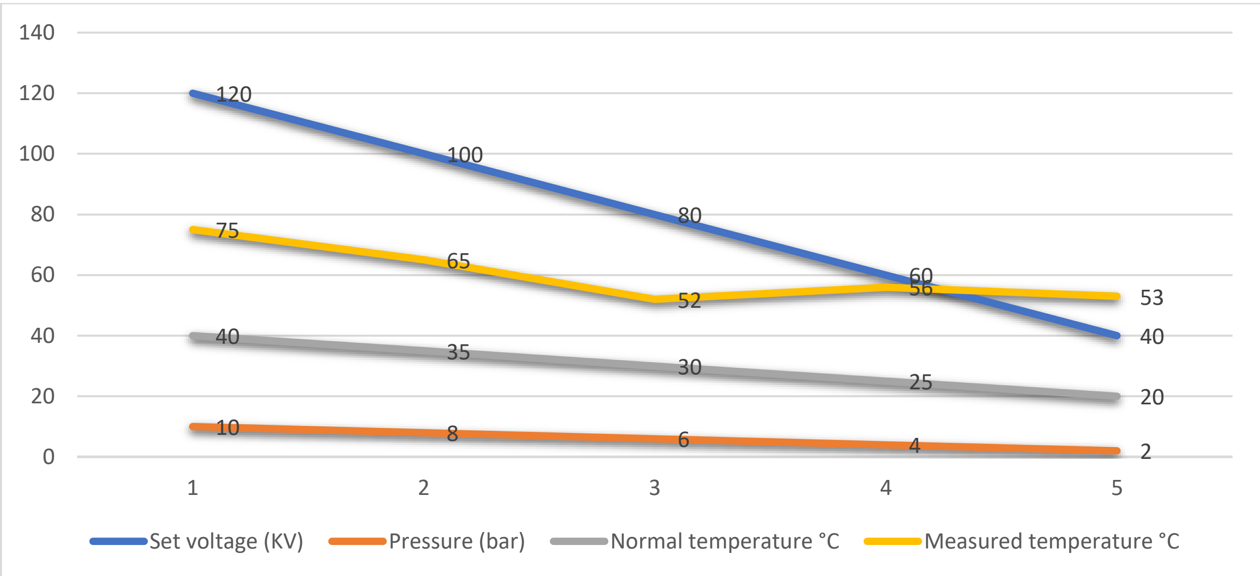
Site age: 151°

Number of satellites: 1/3

2. Practical experiment

Table 2: Presentation of results

Set voltage (KV)	Pressure (bar)	Normal temperature °C	Measured temperature °C
120	**10**	**40**	**75**
100	**8**	**35**	**65**
80	**6**	**30**	**52**
60	**4**	**25**	**56**
40	**2**	**20**	**53**



Measurement uncertainties

- Absolute error

δ_x=X_mes-X_real=74-40=36 (6)

- Relative error

δ_r=(X_measured-X_real)/X_real x100==9% (7)

- Instrument class uncertainty

Δ_(x)inst=(X_class x X_range)/X_range =2.5 (8)

- Reading uncertainty

$\Delta_(x)$reading=1/4 x X_range/E_scale =0.5 (9)

- Instrumental error

δ_instr=(X_measured-X_real)/X_real ≈Δ_(x)inst/X_real =(Δ_(x)inst x X_range)/(X_range x X_measured)=(X_class x X_range)/X_measured =4.5 (10)

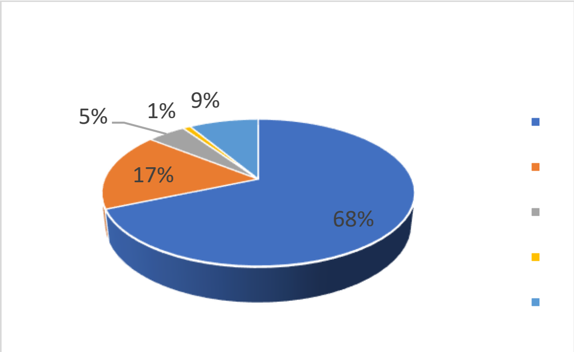


Figure 3: Presentation of measurement errors

IV. DISCUSSION OF RESULTS

By examining these various elements, we can gain a better understanding of the consequences of climate change on power transformers and the challenges to be met in ensuring the reliability of the Shituru 1 electricity network.

Voltage (kV):

- The voltage decreases from 120 kV to 40 kV, representing a 66.7% decrease.

