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Electrical Engineering

# ***Assessment and Modernization of Relay Protection Systems for Auxiliary Transformers at Thermal Power Plant No. 4***

Bachelor Thesis

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#### **Assessment and Modernization of Relay Protection Systems for Auxiliary Transformers at Thermal Power Plant No. 4**

I did not use any sources other than those stated. In case that the work is additionally submitted on a data medium, I declare that the written and the electronic form are completely identical. The work was not submitted in the same or similar form to any examination authority.

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## ABSTRACT

This thesis presents an engineering assessment and modernization proposal for the relay protection system of auxiliary transformer 2BT at Thermal Power Plant No. 4 in Mongolia. The reliable operation of the auxiliary power supply system is essential for maintaining the continuous and safe operation of major plant auxiliaries, including boiler feed pumps, draft fans, circulating pumps, and other motor-driven equipment required for unit operation.

The study evaluates the technical condition of the existing 25 MVA, 10.5/6.3/6.3 kV auxiliary transformer 2BT and its associated relay protection system. The assessment includes connected load analysis, transformer loading verification, short-circuit current calculation, review of the existing protection functions, selection of a suitable replacement transformer, and calculation of relay protection settings for the proposed modernization scheme. The load calculation was performed using the demand-factor method, while the short-circuit current calculation was carried out using the per-unit method.

The calculated apparent load of transformer 2BT is 26.25 MVA, which exceeds the rated capacity of the existing 25 MVA transformer. This indicates insufficient loading reserve under the considered operating condition and justifies the replacement of the existing unit with a higher-rated transformer. Based on technical compatibility and capacity requirements, the ТРДН-32000/10 Y1 transformer with a rated power of 32 MVA is selected as the preferred replacement option. The calculated three-phase short-circuit currents are 26.07 kA at the 10.5 kV side and 15.08 kA at the 6.3 kV auxiliary bus section.

The existing electromechanical relay protection devices are identified as technologically outdated due to limited setting flexibility, absence of self-diagnostics, lack of disturbance recording, and restricted communication capability. Therefore, the SEL-387A microprocessor-based transformer protection relay is proposed for modernization. This relay provides three-winding differential protection, backup overcurrent protection, harmonic restraint, thermal overload protection, breaker failure protection, event recording, and communication functions. The economic evaluation shows an estimated annual saving of 33,000,000 MNT and a payback period of approximately 9.4 years. The results demonstrate that the proposed transformer replacement and relay protection modernization will improve the reliability, selectivity, sensitivity, and maintainability of the auxiliary power supply system at TPP-4.

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## CHAPTER 1: INTRODUCTION

### 1.1 Background of the Study

Electricity demand in Mongolia has increased steadily in recent years, placing greater pressure on the national power system and on the reliable operation of major generating stations. In 2024, Mongolia's total electricity consumption reached 11.6 billion kWh, which was 5.9% higher than the previous year. During the same period, the winter peak load reached 1,655 MW, representing a 1.2% increase compared with the previous year. Of the total electricity consumed in 2024, 75.3% was supplied by domestic generation, while 24.7% was covered by electricity imports. These figures show that Mongolia continues to operate with limited domestic generation reserves and remains partly dependent on imported electricity(1).

Within this context, Thermal Power Plant No. 4 plays a strategically important role in Mongolia's Central Energy System. The plant has an installed electrical capacity of 772 MW and a thermal capacity of 1,586 Gcal/h. It is the largest thermal power plant in Mongolia and one of the most important facilities for maintaining the reliability of electricity supply and district heating in Ulaanbaatar. According to available plant information, TPP-4 generates approximately 70% of the electricity supplied to Mongolia's Central Energy System and provides around 65% of the heat used by the Ulaanbaatar district heating system(2)(3).

The reliable operation of TPP-4 depends not only on its main equipment, such as boilers, turbines, generators, and main transformers, but also on the stable operation of its auxiliary power supply system. Auxiliary power transformers supply essential internal loads, including pumps, fans, mills, conveyors, oil pumps, control systems, and other service equipment required for the start-up, continuous operation, and safe shutdown of generating units(4,5).

If an auxiliary transformer is overloaded, experiences an internal fault, or is protected by an inadequate relay protection system, the interruption of auxiliary power supply may directly affect the technological process of the generating unit. Therefore, auxiliary transformers should be considered critical electrical assets of the power plant rather than secondary supporting equipment(4,6).

Considering the increasing electricity demand, the long service life of existing plant equipment, and the strategic role of TPP-4 in the Central Energy System, the assessment and modernization of relay protection systems for auxiliary power transformers is technically necessary and practically justified(1,2,6).

## 1.2 Problem Statement

A significant part of the electrical equipment at TPP-4 has been in operation for many years. Long-term service under changing system conditions creates additional technical, operational, and maintenance challenges. At the same time, the growth of national electricity demand and winter peak load has increased the operating pressure on major thermal power plants and their internal auxiliary power supply systems(1,2).

Auxiliary power transformers are exposed to variable loading conditions, motor-starting currents, thermal stress, and short-circuit conditions. Under these circumstances, the relay protection system must operate with sufficient sensitivity, selectivity, speed, and reliability. If the loading condition, short-circuit current level, and protection settings of auxiliary transformers are not evaluated according to present operating requirements, several technical problems may occur(6,7,8).

These problems may include transformer overloading, excessive voltage drop during motor starting, delayed or insufficient relay operation during faults, loss of selectivity between transformer and feeder protection, and interruption of power supply to critical auxiliary equipment. Such conditions may reduce the reliability of unit operation and negatively affect the technical performance of the power plant(4,6,8).

Therefore, it is necessary to assess the current operating condition of auxiliary transformer 2BT, evaluate the adequacy of its existing relay protection system, and determine whether modernization is required to improve the reliability and safety of the auxiliary power supply system.

### 1.3 Objectives of the Study

The main objective of this thesis is to perform an engineering assessment of auxiliary transformer 2BT and to develop a modernization proposal for its relay protection system at Thermal Power Plant No. 4.

The specific objectives of the study are as follows:

1. To examine the role of auxiliary transformer 2BT in the auxiliary power supply system of TPP-4.
2. To identify and summarize the connected 6.3 kV auxiliary loads supplied by transformer 2BT.
3. To calculate the electrical load demand of transformer 2BT using the demand-factor method.
4. To evaluate whether the existing 25 MVA transformer has sufficient loading capacity under the considered operating condition.
5. To select a technically suitable replacement transformer based on load demand, voltage level, rated power, and compatibility with the existing auxiliary power supply system.
6. To calculate the three-phase, two-phase, and peak short-circuit currents at selected fault points using the per-unit method.
7. To assess the existing relay protection system and identify the technical limitations of the installed electromechanical relays.
8. To compare suitable microprocessor-based transformer protection relays for the proposed modernization scheme.
9. To select an appropriate numerical relay for the protection of the replacement auxiliary transformer.
10. To calculate the main relay protection settings for the proposed modernized protection scheme.
11. To estimate the economic feasibility of the proposed modernization by calculating investment cost, annual operating cost reduction, annual savings, and payback period.

## CHAPTER 2: STATE OF THE ART AND EXISTING SYSTEM OVERVIEW

### 2.1 Overview of Thermal Power Plant No. 4

Thermal Power Plant No. 4 (TPP-4) is one of the most important combined heat and power plants in Mongolia and a major generating facility within the Central Energy System (2,3). The plant is located in the 20th khoroo of Bayangol District, Ulaanbaatar, on Energy Street. The total site area of the plant is approximately 49,275 m<sup>2</sup>. Within this area, the 220/110 kV outdoor switchyard forms an essential part of the station electrical system and serves as the main interface between the power plant and the interconnected transmission network.

The development of TPP-4 began in the late 1970s. The plant was established in 1979, and construction work started in the same period. In 1982, the plant entered its early operating stage by connecting to Thermal Power Plant No. 3 through an overhead transmission line and supplying its own service loads through the start-up transformer. On 18 October 1983, the first generating unit, Turbo-generator No. 1, was synchronized with the grid, marking the beginning of electrical energy production at the station.

Since its commissioning, TPP-4 has expanded into the largest thermal power plant in Mongolia. At present, the plant consists of seven turbo-generators, TG-1 to TG-7, and eight boilers, K-1 to K-8. Its installed electrical capacity is 772 MW, and its installed thermal capacity is 1,586 Gcal/h(2). The plant supplies a significant share of the electrical energy demand of Mongolia's Central Energy System and a major part of the district heating demand of Ulaanbaatar (2,3).

From an engineering point of view, TPP-4 operates as a combined heat and power station. Thermal energy produced by coal-fired boilers is converted into mechanical energy in steam turbines and then into electrical energy by synchronous generators (3,4). The main electrical equipment of the plant includes generators, block transformers, auxiliary transformers, autotransformers, station service transformers, switchgear, busbars, circuit breakers, disconnectors, measuring transformers, relay protection devices, automation equipment, and control systems(5,7).

## Assessment and Modernization of Relay Protection Systems for Auxiliary Transformers at TPP-4

The electrical system of TPP-4 is arranged according to the generator–transformer block principle. Each generating unit produces electrical energy at the 10.5 kV voltage level. From this voltage level, the generated electrical power is supplied in two main directions. First, power is transmitted through block transformers, where the voltage is stepped up to 110 kV or 220 kV and delivered to the external transmission network. Second, part of the generated power is supplied through auxiliary transformers to meet the internal power demand of the plant.

The 220/110 kV outdoor switchyard has a strategic function in the electrical arrangement of TPP-4. It connects the power plant to the transmission system and enables the distribution of generated electrical energy to consumers through overhead transmission lines. The switchyard mainly consists of 110 kV and 220 kV sections, which are interconnected through autotransformers AT-1 and AT-2. These autotransformers provide operational flexibility between the two voltage levels and allow bidirectional power transfer depending on system operating conditions.

From a power system perspective, the TPP-4 switchyard is also an important transmission node in the Mongolian power network. It connects the Ulaanbaatar, Erdenet, and Darkhan energy systems and supports power flow between different parts of the Central Energy System. The switchyard is connected to several important substations and overhead transmission lines, including:

- Line 208 to the 220 kV Darkhan substation;
- Line 204 to the 220 kV Erdenet substation;
- Line 211 to the 220/110 kV Songino substation;
- Lines 205 and 206 to the 220/110 kV Ulaanbaatar substation;
- Lines 109 and 110 to the Khuchit Shonkhor substation;
- Lines 111 and 112 to TPP-3 / 110/35 kV switchyard;
- Line 117 to the Bornuur substation;
- 110 kV Geo line to the 110/10/10 kV Geo substation;
- 110 kV Yarmag A and B lines to the 110/35/10 kV Yarmag substation.

These interconnections show that TPP-4 is not only a generating station but also a technically important transmission node in the national power system.

