

Case Study on: Role of Tap Changing Transformer in Voltage Control of Power System

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ABSTRACT: One of the most urgent issues facing modern electrical power systems is voltage regulation, especially as intermittent renewable energy sources become more widely integrated, loads rapidly vary, and the existing grid infrastructure is modernized. One of the numerous appliances used in voltage control is the Tap Changing Transformer (TCT), or On-Load Tap Changer (OLTC) which is one of the keystone mechanisms in ensuring voltage profiles within acceptable statutory limits throughout the transmission and distribution networks. This paper provides a detailed case study to discuss the working principle, control techniques, mathematical modeling and the actual implementation of tap changing transformers in power system voltage regulation. As the model of the simulation, an IEEE 33-bus radial distribution system is used. The dynamic interactions between OLTC operations, reactive power compensation, Battery Energy Storage Systems (BESS), and photovoltaic distributed generation are analyzed. Simulation findings carried out in MATLAB/Simulink have shown coordinated control of OLTC with smart inverter reactive power injection decreases bus voltage deviation by a factor of up to 62 than uncoordinated traditional methods. The research also explores the hunting phenomenon, reverse action effect and adaptive dead-band control strategies. The results provide a technical and economic rationale to support intelligent OLTC implementation in modern smart grids and distribution networks with a larger share of renewable energy.

KEYWORDS: On-load tap changer (OLTC), voltage regulation, power system stability, distributed generation, smart grid, reactive power control, battery energy storage, IEEE 33-bus system, dead-band control.

I. INTRODUCTION

Controlling bus voltages to fall within a small range of acceptable values - usually, between +5 and -5 of the nominal value as recommended by national and international grid codes - is the key to the reliable and efficient operation of a power system. Going out of this band causes poor power quality, transmission losses, stress on equipment, possible damage to sensitive loads and in worst-case scenarios, voltage collapse and blackouts across much of the system [1]. Voltage regulation has become a problem of a new complexity and acuity as the structure of modern power systems becomes more and more decentralized, less and less dominated by centralized synchronous generators, more dense in inverters.

The transformer, the workhorse of the transfer of electrical energy, has long been used in two applications: to provide long-distance transfer of power at high voltages, by means of the high-voltage transformation, and to provide local adjustment of voltages, by tapping of the transformer. In the tap changing transformer, specifically, the turns ratio can be changed in discrete steps, and thus the secondary (output) voltage can be adjusted to varying load conditions or changes in upstream supply. There are two main types: the Off-Load Tap Changer (OLTC- or DETC, De-energized Tap Changer) where the transformer must be de-energized before it can be adjusted, and the On-Load Tap Changer (OLTC), where a tap can be positioned and the transformer continues to operate under load.

The On-Load Tap Changer is the most common industrial selection in transmission substations, bulk power supply points, and to a growing extent, medium-voltage distribution substations. The OLTC, with an Automatic Voltage Regulator (AVR), is able to respond independently to changes in voltage, changing its tap position according to predefined dead-band and time-delay parameters. The advent of high-penetration distributed generation (DG), especially solar photovoltaic (PV) systems and wind turbines, however, has brought about bidirectional power flows, rapid voltage transients and reactive power imbalances, which put a strain on the traditional OLTC control logic. Unintended OLTC actions, the so-called reverse action phenomenon, may occur due to reverse power flow, which may worsen instead of improve the voltage state [2].

Moreover, it was identified that the big blackout of the South-Eastern Continental European power system on June 21, 2024, that left some parts of Albania, Montenegro, Bosnia-Herzegovina, and Croatia without power, involved OLTC activities as a cause of the voltage collapse chain [3]. This practical event highlights the two-sidedness of OLTC devices; they are invaluable in regular system operation, but they will act in a self-competing way with load dynamics and other control systems during stressful system conditions.

The reason behind writing this paper is the necessity to present a simulation-validated case study of OLTC behaviour within a variety of operating conditions, including, but not limited to, normal load variation, high-PV-penetration operating conditions, and coordinated, multi-device voltage control operating strategies. The main contributions of this work are as follows:

- 1) Mathematical model of the OLTC transformer and AVR control logic, with deadband and time delay and tap limit formula.
- 2) Case studies of the modified IEEE 33-bus radial distribution system simulation in different load, large-PV density, and coordinated OLTC-BESS control conditions.
- 3) Prediction of the hunting phenomenon, the reverse action effect and risk of the voltage collapse in OLTC equipped networks.
- 4) Comparison of performance of uncoordinated versus coordinated OLTC control strategies, measured in terms of improvement in voltage compliance rate, and tap operation count.
- 5) Suggestions on adaptive OLTC implementation in future smart grid and renewable-integrated utilities.

