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Review

Analysis of Voltage and Reactive Power Algorithms in Low Voltage Networks

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Abstract: The rapid development of renewable energy sources and electricity storage technologies is further driving the change and evolution of traditional energy systems. The aim is to interconnect the different electricity systems between and within countries to ensure greater reliability and flexibility. However, challenges are faced in reaching it, such as the power grid complexity, the system control, voltage fluctuations due to the reverse power flow, equipment overloads, resonance, incorrect island setting, and the diversity of user needs. The electricity grid digitalization in the market also requires the installation of smart devices to enable real-time information exchange between the generator and the user. Inverter-based distributed generation (DG) may be used to control the grid voltage. Smart PV inverters have the capability to supply both inductive and capacitive reactive power to control the voltage at the point of interconnection with the grid, and only technical parameters of smart PV inverters limit this capability. Reactive power control is related to ensuring the quality of voltage in the electricity distribution network and compensating reactive power flows, which is a technical–economic aspect. The goal of this research is to present an analysis of controllers that supply reactive power to the electrical grid via PV systems. This research analyzes recent research on local, centralized, distributed, and decentralized voltage control models in distribution networks. The article compares various approaches and highlights their advantages and disadvantages. The voltage control strategies and methodologies mentioned in the article can serve as a theoretical foundation and provide practical benefits for PV system development in distribution networks. The results of the research show that the local voltage control approach, as well as linear and intelligent controllers, has great potential.

Keywords: voltage control; reactive power; renewable energy source; distributed generation; controller

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1. Introduction

The rising demand for electricity, together with cost reduction needs and higher reliability requirements, have led to renewed interest in the distributed generation (DG) principles [1]. The use of photovoltaics (PV) is among the key strategic measures to reduce environmental pollution and overcome the energy crisis, as well as a way to develop active distribution networks and smart grids [2]. With high penetration of renewable energy sources (RES), an appropriate online (real-time) control scheme is also needed to optimize voltage and reactive power control in active distribution systems (ADS) [3]. A smart grid is an electrical network integrated with various types of generation sources of various magnitude, with information and communication technologies (ICT), and with power electronics devices for better monitoring and control [4,5]. A large portion of renewables consist of small DG units connected to low voltage (LV) and medium voltage (MV) networks using alternating current (AC) inverters [6,7]. Inverter integration into smart grids can achieve a fuller reactive power control from the transmission system level to the end user one [8].

Voltage control methodologies have been developed to ensure network voltage within acceptable limits [9]. Conventional voltage regulation methods that depend on an on-load tap changer (OLTC) and VAR compensation devices, such as step voltage regulators (SVRs) and switched capacitor banks (SCBs), cannot effectively control the voltage profile as the devices have a slow response, and discrete actions and independent control mechanisms [9–15]. In an LV network, voltage is regulated by manual branch switches instead of automation. Usually, branch locations are calibrated and moved only when the network is expanded or modified [1]. Power controllers, such as flexible AC transmission systems (FACTS), may also be categorized as applied control methods [16]. There are many corrective and preventive control actions to mitigate voltage issues, but most of them are either expensive or impractical. Moreover, some control actions, such as switching transmission lines by using flexible AC transmission system devices and synchronous capacitors, are commonly used at the substation level despite reasonable costs and are not useful in distribution systems [8].

The existing inflexible voltage control strategies in LV and MV networks, the growing penetration of distributed energy resources into distribution networks (DN), and sudden load increases due to electric vehicle charging may lead to various issues, such as those related to stability, protective devices, and voltage regulation [17–20]. Interferences may cause overvoltages, undervoltages, higher system losses, and a shortened life cycle of the on-load tap changer (OLTC) [3,21].

There are two main reasons for voltage imbalances in LV distribution networks. Primarily, single-phase and three-phase loads are distributed randomly throughout the network, and their instantaneous demand is constantly changing. Secondly, small-scale single-phase generators are installed disproportionately over the three phases [1]. Thus, one of the key network operation problems is overvoltage due to reverse power flow or voltage limit violation (e.g., ±5% of nominal voltage) in the distribution network due to high PV penetration [1,3,22]. The Volt/Var issue in distribution systems may be seen as a system control or planning process [13].

To mitigate the voltage control issue, scientific articles mainly focus on the following three aspects: active power control (APC), reactive power control (RPC), and active and reactive power coordination control (A/RC) [2]. Based on a coordinated approach to voltage profile control in power lines, the reactive power resources of the generator must be regulated so that all voltages are kept within range without unduly affecting their operation [17]. It is therefore necessary to properly plan for the penetration of variable RES in order to meet the techno-economic criteria for the DN operation, including loss reduction, voltage stability improvement, voltage profile enhancement, etc. [23]. Harmonizing controls of all reactive power sources is needed, which can only be done by calculating steady states (SS) for each network segment [24]. Recently, a number of distributed voltage control methodologies have been proposed for LV DN, using either reactive power supply or active power reduction [1]. Thus, in recent years, the need to select/develop appropriate control methods in order to enable consumer power supply compliant with power quality and reliability standards (PQR) has become an urgent issue [18].

The latest technological achievements in distribution networks have caused a growing interest in the issue of voltage regulation by using distributed energy resources (DER) of inverter interfaces [19]. Control of reactive inverter power compatible with DG is a way to solve this issue [16]. Smart PV inverters are considered a promising reactive energy resource that has not been allowed under current standards. The reactive power capability of PV inverters is limited by the instantaneous generation of active power, and their reactive power is limited to the maximum apparent inverter capacity [22,25]. Thus, reactive power control strategies alone cannot provide sufficient voltage regulation when PV power is high. Active power reduction is considered another lucrative option together with reactive power control to prevent distribution overvoltage. Moreover, voltage may be better regulated by reducing the actual power, given the resistive nature of the distribution network (high R/X ratio) [22]. However, the rapid growth of renewables has led to a revision of the existing standards so that distributed resources can play an active role in regulating power supply voltages in general [22]. As well as reducing the voltage rise, inverters can also mitigate sudden voltage drops or undervoltage scenarios using capacitive VAR compensation [22]. As the physical characteristics of inverters are fundamentally different from those of conventional electric generators, i.e., synchronous generators (SG), they require different control methods [6].

The demand for electricity and the penetration of small-scale distributed generators are rapidly growing in LV distribution networks, thus, the existing electrical systems will need future adjustments. Inverters for distributed energy resources (DERs) have been released with standards and grid codes for interconnection with the distribution grid. To include increased DERs' penetration and optimize DERs' value to the grid, the new standard and grid codes anticipate DERs to perform a range of power system support roles. The following are more widespread measures to detect violations of the upper voltage limit: voltage and reactive power control by PV inverters, demand response (DR), and storage.

This article analyzes the literature on voltage and reactive power control in the electrical network. The aim of the study is to present a design methodology for controllers that supply reactive power to the electrical network via PV systems. Each controller's advantages and disadvantages are discussed, as well as comparisons to previous controllers.

This article differs from others as it provides a detailed analysis of voltage control methodologies, and includes the most recent research and prospects.

The main contributions of this article are as follows:

- The literature was selected following a chronological review of scientific publications, programmes, and projects related to issues of voltage control; a structured and systematic analysis is proposed.
- This article is different in that it explains the fundamental differences and similarities between voltage control techniques in detail.
- Differently than in many other studies similar to this one, this article analyzes the controllers for voltage and reactive power control.
- The voltage control strategies and methods overviewed in this article may serve as a theoretical basis and provide practical benefits for the development of PV systems in the distribution networks.

