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Volt/VAr Control Strategies in Distribution Feeders under DER-EV Penetration: A Bibliometric Review

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Abstract*– Volt/VAr control is a fundamental strategy for maintaining power quality within predefined limits, reducing energy losses, and improving the operational efficiency of distribution feeders. However, the increasing penetration of distributed energy resources (DERs) and electric vehicles (EVs) has imposed significant challenges on traditional Volt/VAr control schemes. In this regard, this work presents a PRISMA-aligned review of Volt/VAr control strategies applied to distribution feeders with high DER/EV penetration. This review employs a six-stage workflow encompassing database searches Scopus and The Lens, corpus screening eligibility criteria and citation tracking, and evidence synthesize through temporal trends, VOSviewer-based keyword co-occurrence mapping, and a narrative assessment structured around seven research questions. The results reveal steady growth in the field since 2014, with a marked acceleration driven by rising DER penetration and new inverter grid-support requirements. Four main research fronts emerge: deterministic Volt/VAr optimization using traditional devices; inverter-based reactive-power and power-quality control; PV-centric voltage regulation; and AI-enabled coordination strategies for EV charging management. In addition, the literature converges on hierarchical, multi-timescale control schemes that integrate OLTCs and capacitor banks with smart inverters, energy storage systems, and reactive-capable EV chargers, all supported by advanced computational and optimization tools.

***Keywords*—— Distributed energy resources, electric vehicles power distribution feeders, Volt/VAr control scheme.**

I. Introduction

Voltage regulation and reactive-power control are essential operational strategies in distribution networks, forming the basis for maintaining voltage stability, power-quality compliance, and efficient system performance [1]. To tackle the Volt/VAr control (VVC) problem, the literature reports different approaches, including evolutionary-algorithm-based strategies [2], [3] and classical optimization-driven methods [4], [5].

However, nowadays the accelerated penetration of inverter-based distributed energy resources (DER), predominantly photovoltaic generation, along with the growing prevalence of electric-vehicle (EV) charging, has evolved VVC from a device-centric task into a multi-layer cyber-physical control challenge [6], [7].

Increasing penetration of DERs and EVs intensifies voltage rise during peak PV generation and aggravates voltage drops during coincident EV charging demand. Meanwhile, traditional devices such as OLTCs, switched capacitor banks, and step-voltage regulators are constrained by discrete actions, slow response, and accelerated mechanical degradation when subjected to such rapidly varying conditions [8]. These issues are often intensified by radial feeder structures, limited low-voltage observability, and phase imbalance driven by single-phase loads and residential DER interconnections [9], [10].

In parallel, VVC research has expanded steadily, with recent studies leveraging data-driven and artificial-intelligence methods to address uncertainty and the growing dominance of power-electronics-interfaced resources. Within this context, this paper synthesizes how VVC mechanisms, EV charging management strategies, simulation toolchains, and interconnection requirements have co-evolved in DER- and EV-rich distribution feeders.

Although classical voltage regulation has relied on OLTCs, capacitor banks, and voltage regulators, DER- and EV-driven operating conditions require coordinated strategies integrating fast inverter-based reactive support, controllable charging, and supervisory decision-making. However, Volt–VAr control research has evolved across partially disconnected streams, including device-centric regulation, smart inverter Q(V) functions, optimization-based coordination, data-driven control, and EV-grid interaction. Therefore, an integrated synthesis of research evolution, dominant themes, validation toolchains, and regulatory adoption remains valuable, particularly for Latin American distribution systems, where limited visibility and communications hinder real-time coordination. To address this gap, this paper presents a PRISMA-aligned systematic and bibliometric review of Volt–VAr control literature, complemented by thematic mapping and narrative synthesis. The contributions are fourfold:

- Provide a comprehensive mapping of research trends that quantifies and interprets the evolution of scientific production related to Volt–VAr control strategies.
- Identifying dominant thematic clusters and the transition from legacy devices to inverter- and algorithm-based coordination.
- Synthesizing simulation and optimization toolchains for VVC studies incorporating DER and EV charging.
- Provide a comprehensive perspective to consolidate reported standards and regulatory requirements for Volt–VAr capabilities and discuss barriers and advances with explicit attention to Latin American distribution feeders.

II. METHODOLOGY

PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology was adopted as the reporting framework to document study identification, screening, eligibility, and inclusion.

As summarized in Fig. 1, the workflow follows six stages: (1) definition of keywords and a structured search string for Volt–VAr control in distribution feeders, including intersections with smart inverters and EV charging; (2) execution of the query in Scopus as the primary indexing database and cross-checking in The Lens, followed by export of bibliographic metadata; (3) de-duplication and title/abstract screening; (4) full-text eligibility assessment using predefined inclusion and exclusion criteria focused on distribution-level voltage regulation and reactive-power control, coordinated VVC, smart-inverter Q(V) functions, DER/EV voltage impacts, and control/optimization approaches for active distribution networks; (5) backward and forward snowballing via references and citation links to refine and expand the corpus; and (6) bibliometric trend analysis, keyword co-occurrence mapping, and narrative synthesis, with the resulting insights consolidated into the figures developed in this study to answer RQ1–RQ7.

