Review

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A Review of Demand-side Resources in Active Distribution Systems: Communication protocols, Smart metering, Control, Automation, and Optimization

Mukovhe Ratshitanga , Efe Francis Orumwense * , Senthil Krishnamurthy , Moteane Melamu

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Review

A Review of Demand-Side Resources in Active Distribution Systems: Communication Protocols, Smart Metering, Control, Automation, and Optimization

Mukovhe Ratshitanga [1], Efe Orumwense [2,*], Senthil Krishnamurthy [1] and Moteane Melamu [1]

[1] Department of Electrical, Electronics and Computer Engineering, Cape Peninsula University of Technology, Cape Town, 7535, South Africa; ratshitangam@cput.ac.za (M.R.); krishnamurthys@cput.ac.za (S.M.); moteanelm@gmail.com (M.M.)

[2] Department of Mechanical and Mechatronic Engineering, Cape Peninsula University of Technology, Cape Town, 7535, South Africa; orumwensee@cput.ac.za.

* Correspondence: orumwensee@cput.ac.za; Tel.: +27-21-953-8712

Abstract: Power systems have been going through a barrage of transformations due to the recent developments in the field, such as deregulation and restructuring of the electric power supply chain, the proliferation of distributed generation (DG), and advancements in information and communications technologies. These have significantly impacted the approach to the planning, design, and operation of active distribution networks or systems. Due to this constant change, the system has become more complex to plan, maintain, and control. In this paper, the benefits, and challenges of active distribution systems relative to traditional passive and active distribution systems are evaluated and investigated while the management and operational characteristics of demand-side resources in Active Distribution Systems (ADS) are studied. In a typical ADS, there exist several vulnerabilities and threats that eventually pose a challenge in the control and automation of substations. These vulnerabilities and threats are reviewed, and potential mitigation measures are suggested. Also in this paper, the communication technologies, and their implementation in terms of control and automation capabilities in active distribution networks are also studied. From this work, it is concluded that communication technologies play an integral role in the realization of a more active distribution networks and that the internet of energy (IoE) is a major player in ADS in the reduction of faults due to human error, fast responses, and improving the stability of power supply. Cyber threats are also and will still be a continuous challenge in smart metering technologies and in substation automation systems (SAS) which will require frequent evaluation and mitigation measures so as not to prevent the power supply system from collapsing.

Keywords: active distribution systems (ADS); demand side resources; IEC61850; smart metering; control & automation in ADS; optimization techniques in ADS

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1. Introduction

The involvement and incorporation of active components such as Distributed Generation (DGs) have transformed power systems from being passive ones (operated based on unidirectional power flow) to being non-passive (based on bidirectional power flow) or active distributed systems (ADS). ADS is a part of a smart grid (SM) whose operational characteristics are dependent on advanced controllers, and smart communication infrastructures including smart meters to meet users' needs and utility preferences effectively.ADS is a relatively recent concept that has arisen in the context of the developments that have evolved over the past few decades in the area of electric power supply. It essentially relates to a salient shift in the manner in which electric power distribution systems are planned, designed, and operated [1].

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The distribution network is a key component of the electric power supply system, creating the vital link between (large-scale, centralized) electric power generation and high-voltage transmission on the one side, and end-users of the power supply on the other. Traditionally, it has fulfilled this role in a largely "passive" manner, having little to no real-time automation and power flow control. Distribution networks have traditionally been designed to passively cater to all possible load scenarios, as well as contingencies, without much reliance on active control. Moreover, with one-way (and largely predictable) power flow, protection coordination and response to abnormal system conditions have also been fairly manageable, with little need for sophisticated protection solutions. This approach to electrical distribution system design and operation has served the intended purpose quite well for a long time. New developments, however, notably the deregulation of the electric power supply industry (in most countries), as well as the growth of distributed generation, have necessitated a reconsideration of the adequacy of the traditional approach, leading to the concept of "*active distribution systems*."

Grid-integrated distributed systems [2] in general have in the last few decades gone from being nearly non-existent to becoming a significant (and growing) component of all new generations in most parts of the world.[3,4]. In South Africa, the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), launched in 2011, has since its launch resulted in the contracting of nearly 12 GW of renewable energy, of which about 6.1 GW has thus far been integrated into the electric power grid[5]. Through the Integrated Resource Plan (IRP) 2010-2030, very ambitious targets have been set for the contribution of environmentally friendly generation to the meeting of total South African energy needs going forward, especially given the need to honor the carbon emissions reduction commitments made by the South African government [6] and the ongoing challenge of severe electric power supply shortages the country is facing.

In the context of an ever-growing share of distributed (and especially variable renewable) generation in the power system, the efficient grid integration and management of these new forms of generation have been identified as being pivotal to ensuring the continued operation of a stable, efficient and more economic electric grid (Pierros, 2016). This in turn raises the need for efficient control and grid integration strategies that enable the active contribution of distributed energy resources (DER) to the realization of the power system's operational objectives [2,7]. One strategy for the grid integration of DERs that has been widely studied is that of aggregating a variety of DER technologies and operating them in a coordinated manner to combine their synergistic characteristics, and simultaneously enhance the exploitation of intermittent renewable generation. Microgrid and Virtual Power Plant (VPP) are two such aggregation approaches that continue to be active areas of extensive research [8].