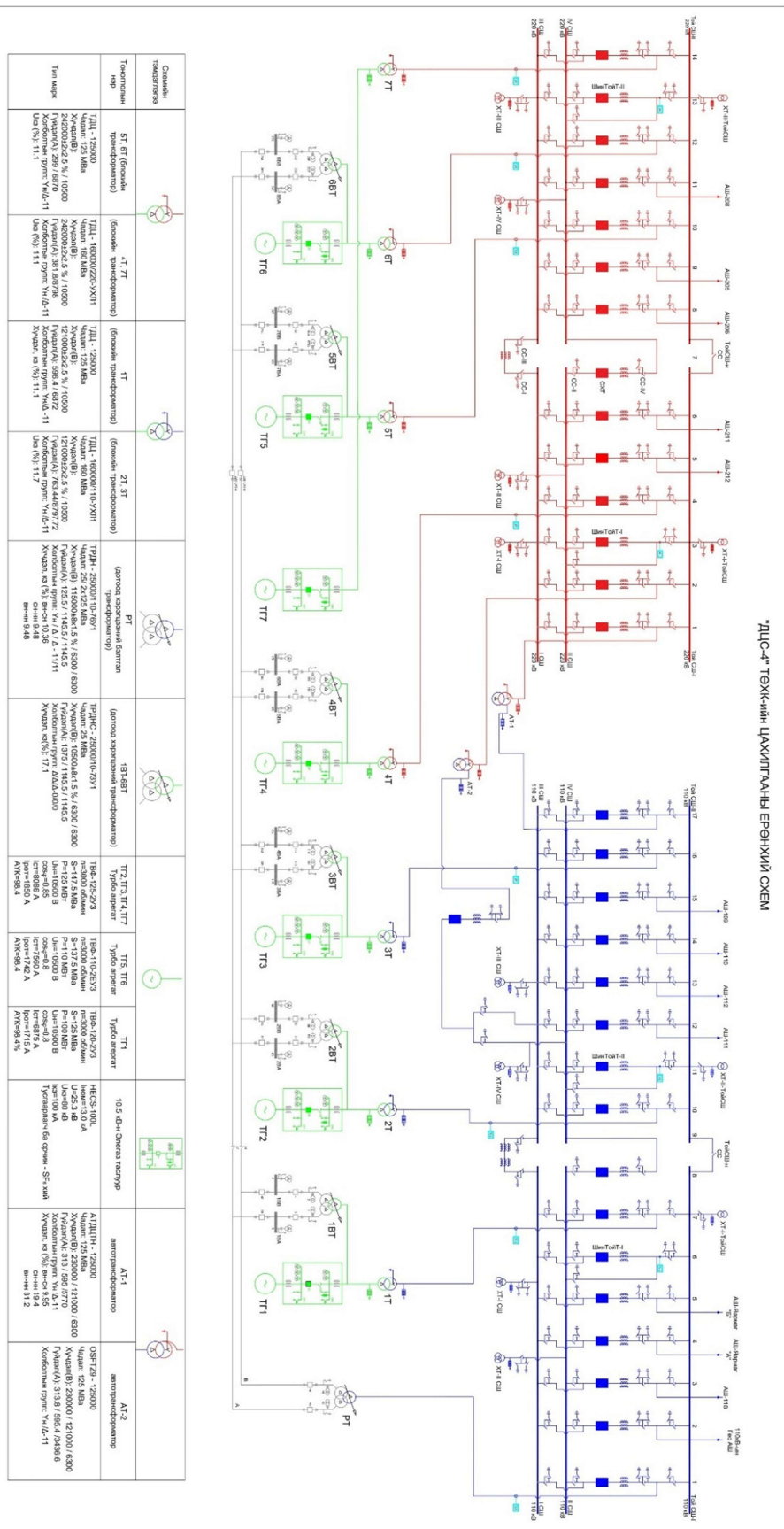


Figure 1. General Single-Line Electrical Scheme of Thermal Power Plant No. 4

## 2.2 Auxiliary Power Transformers

The auxiliary power supply system is a critical subsystem of a thermal power plant. Its main function is to supply electrical energy to internal consumers required for unit start-up, normal operation, emergency operation, and safe shutdown. In a thermal power plant, the interruption of auxiliary power may directly affect the operation of boilers, turbines, generators, fuel supply systems, cooling systems, lubrication systems, control systems, and protection circuits (4,5).

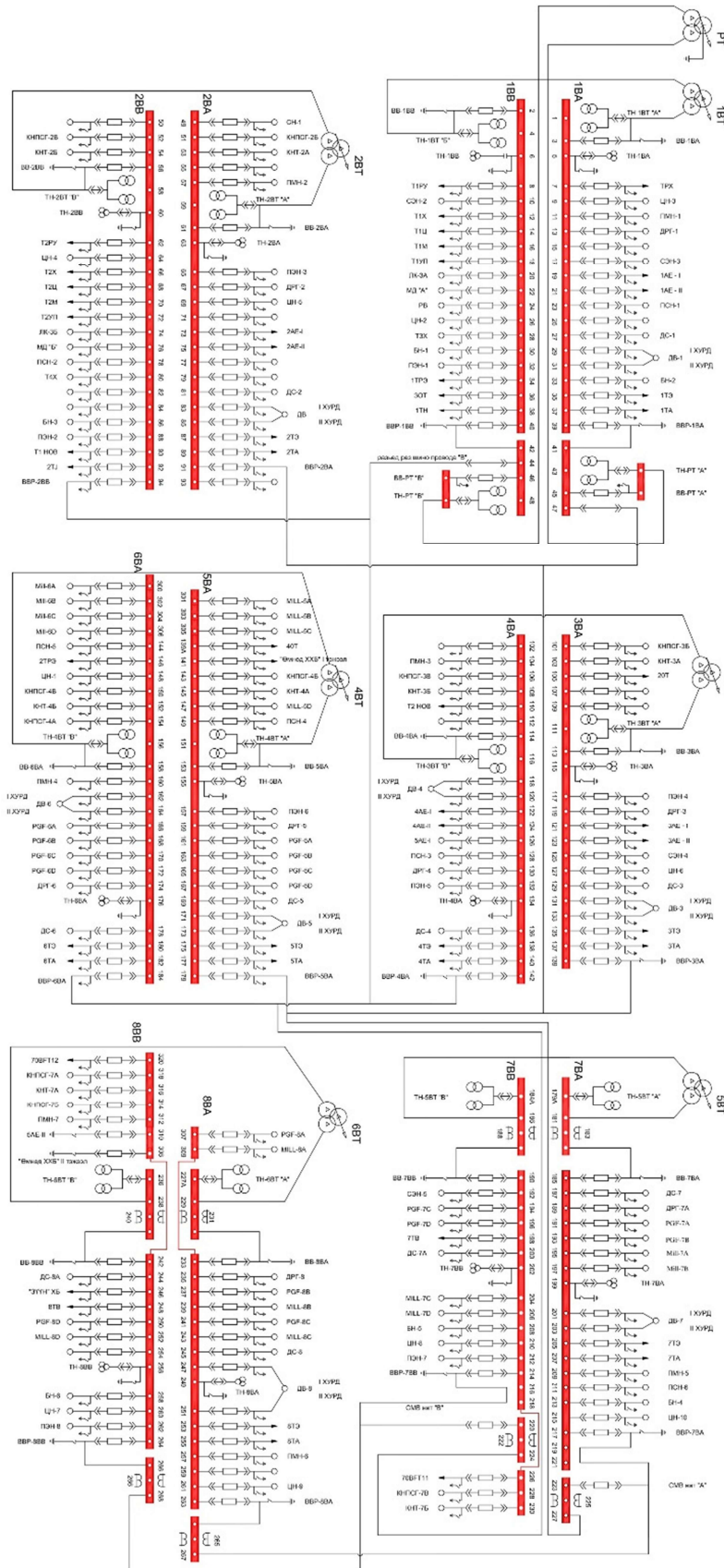
At TPP-4, auxiliary power transformers are connected to the generator-side voltage level and step down the voltage from 10.5 kV to 6.3 kV. The 6.3 kV voltage level is the main medium-voltage level used for the station auxiliary distribution system. It supplies high-power and medium-power auxiliary consumers, including boiler feed pumps, draft fans, forced-draft fans, circulating pumps, mills, conveyors, oil pumps, and other technological mechanisms (4,5).

The auxiliary power supply system at the 6 kV level is arranged as a sectionalized busbar system. This arrangement includes incomer circuit breakers, bus section circuit breakers, reserve supply connections, and outgoing feeders to auxiliary loads. The sectionalized bus arrangement improves operational reliability because it allows power supply transfer, reserve feeding, and selective isolation of faulty sections during abnormal operating conditions or maintenance work (5,7).

The use of sectionalized 6 kV busbars is especially important in thermal power plants because many auxiliary consumers are motor-driven loads. Motor loads can create high starting currents, voltage dips, and high reactive power demand. Therefore, the auxiliary transformer and its relay protection system must be properly selected and coordinated with the downstream feeder protection devices (5,7,9).

In the auxiliary distribution system of TPP-4, each bus section supplies a specific group of auxiliary consumers. During normal operation, each section is supplied by its assigned auxiliary transformer. Under emergency or maintenance conditions, reserve supply arrangements can be used to feed the affected section from another source. This improves the continuity of auxiliary power supply and reduces the risk of complete unit shutdown due to a single equipment fault (5,7).

# Assessment and Modernization of Relay Protection Systems for Auxiliary Transformers at TPP-4



Догод хэрэглэний 6 кВ-ын секцийн схем

Figure 2. Single line scheme of 6kV Auxiliary Section of TPP-4

## 2.3 Technical Characteristics of Auxiliary Transformer 2BT

Within the scope of this thesis, auxiliary transformer 2BT is selected as the main object of study. Transformer 2BT supplies the 6 kV auxiliary sections associated with Unit 2 and is directly related to the reliable operation of important station service loads (6).

The selected auxiliary transformer has the designation ТРДНС-25000/10-73У1. This designation indicates the main constructional and operational characteristics of the transformer. In general, technical interpretation, the designation may be explained as follows:

- Т — three-phase transformer;
- Р — transformer intended for auxiliary or service application;
- Д — three-winding transformer;
- Н — outdoor installation or natural oil insulation type;
- С — transformer series or design classification;
- 25000 — rated apparent power of 25 MVA;
- 10 — high-voltage class corresponding to the 10.5 kV side in actual operation;
- 73У1 — design version and climatic installation category.

Therefore, transformer 2BT is a three-phase, three-winding, oil-immersed auxiliary power transformer with a rated capacity of 25 MVA. It operates between the 10.5 kV generator-side voltage level and two 6.3 kV auxiliary winding outputs.

The principal rated technical data of auxiliary transformer 2BT are presented in Table 1.

| Transf<br>ormer | Model                   | Rated<br>power | HV      | LV     | Rated<br>Current<br>(HV/LV)   | Vector<br>Group                   | $U_k$ |
|-----------------|-------------------------|----------------|---------|--------|-------------------------------|-----------------------------------|-------|
| 2BT             | ТРДНС-<br>25000/10-73У1 | 25 MVA         | 10.5 kV | 6.3 kV | 1375A/<br>1145.5A/<br>1145.5A | $\Delta/\Delta/\Delta$ -<br>0/0/0 | 17.1% |

*Table 1. Rated technical data of auxiliary transformer 2BT*



*Figure 3. External view of Auxiliary Transformer 2BT*

The technical data show that transformer 2BT is designed to supply two 6.3 kV auxiliary bus sections. Since it has been in operation for many years and supplies essential auxiliary loads, its loading condition, thermal reserve, and relay protection system require careful assessment. Long-term operation may increase the probability of insulation ageing, thermal stress, mechanical wear, degradation of auxiliary circuits, and reduced reliability of protection and control equipment (6,10).

For this reason, transformer 2BT is used as the basis for the load calculation, transformer capacity assessment, short-circuit calculation, and relay protection modernization study in the following chapters.

## 2.4 Connected Load Data of Auxiliary Transformer 2BT

In order to evaluate the operating condition of auxiliary transformer 2BT, the connected auxiliary loads supplied from its associated 6 kV bus sections were identified and summarized. Connected load data are necessary for transformer capacity assessment because the transformer loading level, voltage drop, power factor, reactive power demand, motor-starting condition, and relay protection requirements depend directly on the type and rated power of the connected consumers(5,8,9).

According to station documentation, transformer 2BT supplies two main 6 kV auxiliary bus sections:

- 2BA bus section;
- 2BB bus section.

These bus sections supply high-capacity and medium-capacity motor-driven auxiliary equipment. The connected consumers include pumps, fans, technological mechanisms, and other service equipment. This confirms that transformer 2BT supplies a motor-dominated auxiliary network, which is typical for the internal service system of a thermal power plant (4,5).

Motor-driven loads are technically important because they require reactive power for magnetization and may produce high starting currents during energization. High motor-starting currents can result in temporary voltage drops on the auxiliary busbars and may influence relay protection coordination. Therefore, the connected load data form the technical basis for the electrical load calculation and protection assessment performed in the following chapters (5,7,9).

Some equipment codes used in the plant documentation are written in abbreviated form. The main examples are:

- ПЭН — boiler feed pump;
- ДС — draft fan;
- ДВ — forced-draft fan;
- ЦН — centrifugal pump.

The connected load data of transformer 2BT are presented in Table 2.

