



Simulation and Analysis of Transformer Tap Changer Settings for Voltage Regulation in Electrical Distribution Systems

Ichal Priski ^{a,*}, Andi Asri Mulyadi ^a, Aika Nurjanna ^a

^a *Electrical Engineering Department, Polytechnic State of Ujung Pandang, Makassar, Indonesia*

ABSTRACT

Transformer tap changers are widely used in distribution systems to regulate voltage and maintain acceptable steady-state operating conditions. This study presents an application-oriented ETAP 19.0.1 load-flow assessment of five discrete tap positions (-5%, -2.5%, 0%, +2.5%, and +5%) for Transformer T2 in a multi-source distribution network containing utility and generator supplies, motor and static loads, a capacitor bank, and a photovoltaic unit. The adopted ETAP convention places the tap adjustment on the primary winding; consequently, a negative tap reduces the effective primary turns ratio and raises the secondary-side voltage. For the investigated operating point, Bus3 remains nearly constant at 19.68–19.70 kV (98.4–98.5% of nominal), whereas Bus4 and Bus5 are strongly affected by tap position. The -5% setting gives 3.63 kV at Bus4 (100.8%) and 0.395 kV at Bus5 (98.8%), while the +5% setting reduces them to 3.28 kV (91.1%) and 0.357 kV (89.3%). The study therefore identifies -5% as the best of the five tested settings for this specific operating condition. The contribution is a reproducible comparative tap-setting procedure and a practical voltage-regulation recommendation for the modeled network, rather than a new OLTC control algorithm. Active and reactive power-flow trends are also examined to complement the voltage-profile assessment.

Keywords: Transformer tap changer; voltage regulation; load flow analysis; voltage profile; power quality.

1. Introduction

The increasing demand for electrical energy has created greater challenges in maintaining the reliability and power quality of electrical power systems. Among the various power quality indicators, voltage regulation is critical because voltage levels directly affect the performance, efficiency, and service life of electrical equipment connected to the network. Therefore, maintaining voltage within the permissible operating range is essential to ensure stable and reliable power system operation [1, 2].

Voltage variations commonly occur in distribution systems due to changes in load demand, network configuration, line impedance, and power-flow conditions. These variations may result in undervoltage or overvoltage conditions that adversely affect system performance and customer equipment. Excessive voltage drops can increase system losses and reduce the efficiency of electrical devices, while excessive voltage rises can cause insulation stress and equipment damage. Thus, effective voltage regulation methods are required to maintain an acceptable voltage profile throughout the distribution network [3].

Transformers play an important role in voltage regulation within electrical power systems. One practical method for controlling transformer output voltage is tap changer operation. A tap changer adjusts the transformer turns ratio,

enabling the secondary voltage to be increased or decreased according to operating requirements. Proper tap settings can reduce voltage deviations caused by load fluctuations and network conditions, improve voltage profiles, and minimize the risk of voltage-limit violations without major modifications to the existing electrical infrastructure [4, 5].

Advances in power system simulation tools have enabled engineers and researchers to evaluate voltage regulation methods through computer-based analysis. Simulation allows various operating scenarios to be investigated efficiently without affecting the actual electrical network [6]. Load-flow analysis is commonly used to assess voltage magnitudes, power-flow distribution, and system operating conditions under different tap changer settings. Such analysis provides useful information for determining appropriate transformer tap positions and understanding their influence on system performance [7].

This study evaluates five fixed transformer tap positions using ETAP 19.0.1 to determine how the adopted primary-winding tap convention affects voltage regulation in the modeled distribution network. Unlike recent studies that develop automatic or coordinated OLTC controllers using fuzzy logic, distributed inverter control, energy storage, or real-time optimization, the present work focuses on a transparent static sensitivity assessment that can be

* Corresponding author.

E-mail addresses: risaloka01@gmail.com.

Received 1st July 2026; Received in revised form 8th August 2026; Accepted 10th August 2026

Available online 25th September 2026

© 2026 The Authors. Published by Research Institute for Applied and Social Science (RIASS), Indonesia. This is an open access article distributed under the terms of the Creative Commons Attribution 4.0 International (CC BY 4.0) license.

reproduced directly from a conventional load-flow model. The practical contribution is the identification of a suitable operating tap for Transformer T2 under the investigated network condition, which includes multiple voltage levels, conventional sources, motor and static loads, a capacitor bank, and photovoltaic generation.

Accordingly, the research gap addressed here is not the basic transformer turns-ratio relationship, which is well established, but the lack of a clearly documented, scenario-by-scenario assessment of how a specific transformer tap convention propagates through medium- and low-voltage buses in this modeled network. The analysis is intentionally limited to five discrete steady-state cases; therefore, claims are restricted to the investigated operating point and should not be interpreted as a universal or adaptive OLTC control strategy.

2. Literature Review

2.1. Transformer

A transformer is a static electromagnetic device used to transfer electrical energy between circuits through magnetic coupling without changing the frequency of the electrical supply. Transformers are among the most critical components in electrical power systems because they enable efficient power transmission and distribution by adjusting voltage levels according to operational requirements. High-voltage transmission reduces current flow and minimizes power losses, while lower voltages are required for safe distribution to consumers [1, 2, 7].

The fundamental relationship between primary and secondary voltages in an ideal transformer is expressed as:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} \quad (1)$$

where:

V_p = primary voltage (V)

V_s = secondary voltage (V)

N_p = number of primary winding turns

N_s = number of secondary winding turns

The ratio

$$a = \frac{N_p}{N_s} \quad (2)$$

Where a is known as the transformer turns ratio. This parameter determines whether the transformer operates as a step-up or step-down unit. Any modification of the effective turns ratio directly affects the output voltage, which forms the basis for transformer tap changer operation [8, 9].

2.2. Voltage Quality

In electrical distribution systems, voltage levels are continuously affected by changes in load demand, feeder length, conductor impedance, transformer loading, and reactive power conditions. As power flows through network components, voltage drops occur due to line impedance and load current. Therefore, maintaining voltage within acceptable operating limits is a primary objective of power system operation and planning [10].

1. Under Voltage

Under-voltage is a condition in which the RMS voltage falls below the lower acceptable operating limit for a specified duration. According to common power system standards, under-voltage generally occurs when the voltage decreases below 95% of its nominal value.

$$V < 0.95V_n \quad (3)$$

where:

V = actual voltage

V_n = nominal voltage

Several factors contribute to under-voltage conditions, including:

1. Excessive loading
2. Long distribution feeders
3. Reactive power deficiency
4. High transmission losses
5. Fault conditions in the network

Under-voltage may result in reduced motor torque, overheating of electrical equipment, increased current consumption, poor lighting performance, and deterioration of system stability [2].

2. Over Voltage

Over-voltage occurs when the voltage exceeds the upper permissible limit.

$$V > 1.05V_n \quad (4)$$

This condition may arise due to:

1. Light-load operation
2. Excessive reactive power compensation
3. Improper transformer tap settings
4. Switching operations
5. Distributed generation penetration

$$0.95V_n \leq V \leq 1.05V_n$$

For a 20 kV distribution system, the allowable voltage range is:

$$19 \text{ kV} \leq V \leq 21 \text{ kV}$$

Maintaining voltages within these limits is essential for ensuring power quality, minimizing losses, and protecting customer equipment. Therefore, voltage regulation devices such as transformer tap changers, capacitor banks, and voltage regulators are commonly utilized in modern power systems [8, 11].

2.3. Transformer Tap Changer

A transformer tap changer is a voltage regulation device installed on a transformer winding to adjust the transformer turns ratio and maintain the desired output voltage level. In electrical power systems, voltage levels continuously fluctuate due to changes in load demand, network impedance, reactive power flow, and operating conditions. These fluctuations can cause the secondary voltage of a transformer to deviate from its nominal value. Therefore, transformer tap changers are utilized to compensate for such variations and ensure that voltage remains within acceptable operating limits [10, 11].

The basic operating principle of a tap changer involves changing the effective number of turns in one of the

transformer windings. Since the voltage transformation ratio depends on the ratio of primary and secondary winding turns, modifying the number of active turns will directly affect the output voltage. By selecting an appropriate tap position, the transformer can increase or decrease its secondary voltage according to system requirements [1, 11].

The relationship between transformer voltage and turns ratio is expressed by:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} \quad (5)$$

From this equation, it can be observed that changing the effective number of windings turns results in a corresponding change in the voltage ratio. Consequently, transformer tap changers provide a practical means of voltage regulation without requiring additional compensation equipment.

In modern power systems, tap changers are commonly installed on the high-voltage winding because the current level is lower than that of the low-voltage winding. This arrangement reduces switching stress and minimizes contact wear during tap-changing operations. Depending on the transformer design, tap positions are typically provided in discrete steps, such as $\pm 2.5\%$, $\pm 5\%$, $\pm 7.5\%$, or $\pm 10\%$ of the rated voltage [9, 13-17].

