

Challenges of Transformers OLTC Operation in the Power System That Includes Solar PV Systems and FACTS Devices

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Abstract

An increase in penetration of photovoltaic (PV) systems in a distribution system causes voltage regulation issues that create serious problems for the On-Load Tap Changer (OLTC) of the power transformer, leading to higher tap-changing frequency and reduced transformer life. Traditional voltage control methods are ineffective when PV penetration exceeds load demand, and more sophisticated control methods are needed. This paper combines a systematic literature review conducted in accordance with the PRISMA 2020 guidelines with a case study on operational issues of OLTC transformers under both normal and non-normal operating conditions. It entails a detailed examination of the effect of PV integration on the operating characteristics of OLTC in a systematic approach and also dwells upon coordination processes between OLTC and Flexible AC Transmission Systems (FACTS) devices, such as Distribution Static Synchronous Compensator (D-STATCOM) or Static VAR Compensator (SVC), which are highly effective in reducing tap operations. The future directions covered in the review include the operation of hybrid systems, cost-effective implementations, weather effects, predictive analytics, adaptive control techniques, etc. The case study included online monitoring of OLTC performance in two scenarios at the cement factory. First, under supply changes and load changes. Second, including PV penetration. The results show that OLTC increases the average daily tapping frequency (90 taps/day) by about 60%, with full PV penetration. It is concluded that this can't be applied without coordinated control among OLTC, D-STATCOM, and PV inverters to maintain transformer life, improve reliability, and provide stable voltage profiles even under highly variable PV generation conditions. These results aim to provide a comprehensive resource for academics and practitioners, facilitating the advancement of advanced voltage control methods to support the transition to sustainable energy systems.

Keywords: on-load tap changer; OLTC; photovoltaic systems; voltage regulation; FACTS devices; D-STATCOM; SVC; reactive power compensation; smart grid; PV-rich; PV penetration

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1. Introduction

Throughout the 20th century, the growing energy demand was met by relying on relatively cheap and readily available fossil fuels. However, rising fuel prices and consumption are set to cause price fluctuations and energy deficits in countries without fossil fuel reserves, at a time when the world fears carbon dioxide (CO₂) emissions and climate

change are on the rise. Smart grids, in this case, are a revolutionary technology that can transform how electricity is generated, managed, and consumed [1]. Smart grids are the future of electrical grids because they integrate energy generation, transmission, and distribution to offer more efficient, secure, and reliable services. They also facilitate two-way communication between consumers and utilities, promote the use of green energy, and implement demand response mechanisms. Ensuring proper voltage profiles and optimizing distribution network operation to minimize energy losses could also be achieved [2]. One of the key aspects of smart grids is the integration (Hybrid) of renewable Distributed Generation (DG) sources, such as solar and wind energy, into the national grid to enhance stability [3]. The traditional one-way transfer of power from power generation points through transmission and distribution networks to consumers is envisaged to shift to bi-directional power-flow networks, for which advanced voltage-control techniques would be needed to maintain grid stability and reliability [4]. The increasing penetration of Distributed Energy Resources (DERs), especially PV systems and wind power, creates significant voltage regulation challenges for distribution systems [5,6]. These challenges include voltage collapse, sharp voltage fluctuations, voltage rise issues, and imposed operating stress on traditional voltage regulation devices, such as on-load tap changers (OLTCs) [7,8], which may threaten system stability and lead to its total collapse. The underload voltage regulator, i.e., OLTC, plays a pivotal role in conventional voltage regulation by gradually adjusting the conversion ratio, but its slow mechanical response makes it unable to keep pace with the rapid changes in solar energy sources; these stresses may lead to blackouts, as in the U.S.-Canadian blackout of 14 August 2003 [9]. Therefore, coordinated control strategies have been proposed, including integrating OLTC with capacitors and energy storage systems within multi-period algorithms [7] and developing decentralized approaches that coordinate OLTC with solar inverters in high-penetration radial distribution networks without requiring a complex central control architecture [8]. In this regard, voltage control is a part of regular power system operation and may be achieved using reactive power control devices such as switching capacitors [10,11]. Modern power systems are increasingly relying on Flexible AC Transmission Systems (FACTS) devices for active and reactive power control. Static VAR Compensators (SVCs) and Static Synchronous Compensators (STATCOMs) are among the most popular FACTS devices used to control voltage and reactive power [12–14]. Proper coordination of these devices, the generator excitation systems, and the OLTC is vital to achieving voltage stability at load buses. Thus, the primary objective is to determine the optimal settings of these control devices to minimize voltage deviations across the network. Nonlinear optimization techniques are typically used to determine the optimal setup and enhance system performance [15–17]. However, the conventional OLTC operation was designed for predictable load variations and could suffer from over-tap operations under high PV penetration. Hence, coordination of OLTCs with fast-acting optimal coordination compensation devices, such as DSTATCOMs, has become important for the maintenance of voltage stability and the minimisation of unnecessary tap-changing actions.

Figure 1 presents a network diagram that shows the research landscape on OLTC and voltage control in distribution power systems with significant PV penetration. This landscape is derived from a SciSpace-assisted examination of 222 academic articles published between 2016 and 2025, most of which are included in this work. To ensure accuracy, all mapping and article extractions were manually rechecked and verified.

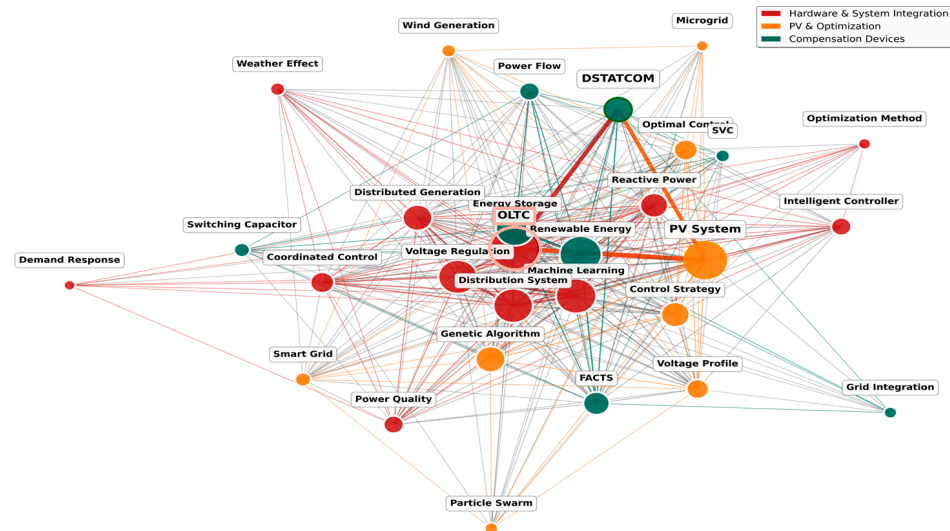


Figure 1. Network diagram of the research landscape on OLTC and voltage control in distribution power systems, where each colored node group represents a defined cluster.

The current work and the results of the research landscape in Figure 1 were collected from major scientific databases, following PRISMA 2020 guidelines, including Web of Science, Scopus, IEEE Xplore, Elsevier (ScienceDirect), IET/Wiley, MDPI, Springer, Taylor & Francis, and Others. Figure 1 depicts three key research groups: Hardware and system integration (red, with OLTC, D-STATCOM, and FACTS), PV and Optimization (yellow, with solar systems and algorithms), and Compensation Devices (green, with D-STATCOM and energy storage). The main point is that current voltage regulation must handle three major components simultaneously: OLTC transformers for gradual voltage changes, D-STATCOM for rapid reactive power compensation, and PV systems, which are both a problem and a potential solution. OLTC-PV coordination and D-STATCOM-PV coordination are the most significant research links. The integration of machine learning is the most common trend, indicating that the concept of voltage control will become smarter and enable the coordination of multiple devices in real time. This picture includes visual elements, with nodes (circles) representing research areas or technologies. The size of a node indicates how often it appears in the literature (larger nodes indicate more publications). The color of the node shows which cluster it belongs to (related research subjects). The thicker the line, the stronger the relationship (thicker lines mean more publications discuss both themes together).

This paper presents a detailed study of the OLTC, followed by an analysis of the controllers used to operate it. It also provides an overview of renewable energy sources, with a specific focus on PV energy and its impact on OLTC performance in electrical power systems. In addition, it addresses FACTS devices and how they relate to those that operate alongside the OLTC, such as the D-STATCOM, addresses the major challenges in OLTC operation, and conducts an extensive review of the existing literature on these challenges and the use of controllers to address them. This work also included a case study on the online monitoring of an OLTC in a cement factory under load and PV variation challenges. Figure 2 illustrates, as an example, the coordination operation between an OLTC and a D-STATCOM in a distribution power system with PV penetration, collected across 5 panels. Panel 1 explains the 6.6 kV distribution power system with an OLTC, a PV-rich system with higher penetration and different loads. Panel 2 shows the OLTC of the power transformer with the motor drive and the control unit. Panel 3 shows the D-STATCOM.

Panel 4 explains the procedure for cooperation between the OLTC and the D-STATCOM to keep the voltage profile shown in Panel 5 within the standard limit.

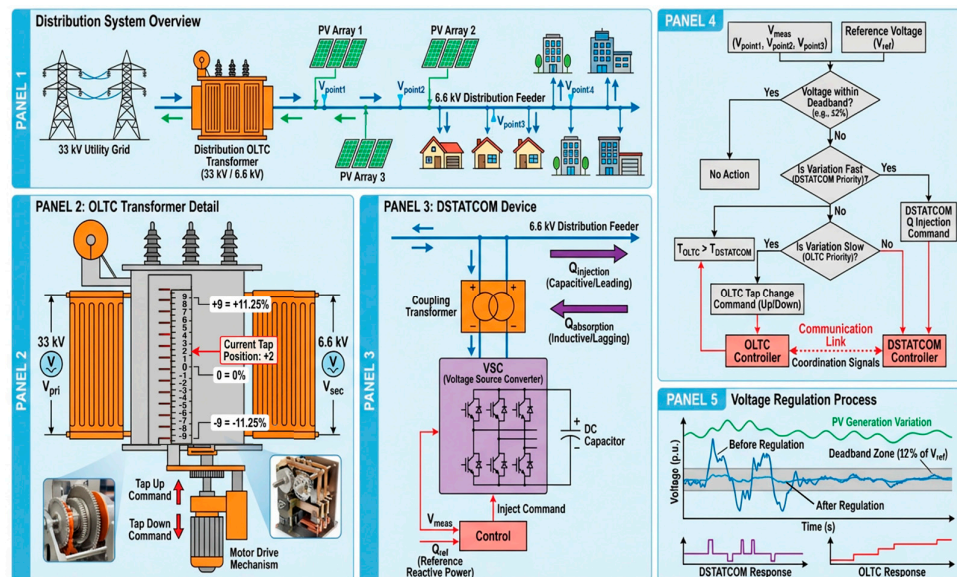


Figure 2. The coordination operation between an OLTC, D-STATCOM, and PV penetration.

2. On-Load Tap Changer Transformer

Most power transformers have an OLTC to control and regulate the secondary output voltage. The following paragraphs describe the OLTC structure and types.

2.1. OLTC Transformer Structure

Voltage regulation is one of the most important functions for ensuring the stability and operational efficiency of electrical systems. It is achieved by adjusting the turns ratio of the primary and secondary windings of transformers to set the output voltage according to system requirements. As illustrated in Figure 3, additional turns can be added to the secondary winding to obtain an output voltage from a fixed value V_2 to $V_2 \pm \Delta V$ by reducing the primary-to-secondary turns ratio, depending on the selector and A, B, C, and D contact points [18].

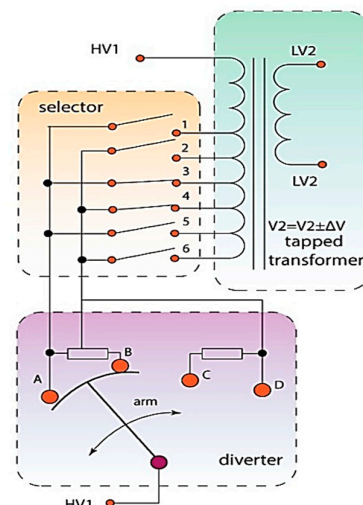


Figure 3. A simplified view of the classic OLTC mechanics.

Tap changers are used to adjust the number of turns, thereby enabling precise voltage control. The number of tap positions available, however, is realistically limited by technical constraints, i.e., the physical size of the tap changer and the insulation requirements between adjacent taps. Tap changer-controlled voltage regulation is therefore smoothly adjusted to provide precise control and avoid sudden voltage changes, which would be undesirable for system stability [19].

Tap changers may be either manually or motorized operated. In some designs, the tap changer will be externally mounted on the transformer tank, and in these cases, a separate oil insulation will be provided to facilitate maintenance and repairs. In other constructions, the tap changer is installed within the principal transformer tank as it is economical and has reduced dimensions. High in efficiency and simplicity, such systems are commonly applied in small-scale dry-type distribution transformers.

The OLTC has two main components: the tap selector and the diverter switch. The major purpose behind this mechanism is that there must not be any disparity in power supply to the load when changing a chosen tap and any other adjacent tap. This is done by using a well-designed series circuit, ensuring continuity and consistency during switching. Transition resistors are used to perform switching, ensuring the step voltage and current pass at rated values during the brief transition time, which usually takes tens of milliseconds.

2.2. OLTC Transformer Types

Power transformers have tap changers, which are important devices that modify voltage levels by changing the number of turns active in the transformer winding. There are various types of tap changers depending on their operating conditions and capabilities, as highlighted below [20,21]:

1. Off-circuit tap changer: This type offers tap changing only when the transformer is de-energized or disconnected from the power supply. It typically consists of simple mechanisms mounted near the tap points and immersed in oil for insulation. Tap changing can be achieved only when the transformer is fully de-energized, without interrupting current flow. These tap changers are manually operated by a handle or wheel located outside the transformer tank and are thus suitable for use in applications where regular tap changes are not required.
2. Off-load tap changer: This type of tap changer is adjusted when the transformer is energized but not carrying load current. It is a compromise between off-circuit and on-load tap changers.
3. On-load tap changer (OLTC): This type of tap changer allows a tap position change when the transformer is under load. Due to the complexity of the operation, this type of tap changer is adjusted for steady load conditions. Studies, such as the CIGRE 1983 report, indicate that OLTC accounts for approximately 40% of transformer failures in large power systems. OLTCs provide tap changing without interruption of the supply and are therefore essential to systems requiring continuous voltage regulation [22].