Assessment and Modernization of Relay Protection Systems for Auxiliary Transformers  
at TPP-4

| Cell№           | Consumer      | Number (n) | Power (kW) | Current (A) |
|-----------------|---------------|------------|------------|-------------|
| 2BA Bus Section |               |            |            |             |
| 49              | СЭН-1         | 1          | 1350       | 1440        |
| 51              | КНПСГ-2Б      | 1          | 250        | 29.2        |
| 53              | КНТ-2А        | 1          | 250        | 29.2        |
| 55              | КНПСГ-2А      | 1          | 250        | 29.2        |
| 57              | ПМН-2         | 1          | 320        | 36.7        |
| 65              | ПЭН-3         | 1          | 4000       | 431         |
| 67              | ДРГ-2         | 1          | 400        | 48          |
| 68              | ЦН-5          | 1          | 400        | 38          |
| 81              | ДС-2          | 1          | 1700       | 216         |
| 83              | ДВ-2(I хурд)  | 1          | 725        | 92          |
| 85              | ДВ-2(II хурд) | 1          | 1250       | 147         |
| 87              | 2ТЭ           | 1          | 1000       | 92.6        |
| 89              | 2ТА           | 1          | 1000       | 92.6        |
| 2BB Bus Section |               |            |            |             |
| 52              | КНПСГ-2В      | 1          | 250        | 29.2        |
| 54              | КНТ-2Б        | 1          | 250        | 29.2        |
| 62              | Т2РУ          | 1          | 1000       | 92.6        |
| 64              | ЦН-4          | 1          | 1000       | 125         |
| 66              | Т2Х           | 1          | 1000       | 92.6        |
| 68              | Т2Ц           | 1          | 630        | 58.7        |
| 70              | Т2М           | 1          | 630        | 58.7        |
| 72              | Т2УП          | 1          | 630        | 58.7        |
| 74              | ЛК-3Б         | 1          | 315        | 38          |
| 76              | МД-Б          | 1          | 1250       | 147         |
| 78              | ПСН-2         | 1          | 766        | 780         |
| 80              | Т4Х           | 1          | 800kVa     |             |
| 86              | БН-3          | 1          | 400        | 48          |
| 88              | ПЭН-2         | 1          | 4000       | 431         |

|    |        |   |      |      |
|----|--------|---|------|------|
| 90 | T1 HOB | 1 | 1000 | 92.6 |
| 92 | 2TJ    | 1 | 1000 | 92.6 |

Table 2. Connected load data for 2BT auxiliary transformer

## 2.5 Existing Relay Protection System of Auxiliary Transformer 2BT

The existing relay protection system of auxiliary transformer 2BT includes transformer differential protection, backup overcurrent protection, gas protection, on-load tap changer protection, cooling and thermal supervision, and protection of the associated 6 kV auxiliary bus sections. These protection functions are intended to detect internal transformer faults, external short circuits, overload conditions, abnormal thermal conditions, gas accumulation, and abnormal voltage conditions (11,12,13).

Based on the protection setting sheets, the protection arrangement includes both transformer-side and bus-side protection functions. The transformer-side protection is mainly based on older electromechanical relays, while the 6 kV section protection includes more modern relay equipment.

### 2.5.1 Transformer Differential Protection

Transformer differential protection is the main protection function of auxiliary transformer 2BT. It compares the currents entering and leaving the protected transformer zone. Under normal operating conditions and during external faults, the vector sum of the currents should remain approximately balanced after compensation for transformer ratio and vector group. During an internal fault, a differential current appears and the relay trips the transformer circuit breakers (11,13,14,15).

Differential protection is intended to detect internal transformer faults, including phase-to-phase faults, winding faults, inter-turn faults, bushing faults, and faults inside the current transformer protection zone. Because internal transformer faults can produce severe thermal and electrodynamic damage, differential protection must operate rapidly and selectively (10,11,13,14,16).

The existing transformer differential protection of 2BT is provided by a ДЗТ-11 relay commissioned on 1 April 1987. The settings are summarized in Table 3.

| Description                               | Setting/ Value    |         | Commission Date |
|-------------------------------------------|-------------------|---------|-----------------|
| Protection relay type                     | ДЗТ-11            |         | 1987/04/01      |
| Current transformer ratio                 | 10 kV side        | 1500/5  |                 |
|                                           | 6.3 kV side       | 1500/5  |                 |
| Circuit coefficient                       | 10 kV side        | 1       |                 |
|                                           | 6.3 kV side       | 1       |                 |
| Protection operating current, 10 kV side  | Primary current   | 2308 A  |                 |
|                                           | Secondary current | 7.693 A |                 |
| Protection operating current, 6.3 kV side | Primary current   | 3750 A  |                 |
|                                           | Secondary current | 12.5 A  |                 |
| Equalizing (balancing) winding            | Connected side:   | 6.3 kV  |                 |
|                                           | Number of turns:  | 5       |                 |

Table 3. Differential Protection Settings of Transformer 2BT

### 2.5.2 10.5 kV-Side Overcurrent Protection

The 10.5 kV-side overcurrent protection provides backup protection for external short circuits and for cases where the main transformer protection or downstream feeder protection fails to operate correctly. Unlike differential protection, which is limited to faults within the protected zone, overcurrent protection can respond to high-current faults outside the transformer zone after a selected time delay (12,13).

The existing 10.5 kV-side overcurrent protection is provided by a PT-40/10 relay commissioned on 1 April 1987. The settings are presented in Table 4.

| Description                    | Setting/ Value    |        | Commission Date |
|--------------------------------|-------------------|--------|-----------------|
| Protection relay type          | PT-40/10          |        | 1987/04/01      |
| Current transformer ratio      | 1500/5            |        |                 |
| Circuit coefficient            | 1                 |        |                 |
| Operating time delay           | 1s                |        |                 |
| Protection operating current   | Primary current   | 2100 A |                 |
|                                | Secondary current | 7 A    |                 |
| Voltage transformer ratio,     | 6000/100          |        |                 |
| Secondary-side voltage setting | Forward direction | 60 V   |                 |
|                                | Reverse direction | 9 V    |                 |

Table 4. 10.5 kV-Side Overcurrent Protection Settings

### 2.5.3 Gas Protection and Tap Changer Gas Protection

Gas protection is used to detect internal transformer abnormalities that generate gas inside the transformer oil. Such abnormalities may include insulation deterioration, overheating, low-energy arcing, partial discharge, and internal faults developing inside the transformer tank. Gas protection is important because some transformer faults develop slowly before becoming severe electrical faults (6,9).

The on-load tap changer has a separate oil compartment and therefore requires independent gas or oil-flow protection. This protection detects abnormal gas generation or oil flow caused by faults inside the tap changer compartment.

| # | Description                               | Setting/ Value | Commission Date |
|---|-------------------------------------------|----------------|-----------------|
| 1 | Transformer Gas Protection                |                |                 |
|   | Protection relay type                     | BF-80/Q        | 1987/04/01      |
| 2 | On Load Tap Changer (OLTC) Gas Protection |                |                 |
|   | Protection relay type                     | URF-25/10.2K   | 1987/04/01      |
|   | Operating setting                         | 2.5 m/s        |                 |

Table 5. Gas Protection and OLTC Gas Protection Settings

### 2.5.4 Cooling and Thermal Supervision Functions

Cooling and thermal supervision functions are used to prevent excessive transformer temperature and reduce the risk of insulation ageing. These functions are not primary short-circuit protection functions, but they are essential for long-term transformer reliability and service life (6,9,17).

The existing system includes load-current-based cooling control, oil-temperature-based cooling control, and high oil-temperature alarm. The settings are shown in Table 6.

| # | Description                                         | Setting/ Value       |        | Commission Date |
|---|-----------------------------------------------------|----------------------|--------|-----------------|
| 1 | Automatic Cooling Control Based on Transformer Load |                      |        |                 |
|   | Protection relay type                               | PT-40/10             |        | 1987/ 04/01     |
|   | Current transformer ratio ( $K_{CT}$ )              | 1500/5               |        |                 |
|   | Circuit coefficient ( $K_{cx}$ )                    | 1                    |        |                 |
|   | Protection operating current                        | Primary current      | 900 A  |                 |
|   |                                                     | Secondary current    | 3 A    |                 |
|   | Operating time                                      | Cooling system start | 19.5 s |                 |
|   |                                                     | Alarm signaling      | 20s    |                 |
| 2 | Automatic Cooling Control Based on Oil Temperature  |                      |        |                 |
|   | Temperature controller type                         | AT-70                |        | 1987/04/01      |
|   | Temperature sensor type                             | WZP (PT-100)         |        |                 |
|   | Cooling start temperature                           | 55°C                 |        |                 |
|   | Cooling stop / return temperature                   | 45°C                 |        |                 |
| 3 | High Oil Temperature Alarm                          |                      |        |                 |
|   | Temperature controller type                         | AT-70                |        | 1987/04/01      |
|   | Temperature sensor type                             | WZP (PT-100)         |        |                 |
|   | Cooling start temperature                           | 70°C                 |        |                 |
|   | Cooling stop / return temperature                   | 65°C                 |        |                 |

Table 6. Cooling and Thermal Supervision Settings

### 2.5.5 Protection of the Associated 6 kV Auxiliary Bus Sections

Transformer 2BT supplies the 6 kV auxiliary bus sections 2BA and 2BB. Therefore, its protection system must be coordinated with the protection of the associated bus sections and outgoing feeders. Proper coordination is necessary to ensure that faults are isolated selectively and that healthy sections remain in operation whenever possible (12,13).

The protection of the 6 kV section incomers and reserve/tie incomers is provided by RID-300N relays. These relays provide overcurrent protection, overload protection, and abnormal voltage supervision. The settings are summarized in Table 7.

| # | Description                                              | Setting/ Value    |        | Commission Date |
|---|----------------------------------------------------------|-------------------|--------|-----------------|
| 1 | Overcurrent Protection of the 6 kV Section Incomer       |                   |        |                 |
|   | Protection relay type                                    | RID-300N          |        | 1987/04/01      |
|   | Current transformer ratio                                | 1500/5            |        |                 |
|   | Circuit coefficient                                      | 1                 |        |                 |
|   | Operating time delay                                     | 0.5 s             |        |                 |
|   | Protection operating current                             | Primary current   | 1700 A |                 |
|   |                                                          | Secondary current | 5.67 A |                 |
|   | Voltage transformer ratio,                               | 6000/100          |        |                 |
|   | Secondary-side voltage setting                           | Forward direction | 60 V   |                 |
|   |                                                          | Reverse direction | 9 V    |                 |
| 2 | Overload Protection of the 6 kV Section                  |                   |        |                 |
|   | Protection relay type                                    | RID-300N          |        | 1987/04/01      |
|   | Current transformer ratio                                | 1500/5            |        |                 |
|   | Circuit coefficient                                      | 1                 |        |                 |
|   | Operating time delay                                     | 9 s               |        |                 |
|   | Protection operating current                             | Primary current   | 1400 A |                 |
|   |                                                          | Secondary current | 4.67 A |                 |
| 3 | Overcurrent Protection of the 6 kV Reserve / Tie Incomer |                   |        |                 |

|  |                                |                    |           |            |
|--|--------------------------------|--------------------|-----------|------------|
|  | Protection relay type          | RID-300N           |           | 1987/04/01 |
|  | Current transformer ratio      | 1500/5             |           |            |
|  | Circuit coefficient            | 1                  |           |            |
|  | Operating time delay           | 0.5 s              |           |            |
|  | Protection operating current   | Primary current    | 1700 A    |            |
|  |                                | Secondary current  | 5.67 A    |            |
|  | Voltage transformer ratio      | 6000/100           |           |            |
|  | Secondary-side voltage setting | Voltage relay type | PH-54/160 |            |
|  |                                | Forward direction  | 60 V      |            |

Table 7. Protection Settings of 6 kV Auxiliary Bus Sections

### 2.5.6 Preliminary Assessment of the Existing Protection System

The existing relay protection system of auxiliary transformer 2BT includes the main protection functions required for transformer operation. These functions include differential protection, backup overcurrent protection, gas protection, tap changer gas protection, cooling control, thermal supervision, and protection of the associated 6 kV auxiliary bus sections. Therefore, from a basic functional point of view, the protection scheme is generally complete (9,12,13).

However, the main transformer-side protection devices are technologically outdated. The ДЗТ-11 differential relay and PT-40/10 overcurrent relay were commissioned in 1987 and are based on electromechanical relay technology. Although electromechanical relays are robust and have historically provided reliable basic protection, they have several disadvantages compared with modern numerical relays (13,18,19,20).

The main technical limitations of the existing electromechanical protection system are as follows (13,18):

- limited setting flexibility;
- lower measurement accuracy compared with numerical relays;
- absence of self-diagnostic functions;
- absence of integrated event recording;
- absence of disturbance waveform recording;
- limited communication capability with SCADA or digital control systems;

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- higher maintenance requirements due to mechanical and electromagnetic components;
- more difficult post-fault analysis;
- limited adaptability when transformer rating or system configuration changes.

In addition, transformer 2BT has been in operation for many years and supplies essential motor-driven auxiliary loads. The connected load data show that the transformer supplies several large consumers, including boiler feed pumps, fans, pumps, conveyors, and other technological mechanisms. Because these loads are important for continuous unit operation, the transformer and its protection system must satisfy present reliability and protection requirements (5).

For these reasons, a detailed assessment of transformer loading, short-circuit current levels, and relay protection adequacy is necessary. The following chapters present the calculation methods, technical assessment, replacement transformer selection, relay modernization proposal, and economic evaluation of the proposed modernization scheme (9,12).

## **CHAPTER:3 LOAD AND SHORT-CIRCUIT ANALYSIS**

### **3.1 Electrical Load Calculation**

#### *3.1.1 Importance of Load Calculation*

Electrical load calculation is one of the most important stages in the assessment of a power supply system. The calculated load determines whether the existing transformer, conductors, switching devices, and protection systems are suitable for present operating conditions. In a thermal power plant, this calculation is especially important because auxiliary power transformers supply essential equipment required for the start-up, stable operation, and safe shutdown of generating units (4,5,17).