2. Voltage Control Schemes

Due to the stochastic and non-uniform character of DERs, the number of control points and control devices will inevitably increase, considerably increasing the system operator's burden at the secondary control level. Due to system communication and control bandwidth, the position may become impractical for real-time control in some circumstances. This potential control difficulty will be mitigated through autonomous operation and decentralized control.

Controlling the voltage and reactive power of a network necessitates the geographical and temporal coordination of several on-field components and control functions, which a hierarchical control system may provide. The different levels in hierarchical control schemes are: (a) the primary level, which supervises the control of the DER units; (b) the secondary level, which is responsible for the system voltage and frequency modification in coordination with the primary level; (c) the tertiary level, which is the core control of the system and includes demand–supply management, storage management, renewable integration, power flow control, parameter optimization, and control strategies.

In LV distribution networks with PV (photovoltaic) systems, power usually flows from the low voltage (LV) distribution transformer to the nodes at the load voltage ends, which reduces the voltage across the power line. However, when users start supplying active power generated by PV systems to the network, the reverse power flow appears to increase the voltage and exceed the permissible voltage range [26]. The PV system usually reaches its peak around noon, which indicates that the inverter is not fully utilized most of the day. As a result, the remaining inverter capacity may be used for providing services, such as reactive power compensation, voltage control, and overvoltage reduction [27]. In general, four forms of reactive power control functions can accomplish voltage regulation capability: constant power factor (PF) mode, PF-active power (PF-watt) mode, voltage-reactive power (volt-var) mode, and voltage-active power (volt-watt) mode. The reactive power requirements in Figure 1 vary by country, and various grid codes have varied clearing time values for voltage ride-through and frequency ride-through requirements.

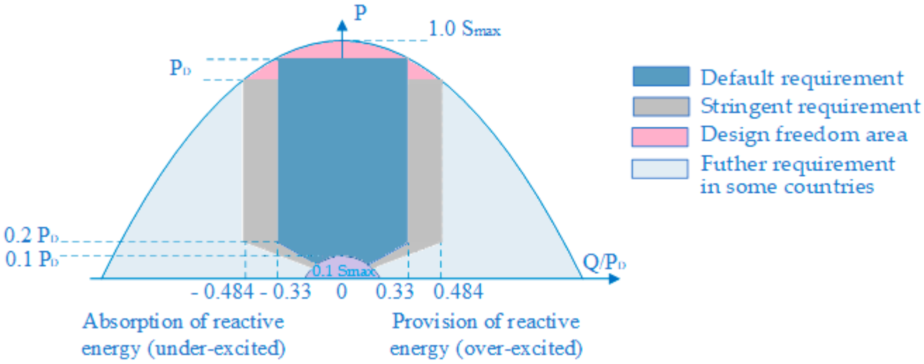


Figure 1. Reactive power needs of distributed energy resources.

Control requirements for voltage and reactive power are anticipated to grow more strict in the future. It is believed that the reactive power will be controlled using the characteristics that can be seen in Figure 1. Lithuania, for example, intends to use these qualities in power plants with a capacity of more than 3.6 kW.

Failure to implement a reasonable and efficient voltage regulation will seriously affect the safe and stable operation of users' electrical equipment [15].

Voltage control schemes may be grouped into communication-based (centralized, decentralized, distributed), local (or autonomous), and hybrid (e.g., communication–local) [10,21,27,28].

2.1. Communication-Based Schemes

2.1.1. Centralized Control

Voltage is controlled by an on-load tap changer (OLTC) of a secondary distribution transformer located at the central substation of the low voltage (LV) network. Moreover, a communication infrastructure is required to measure data of all the network users [1]. One central coordinator (CC) is responsible for collecting the necessary information from the network [12,29,30], potentially through smart meters and/or remote terminal devices installed in households, for providing problem solutions via suitable communication connectors, and for responding to setpoints of intelligent electronic devices (IED) [1,12,31]. The control scheme allows optimizing the operation of the LV distribution network both on the local and on the regional basis, by setting an overall limit beneficial both for generators and users [26]. The central coordinator is the only network component that can initiate a control action while achieving global optimality [28,30,32]. In order to regulate voltage in the distribution line and keep it within the acceptable range, the central coordinator needs to know the accurate voltage of each network node [12].

Centralized control schemes use network-wide optimization to achieve optimum active/reactive input setpoints for the inverter(s) [22].

A centralized control scheme is provided in Figure 2, where CC is the central coordinator and IED means an intelligent electronic device (controller).

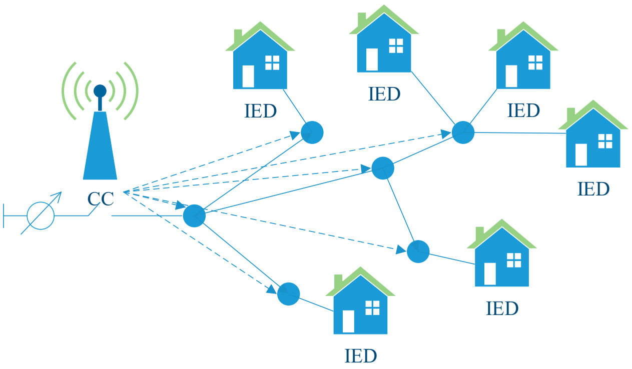


Figure 2. Example of centralized voltage control strategy [28].

Centralized control advantages:

1. With all the centrally available system information, the VAR control problem may be identified as optimal power flow (OPF), which reduces system operating costs such as power losses and voltage violation [19].
2. Centralized methods may be better, especially in small-scale systems [25].

Centralized control disadvantages:

1. It has no specialized control unit that could individually control the distributed generation (DG) devices [4].
2. Qualitative real-time measurements are needed to control loads and distributed generation (DG) power [3,19].
3. During the restructuring steps, the system parameters need to be updated by changing the network topology [3,4].
4. In order to adjust each subsystem, the controller of the entire system must be readjusted, and only local changes are insufficient [4].
5. If a system part needs replacement, the generation must be suspended [4].
6. Convergence issues are complex [3].
7. Communication issues due to geographical location are possible [3,4].
8. In such control schemes, the calculation of control actions often depends on the problem of formulating the optimal power flow (OPF) and requires an expanded communication infrastructure and a network model [31].
9. Significant investment into control centers, devices, and control systems is required, and all centralized methods require a highly reliable communication channel through a common DN, which may lead to obstacles due to geographically remote systems [4,6,18,21,25,27].
10. A high level of reliability and security of the central coordinator is required to prevent failures [4,8].
11. Practical adaptations of centralized control are very likely to be complicated in smart networks due to communication issues [8].
12. To regulate voltage in the distribution network and keep it within the permissible range, the central coordinator needs accurate voltage information of each network node. For instance, 11 kV distribution networks take real-time measurements only at the primary substation. Thus, making sufficient real-time measurements on power lines is seldom possible. This shortage of real-time measurements needs to be compensated by calculated measurements [12].
13. If the control center fails, the system cannot be operated [8].

2.1.2. Decentralized Control

This represents an intermediate state between centralized and distributed control [28,31,32].

As demonstrated in Figure 3, decentralized voltage controllers influence the voltage curves by adding a voltage step using an OLTC; ZC stands for zone coordinator.

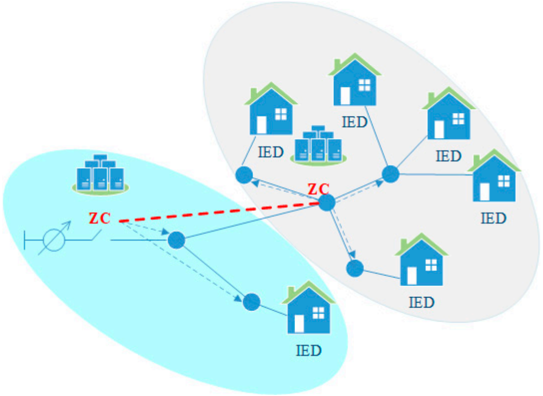


Figure 3. Example of a decentralized voltage control strategy [28].

