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Optimal On-Load Tap Changer Tap Control Method for Voltage Compliance Rate Improvement in Distribution Systems, Based on Field Measurement Data

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Abstract: This paper proposes an optimal control method for the on-load tap changer (OLTC) of a substation's main transformer (M.TR), to maximize the voltage compliance rate (VCR) in distribution system feeders. The conventional auto voltage regulator (AVR)'s line-drop compensation (LDC) control method struggles with accurately determining load centers and has limitations in managing voltage due to the variability of distributed energy resources (DERs). To address these challenges, this study defines sample number-based VCR (SNB-VCR) as the performance index function to be maximized. The optimal tap positions for the OLTC are obtained using the gradient ascent method. Since the SNB-VCR evaluates voltage compliance using 15 min interval data collected from all the load and DER connection points in the distribution system, the tap position obtained by the gradient ascent method maximizes voltage quality for every feeder included in the system. Using a simulation, it is verified that the proposed tap control method improves the overall voltage quality and reduces the occurrence of overvoltage or undervoltage compared to LDC control. The proposed control strategy offers a practical solution for enhancing voltage management efficiency in modern distribution systems, particularly those with high penetration of DERs.

Keywords: distribution system; OLTC tap control; voltage compliance rate; smart meter

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1. Introduction

Developed countries such as North America and Europe are setting a common goal of achieving carbon neutrality and moving forward in order to resolve global warming and climate abnormalities worldwide. The main trend in the energy sector is to restructure the power grid into one that is centered on eco-friendly renewable energy by connecting distributed energy resources (DERs), such as photovoltaic (PV) systems, wind turbines (WTs), and energy storage systems (ESSs), to the power grid. Many utilities are gradually preparing for the transition to an active power grid in order to maintain the stability of one which is becoming more complex due to the connection of DERs [1,2].

However, traditional issues of voltage stability are still continuously occurring in the distribution system, even in a situation where the paradigm of the power grid is changing significantly [3]. Recently, the evolution of advanced industrialization due to the expansion of AI universality has been aggravating huge load increases and load volatility every year, and the rapid connection of DERs has aggravated the issue of overvoltage due to their intermittent and variable output [4–7]. Therefore, the changes occurring in the power grid are making the voltage management of utilities more complex and difficult. Many advanced studies have been conducted on resolving the issues of overvoltage, undervoltage, and load variability based on M.TR OLTCs, Static Voltage Regulators (SVRs), Pole Transformers (P.TRs), and inverter control, which have represented the classical voltage management technologies of distribution networks [8–12]. In particular, many papers have been published on the purpose of preventing lifespan shortening by reducing the number of tap operations of M.TRs, along with solutions for cooperative control operation methods between M.TR OLTCs, which are the starting point of voltage management that determine the starting point voltage of distribution feeders, and adjust the overall voltage profile of the feeder and other devices.

Kojovic et al. proposed a voltage management solution through cooperative control between M.TR OLTCs and SVRs [13], and Le et al. proposed a cooperative control method between M.TR OLTCs and DERs [14]. Muttaqi et al. extended the concept of [14] to distinguish the control sectors between OLTCs and DERs through voltage sensitivity analysis, and introduced time delay and hysteresis bands to reduce the number of facility operations and reduce maintenance and operating costs by managing voltage effectively through the determination of operation priorities. [15]. Long et al. proposed a systematic approach for the voltage control of PV penetration networks using OLTCs and capacitor banks, and improved PV capacity by implementing high voltage stability and minimizing facility operations through real-time remote monitoring [16]. Nakamura et al. presented the results of a voltage stability improvement that resolved the voltage violation problem by precisely reflecting PV output variability with 5 min data, while minimizing the increase in communication volume through changing the smart meter data of some loads [17]. Gevaert et al. proposed a method to gradually reduce the number of switching times and efficiently improve voltage quality by introducing voltage deadbands and switching reduction factors to OLTC control to suppress unnecessary tap changes [18]. Cui et al. proposed an algorithm for cooperative control between OLTCs and air conditioners (ACs) to provide a voltage regulation service preferentially until the OLTC completes regulation, thereby giving priority to voltage regulation for nodes with serious voltage problems [19]. Yoon et al. designed an OLTC algorithm that operates under reverse power flow conditions, and proposed an optimal control method to solve voltage problems by adjusting the reference voltage according to the power flow direction [20]. Maataoui et al. proposed an OLTC controller based on an adaptive neuro-fuzzy inference system (ANFIS), and showed that stable voltage quality and minimized OLTC tap hunting under PV output fluctuation and load change conditions could be achieved by effectively controlling voltage fluctuations using an active power cut controller and an auxiliary reactive power regulation controller [21]. Lee et al. proposed a method to control the SVR voltage according to the power flow by using the output voltage of an under-load tap changer (ULTC) [22].

The control methods and voltage quality improvement effects of the papers studied so far have focused on improving the voltage quality centered on the medium-voltage (MV) main line of the feeder. However, there has been limited research on optimal OLTC control that considers the voltage quality of the low-voltage (LV) local line connected to the secondary side of the feeder P.TR, which accounts for a very large proportion of the distribution system [23,24]. In addition, although most studies present the results of the voltage quality improvement effect, there are few research methods which calculate quantitative indicators. Therefore, it is necessary to study an OLTC tap calculation technique that considers the voltage quality of LV local lines in detail as well as MV main lines, and it is essential to calculate indicators that can be thoroughly quantified.

In this paper, a low-voltage (LV) local distribution system is considered, where the M.TR unit contains multiple feeders. To evaluate the supplying voltage quality of all the measuring points in every feeder, voltage samples measured by a smart meter at each point on each feeder are used. The proposed performance index is the ratio of the number of samples satisfying voltage regulation to the total number of measured samples. The optimal OLTC tap is obtained by maximizing the performance index, and the maximization problem is solved by the gradient ascent algorithm. The obtained OLTC tap improves the overall quality of voltage supplied to customers and reduces the effects of voltage fluctuations induced by DERs on all feeders. The optimal OLTC tap control can be implemented by setting the optimal tap at predetermined time intervals, which requires a discrete-time controller. The control period can be decreased to achieve better performance. However, since frequent tap changes shorten the lifespan of components, it is necessary to adjust the control period appropriately. The proposed control method is verified using a 154 kV/22.9 kV substation with a main transformer (M.TR), an on-load tap changer (OLTC), and three distribution feeders. The main contributions of this paper are summarized as follows:

(1) An optimal OLTC tap control method is proposed to ensure effective voltage regulation across all feeders. The controller operates according to a discrete-time system, applying the optimal OLTC tap at predefined, fixed control intervals.
(2) To describe the voltage quality for all the feeders connected to M.TR, SNB-VCR is proposed as a performance index to be maximized.
(3) The maximization problem of the SNB-VCR is solved by the gradient ascent method.
(4) The proposed method implements a controller using the measurements of smart metering systems as feedback signal.