Figure 4 illustrates the tap changer classification, with a hierarchical arrangement of different types based on their operational characteristics and design aspects [23].

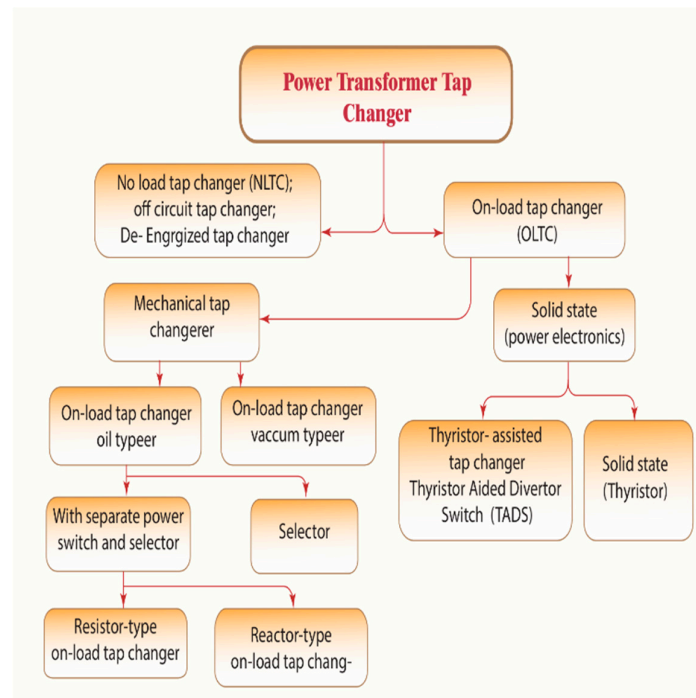


Figure 4. Tap changer classification.

OLTCs are further classified based on their design and operation mechanisms into:

1. **Mechanical OLTCs:** These are the most common and use oil as an insulator, a coolant, and for arc quenching. With time, however, impurities formed when the arc is quenched, such as carbon compounds and gases, may degrade the oil's insulating properties and require routine maintenance. Discrete selectors and power switches are used in larger transformers to enable safe and efficient switching. Rotary switches with simpler designs are used in smaller transformers.
2. **Solid-State OLTCs:** This recent equipment eliminates electric arcs and permits high switching frequencies without the need for interruptions between operations. They feature reduced operating costs, high reliability, and non-sequential tap switching. Solid-state OLTCs can be hybrid with electronic and mechanical components, or all-electronic, using purely solid-state switches [24].

Transformer tapping arrangements are primarily categorized into three configurations: linear, reversing, and coarse/fine, each with merits and limitations suited to specific applications. These arrangements, in the basic forms of tapped windings to be employed in power transformers, are illustrated in Figure 5.

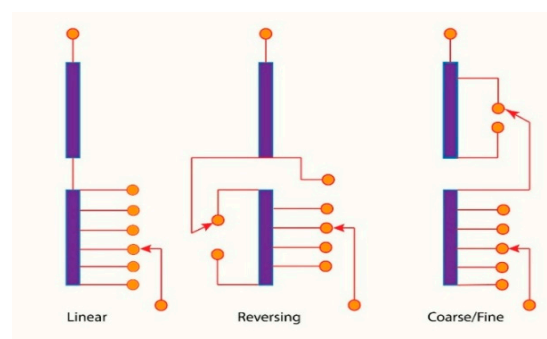


Figure 5. Tapped arrangement of power transformer OLTC.

2.3. OLTC Control

The On-Load tap changer (OLTC) is a very important component of automatic voltage regulation in electrical networks. It switches the tap position in the high-voltage (HV) operation to reinstate the normal level of voltage in the low-voltage (LV) side when perturbations happen to cause significant dips in voltage. The OLTC control system focuses on the re-allocation of reactive power between the levels of voltage to prevent the occurrence of a feedback effect, as a result of which the voltage level can collapse [25,26]. This is achieved through freezing the tap position where additional adjustments harm the stability of the system and then unfreezing it once the level of voltages gain back.

The OLTC is continuously notified of tap positions and changes in voltage and current and is regulated in discrete steps. The control system includes a delay mechanism to synchronize the actions of the transformer tapping mechanism and avoid unnecessary switching. There is also a delay time set by the controller to achieve long-term stability of the voltage medium and long-term stability without introducing unwarranted switching operations to the latter and without ensuring the safety of the former [27].

The control and action process of the OLTC is as follows: The OLTC tap is generally connected to the HV side, and the positive-sequence voltage at the LV side loads is measured and calculated. If the load voltage is below the set value, the tap actuator is triggered after a Time Delay (T_d) to shift the tap position, thereby regulating the load voltage. The time delay of action (T_m) is relatively long for a mechanical-type actuator, usually 5–10 s. The time delay (T_d) is typically 30–120 s, accounting for the need to avoid responding to momentary voltage dips during fault conditions, as specified in IEEE Standard C57.15-2017.

Line drop compensation (LDC) is a widely used method for distribution network operators to control voltage at the bulk supply point. In this method, feedback for the OLTC control is obtained by estimating the voltage at a distant point in the network, thereby compensating for the voltage drop along the line. By doing so, the OLTC can maintain proper voltage levels throughout the distribution system, not just at the transformer secondary terminals.

3. PV Systems

3.1. PV System Overview

Solar photovoltaic (PV) technologies are among the fastest-developing renewable energy sources globally, permeating electrical power systems extensively. Low-voltage distribution networks connected to these systems, however, nevertheless experience technical problems, most notably voltage rise, that limit their ability to support high penetration levels of solar systems. Networks are frequently fitted with an OLTC transformer in order to prevent such issues, and it increases the voltage control activity [28–33].

Integration of non-renewable sources with solar power is also a notable step towards reducing fossil fuel use and enhancing environmental sustainability. Solar power used in PV systems harnesses available solar energy by converting Direct Current (DC) electricity to Alternating Current (AC) for effective use in power grids. When there is a penetration of over 30 percent in renewable energy, smart grid technologies play a very important role in ensuring the grid operation is reliable [34].

The two broad types of solar electricity production include Photovoltaic (PV) and Concentrated Solar Power (CSP). In a way similar to traditional power plants, CSP uses the thermal energy of concentrated sunlight to generate electricity via steam turbines. PV plants, in their turn, utilize the so-called photovoltaic phenomenon to transform sunlight directly to DC electricity without any thermal intermediate [31].

The main feature of PV systems is that they produce electricity directly, but they have limited energy storage at large scales because existing battery technologies are limited.

Another advantage of CSP systems, however, is that they can store energy as heat using advanced thermal storage technologies, making them more stable on the grid and reducing the intermittency problem typically associated with PV systems. CSP systems are more appropriate as a storage and integration tool but have not been allowed the freedom of general usage due to their expensive initial cost and complex infrastructure. In the meantime, PV systems have become more attractive due to the reduction in the costs of installation and the addition of improved efficiencies and have become a popular system of choice in large-scale renewable energy projects around the world [35].

3.2. Solar-Grid Integration

Solar-grid integration is the technology that connects large-scale solar energy generated by photovoltaic (PV) or concentrated solar power (CSP) systems to the existing power grid. The technology requires meticulous attention to several aspects, including the manufacture, installation, and operation of solar devices. Integration of solar energy with the transmission grid must be successful to ensure compatibility and optimal performance [35].

As illustrated in Figure 6, a photovoltaic (PV) power station comprises several key components for grid connection. The most significant component in achieving this is the inverter, which converts the direct current (DC) output of solar panels to an alternating current (AC) to match the grid used by commercial appliances [36].

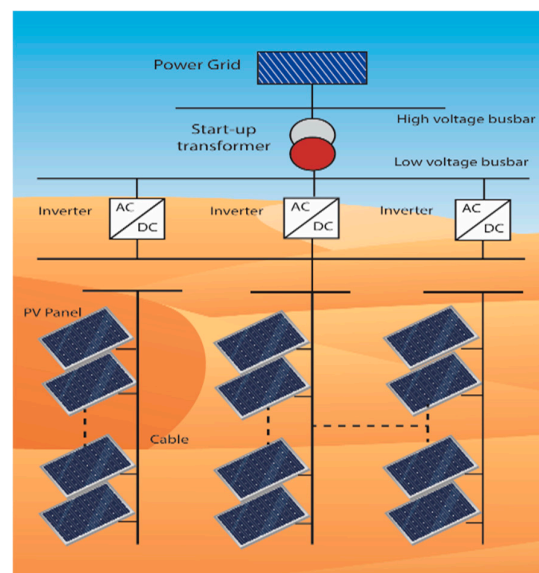


Figure 6. Schematic of a PV power station.

The other essential components of a PV power plant are the solar power generator (solar modules), generator junction box, meters, grid connection points, and DC and AC cabling. Inverters are the key component of any solar power system and, in some cases, are aptly described as the “brain” of the project. Their main function is to convert DC power into a stable voltage and frequency, even as load conditions change. They are also able to provide and absorb reactive power as required, thus improving grid stability [37].

Apart from the conversion function, inverters also balance the various system components to feed solar energy into the grid with maximum efficiency. The performance of a PV installation depends heavily on the inverter’s efficiency and reliability, as well as other factors such as orientation, interconnection, and the quality of the PV modules [38].

3.3. Impact of PV Systems on OLTC Transformers

A PV-rich distribution grid faces significant challenges in voltage stability due to the increasing penetration of photovoltaic (PV) systems. A PV-rich distribution network is a system operating at high PV penetration levels, where photovoltaic generation significantly affects voltage regulation, power-flow patterns, and OLTC performance. Excess PV production can exceed the tolerance limits of the European standard EN 50160 [39]; a range is available for renewable energy absorption due to voltage losses in loads. This limitation impedes the capacity of the network to accept additional levels of solar energy [40–42]. Figure 7 illustrates the potential problems faced by network operators in high-PV penetration distribution networks without OLTC. The last bus has a load and PV-rich system. Voltage variations can exceed statutory levels during periods of high PV generation, with a $\pm 10\%$ voltage range considered admissible. In low-voltage grids, only 3% to 5% of this is attributed to operational issues for the network [43].

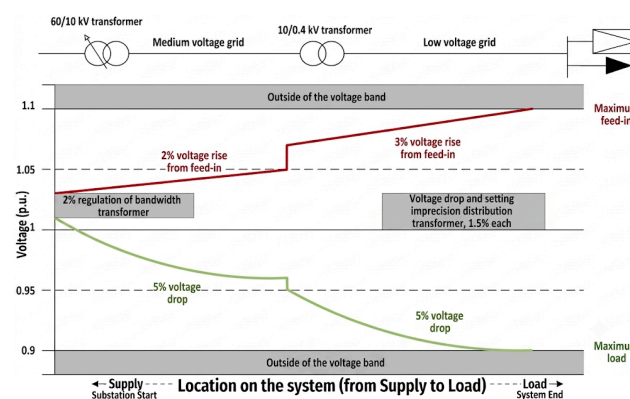


Figure 7. Possible problems faced by the network operator without OLTC [43].

To overcome these problems, the OLTC is a promising solution that actively controls the voltage between medium-voltage and low-voltage networks. This increases renewable energy hosting capacity to up to 11% without disconnecting the load. OLTC assists in improving voltage stability and reduces the need for costly network reinforcement [43]. Figure 8 illustrates the benefits to the network operator with OLTC. The transformer can adjust its tap position to keep the voltage within tolerable limits, even with variations induced by PV generation.

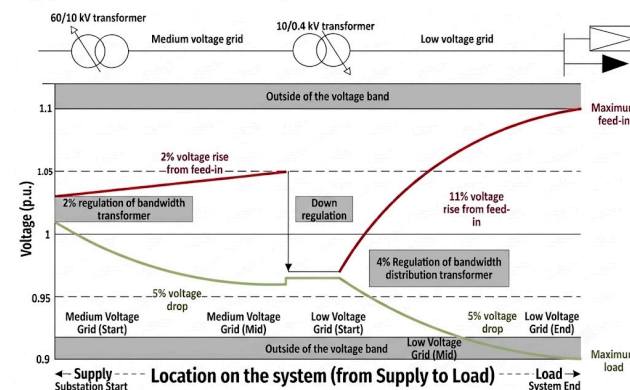


Figure 8. Benefits provided to the network operator with OLTC [43].

Intermittent renewable generation in distribution systems poses serious issues, including power and voltage fluctuations and reverse power flow, that negatively affect

grid stability. Therefore, the OLTC is highly stressed due to the high penetration of photovoltaic (PV) systems, as continuous voltage fluctuations increase operational activity to restore voltage to its normal range, which can affect its efficiency and life [44]. However, the impact of weather conditions, i.e., passing clouds, on OLTC performance has not been adequately studied, even though available research indicates that these conditions may cause unnecessary operation of control equipment and reduced efficiency [4].

Research has indicated that tap changes in OLTC transformers can rise considerably with increased PV penetration. For instance, a study by Yan et al. found that with 50% PV penetration, tap changes increased by about 84% compared with scenarios without PV. This increased operational frequency of the OLTC not only increases mechanical wear but also increases maintenance needs and expenses, which can shorten the transformer's useful life [45,46].

4. FACTS Devices

4.1. Overview of FACTS

The power system is one of the pillars of the world economy, and its operations are subject to increasing operational stress amid unrelenting growth in energy demand. One of the most significant reasons for violations of operating boundaries and the risk of voltage collapse is voltage instability. Reactive power control plays an important role in assisting voltage stability, and FACTS provide additional flexibility and dynamic control of reactive power flow, thus enhancing the overall performance of the electrical network. FACTS devices include a broad range of power electronic solutions such as SVC (Static VAR Compensator), STATCOM (Static Synchronous Compensator), TSSC (Thyristor Switched Series Capacitor), TCSC (Thyristor Controlled Series Capacitor), SSSC (Static Synchronous Series Compensator), TCPST (Thyristor Controlled Phase Shifting Transformer), TCPAR (Thyristor Controlled Phase Angle Regulator), TCVR (Thyristor Controlled Voltage Regulator), UPFC (Unified Power Flow Controller), IPFC (Interline Power Flow Controller), and UPQC (Unified Power Quality Conditioner) [47].

The hierarchical diagram of FACTS devices provides the overall picture, as shown in Figure 9. The power system is among the key foundations of the world economy, which has been facing mounting operational problems due to unmanaged growth in energy demand. One of the most dangerous issues is voltage instability, which can cause operating limits to be exceeded and voltage collapse. Reactive power control is an important factor in maintaining voltage stability, and FACTS improve the flexibility and dynamic control of reactive power flow, which leads to better performance of the overall electrical network [48–50].