In the case of decentralized control, the electrical network is divided into zones, where each zone includes local controllers and an individual zone coordinator that operates in the zone the same way as a central coordinator [27,28,31]. Each control unit operates only on the basis of local information [29]. Once a control setting is received, the inverter operation does not need any other control settings from the central entity [31]. The uniqueness of decentralized control is that communication with other RES is not necessary, which provides plug and play capabilities [4]. However, to achieve a specific purpose, coordinators can interface for control purposes in the same way as in the case of distributed control [28].

The key issue with OLTC transformers or voltage regulators is that the permissible voltage rise step is limited if there is a load near the voltage regulator, which is common in LV distribution networks; thus, additional voltage regulators along the power line are necessary [26].

Decentralized control advantages:

1. Applying decentralized control in DG allows the DN to provide additional services, such as back-ups and voltage maintenance [18].
2. As systems are flexible, they can reduce network losses and increase electrical network capacity [18].
3. Decentralized voltage control methods can respond faster than centralized as they only use measurements of local voltage and/or PV power generation and can therefore be used in real time [22,29].
4. DG can provide additional services to the DN, such as storage (backup services) and voltage maintenance [18].
5. Their flexibility may have a positive effect on loss reduction and higher generation capacity [18].
6. This control strategy interacts with the intermediate level of the network, which means that low voltage (LV) systems may be grouped into separate cells using intelligent, controlled substations [26].

Decentralized control disadvantages:

1. Decentralized methods assume that subsystem interoperability is negligible, but this assumption is not always justified and may lead to system-wide poor performance [4].
2. The dynamics of the distribution system must be well interfaced, and if the control systems are designed without taking these interfaces into account, the system performance deteriorates due to the operation of local controllers, and may potentially cause the system instability [29].

2.1.3. Distributed Control

In a distributed control system, devices are controlled in a distributed way, without a centralized control entity [30,31]. Distributed control means that physically close agents are allowed to communicate, and they can share information in order to work together aiming for predefined goals. Thus, having general information of the network (i.e., the status of all the nodes) is not needed to identify a control solution [28,29,33]. Distributed coordinators often use local information to control each device individually [31]. The purpose of the distributed coordination structure is to achieve an autonomously operating electrical network that could effectively cope with issues that may arise from local interaction alone [28]. A control task assigned to different devices is based on operation at different time intervals and is considered to be a hierarchical control system (primary, secondary, tertiary). At higher levels (secondary and tertiary), the need to distribute methods arises from the desire and need for higher reliability, security, and situational awareness [4].

A distributed voltage control scheme is provided in Figure 4 where DC means distributed coordinator.

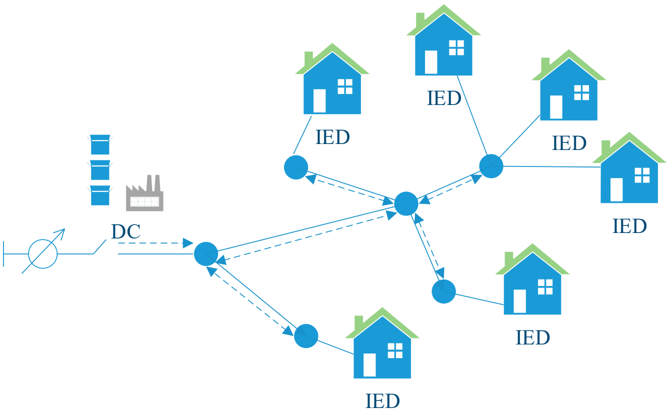


Figure 4. Example of a distributed voltage control strategy [28].

Distributed control advantages:

1. Compared to centralized control, this control type can distribute calculation and communication tasks between local controllers operating in parallel [30,34].
2. Failure of one controller does not result in the failure/stopping of the entire system [30].
3. Distributed control is more suitable for future electrical networks, where distributed generation, fast optimizing calculations, fast response speed, and plug and play capability are highly significant [35].

Distributed control disadvantages:

1. In general, the efficiency of voltage regulation is lower than that of centralized control [8].
2. The use of reactive power at the line end nodes may result in insufficient reactive power in local regions, as end-users behave stochastically, and their consumption fluctuates stochastically [8].
3. If communication between the neighboring agents is not ensured and the amount of reactive power in the local region is insufficient, the subsystem cannot communicate with other neighboring agents and address its issue [8].
4. If the local control center is damaged, the local regional control system will not be used [8].
5. Applying distributed control to distribution systems with highly significant distributed generation (DG) requires a special communication infrastructure and may therefore be unviable, especially in the case of the existing distribution systems where such infrastructure is non-existent [29].

2.2. Local (Autonomous) Control

In the regulation and use of PV systems, Germany was the first to propose the VDE-AR-N 4105 code to ensure a reliable standard enabling residential PV systems to supply active power to the network through a local reactive power controller in order to control power generation [26,36]. The standard provides a reactive power control strategy, a power factor (PF) control strategy, a cos $(\varphi)(P)$ control strategy based on PV active power output, and a Q(U) control strategy that regulates reactive power based on the voltage level of the connected point [15,36]. User PV inverters are used for reactive power supply Q(U) and active power reduction P(U), and the inverters are synchronized with local connection points where measurements are made [1].

The local (autonomous) control strategy is based only on the value of each user (just measurements at the common connection point), without taking into account the impact on the neighboring users [10,26]. An example of a local voltage control strategy is provided in Figure 5.

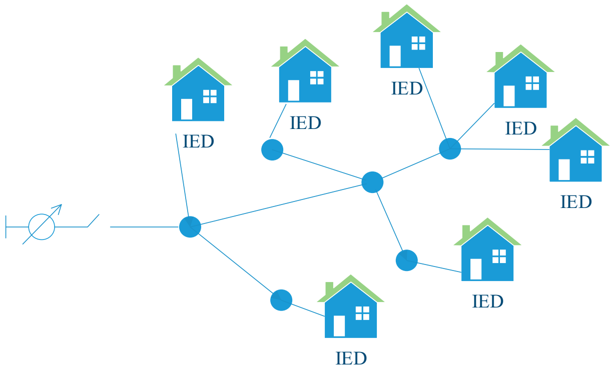


Figure 5. Example of a local voltage control strategy [28].

Thus, these schemes may not guarantee the optimum control of the intelligent LV distribution system [26]. Local control is instantaneous and uses only data obtained where a PV is located [37].

Local control schemes (also known as droop-based control strategies) provide local control of reactive power supply through the characteristic curves [26]. There are several methods that are attributed to local control through PV inverters on the user side [38,39]. First, Q(U) droop control (reactive power output is a node voltage function), and second, Q(P) droop control (reactive power output is a PV active power function). The Q(U) method may cause an instability issue if the droop curve has incorrect parameters, and the Q(P) method does not take this concern into account [27]. The Q(U) method is primarily applied when any voltage limit is violated in order to limit the amount of reduced active power. However, the amount of reactive power may be insufficient to maintain the voltage profiles within the permissible range [1]. An example of a Q(U) method is provided in Figure 6.

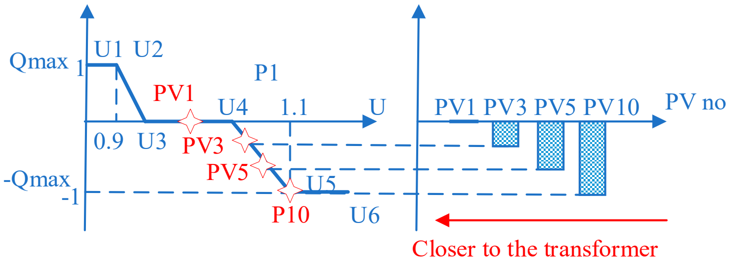


Figure 6. Q(U) method [26].