The structure of this paper is as follows. Section 1 explains the research background. Section 2 proposes the concept of voltage compliance rate. Section 3 proposes an optimal OLTC tap control technique to maximize the voltage compliance rate from MV main lines to LV local lines. Section 4 verifies the superior performance and validity of the proposed technique through a case study of a real distribution network.

2. Voltage Management in Distribution Network

Voltage management in South Korea adheres to strict regulations outlined in the Electric Utility Act and related guidelines. For low-voltage (LV) networks, the standard voltage is 220 V for single-phase systems, with an allowable range of ±6% (220 ± 13 V), and 380 V for three-phase systems, with an allowable range of ±10% (380 ± 38 V).

For medium-voltage (MV) networks, permissible ranges are specified as 12,000–13,800 V for 13.2 kV systems and 20,800–23,800 V for 22.9 kV systems. Adjustments are made to minimize the risks of overvoltage or undervoltage across the distribution system, ensuring compliance with regulatory standards [19].

2.1. Conventional Methods for OLTC Tap Changing and Their Limitations

There are three primary approaches to managing on-load tap changer (OLTC) operations in medium-voltage (MV) networks. The first is the constant voltage control method, which maintains a fixed setpoint regardless of load changes; however, this approach often proves insufficient when rapid load fluctuations occur or when large amounts of distributed generation (especially solar PV) cause unpredictable power flow. The second is the digital voltage meter (DVM) method, which involves measuring voltage at selected network points and adjusting taps accordingly. While this can be effective in single-feeder systems, it becomes increasingly complicated in multi-feeder networks with diverse load characteristics. Lastly, the line-drop compensation (LDC) technique calculates the voltage at a notional load center by using current and line impedance data, and it is widely adopted because it provides better voltage regulation in many scenarios. However, LDC can encounter accuracy issues under conditions such as reverse power flow caused by high levels of PV generation.

As shown in Figure 1, multiple feeders often exhibit varying load profiles and are subject to seasonal fluctuations and ongoing system reconfiguration, such as feeder switching to balance loads or perform maintenance. When feeder topology changes, the preconfigured LDC settings may no longer accurately reflect the actual load distribution, resulting in tap adjustments that either overcompensate or undercompensate for voltage drops. Maintaining accurate LDC parameters requires continuous data collection and periodic recalculations of feeder impedances and load profiles, making manual updates to the automatic voltage regulator (AVR) both time-consuming and error-prone. Consequently, a more automated approach—integrating real-time data and adaptive control algorithms—may be essential for achieving robust and precise voltage control in modern MV networks.

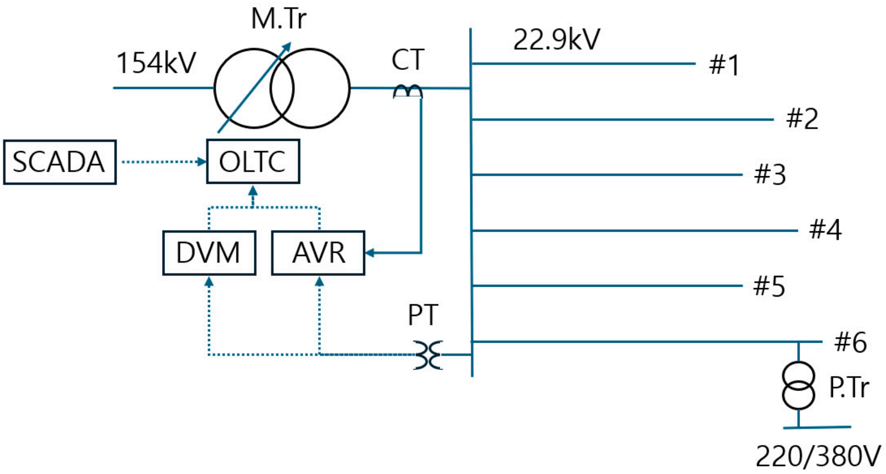


Figure 1. A 154 kV/22.9 kV substation with an M.TR in a distribution network.

2.2. Voltage Compliance Rate

Voltage compliance rate (VCR) is defined as a power quality indicator to evaluate the effectiveness of voltage management in order to minimize deviations from legally defined regulation ranges. By focusing on voltage levels at low-voltage (LV) load supply points, the VCR provides a direct representation of the power quality experienced by end-users. This unique perspective makes VCR a highly relevant and practical metric for assessing the real-world impact of voltage stability and compliance in the distribution networks.

VCR is useful for modern power systems in which the complexity of voltage management has increased due to the rapid growth of distributed energy resources (DERs). It serves as a benchmark for assessing the stability and reliability of distribution networks, and helps to identify areas for improvement in maintaining voltage conditions within regulatory standards. The legal voltage regulation range varies by country, and is typically within ±6% or ±10% of the nominal voltage. The definition and evaluation of VCR are adapted to align with these standards.

To enable a comprehensive analysis of voltage conditions and abnormalities, this study defines VCR from two complementary perspectives. The first is meter number-based voltage compliance rate (MNB-VCR). The MNB-VCR evaluates whether the voltage at each measuring point in the distribution network remains within the legal regulation range. Using data from individual smart meters, it enables detailed regional analysis of voltage quality. The mathematical expression for MNB-VCR is given as Equation (1):

$$R_M = \left(1 - \frac{M_{Non-compliant}}{M_{Total}}\right) \times 100(\%) \tag{1}$$

where R_M represents the compliance rate by meters, $M_{Non-compliant}$ is the number of non-compliant meters, and M_{Total} is the total number of meters.

The second is samples number-based voltage compliance rate (SNB-VCR). SNB-VCR assesses voltage conditions over specific time intervals, making it particularly effective for identifying and analyzing temporal patterns of voltage anomalies. This metric is especially useful for improving voltage stability during peak load periods. By analyzing the voltage data collected during each time interval, SNB-VCR provides insights into the performance of the voltage management system over time. The definition of SNB-VCR is given as Equation (2):

$$R_S = \left(1 - \frac{S_{Non-compliant}}{S_{Total}}\right) \times 100(\%) \tag{2}$$

where R_S represents SNB-VCR, $S_{Non-compliant}$ is the number of non-compliant samples, and S_{Total} means the number of total samples. One sample refers to a 15 min average voltage of each smart meter.