A microgrid is generally defined as an interconnection of various DERs (intermittent and dispatchable distributed generation, distributed storage, demand response, etc.) and loads, with suitable control and electrical protection functions to enable it to operate either autonomously or in parallel with the electric grid while meeting the operational requirements in either mode. It is usually considered to be connected to the low or medium-voltage distribution network and has the desirable characteristic that it appears to the grid as a single controllable entity, thus considerably enhancing the grid integration of several heterogeneous DERs [9]. A microgrid may be designed to serve a variety of needs, but a primary goal is often the enhancement of (local) electric power supply reliability, with the microgrid's capability to operate either in parallel with the grid or autonomously [10].

A Virtual power plant (VPP) is yet another concept for the aggregation of a variety of DERs, of differing characteristics and technologies, operated collectively based on an advanced ICT infrastructure and an advanced EMS, to realize more benefits from the coordinated utilization of the available resources than would be possible in the case of individual resource operation (Saboori, 2011). While a microgrid is mainly designed to improve the supply reliability and power quality for a local load or a part of the distribution network [4] the development of the VPP concept has mainly been driven by the intention to effectively integrate DERs into various sections of the electricity market (Pudjianto, Ramsay, & Strbac, 2007). Additionally, the resources making up a microgrid (to a

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large extent) tend to be situated in one geographical location, whereas a VPP may aggregate resources spanning a wide geographical topography, relying on advanced ICT infrastructure and an efficient EMS to coordinate the operation of the various resources (Othman, 2015). These characteristics of the VPP provide an opportunity for it to offer various system-wide services necessary for the reliable operation of the electric power supply system. Distributed generation and demand-side management, demand response is another component that has been identified as having significant potential in supporting the realization of the electric power system's operational objectives (Pilo F., 2015). Together, distributed generation and demand response can be referred to as demand-side resources. The effective management, control, automation, and optimization of these demand-side resources in active distribution systems is the focus of this review.

The work is structured thus: Section 2 investigates major differences between traditional passive distribution systems and active distribution systems, it further focuses on planning, design, and operation in these systems. Section 3 presents a detailed overview of distributed energy resources including their classifications and investigates the benefits of distributed generation. In Section 4, the implementation of communication technologies for control and automation capabilities in ADS, their roles in active distribution systems, vulnerabilities and security threats associated to them are discussed. State of art control and automation strategies in distribution networks are presented in Section 5. Section 6 details a survey of various optimization methods employed on the demand side resources of ADN while Section 7 concludes the paper and presents recommendations for further studies.

2. Comparison between Active and Passive Networks

There is a massive energy shift from the traditionally centralized power systems in which power flows in one direction to unidirectional power flow, operating electrical networks with smart grids, communication flow, and information exchange [1]. The centralized electrical network has challenges such as reliability, scalability, and slow responses from the central point [11]. The continuous technological development is pivotal in how electrical distribution networks are evolving. The solutions from these technological advancements provide benefits to entities operating in that space. Nevertheless, the implementation of such technologies in a slow-maturing distribution network undoubtedly results in challenges [12].

In an ideal working operation, the distribution network works as a perfectly balanced three-phase system. However, the increased penetration of DG and power electronic interface devices are but some of the equipment that introduces disturbances that require mitigation for system stability [13]. The electrical network's primary objective is to dispatch power between bulk power systems and the consumer and to regulate voltage to its nominal values and power quality [13]. The active distribution network is a system that has adequate control to manage a mix of different generators, loads, and energy storage systems [14]. Passive distribution networks are dependent on huge generating capacity to deal with disturbances in load variation to maintain continuous power flow and have a relatively simple control technique [15].

Active distribution systems possess the ability to be able to handle real-time monitoring and control of the electrical network and are capable of employing distributed generators to provide stability on low-voltage networks [16]. Controlling and monitoring of the active distribution network are through the centralized systems and distribution management systems. This is done at the primary substation and at medium voltage (MV) feeder to improve grid stability [17,18].

2.1. Traditional planning, design, and operation of the distribution network

For distribution networks to fulfill their intended function, it has to be managed appropriately, and this role is carried out by the distribution network operator (DNO), and normally regulated by a national regulatory authority(NERSA). Thus, according to a *European Commission directive* (Article 25(1), Directive 2009/72/EC), the DNO is "responsible for ensuring the long-term ability of the system to meet reasonable demands for the distribution of electricity and for operating, maintaining and developing under economic conditions a secure, reliable and efficient electricity distribution system

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in their area with due regard for the environment and energy efficiency."And according to the *South African Distribution Code: System Operating Code* (NERSA, 2014), the DNO (referred to in the document as the "Distributor") is mandated to 'so operate the distribution system as to achieve the highest degree of reliability, to coordinate voltage control and demand control, and to monitor (system) security to assure safe, reliable, and economic system operation.

From the two excerpts above, it could be stated that the DNO is tasked with operating the electric distribution supply system to maintain the security, reliability, and high quality of supply and achieve the above-stated goal in an efficient, economical, and (environmentally) sustainable manner. Network security and reliability of supply are two closely related measures of performance, as they both characterize the network's ability to meet load demand at any time and without interruption [19]. The nature of the distribution network load is such that it varies considerably and in a largely unpredictable pattern over time (daily and/or seasonally), and network security requires that enough capacity is maintained in the system, not only to meet the peak demand but also to provide for uncertainty in generation availability as well as unpredicted demand increase. Reliability of supply also requires that supply interruptions (typically due to fault conditions on the network) be limited both in extent (i.e. number of affected customers) and duration. Several performance indices are employed in evaluating the reliability of supply,prominent among them being the loss of load probability (LOLP), specifying the probability (or risk) of the available generation capacity being insufficient to meet peak demand, loss of load expectation (LOLE), reserve margin and expected energy not served (EENS).