If the load is underestimated, the transformer and connected equipment may be overloaded during operation. This can lead to excessive heating, accelerated insulation ageing, voltage drop, higher power losses, and reduced reliability. On the other hand, if the load is significantly overestimated, selected equipment may become unnecessarily oversized, increasing investment cost and reducing equipment utilization efficiency (6,9).

Therefore, the electrical load calculation of auxiliary transformer 2BT is necessary to evaluate whether the existing 25 MVA transformer has sufficient loading reserve under the present connected load condition.

#### *3.1.2 Load Calculation Method*

Several methods can be used to determine electrical load depending on the available data and the purpose of the study. In this thesis, the demand-factor method is used because the available data mainly consist of the rated powers of the connected 6 kV auxiliary consumers (5,20,21).

The demand factor method considers that not all connected consumers operate continuously at rated power at the same time. Some motors operate continuously, some operate intermittently, and some are used as reserve or standby equipment. Therefore, the actual maximum demand is usually lower than the total installed power (20,21).

### 1. The calculated active power

$$P_{calc} = K_x \cdot \sum P_{nom} \quad (1)$$

where:

- $P_{calc}$ : calculated active power, kW
- $K_x$ : demand factor
- $P_{nom}$ : rated power of the load, kW

### 2. The reactive power

$$Q_{calc} = P_{calc} \cdot \tan \varphi \quad (2)$$

where:

- $Q_{calc}$ : calculated reactive power, kVAr
- $\tan \varphi$ : tangent corresponding to the power factor of the load

### 3. The value of $\tan \varphi$ is calculated from the power factor

$$\tan \varphi = \frac{\sqrt{1 - \cos^2 \varphi}}{\cos \varphi} \quad (3)$$

where:

- $\cos \varphi$ : power factor (PF)

### 4. The calculated apparent power

$$S_{calc} = \sqrt{P_{calc}^2 + Q_{calc}^2} \quad (4)$$

where:

- $S_{calc}$ : calculated apparent power, kVA

### 3.1.3 Selection of Demand Factor and Power Factor

The demand factor  $K_x$  and power factor  $\cos\varphi$  are selected according to the type and operating characteristics of the connected 6 kV consumers. Since most of the auxiliary loads supplied by transformer 2BT are motor-driven loads, their power factor is lower than unity due to the reactive power required for motor magnetization (5,20,21).

| Load category                         | Consumers                             | $K_x$      | $\cos\varphi$ |
|---------------------------------------|---------------------------------------|------------|---------------|
| Pump loads                            | ПЭН, ЦН, ПМН, ПСН                     | 0.8        | 0.8 – 0.88    |
| Fan loads                             | ДС, ДВ, ДРГ                           | 0.6 – 0.7  | 0.7 – 0.75    |
| Conveyor and technological mechanisms | ТЭ, ТА, Т2РУ, Т2Х, Т2Ц, Т2М, Т2УП, МД | 0.55 – 0.7 | 0.65 – 0.8    |
| Service and auxiliary mechanisms      | КНПСГ, КНТ, СЭН, БН                   | 0.5 – 0.75 | 0.58 – 0.75   |

Table 8. Reference Values for Demand Factor and Power Factor

### 3.1.4 Electric load calculation for Transformer 2BT

Transformer 2BT supplies the 2BA and 2BB 6.3 kV auxiliary bus sections. The connected loads are mainly motor-driven auxiliary mechanisms. The calculated active and reactive powers are obtained using Equations 1–4 (20,21).

A sample calculation is presented below for one load group.

- СЭН-1

$$P_{calc} = n \cdot P_{nom} \cdot k_x = 1 \cdot 1350 \cdot 0.7 = 945 \text{ kW}$$

$$\tan\varphi = \frac{\sqrt{1 - \cos^2\varphi}}{\cos\varphi} = \frac{\sqrt{1 - 0.7^2}}{0.7} = 1.0202$$

$$Q_{calc} = P_{calc} \cdot \tan\varphi = 945 \cdot 1.0202 = 964.1 \text{ kVar}$$

The same calculation method is applied to the remaining connected loads. The summarized load calculation results are shown in Table 9.

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| #  | Consumer      | $P_{nom} (kW)$ | $k_x$ | $\cos\varphi$ | $\tan\varphi$ | $P_{calc}$ | $Q_{calc}$ |
|----|---------------|----------------|-------|---------------|---------------|------------|------------|
| 1  | СЭН-1         | 1350           | 0.7   | 0.7           | 1.0202        | 945        | 964.093    |
| 2  | КНПСГ-2Б      | 250            | 0.7   | 0.7           | 1.0202        | 175        | 178.54     |
| 3  | КНТ-2А        | 250            | 0.7   | 0.7           | 1.0202        | 175        | 178.54     |
| 4  | КНПСГ-2А      | 250            | 0.7   | 0.7           | 1.0202        | 175        | 178.54     |
| 5  | ПМН-2         | 320            | 0.8   | 0.85          | 0.6197        | 256        | 158.655    |
| 6  | ПЭН-3         | 4000           | 0.7   | 0.85          | 0.6197        | 3200       | 1983.182   |
| 7  | ДРГ-2         | 400            | 0.7   | 0.73          | 0.9362        | 280        | 262.144    |
| 8  | ЦН-5          | 400            | 0.8   | 0.88          | 0.5397        | 320        | 172.72     |
| 9  | ДС-2          | 1700           | 0.7   | 0.73          | 0.9362        | 1190       | 1114.113   |
| 10 | ДВ-2(I хурд)  | 725            | 0.65  | 0.73          | 0.9362        | 471.25     | 441.198    |
| 11 | ДВ-2(II хурд) | 1250           | 0.65  | 0.75          | 0.8819        | 812.5      | 716.558    |
| 12 | 2ТЭ           | 1000           | 0.67  | 0.7           | 1.0202        | 670        | 683.537    |
| 13 | 2ТА           | 1000           | 0.67  | 0.7           | 1.0202        | 670        | 683.537    |
| 14 | КНПСГ-2В      | 250            | 0.7   | 0.7           | 1.0202        | 175        | 178.54     |
| 15 | КНТ-2Б        | 250            | 0.7   | 0.7           | 1.0202        | 175        | 178.54     |
| 16 | Т2РУ          | 1000           | 0.7   | 0.7           | 1.0202        | 700        | 714.143    |
| 17 | ЦН-4          | 1000           | 0.8   | 0.85          | 0.6197        | 800        | 495.796    |
| 18 | Т2Х           | 1000           | 0.7   | 0.7           | 1.0202        | 700        | 714.143    |
| 19 | Т2Ц           | 630            | 0.7   | 0.75          | 0.8819        | 441        | 388.93     |

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|                                                                        |        |         |      |      |        |          |          |
|------------------------------------------------------------------------|--------|---------|------|------|--------|----------|----------|
| 20                                                                     | Т2М    | 630     | 0.7  | 0.75 | 0.8819 | 441      | 388.93   |
| 21                                                                     | Т2УП   | 630     | 0.7  | 0.75 | 0.8819 | 441      | 388.93   |
| 22                                                                     | ЛК-3Б  | 315     | 0.8  | 0.85 | 0.6197 | 252      | 156.176  |
| 23                                                                     | МД-Б   | 1250    | 0.8  | 0.85 | 0.6197 | 1000     | 619.744  |
| 24                                                                     | ПЧН-2  | 766     | 0.8  | 0.85 | 0.6197 | 612.8    | 379.78   |
| 25                                                                     | Т4Х    | 800kVar | 0.8  | 0.85 | 0.6197 | 544      | 337.141  |
| 26                                                                     | БН-3   | 400     | 0.75 | 0.7  | 1.0202 | 300      | 306.061  |
| 27                                                                     | ПЭН-2  | 4000    | 0.8  | 0.85 | 0.6197 | 3200     | 1983.182 |
| 28                                                                     | Т1 НОВ | 1000    | 0.7  | 0.7  | 1.0202 | 700      | 714.143  |
| 29                                                                     | 2ТJ    | 1000    | 0.7  | 0.7  | 1.0202 | 700      | 714.143  |
| Sum                                                                    |        |         |      |      |        | 20521.55 | 16373.64 |
| $S_{calc} = \sqrt{20521.55^2 + 16373.6375^2} = 26253.1907 \text{ kVA}$ |        |         |      |      |        |          |          |

Table 9. Electrical Load Calculation Results for Auxiliary Transformer 2BT

### 3.1.5 Transformer Loading Assessment

The rated apparent power of the existing auxiliary transformer 2BT is:

$$S_{2BT} = 25MVA$$

The calculated apparent load is:

$$S_{calc} = 26.25MVA$$

Therefore:

$$S_{calc} > S_{2BT}$$

This result shows that the calculated load exceeds the rated capacity of the existing transformer. This indicates that transformer 2BT does not have sufficient loading reserve under the considered operating condition (9,22).

Operation above rated capacity may lead to increased winding temperature, higher oil temperature, accelerated insulation ageing, increased losses, and reduced operational reliability. In addition, limited loading margin may negatively affect the transformer during motor starting, reserve-feeding operation, or future load growth (6,9).

Therefore, from an engineering point of view, the capacity of the existing 25 MVA transformer should be reassessed, and replacement with a higher-rated auxiliary transformer should be considered (9,22).

## 3.2 Selection of Replacement Auxiliary Transformer

### 3.2.1 Candidate Transformer Options

Based on the load calculation result, the existing 25 MVA transformer is not sufficient for the calculated operating load. Therefore, two candidate replacement transformers are considered in this study (9,22).

The first option is the TPДHC-32000/10 Y1 transformer, which is a Russian/CIS-type auxiliary transformer. The second option is the SFSZ11-31500/10.5/6.3/6.3 transformer, which is a Chinese IEC-equivalent transformer.

| Parameter               | Option 1                     | Option 2                        |
|-------------------------|------------------------------|---------------------------------|
| Transformer type        | ТРДНЧ-32000/10 Y1            | SFSZ11-31500 / 10.5 / 6.3 / 6.3 |
| Country / design origin | Russian/CIS design           | Chinese / IEC-equivalent design |
| Rated power             | 32 MVA                       | 31.5 MVA                        |
| HV voltage              | 10.5 kV                      | 10.5 kV                         |
| LV voltage              | 6.3 / 6.3 kV                 | 6.3 / 6.3 kV                    |
| Cooling system          | Oil-immersed, ONAF           | Oil-immersed, ONAN/ONAF         |
| Vector group            | $\Delta/\Delta/\Delta-0/0/0$ | Custom IEC equivalent           |

*Table 10. Comparison of Candidate Replacement Auxiliary Transformers*

### 3.2.2 Verification of the Candidate Transformers

For the selection of the replacement transformer, the following conditions are checked (9,22):

1. The transformer should be able to supply the calculated load with sufficient reserve.
2. The transformer should be able to supply at least 75% of the calculated load under reserve or emergency operating conditions.
3. The emergency loading coefficient should be less than 1.3.
4. The transformer should be compatible with the existing auxiliary power supply system.

#### A. Full-load supply verification

- For Option 1:  
 $32000 \text{ kVA} > 26253.19 \text{ kVA}$
- For Option 2:  
 $31500 \text{ kVA} > 26253.19 \text{ kVA}$

Both candidate transformers satisfy the full-load supply condition (9,22).

### B. 75% reserve loading verification

The 75% loading value is calculated as:

$$S_{75\%} = 0.75 \cdot S_{calc} \quad (5)$$

$$S_{75\%} = 0.75 \cdot 26253.19 \text{ kVA} = 19689.89 \text{ kVA}$$

- For Option 1:  
 $32000 \text{ kVA} > 19689.89 \text{ kVA}$
- For Option 2:  
 $31500 \text{ kVA} > 19689.89 \text{ kVA}$

Both candidate transformers satisfy the 75% reserve loading condition (9,22).

### C. Emergency loading coefficient verification

The emergency loading coefficient is calculated as:

$$K_{av} = \frac{0.75 \cdot S_{calc}}{S_n} \quad (6)$$

- For Option 1:  
$$K_{av1} = \frac{0.75 \cdot 26253.19 \text{ kVA}}{32000 \text{ kVA}} = 0.615$$
$$0.615 < 1.3$$
- For Option 2:  
$$K_{av} = \frac{0.75 \cdot 26253.19 \text{ kVA}}{31500 \text{ kVA}} = 0.625$$
$$0.625 < 1.3$$

Both options satisfy the emergency loading coefficient requirement.

### F. Verification Result

The comparison shows that both candidate transformers satisfy the required loading conditions. The SFSZ11-31500/10.5/6.3/6.3 transformer has the advantage of IEC-equivalent design and may offer improved customization and monitoring options.