This study places a particular emphasis on the SNB-VCR due to its advantages in temporal analysis. The SNB-VCR provides a comprehensive understanding of how voltage stability evolves over time, enabling the identification of critical periods requiring intervention and the selection of a target voltage for voltage management. This study leverages this indicator by focusing on its potential as a fundamental tool for improving the operational efficiency and stability of distribution networks.

3. OLTC Optimal Tap Control for Improving VCR

3.1. Relationship Between OLTC and VCR

The VCR is a key metric for evaluating voltage quality in distribution feeders. It serves as a benchmark for assessing the operational efficiency and stability of distribution systems, providing essential insights for power quality evaluations that account for the temporal characteristics and load variability of the network.

In this study, we adopt the SNB-VCR with two VCR criteria to rigorously validate the voltage quality contributions of the proposed optimal OLTC tap control. SNB-VCR is directly influenced by the tap control strategy of the M.TR OLTC, and exhibits fluctuations with each OLTC control cycle. OLTCs are critical devices for dynamically regulating voltage in distribution networks by adjusting the internal transformer tap positions in real time. Installed at the M.TR level, OLTCs control the voltage supplied to distribution feeders by altering the ratio between the primary and secondary windings of the transformer. When the OLTC adjusts the tap position upward, the average feeder voltage increases, resolving undervoltage issues at the feeder endpoints. This reduces the number of non-compliant samples exceeding the voltage regulation range, thereby improving the SNB-VCR. Conversely, a downward adjustment lowers the average feeder voltage, mitigating overvoltage issues caused by DERs, and similarly reduces non-compliant samples, enhancing the SNB-VCR.

As shown in Figure 2, an M.TR typically supplies power to 5–7 distribution feeders, each of which may be equipped with thousands to tens of thousands of smart meters. For instance, if a single M.TR connects to five feeders, with each feeder having 1000 smart meters, the total number of smart meters associated with that transformer would be 5000. The voltage data measured by individual smart meters vary due to the feeder's length and load distribution characteristics. While OLTC tap control impacts the voltage data of all smart meters connected to a single M.TR, it determines the tap position based on the average voltage condition across all the distribution feeders linked to the transformer. As a result, OLTC control cannot fully account for the unique characteristics and temporal voltage variations of individual feeders. This limitation can lead to instances of specific feeders exceeding the voltage regulation range, acting as a restrictive factor for improving the SNB-VCR.

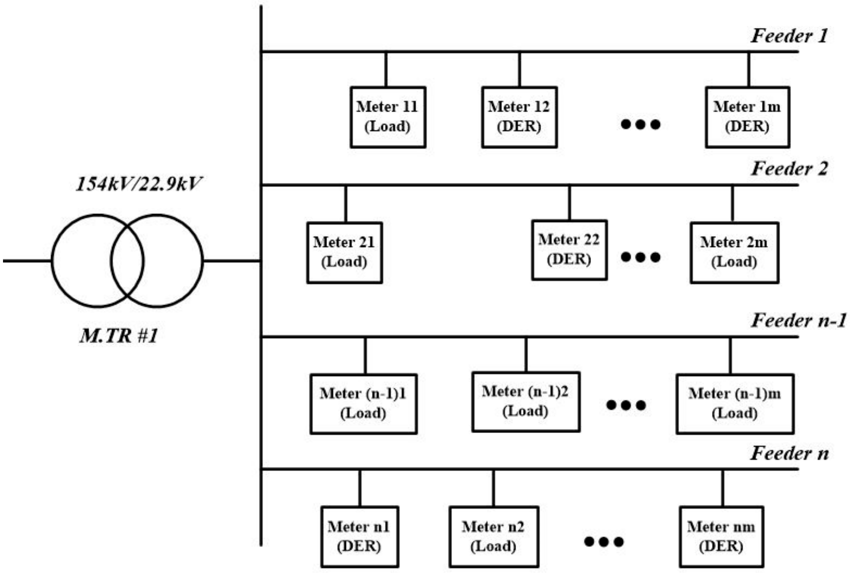


Figure 2. Smart meter integration diagram by feeder.

The simulation results of the SNB-VCR based on simple tap changes of the OLTC are summarized in Table 1 below. Tap Position represents the tap position of the OLTC, Total Samples indicates the total number of samples analyzed in the simulation, Non-Compliant Samples refers to the number of samples exceeding the legal voltage regulation range, and R_s (%) denotes the calculated SNB-VCR.

Table 1. Simulation results of SNB-VCR according to tap changes of OLTC.

Tap Position	Total Samples	Non-Compliant Samples	R_s (%)
0	5000	500	90
1	5000	200	96
−1	5000	300	94

The simulation results in Table 1 confirm that adjusting the OLTC tap position can effectively reduce the number of non-compliant samples. When adjusted to +1, the SNB-VCR reached its highest value at 96%, indicating favorable results for resolving undervoltage issues. However, since OLTC control operates based on the average voltage across all distribution feeders, it may not fully account for the distinct voltage characteristics of individual regions.

3.2. SNB-VCR Analysis Using Field Measurement Data

Based on field measurement data from a specific M.TR feeder, a 15 min average voltage dataset from 4399 smart meters connected to three feeders under a single M.TR was analyzed to optimize OLTC tap control using the SNB-VCR. Table 2 presents the voltage statistics for each of the three feeders. The average voltage of Feeder 1 is the highest at 233.73 V, with a standard deviation of 5.53, indicating the greatest voltage variability among the three feeders.

Table 2. Voltage measurement data of specific KEPCO feeders (smart meter: 4399).

Feed_No.	Mean_Voltage	Std_Deviation	Max_Voltage [V]	Min_Voltage [V]	Sample_Count
1	233.73	5.53	261.74	205.05	219,552
2	232.57	3	248.07	216.3	177,312
3	232.08	4.48	249.43	210.94	25,440
ALL	232.79	4.34	261.74	205.05	422,304

Figure 3 visualizes the voltage distribution of all 4399 smart meters, comprising 422,304 sample voltage data points from Table 2, using histograms for each feeder. The red line and blue line represent the upper and lower voltage thresholds used to calculate the SNB-VCR. Despite being connected to the same M.TR, the feeders exhibit distinct voltage distribution characteristics, likely due to differences in load and DER generation profiles. Most samples fall within the ±10% threshold, indicating generally good voltage quality. However, some feeders show overvoltage regions exceeding the upper threshold (red line), while no undervoltage samples below the lower threshold (blue line) can be observed. Feeder 1 displays a relatively wide voltage distribution, indicating the highest voltage variability, consistent with its standard deviation. In contrast, Feeder 2 exhibits the narrowest distribution, making it the feeder with the lowest voltage variability. These findings highlight the varying voltage characteristics among feeders connected to the same transformer.

