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Control strategies applied to distribution networks with the integration of distributed energy resources - A review

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Abstract. The continuous integration of distributed energy resources (DERs) in power systems has opened the need to propose control strategies that tend to mitigate the possible impacts that an unlimited integration can produce. Authors have presented studies that present different control strategies that take advantage of the devices already present in the network or of new elements added, such as DERs. Also, different control architectures that can take full advantage of the capabilities that DERs can offer are studied. Therefore, this article focuses on reviewing the recent literature related to control strategies and architectures applied to distribution networks with DERs as protagonists. The control strategies that exploit the characteristics of DERs to perform control actions are described, and the control architectures adapted to the integration of DERs in distribution networks are detailed. Device modeling approaches are also mentioned, considering that some DERs depend on random variables and can introduce uncertainty in the analyses if their behavior is not modeled correctly. Finally, current and future trends in this area are discussed.

Keywords. Control architectures, control strategies, deterministic approach, Distributed Energy Resources, stochastic approach.

1. Introduction

According to REN 21, in 2022, there was an increase of 348 GW in installed renewable energy capacity, with solar photovoltaic (PV) accounting for 25%. Additionally, there has been a general trend of growth in the use of energy storage systems and electric vehicles (EVs) over the past decade, with a 24% increase [1].

The integration of new technologies in electrical grids, such as distributed energy resources (DER), requires physical and operational adjustments in the electrical system [2]. Several studies have shown that the high penetration of DERs can have an impact on technical aspects, such as changes in power quality parameters, variations in voltage profiles, and effects on protection coordination and grid reliability, among others [3]–[5].

Johansson *et al.*[4] suggest that integrating EVs into the power system excessively may cause congestion problems and an increase in peak demand. Similarly, Zeraati *et al.*[6] have demonstrated that a high penetration PV inverters in distribution networks can cause regulation disturbances and voltage level imbalances.

To address the challenges posed by the negative impacts of integrating new technologies on distribution network operations, control strategies for both active and reactive power have been developed.

In general, these strategies are effectively applied to regulate voltage magnitude within the limits established by regulations. However, it has been observed that active power control, particularly generation curtailment, is ineffective in distribution networks where current unbalance and undervoltage are to be corrected [7]. On contrary, reactive power control is proposed as a viable solution to correct imbalances and regulate voltage [7], [8].

In this context, control strategies can be implemented using two types of architectures: those based on communication, such as centralized, decentralized, and distributed schemes, or autonomous ones, such as the local scheme [9]. However, due to the multiple levels of integration in distribution networks and the variability in the operation of DERs, it is necessary to consider a coordinated control scheme. This approach allows taking advantage of the benefits of different control architectures by applying them specifically at each level of the coordinated control scheme.

In addition, the stochastic nature of demand and the uncertainty and variability of new grid-integrated technologies (PV systems and electric vehicles) have created the need to analyze distribution networks from a stochastic approach [3]. The analysis of electrical networks is typically approached deterministically with fixed operating values. However, in recent years, a stochastic approach has been used to model the behavior of devices and DERs for studies on their impacts on electrical networks [3], [10].

As the integration of DERs into distribution networks continues to grow, it is important to seek alternative solutions to mitigate their negative impacts on the electrical network. New control strategies should aim to coordinate the operation of network devices, while considering the penetration levels of DERs and regulatory restrictions that must be met during steady-state operation.

Similarly, control strategies must consider the variability and uncertainty inherent in generation and demand to accurately analyze device behavior.

This review of the state of the art explores various approaches to control strategies using DERs for control action. The authors aim to address the following questions: i) How have DERs been integrated into distribution network control strategies? ii) What control architectures are employed with DERs in distribution networks? and iii) What modeling approaches have been used in control strategy studies?

This document is structured as follows: Section 2 presents the methodology used for the literature review. Section 3 discusses the different control strategies applied with DERs. Then, Section 4 shows the control architectures used in distribution networks when DERs are integrated. Section 5 presents the two modeling approaches used in control strategy studies, and finally, Section 6 presents the main conclusions of the state-of-the-art review.