However, it may require additional adaptation because the existing auxiliary power supply system of TPP-4 is based mainly on CIS-type equipment and design practice (11).

The ТРДНHC-32000/10 Y1 transformer is closer to the existing transformer type and is more compatible with the original auxiliary power supply arrangement of TPP-4. It also provides a slightly higher rated capacity than the 31.5 MVA IEC-equivalent option.

Therefore, from the viewpoint of rated capacity, technical compatibility, and easier integration into the existing system, Option 1: ТРДНHC-32000/10 Y1 is selected as the more suitable replacement transformer for auxiliary transformer 2BT.

### 3.3 Short Circuit Calculation

#### *3.2.1 Purpose of Short Circuit Calculation*

Short-circuit calculation is an essential part of relay protection assessment and modernization. The purpose of the short-circuit calculation is to determine the prospective fault-current levels at the transformer terminals and at the associated 6.3 kV auxiliary bus sections (9,23).

The calculated short-circuit currents are required for:

- checking the sensitivity of relay protection;
- coordinating transformer and feeder protection;
- evaluating the suitability of circuit breakers and busbars;
- determining peak fault-current stress;
- verifying the technical suitability of the selected replacement transformer.

During a short circuit, the impedance of the electrical circuit decreases sharply and the current rises to a value much higher than the normal load current. This fault current may produce thermal and mechanical stress in transformers, cables, busbars, current transformers, circuit breakers, and other electrical equipment. Therefore, short-circuit current calculation is necessary for reliable protection setting and safe equipment operation (5,9,10).

In this thesis, the following short-circuit values are calculated:

- Three-phase short-circuit current,  $I_k^{(3)}$
- Two-phase short-circuit current,  $I_k^{(2)}$
- Peak short-circuit current,  $I_p$

The three-phase short-circuit current is used as the main reference value for equipment checking. The two-phase short-circuit current is used for checking the sensitivity of overcurrent protection because it is lower than the three-phase short-circuit current. The peak short-circuit current is used for checking the electrodynamic withstand capability of electrical equipment (9,10).

### *3.3.2 Short Circuit Calculation Scheme and Equivalent Circuit Diagram*

Before performing the short-circuit calculation, a simplified short-circuit calculation scheme is prepared for auxiliary transformer 2BT and its associated 6.3 kV auxiliary bus sections. The purpose of the calculation scheme is to define the selected fault points and identify the main electrical elements that influence the short-circuit current (9,23).

In this study, the upstream power system is represented by an equivalent source reactance  $X_c$ . The connection between the source and the transformer is represented by cable reactance  $X_L$ , and the auxiliary transformer is represented by transformer reactance  $X_T$ . Measuring devices, relay circuits, switching-device contact resistance, and connected load impedances are neglected because their influence on the maximum prospective short-circuit current is relatively small (9,23).

Two fault points are selected for the calculation:

- K1 — fault point on the 10.5 kV side of the auxiliary transformer;
- K2 — fault point on the 6.3 kV auxiliary bus section supplied by the transformer.

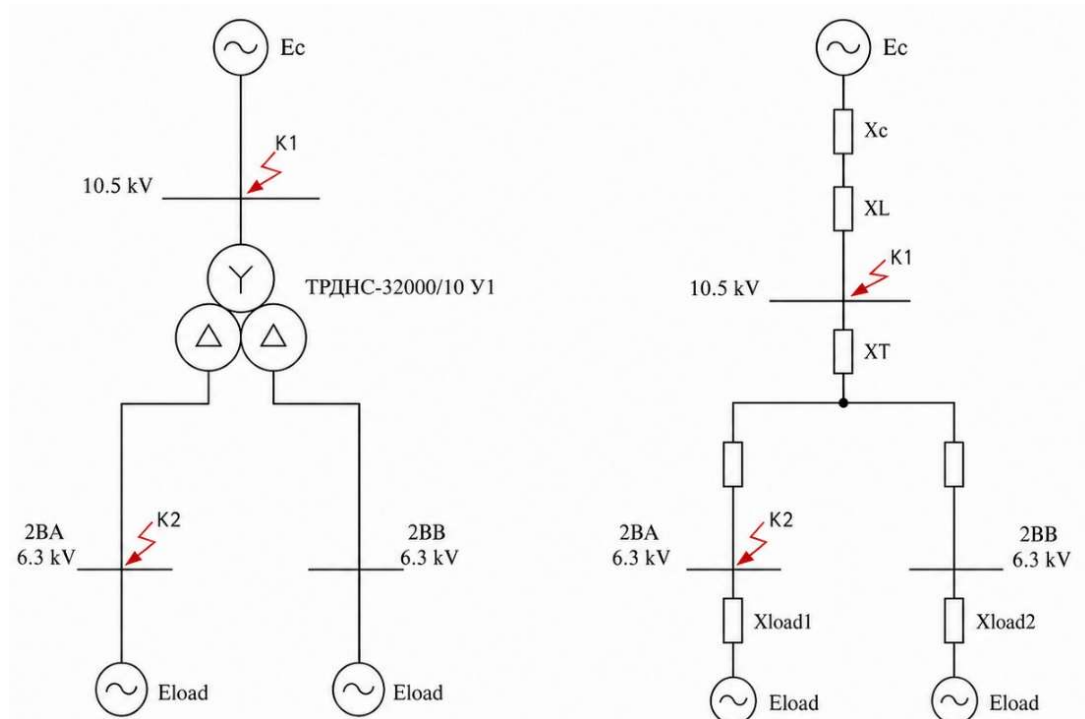


Figure 4. Short-circuit calculation scheme of auxiliary transformer 2BT

### 3.3.3 Technical Data Used for Short-Circuit Calculation

The short-circuit calculation is performed for the selected transformer ТРДНС-32000/10 Y1. The technical data used for the calculation are shown in Tables 11 and 12.

| Parameter                         | Value             |
|-----------------------------------|-------------------|
| Transformer type                  | ТРДНС-32000/10 Y1 |
| Rated power                       | 32 MVA            |
| High-voltage side                 | 10.5 kV           |
| Low-voltage side                  | 6.3 kV            |
| Short-circuit voltage, $U_k$      | 12.7%             |
| Base power, $S_b$                 | 147.5 MVA         |
| The short-circuit power, $S_{sc}$ | 500 MVA           |

Table 11. Technical data of selected transformer for short-circuit calculation

| Parameter               | Value           |
|-------------------------|-----------------|
| Cable type              | YJV-10          |
| Cable length, L         | 0.15 km         |
| Reactance per km, $x_0$ | $0.08\Omega/km$ |

Table 12. Cable data used for short-circuit calculation

### 3.3.4 Short Circuit Calculation Formulas

1. The equivalent source reactance in per-unit is calculated as:

$$X_C = \frac{S_b}{S_{sc}} \quad (7)$$

where:

- $S_{sc}$  — short-circuit apparent power of the source at the 10.5 kV bus, MVA
- $X_C$  — equivalent source reactance, p.u.
- $S_b$  — base apparent power, MVA.

2. The transformer reactance in per-unit is calculated as:

$$X_T = \frac{U_k}{100} \cdot \frac{S_b}{S_{nom}} \quad (8)$$

where:

- $X_T$  — transformer reactance, p.u.
- $U_k$  — transformer short-circuit voltage, %
- $S_{nom}$  — rated apparent power of the transformer, MVA

**3. Transmission line reactance in per-unit is calculated as:**

$$X_L = x_0 \cdot L \cdot \frac{S_b}{U_b^2} \quad (9)$$

where:

- $X_L$  — transmission line reactance, p.u.
- $x_0$  — transmission line reactance per kilometer,  $\Omega/\text{km}$
- $L$  – equivalent length of the source-side connection, km
- $U_b$  — base line voltage, kV

**4. Base current is calculated as:**

$$I_b = \frac{S_b}{\sqrt{3} \cdot U_b} \quad (10)$$

where:

- $I_b$  — base current, kA;
- $S_b$  — base apparent power, MVA
- $U_b$  — base line voltage, kV

**5. Three-phase short-circuit current in relative units**

$$I_k^{(3)} = \frac{1}{X_\Sigma} \cdot I_b \quad (11)$$

**6. The two-phase short-circuit current is calculated as:**

$$I_k^{(2)} = I_k^{(3)} \cdot \frac{\sqrt{3}}{2} \quad (12)$$

**7. The peak short-circuit current is calculated as:**

$$I_p = \sqrt{2} \cdot k_u \cdot I_k^{(3)} \quad (13)$$

where:

- $k_u$  — peak coefficient.

In this calculation, the peak coefficient is assumed as:

$$k_u = 1.85$$

### 3.3.5 Short-Circuit Calculation at Fault Point K1

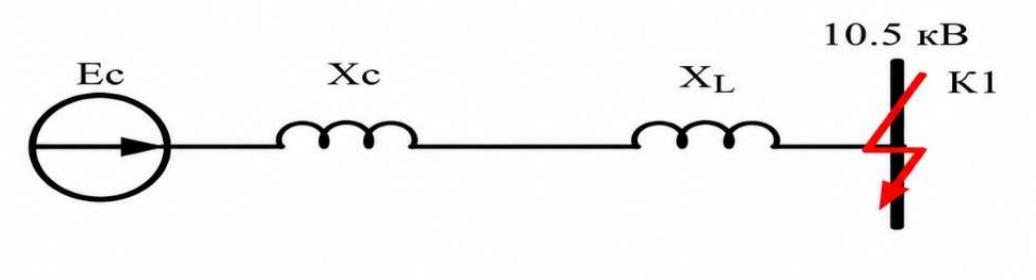


Figure 5. Equivalent circuit diagram for fault point K1

$$X_c = \frac{S_b}{S_{sc}} = \frac{147.5 \text{ MVA}}{500 \text{ MVA}} = 0.295$$

$$X_L = X_0 \cdot L \cdot \frac{S_b}{U_{HV}^2} = 0.08 \cdot 0.15 \cdot \frac{147.5}{10.5^2} = 0.0161$$

$$X_{\Sigma, K1} = X_c + X_L = 0.295 + 0.0161 = 0.3111$$

$$I_b = \frac{S_b}{\sqrt{3} \cdot U_b} = \frac{147.5}{\sqrt{3} \cdot 10.5} = 8.11 \text{ kA}$$

$$I_{k1}^{(3)} = \frac{1}{X_{\Sigma}} \cdot I_b = \frac{1}{0.3111} \cdot 8.11 = 26.07 \text{ kA}$$

$$I_{k1}^{(2)} = I_{k1}^{(3)} \cdot \frac{\sqrt{3}}{2} = 26.07 \cdot \frac{\sqrt{3}}{2} = 22.58 \text{ kA}$$

$$I_p = \sqrt{2} \cdot k_u \cdot I_{k1}^{(3)} = \sqrt{2} \cdot 1.85 \cdot 26.07 = 68.2 \text{ kA}$$

### 3.3.6 Short-Circuit Calculation at Fault Point K2

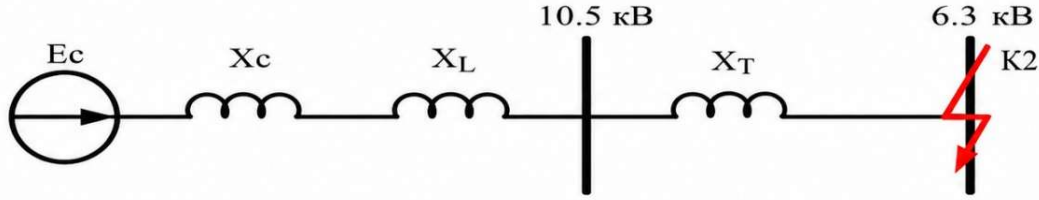


Figure 6. Equivalent circuit diagram for fault point K2

$$X_c = \frac{S_b}{S_{sc}} = \frac{147.5 \text{ MVA}}{500 \text{ MVA}} = 0.295$$

$$X_L = X_0 \cdot L \cdot \frac{S_b}{U_{HV}^2} = 0.08 \cdot 0.15 \cdot \frac{147.5}{10.5^2} = 0.0161$$

$$X_T = \frac{U_k}{100} \cdot \frac{S_b}{S_{nom}} = \frac{12.7}{100} \cdot \frac{147.5}{32} = 0.5854$$

$$X_{\Sigma} = X_c + X_L + X_T = 0.295 + 0.0161 + 0.5854 = 0.8965$$

$$I_b = \frac{S_b}{\sqrt{3} \cdot U_b} = \frac{147.5}{\sqrt{3} \cdot 6.3} = 13.52 \text{ kA}$$

$$I_{k2}^{(3)} = \frac{1}{X_{\Sigma}} \cdot I_b = \frac{1}{0.8965} \cdot 13.52 = 15.08 \text{ kA}$$

$$I_{k2}^{(2)} = I_{k1}^{(3)} \cdot \frac{\sqrt{3}}{2} = 15.08 \cdot \frac{\sqrt{3}}{2} = 13.06 \text{ kA}$$

$$I_p = \sqrt{2} \cdot k_u \cdot I_{k2}^{(3)} = \sqrt{2} \cdot 1.85 \cdot 15.08 = 39.45 \text{ kA}$$

## CHAPTER 4: RELAY PROTECTION MODERNIZATION

### 4.1 Necessity of Relay Protection Modernization

The existing relay protection system of auxiliary transformer 2BT includes the main protection functions required for transformer operation. However, the transformer-side protection devices, including the ДЗТ-11 differential relay and the PT-40/10 overcurrent relay, were commissioned in 1987 and are based mainly on electromechanical technology. Although these relays provide basic protection, they are limited in setting flexibility, monitoring capability, disturbance recording, communication, and self-diagnostics (13,14,18,19).