The review was implemented through a six-stage protocol. Scopus was used as the primary indexed database and The Lens as a complementary cross-checking source. Bibliographic records were exported and screened after duplicate removal. Title, abstract, and full-text eligibility were assessed according to predefined inclusion criteria focused on distribution-level Volt/VAr control, DER/EV integration, smart-inverter Q(V) functions, coordinated voltage regulation, and optimization/control strategies. VOSviewer was used for keyword co-occurrence mapping under full-counting criteria, while temporal and country-level trends were derived from the bibliographic metadata. Finally, the selected corpus was synthesized narratively according to seven research questions covering publication trends, control evolution, software tools, EV charging management, grid-code adoption, and Latin American implementation barriers.

III. RESULTS AND DISCUSSIONS

A. What are the trends in publishing involving Volt VAr in distribution systems?

A Scopus search on Volt/VAr (Q(V)) control in distribution systems was performed for the 26-year period analyzed (Fig. 2), tracking annual publication counts in journals and conferences. From 2000 to 2008, output remained low and relatively stable (<5 papers/year), starting with 2 papers in 2000 and fluctuating between 1 and 8 per year. In 2009, publications increased to 11, marking the first clear inflection point and the onset of subsequent growth.

Between 2010 and 2013, the number of publications was relatively low, with 20 publications in 2010. Over the following three years, there were around 30 publications per year, accounting for approximately 8% of total publications.

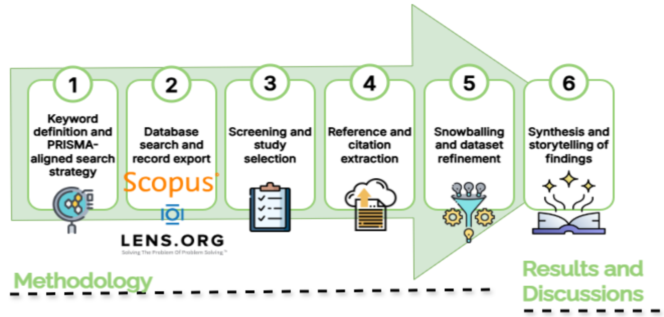

Fig. 1 Systematic Literature Review stages for the study

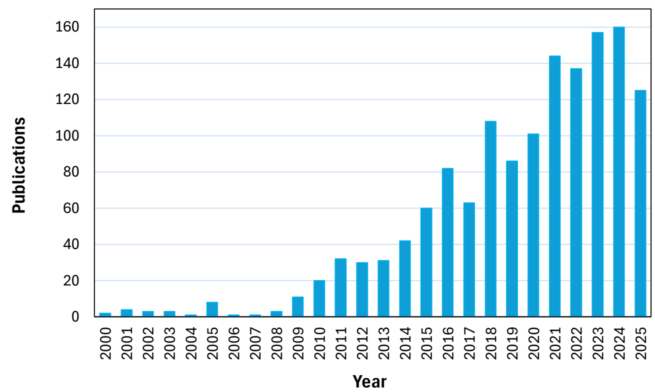

Fig. 2 Evolution of studies involving Volt VAr in recent years.

During this stage, the concepts of Smart Grid and distribution automation began to be consolidated [11]. Academic research was encouraged following the increase in oil prices in 2008, alongside various regulatory policies established in previous years, such as the Energy Independence and Security Act (EISA) [2], the American Recovery and Reinvestment Act (ARRA) [12], and the 20-20-20 objectives. These policies not only called for more efficient networks but also provided financing for Smart Grid projects.

The variability of renewable energy increases the complexity of voltage profile management, which led to research on coordinated control strategies [14] and the use of smart inverters [15]. Starting in 2014, there was a constant growth in the number of annual publications, going from 42 articles published in 2014 to 108 articles in 2018, reflecting the increase in academic interest. During this period, distribution networks began to show increasing penetration of distributed energy resources (DER), mainly photovoltaic energy [13]. The variability of renewable energy increases the complexity of voltage profile management, which led to research on coordinated control strategies [14] and the use of smart inverters [15].

During 2019 and 2020, the values were slightly lower compared to the previous peak, but in 2021, a peak of 144 published articles were recorded. Despite the global situation, the publication of articles registered notable growth. In 2022, a high value of 137 articles was maintained, in 2023, a value of 157 published articles was reached, being surpassed in 2024 with 160 articles. At this stage, the research area has included artificial intelligence techniques and Deep Reinforcement Learning [16]. The peak of publications in 2024 can be attributed to different factors, such as the adoption of the IEEE 1547-2018 standard and the increase in DERs. Furthermore, the growing interest in grid flexibility [17], [18], microgrids, and power electronics-dominated distribution systems has further boosted research output during this period [19], [20].

In the most recent years, the apparent decrease or fluctuation in indexed publications should be interpreted cautiously, since database-indexing delays may affect incomplete years. Therefore, these values should not be read as evidence of declining interest. Broadly speaking, the evolution of scientific production between 2000 and 2025 has shown a long-term upward trend. The topic has transitioned from traditional VVC towards the implementation of more advanced control strategies, such as the use of artificial intelligence and the management of electric vehicle charging infrastructure[21], [22].

