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A Comprehensive Review of Distributed Control Techniques for the Operation of Modern Electrical Distribution Networks

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ABSTRACT

Currently, power systems are undergoing a rapid energy transition characterized by significant changes. This transformation encompasses the emergence of smart grids and microgrids, incorporating distributed generation, infrastructure digitization, the integration of prosumers, and the advancement of information and communication technologies. These developments necessitate that modern electrical networks adopt new architectures and control techniques, ensuring optimal operation, power system stability, and efficient economic and environmental management. Furthermore, these networks are required to achieve the objectives of advanced distribution network automation, encompassing remote control, automatic reconfiguration, asset management, fault location, and self-management. This review provides a comprehensive overview of distributed control techniques employed in the operation of distribution networks. A detailed analysis of several distributed control techniques is presented, including consensus and decomposition-based techniques, predictive control models, multi-agent systems, and distributed cooperation. The technical challenges and requirements associated with each of these techniques within the context of modern distribution network operation are also summarized. Lastly, the review delineates the advantages, disadvantages, and challenges associated with the implementation of distributed control techniques in the operation of electrical distribution networks.

1. INTRODUCTION

Traditional electrical networks, predicated on centralized generation schemes, have historically been characterized by unidirectional power flow, intended to meet daily power demand. Nevertheless, this mode of generating, transmitting, and distributing energy has proven inefficient due to significant losses encountered in transmission and distribution lines [1].

In prevalent power systems, the majority of power generation is still derived from large-scale power plants, such as hydroelectric and thermal generation facilities. Thermal generation, largely reliant on fossil fuels anticipated to be depleted in the foreseeable future, will thereby experience escalating costs, rendering it economically untenable. Moreover, this form of energy production contributes to elevated pollution levels, necessitating extensive environmental protective measures.

An energy transition is thus crucial to address these issues. The integration of smart grids (SGs) and microgrids (MGs) represents a viable solution, yet the implementation of non-conventional energy sources, such as solar and wind resources, which exhibit stochastic variations, presents significant challenges.

The escalating deployment of new technologies within smart electrical networks necessitates the proficient operation and control of equipment. Consequently, enhanced information storage, reduced response time, and improved decision-making are required, achievable through the utilization of distributed control techniques to ensure a resilient, safe, and reliable network.

With the incorporation of distributed control within the SG, the following objectives are attainable [2]:

i. Facilitate the suitable integration of intermittent renewable energy sources through improved controllability.
ii. Enable reliable bidirectional information flows using diverse distributed control techniques.
iii. Promote energy efficiency, effective demand management, and customer choice through the application of distributed control techniques.
iv. Ensure self-recovery from power disturbance events using appropriate distributed control techniques.

Allow for flexible operation in the face of physical and cyber-attacks through the adequate integration of distributed control techniques.

Hence, the transition from conventional electrical networks to SGs necessitates novel tools and control architectures that assimilate new operational features. The system must take into account advanced distribution automation (ADA) to facilitate remote control, automatic reconfiguration, asset management, fault location, and self-remediation. An ADA-equipped system, crucial in determining power system stability, economic operation, and environmental management, should be considered.

This paper presents an overview of distributed control techniques employed in the operation of distribution networks, focusing on techniques based on consensus and decomposition, predictive control models, multi-agent systems, and distributed cooperation. These techniques are analyzed to ascertain the technical requirements for their implementation in electrical distribution networks. The transition from conventional centralized control to distributed control necessitates new considerations, such as cybernetic and physical layers, information and communication technologies, cybersecurity, high technological complexity IEDs, and the application of new control techniques of high algorithmic complexity.

Finally, a synopsis of the technical challenges and requirements of each of the distributed control techniques for the operation of modern distribution networks is presented. This includes the type of technique, control variables, control objective, technological capacity, algorithmic complexity, and other particularities required for the implementation of distributed control techniques in smart grids.

2. ADVANCED DISTRIBUTION AUTOMATION

The aim of ADA is to improve reliability and power quality, as well as to make the electrical system more efficient. This must be performed through the automation of distribution processes, analysis, and data collection close to real-time operation. The installation of metering infrastructure and information and communication technologies help optimize decision-making processes and control distribution operations in coordination with the generation and transmission systems [3, 4].