A. Types of Transformers Tap Changers

Transformer tap changers are generally categorized into two types based on their operating characteristics.

1. Off-Circuit Tap Changer (OCTC)

An Off-Circuit Tap Changer (OCTC), also known as a De-Energized Tap Changer (DETC), requires the transformer to be disconnected from the power system before the tap position can be changed. Because the transformer must be taken out of service during adjustment, OCTCs are mainly used in applications where voltage regulation is not frequently required [18].

2. On-Load Tap Changer (OLTC)

An On-Load Tap Changer (OLTC) allows tap position changes while the transformer remains energized and connected to the load. OLTCs are widely used in transmission substations, distribution substations, and large power transformers where continuous voltage regulation is essential [19].

Due to these advantages, OLTCs have become one of the most important voltage control devices in modern power systems.

B. Tap Position and Voltage Regulation

Each tap position corresponds to a specific voltage adjustment level. The percentage change in voltage depends on the transformer design and tap step size. The relationship between the adjusted voltage and tap setting can be approximated as:

$$V_{\text{new}} = V_{\text{rated}}(1 + \Delta\text{Tap}) \quad (6)$$

where:

V_{new} = adjusted voltage

V_{rated} = rated voltage

ΔTap = tap adjustment percentage

For example, if a transformer has a rated secondary voltage of 20 kV and the tap position is increased by +5%, the resulting voltage becomes:

$$V_{\text{new}} = 20(1 + 0.05)$$

$$V_{\text{new}} = 21 \text{ kV}$$

$$V_{\text{new}} = 20(1 - 0.05)$$

$$V_{\text{new}} = 19 \text{ kV}$$

1. Improvement of voltage profiles
2. Reduction of under-voltage conditions
3. Reduction of over-voltage conditions
4. Enhancement of voltage stability
5. Improvement of power quality
6. Increased reliability of electrical supply

Conversely, inappropriate tap settings may lead to undesirable operating conditions. Excessive tap increases can cause over-voltage problems, while insufficient tap adjustments may fail to mitigate voltage drops. Therefore, determining the optimal tap position is a critical aspect of power system operation and planning [18, 19].

The effectiveness of transformer tap changer settings is commonly evaluated using load flow analysis. Load flow studies provide information regarding bus voltage magnitudes, active power flow, reactive power flow, transformer loading, and system losses under various operating conditions [20].

2.4. ETAP Software

Electrical Transient Analyzer Program (ETAP) is a comprehensive software package designed for the modeling, simulation, analysis, operation, and optimization of electrical power systems. The software provides an integrated platform for engineers and researchers to evaluate electrical network performance under various operating conditions. Through a graphical single-line diagram interface, ETAP enables the representation of power system components such as generators, transformers, transmission lines, buses, loads, and protection devices in a realistic simulation environment [9, 15].

The development of power system simulation software has significantly improved the efficiency of power system studies. Rather than performing extensive calculations manually, engineers can utilize simulation tools to analyze system behavior under different scenarios while reducing computational time and minimizing the risk of calculation errors. ETAP has become one of the most widely used software applications in power system engineering due to its comprehensive analysis capabilities and its ability to integrate multiple studies within a single platform [15].

One of the major strengths of ETAP is its digital modeling capability. The software allows users to create a virtual representation of an electrical network by entering equipment parameters according to manufacturer specifications and system design data. This digital model can then be used to investigate various operating conditions without affecting the actual system. Such an approach provides a safe, economical, and efficient method for evaluating system performance before practical implementation [22].

ETAP offers numerous analysis modules that support different aspects of power system engineering. These modules include load flow analysis, short-circuit analysis, protective device coordination, transient stability analysis, motor starting analysis, harmonic analysis, reliability assessment, and arc-flash studies. The integration of these modules enables engineers to perform comprehensive investigations of electrical system performance using a single software environment [16, 19, 21].

Among these features, load flow analysis is one of the most frequently utilized tools in power system studies. Load flow analysis calculates the steady-state operating conditions of the system, including bus voltage magnitudes, voltage angles, active power flow, reactive power flow, current magnitude, and power losses. The results provide essential information regarding the operational condition of the network and are commonly used as the basis for planning, operation, and optimization studies [23].

In transformer voltage regulation studies, load flow analysis plays a particularly important role because it allows the evaluation of voltage profiles under different transformer tap settings. Changes in transformer tap positions directly affect transformer voltage ratios, which in turn influence bus voltages throughout the electrical network. Through simulation, the impact of each tap position can be observed and compared systematically without interrupting actual system operation [13, 24].

The software also provides detailed transformer modeling capabilities, including transformer ratings, impedance characteristics, winding configurations, and tap changer settings. These features enable accurate representation of transformer behavior during simulation studies. As a result, ETAP is frequently employed to evaluate transformer voltage regulation strategies and determine the optimal tap position required to maintain voltage levels within prescribed operating limits.

Furthermore, ETAP enables users to conduct multiple simulation scenarios efficiently. Engineers can compare system performance under different loading conditions, network configurations, and voltage control strategies. This capability is particularly useful when investigating under-voltage and over-voltage conditions because it allows a comprehensive assessment of the effectiveness of transformer tap adjustments before implementation in the actual system [26].

In this research, ETAP 19.0.1 is utilized to perform load flow simulations and evaluate the effect of transformer tap changer settings on voltage regulation. Various tap positions are applied to the transformer model, and the resulting voltage profiles are analyzed to determine the most effective tap setting for maintaining voltage levels within acceptable operating limits. The simulation results are expected to provide a better understanding of transformer tap changer performance and its contribution to improving voltage quality in electrical distribution systems [27].

2.5. Previous Studies

Table 1 summarizes previous studies relevant to Simulation and Analysis of Transformer Tap Changer

Settings for Voltage Regulation in Electrical Distribution Systems.

Table 1
State Of the Art

No	Authors	Year	Research Focus	Method	Main Findings
1	Yoon et al.	2022	OLTC operation considering reverse power flow caused by photovoltaic penetration in distribution systems[1]	Distribution system simulation	Proposed an OLTC operation strategy capable of mitigating over-voltage and maintaining voltage within acceptable limits under high PV penetration.
2	Maataoui et al.	2022	Voltage regulation using a fuzzy logic-based OLTC controller in active distribution systems [2]	Fuzzy logic and simulation analysis	The proposed controller improved voltage regulation performance and reduced voltage deviations compared with conventional OLTC control methods.
3	Spertino et al.	2022	Voltage control in low-voltage networks using OLTC and distributed PV inverters [3]	Simulation-based optimization	Demonstrated that OLTC operation significantly contributes to maintaining voltage quality and reducing voltage violations.)
4	Li et al.	2022	Coordinated voltage regulation between flexible OLTC and distributed generation [6]	Simulation using coordinated control strategy	The coordination between OLTC and distributed generators improved voltage regulation effectiveness and system stability.
5	Jafari et al..	2022	Decentralized control of OLTC and PV inverters for voltage regulation in radial distribution networks with high PV penetration [27]	Decentralized control strategy and simulation	The proposed decentralized OLTC and PV inverter control effectively improved voltage profiles while minimizing unnecessary tap operations and maintaining system stability.

No	Authors	Year	Research Focus	Method	Main Findings
6	Khan and Rihan	2022	Voltage fluctuation mitigation using coordinated OLTC and energy storage control in high PV penetration distribution networks [10]	Coordinated control and simulation	Coordinated operation of OLTC and energy storage significantly reduced voltage fluctuations and enhanced voltage stability under varying loading conditions.
7	Aydin et al.	2022	Decentralized voltage management using OLTC-fitted distribution transformers to increase residential PV hosting capacity [17]	Decentralized voltage management and simulation	The proposed approach increased PV hosting capacity while maintaining distribution voltages within acceptable operating limits.
8	Bhatta and Patidar	2023	Intelligent transformer tap controller for harmonic elimination in photovoltaic interfaced micro-grid networks [18]	Intelligent control algorithm and simulation	The intelligent tap controller improved voltage regulation, reduced harmonic distortion, and enhanced overall power quality in micro-grid operation.

2.6. Research Gap and Study Positioning

Recent literature has progressed toward coordinated and adaptive OLTC control, including PV-aware tap operation, fuzzy-logic control, coordinated OLTC-energy-storage strategies, decentralized PV-inverter coordination, and field-measurement-based voltage compliance methods. These approaches primarily emphasize automatic control design and multi-device coordination. In contrast, the present study does not propose a new controller. It provides a static comparative assessment of five discrete primary-winding tap settings in a detailed ETAP network and quantifies their effect on bus-voltage deviation and transformer power-flow behavior. This narrower positioning makes the study useful as an engineering tap-setting verification exercise and as a baseline for future automatic OLTC control development.

3. Research Methodology

3.1 Research Method

This study employs a quantitative simulation-based approach to investigate the impact of transformer tap changer settings on voltage regulation in an electrical distribution system. The research is conducted using ETAP 19.0.1 software, which provides an integrated platform for modeling and analyzing electrical power systems under various operating conditions.