Figure 6 shows the QV control curve, which is made up of six points (U1, U2, U3, U4, U5, U6). The positive value of reactive power implies that the PV generation is injecting capacitive reactive power, whereas the negative value shows that the PV generation is absorbing inductive reactive power. The local voltage control dead zone [U3, U4] is where inverters are unable to generate reactive power. Maximum reactive power provision and absorption voltage thresholds are set at 0.9 p.u. and 1.1 p.u., respectively. Only two parameters, U3 and U4, need to be specified in order to establish this control curve. When U3 equals U4, the 6-point control mode transforms into a 4-point control (U1, U2, U5, U6).

$Q_{\max}$ in Figure 6 is formulated by (1)

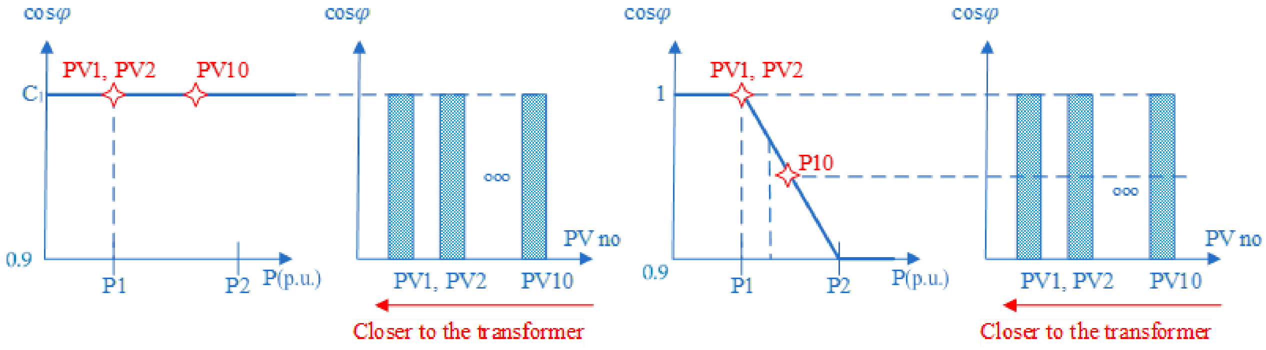
$$Q_{\max} = \sqrt{(S_{\max})^2 - (P)^2} \tag{1}$$

where $Q_{\max}$ is the PV inverter's current maximum reactive power. The PV inverters up-per capacity limit is known as $S_{\max}$. PV's active power output is denoted by P.

The voltage level grows with distance away from the transformer in a single branch radial distribution network, and under the Q(U) method, the DER inverters absorb more reactive power as the voltage level increases.

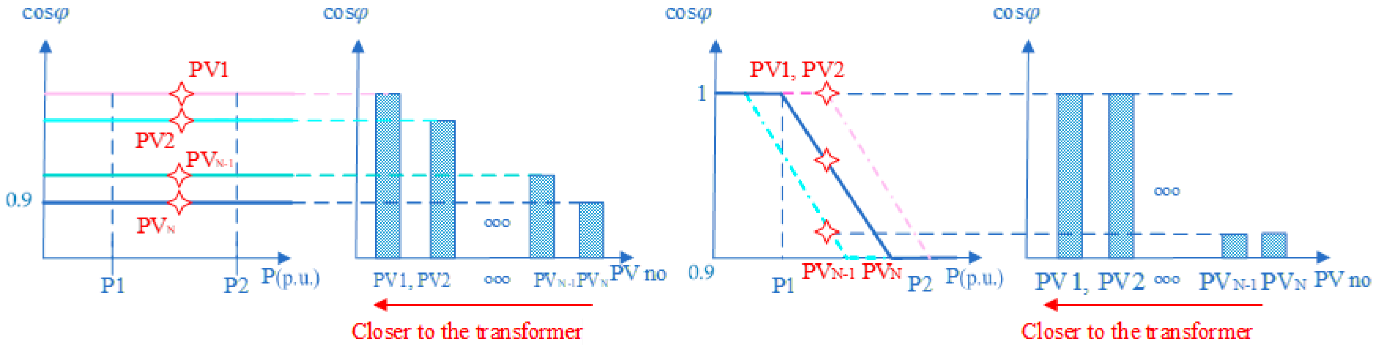
The fixed cos (φ) method, cos (φ)(P), fixed PF method with location, and cos (φ)(P) method with location variance schemes based on the droop characteristic are provided in Figure 6 [26].

In the constant PF technique, DER inverters must operate at a target PF set by the power system operator, independent of DER location or feed-in active power levels, as illustrated in Figure 7a. cos (φ)(P) controls the PF as the active power function, and the maximum power factor is 0.95 [36,38,39]. This method has a clear possibility of regulation, but does not take into account the actual network voltage and may, therefore, cause unnecessary Q flows and losses [38,39].



a. Fixed cos(φ) method

b. cosφ (P) method



c. Fixed PF method with location variance

d. cosφ (P) method with location variance

Figure 7. (**a**). Fixed cos (φ) method, (**b**). cos (φ)(P) method, (**c**). Fixed PF method with location, (**d**). cos (φ)(P) method with location variance schemes [26].

The cos (φ)(P) approach adjusts the PF as a function of the active power output following a target piecewise linear PF-watt characteristic as illustrated in Figure 7b. to prevent reactive power flow via inverters when the risk of overvoltage is low.

Figure 7c shows a constant PF technique with location variation, where inverters closer to the transformer absorb less reactive power and inverters farther away absorb more reactive power as the voltage sensitivity to reactive power grows with distance away from the transformer.

The cos (φ)(P) method with location variance is shown in Figure 7d, which allows inverters near the essential bus to run with a lower curve (green line) and inverters near the transformer to operate with a higher curve (purple line), allowing for more efficient use of reactive power.

The left part of the figure includes the droop control schemes, and the right part includes intelligent PV inverters that determine the reactive power [26].

The cos (φ)(P, V) approach may be created by combining the benefits of the cos (P) and Q(V) methods. This technique generates a Power Factor (PF) limit for each PV inverter based on the droop function of Q(V), then gives a target PF to each inverter based on cos (φ)(P).

The above shortcomings are eliminated by Q(U), as it generates or uses reactive power if the voltage at the connection point outside the dead-band reduces the network losses. The efficiency of the methods depends on the R/X ratio and the voltage distribution in the power line [38,39].

Local control strategies may be classified based on the following variables:

1. tan ϕ = f(u): Tangent ϕ control based on the voltage of the point of common coupling (PCC). This method includes two conditions: a normal operating situation where no control action is required, and a situation where the first voltage limits are violated.
2. q = f(u): Reactive power control based on the voltage of the point of common coupling (PCC). It is similar to the one mentioned above, but reactive power is directly modulated by the voltage measured on the PCC.
3. tan ϕ = f(p): Tangent ϕ control is based on active power injection.
4. q = f(p): Reactive power control based on active power generation injection [21,40].

Local control advantages:

1. Less communication is required compared to the centralized method as information needs to be exchanged only with the secondary substation. Reactive power output depends only on locally measured data [1,27].
2. These schemes may quickly respond to distributed generation (DG) variability and are not affected by communication failures [28].
3. Local voltage control methods may respond faster than centralized ones as they only use measurements of local voltage and/or solar energy generation and may therefore be used as online ones [1,19,22].
4. Local supply of reactive power reduces distribution losses and line load in distribution systems [32].
5. Due to the existing condition of the low voltage network, local control is the most practical compared to other control methods or other strategies [27].