Traditional voltage regulation methods, such as OLTC, reactive power compensation, and network reinforcement, are typically employed to ensure voltage stability. Nevertheless, reducing the produced power will reduce the maximum utilization of distributed generation sources, while network reinforcement is typically considered an expensive and time-consuming process, thus not a desirable solution in most instances [51].

While reactive power compensation technology and OLTC are suitable for voltage regulation, each has advantages and operating limitations. Thus, the coordinated use of OLTC with FACTS devices represents a promising means of achieving optimal voltage regulation to enhance the operating efficiency and reliability of power systems [52].

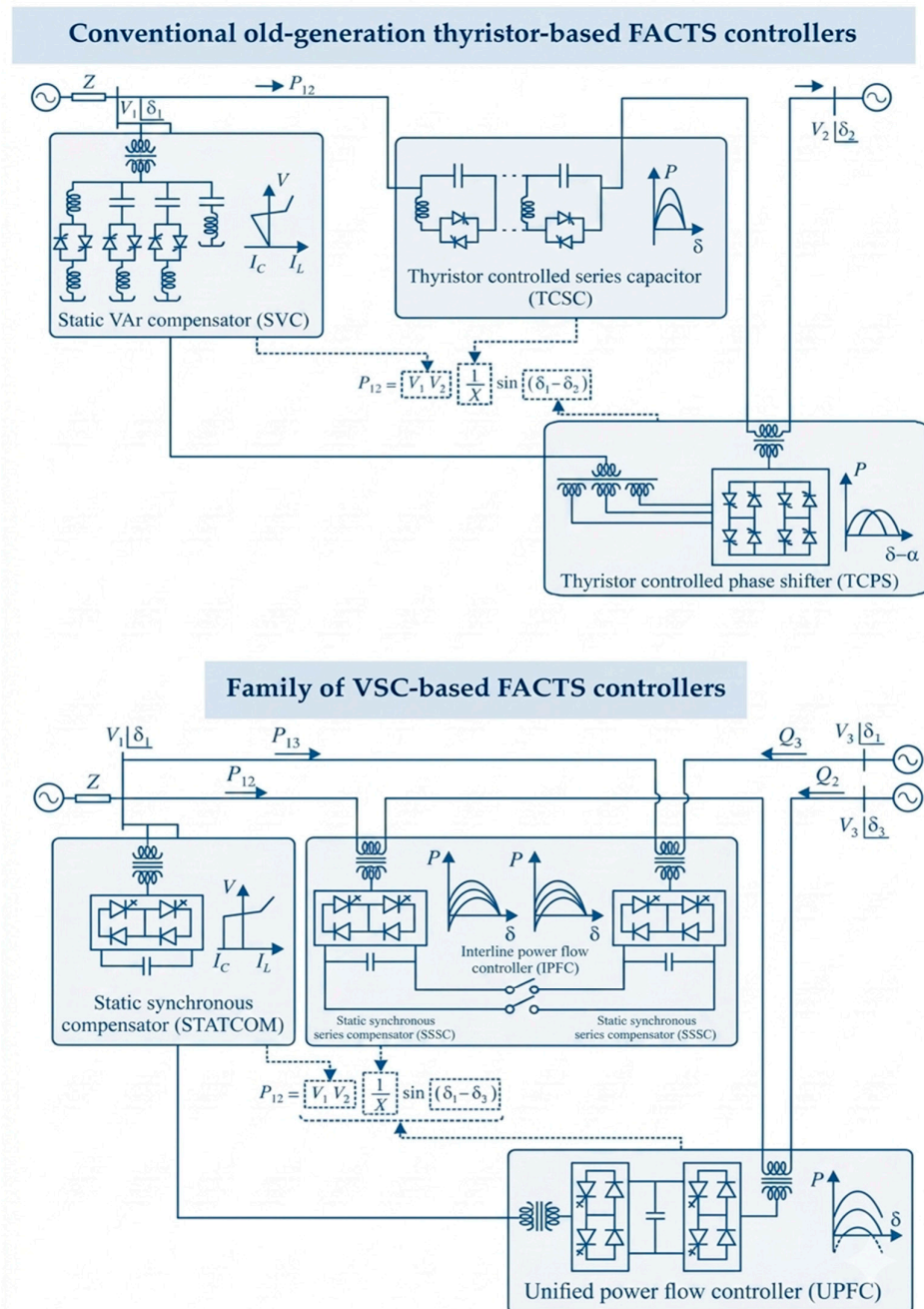


Figure 9. The comprehensive hierarchical diagram of FACTS devices [48].

4.2. Types of FACTS Devices

Various FACTS devices [53] can be synchronized with OLTC to provide fast, accurate feedback on voltage fluctuations and increase reactive power transfer. The most commonly used types with the OLTC include:

- **Static Synchronous Compensator (STATCOM) and Distribution STATCOM (D-STATCOM):** These are voltage source converters that provide reactive power compensation for the purpose of maintaining voltage stability. They can inject or absorb reactive power quickly based on system requirements, thereby helping mitigate voltage oscillations [54–56].

- Static VAR Compensator (SVC): SVCs consist of thyristor-switched capacitors and thyristor-controlled reactors that provide dynamic reactive power compensation. SVCs are effective in maintaining voltage stability and improving power factor in distribution networks [57].
- Unified Power Flow Controller (UPFC): UPFC is a unit that integrates the functions of a static compensator and a phase shifter and thus can control both active and reactive power flow over transmission lines. UPFCs have the ability to provide full power flow control to improve the reliability and stability of the system [58].
- D-STATCOM and STATCOM stabilize the system with a DC power supply to provide an output voltage that is in-phase with the network voltage through a Voltage Source Converter (VSC), which provides reactive power injection and phase-angle regulation [59]. Figure 10 illustrates the characteristic V-I curve of a D-STATCOM, illustrating its operating regions and voltage regulation capabilities.

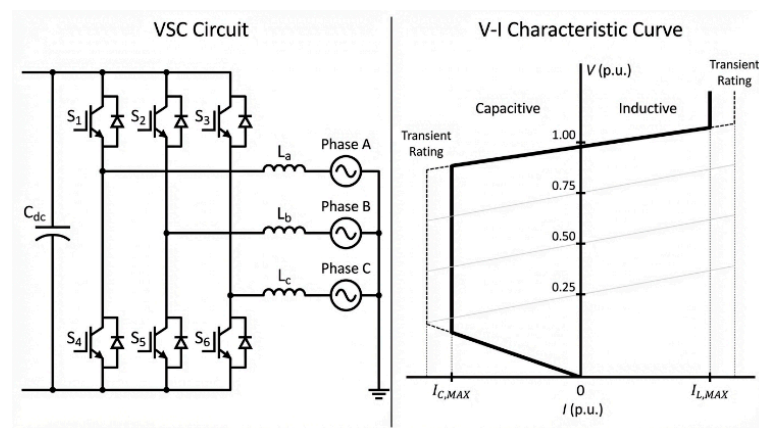


Figure 10. Power circuit topology with typical V-I characteristic of D-STATCOM [54].

SVCs are dynamic components of modern power supply systems that dynamically regulate voltage through reactive power compensation. This is achieved by injecting or absorbing reactive power in response to instantaneous voltage fluctuations, providing temporary network stability without modifying the transformer's tap ratio, unlike an OLTC. SVCs typically include fixed reactors (thyristor-controlled reactors) during high-voltage reactive power absorption and fixed capacitors (thyristor-switched capacitors) at low voltage to provide reactive power, all controlled by a master unit that samples network voltage and adjusts SVC response based on operational requirements [60].

4.3. Coordination of OLTC and FACTS Devices

The coordination between FACTS devices and OLTC is considered a satisfactory solution to improve voltage stability and the operation of electrical networks. The coordinated control strategy between OLTC and FACTS devices is based on the principle of role distribution to achieve voltage stability and improve power quality in electrical distribution networks.

Figure 11 illustrates the operating range of every controller in a proposed voltage regulation system at the regulated point. The approach prescribes allowable voltage operating limits for optimal device operation. OLTC is allowed to operate within a set range to ensure long-term voltage stability, while the FACTS device (D-STATCOM) accommodates sudden changes within these limits. As an example, refer to [61]; the dead band in Figure 11 indicates that no action is required within the allowable voltage range ($\pm 3\%$) i.e., if the bus voltage is within the permissible range, the OLTC will not intervene. Adjust the feeder's ending point voltage when the regulated point voltage exceeds the allowable

range, using the forced OLTC mechanism limitation ($\pm 2.5\%$) over the permitted range. Figure 2 also illustrates how D-STATCOM uses reactive power compensation to bring the voltage of this bus within the allowed range for OLTC action when it exceeds the prescribed range. A D-STATCOM is used when OLTC action reaches its limits (105.5 and 94.5 for the upper and lower limits, respectively) and cannot function. In this case, OLTC handles $\pm 2.5\%$ of the voltage violations, while D-STATCOM compensates for the remainder. D-STATCOM quickly, with a fast response, restores voltage to the upper or lower limits of the OLTC action (105.5 and 94.5, respectively) during high-voltage violations. By using D-STATCOM, OLTC can efficiently handle voltage violations within the set range.

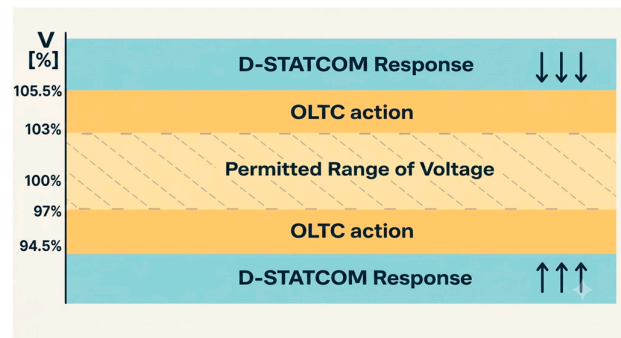


Figure 11. Working ranges of each controller in the proposed voltage regulation scheme at the regulated point [61].

To maintain the distribution system voltage within the permissible operating limits under varying photovoltaic (PV) penetration levels, a coordinated control strategy between the On-Load Tap Changer (OLTC) and the Distribution Static Synchronous Compensator (DSTATCOM) is employed [62]. Equation (1) shows the effect of PV and DSTATCOM on the voltage deviation.

$$\Delta V \approx \frac{R(P_L - P_{PV}) + X(Q_L - Q_{PV} - Q_{DSTATCOM})}{V_{bus-old}} \quad (1)$$

where ΔV is the voltage deviation at the bus, R is the feeder resistance, X is the feeder reactance, P_L is the load active power, Q_L is the load reactive power, P_{PV} is the photovoltaic active power generation, Q_{PV} = Photovoltaic reactive power generation, $Q_{DSTATCOM}$ is the reactive power injected (or absorbed) by the DSTATCOM, and $V_{bus-old}$ is the old bus voltage magnitude before change.

The OLTC regulates the voltage by adjusting the transformer tap position according to Equation (2), modified to Equation (3):

$$V_{bus-new} = V_{source}(1 + n\Delta T) - \Delta V \quad (2)$$

$$V_{bus-new} = V_{source}(1 + n\Delta T) - \frac{R(P_L - P_{PV}) + X(Q_L - Q_{PV} - Q_{DSTATCOM})}{V_{bus-old}} \quad (3)$$

where V_{source} is the source voltage, $V_{bus-new}$ is the controlled bus voltage, n denotes the tap position, and ΔT is the tap step size.

The DSTATCOM provides fast dynamic voltage support through reactive power injection or absorption. The reactive power output is controlled according to the voltage deviation at the point of common coupling (PCC). The coordination objective is to minimize voltage deviations while reducing unnecessary OLTC tap operations. Therefore, the optimization problem constraints are: OLTC operates for slow change, minimum tapping operation, $V_{min} \leq V_i \leq V_{max}$, and $Q_{min} \leq Q_{DSTATCOM} \leq Q_{max}$.

In the proposed coordination scheme, the DSTATCOM serves as the primary fast-response voltage regulator to compensate for short-term voltage fluctuations caused by

PV intermittency, whereas the OLTC provides slower voltage correction for sustained voltage deviations. This coordinated operation improves voltage profile regulation, enhances system stability, and reduces mechanical wear of the OLTC.

The coordination strategy is based on achieving a balance between the two services and agencies:

- Rapid Response vs. Progressive Control: FACTS devices like D-STATCOM or SVC are used as rapid-response devices to counter transient voltage oscillations, while OLTC provides long-term voltage control to maintain grid stability.
- Division of role: under regular situations, OLTC is utilized to execute gradual voltage adjustments based on load variables. Instantaneous processing is implemented through FACTS devices when the threshold levels are violated.
- The interdependence of the two devices on one another is dependent on smart coordination to deliver better network performance, and this can be achieved through:
 1. Operation in sequence: FACTS equipment is operated first to adjust voltage quickly, and in the event of non-viability of full correction, OLTC is excited.
 2. Control by sensors: sensors are employed to sense voltage at critical locations of the network to send control signals to the respective device.

Coordination between these devices assists in achieving a series of operational benefits, including improved voltage stability through maintenance of voltage within reasonable ranges and reduction of sudden changes, reduced operational losses by optimizing the flow of reactive power in the network, improved network reliability through enhanced operational capability and faster response to load fluctuations, and increased equipment life through reduced frequent switching in the OLTC, which reduces mechanical wear.

5. Literature Review

The literature review section provides an extensive overview of challenges in OLTC operation with high PV penetration and discusses coordination strategies with FACTS devices. The section is arranged chronologically, from the earliest to the most recent studies in each subsection, with particular emphasis on the most recent research findings from 2023 to 2026. This work selection process involved screening titles and abstracts, followed by full-text assessment. Duplicate and irrelevant studies were removed. The selection process followed PRISMA guidelines. A formal risk-of-bias assessment was not conducted; however, only peer-reviewed, high-quality studies were included to ensure reliability. Figure 12 presents the studies taken from databases, based on a focused, step-by-step classification following the literature identification and selection stages and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [63].