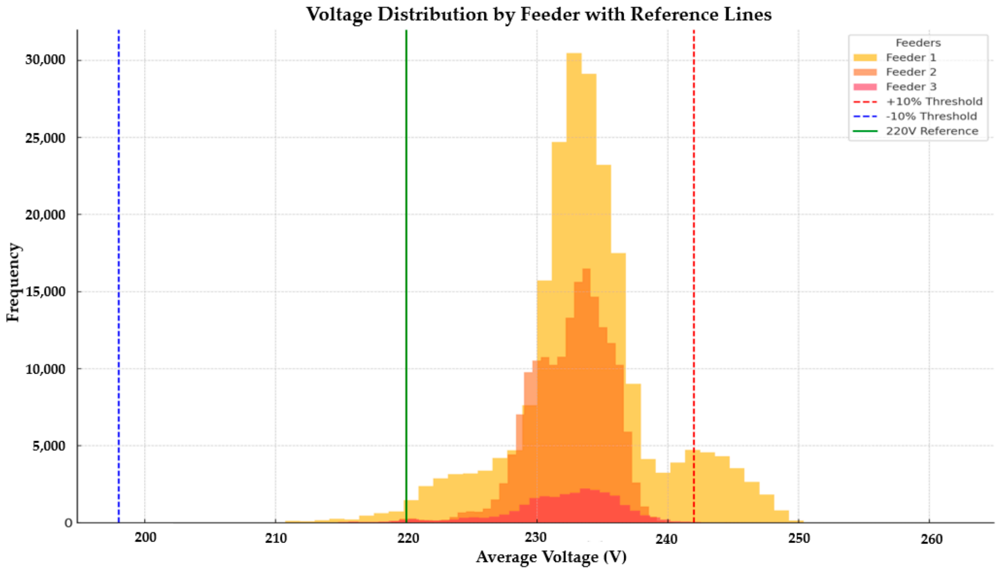


Figure 3. Voltage histogram by feeder.

Figure 4 illustrates the time-based average voltage data for the three feeders. Feeder 1 showed a tendency for its average voltage to approach or exceed the upper limit of 242 V during specific time periods, influenced by load characteristics and solar generation output. While the voltage for most time periods remained within the ±10% range, Feeder 1 had a higher likelihood of overvoltage in certain time periods. However, no undervoltage instances (below 198 V) were observed, indicating overall good voltage quality. Across all feeders, the average voltage exhibited relatively stable changes, although some time periods showed increased variability. These findings suggest that while voltage quality is generally maintained, specific periods of heightened variability warrant attention for improved voltage management.

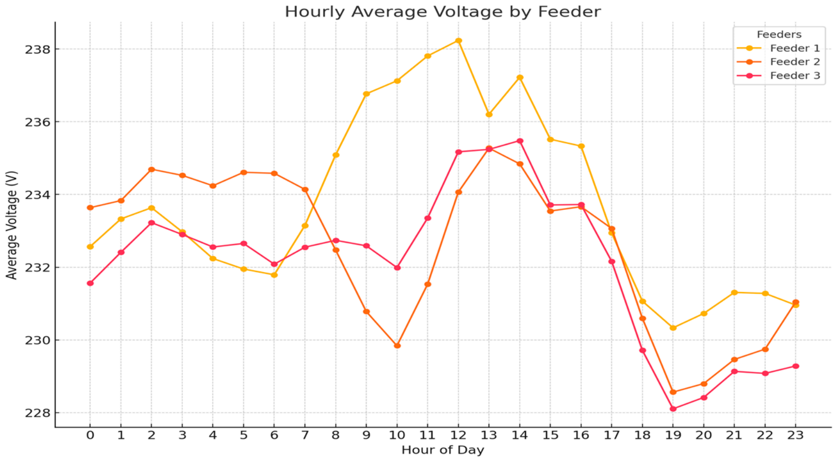


Figure 4. Hourly average voltage by feeder.

Tables 3 and 4 compare the analysis results of the MNB-VCR and SNB-VCR under the same conditions.

Table 3. MNB-VCR analysis results.

Feed_NO	Total_Meters	Non-Compliant Meters	Compliant Meters	R_M (%)
1	2287	553	1734	75.82
2	1847	2	1845	99.89
3	265	10	255	96.23
ALL	4399	565	3834	87.16

Table 4. SNB-VCR analysis results.

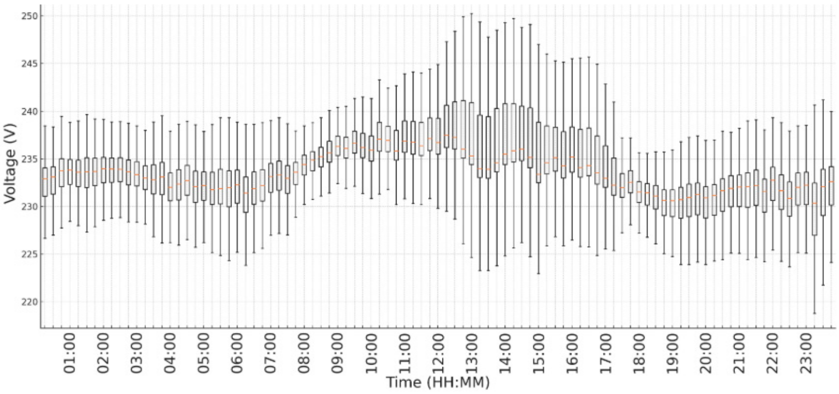
Feed_NO	Total Samples	Non-Compliant Samples		Compliant Samples	R_S (%)
		Overvoltage	Undervoltage		
1	219,552	20,064	0	199,488	90.86
2	177,312	97	0	177,215	99.95
3	25,440	112	0	25,328	99.56
ALL	422,304	20,273	0	402,031	95.2

Table 3 calculates the MNB-VCR (%) by presenting the total number of meters per feeder, the number of meters experiencing overvoltage and undervoltage, and the number of meters within the normal range. Table 4 calculates the SNB-VCR (%) by providing the number of overvoltage, undervoltage, and normal samples for each feeder.