2. Methodology

This literature review follows the methodology detailed in Figure 1. The authors used the database SCOPUS and the bibliometric tool VOSviewer to identify relevant studies on the main topic.

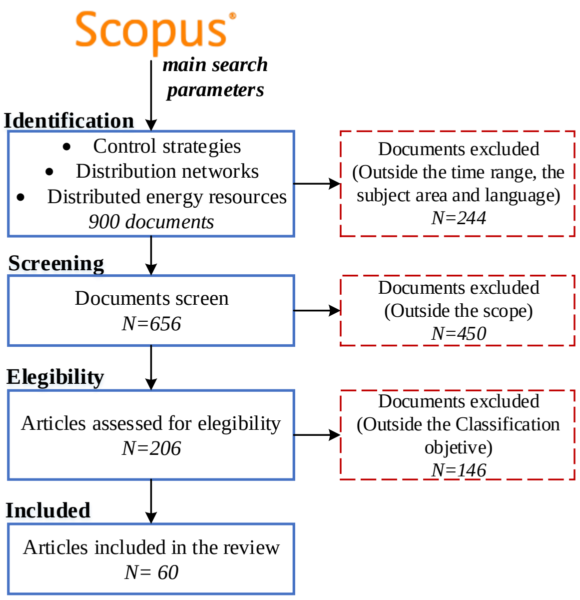

Fig. 1. Literature review methodology.

Initially, a search was conducted in the SCOPUS bibliographic database using the key parameters: 'control strategies,' 'distribution networks,' and 'distributed energy resources.' A first filter was applied to the results, taking into account the time period, subject area and language of the documents.

The third phase of the methodology involved an additional filter through a bibliometric analysis of the keywords present in the documents, using the VOSviewer tool. This allowed for a clearer understanding of the key aspects addressed in the literature review.

Finally, the authors carried out a classification of the articles in order to answer the questions posed in section 1. This allowed them to discuss the current state of the topic, identify any shortcomings found, and propose possible directions for future work.

3. Control strategies with DERs

Control strategies have been proposed to exploit the characteristics that distributed energy resources (DERs) bring to the grid. These strategies are categorized into Active Power Control (APC), which includes demand response programs [11], generation curtailment, and the use of storage systems, and Reactive Power Control (RPC), which uses the reactive power available from the DERs themselves [12]. Table I present a summary of the general characteristics of the control strategies applied with DERs.

Table I. General characteristics of control strategies applied with DERs

	Strategy	Control variable	Operating device	Variable to be controlled
APC	Generation *curtailment*	Active power	PV inverter	Voltage (Overvoltage)
	Storage systems		Battery	Voltage (Overvoltage and undervoltage)
	Demand respond		Customer	Voltage, loadability
RPC	PV systems	Reactive power	PV inverter	Voltage (profile and unbalance)
	Electric vehicles		EV charger	Voltage (profile and unbalance)

A. Active power control strategies (APC)

Active power control strategies are commonly used to address overvoltage issues in power grids and to manage peak demand. It is important to note that these strategies are not limited to these options and may vary depending on the specific situation. These strategies include active power curtailment of PV systems [6], [13], demand response programs [11], [14]–[16], and storage systems [17].

For instance, Zeraati *et al.*[6] propose a distributed control strategy to regulate voltage in low voltage distribution networks with high penetration of PV systems. This is achieved by coordinating the charging and discharging of EVs. The proposal applies two consensus algorithms. One of these implements active power curtailment in PV inverters, while the other determines the power exchange between EVs and the power grid.

Gerdroodbari *et al.*[13] presented a decentralized control strategy applied by PV inverters to control the voltage magnitude of nodes in a grid with high penetration of PV systems. The authors prioritize reactive power before performing active power curtailment to maximize the profits of PV system owners by taking advantage of the inverters' active and reactive power control capabilities.