Figure 3 complements the annual trend in Figure 2 by showing that growth in Volt/VAr (Q(V)) research in distribution feeders is driven by a few countries. The United States accounts for the largest share of publications, followed by China and India, while the remaining output is distributed across multiple countries with lower volumes. This geographic concentration aligns with the inflection in the annual series, where publication counts rise from modest early levels to sustained high output after the mid-2010s, reflecting the increasing relevance of inverter-based resources and distribution-level voltage control as DER and EV penetration expand.

Figure 4 shows the keyword co-occurrence network, generated using the VOSviewer software, from the bibliometric data set related to Volt/VAr control (VVC) in distribution networks. The analysis considered all keywords using full counting. The resulting map reveals four thematic clusters, capturing the interplay between conventional VVC and emerging smart-grid technologies.

The first cluster focuses on the optimization of voltage control in distribution systems and includes terms such as Volt/VAr optimization, capacitors, distribution management system, smart grid, and integer programming. This cluster represents deterministic optimization approaches and the use of traditional devices, such as capacitor banks and voltage regulators, commonly used in distribution operation. The second cluster covers AI-based Volt/VAr control, highlighting terms such as deep reinforcement learning, electric vehicles, renewable energy sources, and stochastic systems. It reflects the increasing use of machine learning to address uncertainty and variability under high PV/EV penetration and stochastic load behavior.

The third cluster focuses on reactive power control and power quality, and includes terms such as reactive power, energy sources, distribution grids, reactive power control, controllers, inverters, and quality control. This cluster suggests the growing role of inverter-based controllers to mitigate power quality issues driven by DER intermittency, while supporting voltage regulation mainly through local control schemes.

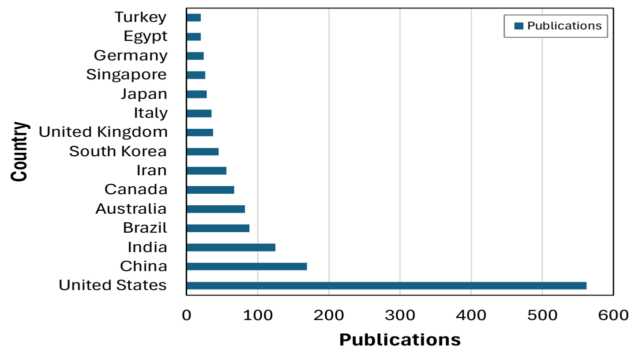

Fig. 3 Countries with more than 20 papers related to Volt/VAr control

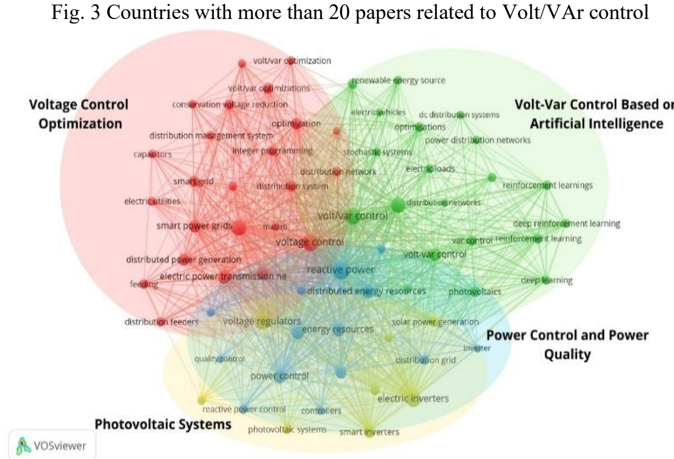

Fig. 4 Thematic keyword map for Volt/VAr control

Finally, the fourth cluster focuses on photovoltaic voltage control, grouping voltage regulators, solar generation, electric inverters, smart inverters, and PV systems. It reflects the transition of PV from a passive resource to an active grid-support element. Overall, the map shows a shift from conventional devices and deterministic optimization toward flexible VVC strategies integrating AI, DERs, and power electronics for voltage and power-quality support.

B. What is the evolutionary panorama of Volt-VAr control mechanisms in distribution systems?

The evolutionary panorama of Volt-VAr control (VVC) in distribution systems has transitioned from an exclusive reliance on electromechanical devices toward a sophisticated integration of power electronics-based technologies and algorithms. In the past, electromechanical devices such as capacitor banks (CBs), voltage regulators (VRs), and on-load tap changers (OLTCs) have been widely used to realize VVC in distribution networks [17], [23], [24], [25].

Although OLTCs and CBs are widely used in distribution networks for voltage regulation, in [26] it is mentioned that OLTCs are usually used to regulate a relatively large area network and only monitor the voltage at specific nodes. Capacitor Banks, although they react quickly, are not installed throughout the network; they have been the most popular option to reduce power losses in distribution systems [27]. Therefore, these devices lack the flexibility necessary for voltage regulation in active distribution networks. The literature agree that these devices have worked until now, they alone cannot sustain the network without violating standardized limits, since they present intrinsic limitations in the context of modern networks: they operate under slow response schemes, have discrete configurations and suffer significant mechanical degradation in the face of frequent switching, which increases maintenance costs and shortens their useful life [17], [15], [28], [29], [30].