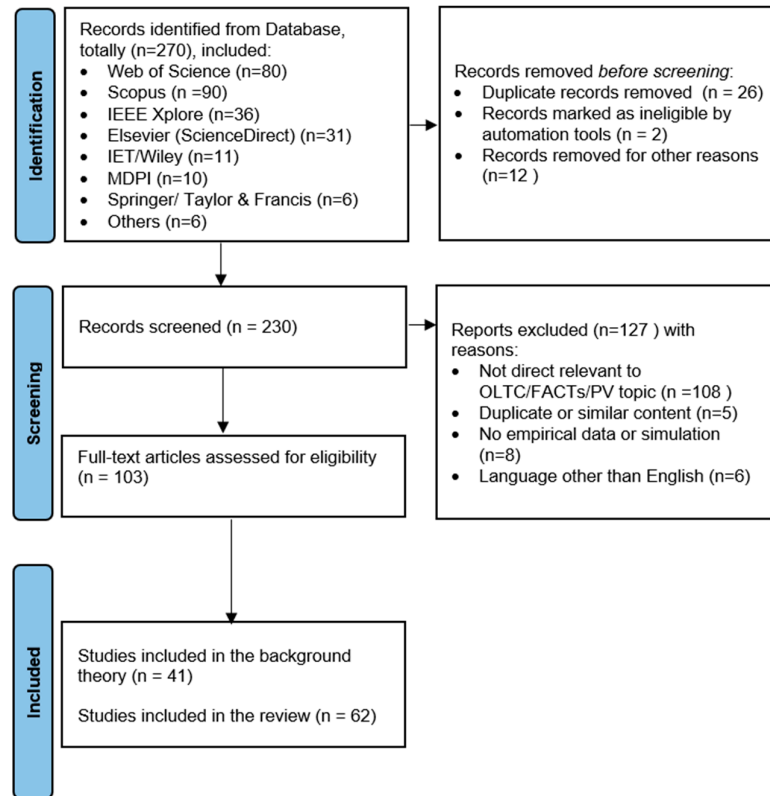


Figure 12. Identification of studies via databases using PRISMA.

5.1. Challenges of Operating OLTC with High PV Penetration

Impact on tap-changing frequency: Initial studies on OLTC performance in interconnected PV networks laid the foundation for understanding the relationship between PV penetration and tap-changing frequency. Yan et al. (2014) [64] conducted extensive simulations using Queensland, Australia's annual data to indicate that with 50% PV penetration; tap changes increased by almost 84% compared to no PV system simulations. The main limitations of this study were that it used a single Australian LV network, that it did not evaluate the economic viability of DSTATCOMs, and that the MATLAB R2021b model may not fully capture three-phase unbalance effects; it also lacks specific quantitative metrics (e.g., tap changes/day per penetration level). Lau et al. (2016) [29] extended these findings further by providing evidence of a near-linear relationship between tap changes and up to 50% PV penetration, after which the rate became exponential. Their simulation of an IEEE 33-bus distribution system found that tap changes at 50% PV penetration were 38% higher than at 0% penetration and doubled at 90% penetration. This study focuses only on cloud-passing transients; it ignores seasonal and diurnal variation; the Malaysian context limits generalizability. It also characterizes transient responses but does not quantify cumulative daily or annual tap change increases for wear assessment. According to this, Wanik et al. (2017) [4] certified that OLTC performance is significantly affected by weather, such that 50% more tap operations take place on cloudy days than on clear days. This work provides minimal quantitative data under different PV penetration scenarios. Also, a study by Gan et al. (2017) [65] showed that a great change in the solar day could increase the tap changes by 600% as compared to a clear sky day in the Malaysian distribution grid. It does not provide a clear before/after quantitative comparison of tap-changing frequency with vs. without PV. Sreckovic et al. (2019) [2] confirmed that OLTC stress increases non-linearly with increasing PV penetration, particularly in the summer when

solar irradiance is highest. It treats OLTC operations as a control variable—does not quantify frequency increases.

Voltage regulation problems: Some initial research by Jafari et al. (2022) [8] identified voltage rise due to reverse power flow as a primary barrier to PV expansion in distribution grids. Their research demonstrated that conventional voltage regulation schemes are ineffective at higher PV penetration levels. Ciocia et al. (2020) [32] experimented with voltage regulation performance in high-penetration LV networks using OLTC transformers. According to their results, conventional control methods deteriorate at more than 30 percent of PV penetration. They suggested that the acceptable voltage band should be divided into zones, with separate control measures for each zone to enhance performance. Li et al. (2020) [66] coordinate fast-acting PV smart inverters with slow mechanical on-load tap changers (OLTCs) to regulate voltage in unbalanced distribution networks. To achieve this, it employs a novel linearization method that converts complex, nonlinear power-flow equations into an efficient Mixed-Integer Linear Programming formulation. This convex approach significantly reduces computational overhead and guarantees mathematical convergence while accommodating errors in load and solar forecasting. When tested on IEEE and California utility feeders, the method successfully eliminates over-voltage and phase imbalances while preventing unnecessary, wear-inducing OLTC tap operations. Custodio et al. (2020) [67] used Q-learning to control OLTC transformers in distribution networks that are mostly controlled by PV sources. A three-phase simulation model of the MV/LV Brazilian distribution system has shown that traditional OLTC control systems struggle to handle high PV penetration. Dutta et al. (2022) [68] introduces a centralized, three-stage model predictive control (MPC) framework that simultaneously manages electric vehicle (EV) charging and traditional Volt/VAR distribution devices by blending centralized coordination with local smart-inverter rules; the scheme successfully prevents grid voltage violations while guaranteeing that EVs reach their target state-of-charge before departure. Alabri and Jayaweera (2022) [69] present an optimal coordination scheme that integrates on-load tap changers, EV phase connections, D-STATCOMs, and PV inverters to mitigate voltage unbalance and minimize power losses. It utilizes an Advanced and Hybrid Particle Swarm Optimization (AHP SO) algorithm to compress the control variable search space and drastically accelerate convergence. Simulated test cases validate that this coordinated approach maintains voltage levels within strict statutory limits while efficiently handling high renewable energy and electric vehicle charging uncertainties. Chen et al. (2022) [70] present an optimization model designed to address the grid losses and voltage deviations caused by the rapid expansion of large-scale electric vehicle (EV) charging and distributed generation. The framework coordinates various active distribution network assets, including energy storage, on-load tap changers, capacitor banks, static Var compensators, and inverter units. By applying second-order cone programming (SOCP), the non-convex power flow equations are converted into a convex formulation that guarantees mathematical convergence and drastically accelerates solving speeds. In 2023, Wang et al. [71] presented a radical framework of soft coordination that was specially designed to tackle the voltage control problem in high PV penetration. Their approach applies decision-making commands on inverters alone while keeping OLTC's operating rules intact, and system voltage is indirectly regulated through inverters' reactive power control.

OLTC and PV system operational conflicts: Bakhshideh Zad et al. (2013) [55] noted that in radial distribution networks with distributed generation, traditional voltage control methods become less effective due to changes in the direction of power flow. Their research showed that line drop compensation (LDC), a common OLTC control method, cannot accurately estimate voltage profiles when significant PV generation reverses the power flow direction. Ku et al. (2019) [72] provided the conditions under which PV

inverter's reactive power control and OLTC operations would interact to cancel their effects and hence induce voltage instability. Under poor coordination, such control systems, according to their research, would cancel each other out. Racewicz et al. (2020) [15] noted that excessive penetration of PV can lead to tap changer saturation, rendering OLTC incapable of controlling voltages within the regulation range. This condition becomes worse with increased PV penetration and may require additional voltage regulation devices. The recent research of Tolulope et al. (2025) [73] applies machine learning techniques to predict conflicts in the operation of PV and OLTC devices, enabling control adjustments in advance that reduce the need for tap operations compared to conventional methods.

Fluctuations of PV power and their consequences: Alam et al. (2014) [74] described how cloud-induced fluctuations in PV power lead to high-frequency voltage oscillations that put a strain on traditional OLTC control systems that are suited for comparatively sluggish load fluctuations. Alkahdely et al. (2023) [75] although OLTC can readily handle a small disturbance, its ability to restore the voltage level during a large disturbance depends on its ratings and setting values. When the OLTC transformer performs reverse action, the voltage system may collapse if it is unable to recover the voltage value in a short amount of time.

Recent work by Dabaghi-Zarandi et al. (2023) [76] relates to the design of condition-monitoring OLTC systems for use in highly variable operating conditions, where vibro-acoustic signal analysis is employed to detect the initial signs of mechanical stress caused by multiple tap changes due to PV variance.

5.2. Voltage Regulation Measures in PV-Highly Infused Networks

Voltage regulation starts with traditional methods. Weckx et al. (2014) [77] introduced a hybrid central and local active and reactive power control strategy for PV inverters. Their strategy considered both local voltage levels and system requirements, allowing up to 75% PV penetration without compromising statutory voltage levels. Dutta et al. (2020) [78] demonstrate that one of the biggest problems with distribution networks that are linked with renewable energy sources is voltage management. To ensure that the voltage magnitudes at various points in the distribution networks are suitable, this paper proposes a control methodology to coordinate distribution static synchronous compensator (D-STATCOM), active power curtailment, and OLTC. Gush and Kim (2024) [79] compared traditional voltage-control approaches and reported a lower efficiency with PV penetration greater than 30%. Their study discovered the causes that line drop compensation failed to forecast the voltage profiles in instances of high PV generation. Silva-Quinonez et al. (2025) [80] proposed an improved reactive power control method that enables the synchronous operation of parallel grid-connected photovoltaic (PV) plants and an on-load tap changer (OLTC) transformer. The proposed Energy Management System (EMS) applies an improved Teaching-Learning-Based Optimization algorithm in combining OLTC tap management and inverter-level active and reactive power dispatch. The EMS minimizes operational costs without compromising voltage stability or electrical or mechanical limits. It has faster convergence and better resistive capability than traditional algorithms, leading to more reliable operations under varying irradiance and load conditions. This provides an effective remedy to dynamic energy control in large-scale PV systems to improve grid stability and uptake of renewable energy.

5.3. Active Power Curtailment Strategies

El Moursi et al. (2011) [28] suggested a method of voltage control for wind farms using STATCOM and an OLTC transformer. Active power curtailment was the last resort applied if OLTC and reactive power control were unable to keep voltages within limits. Ciocia et al. (2020) [32] contrasted the benefits of running OLTC in LV networks with high

PV penetration. Based on their results, coordinated OLTC control and active power curtailment could maintain voltages even at 90% PV penetration, albeit with some loss of energy output. Jafari et al. (2022) [8] contrasted different active power curtailment techniques and their effectiveness in managing voltage rise problems due to the reverse power flow. They found that despite being effective, large-scale curtailment seriously erodes the economic benefits of PV systems.

5.4. Coordination Between OLTC and FACTS Devices

1. Benefits of coordination: Early research by Bakhshideh Zad et al. (2013) [55] explored D-STATCOM- and OLTC-coordinated control of voltage regulation in radial distribution networks with DG units. They concluded that coordinated control precisely regulated voltage profiles within legal limits while minimizing tap operations. Yan et al. (2014) [64] estimated coordinated OLTC and D-STATCOM control benefits. From their studies, proper D-STATCOM sizing could potentially save OLTC operation by 60% and significantly enhance the lifespan of the operating transformer. Wanik et al. (2017) [4] carried out OLTC coordination studies based on PV system reactive power capabilities. Uncoordinated injection of reactive power resulted in 26% increased OLTC operation, but coordinated control reduced tap operations by approximately 15%. A modified D-STATCOM control scheme was proposed by Singh et al. (2023) [62]; they found that the best strategy for voltage control and power loss reduction is a critical task for distribution network operators, specifically designed to be coordinated with and without OLTC for voltage control. Their strategy uses processed line-voltage feedback, which allows them to provide less compensation output in the steady-state circuit while maintaining high compensation capacity in the event of contingencies.
2. STATCOM; El Moursi et al. (2011) [28] investigated a coordinated voltage control strategy using a substation STATCOM and an OLTC transformer. Their methodology improved voltage stability under all operating conditions and reduced OLTC operations by up to 45%. Ciocia et al. (2020) [32] compared centralized voltage regulation employing OLTC with distributed voltage control of PV inverters acting as miniature STATCOM units. Their simulation revealed that this hybrid solution could enable up to 80% penetration of PVs while maintaining the voltages in statutory limits.
3. D-STATCOM; Bakhshideh Zad et al. (2013) [55] proposed a coordinated control method of OLTC and D-STATCOM, which successfully dampened voltage oscillations in DG-interfaced radial distribution systems. Their control technique utilized an infrastructure-independent signaling technique. Yan et al. (2014) [64] analyzed D-STATCOM sizing to coordinate control with the OLTC. They also came to the conclusion that a relatively small DSTATCOM (15 kVAr three-phase) is capable of effectively limiting the activities of OLTC and also enhances the voltage profiles. Dutta et al. (2020) [78] proposed a coordinated voltage control strategy using OLTC and D-STATCOM through model predictive control. The scheme was found to be stable under various load and generation conditions. Their simulations showed that model predictive control outperformed traditional PI controllers, especially with sudden irradiance changes. Mahmoud et al. (2021) [81] presented an Optimal Voltage Regulation Scheme (OVRs) that utilizes metaheuristic optimization to coordinate the reactive power capabilities of photovoltaic (PV) inverters and D-STATCOMs alongside conventional step-voltage regulators and on-load tap changers. To efficiently manage the grid structure, a specialized data structure algorithm is introduced to partition the active distribution system into layered zones. The regulatory framework operates across three distinct levels—ranging from rapid, local reactive power injection to

decentralized, upstream parental zone management—effectively preventing voltage violations under highly fluctuating solar irradiance profiles. Rohouma et al. (2022) [82] effectively mitigated rapid, solar-induced voltage fluctuations and power quality issues caused by non-linear loads by evaluating a matrix converter-based, capacitorless D-STATCOM that replaces short-lived electrolytic capacitors with inductors, thereby extending the device's service life in low-voltage networks. Using a comprehensive Model Predictive Control (MPC) strategy that accounts for all converter-grid interactions, the system delivers fast, continuously adjustable reactive power compensation. Simulation results validate this approach. The latest research by Singh et al. (2023) [62] indicates that modern D-STATCOM units with the latest semiconductor technology can respond to voltage changes within a very short time (milliseconds), thereby enabling almost flawless coordination with OLTC to provide stable voltage profiles even under highly variable PV generation conditions.