Demand response programs have been used to alleviate the impacts of demand peaks, save operating costs, and delay new generation investments. In [14] , an algorithm based on demand response programs is introduced to improve network characteristics, such as reliability, voltage profile, and losses. The authors propose a demand response model that predicts user behavior to create new demand profiles, improving grid reliability and reducing power losses.

Storage systems are used to control the active power injected into the grid as an alternative to curtailing PV system generation. The main role of storage systems is to maintain voltage within established limits [17]. Emarati *et al.*[17] propose a two-level control strategy. The first level involves adjusting the taps in the OLTC of the grid and taking into account the battery storage for day-ahead dispatch. The second level involves compensating with reactive power from the PV inverters to correct any possible violations in the voltage profile.

B. Reactive power control strategies (RPC)

Reactive power control strategies are used to ensure that the voltage at the power system nodes is within the specified limits by either injecting or absorbing reactive power into or from the system [12], [18].

Although these strategies have been adopted as a solution to voltage regulation in low voltage networks, their effectiveness is reduced by the high R/X ratio of the conductors [7], [8]. Various strategies have been proposed in literature for applying PV inverters [7], [8], [13], [17], [19] or V2G EVs[20]–[23].

For instance, [7] presents a reactive power control approach for PV inverters to improve the magnitude and voltage unbalance. The proposed methodology involves stepwise control and local measurement of the voltage signal.

In [8], a distributed control scheme is proposed for optimal voltage regulation in unbalanced low voltage networks, considering minimum power losses. In the scheme, local decisions are made using information obtained from node measurements, PV inverter measurements, and sensitivity theory.

However, in reference [20], an experimental validation of a control strategy is presented with three main objectives: (i) tracking a set-point of aggregate reactive power imposed by the grid controller to the EV charging station, (ii) minimizing the usage of the EV battery, and (iii) strategically locating the EV power within the grid. The purpose of the authors is to assess the effectiveness of the real-time control strategy in light of the rapid changes in the grid state caused by variable resources such as PV systems.

Mejia-Ruiz *et al.* [21] propose a hybrid and optimal control strategy to improve the voltage profile of a highly unbalanced distribution network by coordinating reactive power injection from multiple EV charging stations. The authors found that the proposed control strategy enables voltage regulation at all grid nodes, even under extreme operating conditions, when the metering equipment, controllers, and charging stations are dispersedly located in the grid.

Sun and Qiu [23] propose a two-stage real-time control strategy that uses Deep Reinforcement Learning (DRL) to coordinate electric vehicle (EV) charging and prevent voltage limit violations in the grid. In stage 1, they perform day-ahead reactive power dispatch to minimize losses. Stage 2 involves applying the local control strategy, which uses active and reactive power flows from EVs to correct voltage profile violations.

4. Control architectures with DERs in distribution networks

A control architecture is a structure that includes controllers of a control system and the various forms of communication necessary for proper operation. Figure 2 presents diagrams of the architectures traditionally used in controlling electrical variables. These diagrams can be based on centralized control, decentralized control, distributed control, or autonomous local control schemes.

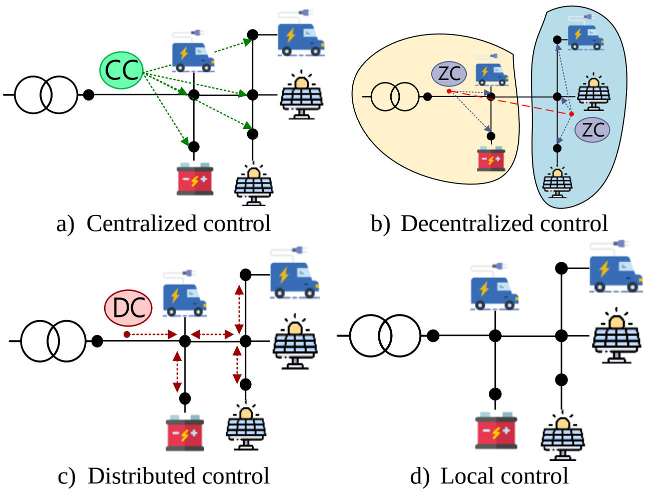

Fig. 2. Diagrams of traditional control architectures

Figure 2a) shows the centralized control diagram. In the control with DERs, they are connected to a central communication unit that calculates the active and reactive power set-points for each device [13], [24]. While the scheme is robust and can provide a global solution to the control problem, it requires a reliable communication network that incurs a high economic investment in its implementation [9], [25].