Local control disadvantages:

1. As there is no coordination, the full potential of distributed control devices is underexploited, which may lead to sub-optimal control solutions [28,41].
2. Calculation complexity is the key obstacle in determining voltage fluctuations as the response to power fluctuations in the distribution networks [1].

2.3. Hybrid Methods

Hybrid methods include combinations of various voltage control schemes aiming for the most efficient solution of voltage and reactive power control in a low voltage network, such as centralized and local control (for example, Q(U)/OLTC or Q(U)/P(U) + OLTC), centralized and decentralized control, etc. [1]. The hybrid method combines decentralization and grid assurance and allows users to collaborate in microgrids of varying sizes that are linked to the centralized grid. Users in these regions have a constant interest in choosing between local supply and the centralized grid, which they employ when local output is insufficient or surplus. Users can pick the quality of their electricity by investing in storage technology or contracting with the grid, which serves as an insurance provider. Production exchanges can occur across microgrids, but physical transfers are technically regulated by the centralized grid, which must maintain a good overall perspective of the system and guarantee general supply and demand balance. Both the local and centralized systems are in charge of investments. It has the disadvantage of double the standard network and local loops, which necessitates large investments that users may be unwilling to make [1,42,43].

Result analysis and discussion: Centralized control requires accurate real-time knowledge of the DN's state, as given by a state estimation algorithm, as it consists of close-to-real-time optimization and control of the network. It is difficult to achieve the demand for quick voltage and reactive power regulation using centralized control, which is constrained by computational and communication costs. The centralized voltage controller must collect network-wide measurement data and perform a huge number of difficult computations. Because the central controller must gather and analyze all of the data for reactive power optimization, the volume of the data generated as a consequence of the large-scale integration of DGs is projected to pose a communication bottleneck in the near future. Another critical problem is the cyber–physical systems' resilience. As a result, the controller becomes a target for both cyber and physical attacks. It is probable that the information transmission failure will coincide with the collapse of major information network accidents in the event of a centralized controller. Worse, massive increases in the range of controlled devices with complicated control needs are widely dispersed throughout distribution networks. This type of control is impractical when power sources are scattered over a large area with substantial distances between them since if the control operator fails to assure control for any reason, the entire system may cease to operate.

Decentralized voltage regulation makes use of local data to improve grid functioning by adjusting the voltage of the monitoring point independently. This voltage regulation approach does not require a large quantity of reactive power injection or reactive power absorption and can offer efficient voltage regulation while saving a significant amount of money on centralized control. Because individual units are independent of one another and responsible for their own voltage and frequency management, this control system offers the advantage of increasing grid dependability. The amount of decentralization is determined by the intelligence of IEDs (local controllers), which can be used to carry out higher-level directives or make their own decisions.

Local voltage control provides substantial benefits over centralized control in terms of non-communication, high computation efficiency, and high reliability, making it suited for real-time reactive power adjustment in PV inverters. Furthermore, because the local voltage control approach does not require any telecommunication abilities, it may be deployed quickly.

Different types of controls in the energy management system and their characteristics are given in Table 1 [43,44].

Table 1. Different types of controls in the energy management system and their characteristics.

Criteria	Communication-Based Schemes			
	Centralized	**Decentralized**	**Distributed**	**Local**
Grid Structure	Centrally controlled	Locally controlled	Both centrally and locally controlled	Locally controlled
Access to Information	IED pass information to the CC [28]	Data from other IED (local controllers) are used to give independent control [28]	Interoperability and data transmission across all devices [28]	Control is instantaneous and uses only data obtained where a PV is located [28]
Information Exchange	Information from the IED to the CC is synchronized [1,12,29–31]	Asynchronous information is shared between IED [27–29,31]	Communication is both locally and globally asynchronized [28,30,31]	Communication is locally asynchronized [1,10,26]
Real-time operation	Complicated [12]	Passable [22,29]	Easy [35]	Easy [1,27,28]
Costs	More [4,6,18,21,25,27]	Less [4]	Less [28,29,33]	Less [1,27]
Safety precautions	Less [1,12,31]	More [4,18,29]	High [4]	High [1,27]
Computation	Computational burden [4,28,30,32]	Parallel computation [4,18,31]	Low computational cost (parallel computation) [30,34]	The real-time measurements have a fast response to the frequent PV fluctuations [1,28,37]
Communication	Requires a high level of connectivity [1,8,12]	Absence of communication links between agents restricts performance [4]	Needs a two-way communication infrastructure [30,34]	Local communication infrastructure [26,36]
Adaptation to SGs	Not easy to expand (so it is not suitable for SGs) [8]	Possible [18,22,29]	A practical solution for the SG's plug and play capability [35]	Possible [1,19,22]

In the case of local control, it is recommended to install all cases of control choices. However, due to voltage control, the attitudes and implementation of distribution network operators can differ significantly, even if these operators are from the same country. Due to the great variety of approaches, entering parameters into the controller is not always an easy task. Using the Q(U) method, there is no precise uniform way to measure voltage. Several measurement options are available: direct sequence measurement, average of independent linear or phase voltage measurements, or the supply of reactive power to each phase separately based on the results of independent voltage measurements of each phase. The dynamic accuracy must be ±5%. The Q(U) algorithm should not be used due to its dead zones where voltage fluctuations are negligible. For example, the German standard VDE-AR-N 4105 has a stricter error, the tolerance is ±4%, while the Lithuanian standard is ±5%. The time constant is the same as in the Lithuanian standard—3τ corresponds to 10 s. According to the Lithuanian standard LST EN 50549, it is recommended to use four voltage control methods for low voltage and five for medium voltage (Q(P) method is added). It can be distinguished that the Q(P, U) algorithm is usually the best choice because Q(P, U) has the property of reducing the voltage fluctuation range; Q(P, U) enables the distributed generation to supply the network with reactive power, thus providing an additional service and not exceeding the capacity limit; the supply of reactive power to the distributed generation reduces the flow of reactive power (its demand) from the high voltage side (from the system). In this way, it contributes to the reduction in losses; Q(P,

U) also works well and provides the network with reactive power when the generation of renewables is relatively small, such as at night. Not only reactive power, but also active power can be controlled to maintain the required voltage level. The concept used in Austria and Germany is Q(U)/P(U) management. It can be argued that the use of a transformer with branch switching is a much more expensive solution than the implementation of voltage control algorithms (up to 4 times according to German sources).

The recommendations of the Lithuanian Energy Institute prepared by the order of Energijos Skirstymo Operatorius AB "Study on the selection of technical and functional chat characteristics of type A and B solar power plants connected to the grid of Energijos Skirstymo Operatorius AB" are presented in Table 2.

Table 2. Recommendations for the application of voltage control techniques.

Method	**"Q Set Point"**	**Q(U)**	**Q(P)**	**Cosfi**	**"Q Set Point"**
V	**LV and MV**	**LV and MV**	**MV**	**LV and MV**	**LV and MV**
In substations					•
In regions with high solar power capacity				• *	(•)
User with generation, operating at approximately constant power (P, Q)	•				
Distant line				• *	(•)
LV line with high voltage asymmetry		•			
In strong network nodes			•		
In weak network nodes		•			
City with high user density (strong network nodes are usually designed)			•		
Rural area with low user density (weak network nodes are usually designed)		•			

* if the power factor constant is selected correctly.

3. Controllers for Distribution Network PV Systems

Integrated system control functions (e.g., grid-forming and regulation capabilities), distributed system stabilization functions, integrated system protection functions, integrated sensing and measurement functions, and integrated cybersecurity functions are the five integrated system functions that smart inverters are defined to provide.