In the case of disturbances leading to supply interruption, the following performance indices are commonly used as a measure of the actual extent of the impact on customers' system average interruption frequency index (SAIFI), a measure of the amount of supply interruptions at a given voltage level over a certain period, system average interruption duration index (SAIDI), indicating the average duration of the supply interruptions (that are expressed by the SAIFI), customer average interruption duration index(CAIDI), quantifying the average duration of the supply interruptions for a given customer type. These indices are mainly used in network planning, particularly to determine the generation capacity required to deliver the desired level of supply reliability as expressed through one or more of the indices.

Following network security and reliability of supply, the quality of supply is another very important aspect of distribution network operation. In the NER *Directive on Power Quality* [19], power quality is defined as "all waveform variations from the ideal 50 Hz sinusoidal waveform (including dips and interruptions)." This definition of power quality is made concerning the quality of the voltage waveform (in terms of the magnitude, distortion, imbalance, & fluctuation), as well as voltage events (such as dips, sags, interruptions, & rapid voltage changes), as further specified in the directive. The importance of voltage quality as a measure of the quality of electricity supply is evident from the fact that the standard: NRS 048-2:2003: Electricity Supply-Quality of Supply: Part 2 [19], is wholly dedicated to the definition of the voltage characteristics, compatibility levels, limits and assessment methods that apply to all levels of the electric supply system (in South Africa), and which the DNO is required to provide for, at the distribution network level.

It is acknowledged in the NER directive that the nature of the electric power supply system effectively precludes the total avoidance of power quality degradation (largely dictated as it is by the environment (within which the system operates), particularly the nature of loads connected to the supply system, which by the nature of the current drawn tends to introduce distortion, fluctuation, imbalance, and other adverse characteristics into the system). This notwithstanding, the utility (i.e. network operator) is required to ensure that the network is designed and operated to achieve an acceptable level of power (i.e. voltage) quality, acceptable concerning meeting the needs of all customers served by the utility.

The second operational objective of the distribution system (that of efficiency, economy, and sustainability) also has to be achieved by a suitable design of the network and its effective operation. For instance, network efficiency is improved in part by minimizing network losses (associated with power delivery). The efficiency along with optimal asset utilization (among other operational aspects), will in turn impact the economy of system operation. Sustainability demands that the environmental impact of the electric power supply system be accounted for in the planning, design, and operation thereof [20].

2.2. Planning, design, and operation of Active distribution networks

The need to integrate DERs into distribution networks (as opposed to just connecting them thereto) can be singled out as a pivotal driver for active distribution networks. As the penetration of DERs in the distribution network grows, so does the need to consider their impact on the network, from the planning, right through to the design and operation of the network [2].

While the operational objectives of the distribution network (in the traditional sense, as discussed above) have hardly changed, the environment within which they have to be realized has done so, and this is a key motivating factor behind the concept of active distribution networks. Present and future distribution network planning, design, and operation (amongst others) are expected to be influenced by the liberalization of the electricity markets, technological advancements, new requirements for efficiency, security, and quality of power supply, changing consumer needs and expectations and distributed energy resources (DER) integration.

Table 1 belows shows the major differences between passive and active distribution networks.

Table 1. Difference between Passive and active distribution networks [14].

Consideration	Passive Distribution Network	Active Distribution Network
Degree of automation	Very little	Omnipresent
Control Philosophy	Local control	Integrated Hierarchical
Advanced distribution applications	Not applicable	Ability to analyze multiple applications in parallel.
Modeling communication networks	Not applicable	Assessment of dependence on different telecom performance
Reliability	Predictable	Several points of failure on DG and equipment. Requires a deep analysis of models integrated with other analysis
Demand side integration	Contribution of large customers to system peak	Probabilistic based models Multiple participation
Modeling DG	Synchronous machine models	Multiple DG models Energy forecast Several control model Accurate short circuit model
Security	Little security and privacy concerns	Multiple security and privacy challenges
Scalability	Little option for network expansion	It can expand fast and support a large number of connectivities

3. Demand Side Resources in Active Distribution Systems

Demand-side resources are any technology hardware or software utilized by consumers that can deliver grid services such as energy dispatch from rooftop solar to the grid, capacity to provide stored power from energy storage system based on load fluctuations and provide ancillary services for grid stability [21]. This is attained through the deployment distribution generators (DG) on a medium to low voltage level. DG system is a small electrical generation technology that is located closer to the load. There are several of such technologies which include renewable energy sources such as wind and solar, natural gas-fired fuel gas, biomass, tidal power, geothermal power, and non-renewable generators as depicted in Figure 1 [22].

These DG can be directly connected to the grid via power electronic devices or power a local load while dispatching access to the grid. DG can also affect the distribution network negatively due to the unidirectional power flow. The challenges with unidirectional power from the rise in DG lead to voltage quality, protection devices setting, increment in maintenance, and fault current that affect a huge portion of the distribution network. DG however possesses several benefits such as reduction in transmission and distribution loss due to proximity to the load which could further assist in expansion alternatives. In peak hours they cater for a portion of the load therefore reducing the peak demand moreover improving power quality and network stability because of their quick start time and ability to dispatch almost instantaneously. In addition that can also mitigate possible blackouts of the entire network [23]. Demand-side resources can be used in several ways in the energy markets. DR is an active source of active distribution Networks (ADN) and also comprises of flexible loads, electric vehicle(EV), DR inflexible loads, and energy storage on the consumer side [24]. Load balancing still remains a challenge in DG dominated by renewable energy sources in which there is a frequent need to match between supply. There are several demand-side management (DSM) resources to mitigate load-balancing challenges and avoid the need to use the supply-side resources to balance renewable power increase. The demand side resources can be classified into energy efficiency and demand responses. Electrical power networks have embarked on programs that encourage the use of high energy efficient appliances such as lighting or equipment that employs variable speed drives. This however, does not form an active resource which means it cannot balance renewable fluctuations in real time but energy efficiency therefore balances renewable fluctuations over a longer period through resource planning [25].