Figure 2b) shows the structure of a decentralized control diagram, where the electrical network is divided into zones, and each zone has its own controller responsible for solving the corresponding control problem. Decisions made in this type of scheme are partially centralized and distributed without regard to computational processes or information signals [24]. However, this scheme presents a lack of coordination between devices and focuses on meeting local rather than global objectives [9].

The distributed control (Figure 2c) is characterized by the cooperation between the controllers of each device to meet a set-point established by the network operator. Each controller can only communicate with another controller of a device installed in an immediately nearby node, making the power grid capable of solving problems that may arise during operation [25]. This type of architecture has gained attention due to its high robustness to communication failures and near-optimal operation of the power grid [8].

The local architecture diagram is shown in Figure 2d). This architecture does not require a communication infrastructure, making it easily implementable in distribution networks. This architecture has the advantage of responding quickly to the variations produced by DERs, but the lack of coordination between devices diminishes the distributed nature of the devices [13].

A. Coordinated control architecture

Given the increasing integration of Distributed Energy Resources (DERs) into distribution networks and the advancements in communication systems, multi-stage control schemes have been proposed to proactively coordinate DERs and other network-connected devices in an optimal manner [26]. Therefore, it has been proposed to include the concept of coordinating as a more than one-stage control architecture scheme where it is possible to apply a traditional per-stage control architecture as well as several control strategies.

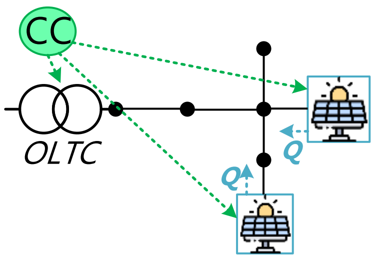

Fig. 3. Example of a coordinated control architecture scheme

Figure 3 presents an example of a coordinated control architecture. The first stage involves centralized control of OLTC transformer taps and generation dispatch. The second stage involves local control of reactive power injection of the PV systems at the grid connection nodes.

This control scheme involves a coordinator and subsystems, each with its own controller. It is used when objectives cannot be met by applying distributed control, with or without communications [25], [27]. The coordinating control architecture has become an effective solution for meeting requirements in terms of voltage control, energy balance, and user and network operator satisfaction [27], [28].

Different ways of applying this type of scheme can be found in the literature. Two-stage schemes propose combining two types of control architecture, such as centralized, distributed, or local control [12], [26], [29], [30]. Other schemes present real-time control stages with measurements at the nodes using PMUs [12], [26], [28], [30], [31]. Finally, some schemes allow for the coordination of device control, such as on-load tap changers (OLTC), capacitors banks (CB), electric vehicles (EVs), photovoltaic (PV) systems, batteries, and controlled loads [26], [27], [30], [31].

For instance, in their article, Wang, John and Xiong [29] suggest a two-level coordinated control scheme for EV chargers to regulate voltage in a LV distribution network. The upper level uses a consensus algorithm to ensure equal usage of all chargers, while the lower level determines the injected or absorbed active and reactive power, taking into account the limits and requirements of each charger. The authors note that there is a limited amount of research on the coordinated control of active and reactive power of EV chargers in LV networks.

In reference [31], they propose a real-time control system that coordinates PV inverters, OLTC, and batteries to address the issue of rapid voltage fluctuations in a distribution network. The scheme aims to ensure that voltage regulation devices are always available to address regulation issues, with batteries providing support during prolonged violations.