One of the main concerns is to control the limits on the voltage profiles that could otherwise lead to reduced load or renewable energy generation [15]. On the other hand, uncoordinated EV charging would cause transformers to operate beyond their thermal limits, causing them to fail [30]. Therefore, a control strategy is necessary to overcome the concurrent problems that arise due to the integration of photovoltaic generators or power stations in distribution networks, since these devices are not capable of mitigating voltage deviation and fluctuation problems in distribution networks [24], [31].

The proliferation of distributed energy resources (DER) has driven the development of new edge-of-grid control technologies, such as smart photovoltaic inverters, and EVs [17], [24], [7], [32]. Coordinated voltage control enables active management of voltage levels across electricity distribution networks by leveraging the voltage support capabilities of existing grid-connected PV inverters [22]. In [15], [33], they address the Volt-VAr control of the smart photovoltaic inverter as a promising method to regulate the injection or absorption of reactive power to maintain the terminal voltage within the allowed voltage limits. In the field of dynamic stabilization, distribution static synchronous compensators (DSTATCOM) are devices dedicated to high-speed reactive power compensation that regulate voltages independently and can reduce the use of large photovoltaic inverters [34], [35]. Current research shows that DSTATCOM can reduce the need to oversize PV inverters by regulating voltages independently [24].

Papers [17] and [29] propose a hybrid Volt-VAr control architecture, which takes advantage of DER capabilities to manage voltages in the distribution network by coordinating the injection of reactive power from multiple external EV chargers. Under this hybrid scheme, traditional devices such as OLTCs and CBs manage the base voltage profile on slow (hourly) time scales, while PV inverters and EV chargers act as fine-tuning to mitigate rapid fluctuations caused by weather intermittency or demand spikes [17], [24], [31], [36].

To achieve this coordination, advanced methods are used, such as Model Predictive Control (MPC), being an online corrective controller, and Deep Reinforcement Learning (DRL), through algorithms such as TD3 and DDPG, is allowing adaptive and model-free control [16], [22], [19], [30], [37].

Numerous next-generation VVC strategies use traditional VVC devices and smart inverters to address voltage violations in active distribution networks (DNs) with higher DER penetration [16]. In [24], they use an MPC-based control scheme that optimally coordinates traditional Volt-VAr control devices (EVS, PV inverters, OLTC, and DSTATCOM) with different temporal characteristics to regulate the grid voltage profile, while performing congestion management. A Distributed Model Predictive Control (DMPC) strategy for VVC controls the voltage regulator, the state of the CBs, and the reactive power injected by the interconnected DERs through smart inverters is presented in [38].

In [23], they reduced losses by 20% in a 24-hour period by using the proposed VVC for coordinated control of traditional equipment (VR and CB) and power electronic devices (inverters, transformers with electronic switching, and distributed resources). Meanwhile, in [39], it raises the advantage of eliminating SVR, OLTC, and capacitor banks so that future distribution networks with high DER penetration completely depend on inverter control.

Modern inverters play a crucial role in enabling continuous modulation of active and reactive power, four-quadrant operation, and mitigating rapid voltage fluctuations almost instantaneously [7], [40], [41], [42]. For its part, Vehicle-to-Grid (V2G) technology and Fast Charging Stations (FCS) allow vehicles to function as mobile storage; These can inject reactive power to stabilize the grid without degrading the useful life of their batteries, as long as excessive active power discharge cycles are avoided [40], [29], [43], [44], [37], [45], [46]. Research suggests that V2G can improve grid stability, thereby encouraging greater adoption of electric vehicles [47].

In turn, EV chargers operating in V2G mode can extend the benefits of EVs in electric power systems by providing ancillary services to the grid [29]. [40] makes a comparison between conventional charging stations and FCS, showing that the voltage deviation is reduced by 36% when FCS are included. The management of these stations is optimized through dynamic control systems, such as MPC, which allows alternating between adaptive charging and fast charging modes depending on real-time factors such as network availability and renewable energy generation [48].

C. Which software tools are commonly used to develop, simulate, and validate Volt/VAr control strategies in EV-integrated distribution networks

Recent literature emphasizes the role of Volt/VAr control in electric-vehicle–integrated power systems, where new strategies depend strongly on simulation and optimization platforms. Methodologically, these studies combine three layers: power-system simulation environments, programming languages for algorithm development, and mathematical optimization tools. MATLAB and OpenDSS are widely used for infrastructure modeling and power-flow analysis, with MATLAB valued for its flexibility in active network planning, hybrid control architectures, and multi-objective optimization.