The functionalities considered for this technology are:

- Remote control: This functionality refers to the ability to operate remotely on cutting and maneuvering elements of the distribution network.
- Troubleshooting: This functionality contributes to improving supply continuity and reducing service replacement times in case of failure.
- Self-Healing: This functionality adds automation for the detection and location of faults and the replacement of power supplies to minimize power supply interruption time. This option is considered the most advanced function of ADA technology.
- Automatic reconfiguration: This advanced functionality involves the development of optimal reconfiguration algorithms that make use of information from the state of the network topology. The optimization of the network configuration allows the improvement of energy efficiency (balancing energy flows) and the increase in the useful life of its elements by avoiding/reducing overloads.
- Asset management: Virtually all the technologies and functionalities of the SG can bring benefits to the optimization of CAPEX (capital expenditures) and OPEX (operating expenses). Asset management includes all those activities aimed at improving maintenance, extending the useful life, and planning investments in network elements.

3. CONTROL CONCEPTS ON SMART GRIDS

SGs consider many DGs with renewable energy sources and distributed topology that must be measured to obtain relevant information continually. However, traditional electrical networks use supervisory control and data acquisition (SCADA) systems, which are centralized systems located in control centers. These centralized controllers are not capable of meeting the computational and communication requirements of the large number of devices connected to the network [5, 6]. Therefore, a distributed, local, and adaptive control scheme is required to decide autonomously [2, 7-9]. The architectures for the control system can be divided into local, centralized, distributed, and decentralized [2, 10].

3.1 Control systems with local architecture

The local controllers are IEDs that are found in the DG points or loads. This type of controller has a quick response to the variability of the DG or the loads. In addition, this is not affected by communication failures. However, they do not coordinate and communicate with the other IEDs in the system, not performing 100% of their capacity as control components. This issue can prevent the system from finding an optimal global solution [10].

3.2 Control systems with centralized architecture

Centralized control is the most common way to control systems. It consists of a computer, a process interface, and an operator station (operating interface). In the centralized control, there is a central controller that receives all the required measurements from the network, either from the IEDs or from remote smart meters. The central controller executes the necessary control actions with all data measured in the network. This central controller is the only network component that can start control actions in this architecture [10-12]. The architecture facilitates the flow of information and makes it possible for the global optimization objectives of the process to be achieved [11, 13, 14].

3.3 Control systems with distributed architecture

In a distributed architecture, the controllers cooperate to decide control actions according to established objectives (stability, optimization, fault restoration, etc.). Each controller can only communicate with neighboring nodes and therefore does not require global system information to take a control action. However, a global view of the system is obtained with the data collected from neighboring controllers and seeks solutions to the global state of the system. The objective of a distributed control architecture is to reach an automated network. This system can have an effective response to problems that may arise in local interactions, as well as being flexible and scalable [5, 10, 11].

3.4 Control systems with a decentralized architecture

The decentralized control is an intermediate state between centralized and distributed control. It considers local and global orders of a system to make control decisions. For this control architecture, the system or the network is divided into zones. Each zone is equipped with a central controller and coordinated with the controllers of other zones to achieve a specific objective similar to distributed control [10, 11, 15-17].

3.5 Communications infrastructure

The information and communications technology (ICT) infrastructure is of great importance and one of the fundamental pillars in the operation of an SG. It serves as a link to transmit the information and data of the different elements (generation sources, distribution systems, etc.) to the management blocks that ensure stability for the proper operation of the SG. The infrastructure is closely linked to the type of control algorithms implemented, also having typical approximations or configurations with centralized or distributed architectures [18].

For implementing distributed control techniques in the operation of distribution networks, there must be a regulatory framework and standards that allow the exchange of information and data between different systems and manufacturers (interoperability).

3.6 Intelligent electronic devices

IEDs comprise a wide range of devices that allow one or several protections, measurement, fault recording, and control functions. An IED comprises a signal processing unit, a microprocessor with inputs and outputs, and an EIA 232/EIA 483, Ethernet, Modbus, or DNP3 communications interface [19].