The primary objective of this research is to evaluate the effectiveness of different transformer tap positions in maintaining bus voltages within the permissible operating

range. The analysis is performed through load flow simulations, which allow the determination of voltage magnitude, power flow, and operating conditions throughout the electrical network. By comparing the voltage profiles obtained from different tap settings, the most suitable tap position can be identified.

Unlike field testing, simulation-based studies provide a safer and more economical approach for evaluating system performance because various operating scenarios can be investigated without affecting actual power system operation. Therefore, the simulation method is considered appropriate for analyzing transformer voltage regulation characteristics and assessing the influence of tap changer adjustments on distribution system performance.

3.2 System Modeling

The electrical distribution system is represented using a single-line diagram developed in ETAP 19.0.1. The model consists of the main components commonly found in a distribution network, including a utility source, transformer, buses, connecting cables, and electrical loads.

All equipment parameters are entered based on their technical specifications. The transformer model includes its rated capacity, primary voltage, secondary voltage, impedance characteristics, and tap changer configuration. Similarly, the load model includes active and reactive power requirements, while cable parameters include impedance and voltage ratings.

3.3 Transformer Tap Changer Simulation

The transformer tap changer simulation constitutes the core of this study. The simulation is conducted by varying the transformer tap position while maintaining all other system parameters unchanged. This approach ensures that any observed voltage variation is solely caused by changes in transformer tap settings. The transformer tap positions investigated in this study are presented in Table 2.

Table 2
Transformer Tap Position Scenarios

Tap Position	Tap Setting (%)
Tap 1	-5.0 %
Tap 2	-2.5 %
Tap 3	0 %
Tap 4	+2.5 %
Tap 5	+5.0 %

For each tap position, a load-flow simulation is performed in ETAP while all non-tap model parameters are kept unchanged. The resulting voltage magnitudes and power-flow quantities are recorded for comparison. In the adopted ETAP model, the tap changer is applied to the primary winding of Transformer T2. The transformer relationship can be written as $V_s/V_p = N_s/N_p$. Therefore, a negative primary-side tap decreases the effective number of primary turns N_p and increases the secondary voltage V_s for an approximately unchanged primary voltage; conversely, a positive tap increases N_p and reduces V_s . This sign convention explains why the -5% case produces the highest Bus4 and Bus5 voltages in the simulation results.

Negative tap positions are expected to reduce the transformer secondary voltage, whereas positive tap positions increase the secondary voltage. Through this

simulation, the relationship between tap adjustment and voltage regulation performance can be clearly observed.

3.4 Load Flow Analysis

Load-flow analysis is used to determine the steady-state operating condition of the ETAP network for each of the five tap cases. The same network topology, source conditions, load data, capacitor-bank status, PV representation, and component parameters are retained in every scenario; only the T2 tap position is changed. For each case, bus-voltage magnitude, branch current, active power, reactive power, apparent power, power factor, and transformer loading are recorded from the ETAP results. This controlled scenario design allows changes in voltage and P/Q flow to be attributed to the tap adjustment rather than to simultaneous changes in other model inputs. The exact ETAP numerical solver option, convergence tolerance, and iteration limit are properties of the saved ETAP study case and should be reported directly from that project file for complete independent reproducibility.

The load flow results provide information regarding the ability of each tap setting to maintain acceptable voltage levels throughout the system. Consequently, load flow analysis forms the basis for comparing transformer tap positions and identifying the most effective voltage regulation strategy.

3.5 Data Analysis

The simulation results are analyzed by comparing the voltage profiles obtained from each tap position. The voltage magnitude at every bus is evaluated and compared against the allowable operating limits discussed in Section 2.2.

Particular attention is given to buses experiencing the largest voltage deviations, as these locations are typically the most sensitive to transformer tap adjustments. The effectiveness of each tap setting is determined by examining its ability to improve voltage profiles and reduce voltage deviations.

The comparison between simulation scenarios enables a comprehensive assessment of transformer tap changer performance under different operating conditions. The resulting voltage profiles are presented in tabular and graphical forms to facilitate interpretation and comparison.

3.6. Research Workflow

The research stages illustrate the systematic procedure followed in this study, from the initial literature review to the determination of the optimal transformer tap position. The overall process begins with a literature review on transformers, voltage quality, and transformer tap changers, which is then followed by modeling the electrical distribution system as a Single Line Diagram in ETAP 19.0.1 and verifying the model through an initial load flow simulation. Once the model is confirmed to be free of errors, the tap position of Transformer T2 is set sequentially to each of the five predefined scenarios (-5%, -2.5%, 0%, +2.5%, and +5%), and a load flow simulation is executed for every tap setting to record the resulting voltage magnitudes at Bus3, Bus4, and Bus5. This procedure is repeated until all five tap positions have been simulated.

The recorded voltage profiles are then compared against the permissible $\pm 5\%$ voltage standard described in Section 2.2 to identify the buses experiencing the most significant deviations. Based on this comparison, the tap position that produces the most favorable voltage profile while maintaining transformer loading within safe operating limits is determined as the optimal setting. The complete sequence of these research stages is illustrated in the flowchart presented in Figure 1.

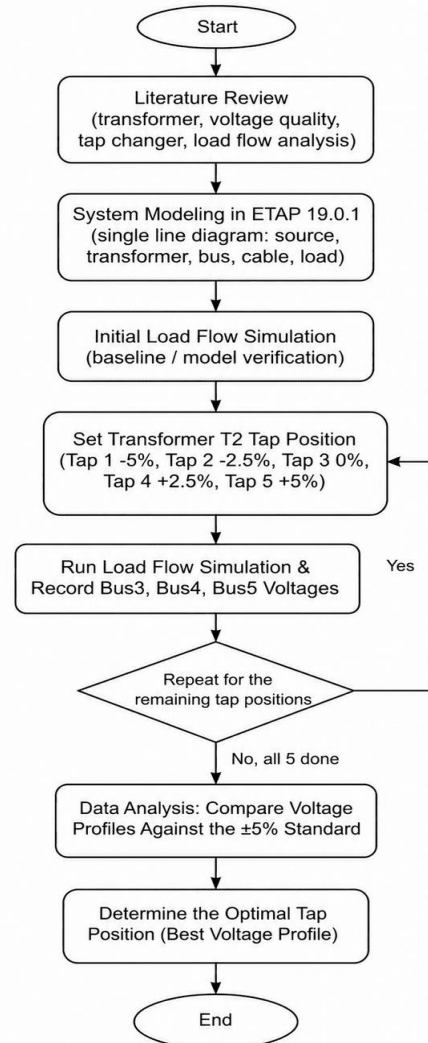


Fig.1. Flowchart of the Research Stages

4. Results and Discussion

4.1 Single Line Diagram of the Simulated System

The first stage of this study involves developing a power system model using ETAP 19.0.1. The simulation model is represented in the form of a Single Line Diagram (SLD), which illustrates the interconnection of major electrical components within the system. The modeled network consists of utility and generator sources, power transformers, distribution buses, transmission cables, loads, capacitor banks, and a photovoltaic (PV) system. This configuration enables the evaluation of power flow and voltage profiles under different transformer tap changer settings.