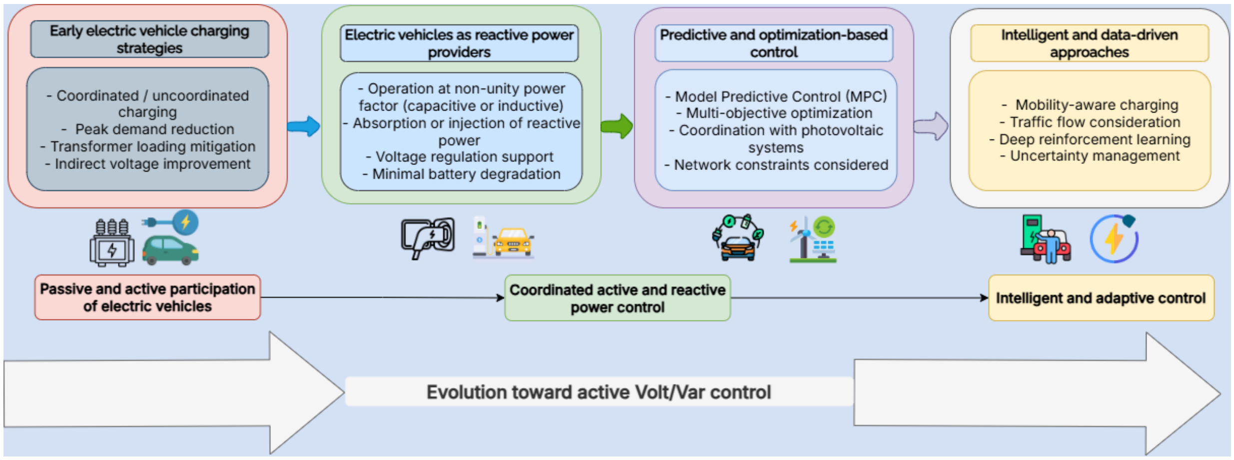

Fig. 5 Evolution of EV-based Volt/VAr control from early charging to intelligent, coordinated strategies.

In contrast, OpenDSS is frequently employed in hosting-capacity assessments and in evaluating smart-inverter performance in low- and medium-voltage networks. In addition, pandapower provides a Python-based environment for distribution-network modeling and power-flow analysis and is increasingly used in voltage-stability–oriented studies. Consistent with Fig. 5, the literature shows a shift from MATLAB-centric implementations to hybrid and Python-based workflows. Table I summarizes the main software tools and their typical Volt/VAr applications.

In particular, in the study presented in [49] MatLab is used to implement the control algorithm and solve the associated optimization problem, since the authors develop a model-predictive control scheme for electric vehicle charging stations integrated into microgrids. Similarly, in [50], the authors employ MatLab software along with optimization tools to handle network constraints and multiple control variables, proposing an optimal EV coordination strategy to provide voltage support in distribution networks. Likewise, in [14] the controller is implemented in MatLab to analyze the dynamic response of the system, where a plug-and-play approach is introduced, applied to a system modeled as a radial distribution feeder, where the electric vehicle chargers are connected to different nodes, allowing each electric vehicle to locally solve its optimization problem.

Additionally, some studies use MatLab together with multi-object optimization formulations to analyze the impact of coordinated charging of electric vehicles on the voltage profile, electrical losses, and the operation of regulation devices. An example of this is [24], where it is used due to its flexibility to integrate electric vehicle models, photovoltaic generation, and the electrical grid, presenting a two-stage control scheme for the coordination of EV and PV. In a complementary way, in [42] MatLab is combined with AMPL and specialized solvers to formulate a Volt/VAr optimization problem involving electric vehicles oriented to the reduction of voltage in the feeder.

OpenDSS is widely used in Volt/VAr studies for feeder modeling and power-flow simulations. For example, [41] evaluates inverter controls to mitigate voltage surges, [27], assesses voltage profiles and losses in real-network simulations, and [33] analyzes smart-inverter functionalities. In these works, OpenDSS typically provides the electrical model, while the control logic is implemented externally.

More recent studies report a shift toward Python-based platforms (e.g., pandapower and TensorFlow) for algorithm development and validation. In [16], Python deep-learning libraries are used to schedule EV charging with voltage-stability objectives, while [22], employs Python to train AI-based voltage regulators for active distribution networks.

TABLE I
SOFTWARE USED FOR VOLT/VAR SIMULATION IN POWER SYSTEMS

Year	Software used for the Study	Application	Ref.
2021	MatLab	Evaluation of voltage stability in active networks with distributed resources	[51]
2021	OpenDSS and MatLab	Detailed modeling of medium voltage networks and voltage profile analysis	[52]
2022	Optimization Toolbox in MatLab	Reactive power optimization considering multiple distributed resources	[53]
2025	OpenDSS, Python (GLPK)	Simulation of real networks and evaluation of coordinated control of inverters for voltage regulation.	[54]

D. How have EV charging management strategies evolved to enable Volt/VAr support in distribution networks, and which control mechanisms underpin this transition?

This evolution aligns with hierarchical Volt/VAr architectures (Figure 6) in which legacy devices act on slow timescales (Level 1), inverter-based DER and EV charging systems provide fast distributed support (Level 2), and predictive or data-driven supervisory controllers operate at sub-second timescales over smart inverters (Level 3).