The IEDs receive information from the sensors to issue control actions on storage devices, distributed energy sources, loads, etc. [20]. Figure 1 illustrates a communication system for an MG with the most relevant components such as distributed energy sources, storage elements, monitoring system, and data recording system [20]. These components are linked by the interconnection network [18].

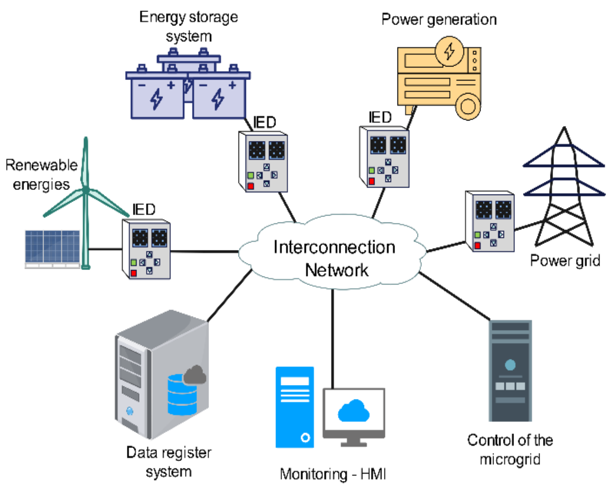

Figure 1. Communication systems in MGs with IEDs [20]

4. DISTRIBUTED CONTROL TECHNIQUES IN THE OPERATION OF MODERN DISTRIBUTION NETWORKS

4.1 Distributed control techniques based on consensus and decomposition

Consensus is an algorithmic approach to solving distributed optimization problems and offers a flexible formulation that promises extensibility and scalability. The aim of the consensus is to achieve that the IEDs of the system converge to a common state [10, 21]. An important application of distributed algorithms based on consensus is the optimization of large-scale systems with a very high number of control variables. In this framework, consensus-based algorithms provide a platform in which the need for a centralized optimizer is avoided and the computational effort is evenly distributed among multiple entities [22].

Consensus-based algorithms are complemented by decomposition techniques that seek to decompose optimization problems into a series of subproblems that are iteratively solved until convergence is reached. Many of these methods decompose the optimization problem into areas, although propose different ways of defining these areas, such as sensitivity analysis or control capacity of the system nodes. In the SGs, they can be defined based on the availability of information, that is, areas where IEDs communicate with each other [23]. Some consensus-based distributed strategies have been proposed to address the problem of real-time optimization in SGs considering DG reactive power availability [22] and simple consensus algorithms have been applied.

4.2 Distributed control techniques based on predictive control models

Predictive control models (MCP) are standard in the industry for the control of large process plants. They offer some very good characteristics, such as multivariable control management, ease of coordination, and explicit consideration of restrictions [23]. The MCP is a discrete-time control strategy in which the system control sequence is determined by minimizing a cost function associated with the performance of a system. The cost function is a combination of terms corresponding to minimizing the deviation of the system states and those that reflect the deviation of the set points [23].

4.3 Distributed control techniques based on multi-agent systems

Multi-agent systems are software components associated with an IED that has autonomy. They also can share information with other agents and use it to achieve common goals [8]. The main characteristics of a multi-agent system are:

- Scalability: Each existing agent does not know what is beyond its closest environment and can adapt to it dynamically. The agent can detect changes in the environment and adapt to them instantly without the need to restart or reconfigure it [8].
- Autonomy: Each agent receives stimuli from its environment and responds to them through actions to achieve its objectives, and for this, the agent contacts the other agents in its environment [8].
- Distributed: Each agent collects local data (stimuli) and processes it, deciding what action to perform based on this data [8].

Multi-agent systems (SMA) are suitable for large complex systems, such as electric power systems. In this case, many agents of different types interact and most of the required information is available locally. Therefore, SMAs are ideal for applying control strategies for SGs [23-26].

4.4 Distributed control techniques based on distributed cooperation

In MGs, a hierarchical control is commonly proposed, where a centralized secondary control interacts with a distributed primary control (usually droop control). This technique ends up providing a type of distributed cooperative control for voltage, frequency, and power exchange required in the MG [10]. For the primary control of MGs, droop control is commonly used. Nowadays, through mathematical models, this type of control has been adapted to work in DGs that are connected to the MG using power inverters. This method allows the different DGs to work in parallel, distributing the load proportional to its nominal power [27].