II. BACKGROUND AND LITERATURE REVIEW

A. Control of Voltages in Power Systems.

A combination of reactive power management, transformer ratio adjustment, and network switching is used to provide voltage control in power systems. Classical reactive sources of power are synchronous generators in over-excited or under-excited modes, capacitor banks, static var compensators (SVCs) and static synchronous compensators (STATCOMs). Transformer-based voltage control, which is effected through tap changers, is special in that it offers a direct, non-random control of the turns ratio, capable of giving predictable and bounded voltage correction independent of the reactive power ratio at the regulated bus [4].

The total renewable installed capacity in the world was 3,372 GW in 2023, a 260 percent increase since the year 2010 [5]. This voluminous growth of inverter-based generation has radically changed the situation in voltage regulation. Among the problems as include: voltage increase at feeder ends created by reverse power flow in rooftop PV installations; the rapid, minute-to-minute variation of voltage caused by cloud transients and load cycling; an increased sensitivity of the R/X ratio in low-voltage (LV) networks that links active power to bus voltage; and the loss of traditional synchronous generator-provided reactive power support when thermal plants are retired.

B. Recent studies on OLTC-Based Voltage Regulation

The current literature has tackled these issues using a combination of a number of complementary methods. Maataoui et al. (2023) introduced a synchronized algorithm of voltage regulation of a distribution grid with the multiple photovoltaic distributed generators (PVDGs), and the combination of active power curtailment, reactive power adjustment, and OLTC operation, which was tested on a modified IEEE 33-bus system in MATLAB/Simulink [7]. The experiment has found that OLTC action with reactive power management has shown better voltage compliance than traditional single-bus AVR control without the hunting issue with deadband settings.

Li et al. developed a mixed-integer linear programming (MILP) model of optimal coordination of PV smart inverter reactive power injection and OLTC tap operation in multi-phase unbalanced distribution systems, which is used to simultaneously minimize voltage deviations and tap operation number [8]. The convergence of the linearization method applied guarantees convergence and saves much computation time as compared to nonlinear formulations.

Wrolbel et al. (2024) presented a fuzzy OLTC controller to be used at the transition phase of energy system transformation that considers the heightened uncertainty and variability that might be caused by high-penetration renewables [9]. The fuzzy logic methodology is able to tune the deadband and time-delay parameters dynamically, minimizing the number of unnecessary tap operations by about 34 percent over fixed-parameter AVR control.

In terms of voltage stability, Alkاهدely and Alsammak (2023) performed an extensive survey of both normal and reverse action effects of OLTC, determining the conditions of analysis where the OLTC turns into a stabilizing or destabilizing device [10]. Their model of a simple radial power system in MATLAB showed that reverse action can occur when the system is run in a stressed condition, which is close to the voltage collapse boundary, and that proper OLTC placement and tap limit set conditions can be used to avoid such conditions.

In the article by Janiga et al. (2024), the authors suggested an Artificial Neural Network (ANN)-based solution to the control of the OLTC in LV networks with high percentages of photovoltaics and compared the solution with the traditional load compensation techniques mandated by European DSOs on a 116-bus IEEE test network [11]. Under high-PV conditions, the ANN-based controller had shown a 28 percentage drop in voltage limit breaches than the best conventional approach.

The recent South-Eastern Europe incident on June 21, 2024 where OLTC activities were found to contribute to voltage collapse in a cascade event worsened by high air-conditioning load has revived interest in OLTC behavior and its interaction with nonlinear loads and system-level voltage stability margins [3]. This highlights the need to conduct research on intelligent and adaptive OLTC control strategies.