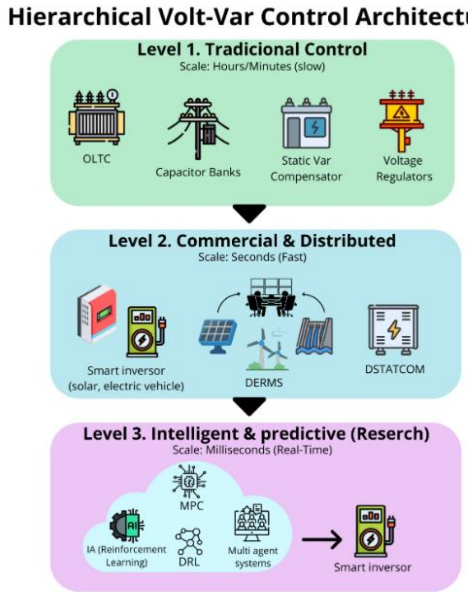

Fig. 6 Hierarchical Volt/VAr control architecture and its link to EV charging management.

EV charging management has evolved from basic coordination schemes toward explicit, active Volt/VAr support in distribution networks. Early studies primarily addressed operational impacts of uncoordinated charging by shifting charging in time to reduce peak demand and mitigate transformer and feeder loading, yielding only indirect improvements in voltage profiles [11], [55], [30].

A subsequent line of work reframed EVs and charging stations as controllable resources capable of providing reactive power support. Under this paradigm, chargers operate at non-unity power factor, enabling reactive power injection or absorption to assist voltage regulation while maintaining negligible battery-degradation impacts, since reactive power exchange does not require significant energy throughput [56],[28],[40]. This shift effectively moves EVs from passive loads to active actuators within Volt/VAr control schemes.

More recent contributions integrate optimization-based control to jointly coordinate active and reactive power. Model predictive control and multi-objective formulations schedule EV charging while explicitly accounting for network constraints, coordination with photovoltaic generation, and user-related requirements, thereby reducing voltage violations and electrical losses [50], [14], and [24]. Finally, emerging approaches incorporate uncertainty and time-varying operating conditions through mobility-aware and data-driven control. For example, EV charging is coordinated considering vehicle flows and urban mobility patterns in [18], while deep reinforcement learning is employed in [16] to schedule charging with voltage-stability objectives explicitly embedded. Collectively, these developments indicate that EV charging management has become a central instrument for Volt/VAr control in increasingly dynamic and DER-rich distribution networks.

E. Which jurisdictions have adopted grid codes or technical standards that mandate Volt/VAr (Q(V)) control capabilities for inverter-based resources in distribution networks?

Across the reviewed literature, more than 30 countries are reported to have grid codes, technical standards, or interconnection rules that include Volt/VAr (Q(V)) requirements at the distribution level [46]. Frequently cited examples include the United States and Australia through IEEE 1547-2018 and AS/NZS 4777.2, respectively [57], [58]. In North America, implementation is further illustrated by local rules such as California Rule 21 and Hawaii Rule 14H, which have operationalized Volt/VAr and Volt/Watt functions in alignment with IEEE 1547-2018 [59], [60], [33], [41].

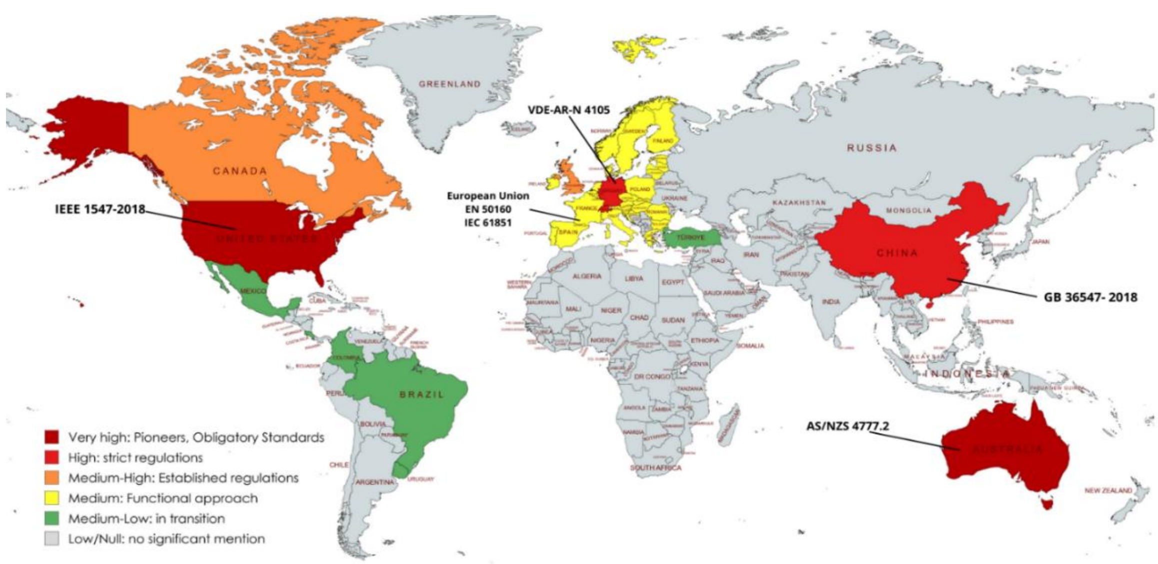

Fig. 7 Global adoption of Volt/VAr (Q(V)) control requirements in distribution networks.