5. TECHNICAL CHALLENGES AND REQUIREMENTS OF DISTRIBUTED CONTROL

Determining the technical challenges and requirements for implementing distributed control in electrical distribution networks is of vital importance. The transition from conventional electrical networks to SGs presents great challenges as moving from conventional centralized control to distributed control. Hence, this type of control considers cybernetic and physical layers, information and communication technologies, cybersecurity, IEDs of high technological complexity, and the application of distributed control techniques of great algorithmic complexity. Tables 1 and 2 present a summary of the technical challenges and requirements of each of the distributed control techniques for the operation of distribution networks. Information on the type of technique, control variables, control objective, technological capacity, algorithmic complexity, and other particularities is presented in these tables. Technical challenges and general requirements for implementing distributed control in the operation of electrical distribution networks have been divided into two parts.

Distributed control techniques for the operation of distribution networks are dictated by technological limitations since specialized equipment is needed capable of carrying IEDs with measurement, communication, actuation, real-time computing, and interoperability capabilities. In addition, they required specific studies of the network topology as algorithms change according to the control required in each network (SG or MG) and with high penetration of DGs. The proper selection of information and communication technologies is a challenge, as distributed control techniques require a robust, resilient, reliable, and secure system.

The technical challenges and requirements are listed below by the use of distributed control techniques in the operation of distribution networks:

- Intelligent equipment (capable of carrying IEDs) with measurement, communication, performance, real-time computing, and interoperability characteristics.
- Construction of optimal algorithms and models for distributed control, that depend on the distribution network topology.
- Implementation of information and communication technologies, to create a robust, reliable, and resilient telecommunications network with high cybersecurity rates.

Table 1. Summary of technical challenges and requirements, part 1

Technique	Electrical Variables to Control	Objective of the Control	Network Classification	Control Network Topology: Physical Layer	Control Network Topology: Cyber Layer	Use of ICT	Based on IEDs	Based on Inverters	Ref.
Consensus/ Decomposition	Voltage, active power, and reactive power of DG	Minimize network losses	SG	Yes	No	Yes	Yes	No	[28]
Consensus/ Decomposition	Voltage, active power, and reactive power of DG	Minimize network losses	SG	Yes	Yes	Yes	Yes	No	[29]
Consensus/ Decomposition	Voltage, active power, and reactive power of DG	Network optimization	SG	Yes	Yes	Yes	Yes	No	[22]
Consensus/ Decomposition	Active power and reactive power of DG	Network optimization	SG	Yes	Yes	Yes	Yes	No	[30]
Consensus/ Decomposition	Voltage, frequency, active power, and reactive power of DG	Network optimization	MG	Yes	Yes	Yes	Yes	No	[31]
MCP	Voltage and frequency	Voltage regulation in the network	MG	Yes	No	Yes	Yes	No	[32]
MCP	Voltage, frequency, and reactive power	Voltage regulation in the network	MG	Yes	No	Yes	Yes	No	[33]
SMA	Voltage, active power, and reactive power of DG	Power balance	MG	Yes	Yes	Yes	Yes	No	[34]
SMA	Voltage, frequency, Active power, and reactive power of DG	Voltage regulation in the network / Network Optimization	MG	Yes	Yes	Yes	Yes	No	[35]
SMA	Voltage, frequency, active power, and reactive power of DG	Network optimization	MG	Yes	Yes	Yes	Yes	No	[36]
Distributed cooperation	Voltage, frequency, active power, and reactive power of DG	Voltage regulation in the network	MG	Yes	No	Yes	No	Yes	[37]
Distributed cooperation	Voltage, frequency, active power, and reactive power of DG	Voltage regulation in the network / Power balancing	MG	Yes	No	Yes	No	Yes	[38]
Distributed cooperation	Voltage, frequency, active power, and reactive power of DG	Voltage regulation in the network	MG	Yes	No	Yes	No	Yes	[39]