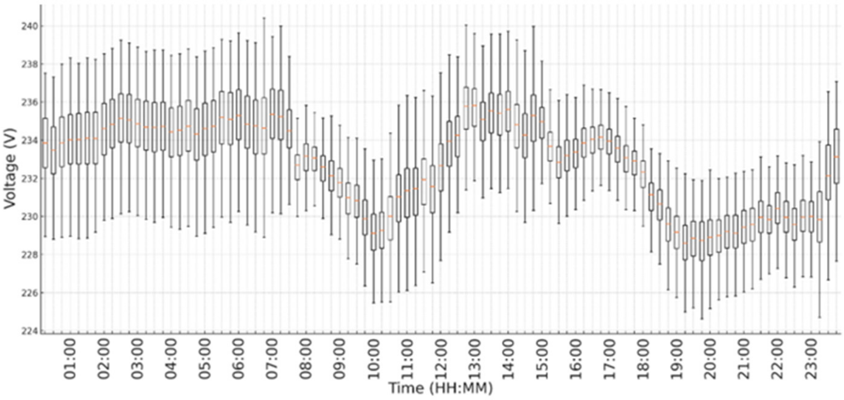
These comparisons highlight the differences in performance metrics when evaluating voltage quality using the MNB-VCR and SNB-VCR approaches, offering insights into the strengths and limitations of each method.

The MNB-VCR and SNB-VCR for Feeder 1 show significant differences. Feeder 1 exhibits a low voltage compliance rate, with a high proportion of smart meters experiencing overvoltage issues. This suggests that Feeder 1 is in a region with a high likelihood of voltage rise due to solar power generation among DERs. As a result, it may require transformer tap adjustments or the installation of additional voltage regulation equipment. Feeder 2, on the other hand, demonstrates highly stable results, with a voltage compliance rate close to 100%. This indicates that the load characteristics of Feeder 2 align well with the transformer output. However, the overall voltage compliance rate (87.16%) remains relatively low. The difference lies in how MNB-VCR and SNB-VCR evaluate voltage quality. MNB-VCR is highly sensitive to any smart meter exceeding the voltage limits, as the inclusion of even one non-compliant sample significantly impacts the regulation rate. The SNB-VCR, by assessing voltage regulation based on 15 min interval samples, provides a more granular and precise representation of voltage quality. Thus, this study adopts SNB-VCR for proposing optimal OLTC tap control on an hourly basis, as it allows for more precise and effective voltage regulation in dynamic distribution system conditions.

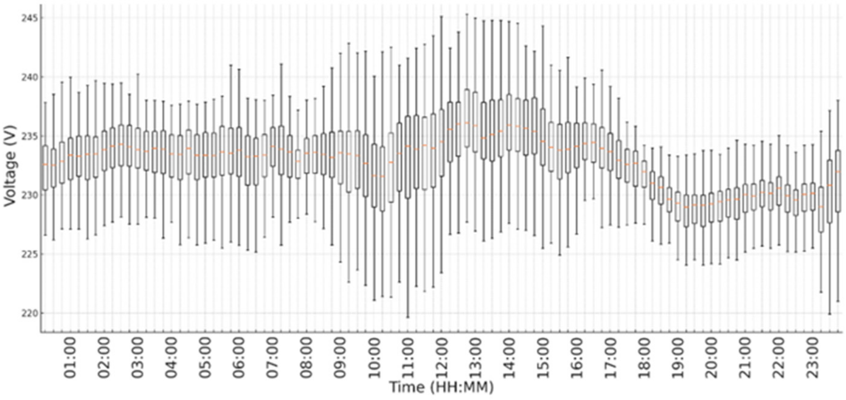
Figure 5 presents the time-based voltage distribution as box plots, with data aggregated in 15 min intervals. Each box represents the median, first quartile (Q1), third quartile (Q3), and range (maximum and minimum values) of the voltage data for the corresponding time point. This visualization enables a comparison of voltage variability across different time intervals, highlighting patterns or trends in voltage stability and fluctuations throughout the day. The box plots provide a clear summary of the central tendency and spread of voltage data for each time block.



(**a**) Voltage distribution at 15-min intervals (Feeder 1)

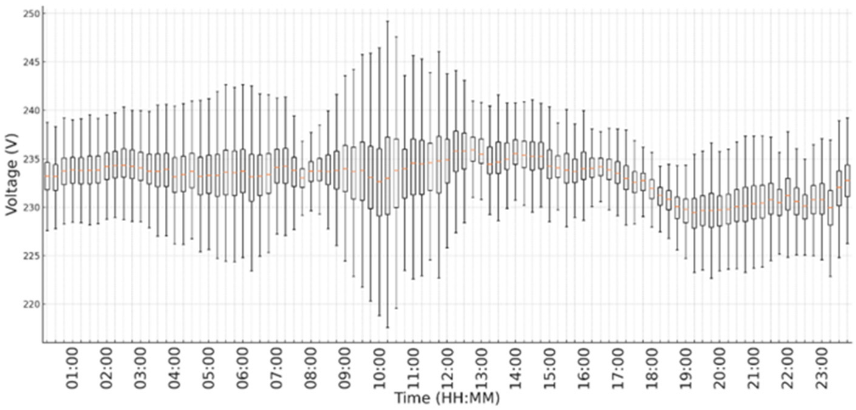


(**b**) Voltage distribution at 15-min intervals (Feeder 2)



(**c**) Voltage distribution at 15-min intervals (Feeder 3)

Figure 5. *Cont.*



(**d**) Voltage distribution at 15-min intervals (All Feeders)

Figure 5. Box plot of hourly voltage distribution (15-min intervals).

3.3. Proposed Optimal Control Method for OLTC

This study proposes an OLTC direct control method to address the limitations of the traditional AVR's LDC control approach, which struggles to adapt to changes in feeder voltage management caused by load or DER output fluctuations and load transfers (line switching). The core of the proposed OLTC control method lies in applying an optimal tap control algorithm at the M.TR level. This ensures that the voltages at all load and DER connection points across n feeders, each with varying load, DER, and line characteristics (e.g., type and length), remain within the upper and lower regulatory voltage limits. Therefore, the method maximizes the real-time SNB-VCR.

As illustrated in Figure 2, the system leverages 15 min interval average voltage data measured from field data collected by m smart meters connected to n feeders. By synchronizing the OLTC control cycle with the smart meter data acquisition interval, the method calculates optimal tap positions in real time. This approach allows continuous management of both the MNB-VCR and SNB-VCR, ensuring high-quality voltage regulation across the distribution network. The OLTC tap consists of a total of 33 taps from −16 to +16, allowing a voltage adjustment of 1.25% per tap, and the voltage according to tap position is calculated as shown in Equation (3):

$$V'_{n,m} = V_{n,m} \times (1 + TAP \times 0.0125) \tag{3}$$

where n and m are the feeder number and smart meter order, respectively. TAP represents the tap position of the M.TR.