3.1. Demand Responses

Demand Response (DR) refers to the strategy to encourage consumers to reduce energy usage in the near term in response to a price signal from the electricity hourly market or a trigger set by the electricity grid operator. DR activities typically last 1 to 4 hours and involves turning off or lowering lighting banks, altering HVAC settings, or shutting down a segment of a manufacturing process. In addition, onsite generating can be utilized to displace load pulled from the power grid [26].

The quest to reduce the electricity generation sector and consumption is paramount. This can be achieved by increasing smart energy solutions (SES) which constitutes one of how that could be achieved. This however cannot be fostered for its own sake, but rather as a tool for attaining common goals [27]. The DR activities are very complex, but the introduction of the Internet of Energy (IoE) revolutionized power production and supply, and the Figure 1 below depicts the IoE with energy trading.

Figure 2 shows automated demand response operability in the different layers.As seen in the Figure 2, the evolution of communication and metering equipment has transformed the traditional distribution grid into the Smart Distribution Grid (SDG). Two-way communication between utility and consumers facilitates the sharing of metering information, allowing them to better utilize their energy resources and engage in automated demand response. To deploy DR in an automated way, smart metering infrastructure, communication technologies, flexible energy supplies, and efficient decision-making tools are of utmost importance. ADS operates in three layers, namely the physical layer, the communication layer, and the software layer as shown in Figure 1. The wide area network (WAN) is managed by the utility or companies while the neigbourhood area network is managed by the aggregator. The home area network, building area network and industrial area network are of the same level and managed by the consumers themselves.

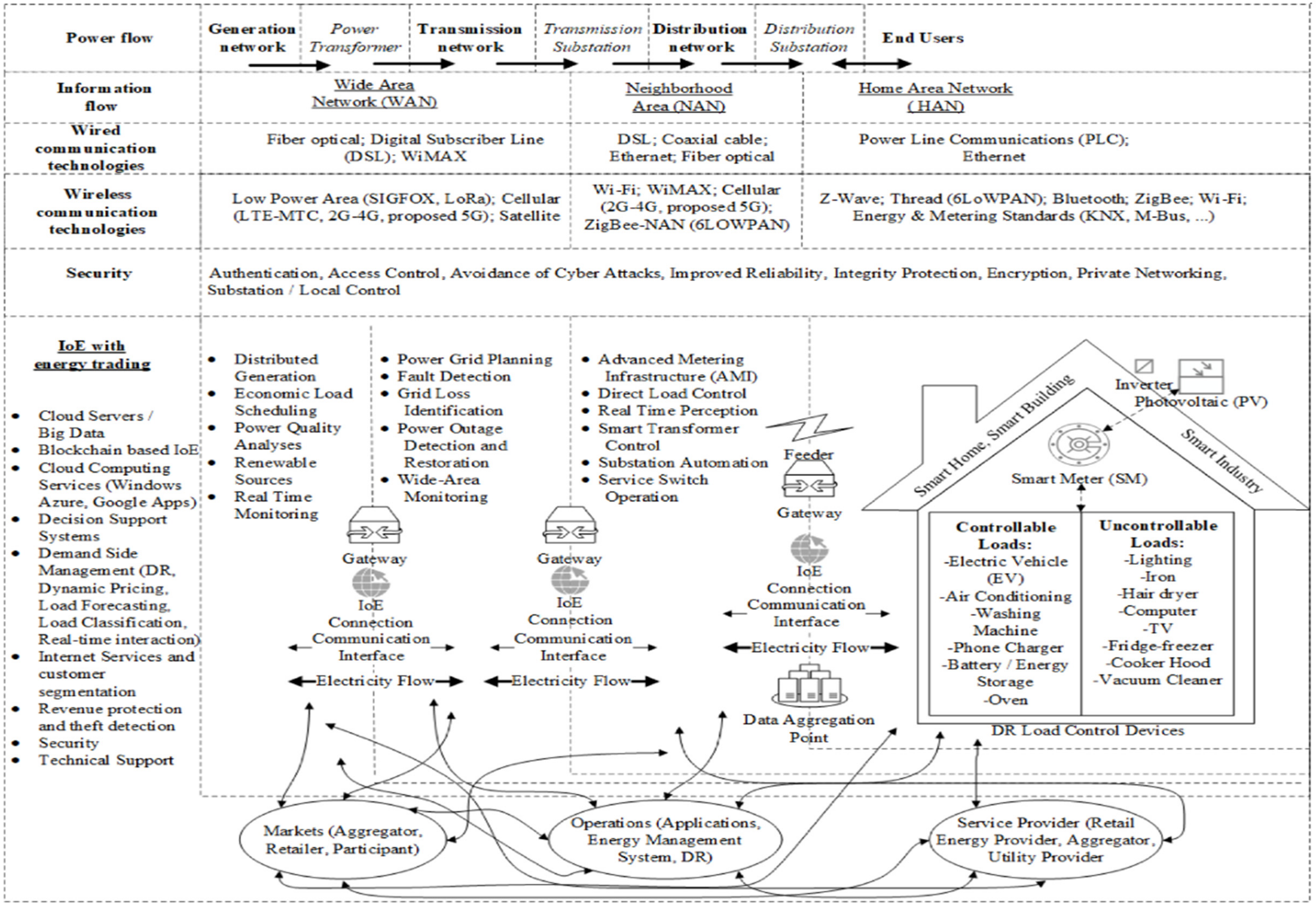

Figure 1. IoE with Energy [27].