Table 2. Summary of technical challenges and requirements, part 2

Technique	Capacity of the IEDs / Inverters: Measurement	Communication	Actuation (Control)	Computation in TR	Interoperability	Complexity in the Development of the Control Algorithm	Algorithm Topology	Particularities	Ref.
Consensus/ Decomposition	Yes	Yes	Yes	Yes	Yes	High	Equivalent semi-definite programming with distributed architecture.	This solution is proposed for SGs with great penetration of DGs.	[28]
Consensus/ Decomposition	Yes	Yes	Yes	Yes	Yes	High	Application of feedback control laws based on dual decomposition.	This solution is proposed for SGs with great penetration of DGs. A robust design of both the physical layer and the cyber control layer is required.	[29]

Technique	Capacity of the IEDs / Inverters: Measurement	Communication	Actuation (Control)	Computation in TR	Interoperability	Complexity in the Development of the Control Algorithm	Algorithm Topology	Particularities	Ref.
Consensus/ Decomposition	Yes	Yes	Yes	Yes	Yes	High	Consensus-based distributed computational intelligence algorithm.	This solution is proposed for SGs with great penetration of DGs and controllable loads.	[22]
Consensus/ Decomposition	Yes	Yes	Yes	Yes	Yes	High	Algorithm based on dual decomposition, for the power dispatch from each DG.	This solution is proposed for SGs with great penetration of DGs and a scalable distributed dispatch strategy that converges rapidly.	[30]
Consensus/ Decomposition	Yes	Yes	Yes	Yes	Yes	High	Distributed averaging algorithm.	This solution is proposed for MGs with great penetration of DGs using only controllers in each DG unit.	[31]
MCP	Yes	Yes	Yes	Yes	Yes	High	Distributed MCP algorithm with nonlinear feedback and acceleration in state convergence.	This solution is proposed for MGs with great penetration of DGs acting on the secondary control with MCP.	[32]
MCP	Yes	Yes	Yes	Yes	Yes	Basic	Mixed logic dynamics algorithm.	This solution is proposed for MGs with great penetration of DGs. It considers a simplified MCP that predicts the behavior of the voltage in the network in future time horizons.	[33]
SMA	Yes	Yes	Yes	Yes	No	Basic	Feedback-based power imbalance adjustment algorithm.	This solution is proposed for MGs with great penetration of DGs. It must guarantee that all agents are equal and autonomous.	[34]
SMA	Yes	Yes	Yes	Yes	Yes	High	Hierarchical agent algorithm. It includes global, area, and local monitoring and control agent.	This solution is proposed for MGs with great penetration of DGs. It seeks the automation of the MG including agents in the form of hierarchical control. The objective is to provide control to electrical variables, guarantee stability, and bring economic and environmental benefits.	[35]
SMA	Yes	Yes	Yes	Yes	Yes	High	Multi-agent algorithms that communicate with each other are developed in JADE and compatible with Foundation for Intelligent Physical Agents (FIPA).	This solution is proposed for MGs with great penetration of DGs. It seeks the optimization and automation of the MG to guarantee stability and minimize the economic operation cost.	[36]
Distributed cooperation	Yes	Yes	Yes	Yes	Yes	Basic	Consensus algorithm with weighted average, compatible with conventional droop control.	This solution is proposed for MGs with great penetration of DGs. It seeks to guarantee the distribution of reactive power and voltage stability, using conventional droop control in cooperation with a distributed consensus algorithm.	[37]
Distributed cooperation	Yes	Yes	Yes	Yes	Yes	Basic	Cooperative consensus algorithm with distributed conventional droop control.	This solution is proposed for MGs with great penetration of DGs, It seeks to maintain nominal voltage and frequency settings, with the limitation of a network only made up of inverters.	[38]
Distributed cooperation	Yes	Yes	Yes	Yes	Yes	Basic	Distributed conventional droop control algorithm together with consensus algorithm.	This solution is proposed for MGs with great penetration of DGs. It seeks the optimization of the MG including hierarchical control where its objective is to provide primary voltage control and secondary frequency control.	[39]

6. ADVANTAGES, DISADVANTAGES, AND CHALLENGES OF DISTRIBUTED CONTROL IN THE OPERATION OF DISTRIBUTION NETWORKS

MGs require going from a conventional centralized control scheme to a distributed control scheme. This type of control must have new considerations, such as cybernetic and physical layers, information and communication technologies, cybersecurity, IEDs of high technological complexity, and highly complex distributed control techniques algorithms. Thus, establishing the advantages, disadvantages, and challenges of distributed control in distribution networks, gives an overview of the current possibility that these techniques are present to be implemented.