Sun *et al.* [30] propose a two-stage cost-benefit coordinated control strategy to mitigate rapid voltage violations while minimizing the total costs of voltage regulation. The first stage involves performing an optimal load flow to determine the day-ahead dispatch with the operation of on-load tap changers (OLTC), capacitor banks (CB), and mobile batteries. In the second stage, real-time control is implemented to regulate the output power of photovoltaic (PV) systems and batteries with one-minute resolution.

5. Modelling approaches in control strategy studies

Power system analysis involves two device modeling approaches: deterministic and stochastic. Each approach has its own considerations when modeling network-connected devices and allows for analysis from different perspectives.

A. Deterministic approach

The approach used in this type of scenario involves fixed operating values for all devices connected to the network, including generators and loads. Control strategies typically employ a deterministic approach with operating scenarios, which includes studying critical cases of DERs integration in distribution networks [32].

For example, Alabri y Jayaweera [7] consider a generation power profile of PV systems that considers setting the maximum power point and constant output voltage provided by a DC-DC converter. Additionally, the authors ensure that the reactive power capacity of the PV system is dependent on the nominal power of the PV inverter.

En [6] the MPPT algorithm is used to maintain a constant power profile for PV systems. The power demand profile for residential users is used as a characteristic profile for the loads and to define the charging and discharging profiles of EVs. The values of charging power, battery capacity, and energy consumption of two devices are also taken into account.

Sun and Qiu [23] employ the trip chain method to estimate the demand profile of electric vehicles. This method describes the daily sequence of electric vehicle use and defines the demand profile of the charging station, taking into account time and space variables.

B. Stochastic approach

Due to the uncertainty and variability of solar PV generation, EV demand profiles, and user consumption, a stochastic approach is necessary to analyze and integrate the various possibilities of operation of these devices in control strategy studies.

One of the most commonly used stochastic methods is Monte Carlo simulations [17], [23], [33]. In [17], the authors describe a method for characterizing the uncertainty of PV generation using the Monte Carlo method. This method involves two parts: first, a Beta distribution is created from historical data of solar generation to propose scenarios, and second, the scenarios that best approximate the behavior of the PV units are selected.

Arshad y Lehtonen [33] use the Monte Carlo method to deal with probabilistic variables such as the location of the PV and OLTC systems within the electrical system under study, repeating an iterative process 1000 times that includes the random selection of the nodes where the OLTC and PV systems are connected.

In [34], a stochastic approach is used to model user demand profiles by creating demand curves with a tool that generates stochastic power profiles that emulate the real behavior of residential users. This is in contrast to the approach taken by Zufferey, Rengeli and Hug [35], who use the quantile forecasting algorithm to predict power consumption, line power, and node voltages, which are the inputs to the optimal voltage control problem proposed by the authors.

6. Conclusion

Different control strategies are employed in the literature to regulate the voltage profile along the network. This can be achieved through the use of conventional control devices such as OLTC, SVR, SVC, and CB, or by taking advantage of the active and reactive power control characteristics of DERs, or a combination of these. The literature has addressed the use of device coordination with various control architectures in the proposed schemes, taking advantage of the benefits offered by each one.

Additionally, the modeling of devices that depend on factors such as meteorological variables for PV systems, or EVs with station arrival times, distance traveled, current battery SOC, among others, is crucial for the performance and validation of control strategies.

In order to deal with time-varying factors in device performance, stochastic modeling techniques are used to incorporate variability and uncertainty in device performance. Although there are few studies that have explored the use of stochastic modeling to represent PV systems, EVs, and user demand curves, it is evident from the literature that this approach is gaining popularity. The variable behavior of these devices poses a challenge to control strategies during the validation phase of their performance in real distribution system scenarios.

Furthermore, the integration of control architectures and strategies for both active and reactive power within a single scheme has the potential to enhance the performance of electrical variables, including voltage profile, voltage unbalance, and losses.

However, further exploration of the performance of possible combinations of control strategies with control architectures is necessary within a coordinated control scheme. Additionally, it is essential to continue incorporating the stochastic approach in both the modeling of network elements and the analysis of load flows.

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