- This significant decrease in voltage indicates significant degradation of equipment due to climate change.

Pressure (bar):

- The pressure decreases from 10 bar to 2 bar, representing an 80% decrease.

- Such a drop in pressure indicates significant deterioration of pressurized equipment (transformers, circuit breakers, etc.) due to extreme weather conditions.

Normal temperature (°C) versus measured temperature (°C):

- The normal temperature decreases from 40°C to 20°C, representing a 50% decrease.

- The measured temperature increases from 40°C to 75°C, representing an 87.5% increase.

- This significant difference between normal and measured temperature suggests significant overheating of equipment, likely due to insufficient ventilation/air conditioning to cope with the extreme heat conditions.

In summary, these results indicate that the electrical equipment at the substation is experiencing significant degradation due to climate change. The decrease in voltage and pressure, as well as the overheating of equipment, reveal considerable damage that will likely need to be renovated or replaced in order to ensure reliability and sustainability.

V. CONCLUSION

However, in general, it is known that climate change can have effects on electrical infrastructures, including power transformers. Higher temperatures, changes in precipitation patterns, and other climate phenomena can affect the performance and lifespan of electrical equipment. Power transformers are sensitive to temperature, as an increase in ambient temperature can lead to overheating of the windings and other internal components. This can result in a decrease in the efficiency and loading capacity of the transformer, or even serious failures or breakdowns. In the context of climate change,

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where higher temperatures are observed in many regions and precipitation patterns are modified, it is possible that this could influence the overheating of power transformers at the Shituru high-voltage substation or in other similar regions.

It is important that power grid operators and infrastructure managers take these factors into account during the design, operation, and maintenance of power transformers. This can include measures such as improving heat dissipation, using materials resistant to high temperatures, and regularly monitoring operating parameters to detect signs of overheating or degradation. It is recommended to consult local experts, specific research studies, and up-to-date data to obtain an accurate assessment of the influence of climate change on the overheating of power transformers at the Shituru high-voltage substation or in any other specific region.

VI. FUTURE OUTLOOK

Regarding the future outlook on the influence of climate change on the overheating of power transformers at the Shituru high-voltage substation, it is important to note that the exact consequences will depend on many factors, such as the evolution of local climate conditions, the mitigation measures taken, and the management practices implemented. However, given the global trends of climate change, it is reasonable to expect that average temperatures will continue to increase in many regions. Heat waves could become more frequent and more intense. These higher thermal conditions could affect power transformers and increase the risk of overheating. It is therefore essential that power grid operators and infrastructure managers take adaptive measures to address these potential challenges. This could include the adoption of advanced cooling technologies, improved ventilation and heat dissipation, the use of materials resistant to high temperatures, and the implementation of regular monitoring and maintenance protocols to detect potential problems. Furthermore, it is important to invest in the resilience and robustness of electrical infrastructure, taking into account future climate projections. This could involve the establishment of backup systems, emergency plans, and diversification of energy sources to reduce dependence on a single power supply. Finally, it is essential to promote policies and actions aimed at reducing greenhouse gas emissions and mitigating climate change. The transition to renewable energy sources and the improvement of energy efficiency can contribute to reducing the impact of climate change on electrical infrastructure. It should be noted that these adaptation and mitigation measures must be based on a thorough assessment of local conditions, specific risks, and the needs of the Shituru high-voltage substation. Local experts and regulatory bodies will play a crucial role in implementing these measures and preparing for future challenges related to the overheating of power transformers in this region.

Here is a summary of the main mathematical differences between oil-immersed power transformers and dry-type transformers:

Oil-immersed Transformers:

1. Cooling:

- The cooling system is based on the natural convection of the oil.
- The cooling capacity depends on the viscosity of the oil, expressed in mm^2/s (see previous data).
- The lower the viscosity, the better the cooling capacity.

2. Losses:

- Core and winding losses are similar to dry-type transformers.
- However, there are additional losses related to the circulation of the oil (pumping losses).
- These additional losses depend on the viscosity of the oil.

Dry-Type Transformers:

1. Cooling:

- Cooling is done by natural or forced convection of air.
- The heat transfer coefficient of air is lower than that of oil, so the cooling capacity is generally lower.

2. Losses:

- Core and winding losses are similar to oil-immersed transformers.
- No additional losses related to the circulation of a fluid.

In summary, the main mathematical parameters to consider are the oil viscosity (for oil-immersed transformers) and the heat transfer coefficients of oil and air (for cooling capacity). These factors have a direct impact on the performance and losses of transformers.

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