4. Static VAR Compensator (SVC); Daratha et al. (2014) [83] proposed a two-step method for addressing the problem of determining the optimal voltage control in an imbalanced radial distribution system with photovoltaic (PV) power, relying on OLTC and SVC to manage voltage. Pezeshki et al. (2018) [84] compared SVC and D-STATCOM performance coordinated with OLTC. The two devices effectively reduced OLTC operations, but D-STATCOM presented superior performance under sudden voltage fluctuations characteristic of PV systems. Gush and Kim (2024) [79] proposed a powerful local coordinating control system of PV smart inverters with SVC and OLTC. Their hierarchical control system prioritized fast SVC during transient voltage violations and left OLTC for steady-state control. Recent research by Licari et al. (2025) [85] presented a comprehensive historical review of many strategies for the use of renewable energy sources (RES) and electric vehicles (EVs), and it is harder to control voltage in low-voltage distribution networks. They are also not easily systematically grouped and assessed, relating grid deployment to control strategies. The paper reviews numerous research articles to identify the factors of implementation, economic factors, and the relevance of each of the approaches. The paper provides a prospective assessment of hybrid systems, inexpensive realizations, predictive analytics, and adaptive control. The findings are expected to support the development of sustainable energy system voltage solutions because they will serve as a comprehensive resource to both researchers and practitioners.

5.5. Advanced Control Algorithms for OLTC and FACTS Coordination

1. Model Predictive Control (MPC); Guo et al. (2019) [86] introduced an MPC-based coordinated voltage control strategy for distribution networks integrated with distributed generations and energy storage systems. Their strategy considered not only current control actions but also their future consequences. A recent study by Dutta et al. (2020) [78] employed MPC for coordinated voltage control of an active distribution network using OLTC and D-STATCOM. Discrete tap change and continuous reactive power control issues were resolved, enabling effective voltage control with low control effort. Yunyun et al. (2020) [87] proposed a method to control voltage using robust model predictive control to optimally coordinate the reactive power outputs of RESs, energy storage systems, and on-load tap changers (OLTCs). Given the prediction error of the RES active outputs, the voltage regulation issue is formulated as a multi-time-period robust optimization model to determine the optimal control actions over the prediction horizon. Raja et al. (2021) [88] introduce a real-time, adaptive online control scheme that eliminates computational delays in Model Predictive Control (MPC) during power system emergency voltage management. By updating nominal offline controls with real-time grid measurements and using Deep Neural

Networks (DNNs) to estimate sensitivities quickly, the method bypasses intensive online optimization. Validated on IEEE test systems, this coordinated approach successfully orchestrates var compensators, load shedding, and tap changers while accelerating computation speed by a factor of 20. Alharbi et al. (2025) [89] present a review of the latest advancements in MPC for grid-connected power inverters in renewable energy applications, highlighting MPC's use in renewable energy systems and demonstrating its ability to optimize power extraction, facilitate maximum power point tracking, and handle multiple energy sources.

2. Artificial Intelligence and Machine Learning Strategies; Sumathi and Bansilal (2015) [15] developed an artificial neural network-based coordinated control for STATCOM, generator excitation, and tap-changing transformer. Their approach mapped system states to optimal control actions in order to achieve effective voltage regulation. Liu et al. (2019) [90] proposed a coordinated control technique for an OLTC and an inverter. The fuzzy controller is used to ensure that the OLTC and the power allocation optimization (PAO) Module work together. The PAO Module ensures that all inverters on a feeder maintain the feeder's terminal voltage within the authorized range while maximizing the inverters' active power output. Fuzzy logic uses state estimation to obtain voltage data from multiple feeder terminals. It then decides whether to maintain stable voltage by adjusting the OLTC or PAOs. So, the efficiency of PV generators may be considerably enhanced. Custodio et al. (2020) [67] applied Q-learning to the OLTC control of PV-rich distribution networks. Their control scheme learned optimal control policies from experience rather than relying on complex system models. Mahdavi et al. (2021) [91] employed predictive cooperative voltage control of highly penetrated PV networks. They combined machine learning prediction with cooperative control techniques. Voltage changes caused by photovoltaic distributed generators (PVDGs) put the distribution system's stability at risk. Separate types and sizes of distribution generators will cause the voltage fluctuation patterns in different feeders to differ in a network with more than one feeder. The recent contribution of Song (2025) [92] highlights the improvement of MPC systems through the use of artificial intelligence, making predictions more accurate and enabling real-time optimization of complex processes. His contribution presents practical uses of AI-based MPC in power systems, where in particular, coordinated OLTC with renewable resources offers certain benefits.
3. Decentralized and Distributed Control Techniques; Valverde and Van Cutsem (2013) [93] took a step toward breaking down the control problem into local subproblems, with limited information sharing among them. For smart distribution networks. Bakhshideh Zad et al. (2019) [61] suggested a signaling strategy for information exchange between PV systems and OLTC without any special communication channels. They applied reactive power differences to regulate the system's transmission state. Distributed model predictive control was used in the active distribution network voltage management. Jafari et al. (2022) [8] suggested a system of decentralized PV inverter and OLTC coordination by use of control. Their plan separated the admissible voltage authority into regions, and corrective measures were implemented without any communication framework. Wang et al. (2023) [71] suggested a distributed voltage control strategy with a consensus-based distributed information synchronization framework and a distributed MPC-based voltage control framework. Their plan allows individual DG units to exchange information with adjacent units only in close proximity and to coordinate the functions of the OLTC.
4. Multi-Agent Systems; Yang et al. (2012) [94] suggested a multi-agent reinforcement learning algorithm to achieve optimal reactive power dispatch. This method allowed autonomous actors to acquire good coordination policies via trial-and-error

interactions. Innovative research article, Tangi et al. (2025) [95] created a multi-agent scheme for voltage control in the active distribution network. It put continentally separate control devices on the agent so they would coordinate without centralization.

5.6. Earlier Case Study and Simulation Findings

1. OLTC performance in various scenarios of PV concurrent penetration; Yan et al. (2014) [64] conducted massive simulations depending on the factual information of Queensland, Australia. They found a strong correlation between PV penetration and OLTC tap changes, with near-load automatic tap changers undergoing many additional operations as PV penetration rose. The IEEE 33-bus distribution system was simulated by Iqbal et al. (2018) [96] under different levels of PV penetration and D-STATCOM installations. Their findings verified the connection between PV penetration and OLTC operation, indicating the efficiency of even small-scale DSTATCOM installations. A comprehensive (2023) field experiment in Germany [19] captured OLTC operating performance in a distribution network when PV penetration increased from 30% to 70% over two years. The experiment confirmed simulation results, which show that tap operations increased by 92% and the number of transformer maintenance events doubled over the course of the experiment.
2. Coordinated control performance evaluation; Bakhshideh Zad et al. (2013) [55] compared D-STATCOM-only, OLTC-only, and coordinated control schemes for voltage regulation of a 50% PV-penetrated radial distribution feeder. The coordinated control reduced OLTC operations by 68% without compromising improved voltage regulation. The growing use of small-scale photovoltaic (PV) systems in the UK is projected to cause significant technical problems due to voltage growth in low-voltage networks. Navarro-Espinosa and Ochoa (2015) [97] examined the techno-economic advantages of employing on-load tap changers (OLTC)-equipped transformers to manage substantial photovoltaic (PV) integration. There are two ways to control voltage: locally (at the busbar) and remotely (at the farthest point). Results are compared to standard network reinforcements. On an actual UK LV network, high-resolution profiles for residential load and PV systems are employed. The results reveal that the transformer with the OLTC enhances the network's hosting capacity. The remote strategy works better than the local one but only when penetration is high (70% or more). Finally, it is demonstrated that the reinforcement option is cheaper at lower penetration levels (up to 60%). Dutta et al. (2020) [78] compared model predictive control of OLTC with and without coordinating with D-STATCOM control on a 33-bus test system. Their coordinated controller reduced OLTC actions by 75% and voltage violations by 92% compared to uncoordinated control. Custodio et al. (2020) [67] compared Q-learning with traditional OLTC control on a Brazilian distribution grid. Q-learning cut voltage violations by 60%, and tap operations remained close.
3. Effect of weather conditions on OLTC operation; Cloaked with a subtle analysis of the weather effects, Yan et al. (2014) [64] presented that partly cloudy days led to a maximum of three times more changes of taps than either completely sunny or cloudy days. Lau et al. (2016) [29] modeled sunny and cloudy day PV profiles. Their findings indicated that the OLTC cycles were 8–26% higher under cloudy conditions than under sunny conditions, meaning that PV variability causes OLTC stress. Disfani et al. (2016) [98] used high-resolution weather prediction to assess OLTC activities according to the patterns of the forecasted cloud cover. Their model reduced unnecessary tap changes by 56% by adjusting voltage setpoints in advance to account for anticipated PV output fluctuations. Figure 13 shows the daily operation of the OLTC under varying weather and PV correlation.

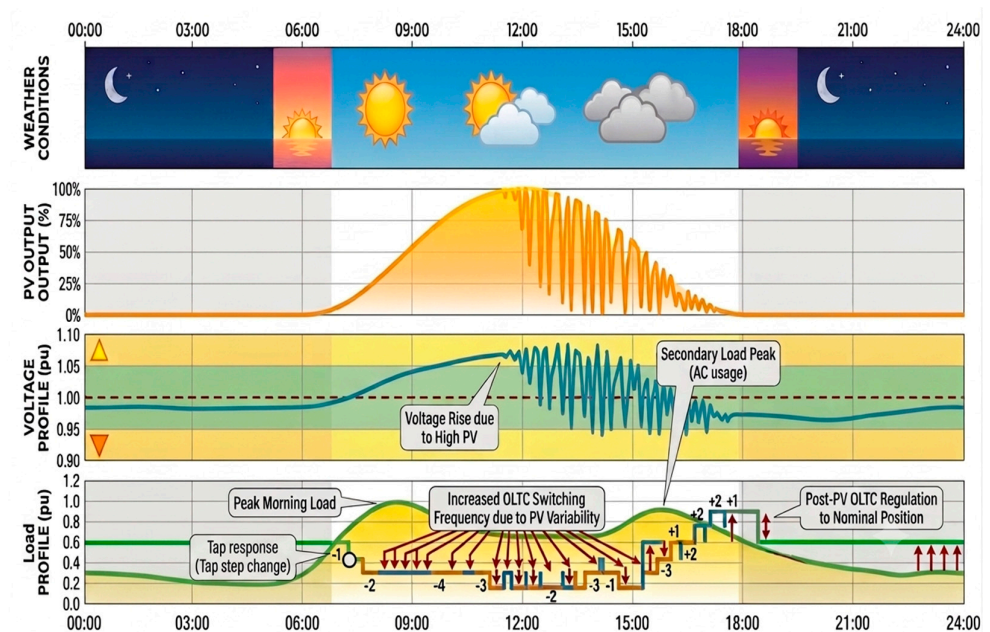


Figure 13. OLTC daily operation with weather and PV correlation.

4. Economic analysis of OLTC and FACTS coordination: Yan et al. (2014) [64] conducted a cost-benefit analysis of D-STATCOM for restricting OLTC operation. They found a 15 kVAr three-phase D-STATCOM costing approximately \$8000 AUD could reduce OLTC operations by 60%, and potentially add several years to transformer life. From an economic perspective, the deployment of dedicated D-STATCOM devices can improve voltage regulation performance and reduce OLTC operations; however, it introduces additional capital and maintenance costs. In contrast, modern PV smart inverters can provide reactive power support and voltage regulation using existing converter infrastructure, potentially reducing the need for additional compensation devices. Nevertheless, inverter-based support is constrained by inverter ratings, operating conditions, and grid-code requirements, whereas D-STATCOM devices offer dedicated and more flexible reactive power compensation. Therefore, the economic viability of D-STATCOM installation versus smart inverter utilization depends on network characteristics, PV penetration levels, and operational objectives. A comprehensive techno-economic comparison of these alternatives remains an important research gap and should be investigated in future studies. Orangi et al. (2024) [99] compared energy storage systems in conjunction. They found that energy storage technologies were not yet cost-effective enough for widespread application, with Li-ion batteries costing less than 120 \$/kWh. Figure 14 shows the price surveys from BloombergNEF [100].

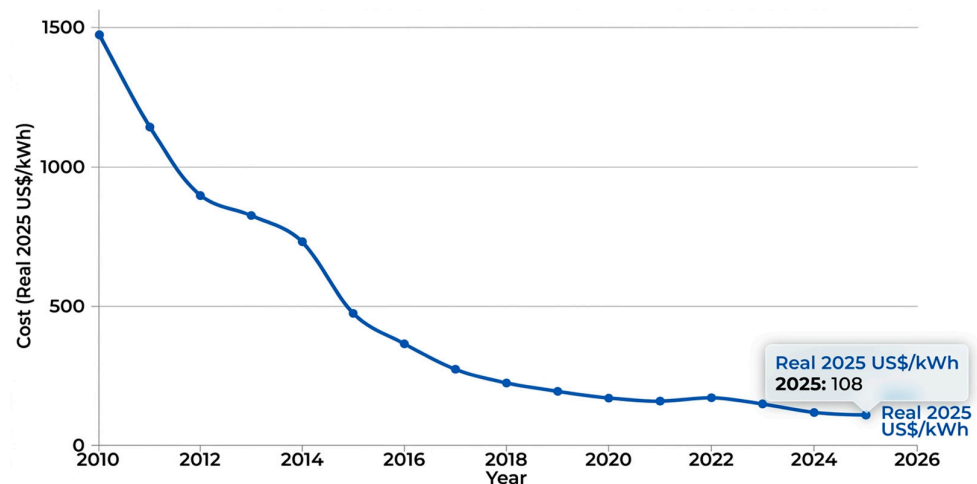


Figure 14. Li-ion battery price surveys depend on BloombergNEF.

Ciocia et al. (2020) [32] compared the costs of different voltage control strategies in high PV-penetrated LV networks. Coordinated operation of available assets (OLTC and PV inverters) was the most cost-effective.

5.7. Future Research Directions

1. Integration with energy storage systems: Liu et al. (2012) [31] described how coordinated control with energy storage systems was able to handle short-term deviations and long-term energy balancing. Hashemi et al. (2013) [101] debated whether the energy storage requirements could be reduced through effective reactive power management. Coordinated operation of OLTC, FACTS devices, and energy storage reduced the storage capacity requirement to a minimum. Tewari et al. (2021) [102] proposed a coordinated control strategy for OLTC and energy storage for voltage regulation in high-PV-penetration networks. Their method addressed both short-term and diurnal changes. Recent research by Tewari et al. (2021) [102] indicates considerable improvement in OLTC coordination with battery energy storage systems (BESS) to justify reasonable voltage magnitudes in distribution feeders. Their optimization approach reduces voltage deviations while requiring fewer tap changes and extending battery life. Hou et al. introduced an enhanced hierarchical Volt/VAr and Volt/Watt control strategy that coordinates active distribution networks integrated with flexible soft open points (SOPs). By optimizing slow-acting legacy grid equipment alongside fast-acting SOPs and inverters across different timescales, the framework successfully mitigates severe voltage deviations caused by fluctuations in renewable energy output. Tested through numerical simulations, this coordinated system minimizes power losses and improves grid voltage profiles while significantly enhancing the network's overall renewable energy hosting capacity [103].
2. Advanced communication and coordination schemes; Bakhshideh Zad et al. (2013) [55] proposed improved coordination possibilities using improved device communication with a focus on robust performance in the event of communication faults. Chakraborty et al. (2016) [104] proposed a cybersecure communication infrastructure for coordinated voltage control in smart distribution networks. Their proposal addressed the increasingly important topic of cybersecurity in grid control systems, providing secure communication infrastructures for coordinated control. Franco et al. (2018) [105] proposed peer-to-peer communication protocols for distributed voltage control of active distribution networks. They have good performance

characteristics and low communication requirements; hence, they are viable for installation in distribution networks.