Table 3 presents a summary of the advantages and disadvantages of distributed control techniques for the operation of distribution networks. The table presents some relevant information about the type of technique, technical advantages, economic advantages, technical disadvantages, and economic disadvantages. The advantages and disadvantages of distributed control techniques applied to distribution networks are framed by the increase in technological capacity that the SGs will present, bringing great technical benefits to the distribution network. However, this implies large initial economic investments in the development of new technologies and modernization of the network.

Table 3. Advantages and disadvantages of distributed control techniques for the operation of distribution networks

Technique	Technical Advantages	Economic Advantages	Technical Disadvantages	Economic Disadvantages
Consensus / Decomposition	Provides voltage and frequency stability in case of connection and disconnection of DGs. Management of active and reactive power exchange in case of connection and disconnection of DGs. Provides flexibility, reliability, and modularity to the network. Measurement, monitoring, detection, and action in real-time operation. Possibility of obtaining all the characteristics of the ADA.	It optimizes the active and reactive power in the network by reducing losses. It optimizes the connection and disconnection of DGs to guarantee the greatest economic benefit. It decreases the duration of faults and interruptions of the power supply.	It continues to depend on global monitoring centers or operations centers. It requires highly complex technological devices (IEDs). It requires the implementation of a complex and robust communications system. Development of highly complex algorithms for the execution of a large number of parallel and real-time tasks.	Large initial investment costs in equipment with great technological capacity. Large costs of operation and maintenance of communication network equipment. Large costs in software development and cybersecurity.
MCP	It provides voltage and frequency stability in case of connection and disconnection of DGs. Management of active and reactive power exchange in case of connection and disconnection of DGs. It provides flexibility, reliability, and modularity to the network. Measurement, monitoring, detection, and action in real-time operation.	It optimizes the active and reactive power in the network by reducing losses. It optimizes the connection and disconnection of DGs to guarantee the greatest economic benefit. It decreases the duration of faults and interruptions of the power supply.	It is only focused on MGs. It requires highly complex technological devices (IEDs). It requires the implementation of a complex and robust communications system. Development of highly complex algorithms for the execution of many parallel and real-time tasks.	Large initial investment costs in equipment with great technological capacity. Large costs of operation and maintenance of communication network equipment. Large costs in software development and cybersecurity.
SMA	It provides voltage and frequency stability in case of connection and disconnection of DGs. Management of active and reactive power exchange in case of connection and disconnection of DGs. It provides flexibility, reliability, and modularity to the network. Measurement, monitoring, detection, and action in real-time operation. Possibility of obtaining all the characteristics of the ADA.	It optimizes the active and reactive power in the network by reducing losses. It optimizes the connection and disconnection of DGs to guarantee the greatest economic benefit. It decreases the duration of faults and interruptions of the power supply.	It requires highly complex technological device agents (IEDs). It requires the implementation of a complex and robust communications system. Development of highly complex algorithms for the execution of many parallel and real-time tasks.	Large initial investment costs in equipment with great technological capacity. Large costs of operation and maintenance of communication network equipment. Large costs in software development and cybersecurity.
Distributed cooperation	It provides voltage and frequency stability in case of connection and disconnection of DGs. Management of active and reactive power exchange in case of connection and disconnection of DGs. It provides flexibility, reliability, and modularity to the network. Measurement, monitoring, detection, and action in real-time operation.	It optimizes the active and reactive power in the network by reducing losses. It optimizes the connection and disconnection of DGs to guarantee the greatest economic benefit. It decreases the duration of faults and interruptions of the power supply.	It is only focused on MGs. It is limited to networks composed only of investors. It requires the implementation of a complex and robust communications system. It cannot perform all features of ADA.	Large initial investment costs in equipment with great technological capacity. Large costs of operation and maintenance of communication network equipment.