In addition, the existing 25 MVA transformer is proposed to be replaced by a ТРДНЧ-32000/10 Y1, 32 MVA transformer. Because the transformer rating, CT ratios, and short-circuit current levels change, the protection settings must also be recalculated. Therefore, the modernization of the relay protection system is required to ensure reliable, selective, and sensitive fault detection under the new operating conditions (9,12).

The proposed modernization aims to improve the protection performance, reduce maintenance requirements, support fault analysis, and enable integration with modern monitoring and control systems (13,18,24).

### 4.2 Microprocessor-Based Relay Protection

#### *4.2.1 Operating Principle and Advantages of Microprocessor Relays*

A microprocessor-based relay, also called a numerical relay, is a digital protection device that performs protection, measurement, monitoring, control, and communication functions using digital signal processing. Current and voltage signals from CTs and VTs are converted into digital values and processed by internal protection algorithms (13,15,16,18).

For transformer protection, a numerical relay can calculate differential current, restraint current, RMS current, voltage, frequency, and harmonic components. If the calculated values exceed the selected protection settings, the relay issues a trip signal to the circuit breaker and records the event (13,16,18,19)..

Compared with electromechanical relays, numerical relays provide several advantages:

- high measurement accuracy;
- wide and flexible setting range;
- multiple protection functions in one device;
- disturbance and event recording;
- self-diagnostic capability;
- communication with SCADA or monitoring systems;
- harmonic restraint for transformer inrush current;
- reduced maintenance requirements.

These characteristics make numerical relays more suitable for the modernized protection of auxiliary transformer 2BT.

#### *4.2.2 Required Protection Functions for the Replacement Transformer*

The selected replacement transformer ТРДНC-32000/10 Y1 is a three-phase, three-winding, oil-immersed transformer with a rated capacity of 32 MVA, operating at 10.5/6.3/6.3 kV. Therefore, the selected relay must support three-winding transformer protection and provide both main and backup protection functions (12,13,14,15,18).

| ANSI code                 | Protection function                   | Application for transformer 2BT                             |
|---------------------------|---------------------------------------|-------------------------------------------------------------|
| 87T                       | Three-winding differential protection | Main protection for internal transformer faults             |
| 87TH                      | High-set differential protection      | Fast tripping for severe internal faults                    |
| Second harmonic restraint | Inrush restraint                      | Prevents unwanted tripping during energization              |
| Fifth harmonic restraint  | Overexcitation restraint              | Improves stability during overexcitation                    |
| 50/51P                    | Phase overcurrent protection          | Backup protection for phase faults                          |
| 50N/51N                   | Earth-fault protection                | Backup protection for ground faults, depending on grounding |

|                             |                             |                                                     |
|-----------------------------|-----------------------------|-----------------------------------------------------|
| 49                          | Thermal overload protection | Protects against long-term overload and overheating |
| 27                          | Undervoltage protection     | Detects severe voltage reduction                    |
| 59                          | Overvoltage protection      | Detects abnormal voltage rise                       |
| 50BF                        | Breaker failure protection  | Provides backup tripping if a breaker fails         |
| Event/disturbance recording | Monitoring function         | Supports post-fault analysis                        |

*Table 13. Required protection functions for the replacement auxiliary transformer*

### 4.3 Comparison of Candidate Microprocessor Relays

Four numerical relays are considered for the modernized protection system (13,14,22,24,25,26):

- SEL-387A
- ABB REF615
- Siemens 7UT86
- ABB RET670

The comparison is based on transformer protection functions, three-winding transformer capability, operating conditions, physical characteristics, and approximate price.

The detailed comparison of the four candidate relays is presented in Table 14.

|       |          |            |               |            |
|-------|----------|------------|---------------|------------|
| Model | SEL-387A | ABB REF615 | Siemens 7UT86 | ABB RET670 |
|-------|----------|------------|---------------|------------|

Assessment and Modernization of Relay Protection Systems for Auxiliary Transformers at TPP-4

| Main application      | Transformer Differential | Transformer/Feeder    | Transformer Differential | Advanced Transformer Protection |
|-----------------------|--------------------------|-----------------------|--------------------------|---------------------------------|
| Nominal Current Input | 1 A or 5 A               | 1 A or 5 A            | 1 A or 5 A               | 1 A or 5 A                      |
| Operating Temperature | -40°C to +85°C           | -40°C to +85°C        | -25°C to +55°C           | -40°C to +85°C                  |
| Size (mm)             | 178 × 483 × 254          | 177 × 226 × 175       | 265 × 483 × 289          | 265 × 483 × 289                 |
| Approx. price         | 12.5–18.0 million MNT    | 10.0–15.0 million MNT | 16.1–23.3 million MNT    | 21.5–32.2 million MNT           |

Table 14. Technical comparison of candidate microprocessor relays

| Parameter                     | SEL-387A  | REF615  | 7UT86 | RET670 |
|-------------------------------|-----------|---------|-------|--------|
| Differential Protection       | +         | +       | +     | +      |
| Overcurrent Protection        | +         | +       | +     | +      |
| Earth Fault Protection        | +         | +       | +     | +      |
| Overload Protection           | +         | +       | +     | +      |
| Inrush Restraint (2nd Harm.)  | +         | +       | +     | +      |
| Overexcitation (5th Harm.)    | +         | +       | +     | +      |
| Thermal Protection            | +         | +       | +     | +      |
| Disturbance Recorder          | +         | +       | +     | +      |
| Self-Diagnostics              | +         | +       | +     | +      |
| 3-winding Transformer Support | + (3W87T) | Limited | +     | +      |

Table 15. Functional comparison of candidate microprocessor relays

#### 4.4 Justification of Selection and its Technical Parameter

Based on the technical and functional comparison of the candidate numerical relays, the SEL-387A Transformer Protection Relay is selected as the most suitable relay for the modernized protection system of auxiliary transformer 2BT (13).

The ABB REF615 has limited suitability for this application because it is mainly intended for feeder and distribution transformer protection, and its three-winding transformer differential protection capability is limited (25). The ABB RET670 has higher cost and greater functional complexity are not necessary for a single auxiliary transformer application (26). The Siemens 7UT86 is technically suitable and supports advanced transformer protection functions, but it has a higher approximate cost and a narrower operating temperature range compared with the SEL-387A (22).

Therefore, from both a technical and economic point of view, the SEL-387A provides the most appropriate balance between protection performance, functional capability, reliability, maintainability, installation suitability, and cost (13).

The complete technical parameters of the selected SEL-387A relay are presented in Table 16.

| Parameter               | Specification                                  |
|-------------------------|------------------------------------------------|
| Model                   | SEL-387A Transformer Protection Relay          |
| Manufacturer            | Schweitzer Engineering Laboratories (SEL), USA |
| Nominal Current Input   | 1 A or 5 A (selectable per winding)            |
| CT Secondary Burden     | Less than 0.2 VA at 5 A nominal                |
| Voltage Input           | Up to 300 V AC                                 |
| DC Power Supply Range   | 24–250 V DC                                    |
| AC Power Supply Range   | 100–240 V AC                                   |
| Communication Ports     | RS-232, RS-485, Ethernet optional              |
| Communication Protocols | SEL protocol, DNP3, IEC 61850, Modbus          |
| Applicable standards    | IEC 60255, ANSI/IEEE C37.90                    |

*Table 16. Technical parameters of the selected SEL-387A transformer protection relay*

## 4.5 Relay Protection Setting Calculation

### 4.5.1 Purpose of Relay Setting Calculation

The relay setting calculation is performed to determine suitable initial settings for the modernized protection system of auxiliary transformer 2BT. The calculation is based on the selected ТРДНГ-32000/10 У1, 32 MVA, 10.5/6.3/6.3 kV replacement transformer and the SEL-387A numerical transformer protection relay (14,18,19).

The purpose of the setting calculation is to ensure that the relay remains stable during normal operating conditions and load variations, but operates reliably during internal faults, external faults, overload conditions, abnormal voltage conditions, and breaker failure conditions. The calculated settings are used for the main and backup protection functions, including differential protection, overcurrent protection, thermal overload protection, undervoltage protection, overvoltage protection, and breaker failure protection (12,13,16,18,19,25).

### 4.5.2 Calculation Formulas and Selected Coefficients

The relay setting calculation is based on transformer rated current, current transformer ratios, voltage transformer ratios, and short-circuit current levels. The main formulas and selected coefficients used in the calculation are presented in this section.

#### 1. Rated current of transformer winding

The rated current of each transformer winding is calculated by:

$$I_n = \frac{S_n}{\sqrt{3} \cdot U_n} \quad (14)$$

where:

- $S_n$ — rated apparent power of the transformer, kVA;
- $U_n$  — rated line voltage, kV;
- $I_n$  — rated current, A.

#### 2. Overcurrent protection pickup setting

The primary pickup current of overcurrent protection is calculated by:

$$I_{set} = \frac{K_n}{K_v} \cdot I_n \quad (15)$$

where:

- $I_{set}$  — primary pickup current of the overcurrent protection, A;
- $K_v$  — return coefficient;
- $K_n$  — reliability coefficient;

The relay secondary current is calculated by:

$$I_{relay} = \frac{K_{cx} \cdot I_{set}}{K_{TA}} \quad (16)$$

where:

- $K_{TA}$  — current transformer transformation ratio;
- $K_{cx}$  — current transformer connection coefficient.

### 3. Short-circuit sensitivity coefficient

$$I_{sen} = \frac{I_k}{I_{set}} \quad (17)$$

where:

- $I_{sen}$  — sensitivity coefficient;
- $I_k$  — minimum short-circuit current at the protected zone, A;

### 4. Thermal overload protection pickup current

$$I_{set.49} = \frac{K_n}{K_v} \cdot I_n \quad (18)$$

where:

- $I_{set.49}$  — thermal overload protection pickup current, A;
- $K_n$  — overload margin coefficient;
- $K_v$  — return coefficient.

## 5. Voltage protection setting

The undervoltage protection primary setting is calculated by:

$$U_{set.27} = K_u \cdot U_n \quad (19)$$

where:

- $U_{set}$  — undervoltage protection pickup voltage, kV;
- $K_u$  — undervoltage setting coefficient;

The relay secondary voltage is calculated by:

$$U_{relay} = \frac{U_{set}}{K_{TV}} \quad (20)$$

where:

- $U_{relay}$  — relay secondary voltage setting, V;
- $K_{TV}$  — voltage transformer transformation ratio.