In Europe, Germany is commonly referenced via VDE-AR-N 4105, while IEC 61851 and ISO 15118 are also noted as enabling standards for communication and reactive power management in electrified transport ecosystems [61], [62], [63]. China is described as applying GB 36547-2018 with an emphasis on centralized control in large urban networks [64]. In Latin America, evidence indicates interconnection standards add voltage-control and power-factor requirements to enable electrification without stressing distribution infrastructure.

Technically, these instruments define minimum reactive power capability, voltage operating ranges, and, in several cases, standardized Volt/VAr curves that prescribe reactive power injection or absorption as a function of local voltage deviations [46], [33], [27], [44]. The response behavior depends on curve settings such as the deadband, which varies by operator and regulatory framework: zero-deadband examples include Danish TR 3.2.2 and IEEE 1547 Category A, whereas IEEE 1547 Category B and VDE 4105 employ a narrow deadband, affecting activation sensitivity and response speed [65], [25]. Under increasing EV and DER penetration, proactive curve designs can strengthen distribution-level voltage support, a consideration that is particularly relevant for emerging regulatory frameworks in Latin America [46] as presented in Figure 7.

The heat map summarizes jurisdictions that have adopted grid codes or technical standards specifying Volt/VAr capabilities for inverter-based resources, highlighting IEEE 1547-2018, AS/NZS 4777.2, VDE-AR-N 4105, EN 50160/IEC 61851, and GB 36547-2018. Color levels indicate reported adoption and prescriptiveness, reflecting evidence from surveyed sources rather than an exhaustive legal inventory.

F. What technical, operational, and regulatory challenges limit effective Volt–VAr control in Latin American distribution networks with high DER/EV penetration, and what advances have been proposed to address them?

In recent years, many Latin American distribution networks have experienced rapidly increasing penetration of distributed energy resources (DER), particularly photovoltaic generation, along with growing electric vehicle (EV) adoption. High PV output can drive voltage rise during midday conditions, while uncoordinated EV charging can intensify voltage drops, transformer loading, and feeder congestion [28], [31]. These effects are exacerbated because a large share of distribution infrastructure was not originally designed for bidirectional power flows, fast variability, and highly unbalanced operating conditions.

A central challenge for Volt VAr control in this region is phase imbalance, driven by the prevalence of single-phase loads and residential DER. Field evidence from countries such as Mexico illustrates that imbalance is recurrent in low and medium-voltage networks, complicating voltage regulation and reactive power dispatch [29]. In parallel, legacy voltage control assets such as on-load tap changers (OLTCs), step voltage regulators, and switched capacitor banks tend to provide slow and discrete control actions. Under frequent PV and load variability, these devices may suffer increased mechanical wear and elevated operating costs, and they may be ineffective against rapid voltage fluctuations [17].