The advantages of distributed control techniques in the operation of distribution networks are currently aimed at guaranteeing the stability of the SGs, optimizing the network, and obtaining a reliable, safe, and flexible network. It is also required to have modularity for the high penetration of distributed generation. On the other hand, the disadvantages can be evidenced by the need for highly complex technological devices and the development of a complex, robust, and reliable communications infrastructure. These items are part of the large costs of developing and implementing the network, considering studies on the transition from conventional networks to SGs

6.1 Advantages of distributed control techniques for the operation of distribution networks

- Increased reliability: construction of an electrical system completely monitored and controlled in real-time operation.
- Operational efficiency and economic optimization: complete automation with integrated control systems that have the appropriate analytical capacity for decision-making activities, reducing losses, and optimizing energy consumption and generation.
- Operation and planning of the network: more detailed information on the demand and the conditions of the electrical system through smart devices.
- Network modularity: the integration of smart devices with interoperability through communication protocols allows the network to connect new distributed generation units or consumer users easily and quickly, without affecting its operation.

6.2 Disadvantages of distributed control techniques for the operation of distribution networks

- High cost: due to the total modernization of the network, the transition from conventional network to smart network, intelligent devices equipped with high technological capabilities. It is required a robust, reliable, resilient information and communications infrastructure with high cybersecurity rates.
- Lack of regulatory standards for distributed control applied to smart distribution networks.

6.3 Applications of distributed techniques

In most cases, distributed control techniques in electrical networks have been applied in the case of distributed energy resources and microgrids. Some applications where the techniques have been very powerful are described below:

1- Primary control: In the scheme proposed by Prodanovic and Green [40], the control actions of a voltage-fed converter (VSC) are divided between a local controller and controller central one. The central controller ensures that the units identify steady-state reference points and filter out low-frequency signals, while the local controllers filter out the high-frequency component.

2- Voltage coordination: The objective of voltage coordination is to provide a voltage profile in the microgrid. Voltage coordination is performed locally or centrally. The former control scheme is performed directly through an internal control loop by increasing the voltage drop control, while in the latter scheme, a centralized or distributed controller updates the reactive set points of each DER unit, as described presents and shows in studies [41, 42].

3- Power coordination: Power coordination and economic operation are important operational considerations. The optimal power flow problem aims to solve this centrally. Generic distributed optimization strategies do not consider the temporal variability of communication links and require extensive calculations. Some methods consider the time variability of the communication links, but require the constraint sets to be the same for each local generator. That is why in studies [43-45], some real application cases are presented where this problem is addressed, giving it a solution employing discrete variables and methods based on decomposition.

4- Frequency coordination: Frequency control is applied in the following applications: Microgrids connected through a multidrop HVDC link and DER units that are electronically interconnected so they can control the frequency independently. The goal of frequency control is to make different units converge to a common frequency. Each unit can have its own minimum and maximum values for power and voltage. An example of frequency control is presented in the study [46], which adds a proportional term to the time derivative of the frequency in the power control loop.

6.4 Challenges of distributed control techniques

In the transition from conventional electrical networks to SGs, the main challenges of distributed control applied to the operation of distribution networks are in technological development. Hence, intelligent devices (IEDs/inverters) must consider measurement, computing, actuation, and communication characteristics, besides creating a reliable, robust, and secure communications infrastructure. All this makes the use of distributed control techniques for the operation of distribution networks currently highly expensive and limited in terms of application. Therefore, these challenges are expected to be addressed in the future, with the development of smart devices and communication infrastructures that comply with the technical characteristics and are economically affordable.

Electrical distribution networks are constantly changing, and distributed control techniques have been gaining great importance for quick decision-making [47, 48]. Therefore, new developments and applications have been presented in the literature. For example, in the study [49], some authors have proposed an improved tunicate swarm algorithm for the automation of distribution networks with distributed generation and capacitor banks. In the study [50], other authors presented a physics-constrained adversarial training method to enhance the robustness of neural networks and locate faults in power grids. The method consists of a training strategy that includes the physical constraints in the machine learning models.