4.2 Load Flow Simulation Results

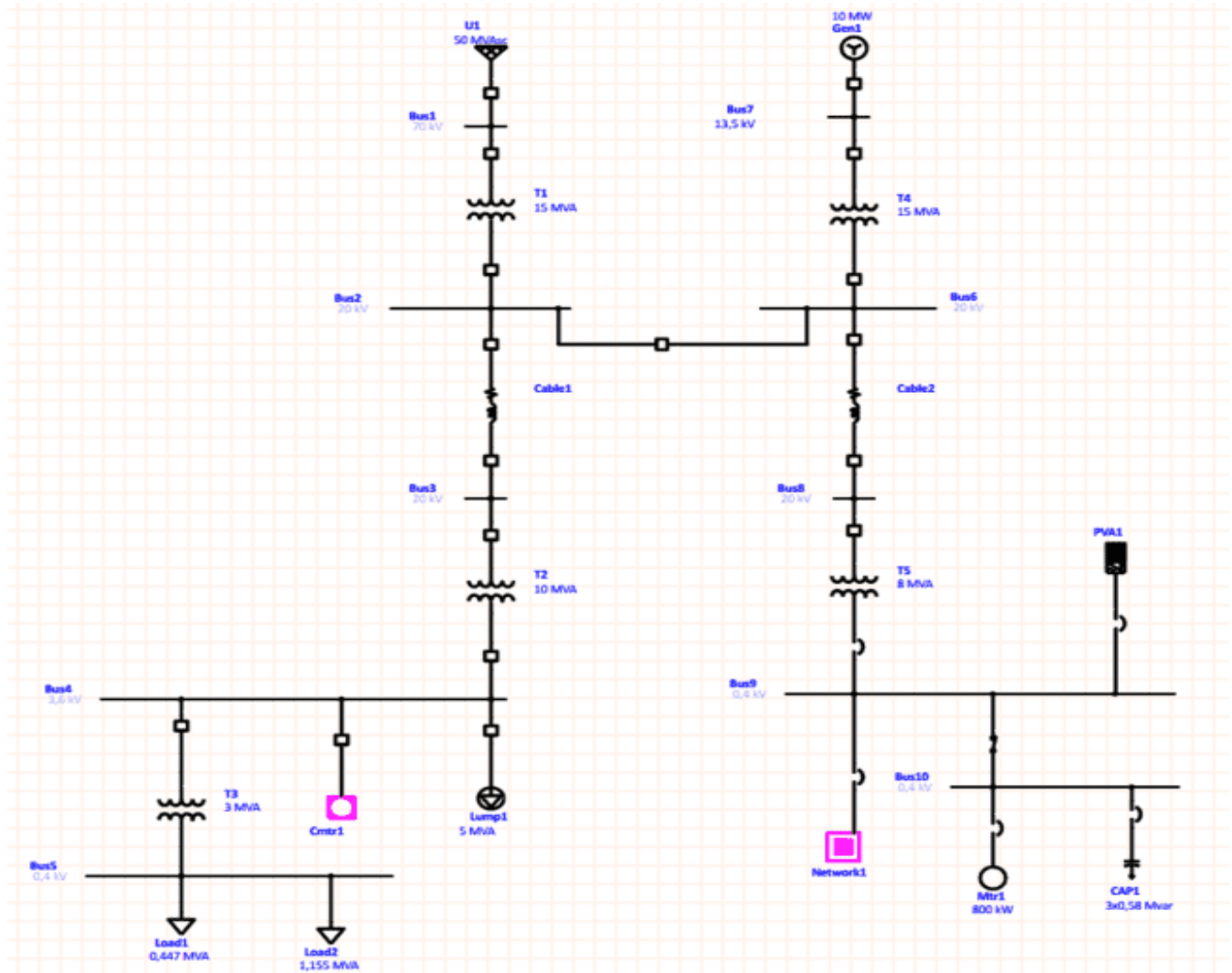


Fig.2. Single Line Diagram of the Simulated Electrical Distribution System

The utility grid supplies electrical power through a 70 kV bus connected to a 15 MVA transformer, which steps down the voltage to the 20 kV distribution level. In addition, a 10 MW generator is connected to the system through another 15 MVA transformer, providing an additional power source for the network. The medium-voltage buses are interconnected through distribution cables, allowing power transfer between different sections of the system.

At the load side, several transformers are utilized to further reduce the voltage from 20 kV to 0.4 kV for low-voltage consumers. The system includes lumped loads, static loads, an induction motor load, and a capacitor bank for reactive power compensation. Furthermore, a photovoltaic (PV) unit is integrated into the low-voltage network to represent renewable energy penetration within the distribution system [16, 22].

The developed SLD serves as the basis for conducting load flow simulations and evaluating the influence of transformer tap changer adjustments on voltage regulation. Various tap positions are applied to the main transformer, and the resulting voltage profiles are analyzed to determine the effectiveness of voltage regulation under different operating scenarios.

After the system model was developed in ETAP 19.0.1, a load flow simulation was performed to evaluate the steady-state operating condition of the electrical distribution network under normal operating conditions. The load flow analysis provides comprehensive information regarding voltage magnitude, power flow, current flow, and loading conditions at each bus and system component, including transformers, cables, and loads. This analysis is essential for assessing the overall performance of the power distribution system, identifying voltage deviations, and detecting potential overloading conditions that may affect system reliability and operational efficiency. Furthermore, the simulation results serve as the basis for evaluating the effectiveness of voltage regulation through transformer tap adjustment, allowing the impact of different tap positions on the voltage profile and overall system performance to be systematically analyzed.

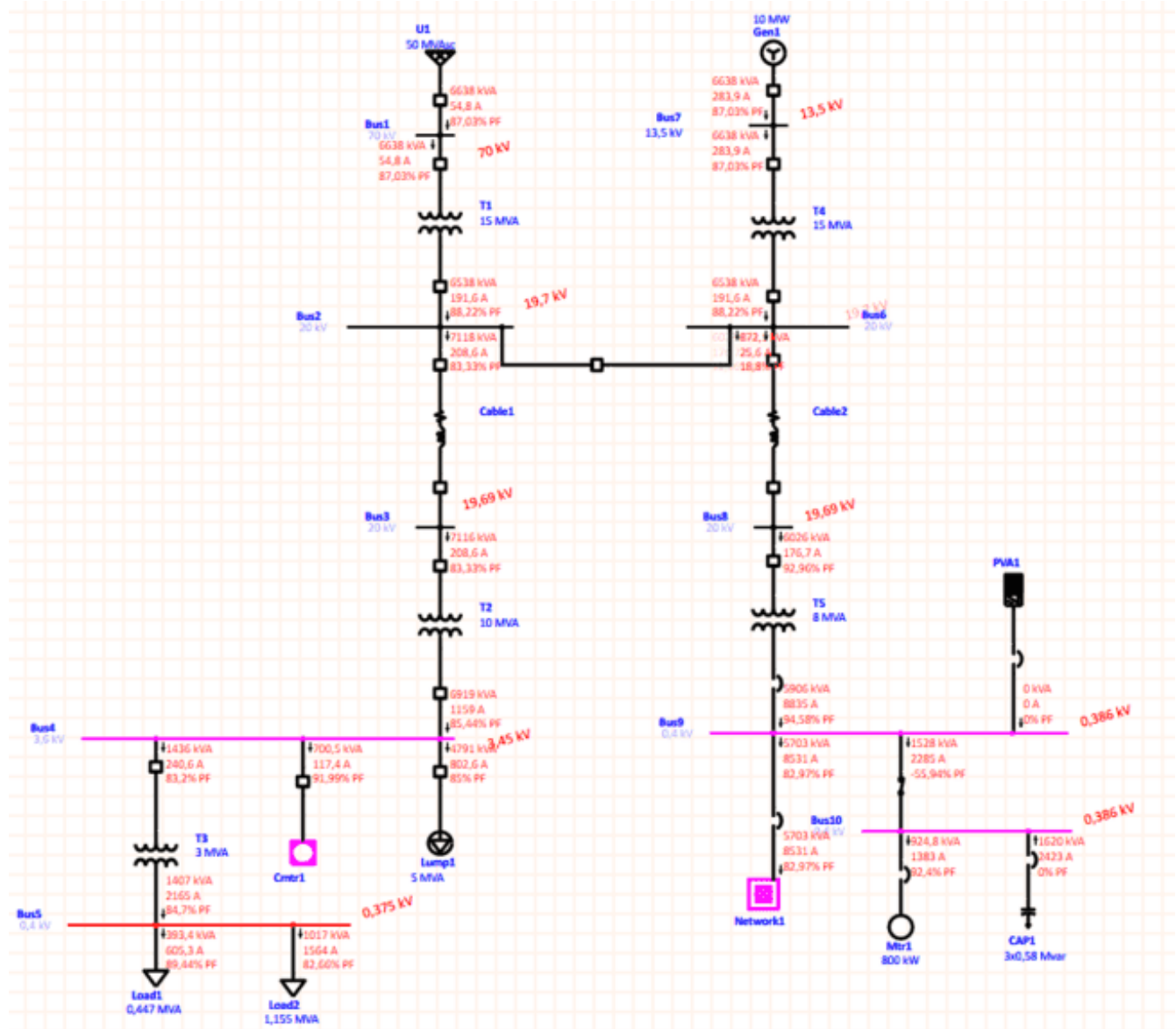


Fig.3. Load Flow Simulation Results

Based on the simulation results shown in Figure 3, the majority of medium-voltage buses operate close to their nominal voltage level. The voltage at Bus1 remains at approximately 70 kV, while Bus7 operates at approximately 13.5 kV, indicating that the primary power sources are supplying the system under normal operating conditions. After passing through the main transformers, the voltages at Bus2, Bus3, Bus6, and Bus8 are approximately 19.69–19.71 kV, which is slightly below the nominal 20 kV level but still within the acceptable voltage regulation range.

Several buses are highlighted in different colors by ETAP to indicate their voltage conditions. The pink-colored buses represent buses that are operating close to the lower voltage system operation. In this simulation, the buses located on the low-voltage side of the network, such as Bus4 and Bus9, exhibit voltages of approximately 0.375 kV and 0.386 kV, respectively. These values are lower than the nominal voltage of 0.4 kV, indicating the occurrence of voltage drops caused by transformer loading, cable impedance, and connected loads.

Meanwhile, the red-colored buses indicate buses experiencing more significant voltage deviations from their nominal values. The most noticeable voltage drop occurs at Bus5, where the voltage decreases to approximately 0.369 kV. This condition suggests that the bus is located at the end of a feeder supplying multiple loads, resulting in greater voltage reduction due to line impedance and load demand. Such conditions make these buses suitable observation points for evaluating the effectiveness of transformer tap changer adjustments.