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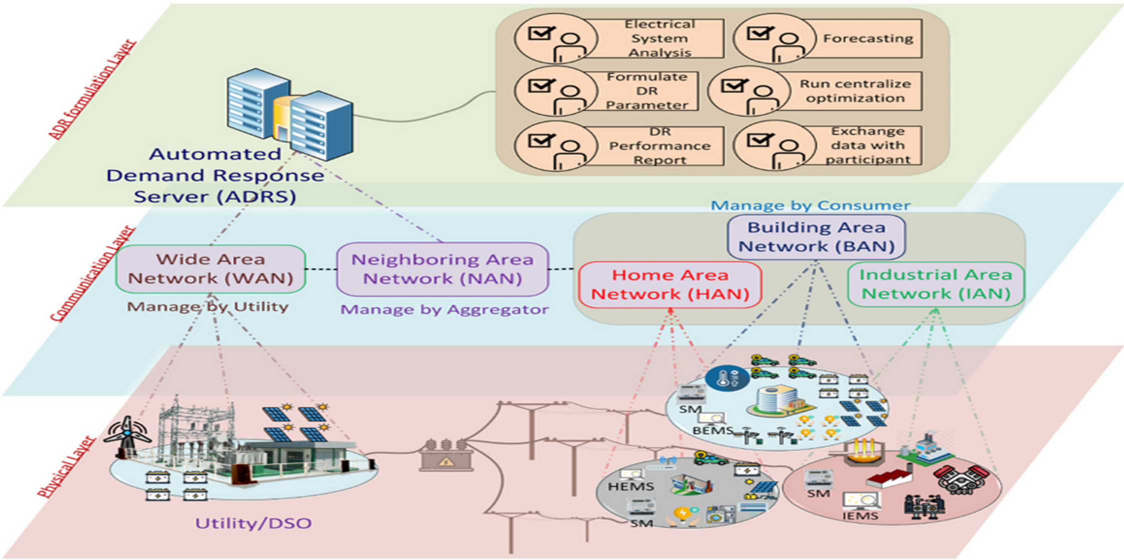

Figure 2. Automated Demand Response Operability layers [28].

3.2. Demand Response Systems Objectives and Deployment Barrier

Depending on the aim of the specific DR implementation and design, there exist several objectives of DR systems such as reducing total energy consumption to achieve greater profits by both the supplier and the consumer. Another important objective is to also reduce the total generated power due to the reduced energy consumption and changing the demand while considering the current supply to improve the overall reliability of the system. One of the vital objectives of DR systems is to mitigate distribution system overload through a distribution management system by monitoring the distributional services provided by the system and using real-time adjustments to increase system robustness [29].

There are a few hindrances to DR deployment firstly is the problem of technology-based barriers caused by a lack of protocols and standards. Secondly, is the markets and regulatory frameworks hindering DR deployment due to market entry barriers and unequal treatment of participation. Another deployment barrier which also poses a hindrance is the privacy of information which is mostly called consumer privacy [30]. Finally, uncertainty in demand and renewable energy generation for aggregators to predict ADR potential for the consumer is also an important deployment barrier faced by DRs [28].

4. Communication Technologies Implementation for Control and Automation Capabilities in Active Distribution Networks

The integration of DG into power networks to form a more intelligent power grid is at the forefront of modernizing the electrical grid so as to accommodate renewable energy sources, decentralized generation, and increasing demand. This relatively new power system architecture requires information and communication technologies(ICT) for integration [31]. This ICT helps in managing the complexity of ADNs effectively, and the implementation of control and automation functionalities [32]. The heart of modern ADNs lies in their ability to communicate, collect data, and make real-time decisions. This work reviews the critical role played by communication technologies such as the Internet of Things (IoT), 5G networks, and Low-Power Wide-Area Networks (LPWANs). It discusses their suitability for different use cases within ADNs, including monitoring, control, and demand response. The distance coverage, rates, ranges, and power consumption of several wireless communication technologies that can be employed in ADNs is depicted in Figure 2. A key requirement for the development of the IoT is achieving low power consumption. There are also

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additional requirements that need to be considered in addition to reducing power consumption in ADNs [33].

This section delves into the various enabling technologies, communications technologies, and protocols that play a pivotal role in achieving this transformation.