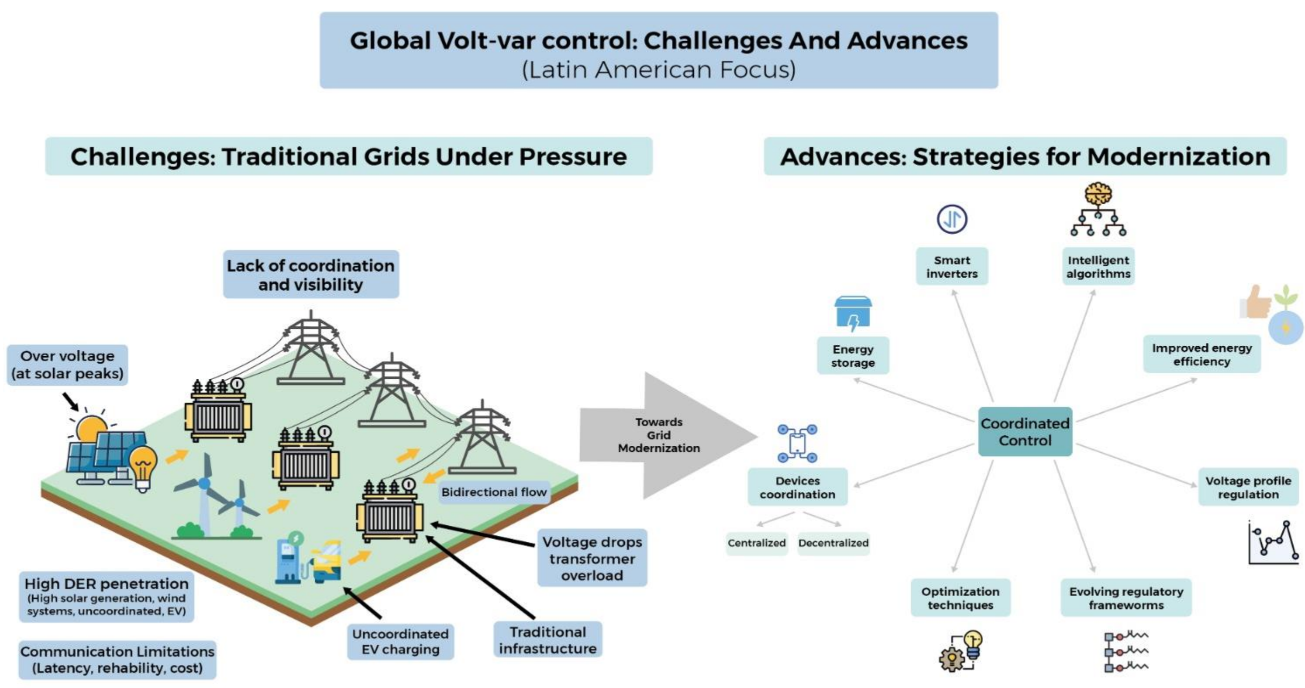

Fig. 8 Challenges and advances in Volt/VAr control for DER- and EV-rich distribution grids (Latin America focus)

Multiple studies in Mexico, Brazil, and Costa Rica report that poor coordination between DER controls and conventional voltage regulation devices can lead to conflicting actions, oscillatory tap behavior in OLTCs, and local voltage excursions, reinforcing the need for coordinated Volt VAr schemes tailored to Latin American feeders [23], [29], [66].

Another persistent barrier is limited visibility, particularly in secondary low voltage systems, because medium voltage instrumentation may not capture customer level voltage problems, constraining both diagnosis and closed loop control [66]. Finally, communication infrastructure limitations, including latency, reliability, coverage, and cost, remain practical obstacles for implementing real-time coordinated or optimization-based Volt VAr control in several countries[29].

To address these challenges, regional research increasingly proposes coordinated control frameworks that combine legacy devices such as capacitor banks and voltage regulators with emerging technologies such as smart inverters and energy storage systems [23], [7], [38]. Both centralized and decentralized approaches have been explored, often supported by optimization or intelligent algorithms, aiming to improve voltage profiles, reduce losses, and mitigate overvoltage and reverse power flow impacts under high DER penetration [23], [29], [67].

Several works also emphasize that Volt VAr strategies should be adapted to Latin American system characteristics, including predominantly radial topology, high renewable variability, and evolving regulatory requirements, so that technical performance and implementability are aligned with local operational constraints [22],[68], [57]. Collectively, these advances position Volt VAr control as a key enabler for distribution modernization in Latin America. Figure 8 synthesizes the main technical, operational, and regulatory barriers reported for Volt/VAr control in Latin American feeders and summarizes the modernization strategies proposed to overcome them.

A cross-comparison indicates that no single Volt/VAr strategy is sufficient under high DER/EV penetration. Conventional devices remain useful for slow baseline regulation but are limited by discrete operation and mechanical wear. Smart inverters and EV chargers provide faster local support, although their effectiveness depends on coordination, communication availability, and suitable Q(V) curve settings. Optimization- and AI-based methods improve adaptability under uncertainty but require greater observability, reliable data exchange, and validation beyond simulation. Therefore, the most implementable pathway for Latin American feeders is staged coordination between existing regulation devices, inverter-based resources, and simplified supervisory control adapted to local sensing and communication constraints.

IV. Final Considerations

This review showed sustained growth in Volt/VAr control research from 2000 to 2025, with a clear shift from device-centric regulation toward coordinated control in active distribution networks driven by DER and EV integration and by the adoption of inverter grid-support requirements such as IEEE 1547-2018. The keyword structure indicated as consolidation around four coupled fronts: (i) optimization-based VVC with legacy devices, (ii) data-driven and AI-enabled coordination under uncertainty, (iii) inverter-based reactive-power and power-quality control, and (iv) PV-centric voltage regulation where power electronics become key actuators. Together, these findings support multi-timescale architectures combining slow legacy assets with fast inverter and EV-related actions.

Methodologically, most studies rely on distribution simulators and power-flow engines integrated with optimization and machine-learning toolchains, with MATLAB/OpenDSS remaining prevalent and increasing adoption of Python environments and deep-learning frameworks.

For Latin America, the literature highlights persistent implementation barriers, including phase imbalance, limited low voltage observability, and communication constraints, which complicate real-time coordination under PV-driven voltage rise and EV-driven voltage drops. Proposed advances converge on coordinated frameworks that integrate OLTCs, regulators, and capacitor banks with smart inverters and storage under centralized or decentralized schemes adapted to radial feeders and evolving regulation.

Finally, reported grid-code diffusion of Q(V) requirements across multiple jurisdictions indicates increasing regulatory maturity and provides a reference pathway for implementable VVC adoption. Future work should prioritize field-validated, unbalance-aware three-phase coordination under realistic sensing and latency limits, including explicit device-wear constraints and joint optimization of inverter setpoints and EV charging.

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