At the current time $t(k)$, the voltage measured by the smart meters is used to evaluate multiple adjusted tap positions, considering a voltage variation of ±1.25% based on the tap setting at the previous time $t(k-1)$. The tap position that maximizes the SNB-VCR is then selected for application.

$$Maximize\ R_s = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} 1_{[V_{\min threshold} \le V_{i,\ j} \le V_{\max threshold}]}}{\sum_{i=1}^{n}\sum_{j=1}^{m} 1} \times 100(\%) \tag{4}$$

where $1_{[V_{\min threshold} \le V_{i,\ j} \le V_{\max threshold}]}$ is an indicator function that equals 1 when the voltage V is within the range, and 0 otherwise.

The optimal tap is determined based on the gradient ascent method, considering the voltage compliance rate calculated in (4) and (5):

$$TAP_{t+1} = TAP_t + \alpha \cdot \frac{\partial R_s}{\partial TAP} \tag{5}$$

where α represents the learning rate. By applying the above equation, the algorithm for finding the optimal tap position can be visualized as shown in Figure 6.

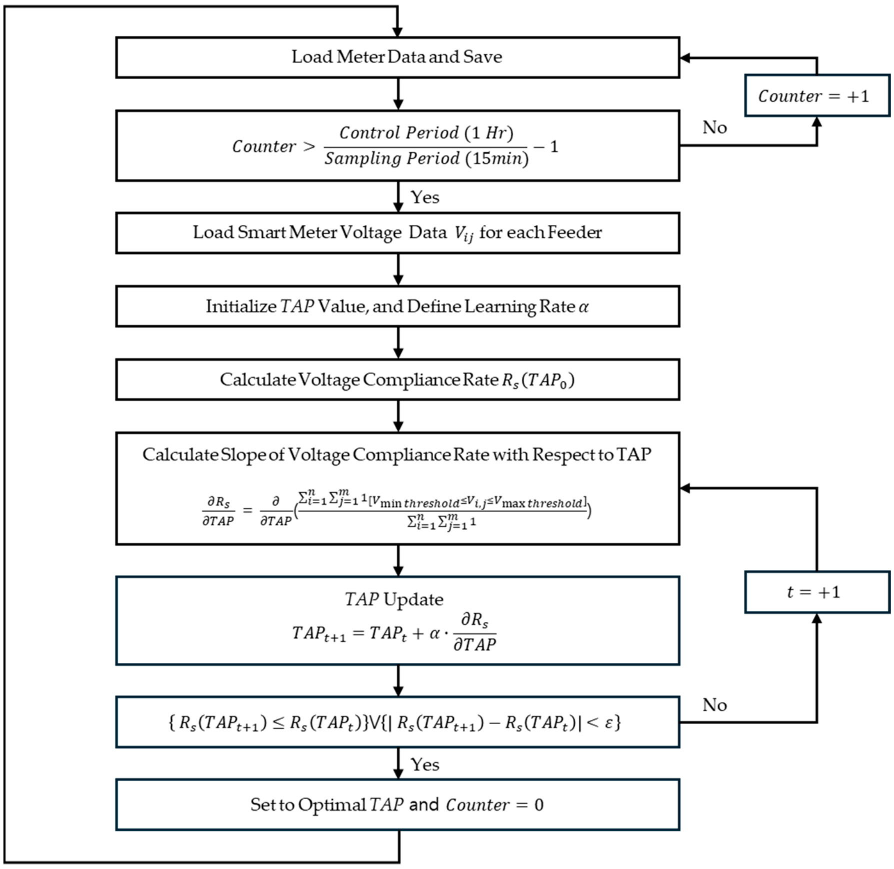


Figure 6. Flow chart of proposed OLTC optimal control method.

The optimal control method proposed in this study rapidly identifies the optimal tap position through iterative tap updates. It dynamically optimizes the system by integrating real-time voltage data with tap adjustments. To efficiently calculate the VCR across the entire system, which includes multiple feeders and smart meters, the method employs a simple and fast gradient ascent algorithm, rather than complex optimization algorithms. This approach enables quick convergence to the optimal solution, making it suitable for real-time dynamic optimization in distribution systems.

4. Verification

4.1. Scheme of Electric Network and Regulatory Objects

The electric network used to verify the proposed control method consists of a 154 kV/22.9 kV substation equipped with an M.TR and an OLTC. The substation supplies power to three distribution feeders, which are further connected to LV networks. The key components of the network are shown in Table 5.

Table 5. Scheme of electric network.

Components	Description
Main Transformer (M.TR)	A 154 kV/22.9 kV transformer with an OLTC, featuring 33 tap positions for 1.25% voltage adjustments per tap.
Smart Meters	A total of 4399 smart meters providing 15 min interval voltage data for the SNB-VCR calculation.
Feeders	Three feeders with unique load profiles, DER levels, and voltage regulation challenges.
Regulatory Standards	A voltage range of ±10% for MV and ±6% for LV, as per South Korean Electric Utility Act.

4.2. Voltage Distribution When Optimal Tap Is Selected

Figure 7 presents eight histograms—one for each time interval (e.g., 0:00–0:59, 3:00–3:59, etc.)—showing how the voltage distribution changes when the optimal tap setting is selected for the OLTC. The orange histograms represent the original tap setting, whereas the blue histograms show the distribution after applying the optimal tap. The ±10% range (approximately 198 V to 242 V) is indicated by the red and blue vertical lines, and the 220 V reference is marked by the green vertical line. Each chart also displays "Optimal TAP: x, Compliance Rate: y%" to indicate the best tap value and the resulting voltage compliance rate for that time.

For each time interval—(a) 0:00–0:59, (b) 3:00–3:59, (c) 6:00–6:59, (d) 9:00–9:59, (e) 12:00–12:59, (f) 15:00–15:59, (g) 18:00–18:59, and (h) 21:00–21:59—the optimal tap value differs slightly. When the optimal tap is applied (blue histogram), the voltage distribution shifts closer to 220 V compared to the original distribution (orange), with a significantly larger portion of samples falling within the ±10% allowable range.