6. Overview of Research

Integration of photovoltaic systems with distribution networks presents complicated voltage regulation problems and operation of OLTC transformers. This section describes the main findings of this study and establishes the trends and the lack of insights in the area. Semi-research findings consistently suggest that the degree of PV penetration is strongly correlated with increased tap changer operations. Various studies indicate that the tap changes are almost linear at lower levels of PV penetration, but at 50 percent, the change becomes exponential. Such a way of operation leads to excessive mechanical wear and tear, high maintenance, and shorter transformer life. This is also worsened by climatic conditions, with studies indicating that stochastically intermittent irradiance during cloudy days is known to contribute 50–200% increases in tap operations compared to the constant profiles of output during sunny days.

There is generally agreement in the literature that the typical approaches to conventional voltage regulation are limited in PV-dominant networks. Traditional line drop compensation methods deteriorate as the PV penetration increases, with a general effect of being completely ineffective once the penetration reaches 50–60 percent or more. It is a common consensus that networks require more sophisticated voltage regulation methods above 30% PV penetration to maintain statutory voltage limits and mitigate stress on voltage regulation equipment.

Reactive power control is the predominant study methodology for voltage control in PV-dominated networks. As most researchers concur that reactive power compensation could greatly alleviate the voltage rise issues, there has been disagreement over optimal control policies. Some of the research works advocate centralized control techniques to achieve optimal system gain, while other research works favor distributed control approaches that are communication-efficient and lead to improved robustness. The dispute has even extended to how the reactive power assignments are allocated, with debate about whether or not control should target equity between PV systems or systemwide efficiency.

Coordinating between OLTC devices and FACTS is a novel area of investigation with more convergence toward its merits. Tests inevitably reveal coordinated use resulting in superior voltage regulation at less tap movement compared to each for voltage regulation of PV-dominated networks. These methods consistently outperform conventional control methods in simulation studies, particularly for highly variable PV networks. The issue of implementation challenges is not well-expressed, e.g., calculation requirements, resistance to measurement error, and performance degradation due to the loss of communication.

The sizes of FACTS devices realistically significantly reduce the tolerable voltage levels for operations in the OLTC. The use of advanced control, especially model predictive control (MPC) and machine learning, is highly promising. The literature is mixed in its approach to economic considerations. Many studies have shown that there are technical differences among the suggested coordination strategies, with methodologies ranging from basic (rule-based) to more complex MPC. The machine is working independently. There are enormous disparities. Research has discovered that, when compared to coordination of OLTC and FACTS, there are fewer studies that represent aggregate economic evaluation. Cost-benefit analysis conducted so far indicates that coordination strategies may prove cost-effective, especially for enhancing the lifespan of the OLTC transformer. Nevertheless, further studies are needed to evaluate these advantages across various network topologies and regulatory systems.

The research with huge potential value is the integration into energy storage systems. Early findings suggest that integrated regulation of OLTC, FACTS apparatus, and energy

storage is beneficial for both short- and long-term energy balancing. The high cost of Energy Storage Systems (ESSs), however, is a major deterrent to their large-scale use, necessitating optimized sizing methods that reduce storage size while maintaining adequate performance.

Coordinated voltage regulation cases, consolidated with communication needs and cybersecurity considerations, have not been adequately brought to focus. Although most studies recommend making plans that incorporate real-time communication between devices, far fewer address communication latency, reliability, and cybersecurity threats. This is an important gap in the literature, especially regarding plans that propose to operate in critical infrastructure.

The literature portrays the gradual shift from device-oriented, human-based approaches to more holistic distribution network management. In more recent studies, voltage regulation is achieved by balancing multiple goals in larger optimization problems, including loss minimization, reliability, and equipment life maximization. The trend is toward greater awareness that voltage regulation cannot be effectively treated separately from the other functions of distribution network management.

In summary, as a contribution to the current review paper, to maintain perfect voltage regulation in a rich-PV power system with minimal OLTC tapping, needed to use DSTATCOM, smart PV inverters for real and reactive power injection control, and ESS. To reduce losses and overall costs, the optimal size and allocation were determined, along with optimal coordinated operation and control across all devices. Despite significant advancements in understanding and solving OLTC operation in PV-prevailing networks, several knowledge gaps remain. They include long-term reliability features of advanced OLTC operations, optimal coordination practices across varying network topologies, thorough economic studies, implementation challenges of advanced control algorithms, and interactions with larger distribution network management systems. Table 1 presents the focus areas, methods, devices, key parameters, techniques, controllers, key findings, and future work for most studies on OLTC operation and coordination with FACTS devices in PV-rich distribution networks (2014–2025).

Table 1. Survey on OLTC operation and coordination with FACTS devices in PV-rich distribution networks (2014–2025).

Ref. No.	Author Year	Focus Area	Methods Devices	Key Parameters	Techniques and Controllers	Key Findings	Future Works
[64]	Yan et al. 2014	Impact of PV fluctuation on OLTC and solution using D-STATCOM	D-STATCOM; OLTC; residential PV systems	Tap operations; voltage fluctuations; PV power variability	Coordinated control using D-STATCOM to reduce OLTC operations	D-STATCOM significantly reduces OLTC tap operations caused by PV fluctuations in residential distribution networks	Further study on optimal D-STATCOM sizing and placement strategies
[42]	Li et al. 2018	Optimal OLTC control to enable high solar penetrations	OLTC; forecasting-based tap optimization	Minimizing feeder voltage deviation from 1 p.u.; tap operation count, and PV forecast horizon	Optimal Tap Control (OTC) convex linearization with forecasted PV; secondary objective to limit TOs	OTC coordinates multiple OLTCs, enabling 67% more PV than conventional ATC while achieving comparable reductions in violations.	Balance OTC tap operations against equipment life and field scalability
[90]	Liu et al. 2019	Unbalance mitigation using phase-switching devices and SVC in LV networks	Phase-switching devices (PSDs); SVC	Phase unbalance; operational constraints; MINCP reformulated to MISOCP	Dispatch model of SVC and PSD decision-making solved via MISOCP reformulation	Combined PSD and SVC dispatch effectively mitigates imbalances in modified IEEE and Australian practical systems.	Real-time control and hardware tests for PSD actuation
[78]	Dutta et al. 2020	Coordinated voltage control in active distribution networks	D-STATCOM; OLTC; PV inverter; active power curtailment	Voltage magnitudes across the network; sudden slack-bus voltage increase scenarios	Model predictive control coordinating D-STATCOM, OLTC, PV curtailment	MPC-based coordination of the D-STATCOM and OLTC maintains acceptable voltages and compares the D-STATCOM's reactive	Investigate broader scenarios and real-time implementation

						support with that of the PV inverter.	
[66]	Li et al. 2020	Coordination of OLTC and smart inverters for unbalanced networks	PV smart inverters; OLTC	Minimize voltage deviations and tap operations; unbalance metrics	Multi-objective optimization with linearization and MILP for convexity and scalability	MILP coordination reduces voltage deviations, mitigates over-voltage and unbalance, and eliminates unnecessary tap operations.	Test with higher forecast errors and hardware-in-loop validation
[81]	Mahmoud et al. 2021	Optimal voltage regulation for PV-rich systems with D-STATCOM and its Optimal allocation.	PV units; D-STATCOM; OLTC	Tap changer stress; PV interactions, D-STATCOM placement; voltage profile; power losses	Optimal Voltage Regulation Scheme coordinating regulation devices, including D-STATCOM	Optimal D-STATCOM placement improves voltage profiles and reduces losses by up to 35% coordinates devices to manage tap stress and PV integration challenges.	Investigate dynamic allocation strategies and real-time optimization. Field validation and broader device mixes
[88]	Raja et al. 2021	MPC with DNN prediction/sensitivity for emergency voltage control	SVC; LTC; load shedding	Real-time computation speed; voltage trajectory prediction; sensitivities	MPC adaptive control using DNNs for prediction and sensitivity estimation to speed up online MPC	Proposed scheme speeds online computation by a factor of 20 and makes MPC feasible for IEEE 9 and 39-bus systems.	Validate at a larger scale and with field measurement noise
[102]	Tewari et al. 2021	Coordination of OLTC and energy storage for high PV	OLTC; BESS	Voltage deviation, number of tap changes, battery life	Coordinated optimization to reduce voltage deviation and OLTC/BESS overuse	Coordinated control improves voltage regulation and optimal resource utilization compared with uncoordinated schemes on IEEE 13/33 buses.	Field deployment and larger feeder studies
[78]	Dutta et al. 2020	Coordinated control of ADNs with PV and ESS	OLTC; DGU; ESS	Voltage regulation, power loss, and control resource usage	Rule-based MPC with three rules adapting objectives by voltage magnitudes	Rule-based MPC mitigates voltage violations and energy losses; ESS improves control resource usage.	Extend robustness studies and runtime performance.
[69]	Alabri et al. 2022	Optimal coordination in an unbalanced distribution with PVs and EV chargers	OLTC; D-STATCOM; PV inverters; EV phase connection control	Voltage magnitude, voltage unbalance, and power losses	Real-time optimal coordination using AHPPO (hybrid particle swarm) to set OLTC taps, reactive exchange, and EV phase connection	The proposed scheme maintains voltage/unbalance limits and minimizes losses on IEEE 37/123-node feeders with time-series validation.	Scalability and further robustness testing under varied PV penetrations
[68]	Dutta et al. 2022	MPC-based coordinated voltage control with CVR and DR	D-STATCOM; OLTC; PV inverters; demand response	Voltage limits; energy efficiency via conservation voltage reduction and demand response	Model predictive control coordinating D-STATCOM reference, OLTC, and PV set-points	MPC improves voltage regulation and demonstrates the benefits of CVR and DR in 33-bus tests.	Integration with field deployments and broader DER portfolios
[70]	Chen et al. 2022	Reactive power and voltage optimization with DGs and EVs	ES; OLTC; capacitor banks; SVC	Network loss; voltage deviation; high DG/EV penetration	Optimization model simplified via SOCP and linearization for IEEE 33-node validation	Model validated on IEEE 33, demonstrating reduction of loss and deviations under DG/EV scenarios.	Integrate stochastic EV behavior and field datasets
[17]	Muthukaruppan et al. 2022	Supervisory Volt/Var coordination with smart inverters	LTC; Voltage Regulators; smart inverters	Volt/Var support; minimize circuit power loss; limited communication	Two-level supervisory VVC shifting Volt/Var characteristics to minimize dispatch frequency	Supervisory VVC maintains voltages within the desired range and minimizes smart inverter dispatch on the IEEE 34-bus system.	Communication-limited deployment and integration studies
[82]	Rhouma et al. 2022	Capacitor-less D-STATCOM for high PV penetration networks	Matrix-converter-based D-STATCOM; PV systems	Reactive power provision; reliability; converter constraints	Detailed converter and system-level analysis	Capacitor-less D-STATCOM offers improved reliability and compensation in high PV LV networks	Investigate long-term reliability and cost-benefit analysis
[8]	Jafari et al. 2022	Decentralized OLTC and PV inverter control without communication	OLTC; PV inverters; decentralized control	Voltage zones, reactive capability reserve, OLTC operation count	Decentralized signaling-based coordination with zone-adaptive actions	Eliminates communication links and reduces OLTC operations using PV reactive support on the IEEE 33-bus	Test on real distribution feeders with varied PV penetration levels
[11]	Yang and Zhong 2022	Day-ahead scheduling of OLTC and switched capacitors	OLTC; switched capacitors; multi-	Voltage deviations, power loss, Pareto front	Multi-Pareto optimality with Manhattan distance selection	Multi-objective scheduling reduces voltage deviations	Integrate with the real-time control layer and