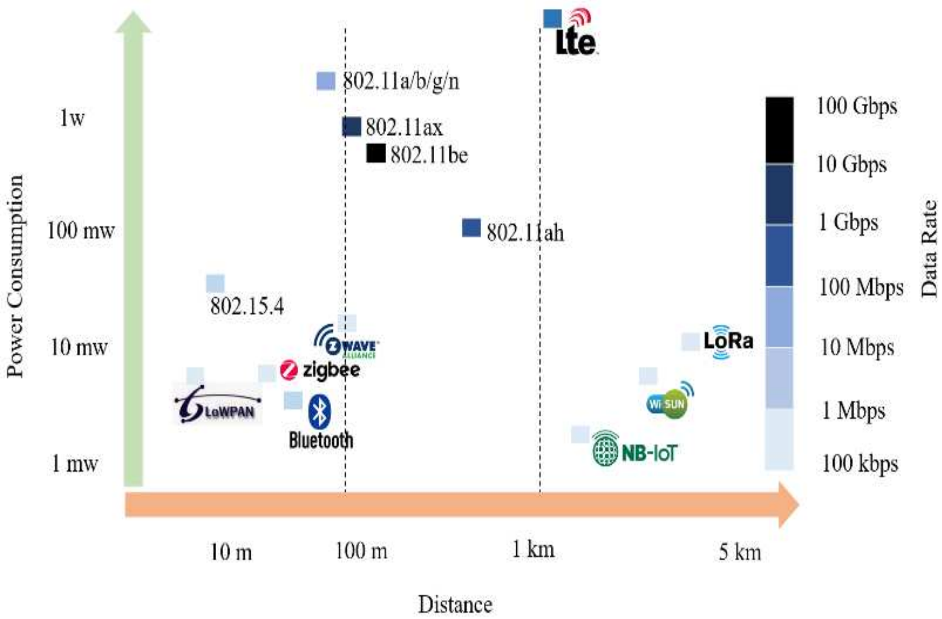

Figure 3. Data rate,coverage distance,and power consumption for various protocols [33].

4.1. Protocols in Active Distribution Systems

The electrical industry employs open protocols, which was created in the 1990s, to manage SCADA systems over great distances. It was created to provide extra services via Ethernet TCP/IP (Transport Control Protocol)/(Internet Protocol) networks and Master/Slave serial communication (RS232, RS485) networks. It is built on four layers: application, pseudo transport, data link, and physical layer. The system consists of master terminal unit (MTU), remote terminal unit (RTU), and IED (Intelligent Electronic Devices) [34]. There are two main categories of communication technologies for the active distribution network: wired and wireless. In terms of dependability, security, and bandwidth, wired technologies are frequently seen as being preferable to wireless ones. In contrast to wireless communication solutions, wired solutions do not rely on batteries and do not have any interference problems. However, wireless communication systems allow for flexible deployments with little cabling and inexpensive installation costs, enabling connectivity to be offered over vast areas or in places where there is no existing communication infrastructure [1]. Because of this, depending on the intended applications and functionality, each of these communication technologies has benefits and drawbacks that must be taken into account. Smart grid communication is based on the IEC61850 standard which provides specifications for the design and operation of those intelligent grids [35].

4.1.1. IEC61850 standard for coordination and control of active distribution systems

In recent times, the smart grid which incorporates several clean energy resources has become a core of electricity and communication, so that the electric network will be always available, live, interactive, interconnected, and tightly coupled with communications in a complex energy and information real-time network. Consequently, this leads to more efficient power systems developed, capable of regulating rising energy demand, providing fault resilience, and smoothly integrating distributed renewable sources such as wind and solar [36]. The exponential growth of DG has resulted in the bidirectional flow of power instead of the old unidirectional one. This growth of DG

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and interconnection to the distribution system poses challenges in power flow and requires monitoring and control. This challenge that is associated with DG in management for high efficiency and stability needs is solved by Information and Communication Technologies (ICT) [37]. Information sharing is a linchpin of the efficient and effective operation of energy systems in real-time. In the 1930s this was executed telephonically where line loads were communicated to the control center and operators, therefore, did the switching at substations [38]. The advancement in digital communication in the early 1960s was little matured to the level that data can be acquired automatically from the substation. Further developments in digital communication space require that energy systems can utilize intelligent electronic devices (IEDs) to control and monitor the electrical network automatically [39]. An electrical substation is a link between the distribution network and the transmission system. They have devices where operators can monitor and control power flow and ensure the safety of the network [40].

There has been a spike in substation automation system (SAS) investments in recent times to reduce power interruptions, identify faults speedily, and restore power flow timely to consumers. SAS was vendor proprietary until 2007 due to the lack of standards which resulted in closed systems with limited range. They also had their specific serial communication, thereby requiring the employment of protocol converters to incorporate a third-party device. The IEC61850 was then introduced to provide guidelines to enable the interoperability of IEDs between different manufacturers. This resulted in a smooth data transfer between several IEDs and that was used to execute different functions in a coordinated way [41]. This standard does not specify how the control logic within IED should work nor how the communication must be but deals with the external behavior of control devices [42]. IEC 61850 was originally conceived and developed as a communication standard within a substation. As this technology started to gain momentum, it metamorphosed into a standard capable of covering other parts of the power system such as electrical protection and control function models, device configuration languages, physical process data models, and electromagnetic compatibility [35].

The automation control of modern substations employs several standards, technologies, and protocols such as MODBUS, IEC60870, and IEC61850 protocols and are managed through an ethernet-based network [43]. The manufacturers established proprietary communication protocols for their IEDs which led to challenges in interoperability between devices. This resulted in the development of IEC61850 to standardize data models in electrical systems equipment and provided operational specifications and engineering standards for required applications in electrical networks so as to mitigate the interoperability challenge amongst devices [40,44]. In traditional substations, the communication signal would travel a long distance from the substation to the control room which resulted in a high frequency of failures, expensive maintenance, and operational costs [44]. Figure 3 depicts three levels of communication that IEC61850 uses and how data is interchanged between them.

Process Level is where there is direct communication with physical substation devices like circuit breakers, voltage and current sensors, and measuring units.

The Bay Level is where the information from devices is relayed and from the data, local control decisions are executed using IEDs. This level conveys the data to the station level.