The overvoltage protection primary setting is calculated by:

$$U_{set.59} = K_u \cdot U_n \quad (21)$$

## 6. Differential protection setting

For preliminary setting, the total unbalanced current is calculated by:

$$I_{unb} = I'_{unb} + I''_{unb} + I'''_{unb} \quad (22)$$

where:

- $I_{unb}$  — total unbalance current, A;
- $I'_{unb}$  — unbalance current caused by CT error and transient component;
- $I'''_{unb}$  — relay measurement and conversion error.
- $I''_{unb}$  — unbalance current caused by transformer ratio mismatch or tap changer deviation;

$$I'_{unb} = K_{aper} \cdot K_{odi} \cdot E \cdot I_k^{(3)} \quad (23)$$

where:

- $K_{aper}$  —aperiodic component coefficient
- $K_{odi}$  — coefficient considering CT similarity
- $E$ — CT error coefficient
- $I_k^{(3)}$ — maximum external short-circuit current, A.

$$I''_{unb} = \frac{\Delta U\%}{100} \cdot I_k^{(3)} \quad (24)$$

where:

- $\Delta U\%$  — transformer voltage regulation or tap changer deviation, %;

The differential pickup current is calculated by:

$$I_{set87T} = K_n \cdot I_{unb} \quad (25)$$

where:

- $K_n = 1.2$

## 7.Breaker failure protection setting

$$I_{50BF} = 0.2 \cdot I_n \quad (26)$$

Assessment and Modernization of Relay Protection Systems for Auxiliary Transformers  
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| Coefficient | Selected value | Explanation                                                                                                                                    |
|-------------|----------------|------------------------------------------------------------------------------------------------------------------------------------------------|
| $K_n$       | 1.2            | Reliability coefficient used to set the pickup current above the rated load current and avoid unwanted operation during normal load variation. |
| $K_v$       | 0.96           | Return coefficient used to provide a reset margin after the current decreases below the pickup value.                                          |
| $K_n$       | 1.1            | Overload margin coefficient used for long-term thermal protection of the transformer high-voltage winding.                                     |
| $K_n$       | 1.05           | Overload margin coefficient used for long-term thermal protection of each low-voltage winding.                                                 |
| $K_u$       | 0.65           | Voltage setting coefficient used to detect severe voltage reduction on the auxiliary power supply system.                                      |
| $K_u$       | 1.2            | Voltage setting coefficient used to detect abnormal voltage increase that may stress insulation and connected equipment.                       |
| $K_{aper}$  | 1.5            | Aperiodic component coefficient used to consider the DC offset component of external short-circuit current.                                    |
| $K_{odi}$   | 1.0            | CT similarity coefficient used when current transformers are assumed to have similar characteristics.                                          |
| $E$         | 0.1            | CT error coefficient representing an assumed 10% current transformer error.                                                                    |
| $K_{cx}$    | 1.0            | CT connection coefficient                                                                                                                      |

*Table 17. Coefficients used in relay protection setting calculation*

### 4.5.3 Relay Setting Calculation

The initial data used for the relay setting calculation are shown in Table 18.

| Parameter                   | Symbol             | Value           |
|-----------------------------|--------------------|-----------------|
| Transformer Rated Power     | $S_n$              | 32,000 kVA      |
| HV-side voltage             | $U_{HV}$           | 10.5 kV         |
| LV-side voltage             | $U_{LV}$           | 6.3 / 6.3 kV    |
| Power of each LV winding    | $S_{LV}$           | 16,000 kVA      |
| Short-circuit current at K1 | $I_{k1}^{(3)}$     | 26.07 kA        |
| Short-circuit current at K2 | $I_{k2}^{(3)}$     | 15.08 kA        |
| HV-side CT ratio            | $K_{TA1}$          | 2500/5 = 500    |
| LV-side CT ratio            | $K_{TA2}, K_{TA3}$ | 2000/5 = 400    |
| HV-side VT ratio            | $K_{TV1}$          | 10500/100 = 105 |
| LV-side VT ratio            | $K_{TV2}, K_{TV3}$ | 6300/100 = 63   |

Table 18. Initial data for relay setting calculation

#### Rated Current of the Transformer

- 10.5 kV side

$$I_{n1} = \frac{32000}{\sqrt{3} \cdot 10.5} = 1759.5 \text{ A}$$

- 6.3 kV side

$$I_{n2} = I_{n3} = \frac{S_n/2}{\sqrt{3} \cdot U_n} = \frac{32000/2}{\sqrt{3} \cdot 6.3} = 1466.3 \text{ A}$$

#### Overcurrent Protection Setting

- 10.5 kV-Side

$$I_{set} = \frac{1.2}{0.96} \cdot 1759.5 = 2199.4 \text{ A}$$

$$I_{rela} = \frac{2199.4}{500} = 4.4 \text{ A}$$

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- 6.3 kV-Side

$$I_{set2} = I_{set3} = \frac{1.2}{0.96} \cdot 1466.3 = 1832.9 \text{ A}$$

$$I_{rel} = I_{relay3} = \frac{1832.9}{400} = 4.58 \text{ A}$$

### Sensitivity Check of Overcurrent Protection

$$I_{sen1} = \frac{26070}{2199.4} = 11.85$$

$$I_{sen2} = \frac{15080}{1833.1} = 8.23$$

### Thermal Overload Protection Setting (49)

- 10.5 kV-Side

$$I_{set.49.HV} = \frac{1.1 \cdot 1759.5}{0.96} = 2016.1 \text{ A}$$

$$I_{relay.49.HV} = \frac{2016.1}{500} = 4.03 \text{ A}$$

- 6.3 kV-Side

$$I_{set.49.LV} = \frac{1.1 \cdot 1466.3}{0.96} = 1604 \text{ A}$$

$$I_{relay.49.LV} = \frac{1604}{400} = 4.01 \text{ A}$$

### Undervoltage Protection Setting (27)

- 10.5 kV-Side

$$U_{set.27.HV} = 0.65 \cdot 10.5 = 6.825 \text{ kV}$$

$$U_{relay.27.HV} = \frac{6825}{105} = 65 \text{ V}$$

- 6.3 kV-Side

$$U_{set.27.LV} = 0.65 \cdot 6.3 = 4.095 \text{ kV}$$

$$U_{relay.27.HV} = \frac{4095}{63} = 65 \text{ V}$$

### Overvoltage Protection Setting (59)

- 10.5 kV-Side

$$U_{set.59.HV} = 1.2 \cdot 10.5 = 12.6 \text{ kV}$$

$$U_{relay.59.HV} = \frac{12600}{105} = 120 \text{ V}$$

- 6.3 kV-Side

$$U_{set.59.LV} = 1.2 \cdot 6.3 = 7.56 \text{ kV}$$

$$U_{relay.59.HV} = \frac{7560}{63} = 125 \text{ V}$$

### Differential Protection Setting (87T)

- 10.5 kV side

$$I'_{unb} = 1.5 \cdot 1 \cdot 0.1 \cdot 26070 = 3910.5 \text{ A}$$

$$I''_{unb} = \frac{12.7}{100} \cdot 26070 = 3310.9 \text{ A}$$

$$I_{unb1} = 3910.5 + 3310.9 + 20 = 7241.4 \text{ A}$$

$$I_{set87T1} = 1.2 \cdot 7241.4 = 8689.7 \text{ A}$$

$$I_{relay87T1} = \frac{8689.7}{500} = 17.38 \text{ A}$$

- 6.3 kV side

$$I'_{unb} = 1.5 \cdot 1 \cdot 0.1 \cdot 15080 = 2262 \text{ A}$$

$$I''_{unb} = \frac{12.7}{100} \cdot 15080 = 1915.2 \text{ A}$$

$$I_{unb2} = 2262 + 1915.2 + 20 = 4197.2 \text{ A}$$

$$I_{set87} = 1.3 \cdot 4197.2 = 5456.4 \text{ A}$$

$$I_{relay87T1} = \frac{5456.4}{500} = 13.64 \text{ A}$$

### Breaker Failure Protection Setting

- 10.5 kV side

$$I_{50BF.1} = 0.2 \cdot 1759.5 = 351.9 \text{ A}$$

$$I_{relay.50.BF.1} = \frac{351.9}{500} = 0.7 \text{ A}$$

- 6.3 kV side

$$I_{50BF.2} = 0.2 \cdot 1466.3 = 293.3 \text{ A}$$

$$I_{relay.50.BF} = \frac{293.3}{400} = 0.73 \text{ A}$$

#### 4.5.4 Final Relay Setting Summary

| Protected section          | Rated power | $I_n$ , A | CT ratio, $K_{TA}$  | Protection function | Primary setting | Time delay | Sec relay setting |
|----------------------------|-------------|-----------|---------------------|---------------------|-----------------|------------|-------------------|
| HV winding<br>10.5 kV      | 32 MVA      | 1759.5    | 2500/5              | 87T                 | 8689.7 A        | t=0 s      | 17.38 A           |
| LV winding<br>6.3 kV (2BA) | 16 MVA      | 1466.3    | 2000/5              | 87T                 | 5456.4 A        | t=0 s      | 13.64 A           |
| LV winding<br>6.3 kV (2BB) | 16 MVA      | 1466.3    | 2000/5              | 87T                 | 5456.4 A        | t=0 s      | 13.64 A           |
| HV side 10.5<br>kV         | 32 MVA      | 1759.5    | 2500/5              | 50/51               | 2199.4 A        | t=1.0 s    | 4.4 A             |
| LV side 6.3<br>kV (2BA)    | 16 MVA      | 1466.3    | 2000/5              | 50/51               | 1833.1 A        | t=0.5 s    | 4.58 A            |
| LV side 6.3<br>kV (2BB)    | 16 MVA      | 1466.3    | 2000/5              | 50/51               | 1833.1 A        | t=0.5 s    | 4.58 A            |
| HV side 10.5<br>kV         | 32 MVA      | 1759.5    | 2500/5              | 49                  | 2016.1 A        | t=9 s      | 4.03 A            |
| LV side 6.3<br>kV (2BA)    | 16 MVA      | 1466.3    | 2000/5              | 49                  | 1604.0 A        | t=9 s      | 4.01 A            |
| LV side 6.3<br>kV (2BB)    | 16 MVA      | 1466.3    | 2000/5              | 49                  | 1604.0 A        | t=9 s      | 4.01 A            |
| HV side 10.5<br>kV         | 32 MVA      | —         | VT<br>10500/10<br>0 | 27                  | 6.825 kV        | —          | 65 V              |

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|                            |        |        |                     |      |          |         |        |
|----------------------------|--------|--------|---------------------|------|----------|---------|--------|
| LV side 6.3<br>kV          | 16 MVA | —      | VT<br>6300/100      | 27   | 4.095 kV | —       | 65 V   |
| HV side 10.5<br>kV         | 32 MVA | —      | VT<br>10500/10<br>0 | 59   | 12.6 kV  | —       | 120 V  |
| LV side 6.3<br>kV          | 16 MVA | —      | VT<br>6300/100      | 59   | 7.56 kV  | —       | 120 V  |
| HV winding<br>10.5 kV      | 32 MVA | 1759.5 | 2500/5              | 50BF | 351.9 A  | t=0.2 s | 0.7 A  |
| LV winding<br>6.3 kV (2BA) | 16 MVA | 1466.3 | 2000/5              | 50BF | 293.3 A  | t=0.2 s | 0.73 A |
| LV winding<br>6.3 kV (2BB) | 16 MVA | 1466.3 | 2000/5              | 50BF | 293.3 A  | t=0.2 s | 0.73 A |

*Table 19. Calculated relay protection settings for the modernized protection of  
transformer 2BT*

## Chapter 5: Economic Calculation

### 5.1 Introduction

This chapter presents the economic evaluation of the proposed modernization of auxiliary transformer 2BT and its relay protection system. The purpose of the economic evaluation is to estimate the required investment cost, compare the annual operating costs before and after modernization, determine the annual economic saving, and calculate the payback period of the proposed project (27,28).

The modernization proposal includes the replacement of the existing auxiliary transformer with a ТРДНЧ-32000/10 У1, 32 MVA transformer and the replacement of the existing electromechanical relay protection system with the SEL-387A microprocessor-based transformer protection relay. The economic calculation is based on equipment cost, labor cost, maintenance cost reduction, and expected operational savings.

### 5.2 Economic Calculation

#### 5.2.1 Investment Cost Calculation

The investment cost includes the purchase cost of the main equipment required for the modernization. The main equipment consists of the replacement auxiliary transformer and the selected numerical transformer protection relay.

| #                         | Equipment name        | Model             | Quantity | Price, MNT  |
|---------------------------|-----------------------|-------------------|----------|-------------|
| 1                         | Auxiliary transformer | ТРДНЧ-32000/10 У1 | 1        | 223,600,000 |
| 2                         | Microprocessor relay  | SEL-387A          | 1        | 19,673,500  |
| Total main equipment cost |                       |                   |          | 243,273,500 |

*Table 20. Main equipment purchase cost*

$$C_{equipment} = 243,273,500 \text{ MNT}$$

### 5.2.2 Labor Cost Calculation

The labor cost includes the work required for dismantling the existing transformer connections, installing the replacement transformer, mounting the relay, wiring CT, VT, and control circuits, checking secondary circuits, configuring relay settings, and performing commissioning tests (18,27).

| #                | Worker / specialist               | Number of workers | Hourly wage, MNT | Daily wage, MNT | 7-day wage, MNT |
|------------------|-----------------------------------|-------------------|------------------|-----------------|-----------------|
| 1                | Protection engineer               | 1                 | 20,000           | 160,000         | 1,120,000       |
| 2                | Relay technician                  | 1                 | 18,000           | 144,000         | 1,008,000       |
| 3                | Transformer installation engineer | 1                 | 20,000           | 160,000         | 1,120,000       |
| 4                | Electrician, 5th grade            | 1                 | 17,000           | 136,000         | 952,000         |
| 5                | Electrician, 4th grade            | 1                 | 15,000           | 120,000         | 840,000         |
| Total labor cost |                                   |                   |                  |                 | 5,040,000       |

Table 21. Labor and installation cost

$$C_{labor} = 5,040,000 \text{ MNT}$$

### 5.2.3 Total Investment Cost

The total investment cost includes the main equipment cost, labor cost, auxiliary installation materials, testing and commissioning cost, transportation, and contingency cost. These additional costs are included because transformer replacement and relay modernization require not only equipment purchase but also installation materials, testing instruments, commissioning activities, and project implementation expenses (27,28).