III. PRINCIPLES OF TAP CHANGING TRANSFORMERS

A. Transformer Turns Ratio and Voltage Regulation

An ideal transformer with a turns ratio of $n = N_1/N_2$ changes the voltage as $V_2 = V_1/n$. Considering a loaded transformer with series impedance, $Z_n = R_n + jX_n$ referred to primary, the true secondary voltage V_2 satisfies:

$$V_2 \approx V_1/n - (P \cdot R_t + Q \cdot X_t)/(n^2 \cdot V_2) - j(P \cdot X_t - Q \cdot R_t)/(n^2 \cdot V_2) \dots (1)$$

P , Q are the active and reactive power that passes through the transformer. The secondary voltage can be increased or decreased by adjusting the tap to increase or decrease n and correct load-induced drops. Normal OLTC transformers have tap steps of around 0.5 percent to 1.75 percent per step with a common range of -9 to +17 steps (19 to 35 discrete tap settings) [12].

B. On-Load Tap Changer Mechanism

The OLTC mechanism permits tap changes when the transformer is energized and has load current flowing. There are the two most common OLTC technologies in service: the diverter type and the selector type. A diverter-type OLTC has a tap switch pre-selected with the next tap at no-load conditions, and the current is switched between taps after which an arcing (diverter) switch is used to transfer the current. During transfer, a transition resistor or reactor is momentarily connected between the two taps to avoid short circuiting between windings of adjacent taps. The OLTC motor mechanism drives the tap selector and a spring-loaded energy store pushes the diverter switch quickly, to shorten the arcing time as much as possible [12].

Selector-type OLTCs use a single arcing contact for tap selection and current transfer, making the construction less complex but with increased contact wear per operation. Both of these are contained in a separate oil tank in the transformer tank, that has no connection with the main insulating oil to avoid contamination by switching arc. Contemporary OLTCs use vacuum interrupters or thyristor-aided switches (hybrid OLTCs) to further reduce arcing and extend contact life to allow higher tap change frequencies required by renewable-integrated grids [13].

C. Automatic Voltage Regulator Control Logic

An Automatic Voltage Regulator (AVR) controls the OLTC and constantly measures the controlled voltage V_n (local LV bus, or a remote bus by line-drop compensation) and compares it to a reference voltage V_0 in a deadband $[V_0 - \epsilon, V_0 + \epsilon]$. The deadband ϵ is normally set near half the per-unit voltage step of a single tap position, to avoid tap hunting at the deadband boundary. To prevent a tap raise or lower command, when the measured voltage is outside the deadband, a timing circuit triggers a delay time T_6 countdown before the command is issued. In the case of voltage returning in the deadband prior to the expiration of the timer, the command is cancelled. The control logic may be written as follows:

$$\text{Tap}(k+1) = \text{Tap}(k) + \text{sign}(V_o - V_m^{\text{on}}) \cdot \Delta n \quad \text{if } |V_m^{\text{on}} - V_o| > \varepsilon \text{ and } t \geq T^d \quad \dots (2)$$

where Δn is the unit change in voltages in one tap step. Tap position is limited by $\text{Tap} :: 63 < \text{Tap} \leq 3 \text{ Tap} \leq 62$, which limits further tap position but necessitates other voltage support options. The nominal voltage should be ± 10 to ± 15 percent of the typical tap limit range [12].

IV. MATHEMATICAL MODELING

A. Power Flow Model with OLTC

For a network of n buses, the power flow equations in polar form are:

$$P_i = V_i \sum_j V_j [G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j)] \quad \dots (3)$$

$$Q_i = V_i \sum_j V_j [G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j)] \quad \dots (4)$$

When an OLTC transformer is placed between bus i and bus j with tap ratio a_{ij} (the ratio of actual turns ratio to nominal turns ratio), the modified Y-bus elements become:

$$Y_{ij}(\text{OLTC}) = y_{ij} / a_{ij}^2 + y_{ij}^{\text{sh}} \quad \dots (5)$$

$$Y_{ij}(\text{OLTC}) = Y_{ij}(\text{OLTC}) = -y_{ij} / a_{ij} \quad \dots (6)$$

where $y_{ij} = 1/Z_{ij}$ is the series admittance of the transformer leakage impedance and $a_{ij} = n_{ij} / n_{ij}^{\text{nominal}}$ is the off-nominal tap ratio. A unit tap ($a = 1$) recovers the standard admittance matrix formulation. The Jacobian matrix used in Newton-Raphson power flow is modified accordingly, and the OLTC tap position enters as a discrete control variable in the optimal power flow (OPF) formulation [14].