4.3 Transformer Tap Changer Adjustment

Based on the initial load flow simulation performed with the transformer operating at the nominal tap position (Tap 3 = 0%), several buses on the low-voltage side of the distribution system experienced significant voltage drops. This condition is clearly indicated by the presence of pink and red-colored buses in the ETAP load flow visualization. These color indicators represent buses whose operating voltages fall below the acceptable voltage limits specified for normal system operation, reflecting inadequate voltage

regulation and poor voltage profiles throughout the distribution network. Such voltage deviations may adversely affect the performance, efficiency, and reliability of electrical equipment connected to these buses, making voltage improvement necessary.

Therefore, this study focuses on adjusting the tap position of Transformer T2, which has a rated capacity of 10 MVA and a voltage ratio of 20 kV/3.6 kV, as illustrated in Figure 4. Transformer T2 was selected because it directly supplies the buses experiencing the most severe voltage drops, making it the most effective point for implementing voltage regulation. The transformer is equipped with an on-load tap changer (OLTC), which enables voltage regulation by changing the transformer turns ratio without interrupting power supply. By modifying the tap position, the secondary-side voltage can be increased or decreased to compensate for voltage drops caused by feeder impedance and loading conditions. In this study, several tap positions were evaluated through load flow simulations to determine the most suitable tap setting capable of restoring bus voltages within the permissible operating limits while maintaining stable system performance and minimizing voltage deviations across the network.

Fig.4. Transformer T2 Parameters Used in the Simulation

To evaluate the influence of tap changer operation on voltage regulation, five tap positions are investigated. The selected tap settings are summarized in Table 3.

Table 3

Tap Position Scenarios for Transformer T2

Tap Position	Tap Setting (%)
Tap 1	-5.0
Tap 2	-2.5
Tap 3	0
Tap 4	+2.5
Tap 5	+5.0

Fig.5. Transformer T2 Tap

For each tap position, a separate load flow simulation is performed while maintaining all other system parameters unchanged. The resulting voltage profiles are then compared to determine the effectiveness of each tap setting in mitigating under-voltage conditions and improving the overall voltage quality of the distribution system.

The primary objective of the tap adjustment is to increase the voltage at the buses experiencing the largest voltage deviations while ensuring that all bus voltages remain within the acceptable operating range. Consequently, the simulation results obtained from each tap position provide valuable information regarding the optimal transformer tap setting required to achieve satisfactory voltage regulation throughout the system.

1. Transformer T2 Tap 3 (0%)

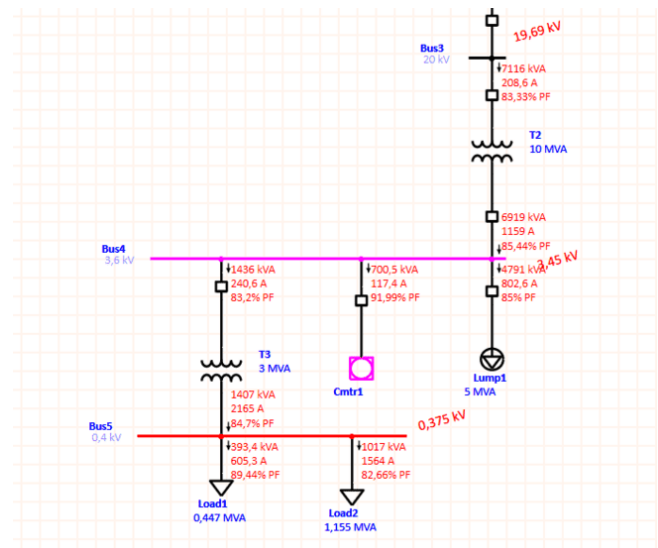


Fig.6. Transformer T2 Load Flow Tap 3 (0%)

At Tap Position 3 (0%), the system operates under stable conditions without any indication of transformer overloading. The voltage at the 20 kV bus (Bus3) is slightly below its nominal value, indicating a minor voltage drop on the medium-voltage side. This condition is reflected by the bus color, which remains within the normal operating range and does not indicate any critical voltage violation. The transformer T2 continues to supply power effectively to the downstream network while maintaining acceptable operating conditions.

On the 3.6 kV bus (Bus4), the voltage is noticeably lower than its nominal value, as indicated by the bus color changing to a lighter shade that represents an undervoltage condition. Although the voltage reduction is still within an acceptable operational range, it suggests that the transformer tap setting

at 0% is not fully compensating for the voltage drop caused by the connected load demand. The load flow results show that the majority of the power is delivered to the large motor load and the downstream distribution transformer, contributing to the observed voltage reduction.

Overall, the Tap 3 (0%) setting keeps Transformer T2 within its reported loading range, but Bus4 and Bus5 remain below their nominal voltages. Because the adopted tap is located on the primary winding, moving toward a more negative tap increases the secondary-side voltage. The comparison therefore indicates that the nominal setting is not the best of the five tested cases for this operating point.

2. Transformer T2 Tap 2 (-2.5%)

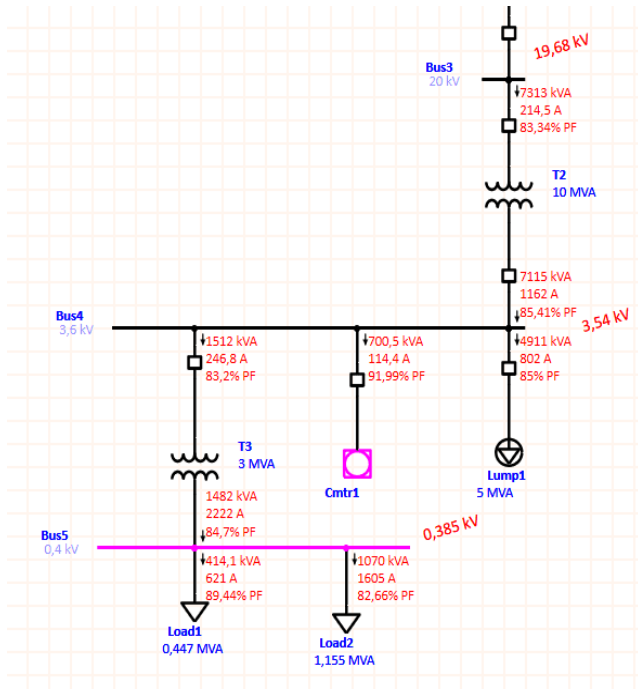


Fig.7. Transformer T2 Load Flow Tap 2 (-2.5%)

At Tap Position 2 (-2.5%), the primary-winding tap is reduced relative to the nominal position, which increases the secondary-side voltage under the adopted ETAP sign convention. Bus3 remains close to nominal at approximately 19.68 kV. Bus4 reaches approximately 3.54 kV and Bus5 approximately 0.385 kV, representing an improvement over the 0% case, although both buses remain below their nominal values. Transformer loading remains within the reported rating, so this tap provides a useful intermediate voltage-regulation condition between the nominal and -5% settings.

On the 3.6 kV bus (Bus4), the voltage decreases to approximately 3.54 kV, which is lower than the nominal value. The bus color changes from the normal condition to a darker shade, indicating an undervoltage condition. This voltage reduction is a direct consequence of the negative tap adjustment and the power demand from the connected motor load and downstream transformer. Although the bus remains operational, the voltage level is farther from the desired nominal value compared to higher tap positions.

3. Transformer T2 Tap 1 (-5%)

At Tap Position 1 (-5%), the transformer operates with the lowest tap setting among the analyzed cases, resulting in the highest secondary-side voltage level. The 20 kV bus

(Bus3) remains stable at approximately 19.68 kV, indicating that the upstream network is largely unaffected by the tap adjustment. The bus color remains within the normal operating range, showing that the primary-side voltage is maintained close to its nominal value and that transformer T2 continues to operate under acceptable loading conditions.

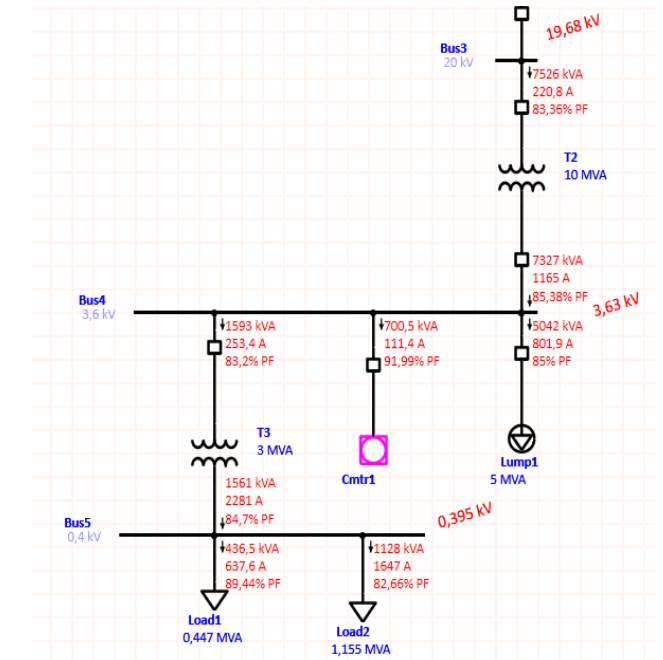


Fig.8. Transformer T2 Load Flow Tap 1 (-5%)

The voltage at the 3.6 kV bus (Bus4) increases to approximately 3.63 kV, which is very close to its nominal rating. This improvement is reflected by the bus color returning to a normal operating condition, indicating that the voltage regulation on the medium-voltage side has significantly improved compared to the previous tap positions. The enhanced voltage profile helps ensure better operating conditions for the connected motor load and downstream distribution transformer.