A specific communication infrastructure is needed to apply centralized/distributed control to distribution systems with multiple distributed generation sources (DGs). In this scenario, decentralized approaches are more appropriate for voltage regulation and stability problems. In a decentralized approach, the main issue to be addressed is related to the coupled dynamics of the distribution network. If control systems are designed without taking these couplings into account, the system performance degrades due to the instability of local controllers [29].

When choosing a control method, it is also important to choose a controller, as the main disadvantage of PV systems is the low energy conversion efficiency compared to other alternative sources. Due to the non-linear characteristics of PV systems caused by irradiation and temperature fluctuations, PV power generation is unpredictable, which ultimately reduces the network stability. Other technical challenges arise from abnormal operating conditions, including network failures. The controller must perform computational and communication tasks.

In terms of control engineering, the PV system represents a complex generation due to its non-linear qualities. PV systems are also affected by different environmental conditions and therefore require a simple and adaptive controller that can adapt to different conditions. Therefore, a simple and reliable controller is needed to effectively, continuously, and accurately monitor the Maximum Power Point (MPP) under all operating conditions. Under rapidly changing environmental conditions, conventional MPPT trackers do not meet these control requirements/rules [45]. Controllers play an important role in the renewable energy sector by improving energy quality and offering a fast system response.

The PV system controllers are grouped into six categories based on the specific operating condition and operation of the electrical network.

3.1. Linear Controller

Controls for linear systems are based on the system characteristics and dynamics. Linear controllers are easy to design and install. Using these control approaches is popular because they are easy to implement in industrial applications. These controllers are analyzed and designed using standard feedback control theory [46,47].

On the other hand, these controllers are extremely sensitive to changes in circuit parameters, as well as changes in the operating state, input supply voltage, and load fluctuations. Many traditional linear controllers have been developed so far:

- Classical controllers are feedback controllers with fixed parameters.
    - Proportional–Integral–Derivative—PID [29,46,48–53]. Adding an integrator to PD control means PID control [54]. When analyzing the variety of controllers, in terms of popularity and application in DG, approximately 90–95% are PID controllers [55]. PID-based controllers offer a promising solution to the design problem due to the relatively light and concise structure consisting of only a few parameters [29,56,57]. It gathers monitoring data from sensors, meters, and other devices [55]. The load dynamics are directly linked to the controller in this control approach, which offers balancing power for changing load parameter values [58]. This controller type is sufficient to solve most control problems, provides good performance, and its built-in parameter K_i removes steady-state error, while the derived parameter K_d improves transient response [56]. PID controllers are predominantly used as regulators in automatic voltage regulator (AVR) systems; thus, its key feature is to maintain the voltage around a reference (setpoint) and to reject load disturbances [59]. The controller is suitable for both reactive and active power control in microgrids [57].

PIDs and derivative algorithms are more practical since they operate with basic control methods [53]. The simplicity and ease of installation of this controller are its main advantages [58]. The benefit of using a PID controller is that it has a better transient response and can reduce steady-state error between the actual and desired outputs [60].

A disadvantage of PIDs is that they cannot track the sine reference signal while preventing steady-state error [41,50]. Controllers do not work well in the presence of harmonics and out-of-balance voltages or currents [50]. PID controllers with a low order transfer function have a lower complexity. It has a limited bandwidth and is not very resilient against load dynamics [57,58].

    - Proportional Integral—PI [41,46,50,51,61–65]. PI controllers have a simple structure, they are simple to design and install, but their performance is dependent on gain parameters and parametric uncertainties [41,50,63–65]. Various PI controllers are used to regulate the voltage of the DC coupling and to control the AC current of inverter-based PV interface systems [66]. PI controllers can take into account the interaction of the DGs and each adjust the voltage amplitude of the node to which the DG is connected by varying the active or reactive power of the DG [29]. The PI controller employed in a traditional four-switching-leg architecture performs well in steady state but not so well when there is non-linearity, parameter fluctuation, or load shift (transient condition). It necessitates a precise mathematical relationship and is thus susceptible to parameter change [67]. PI operation will deteriorate in the case of a sudden change in operating conditions, in the case where it cannot track the sine wave reference without steady-state error [41,50].

To improve the controller performance, various controller modifications have been proposed, such as adaptive PI controller, evolutionary optimized PI controller, etc. [62]. The PI controller is suitable for tiered steps, where the short-time response has to be controlled by proper selection of the controller parameters [63]. An LCL filter may be used to further reduce harmonic distortion in the controller-side (AC) voltage and current, as well as to protect against its capacity to suppress any abrupt voltage changes due to harmonics [62].

They are cost-effective and may be used in real time applications [59]. The PI controller has high gain values in DC systems and sufficient performance in DC signal control applications [68].

The PI controller is not suitable for steady-state operations and system response speed [65]. Due to the use of constant gain parameters, these controllers do not demonstrate their optimum performance with changes in the system and changes in the input(s) under different operating conditions [62,68]. PI controllers are incapable of ensuring global stability and have a slower dynamic response [69]. Like PIDs, PI controllers do not perform well in the presence of harmonics and voltage or current disbalance [50]. As a result, these controllers are ineffective for voltage stability [69]. When precisely tuned, the PI controller produces fewer harmonics but has poor dynamic performance [70]. In addition, the PI controller has a slower transient reaction [69].

- ○ Proportional Derivative—PD [46,52,71]. A PD controller is easy to debug and cannot achieve zero steady-state error under noise and resonance [71]. The controller cannot provide good enough performance in controlling highly complex, non-linear and fuzzy processes [52].
- ○ Proportional—P [46,51]. A P controller is among the simplest to control. The input signal of a P controller is proportional to the output signal of the response. Its function is to adjust the open-loop gain of the system, to improve its steady-state accuracy, to reduce the system inertia, and to speed up the response [72]. A proportional control system is a type of linear feedback control system. The P control includes a linear correlation of the controller output (actuation signal) with the error (the difference between the measured signal and the set value). The P control is mathematically expressed by the following Equation (2)

$$Pout = kp \cdot e(t) + po \tag{2}$$

where $Pout$ is the output of the proportional controller; kp is the proportional gain; $e(t)$ is the instantaneous process errors at time t; po is the output controller with zero error [73].

The error value is defined as the difference between the measured value and the set value [74].

Result analysis and discussion: Due to the non-linear behavior and modelling difficulties of most real systems, classical controllers are not useful for non-linear control applications. PI and PID controllers are easy to install and have a good response rate. However, the above mentioned performances are not achievable with unbalanced disturbance quantities [75]. Moreover, a classical controller only takes action against disturbances when the control variable deviates from a reference level. The disturbance rejection capability can be improved by using degree-of-freedom (DOF) controllers [76]. Furthermore, the PI controller's reaction is often sluggish, and the controller can produce oscillations and overshoot, especially if the P and I parameters are designed incorrectly. The steady-state errors are eliminated by both proportional integral (PI) and proportional integral derivative (PID) controllers; however, changes in system parameters degrade the system performance.

Very limited research is available on the use of P controllers in distribution systems.

- Proportional Resonant (PR) controller [41,46,50,68,77]. The PR controllers are designed to control AC voltage and/or AC current [68]. The basic concept behind the PR controller is to convert the high gain characteristic of the PI controller in DC signals to AC signals [68]. To compare a PI controller with a PR controller, the PR controller allows evaluation of the dynamic system behavior in the case of external disturbances [78]. The main function of the PR controller is to ensure unlimited gain at the selected resonant frequency, so that the steady-state error at this frequency is reduced to zero [79].