In the study [51], a study reviewed the advances in implementing SGs in Colombia. The authors of this paper reviewed the installed measurement, communication, control, and security elements of the traditional power system and compared them to future solutions to identify the advances. Furthermore, they identified the technological advances related to the use of analysis and management software to optimize the operation of the electrical network. Some examples of different projects are presented and they detail some advantages and disadvantages of the different solutions.

The study [52] proposed a perturbation observer-based multiloop adaptive control (POMAC) method for the integrated control of DFIG-WT. They performed some simulations and test the method with hardware in the loop experiments to evaluate the performance. They used two platforms, such as RTDS Simulator and dSpace. In the study [53], some authors have presented some opinions on the control and stability of large-scale power systems with high penetration of renewable energy generation. They presented the challenges of integrating renewable energies into the power system related to operation, decarbonization, and stability. They also presented some comments about the use of some new control technologies and methods to mitigate the impact.

Additionally, in the study [54], the paper evaluates the consumption capability of the distribution network with distributed renewable energy under different energy storage configurations. In another study [55], the paper presents a study of the voltage control problem of the distribution network of integrating large-scale renewable energies. In the study [56], a distributed control that controls the continuous and discrete variables in a distribution grid is presented through simulation. In the study [57], the paper presents a distributed algorithm for the stochastic Volt/Var control for distribution networks; this method allows to perform a dispatch performing control actions tap changers, capacitors distributed generation inverters for real-time operation. Finally, in the study [58], a study presented a distributed reactive power optimization algorithm to optimize the distribution network without requiring a central coordinator; they use a distributed reactive power optimization algorithm to find the global optimum solution of non-convex problems for distribution networks.

Cyberattacks on power grids have already caused large-scale temporary blackouts, resulting in human, economic and environmental losses. Hence, the inclusion of cybernetic capabilities is required as electrical networks are exposed to information security risks. Thus, distributed control systems must manage cybersecurity risks and attacks effectively. For this reason, it is necessary to define strategies to mitigate cyberattacks through a consolidated, planned cybersecurity management approach.

Progress in normative and regulation has been made for implementing policies that allow the integration of new technologies in the electrical system. However, there is a lack of norms and regulations that allow adequate progress with the implementation of distributed control techniques.

Therefore, it is necessary to promote and present technical proposals that demonstrate each of the advantages of modern electrical networks [59]. The implementation of these normative and regulatory mechanisms motivates electricity companies, technology providers, developers, and users. In addition, this could be useful to include this type of investment in their future technologies. This could achieve a massive and accelerated implementation to take advantage of distributed control techniques in the operation and control of smart electrical networks.

7. CONCLUSIONS

This paper has provided a comprehensive overview of the distributed control techniques utilized in the operation of distribution networks. Techniques reviewed encompass those predicated on consensus and decomposition, predictive control models, multi-agent systems, and distributed cooperation. The integration of distributed control within the Smart Grid (SG) facilitates the proficient integration of renewable energy sources exhibiting intermittent characteristics, guarantees reliable bidirectional information flows, ensures energy efficiency, enables effective demand management and consumer choice, provides self-recovery from power disturbance events, and endows the system with flexible operation capabilities against physical and cyber attacks.

The application of a distributed control architecture to the operation of electrical distribution networks remains a work in progress, necessitating significant technological modifications and the integration of new Intelligent Electronic Devices (IEDs), digitization, Distributed Generation (DG) penetration, and a robust communications infrastructure. Modern electrical networks are mandated to adopt new architectures and control techniques that facilitate the approach to Advanced Distribution Automation (ADA) and ensure optimal operation, power system stability, economic management, and environmental preservation. Furthermore, to align with the objectives of ADA, the network must enable remote control, automatic reconfiguration, asset management, fault diagnosis, and self-healing. The integration of distributed control in electrical distribution networks will equip operators with an optimal tool for network operation and management. The diverse techniques presented in this paper can be adapted by operators to their systems, enabling the selection of the best technique according to their individual needs. Distributed control techniques have emerged as viable solutions to confront the challenges in the transition from conventional electrical systems to SGs.

Future works could entail a comparative analysis of communication infrastructures and protocols utilized for distributed control techniques in the operation of electrical distribution networks. Additionally, a comparison between conventional and distributed control techniques applied to electrical distribution networks could be undertaken.

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