B. Dynamic Model of OLTC in Stability Studies

In the case of voltage stability and dynamic simulation studies, the OLTC is represented as a discrete dynamic element. Discrete instants at which the tap ratio a is updated are controlled by the AVR timer, and loads, generators and reactive compensation devices are represented by continuous-time differential equations. The load model is also a vital aspect: constant-impedance, constant-current and constant-power (ZIP) load models react differently to the voltage recovery interventions provoked by the OLTC. In the case of thermostatic loads like air conditioning, the temporary effect of voltage-restorative OLTC action is to reduce load impedance (because the load devices controlled by thermostats use more power when voltage is restored), which is the opposite action to the desired voltage recovery effect that has been measured in recent grid incident analysis [3].

The distance to voltage collapse can be determined with the long-term voltage stability Lyapunov function W , which was introduced in continuation power flow (CPF) analysis. The OLTC provides a balance by changing the equilibrium locus by continually adjusting the load bus voltage to a set-point, essentially restoring load power and lowering the effective system margin. OLTC behavior, tap range and the character of the connected load directly affect the maximum loading point (MLP) of the system the nose point of the P-V curve, [10].

V. CASE STUDY: SYSTEM DESCRIPTION AND SIMULATION SETUP

A. Test System: IEEE 33-Bus Distribution Network

This study uses IEEE 33-bus radial distribution system as the test platform. The network comprises one substation bus (Bus 1, slack bus), 32 load buses and 32 sectional branches. The connected active and reactive loads are 3.715 MW and 2.300 MVar, respectively, in a base voltage of 12.66 kV. The substation transformer is modeled with OLTC that can regulate the voltage by $\pm 10\%$ in 19 discrete steps (± 9 positions), with a nominal step size of about 1.11%/position. The AVR deadband is adjusted to a value of ± 0.5 percent of the nominal voltage and the delay T_6 is 45 seconds with a further delay of 10 seconds between successive operations.

To investigate different attributes of OLTC performance, three simulation scenarios are specified:

Scenario 1: Base case-varying load demand between 60 and 130 percent of nominal, no DG, and the performance of the OLTC voltage regulation at the voltage regulation.

Scenario 2: High-PV-penetration scenario- distributed PV generation at Buses 8, 14, 22 and 30 with total PV capacity set to 40 percent of peak load, which simulates the irradiance variability due to clouds.

Scenario 3: Coordinated control case OLTC synchronized BESS (at Bus 18) and smart PV inverter reactive power injection and compared the results between uncoordinated and coordinated control.

B. OLTC Parameters and AVR Settings

TABLE I OLTC and AVR Parameters for Simulation

Parameter	Symbol	Value
Nominal tap ratio	n_nom	1.0 p.u.
Tap step size	Δa	0.0111 p.u.
Number of tap positions	N_tap	± 9 (19 steps)
Tap range	[a_min, a_max]	[0.9, 1.1] p.u.
Reference voltage	V _o	1.0 p.u.
Deadband (\pm)	ϵ	0.005 p.u.
Initial time delay	T_d1	45 seconds
Subsequent time delay	T_d2	10 seconds
BESS rated capacity	E_BESS	500 kWh
PV total rated power	P_PV	1.5 MW

VI. SIMULATION RESULTS AND ANALYSIS

A. Scenario 1: Load Variation and OLTC Response

In Scenario 1, the load will be ramped up to 130% or 60% of the nominal value at 10% steps at 5 minutes time intervals. The worst-case voltage at Bus 18 (the electrically remote bus in the network) is 0.904 p.u. at 130% loading without the OLTC action, a 9.6% deviation of the nominal, which is quite large compared to the acceptable statutory range of $\pm 5\%$. When OLTC active, and with AVR settings as in Table I, the OLTC performs 6 tap-raise operations during the load cycle, keeping the Bus 18 voltage at or above 0.960 p.u. during the load cycle. Maximum variation in voltage with OLTC is minimized to 4.0% less than nominal at full load.

The tap position change demonstrates that the OLTC varies in its nominal position 0 to position +5 as the load rises, and each step is timed out right by the AVR timer. The regulated bus (Bus 1 LV side) is held within 1.0 p.u. (± 0.5). It is observed that the total active power losses in the system are reduced by 8.3% at 130% loading when OLTC is active as compared to the no-OLTC case, demonstrating that loss reduction benefits are also realized by voltage support via tap adjustment.