Station Level is where the devices for supervision and operation are located. Upon receiving the data from the Bay level, human operators can execute various tasks and configurations of SCADAs and Human Machine Interfaces (HMIs). It also connects the substation to a Remote-controlled room from kilometers away, allowing a central operator or utility to manually modify the state of equipment and monitor the substation's activities [40].

The connection of these different levels is through two busses as per IEC61850 which are the process bus and the station bus as depicted in Figure 3 above. This is where the interconnection of the process level interconnects with the bay level and bay level with the station level where different network protocols are supported with varying communication needs [40]. Internet protocols are slow during transient in real-time systems so the IEC 61850 employs several protocols to attain quicker responses.

Manufacturing Messaging Specification (MMS): Used to deal with application, data exchange, and configuration with information between IED and SCADA.Sampled Measured Values (SMV): Delivers quick and dependable communication of power system measurement from both current and voltage transformers.Generic Object-Oriented Substation Events (GOOSE)**:** It is utilized to convert status information between IEDs to be able to isolate faults and prevent damage to critical parts of the electrical network.

With the introduction of IEC61850, the increasing energy challenge has been mitigated by the smart grid owing to its high scalability and interoperability on various IEDs. However, with the vast data exchange, there are several security threats that inhibits its smooth operation such as compromising data integrity, confidentiality, and availability [45,46]. The next section introduces the threats and security concerns associated with IEC61850.

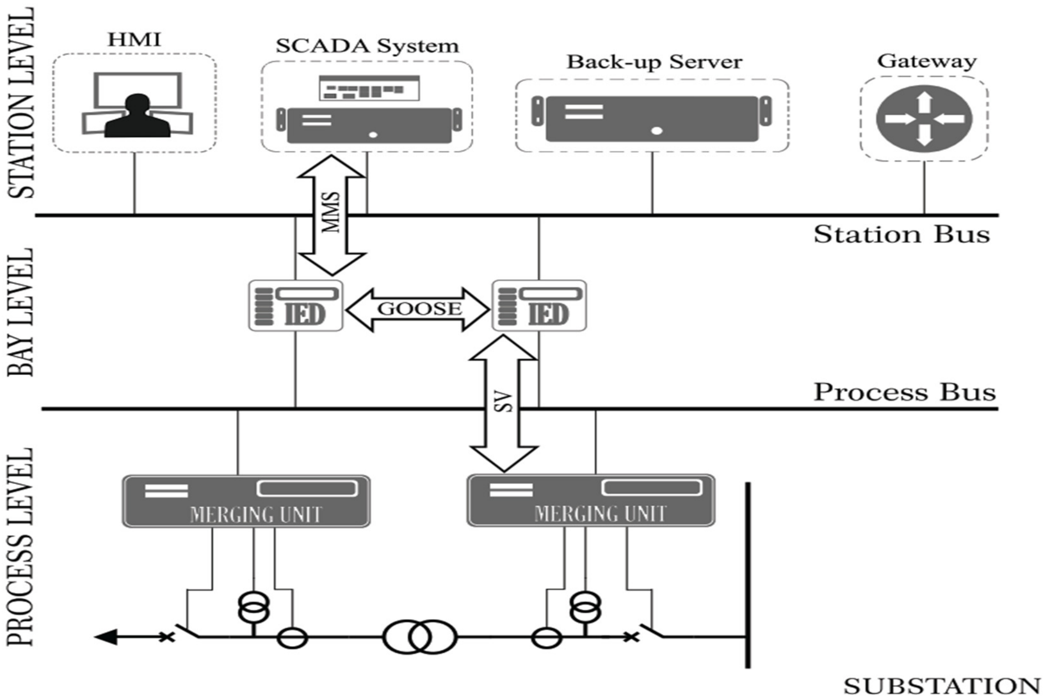

Figure 4. System architecture of IEC61850-based substation [20]**.**

4.1.2. Threats and security concerns in IEC61850 power systems

The vulnerability of the power system automation system is different from the computer internet due to narrow bandwidth and throughput restrictions leading to more overheads because of digital signature and key exchanges. Moreover, communication devices like controllers have miniature memory and processing power hence it is challenging to encrypt them [31]. The wide use of the IEC 61850 standard can be mainly attributed to its interoperability, standardized message structures, and swift and effortless connecting abilities via ethernet instead of the traditional hard-wired systems. The fact that it is very easy to connect, and access has increased its vulnerability to cyber-attacks. The gains for an attacker to infiltrate the system are major to disrupt the services in the IEC 61850 substation by altering or fabricating the data and information exchanges and also to gain access to confidential data and information. Various types of attacks are carried out on substation communication networks aiming at a specific domain, protocol, or node. In the work by [47,48] the authors discussed the malicious Fault Injection Attack (FIA) and the False Data Injection (FDI) that usually targets intelligent electronic devices. This kind of attack is orchestrated by injecting computation errors through invasive or non-invasive techniques. The authors also went further to evaluate the impacts of these attacks on substation security and power grid integrity. In the work by [49], the authors proposed an audit scheme that consists of security metrics that can quantify the security of a certain network. This audit scheme was carried out on the security of the IEC 61850 substation, and it was realized that intrusion attacks are the most common types of attacks on the system. It was however concluded that an intrusion detection technique should be employed as a viable option to counter these attacks.