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| #                     | Cost item                                                      | Cost, MNT   |
|-----------------------|----------------------------------------------------------------|-------------|
| 1                     | Main equipment cost                                            | 243,273,500 |
| 2                     | Labor and installation cost                                    | 5,040,000   |
| 3                     | Auxiliary materials, wiring, terminals, and panel modification | 18,000,000  |
| 4                     | Testing and commissioning cost                                 | 15,000,000  |
| 5                     | Transportation and handling cost                               | 10,000,000  |
| 6                     | Contingency and miscellaneous expenses                         | 20,000,000  |
| Total investment cost |                                                                | 311,313,500 |

*Table 22. Total investment cost summary*

$$C_{total} = 311,313,500 \text{ MNT}$$

### 5.2.4 Operating Cost Before Modernization

Before modernization, the existing transformer and electromechanical relay protection system require more frequent maintenance, inspection, testing, calibration, and troubleshooting. Since the existing transformer and relay protection devices have been in service for several decades, maintenance requirements are higher due to ageing of insulation, relay contacts, mechanical elements, and auxiliary circuits (11,13,18).

| #                                      | Cost item                                | Annual cost, MNT |
|----------------------------------------|------------------------------------------|------------------|
| 1                                      | Planned maintenance of old transformer   | 18,000,000       |
| 2                                      | Relay protection inspection and testing  | 12,000,000       |
| 3                                      | Adjustment and calibration of old relays | 6,000,000        |
| 4                                      | Unplanned repair and troubleshooting     | 12,000,000       |
| Total annual cost before modernization |                                          | 48,000,000       |

*Table 23. Annual Operating Cost Before Modernization*

$$C_{old} = 48,000,000 \text{ MNT}$$

### 5.2.5 Operating Cost After Modernization

After modernization, the new transformer and microprocessor-based relay protection system are expected to reduce maintenance and troubleshooting costs. The SEL-387A relay provides self-diagnostics, event recording, disturbance recording, and communication functions. These functions support faster fault analysis, easier inspection, and more efficient maintenance planning (13,18).

| # | Cost item                               | Annual cost, MNT |
|---|-----------------------------------------|------------------|
| 1 | Planned maintenance of new transformer  | 8,000,000        |
| 2 | Annual relay testing and inspection     | 4,000,000        |
| 3 | Relay setting backup and software check | 1,500,000        |
| 4 | Minor troubleshooting                   | 1,500,000        |
|   | Total annual cost after modernization   | 15,000,000       |

Table 24. Annual operating cost after modernization

$$C_{new} = 15,000,000 \text{ MNT}$$

### 5.2.6 Annual Economic Saving:

The annual economic saving is calculated as the difference between the annual operating cost before modernization and the annual operating cost after modernization (27,28):

$$S_{annual} = C_{old} - C_{new} \quad (27)$$

$$S_{annual} = 48,000,000 - 15,000,000 = 33,000,000 \text{ MNT/year}$$

Therefore, the proposed modernization is expected to reduce annual operating costs by 33,000,000 MNT

### 5.2.7 Payback Period

The payback period is calculated by dividing the total investment cost by the annual economic saving:

$$T_{payback} = \frac{C_{total}}{S_{annual}} \quad (28)$$

$$T_{payback} = \frac{311,313,500}{33,000,000} = 9.4 \text{ years}$$

The calculated payback period is approximately 9.4 years. This means that the investment cost of the proposed modernization can be recovered through reduced operating and maintenance costs over this period.

## CHAPTER 6: DISCUSSION AND CONCLUSIONS

### 6.1 Discussion

#### *6.1.1 Discussion of Technical Results*

The technical assessment carried out in this thesis shows that auxiliary transformer 2BT is an important component of the 6.3 kV auxiliary power supply system of Thermal Power Plant No. 4. The transformer supplies major motor-driven auxiliary loads, including boiler feed pumps, circulating pumps, draft fans, forced-draft fans, oil pumps, conveyors, and other technological mechanisms. Since these consumers are required for unit operation, the reliability of transformer 2BT directly affects the operational reliability and availability of the generating unit.

The electrical load calculation was performed using the demand-factor method. The total calculated active power was 20.52 MW, and the total calculated reactive power was 16.37 MVar. Based on these values, the calculated apparent power of the connected auxiliary loads was 26.25 MVA. Since the existing transformer is rated at 25 MVA, the calculated transformer loading coefficient is approximately 1.05. This indicates that the calculated load exceeds the rated capacity of the existing transformer.

Operating a transformer above its rated capacity may increase winding temperature, oil temperature, power losses, and insulation ageing. In addition, the limited capacity margin may create operational difficulties during motor starting, reserve-feeding operation, or future load growth. Therefore, replacement of the existing transformer with a higher-rated unit is technically justified.

The comparison of candidate replacement transformers showed that both the ТРДНЧ-32000/10 Y1 and SFSZ11-31500/10.5/6.3/6.3 transformers satisfy the calculated loading requirements. However, the ТРДНЧ-32000/10 Y1 transformer was selected because it has a rated capacity of 32 MVA, is closer to the existing CIS-type design, and is more compatible with the existing auxiliary power supply arrangement of TPP-4.

The short-circuit calculation was performed using the per-unit method. The calculated three-phase short-circuit current was 26.07 kA at fault point K1 on the 10.5 kV side and 15.08 kA at fault point K2 on the 6.3 kV auxiliary bus section. The corresponding peak short-circuit currents were 68.20 kA and 39.45 kA, respectively. These results provide

the technical basis for relay protection setting calculation and equipment withstand verification.

### *6.1.2 Discussion of Relay Protection Modernization*

The existing relay protection system of transformer 2BT includes the basic protection functions required for transformer operation, such as differential protection, overcurrent protection, gas protection, thermal supervision, cooling control, and protection of the associated 6 kV auxiliary bus sections. However, the main transformer-side protection devices were commissioned in 1987 and are based on electromechanical relay technology.

Although electromechanical relays can provide basic protection, they have limitations under modern operating requirements. These limitations include restricted setting flexibility, absence of self-diagnostics, lack of event and disturbance recording, limited communication capability, and higher maintenance requirements. These factors make post-fault analysis, relay testing, and protection coordination more difficult.

For the proposed replacement transformer, a modern numerical protection relay is required. The selected transformer is a three-winding, 32 MVA, 10.5/6.3/6.3 kV unit; therefore, the relay must support three-winding transformer differential protection and backup protection functions. Four candidate numerical relays were compared: SEL-387A, ABB REF615, Siemens 7UT86, and ABB RET670.

Based on the technical and functional comparison, the SEL-387A Transformer Protection Relay was selected as the most suitable relay. It supports three-winding differential protection and provides the required functions, including overcurrent protection, earth-fault protection, thermal overload protection, harmonic restraint, breaker failure protection, event recording, disturbance recording, self-diagnostics, and communication capability. Compared with more complex high-end relays, the SEL-387A provides a suitable balance between technical performance, reliability, maintainability, and cost for this application.

The calculated relay settings provide an initial engineering basis for the modernized protection scheme. However, the final relay settings must be verified during detailed engineering and commissioning. This verification should include CT performance checks, VT ratio verification, transformer vector group compensation, tap changer range

consideration, relay slope setting verification, protection coordination studies, and secondary injection testing.

### *6.1.3 Discussion of Economic Feasibility*

The economic evaluation estimated the total investment cost of the proposed modernization as 311,313,500 MNT. This includes the cost of the replacement transformer, SEL-387A relay, labor and installation work, auxiliary materials, testing and commissioning, transportation, and contingency expenses.

Before modernization, the annual operating cost of the existing transformer and relay protection system was estimated as 48,000,000 MNT/year. After modernization, the annual operating cost is expected to decrease to 15,000,000 MNT/year due to reduced maintenance requirements, easier relay testing, self-diagnostic functions, and improved fault analysis capability.

The annual economic saving is 33,000,000 MNT/year

The calculated payback period is 9.4 years

Although the payback period is relatively long, the modernization should not be evaluated only based on direct financial savings. The technical benefits are also important, including improved transformer capacity, more reliable protection operation, better fault recording, improved maintainability, and increased operational security of the auxiliary power supply system. Therefore, the proposed modernization is justified from both technical and operational perspectives.

### *6.2 Limitations of the Study*

This study provides a preliminary engineering assessment and modernization proposal for auxiliary transformer 2BT at Thermal Power Plant No. 4. However, several limitations should be considered when interpreting the results.

First, TPP-4 is a state-owned enterprise, and some technical and operational information could not be disclosed due to confidentiality requirements. Therefore, some detailed plant data were not available for this thesis. As a result, certain coefficients and assumptions used in the load calculation, short-circuit calculation, relay setting

calculation, and economic evaluation were selected based on engineering practice and available reference values.

Second, the load calculation was based on connected load data and selected demand factors. Actual long-term operating measurements from the 2BA and 2BB auxiliary bus sections were not available for all consumers. Therefore, the calculated load may differ from the actual maximum demand during real plant operation.

Third, the short-circuit calculation was performed using a simplified equivalent circuit. The source reactance, cable reactance, and transformer reactance were considered, while detailed network configuration, connected motor contribution, resistance components, and transient effects were neglected. A more detailed short-circuit study using professional power system analysis software may provide more accurate results.

Fourth, the relay protection settings were calculated as preliminary engineering values. Final settings must be verified according to the actual relay configuration, current transformer performance, voltage transformer data, transformer tap changer range, protection coordination requirements, and commissioning test results.

Finally, the economic calculation was based on estimated equipment, labor, maintenance, and operating cost values. Actual market prices, supplier quotations, transportation costs, installation expenses, and exchange rates may change. Therefore, the economic results should be updated during the detailed project planning and procurement stage.

### *6.3 Conclusions and Recommendations*

This thesis assessed the loading condition and relay protection modernization of auxiliary transformer 2BT at Thermal Power Plant No. 4. The study included connected load analysis, transformer capacity assessment, replacement transformer selection, short-circuit calculation, relay selection, relay setting calculation, and economic evaluation.

Based on the load calculation, the existing 25 MVA auxiliary transformer does not provide sufficient loading reserve under the considered operating condition. Therefore, replacement with a higher-rated transformer is technically justified. The ТРДНС-32000/10 Y1, 32 MVA transformer was selected as the preferred replacement option because it satisfies the calculated loading requirement and is compatible with the existing 10.5/6.3/6.3 kV auxiliary power supply system.

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The short-circuit calculation provided the required fault-current values for protection assessment and relay setting calculation. These values confirm the need for proper relay coordination and reliable fault-clearing capability in the auxiliary power supply system.

The existing transformer-side relay protection devices are technologically outdated because they are based on electromechanical relay technology. Therefore, modernization with a numerical transformer protection relay is necessary. The SEL-387A relay was selected because it supports three-winding transformer differential protection and provides the required backup protection, monitoring, recording, and communication functions.

The economic evaluation showed that the proposed modernization requires a significant initial investment, but it can reduce annual operating and maintenance costs. More importantly, the modernization improves transformer loading capability, relay protection reliability, maintainability, fault analysis capability, and operational security.

Therefore, the proposed replacement of transformer 2BT and modernization of its relay protection system are technically justified and beneficial for improving the reliability of the auxiliary power supply system at TPP-4.

For future work, actual operating load measurements should be collected from the 2BA and 2BB auxiliary bus sections to verify the calculated load demand. A detailed short-circuit and protection coordination study should also be performed using professional power system analysis software. Current transformer performance should be evaluated in detail, especially for differential protection stability during external faults. The final SEL-387A relay settings should be verified using the manufacturer's instruction manual, secondary injection testing, trip circuit testing, alarm testing, and communication testing.

The condition of the existing transformer should also be assessed using diagnostic tests such as insulation resistance measurement, winding resistance measurement, transformer oil testing, dissolved gas analysis, and bushing inspection. Since TPP-4 is a state-owned enterprise and some technical information is confidential, future studies should be conducted in closer cooperation with authorized plant engineers and responsible departments. This would allow access to more detailed operational data, actual protection coordination records, relay event reports, and maintenance history while maintaining confidentiality requirements.

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Finally, the economic calculation should be updated during the detailed project planning stage using current supplier quotations, actual transportation and installation costs, and the official exchange rate at the time of procurement. This would provide a more accurate estimation of investment cost and payback period.

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