The PR controller provides high gain at the fundamental frequency and reliably tracks the sine reference, thereby reducing the steady-state error and improving the dynamic performance of the system under external disturbances [78]. PR controllers are typically used in AC voltage and/or AC current control applications, such as interactive grid inverters, to control the output current with fast response and without the steady-state error [68]. At a specific frequency (resonant frequency), the PR controller has a high infinite gain, but at other frequency values, it has no gain [68].

- Linear–Quadratic–Gaussian (LQG) controller [46,53,80]. This is a Kalman filter-based linear–quadratic regulator [57]. The LQG controller optimizes the (steady-state) cost function, which is quadratic in the state and the control input, given a linear dynamical system with known statistics of the noise entering the dynamics, as well as the measurements [57,81]. The standard optimal problem of LQG control is to choose such an input to a linear system that maximizes the expectation of a quadratic function that depends on the output and control of realized state trajectories [79]. The optimal target value depends on the quality of the state monitoring [82]. By reducing the cost function, this controller anticipates future steps and decreases projected error [57].

3.2. Non-Linear Controller

In comparison to simple controllers, these controllers perform exceptionally well. However, they are complicated in terms of design and implementation.

Generally, in control engineering, the development of an accurate system model for non-linear controllers or model-based control is a challenging task due to differences in system performances, system uncertainties, and external disturbances. Thus, studies tend to emphasize intelligent control technologies as a better and more sophisticated technique rather than conventional control methods, as higher performance efficiency can be ensured under such circumstances.

- Sliding mode controller (SMC) [41,46,53,83–85]. The sliding mode controller (SMC) is among the most well-known non-linear control methods, which is known to be an excellent controller to overcome uncertainty problems [85–87]. The SMC works by driving the non-linear phase trajectory onto a specific area in the state space termed the sliding or switching surface and keeping it there for all time [47]. In addition, compared to other non-linear controller design approaches, SMC implementation is quite simple [69]. There are several high-order sliding mode controllers available, which are more robust than one-order SMCs [53]. SMCs offer many advantages over a linear PI or PID controller, providing stability even in the case of high line and load fluctuations, as well as robustness, good dynamic response, and simple implementation [46,47]. The primary disadvantage of traditional SMC is the possibility of chattering, which is defined as switching around the manifold [86,88]. However, due to its complexity and the significant degree of vibration associated with it, the sliding mode control arrangement is also impractical [53].
- Partial Feedback Linearization controller (PFLC) [46,89]. Feedback linearization is a method of non-linear control design that algebraically converts the dynamics of a non-linear system into a completely or partially linear one, allowing linear control techniques to be used [90]. Exact feedback linearization converts a non-linear system into a fully linear one, whereas partial feedback linearization transforms the system

into a partially linearized one [46,89]. Control design is thus based on well-known linear control techniques that cancel out undesirable non-linear components [87].

PFLCs do not require the dynamics of the complete model, which is among their primary advantages [90]. Despite the fact that the technique may be used to manage most non-linear systems, poor control performance is frequently caused by uncertainty in system parameters or unmolded dynamics [87].

- Hysteresis controller (HC) [46,91]. In comparison to other controllers suggested in the literature, hysteresis current controllers are recognized for their resilience, quick error tracking, superior dynamic responsiveness, and ease of implementation [92,93]. A traditional HC employs a separate controller with a predetermined hysteresis band for each phase of the load to determine the switching state of the associated inverter leg in order to maintain current error within the hysteresis band [92]. The benefits of utilizing a hysteresis control are primarily its simplicity, resilience, independence from load factors, and good transient response [94]. However, it has several significant disadvantages, such as limit cycle oscillations, overshoot in current errors, sub-harmonic components in the current, and sub-optimal switching vector selection [70,92,95]. HC has high switching losses and acoustic noise [96]. The hysteresis controller has two major drawbacks: it does not have a set switching frequency, resulting in a broad frequency spectrum, and current ripple is relatively significant, potentially reaching double band limit for the phase current hysteresis controller [94].

3.3. Robust Controller

The goal of these methods is to achieve stability in the presence of partial modeling errors as well as robust performance. Bounds, a clear description, and good criteria must be defined in the robust control. Even in multivariable systems, this controller can guarantee robust performance and stability of closed-loop systems [46,60]. A robust controller ensures the required performance regardless of uncertainties, external disruptions, measurement noise, etc.

- H-Infinity ($H\infty$) controller (HIC) [46,94]. HIC is a repeated control approach for improving the performance of droop controllers, voltage, and current control loops. It has the ability to solve multi-objective and multivariate problems [97,98]. The goals of HIC synthesis include assuring system stability in the face of uncertainty, often known as robust stability [99]. In general, the HIC optimization technique solves robust stabilization and nominal performance designs for linear, time-invariant control systems [95]. To use this approach, the control problem must first be transformed into a mathematical optimization problem [98]. The choice of weighting functions in this controller design may be included into the design goals of tracking performance and desired robustness to create desired loop shapes (ideal profiles of the closed-loop transfer functions). With suitable weighting function adjustment, the synthesized HIC controller may display strong gains near the line frequency and attenuate high-frequency signals [100]. In the presence of system disturbances and uncertainties, the HIC controller is capable of maintaining robust multivariable linear systems' stability [101]. This technique has the benefit of allowing the designer to handle the most generic type of control architecture, allowing for explicit accounting of uncertainties, disturbances, and performance metrics [98]. In both grid-connected and isolated modes, the technique may be used for a variety of applications in power management and the control of DGs [98]. However, one problem of the HIC controller is the difficulty in analog circuit implementation owing to its high order and the necessity of sophisticated manipulation of the system transfer function [100]. Non-linear restrictions are also poorly dealt with [46].
- Mu (μ)-Synthesis controller (MSC) [46,102]. Controller design in Mu-synthesis is based on the concept of structured single value [102,103]. MSC may be used to assess the impact of both structured and unstructured uncertainty on system performance [102].

Uncertainty is divided into two types: parametric uncertainties and unmodeled dynamics [103]. The µ-synthesis approach not only reduces the maximum error energy for all command and disturbance inputs, but it also stabilizes the closed-loop system for structured plant uncertainties with restricted H∞ norm. It is a good feature to consider, especially when developing controllers for plants with unmodeled high-frequency dynamics, when plants experience defective operating circumstances, or when plant parameters change due to aging, e.g., of a power system [104]. MSC may also be used to design control systems that are insensitive to classes of predicted differences between a model and the physical process that has to be controlled [105].

3.4. Adaptive Controller

Adaptive control techniques work well in systems with uncertain or time-varying characteristics [46,53,106–108]. Adaptive control is a type of control that has both changeable parameters and a means for changing them [108]. Accurate system parameters are not required for high performance [109]. Adaptive control is a collection of strategies for automatically adjusting controllers in real time, attaining and maintaining a desired level of control system performance when the plant model's characteristics vary over time and/or are unknown [110]. Inputs, states, outputs, and known disturbances are used to calculate the performance index (IP) of an adaptive control system [110]. Adaptation mechanisms alter the settings of the adjustable controller and create an auxiliary control by comparing the measured performance index to a set of given ones in order to preserve their near approximations. An adaptive controller features an adjustment loop in addition to the traditional feedback loop, allowing it to provide the correct response even when the parameters are disrupted [110]. Many adaptive controllers have been suggested, including a robust adaptive controller, a data-oriented adaptive control method, and an adaptive controller based on parameter identification assignment and pole [53]. The Model Reference Adaptive Control (MRAC) method and the Self-Tuning Control (STC) method are the two major ways for developing adaptive controllers [109]. Many adaptive controllers have been proposed, including a high-resilience adaptive controller, a data-oriented adaptive control technique, and an adaptive controller based on parameter assignment, among others [53].

The computational complexity of this control scheme is high [109].