		objective optimization				and losses on the IEEE 33-bus test system	demand response programs
[56]	Hatata et al. 2023	Centralized voltage coordination with IoT for SDN	D-STATCOM; OLTC; DGs (PV, wind)	Voltage profile limits; power loss; renewable stochasticity; load uncertainty	Central controller with multi-objective optimization using Gorilla Troops Optimization (GTO) over IoT communication	Centralized GTO-based controller yields more accurate results vs. other evolutionary methods on NEDC-24 and IEEE-33 test systems.	Real-time implementation and communication resilience testing.
[24]	Hassan et al. 2023	Centralized IoT-based coordination of OLTC and D-STATCOM	OLTC; D-STATCOM; IoT communication	Voltage coordination; IoT protocol; real-time data exchange	Gorilla Troops Optimization with IoT-based centralized control	GTO-based method achieves better voltage regulation than PSO and GA on IEEE test systems	Validate communication latency impacts and cybersecurity measures
[103]	Hou and Dai. 2024	Hierarchical coordinated Volt/Var and Volt/Watt with SOPs	OLTC; Soft Open Points (SOPs); DG droop controllers	Voltage stability constraints; droop slope optimization; deviation-aware optimization	Three-stage hierarchical framework with day-ahead OLTC scheduling, intra-day droop optimization, and real-time regulation	The framework improves voltage regulation and guarantees stability via chance-constrained programming.	Field trials and robustness to model mismatch
[13]	Zhou et al. 2024	Distributed reactive power control coordinating DPV and SVC	DPV; SVC	DPV limited reactive capacity; node voltage deviation; network losses	Distributed optimization via alternating direction multiplier method with adaptive penalty factor	Coordination enables safe, economic operation on an enhanced IEEE 33-node system.	Test with larger networks and communication constraints
[14]	Song et al. 2024	Double-time-scale stochastic MPC for unbalanced networks	DGs; OLTC; SVR; switched CBs	Voltage deviation, active power curtailment, reactive fluctuation, scenario generation for DG uncertainty	Stochastic MPC with fast-time DG optimization and slow-time OLTC/SVR/CB scheduling using empirical CDF scenarios	SMPC keeps three-phase voltages within a secure range and improves profiles on the IEEE 123 unbalanced test.	Implementation complexity reduction and hardware tests
[79]	Gush and Kim. 2024	Robust local coordination of PV smart inverters with SVC and OLTC	PV smart inverters, SVC, OLTC	Voltage regulation; local coordination; robust control	DNN-based local controllers trained via chance-constrained OPF	DNN controller achieves robust coordination under uncertainty and outperforms conventional methods	Extend to real-time hardware implementation and field testing
[73]	Makanju et al. 2025	Coordination/control of PV and volt-PV smart inverters; age-regulating devices under uncertainties	D-STATCOM; OLTC	Voltage stability; uncertainty handling	Intelligent coordinated control scheme (details in extract limited)	Coordinated control with PV inverters, D-STATCOM, and OLTC enables effective voltage regulation according to the extract.	Incomplete: specific future work not present in the extract
[92]	Song et al. 2025	Voltage regulation in Active Distribution Networks (ADNs) with high renewable DG penetration	OLTC, SVR, Capacitor Banks (CBs), Distributed Generators (DGs)	Voltage deviation, tap positions, DG active/reactive power, prediction horizon (STC: 3 h, FTC: 5 min), uncertainty bounds of DG output	Distributed Robust Model Predictive Control (RMPC) with double-time-scale control (STC + FTC) and ADMM distributed optimization	Proposed DRMPCC reduces maximum voltage deviation by ~63% and maintains bus voltages near nominal despite DG uncertainty	Extend method to more device types and apply to unbalanced distribution networks
[10]	Wang et al. 2025	Coordinated Volt-Var control in the main and distribution networks with distributed PV	Distributed PV inverters, OLTC transformers, capacitors/reactors, ESS, substations, feeders	Bus voltage limits, reactive power limits (Qmax/Qmin), feeder reactive power, network loss (Ploss), and voltage sensitivity coefficients	Three-level AVC (Automatic Voltage Control) with tertiary, secondary, and primary control; Optimal Power Flow and Cross-Approximation Algorithm; quadratic programming for feeder control	Coordinated PV reactive power support reduces network losses by 171.14 kW and improves voltage stability across buses	Improve optimization algorithm, better utilize distributed PV reactive capability, and conduct studies with larger datasets and longer operation periods

7. Case Study

The proposed review study highlights the need to concurrently assess the challenges of operating OLTC transformers under normal conditions and in the presence of solar PV systems and FACTS devices. Adding renewable generation, such as solar PV systems, could increase the system's reliability and dependability. Additionally, system voltage varies depending on the type of renewable energy used. This section presents a case study on the Extension Badoosh Cement Factory in Mosul, Iraq. This factory product, a cement 3000 ton/day, the main power station (P0) consists of two 33/6.6 kV, 30 MVA OLTC transformers: the two transformers supply eight main feeders (6.6 kV) that supply the main high voltage (6.6 kV) to motors and nine (6.6/0.4 kV) transformers, which supplied nine feeders (400 V), seven of them explained on feeders MCCP1 to 7, while MCCP8 and MCCP9, which supplied raw material conveyors and the administration building, connected on two (6.6/0.4 kV) transformers on P0.HV.3. Figure 15 demonstrates this system. The first transformer was taken as the proposed test case. This transformer has an OLTC with 21 taps on the high-voltage side (33 kV) to cover $\pm 10\%$; each step compensates the voltage by ± 0.01 p.u. Figure 16 shows this transformer, OLTC configuration, a mechanical meter for tap location, and a mechanical tap counter, which is used as a reference for the current case study.

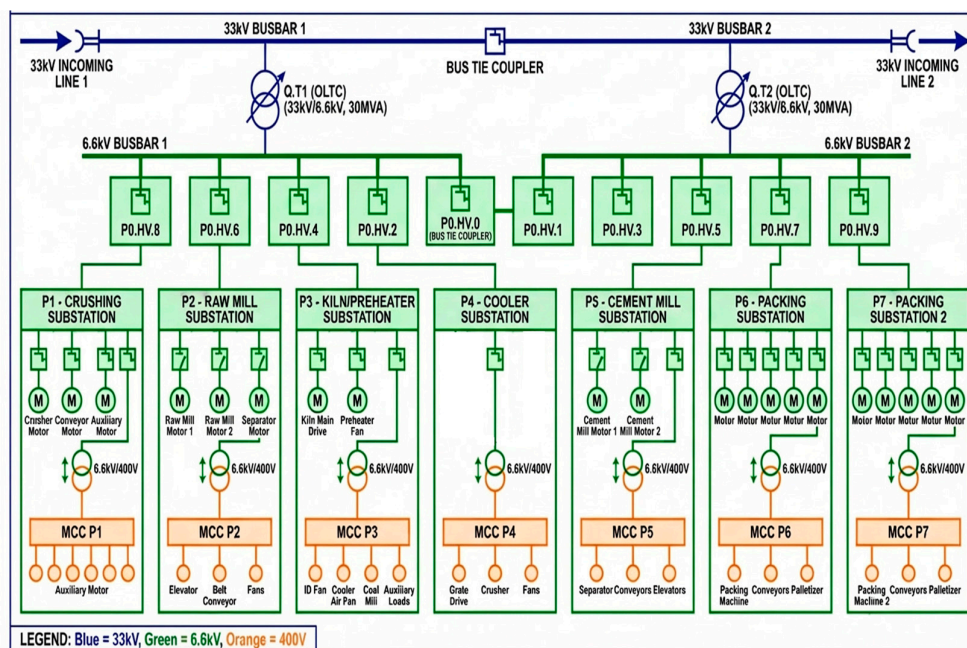


Figure 15. Power distribution system for the extension of the Badoosh Cement Factory.

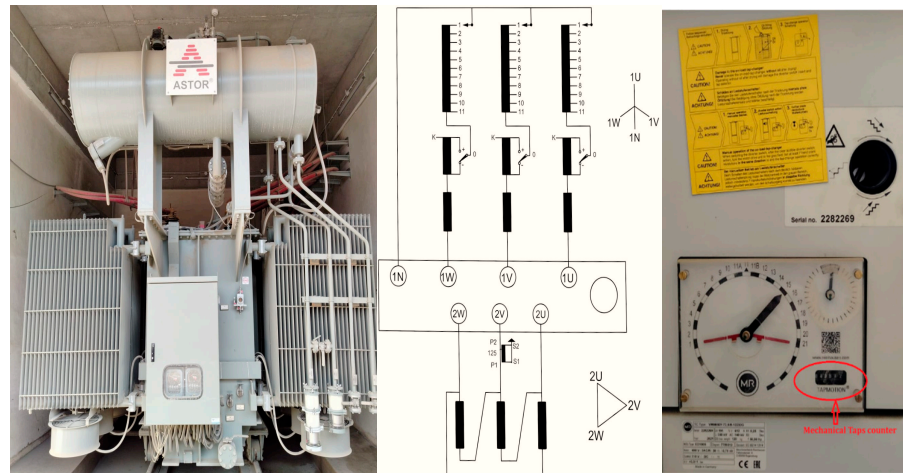


Figure 16. The used power transformer, OLTC mechanical indicator, and counter.

All response data were collected from the first transformer using two EMONIO P3, this device measurement uncertainty $\pm 1\%$ and up to 25,000 measurements/sec, one for transformer primary and second for secondary, as shown in Figure 17, where these devices used as a three-phase power measuring and data logger devices, it measures and collects all data (voltages, currents, real and reactive powers, apparent powers, energies, power factor, and frequency) at one cloud platform with stored in one second intervals.

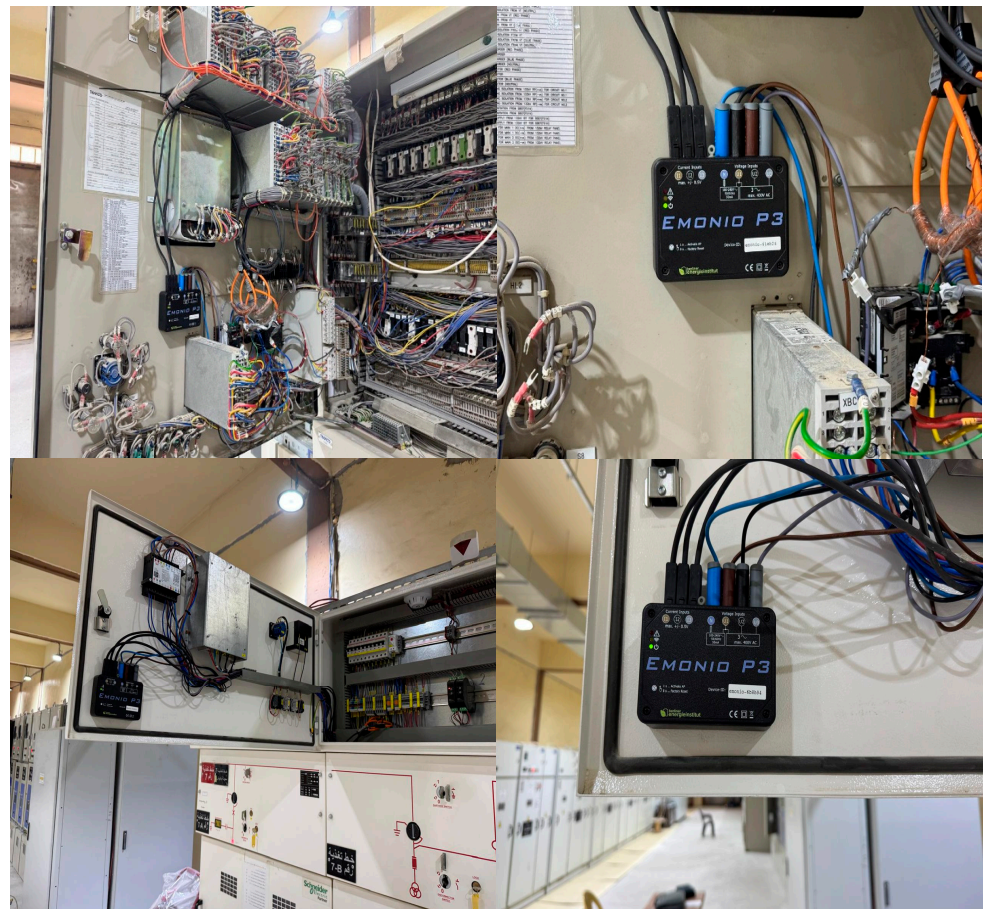


Figure 17. The installed measuring and data-logging devices in the main substation.

The input signals for EMONIO P3 are three-phase voltages and currents, with voltage signals taken from voltage transformers (primary 33 kV to 100 V) and (secondary 6.6 kV to 100 V), and current signals taken from current transformers (primary 1000 A to 1 A) and (secondary 3300 to 1 A). Figure 18 shows the flowchart used to sum the number of frequency changes in tap position during daily variations in supply and load. This flowchart depends on the voltage value where any change in primary voltage (V_s) over the reference value (V_{ref}), with more than ± 0.01 p.u. and less than ± 0.02 p.u. during a period of time, is counted as one tap change ($Tap_No = 1$), and if the difference is double, then the number of tap changes is equal to 2, etc. This method is verified using the OLTC mechanical counter shown in the previous Figure 16. The MATLAB program was used to analyze and generate all results shown in Figures 19–23.

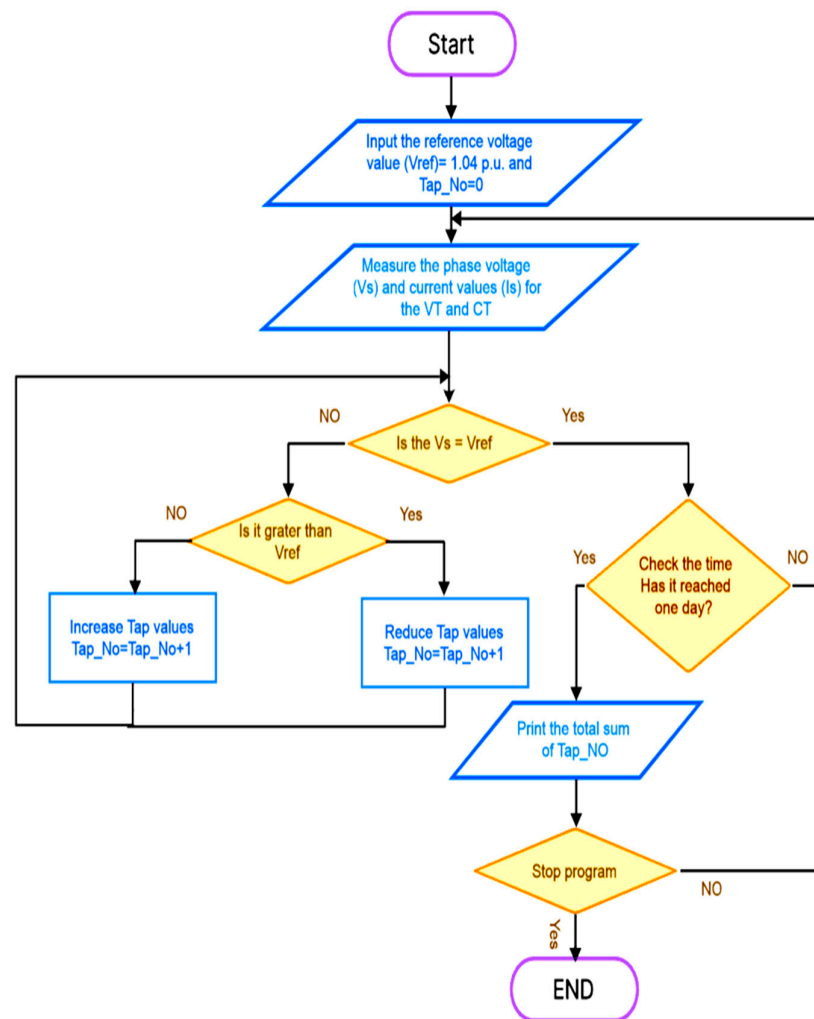


Figure 18. The general flowchart for calculating the tap-changing summation.