On the 0.4 kV bus (Bus5), the voltage rises to approximately 0.395 kV, which is closer to the nominal low-voltage level than in the Tap 2 (-2.5%) and Tap 3 (0%) scenarios. Although a small voltage drop is still present, the bus color indicates a healthier voltage condition and improved voltage quality throughout the low-voltage network. Overall, Tap Position 1 (-5%) provides the best voltage profile among the evaluated tap settings, maintaining voltages closer to their nominal values across both the medium-voltage and low-voltage buses while keeping transformer loading within safe operating limits.

4. Transformer T2 Tap 4 (2.5%)

At Tap Position 4 (+2.5%), the transformer operates at a higher tap setting, resulting in a reduction of the secondary-side voltage compared to the lower tap positions. The voltage at the 20 kV bus (Bus3) remains relatively stable at approximately 19.7 kV, indicating that the upstream transmission system is not significantly affected by the tap adjustment. The primary-side voltage remains within acceptable operating limits, and transformer T2 continues to operate under normal loading conditions with an apparent power flow of approximately 6.93 MVA, well below its 10 MVA rating.

The voltage at the 3.6 kV bus (Bus4) decreases to approximately 3.36 kV, representing a noticeable undervoltage condition compared to its nominal rating. This reduction is reflected by the bus color indication, suggesting that the medium-voltage network is operating outside the optimal voltage range. The lower voltage level may adversely affect the performance of the connected motor load, potentially leading to increased current demand and reduced operational efficiency. The apparent power supplied to the motor load remains around 4.68 MVA, while the current increases to approximately 804 A, indicating the impact of the reduced voltage on load operation.

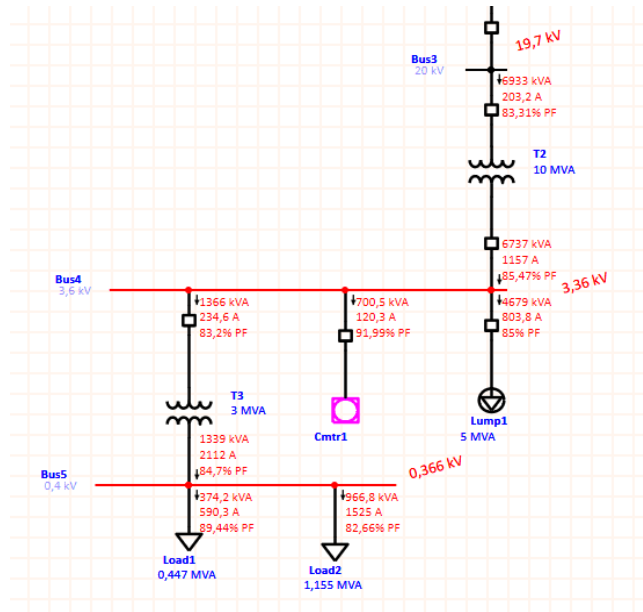


Fig.9. Transformer T2 Load Flow Tap 4 (2.5%)

On the low-voltage side, the voltage at the 0.4 kV bus (Bus5) drops further to approximately 0.366 kV, which is significantly below the nominal voltage level. This indicates a considerable voltage drop throughout the distribution system and may result in poor voltage quality for connected loads. The downstream loads continue to consume approximately 0.447 MVA and 1.155 MVA, respectively, but the reduced voltage level can negatively affect equipment performance and increase system losses. Overall, Tap Position 4 (+2.5%) provides the poorest voltage profile among the evaluated tap settings, producing substantial undervoltage conditions on both the medium-voltage and low-voltage buses while maintaining transformer loading within safe operating limits.

5. Transformer T2 Tap 5 (5%)

At Tap Position 5 (+5%), the transformer operates at the highest tap setting among the evaluated cases, resulting in the lowest secondary-side voltage levels throughout the distribution network. The voltage at the 20 kV bus (Bus3) remains relatively constant at approximately 19.7 kV, demonstrating that the upstream supply system is largely unaffected by changes in the transformer tap position. Transformer T2 carries an apparent power of approximately 6.76 MVA, which is still well below its 10 MVA rating, indicating that the transformer is operating safely from a loading perspective.

The voltage at the 3.6 kV bus (Bus4) decreases further to approximately 3.28 kV, representing a significant deviation from the nominal medium-voltage level. Compared to Tap Position 4 (+2.5%), the voltage profile deteriorates further, indicating a stronger undervoltage condition on the medium-voltage feeder. This reduced voltage level can negatively affect the performance of connected equipment, particularly the motor load, which continues to consume approximately 4.57 MVA while drawing a current of about 805 A. The increased current demand associated with the lower voltage may contribute to higher system losses and reduced operational efficiency.

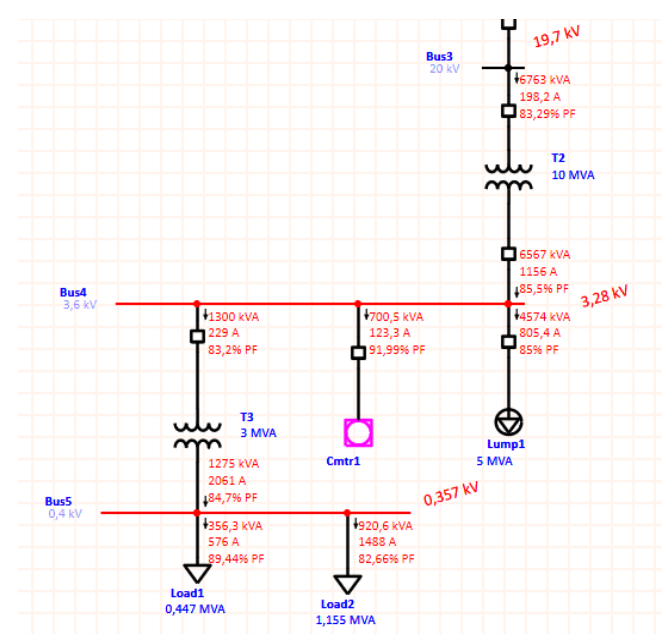


Fig.10. Transformer T2 Load Flow Tap 5 (+5%)

On the low-voltage side, the voltage at the 0.4 kV bus (Bus5) falls to approximately 0.357 kV, which is the lowest voltage recorded among all investigated tap positions. This value is considerably below the nominal low-voltage rating and indicates poor voltage regulation throughout the distribution network. The connected loads continue to consume approximately 0.436 MVA (Load1) and 0.921 MVA (Load2), but the reduced voltage may lead to degraded equipment performance, increased current draw, and potential operational issues for sensitive loads. The bus color also reflects a severe undervoltage condition, highlighting the deterioration of power quality at the consumer level.

Table 3 and 4 summarizes the impact of transformer tap position adjustments on the voltage profile of the distribution network. The analysis was conducted by varying the tap position of transformer T2 from -5% to +5% while observing the voltage levels at Bus3 (20 kV), Bus4 (3.6 kV), and Bus5 (0.4 kV). The results show that the primary-side voltage at Bus3 remains relatively constant for all tap settings, indicating that the upstream network is largely unaffected by the transformer tap adjustment. In contrast, significant changes are observed on the medium-voltage and low-voltage sides. As the tap position increases from -5% to +5%, the voltages at Bus4 and Bus5 decrease progressively, resulting in increasingly severe undervoltage conditions. Among all evaluated cases, Tap Position 1 (-5%) provides the most favorable voltage profile, maintaining bus voltages

closest to their nominal values. Conversely, Tap Position 5 (+5%) produces the lowest voltage levels and the poorest voltage regulation performance. Therefore, the results indicate that a negative tap setting is more effective in improving voltage regulation and maintaining acceptable operating conditions throughout the distribution network.