B. Scenario 2: High-PV-Penetration and Voltage Rise

In Scenario 2, four distributed PV generators are introduced at Buses 8, 14, 22 and 30 each with a rating of 375 kW, adding up to 1.5 MW or 40 percent of peak load. Their irradiance profiles (including realistic cloud transients) are used on a 24 hour simulation period. In morning PV ramp-up (8:00 -10: 00 AM) a sharp increase in upward voltage is seen at feeder-end buses. At the point of Bus 30, the voltage is 1.071 p.u. when the noon irradiance is at peak under 60% loading conditions- a 7.1% overvoltage.

The standard single-bus AVR, by only observing Bus 1 LV voltage, does not detect the feeder-end overvoltage since the substation bus voltage is kept close to nominal by the reverse power flow flattening the feeder voltage profile at that point. This is a common shortcoming of single-point monitoring OLTC control. The traditional OLTC in reality commands a tap-lower signal in response to the apparent elevated voltage at Bus 1, thereby exacerbating the under-voltage situation at the midfeeder, which is the opposite phenomenon.

With the AVR upgraded to a multi-bus monitoring architecture (gathering control signals on the critical end buses as suggested in the smart distribution network studies [14]) the OLTC rightly rises or drops the overall feeder voltage during the high-PV periods, decreasing the peak Bus 30 overvoltage to 1.043 p.u.--still above nominal, but within the 5% tolerance. To completely mitigate feeder-end overvoltage, PV reactive power absorption in the form of inverter coordination as in Scenario 3 is needed. C. Scenario 3: OLTC-BESS-Inverter Co-ordination.

C. Scenario 3: Coordinated OLTC-BESS-Inverter Control

Scenario 3 uses a coordinated control scheme where: (i) the OLTC varies the position of the substation transformer tap depending on the average feeder voltage, (ii) the BESS at Bus 18 injects/absorbs active power on a fast time scale in response to sub-minute voltage transients due to PV variability, and (iii) smart PV inverters at Buses 8, 14 The coordinated scheme is contrasted with an uncoordinated baseline where all devices are controlled by standard fixed-parameter controllers.

TABLE II Performance Comparison: Coordinated vs. Uncoordinated OLTC Control

Performance Metric	Uncoordinated	Coordinated
Min. bus voltage (p.u.)	0.921	0.961
Max. bus voltage (p.u.)	1.071	1.038
Mean voltage deviation (p.u.)	0.0284	0.0108
Voltage deviation reduction	—	62.0%
OLTC tap operations (24h)	47	29
Tap operation reduction	—	38.3%
Voltage compliance rate (%)	84.6%	97.3%
Active power losses (kWh/day)	312.4	274.1
BESS cycling frequency (/day)	N/A	4.2

Table II results show the significant enhancement that occurred with the coordinated control strategy. The average deviation of voltage across all buses during the 24-hour simulation decreases by 62.0 percent, 0.0284 p.u. to 0.0108 p.u. Crucially, the rate of compliance with the statutory limits on voltage, the proportion of bus-hours that the voltage does not exceed the limits, increases by a factor of 0.846 to The count of OLTC tap operations decreases by 38.3 percent (47 to 29 operations day) which contributes to the direct extension of the mechanical life of the tap changer mechanism and decreases the frequency of maintenance.

The results are consistent and extend the findings of Maataoui et al. (2023) [7] and consistent with the ANN-based OLTC control findings by Janiga et al. (2024) [11]. The BESS mitigates high-frequency transient voltage events that would otherwise result in OLTC operation, and the smart inverter reactive power absorption mitigates feeder-end overvoltages, thus permitting the OLTC to operate only to sustained slow-moving voltage events--the operation capability that it was initially designed to perform. B. Hunting Phenomenon Analysis.

D. Hunting Phenomenon Analysis

One known pathological operating mode, which promotes mechanical wear, is the hunting phenomenon, the oscillatory cycling of the tap changer between adjacent positions around the deadband boundary. Hunting was induced in our simulation by simply setting deadband to half the step size (0.0055 p.u.) and then loading a load that sets the steady-state voltage to the deadband boundary at the ± 1 tap position. In this case, the standard fixed-delay AVR would yield repeated tap operations with a period of T 6 of about 45 s, producing up to 84 tap operations per 24 hrs.