3.5. Predictive Controller

Predictive controllers are among the controllers that can achieve a large current loop bandwidth. In predictive controllers, the future behavior of controlled parameters is predicted using a system model. The controller uses this knowledge to achieve the best actuation based on a set of predefined optimization parameters [41,46].

The comparison of the classic controller and this controller reveals that the predictive controller needs an enormous number of calculations.

- DeadBeat controller (DBC) [46,111]. In the evolution of digital systems, deadbeat controllers have become one of the key choices [112]. The deadbeat controller has been demonstrated to be an optimal and resilient controller [113]. Deadbeat control is widely employed in inverters with L filters due to its ease of installation and large control bandwidth [114]. The DB control can reduce the control error to zero in a short period of time, resulting in a quick transient reaction [115]. Due to its fast response, zero steady-state error, digital nature, easy and direct implementation on digital processors, simple algorithm, constant switching frequency, and fast dynamic response, the deadbeat predictive method is among the most widely used approaches for controlling power converters [116]. In general, the goal of a control system is to attain the intended value with zero steady-state error in less than 2 s [113]. In comparison to other predictive control techniques such as the Finite Control Set Model Predictive Controller (FCS-MPC), DBC offers high dynamic performance while maintaining a constant switching frequency [115]. Model and parameter mismatches are frequent causes of controller sensitivity [111].

- Model Predictive Controller (MPC) [46,117]. MPC is an optimum controller built on the basis of a cost function that aids in predicting future states. The MPC controller delivers stable control action with a wide gain and phase margin [57]. The MPC only takes into account system limitations and non-linearities during the design stage of the controller [46]. MPC has the advantage of not allowing the present timeslot to be optimized while considering future timeslots. The model predictive controller's applicability is restricted by its sluggish reaction time and low bandwidth [60].

3.6. Intelligent Controller

Intelligent controllers, unlike traditional control approaches, use artificial intelligence (AI) rather than a mathematical model of the plant.

They are designed to mimic human decision making and are typically more successful than traditional control approaches in complicated systems.

- Neural network controller (NNC) [46,118]. In the systems, neural networks can be utilized as a controller [119]. Self-adaptive characteristics enable NNC to control non-linearities, uncertainties, and parameter changes with remarkable precision [118]. NNC may utilize a neural network in a control system to govern complicated non-linear objects that are difficult to accurately represent mathematically [120]. In order to apply an NNC, four key stages must be completed: data collection; input selection; choosing an NNC architecture; NNC training and testing [121]. The challenges in these approaches are that a significant amount of processing time is necessary for the database in order to train the NNC using the supervised learning algorithm [122]. When the system is in a new control state with an uncertain circumstance, this technique can make an appropriate choice [119]. Due to its self-learning capabilities, parallel design allows the controller to compute quicker, and it does not require perfect input and output relationships, allowing it to manage non-linearity. As a result, it is more durable than a traditional controller [67].
- Repetitive controller (RC) [46,62]. Due to its better error cancelation properties, a repetitive control (RC)-based controller is adept in tracking or eliminating any periodic signal, including any order harmonics [62]. Repetitive controllers, on the other hand, meet the internal model principle (IMP) in a positive feedback loop by using a delay element that corresponds to the fundamental period. A low-pass first-order filter is linked in series with the delay element to provide steady operation while avoiding noise amplification. The reduction in size and displacement of resonance peaks in the controller frequency response causes a loss of tracking ability while following the reference signal, which is one drawback of this method [123].
- Fuzzy Logic Controller (FLC) [46,49,51,52,65,124]. Fuzzy logic has received a lot of attention in structure control due to its simplicity and robustness (reliability) [54]. FLC depends on a set of defined rules that is translated into a fuzzy logic language [125]. Fuzzy control, in essence, is an adaptive and non-linear control that provides stable performance for a linear or non-linear plant with variable parameters. Compared to conventional controllers, FLCs are generally not effective if the structure of the controlled system is uncertain, as simple FLCs (type 1 FLCs) have limited capability to directly handle data uncertainties [52]. The FLC controller has an advantage over the PI controller as it better controls the active power fed to the grid, and better monitors the grid current and maximum power point tracking for the PV array [51,64,65]. Researchers often consider the FLC controller as a black-box function generator that can generate the desired f (function value) or an approximation of it [126]. The main advantage of FLC is that it can be applied to systems that are non-linear, the mathematical models of which are difficult to obtain. Another advantage is that the controller can be designed to apply heuristic rules that reflect human expert experience [52]. The most difficult aspect of employing fuzzy control approaches is determining the proper membership functions and control rules quickly and effectively [58].

Generalization: Each control scheme has advantages and disadvantages. Therefore, choosing an appropriate controller is very important. For example, while the design and implementation of PI controllers are simple, they are sensitive to parametric uncertainties. As a result, if there are sudden changes in operating conditions, the performance of the PI controller will suffer, and steady-state error may occur.

The good properties of a proportional–integral–derivative (PID) controller have piqued the interest of many researchers (i.e., simplicity, applicability, functionality, and comfortability). Scientific literature analysis suggests that, following the incentives of using the PID controller to solve control problems, researchers attempted to develop the optimal PID controller by selecting its parameters through various optimization algorithms. However, the conventional PID controller has a disadvantage of being highly sensitive to the system non-linearity and uncertainty.

Very limited research is available on repetitive controllers used in distribution systems.

Many controllers, such as Fuzzy Logic ones, are available for improving performance; however, they are not satisfactory. Despite the fact that several current control design approaches (H∞ design, Mu-synthesis, SMC, etc.) can be used to design controllers with uncertainty, they cannot guarantee that the developed controller will operate well throughout the entire operating envelope.

4. Discussion

The global demand for electricity is increasing exponentially. To meet the energy demand, energy generated by centralized utilities is commonly used, which results in high transmission and distribution losses. Thus, electricity suppliers may benefit from electricity generation close to consumer premises because of reduced energy losses and higher system reliability. Distributed generations (DG) are compact, efficient, and decentralized energy sources that depend primarily on renewable energy, such as photovoltaic (PV) systems, wind power, fuel cells (FC), etc. DG management was developed as a key area of research in the energy sector.

New strategies are needed to effectively regulate voltage as the number of PVs in power distribution systems grows. To summarize, all centralized controls necessitate the use of a powerful central controller to collect global information and process the complex optimization algorithm. As a result, these control methods are inflexible and vulnerable to single-point failure. Distributed control, as opposed to centralized control, can disperse computational and communication tasks among local controllers through parallel processing, making it more versatile, scalable, and resistant to single-point failure. When PV inverters with a quick response are used in the DN to resolve the voltage variance problem of the distribution system, no additional high-cost equipment is needed, such as static synchronous compensators and energy storage systems.

5. Conclusions

To switch to smart grids as soon as possible, selecting appropriate controls of electrical networks and integrating information and communication technologies (ICT) is required. As by definition the smart networks monitor, analyze, and control data, they need harmonized synergies between control schemes and devices. Distributed PV systems integrated into low voltage distribution networks will replace the unidirectional power flow characteristics of the network. The added value of PV inverters will contribute to feeder voltage control to ensure the voltage profile. The paper presents various voltage control schemes that were assessed to highlight their advantages and disadvantages. The local control method may be noted as the most promising one in the future, as it may be applied to individual users, especially due to the growing number of countries that introduce demand side management.

Based on the overviewed controller category classifications, the most popular controllers used in the studies are the Proportional Integral Derivative (PID) and Proportional

Integral (PI) ones, as well as Fuzzy Logic controllers with input errors defined as a difference between the actual and desired voltage.

The study results demonstrate that the future of the local voltage control method, as well as linear and intelligent controllers, is extremely promising.

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