Table 3

Effect of Transformer Tap Position on Bus Voltages and System Performance

Tap Position	Tap Setting	Bus4 Voltage (3.6 kV)	Bus5 Voltage (0.4 kV)	Voltage Condition	Performance Assessment
Tap 1	-5%	3.63 kV	0.395 kV	Near nominal on all buses	Best
Tap 2	-2.5%	3.54 kV	0.385 kV	Slight undervoltage at Bus4 and Bus5	Good
Tap 3	0%	3.45 kV	0.375 kV	Moderate undervoltage	Acceptable
Tap 4	+2.5%	3.36 kV	0.366 kV	Significant undervoltage	Poor
Tap 5	+5%	3.28 kV	0.357 kV	Severe undervoltage	Worst

Table 4

Bus Voltage Magnitudes Expressed as a Percentage of Nominal Voltage

Tap Position	Bus3 (%)	Bus4 (%)	Bus5 (%)
Tap 1 (-5%)	98.4%	100.8%	98.8%
Tap 2 (-2.5%)	98.4%	98.3%	96.3%
Tap 3 (0%)	98.5%	95.8%	93.8%
Tap 4 (+2.5%)	98.5%	93.3%	91.5%
Tap 5 (+5%)	98.5%	91.1%	89.3%

In this study, the tap changer is installed on the high-voltage (primary) side of transformer T2. When the tap position is moved toward the negative direction (-2.5% and -5%), the effective number of primary winding turns decreases. Since the primary-to-secondary turns ratio becomes smaller, the secondary voltage increases. This behavior can be clearly observed from the simulation results, where the voltage at Bus4 increases from approximately 3.28 kV at Tap Position 5 (+5%) to 3.63 kV at Tap Position 1 (-5%). Similarly, the voltage at Bus5 increases from 0.357 kV to 0.395 kV as the tap position shifts from +5% to -5%.

From an operational perspective, maintaining adequate voltage levels at the load buses is essential because undervoltage conditions can negatively affect equipment performance. For induction motor loads, a reduction in terminal voltage leads to higher current demand in order to maintain the required torque. The increased current may result in higher copper losses, greater heating, reduced efficiency, and a shorter equipment lifespan. Likewise, low-voltage consumer loads connected to Bus5 may experience poor performance, reduced power quality, and potential malfunction when the supply voltage falls significantly below its nominal value [28, 29, 30].

Among all investigated cases, Tap Position 1 (-5%) provides the most favorable operating condition because it maintains the bus voltages closest to their nominal values while keeping transformer loading within safe limits. The voltage at Bus4 reaches approximately 3.63 kV, which is very close to its nominal rating of 3.6 kV, while Bus5 achieves approximately 0.395 kV, representing the highest voltage level among all evaluated scenarios. These results

indicate that reducing the effective number of primary winding turns through a negative tap adjustment can successfully compensate for voltage drops caused by load demand and feeder impedance, thereby improving overall voltage regulation throughout the distribution system [12, 16, 24, 25].

4.4. Voltage and Power-Flow Profiles across Tap Positions

Figure 11 summarizes the normalized bus-voltage profiles for all five T2 tap positions. Bus3 changes by only about 0.1 percentage point, whereas Bus4 and Bus5 show a monotonic reduction as the tap moves from -5% to +5%. The -5% case keeps both downstream buses within the $\pm 5\%$ band, while the 0%, +2.5%, and +5% cases progressively increase undervoltage severity at the low-voltage bus.

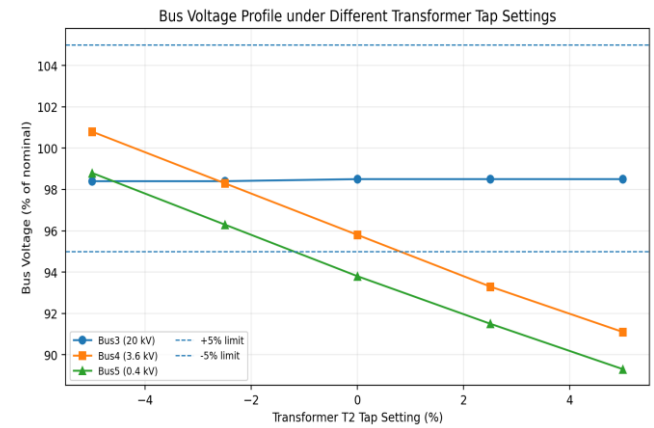


Fig.11. Bus-voltage profile as a function of Transformer T2 tap setting.

To address the influence of tap position on power flow, the active and reactive components at the T2 primary side were calculated from the apparent-power and power-factor values displayed in the ETAP load-flow screenshots using $P = S \cdot PF$ and $Q = S \cdot \sqrt{1 - PF^2}$. The resulting profile is shown in Fig. 12. The calculated active power decreases from approximately 6.27 MW at -5% to 5.63 MW at +5%, while reactive power decreases from approximately 4.16 MVar to 3.74 MVar. This trend indicates that the tap change affects not only downstream voltage magnitude but also the current and complex-power transfer through T2. Because the present study evaluates a single steady-state loading condition, these P/Q trends should be interpreted as scenario-specific rather than as a general dynamic reactive-power control characteristic.

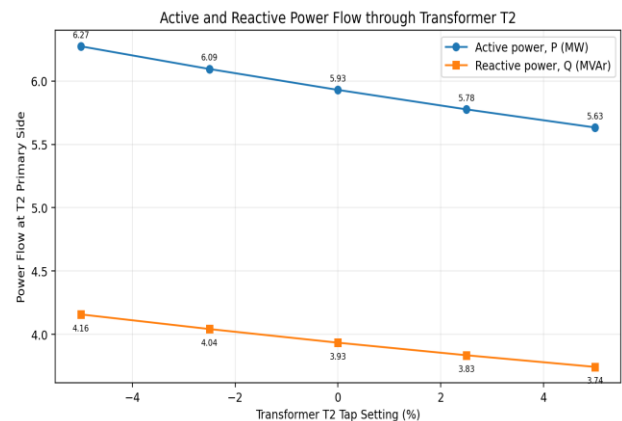


Fig. 12. Active and reactive power flow at the primary side of Transformer T2 for the five tap settings.

5. Conclusion

The ETAP 19.0.1 simulations show that Transformer T2 tap position has a strong influence on the downstream voltage profile for the investigated steady-state operating condition. Five primary-winding tap positions (-5%, -2.5%, 0%, +2.5%, and +5%) were compared while all other model parameters were held constant. Bus3 remained essentially unchanged at 98.4-98.5% of nominal, whereas Bus4 and Bus5 varied substantially. The -5% setting produced 3.63 kV (100.8%) at Bus4 and 0.395 kV (98.8%) at Bus5, while the +5% setting reduced them to 3.28 kV (91.1%) and 0.357 kV (89.3%), respectively.

The sign of this response is consistent with the adopted primary-winding tap convention: a negative tap reduces the effective primary turns ratio and therefore raises the secondary voltage. Power-flow quantities also vary with tap position; based on the ETAP-reported apparent power and power factor at T2, the primary-side active/reactive power changes from approximately 6.27 MW/4.16 MVar at -5% to 5.63 MW/3.74 MVar at +5%.

Among the five tested cases, the -5% tap is the most favorable setting for this specific operating point because it keeps the observed downstream voltages closest to nominal without exceeding the reported transformer rating. This conclusion is intentionally limited to the modeled steady-state case; further validation under different load levels, PV output, capacitor-bank status, and source conditions is required before the setting can be generalized for automatic or real-time OLTC operation.

CRedit authorship contribution statement

Ichal Priski: Conceptualization, Methodology, Writing - original draft, Data curation, Software, Formal analysis.

Andi Asri Mulyadi: Validation, Visualization, Supervision, Writing - review and editing.

Aika Nurjanna: Conceptualization, Methodology, Data curation, Software, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to express their sincere gratitude to the State Polytechnic of Ujung Pandang, Makassar Indonesia and the Smart Grid and Demand Side Management Research Group for their support, facilities, technical assistance, and valuable contributions during the completion of this research.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

[1] K. H. Yoon, J. W. Shin, T. Y. Nam, J. C. Kim, and W. S. Moon, "Operation Method of On-Load Tap Changer on Main Transformer Considering Reverse Power Flow in Distribution System Connected with High Penetration on Photovoltaic System," *Energies*, vol. 15, no.

17, 2022, doi: 10.3390/en15176473.

[2] Y. Maataoui, O. Boutfarjoute, H. Chekenbah, and R. Lasri, "New control scheme of on-load tap changer for voltage regulation in active distribution systems using Fuzzy logic," *ITM Web Conf.*, vol. 48, p. 04001, 2022, doi: 10.1051/itmconf/20224804001.

[3] F. Spertino, A. Ciocia, A. Mazza, M. Nobile, A. Russo, and G. Chicco, "Voltage control in low voltage grids with independent operation of on-load tap changer and distributed photovoltaic inverters," *Electr. Power Syst. Res.*, vol. 211, p. 108187, 2022, doi: <https://doi.org/10.1016/j.eprsr.2022.108187>.