Hunting can be removed by increasing the deadband to 0.008 p.u. (around 72% of the step size), but at the price of a little broader allowable deviations of the voltage. The proposed adaptive deadband strategy (see the fuzzy OLTC controller of Wrobelwski et al. 2024) [9] is the best trade-off: when the variability is low (overnight, fixed load

conditions), the deadband is reduced to allow tighter voltage regulation, whereas when variability is high (PV injection events), the deadband is increased to avoid excessive hunting. This adaptive strategy is simulated by us to provide a 97.3% rate of compliance with the voltage at only 22 tap operations per day at the conditions of the high-PV Scenario 3. WORLD Deployment and Industry perspective.A. Market Trends and Technology Evolution.

E. Market Trends and Technology Evolution

The tap changer market is expected to increase to USD 3.5 billion by 2032 with a CAGR of 5.5% and a current valuation of USD 2.1 billion in 2023 [15]. Driving factors of the growth include faster grid modernization, increased renewable energy penetration, which needs flexible voltage regulation, and increased load density in distribution networks due to urbanization. The regional market share is dominated by Asia-Pacific with 35 percent and North America with 24 percent, with individual markets in India and China being the fastest growing markets due to the massive electrification programs.

Approximately 58% of the tap changer market in revenue is represented by On-Load Tap Changers, since they are predominantly used in medium-voltage and high-voltage substations [15]. The increased propensity in electronic and hybrid OLTCs, or a combination of mechanical strength with semiconductor-assisted arc-free switching, is responding to the increased tap operation frequency requirements of renewable-integrated grids without similar proportional increases in mechanical wear [13].B. Interoperability with Smart Grids.

F. Integration with Smart Grid Technologies

Modern OLTC controllers are becoming more and more connected with smart grid communication infrastructure, allowing centralized and distributed control paradigms previously unachievable with legacy electromechanical relays. Smart meter Advanced Metering Infrastructure (AMI) data may be explored at the substation level and be integrated to create real-time feeder voltage profiles, which the OLTC controller may use to optimize tap position choices on the whole feeder, instead of basing them on the single bus being monitored [16]. This method, similar to the optimal OLTC tap control method suggested by Park et al. (2025) [16] in Korean 154/22.9 kV substations, produced a considerable enhancement in the rate of compliance of the voltage at all measuring points of the feeders. Real time OLTC state monitoring, remote tap position adjustment, and predictive maintenance scheduling of contacts wear models are being facilitated with Internet-of-Things (IoT) integration and IEC 61850 communication standards. It is believed that 20-50 billion devices will be online by 2025 all over the world [17], and OLTC controllers will be a growing part of that, as the grid asset management is being digitalized. OLTC optimization is being explored using cloud computing and edge computing paradigms, which allow faster computational turnaround of more complex multi-objective optimization problems without the need to have a dedicated on-site hardware.

G. South-Eastern European Grid Incident: Lessons Learned, June 2024.

The voltage collapse on Albania, Montenegro, Bosnia-Herzegovina, and Croatia on June 21, 2024, gives a sobering real-world example of the possibility of negative interaction between the OLTC devices and the system level dynamics under stressful conditions [3]. It was triggered by the triggering of two transmission lines which was then followed by a series of OLTC activities in the affected area. The situation was further compounded by the presence of a large fraction of air-conditioning (nonlinear) load (forced by extreme heat) which caused OLTC voltage-restorative actions to temporarily raise load demand, driving up the demand-supply mismatch and voltage collapse faster. The main lessons of this incident are: (1) OLTC blocking schemes are to be automatically enabled when the system voltage reaches a critical value (e.g. 0.90 p.u.) to avoid the occurrence of reverse-action cascades; (2) nonlinear load behavior has to be included in the stability assessment models to be used in the parameterization of AVR; (3) regional coordination of multiple OLTC devices via The OLTC behavior is included in the RDI Roadmap 2024-2034 of the European Network of Transmission System Operators (ENTSO-E) as a high-priority area requiring further research on advanced network control [1].

VII. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Though tap changing transformers are still irreplaceable in terms of the regulation of voltages, a number of issues have to be resolved to make them effective and reliable components of the future power systems: A. Mechanical Wear and Maintenance.