Two scenarios are taken into consideration in this case study:

- Scenario 1 (Practical Test): Assess OLTC operation during daily load changes caused by the main supply and factory's production process, in the absence of renewable energy (PV systems); Figure 19 shows the daily load variation in 2025, and Figure 20 shows the daily average load for the full 2025 year. It is noted that there is some similarity, as the factory operates on a daily schedule with a 20–30-day maintenance period each year. The system has a default power factor correction unit at the P0

substation to maintain a near-unity power factor. The OLTC of the main power transformer maintains the reference voltage (V_{ref}) at 1.04 p.u. The voltage is changing due to the main grid supply or a change in load (e.g., heavy loads such as high-tension, high-power induction motors). So, in this case, the average number of frequency tap changes per day is about 90. Figure 21 shows the daily number of OLTC tap changes operated to regulate the voltage within 1.04 p.u.

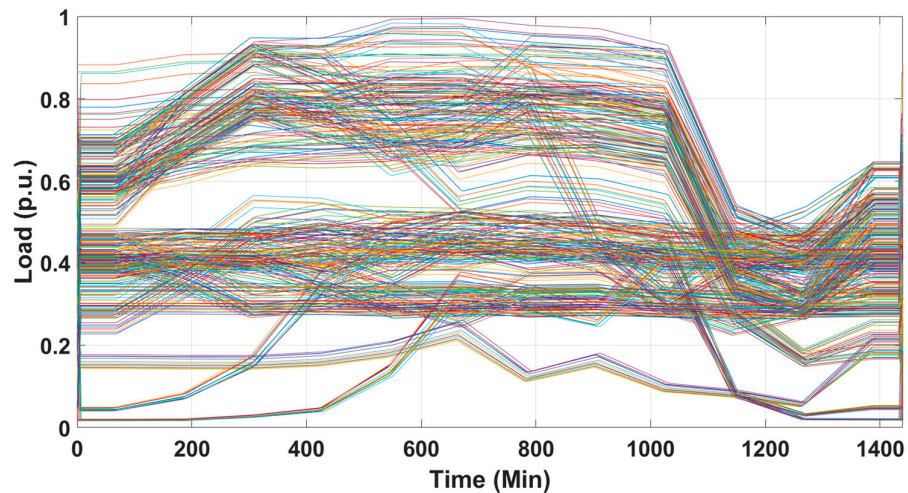


Figure 19. Full-year daily load curves overlaid (0.1440 Minutes).

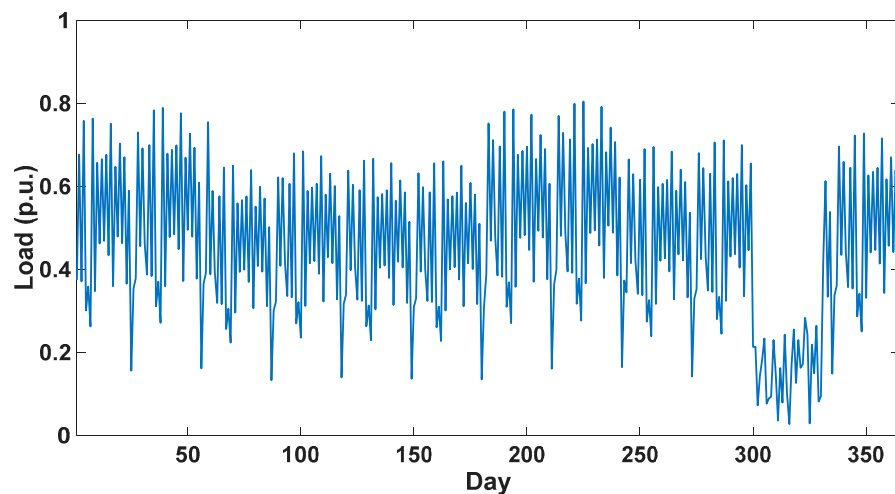


Figure 20. Daily average load for the full 2025 year.

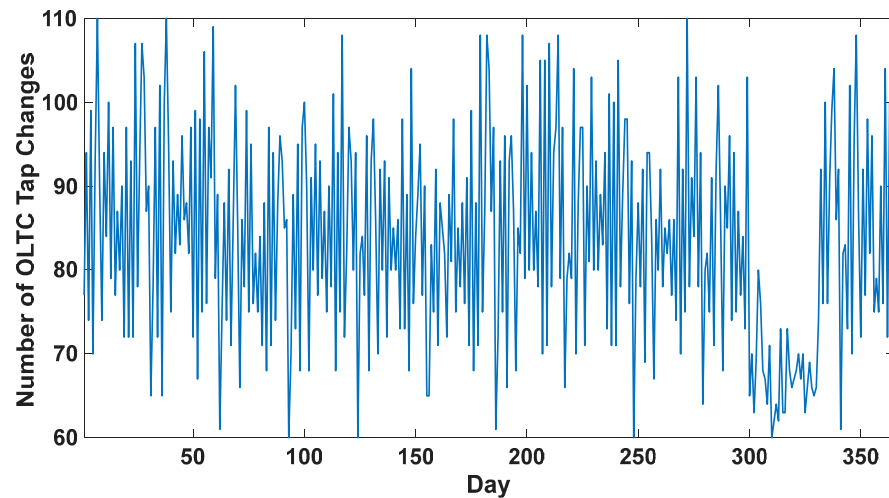


Figure 21. Daily number of OLTC tap changes for voltage regulation at 1.04 p.u.

- Scenario 2 (Hypothetical Case): Assess OLTC operation during supply and daily load changes caused by the factory's production process, in the presence of renewable energy. In this work, it is suggested that, depending on the available clean area beside the factory, the current situation, and the procedure from references [106,107], a 20 MW utility-scale photovoltaic (PV) power plant located at latitude 36.439283° N and longitude 42.927700° E requires approximately 40 hectares ($400,000 \text{ m}^2$ or 0.4 km^2) of land, taking into consideration that the actual area may vary depending on the module technology, row spacing, access roads, and auxiliary facilities. To maximize the annual energy yield, the PV modules should be installed facing true south (azimuth angle of 180°) with a fixed tilt angle of approximately 32° , which is considered close to the optimum inclination for year-round solar energy production at the selected site. This configuration provides a suitable balance between summer and winter solar irradiance capture and is commonly adopted in utility-scale PV installations in regions with similar latitudes. So, the PV system with a rated power of 20 MW can be integrated to compensate for about 35% of the factory's full-load real power. The Global Horizontal Irradiance (GHI), obtained from the NASA Power, 2025 database, varies over time [108]; Figure 22 shows the GHI diurnal curves (Hourly) for 2025 over a wide area adjacent to the factory.

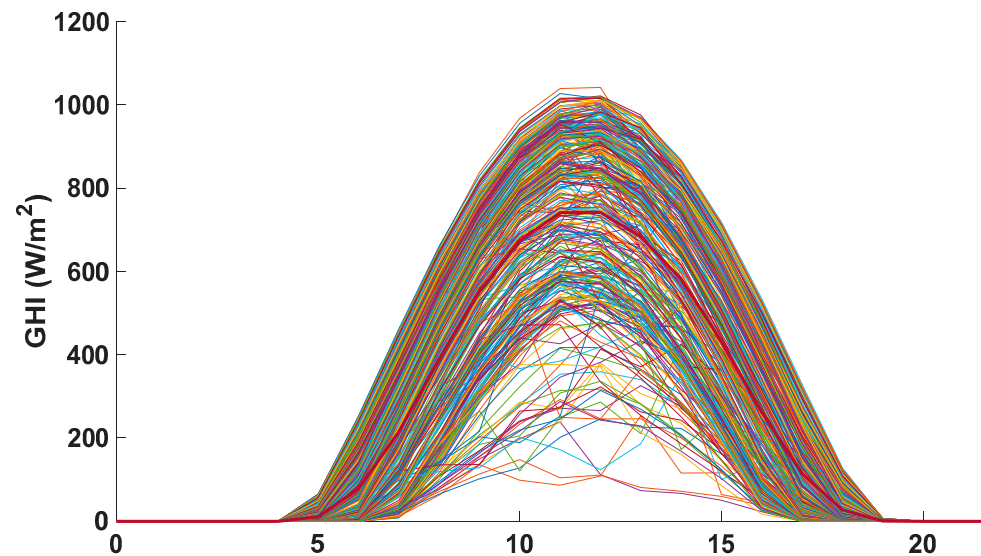


Figure 22. GHI diurnal curves (Hourly) at location latitude: 36.439283, longitude: 42.927700 during 2025.

The OLTC challenge is now based on three main variables: the main source grid, load variation, and variable PV system penetration. These variables will actually increase the average daily tap operations from 90 to 140, resulting in about a 60% increase. Figure 23 shows the change in OLTC tapping frequency with PV penetration.

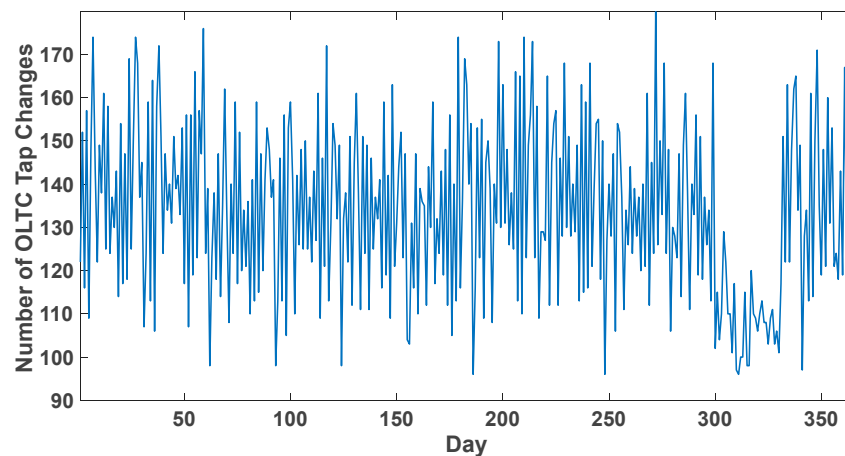


Figure 23. Daily number of OLTC tap changes for voltage regulation at 1.04 p.u. with the PV system.

The analysis results for daily average load, shown in Figure 20 for the two scenarios, indicate that the system will be more reliable and supported in scenario 2, particularly when PV penetration is high, even though PV systems are expensive; the cost can be covered over time. Additionally, it is a balancing act between economics and reliability. On the other hand, operational stress, i.e., tap-changing frequency on OLTC, will increase with PV penetration, and this may be greater in winter due to cloud cover. So, it is important to assess the economics and dependability of the power system when using PV systems, which requires additional solutions to regulate voltage on one side and reduce the huge stress on the OLTC on the other, which may also be worked on for forward and reverse power direction, and may also reverse action reach during heavy load and voltage stability limitation.

To solve this issue, it is very important when adding a PV system in a heavy-duty working area to take into account the system needs, add more devices such as D-STATCOM, and develop an optimal coordinated control strategy for the OLTC with D-STATCOM and PV system inverters to provide the load with a reliable voltage profile, reduce overall losses, and increase transformer life.

8. Conclusions

OLTC is an old device used for voltage control, but with the growing use of renewable energy sources (RES) for generation and electric vehicles (EVs) as loads, it has become increasingly difficult to maintain voltage control in low-voltage distribution networks (LVDNs). This situation makes it hard for the grid to operate normally; new approaches are needed to effectively control voltage profiles. Power management, substation compensation, flexible power electronics, and consumer-located regulators are all modern methods for controlling voltage.

In this paper, a systematic literature review was conducted in accordance with the PRISMA 2020 guidelines. The operational challenges of OLTC transformers in a distributed network with PV penetration were discussed, and coordination with FACTS devices was presented as an option. High PV penetration significantly affects OLTC operation by requiring more frequent tap changes, which in turn affects transformer lifespan and maintenance. Traditional voltage regulation approaches are no longer applicable at PV penetration levels above 30% because of bidirectional power flow and rapid oscillations.

FACTS devices and OLTC transformers are best synchronized by leveraging their complementary characteristics: OLTC provides wide-range voltage control in discrete steps, while FACTS devices offer a continuous, fast response to temporary voltage excursions. D-STATCOM has been found to be particularly effective in OLTC coordination and, even at small sizes, reduces OLTC operations and improves voltage profiles.

It is always better to use advanced smart control algorithms, such as MPC, FIS, AN-FIS, and machine learning, rather than traditional methods. OLTC performance is heavily influenced by weather, with cloudy days associated with more tap operations than sunny days, underscoring the need for climate-specific solutions.

This work presented a case study on the performance of the power transformer OLTC in a cement factory, which is unique due to heavy load fluctuations. So, OLTC will frequently change the taps, on average 90 times/day, to address the challenge of variations in load and the main supply. In addition, PV penetration will increase the average number of taps by about 60% to keep the required voltage within 1.04 p.u. This will require additional solutions to reduce the stress on OLTC operation. These results are consistent with the reviewed literature and highlight the need to develop coordinated voltage control strategies that involve OLTCs, D-STATCOM, and smart inverter functions. Avoiding excessive tap operations may improve transformer lifespan, reduce maintenance requirements, and enhance overall voltage regulation performance in PV-rich distribution networks from an engineering perspective.

Future work should focus on developing cost-effective coordination frameworks that balance technical performance, equipment stress, and economic considerations. Also, areas will involve integration and cooperation strategies for operation with energy storage systems, innovative communication protocols with security features, and end-to-end approaches to distribution network management. These collaborative control methods will become increasingly significant as distribution networks enable greater penetration of renewable energy sources while maintaining system reliability and stability.

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resources, A.N.B.A.; data curation, O.A.H.; writing—original draft preparation, A.N.B.A.; writing—review and editing, O.A.H.; visualization, O.A.H.; supervision, A.N.B.A.; project administration, A.N.B.A. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

PV	Photo Voltaic
OLTC	On-Load Tap Changer
FACTS	Flexible AC Transmission Systems
D-STATCOM	Distribution Static Synchronous Compensator
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
DG	Distributed Generation
DERs	Distributed Energy Resources
CSP	Concentrated Solar Power
TSSC	Thyristor Switched Series Capacitor
TCSC	Thyristor Controlled Series Capacitor
SSSC	Static Synchronous Series Compensator
TCPST	Thyristor Controlled Phase Shifting Transformer
TCPAR	Thyristor Controlled Phase Angle Regulator
TCVR	Thyristor Controlled Voltage Regulator
UPFC	Unified Power Flow Controller
IPFC	Interline Power Flow Controller
UPQC	Unified Power Quality Conditioner
VSC	Voltage Source Converter
EMS	Energy Management System
RES	Renewable Energy Sources
EV	Electric Vehicles
MPC	Model Predictive Control
PVDGs	Photovoltaic Distributed Generators
PAO	Power Allocation Optimization
AI	Artificial Intelligent
BESS	Battery Energy Storage Systems
GHI	Global Horizontal Irradiance

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