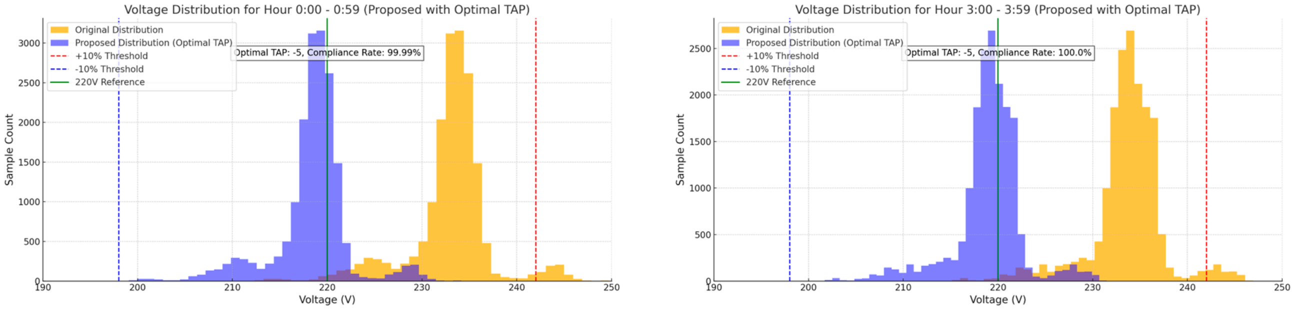
Even though the original (orange) distributions sometimes show relatively high compliance, many samples lie near the upper +10% boundary, which can result in a somewhat lower compliance rate overall. After implementing the optimal tap (blue), out-of-range samples are drastically reduced, pushing the compliance rate above 99.9%, or even to 100% in some intervals. Despite variations in load across different time periods, tap adjustments alone achieve notably high compliance rates.

During late-night or early-morning hours (e.g., 0:00–0:59, 3:00–3:59) when the load is typically low, the voltage can rise. Setting the tap to a lower value (e.g., -5) compensates for higher voltages and brings the distribution closer to 220 V. In daytime (e.g., 12:00–12:59, 15:00–15:59) or evening (18:00–18:59), heavier loads, changes in solar generation, and other factors can alter the optimal tap slightly. Overall, properly chosen tap values reflecting the load behavior in each time window yield consistently high voltage compliance.

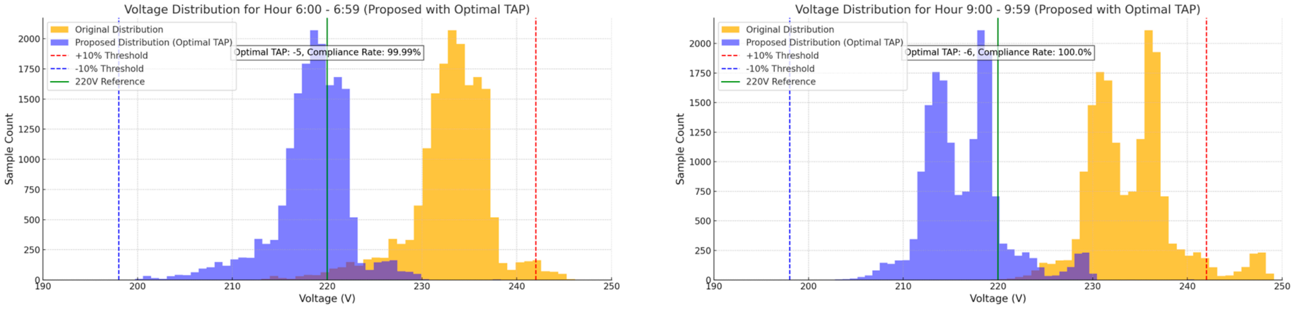
Applying distinct optimal tap values for each time segment can be implemented in real operational settings via automatic or semi-automatic controls (e.g., SCADA, EMS). In grids with strong seasonal variation or significant renewable energy integration (e.g., solar, ESS), more granular load and generation forecasts can support dynamic tap control.

In summary, across all eight time intervals, using the optimal tap moves the voltage distribution closer to the 220 V reference, and significantly reduces the number of samples falling outside of the ±10% range. This demonstrates that adjusting the OLTC tap in line with real-time grid conditions can simultaneously enhance voltage quality and protect equipment.

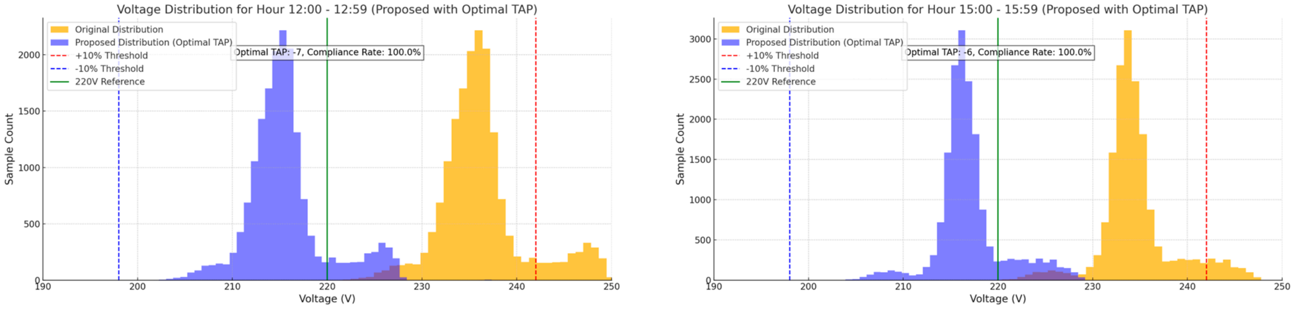
Figure 8 illustrates how the voltage compliance rate, defined as the percentage of samples within the ±10% allowable range, varies with tap values during two time intervals (a) 0:00–0:59 and (b) 3:00–3:59. The horizontal axis represents the tap values, while the vertical axis indicates the compliance rate, with the green dashed line marking the "optimal tap" for each period.



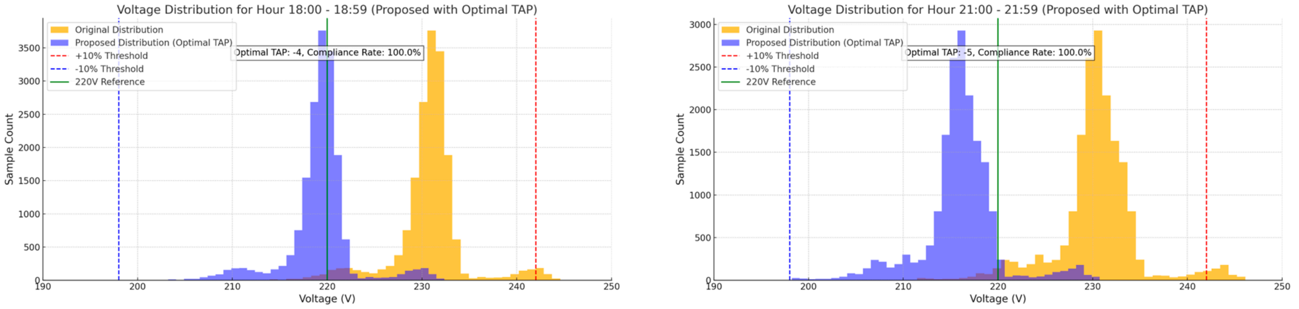
(**a**) Voltage distribution from 0:00 to 0:59 (**b**) Voltage distribution from 3:00 to 3:59