A. Mechanical Wear and Maintenance

Mechanical tap change mechanism is prone to contact arcing, oil spillage and spring wear and tear and therefore requires regular maintenance which is normally after 100,000-500,000 cycles which is predetermined by the technology. The variability of renewable causes an acceleration in the frequency of the tap changes, which shortens the wear and maintenance cycles, raising operational expenses. Arc-free operation and much longer service life are provided with electronic and hybrid OLTC designs, which substitute mechanical contacts with semiconductor switches at a higher capital cost [13]. B. Multi-Device Environment coordination.

B. Coordination in Multi-Device Environments

Distribution networks are more actively using a combination of multiple voltage control devices in parallel, including OLTCs, capacitor banks, SVCs, STATCOMs, smart inverters, and BESS. These devices may maladaptively communicate with each other without proper coordination, resulting in oscillations and a higher number of operation without any better overall voltage compliance. Mixed-integer programming, model predictive control (MPC), and reinforcement learning (RL) models are becoming new promising models in the area of multi-device coordination, yet their real-time computational needs and their communication infrastructure requirements pose a challenge to implementations [8]. C. Renewable-Rich Networks Uncertainty Management.

C. Uncertainty Management in Renewable-Rich Networks

The unpredictability of solar radiation and wind speed is an inherent aspect that creates forecast error in the performance of day-ahead OLTC scheduling methods. Stochastic optimization and robust optimization models using scenarios can be used to offer OLTC setpoints that are resilient to forecast errors, but more computationally complex. Data-driven solutions based on machine learning, such as ANN-based controllers [11] and deep reinforcement learning agents, can be used to handle uncertainty without probabilistic modeling. D. Reverse Action and Voltage Stability Margin.

D. Reverse Action and Voltage Stability Margin

The reverse action effect, where OLTC voltage restoration raises constant-power load demand and exacerbates the reactive power balance, is also a severe issue particularly in systems with high loading close to the voltage stability limit. An active area of research is real-time estimation of voltage stability margin and OLTC blocking or tap-down operation. The combination of phasor measurement units (PMUs) and synchrophasor-based wide-area monitoring systems allows the situational awareness that gives the system operator and automated controls the awareness of closing in on voltage collapse, before it takes place [3].

VIII. CONCLUSION

This paper has provided an in-depth case study of the purpose of tap changing transformers in the control of power system voltages, covering the basic principles, mathematical modeling, simulation based performance assessment, real life incident investigation, and outlook of research in the future. The main results can be summarized as follows:

The most effectively used and common mechanism in slow-acting, sustained voltage regulation in transmission and distribution substations is the On-Load Tap Changer (OLTC) with an Automatic Voltage Regulator (AVR) installed. The OLTC is able to keep bus voltages within statutory limits under normal load variation conditions with only a small number of tap operations, also with active power loss reductions of about 8%.

In high-PV-penetration situations, the traditional single-bus AVR-controlled OLTCs are not sufficient and they can act in a reverse direction, aggravating the voltage situation at feeder ends. Adaptations to the modern distribution networks are multi-bus monitoring and coordinated control with smart inverters.

Coordinated OLTC-BESS-smart-inverter control of the IEEE 33-bus test system reduces the mean voltage deviation by 62.0 per cent, raises the rate of voltage compliance by 84.6 per cent to 97.3 per cent, decreases the number of daily tap operations by 38.3 per cent, and decreases active power losses by 12.3 per cent over un

The hunting phenomenon, leading to excessive wear, can be efficiently suppressed by adaptive deadband strategies that tighten up during stable conditions and relax during high-variability conditions. The 2024 South-Eastern European grid incident of June 2024 shows that improper OLTC operation under stressed conditions may lead to voltage collapse, requiring protective blocking schemes and comprehensive coordination frameworks.

With the acceleration of power systems across the globe to both include more renewable energy and to embrace smart grid technologies, the tap changing transformer will remain more refined than an originally passive electromechanical device, becoming an intelligent, communicating and adaptively controlled node in the voltage regulation hierarchy. Future studies are desired to include predictive and data-driven OLTC control, hybrid solid-state OLTC technologies, and developing coordinated work of multi-device optimization of voltages under deep uncertainty.

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