[4] F. Spertino, A. Ciocia, A. Mazza, M. Nobile, A. Russo, and G. Chicco, "Voltage control in low voltage grids with independent operation of on-load tap changer and distributed photovoltaic inverters," *Electr. Power Syst. Res.*, vol. 211, no. June, 2022, doi: 10.1016/j.eprsr.2022.108187.

[5] H. Lim, J. Jo, and K. H. Chun, "Optimal On-Load Tap Changer Tap Control Method for Voltage Compliance Rate Improvement in Distribution Systems, Based on Field Measurement Data," *Energies*, vol. 18, no. 2, pp. 1–16, 2025, doi: 10.3390/en18020439.

[6] L. Wang, T. Wang, G. Huang, K. Wang, R. Yan, and Y. Zhang, "Softly Collaborated Voltage Control in PV Rich Distribution Systems with Heterogeneous Devices," *IEEE Trans. Power Syst.*, vol. 39, no. 4, pp. 5991–6003, 2024, doi: 10.1109/TPWRS.2023.3347389.

[7] J. Li, Q. Huo, J. Yin, Q. Liu, L. Sun, and T. Wei, "Study on coordinated voltage regulation strategy of flexible on-load tap changer and distributed generator," *Energy Reports*, vol. 8, pp. 601–609, 2022, doi: 10.1016/j.egyr.2022.08.132.

[8] O. D. Montoya, R. I. Bolaños, and L. F. Grisales-Noreña, "A Tutorial on Transformer Tap Optimization in Distribution Grids Using Digisilent Powerfactory's DPL," in *2025 IEEE Colombian Caribbean Conference (C3)*, 2025, pp. 1–6, doi: 10.1109/C366505.2025.11340117.

[9] S. G. Nayak, Anjali. C. Tenginakai, Sahana Nelavigi, and Rahul Reddy, "Development and Analysis of Load Flow for a Distribution Feeder Using ETAP-A Case Study Investigation," *Int. Res. J. Adv. Eng. Hub*, vol. 3, no. 04, pp. 1453–1459, 2025, doi: 10.47392/irjaeh.2025.0207.

[10] A. H. M. Ibrahim et al., "Voltage Conversion in Power Distribution Networks: Transition from 6.6kV to 11kV," in *2025 IEEE PES Conference on Innovative Smart Grid Technologies - Middle East (ISGT Middle East)*, 2025, pp. 1–6, doi: 10.1109/ISGTMiddleEast65737.2025.11314156.

[11] H. A. Khan, M. Zuhair, and M. Rihan, "Voltage fluctuation mitigation with coordinated OLTC and energy storage control in high PV penetrating distribution network," *Electr. Power Syst. Res.*, vol. 208, p. 107924, 2022, doi: <https://doi.org/10.1016/j.eprsr.2022.107924>.

[12] M. Kadri, A. Hamouda, and S. Sayah, "Efficient method for transformer models implementation in distribution load flow matrix," *Electr. Eng. Electromechanics*, vol. 2023, no. 3, pp. 76–82, 2023, doi: 10.20998/2074-272X.2023.3.11.

[13] G. Demirel, S. Grafenhorst, K. Förderer, and V. Hagenmeyer, "Impact and Integration of Mini Photovoltaic Systems on Electric Power Distribution Grids," *Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, vol. 15272 LNCS, pp. 247–265, 2025, doi: 10.1007/978-3-031-74741-0_16.

[14] A. J. Conejo, J. M. Arroyo, N. Alguacil, and A. L. Guijarro, "Transmission loss allocation: A comparison of different practical algorithms," *IEEE Trans. Power Syst.*, vol. 17, no. 3, pp. 571–576, 2002, doi: 10.1109/TPWRS.2002.800894.

[15] M. J. Tahir, B. A. Bakar, M. M. Alam, and M. S. U. Mazlihum, "Optimal capacitor placement in a distribution system using ETAP software," *Indones. J. Electr. Eng. Comput. Sci.*, vol. 15, no. 2, pp. 650–660, 2019, doi: 10.11591/ijeecs.v15.i2.pp650-660.

[16] S. M. A. Alkhdely and A. N. B. Alsammak, "Normal operation and reverse action of on-load tap changing transformer with its effect on voltage stability," *Bull. Electr. Eng. Informatics*, vol. 12, no. 2, pp. 650–658, 2023, doi: 10.11591/eei.v12i2.4556.

[17] S. Nambi, M. Kumar, K. Veeran, and J. K. John, "On-Load Tap Changer (OLTC) Selection and Optimization in Large Power

- Transformers,” in 2024 IEEE IAS Petroleum and Chemical Industry Technical Conference (PCIC), 2024, pp. 1–9. doi: 10.1109/PCIC47799.2024.10832338.
- [18] M. S. Aydin, S. W. Alnaser, and S. Z. Althaher, “Using OLTC-Fitted Distribution Transformer to Increase Residential PV Hosting Capacity: Decentralized Voltage Management Approach,” *Energies*, vol. 15, no. 13, 2022, doi: 10.3390/en15134836.
- [19] P. K. Bhatt and N. P. Patidar, “Intelligent transformer tap controller for harmonic elimination in photovoltaic interfaced micro-grid network,” *Eng. Optim.*, vol. 55, no. 7, pp. 1149–1167, 2023, doi: 10.1080/0305215X.2022.2062335.
- [20] O. Shachnev and V. Zatschina, “Modeling and Features of On-Load Tap Changer Logic under Digital Substation Control,” in 2025 7th International Conference on Control Systems, Mathematical Modeling, Automation and Energy Efficiency (SUMMA), 2025, pp. 962–966. doi: 10.1109/SUMMA68668.2025.11302270.
- [21] R. D. Saputro, S. Wilyanti, and A. Pangestu, “Tap On Load Tap Changer Control For 150 Kv Power Transformer At Peruri Company Based On Artificial Neural Network,” *TESLA J. Tek. Elektro*, vol. 24, no. 2 SE-Articles, pp. 174–183, Nov. 2022, doi: 10.24912/tesla.v24i2.19547.
- [22] W. Wróblewski, R. Kowalik, M. Januszczyński, and K. Kurek, “A Fuzzy OLTC Controller: Applicability in the Transition Stage of the Energy System Transformation,” *Energies*, vol. 17, no. 11, 2024, doi: 10.3390/en17112716.
- [23] K. K. Mehmood, S. U. Khan, S. J. Lee, Z. M. Haider, M. K. Rafique, and C. H. Kim, “A real-time optimal coordination scheme for the voltage regulation of a distribution network including an OLTC, capacitor banks, and multiple distributed energy resources,” *Int. J. Electr. Power Energy Syst.*, vol. 94, pp. 1–14, 2018, doi: 10.1016/j.ijepes.2017.06.024.
- [24] Isdawimah, Muhammad Agung, and Y. Widiawati, “Arc Flash Risk Mitigation in Oil Gathering Station Using ETAP and NFPA 70E,” *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 15, no. 6, pp. 1838–1847, 2025, doi: 10.18517/ijaseit.15.6.21122.
- [25] M. H. Ibrahim, S. P. Ang, M. N. Dani, N. A. Muhamad, and W. Voon, “A Transformer Tap Changer and Vector Group Study for Load Flow Analysis in Brunei Network,” in 2022 International Conference on Green Energy, Computing and Sustainable Technology (GECOST), 2022, pp. 118–123. doi: 10.1109/GECOST55694.2022.10010690.
- [26] M. A. B. Palma, J. E. da Rocha Alves Junior, and G. N. Taranto, “Hardware in loop quasi-static simulations dedicated to evaluation of on-load tap changer distribution voltage regulators,” *Electr. Eng.*, vol. 106, no. 4, pp. 5189–5200, 2024, doi: 10.1007/s00202-024-02249-3.
- [27] N. S. I. Razali, T. S. Gunawan, S. H. Yusoff, M. H. Habaebi, S. L. Ibrahim, and S. N. M. Sapihie, “Voltage Instability and Voltage Regulating Distribution Transformer Assessment Under Renewable Energy Penetration For Low Voltage Distribution System,” *Indones. J. Electr. Eng. Informatics*, vol. 11, no. 3, pp. 673–684, 2023, doi: 10.52549/ijeii.v11i3.4857.
- [28] M. R. Jafari, M. Parniani, and M. H. Ravanji, “Decentralized Control of OLTC and PV Inverters for Voltage Regulation in Radial Distribution Networks With High PV Penetration,” *IEEE Trans. Power Deliv.*, vol. 37, no. 6, pp. 4827–4837, 2022, doi: 10.1109/TPWRD.2022.3160375.
- [29] A. Keane et al., “State-of-the-art techniques and challenges ahead for distributed generation planning and optimization,” *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1493–1502, 2013, doi: 10.1109/TPWRS.2012.2214406.
- [30] S. Elphick, J. C. Knott, G. Drury, T. Langstaff, and D. A. Robinson, “Quantifying the Economic Impact of Supply Voltage Magnitude on Consumers,” *Energies*, vol. 17, no. 22, 2024, doi: 10.3390/en17225590.