(**c**) Voltage distribution from 6:00 to 6:59 (**d**) Voltage distribution from 9:00 to 9:59

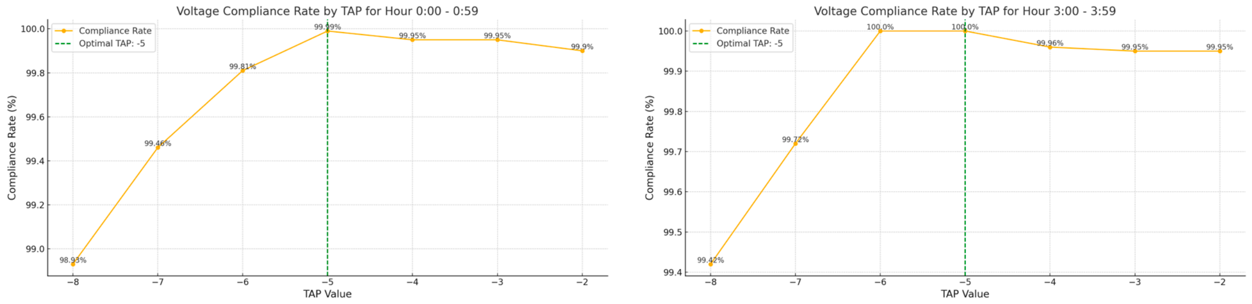


(**e**) Voltage distribution from 12:00 to 12:59 (**f**) Voltage distribution from 15:00 to 15:59



(**g**) Voltage distribution from 18:00 to 18:59 (**h**) Voltage distribution from 21:00 to 21:59

Figure 7. Simulation results of improving the SNB-VCR using the proposed method.



(**a**) VCR values for each tap in the 0:00-0:59 interval. The optima tap achieves 99%.

(**b**) VCR values for each tap in the 3:00-3:59 interval. The optima tap achieves 100%.

Figure 8. Comparing voltage compliance rates for optimal tap.

During the 0:00–0:59 interval, low load levels result in higher voltages, and lowering the tap value to around −5 increases the compliance rate to nearly 99.93%. By 3:00–3:59, the load shifts slightly, and both the −6 and −5 taps achieve 100% compliance. However, operators often prioritize minimizing switching frequency and maintaining the tap closer to the reference point (0) to reduce wear on the on-load tap changer (OLTC) components and manage maintenance costs.

While compliance rates are critical, optimal tap selection also affects mechanical wear, power losses, and forecasted load changes. This comprehensive approach explains the preference for −5 over −6 in (b), even though both achieve full compliance, reflecting broader operational strategies in power systems.

Figure 9 is a graph illustrating how the voltage compliance rate (the percentage of voltages falling within the ±10% allowable range) varies by hour when the distribution of a transformer is optimally adjusted. The blue line shows the tap settings over time (left axis), while the orange line indicates the corresponding voltage compliance rate (%) at each hour (right axis).

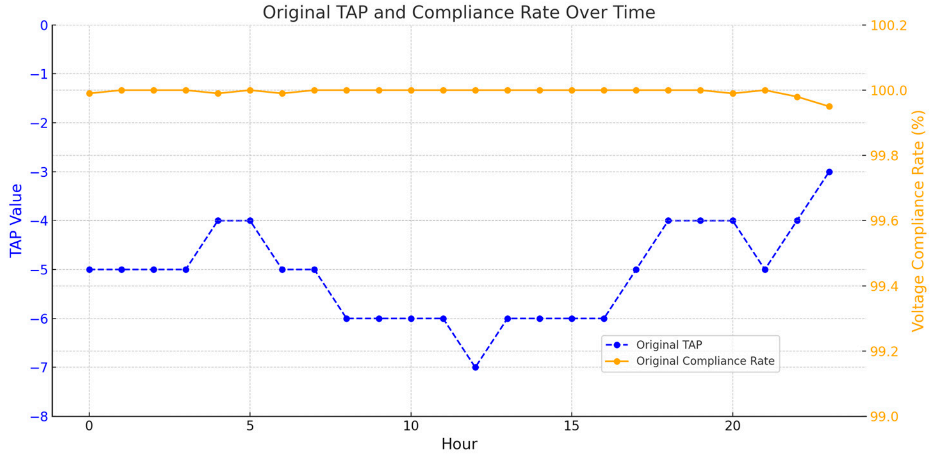


Figure 9. Original TAP and compliance rate over time.

Initially, the tap setting hovers near −5, but it shifts to around −4 or drops below −6 at specific times, reflecting adjustments made to maintain stable voltages as load conditions change. Occasionally, the tap dips to −7 or −8 before returning to the −4 to −5 range, likely as a rapid response to dynamic load or generation variations, such as demand spikes or fluctuations in photovoltaic output.

Despite these adjustments, the compliance rate generally remains high, typically between 99.5% and 99.8%, indicating that most voltages stay within the ±10% range. Extreme tap settings, such as −8, may cause slight dips in compliance, potentially due to increased undervoltage instances, but the rate recovers quickly when the tap returns to moderate values.

Further analysis is needed to determine whether these hourly tap adjustments remain optimal under varying daily or seasonal load patterns. For systems with multiple transformers or significant renewable energy integration, it is essential to consider device interactions to achieve comprehensive, system-wide voltage stability.

5. Conclusions

In this paper, the SNB-VCR is proposed to evaluate voltage quality across all feeders connected to a substation's M.TR. Unlike existing techniques, the proposed method utilizes a direct control approach, integrating real-time voltage data and employing a gradient ascent algorithm to determine optimal tap positions. This ensures precise, system-wide voltage management while minimizing unnecessary tap operations, thereby enhancing equipment longevity and operational efficiency. The SNB-VCR, a novel power quality indicator, is defined based on 15 min or 30 min interval data, allowing for a granular evaluation of voltage compliance across all feeders. The optimal tap controller operates as a discrete-time system, applying the obtained optimal tap position that maximizes the SNB-VCR at each control interval. The simulation results highlight the effectiveness of this approach, showing an impressive improvement in the VCR from 95.2% to 99.99%. This substantial enhancement underscores the method's ability to address both overvoltage and undervoltage issues, ultimately contributing to improved voltage stability across the distribution network.

Future research is needed on developing performance indices that consider tap changing cycles and voltage quality depending on the user environment, as well as designing optimal controllers using these performance indices. In addition, cooperative controllers with other voltage controllers, such as battery energy storage (BES) systems, static VAR compensators (SVCs), static synchronous compensators (STATCOM), and capacitor banks existing in the distribution system, can be studied to improve the power quality.

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