In a typical IEC 61850, each GOOSE message has two parameters which are the status number (stNum) and the sequence number (sqNum) and for each GOOSE message published, the sqNum value is increased by one while the stNum is updated according to the new event. The work by [50] identified three types of attacks on GOOSE messages which is commonly known as GOOSE poisoning. One of those types of attacks is the high-status number attack in which malicious GOOSE messages with high stNum are sent by the hacker. Unknowingly to the subscriber, these malicious messages are processed while the legitimate GOOSE messages with stNum equal to or less than those of the malicious messages are discarded. Another of these attacks is the high-rate flooding attack in which multiple malicious GOOSE messages are delivered as multicast messages while stNum are increased. This however results in the subscriber being expectant of a very high value of stNum for the incoming GOOSE message. The last of these attacks is the semantic attack. This type of attack is undergone is two stages. The first stage is where the attacker monitors the network traffic and decides on the rate of status change while the second stage is where the attacker multicast malicious messages with different rates. The purpose of these malicious messages is to block subscribers from processing legitimate GOOSE messages.

Cyber intrusion attacks on IEC 61850 GOOSE messages and SMV messages have been detailed in [51]. In this kind of attack, the intruders tend to alter GOOSE messages to trip circuit breakers in substations. If an intruder is armed with an SMV message, the intruder can be able to fabricate values that can control centers which can eventually lead to incorrect conclusions and operational decisions. To prevent intruders from gaining access to the substation automation controls, the authors [51] proposed an Integrated Anomaly Detection System (ADS). In the same vein, another intrusion detection system was also proposed by [49] that operates based on data collected from simulated attacks on intelligent electronic devices. To build on this intrusion detection system previously created, the authors [52] proposed an authentication technique that assists in fulfilling the authenticity and message integrity of delivered messages hence ensuring the system is less prone to intrusion attacks.

Man-In-The-Middle (MITM) attack on IEC 61850 was also discussed in [53] which usually targets MMS messages. In the same light, the attacker may further launch other forms of new attacks on the system such as masquerade attacks, eavesdropping, replay, false injection, and Denial of Service (DoS) attacks as seen in [54].

4.3. Sensor and metering technologies

Over time, the need to share information has propelled human activity, influencing how the economy and technology have developed in society [55]. The accuracy and reliability of data acquisition are paramount in ADNs. Sensor and measurement technologies, such as smart meters, phasor measurement units (PMUs), and synchrophasors should be explored. It underscores how these technologies contribute to situational awareness, fault detection, and grid optimization [56]. Notably, data exchange between sensors, controllers, and actuators becomes of vital significance, affecting measurement precision and the potential for stable control of an industrial process.ADNs have witnessed a remarkable transformation in recent years, driven by the increasing penetration of renewable energy sources and the need for improved grid management. Smart metering infrastructure (SMI) has emerged as a foundational technology for enabling control and automation functionalities within ADNs. This point critically examines the key enabling technologies associated with the implementation of control and automation functionalities in ADNs, with a specific focus on SMI.

Table 2. Security concerns and mitigating measures of IEC61850**.**

Authors	Threats/security concerns	Mitigation measures
[46]	Generation of interfering signals and high frequency leading to loss of metering and control data	Improve compatibility between EN 50160 and IEC TS 62749
[47]	Alteration of substation operations by modifying and falsifying information/data exchanges	Auditing IEC61850 automated substation. Auditing uses security matrices that quantify the security of the network. Then intrusion detection system must be deployed as a counter measure [49]
[47,48]	Fault injection attack (FIA) and false data injection on IED through invasive and noninvasive methods	Auditing IEC61850 automated substation. Auditing uses security matrices that quantify the security of the network. Then intrusion detection system must be deployed as a counter measure [49]. An anomaly detection system(ADS) is employed to prevent intruders from gaining access to substation automation control [51]
[57]	Cyber intrusion attacks on IEC61850 modify GOOSE and SV messages and trip substation breakers	The use of a software-defined network(SDN) switch eliminates possible paths of intrusion and network data overload [58].
[50]	GOOSE Poisoning (High-status number attack, High-rate flooding, and sematic attack) due to predictable status number employed in GOOSE messages and processing numbers from the subscriber preventing legitimate GOOSE messages	The employment of SDN provides a secure rule for incoming GOOSE messages. Moreover, it can restrict the flow of messages for a single output port to mitigate the unnecessary spread of GOOSE messages [58].
[35,59]	Lack of real-time scheduling in high availability seamless redundancy (HSR) affects traffic jitter, especially during a high flow of SMVs that share an HSR ring. This leads to network congestion or stoppage.	The use of the quick removing(QR) approach(QR) to remove duplicated frame copies from the network when all nodes have received one copy of the send frame [59]

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5. State of art in Control and Automation in Distribution Networks

The control and automation technologies in ADNs are very important. They enhance grid stability, enable real-time decision-making, and optimize energy distribution. Control algorithms have evolved significantly, enabling more precise and adaptive control strategies [60]. The latest developments in control algorithms include model predictive control (MPC), distributed control, and machine learning-based approaches. The distributed control system is an essential component of an ADN, enabling efficient, reliable, and resilient grid operation in the face of increasing complexity and the integration of renewable energy sources [61]. It empowers utilities and operators to manage the dynamic nature of ADNs effectively and adapt to evolving energy landscapes, ultimately contributing to a more sustainable and efficient energy distribution system. Supervisory Control and Data Acquisition (SCADA) systems are the backbone of control and automation in ADNs. The control and automation technologies are indispensable for managing the complexities of ADNs [17].

Active Distribution Networks (ADNs) enable grid operators to adapt to the changing energy landscape, integrate renewable resources, optimize grid operation, enhance grid resilience, and respond to grid events in real-time, ultimately contributing to a more reliable, efficient, and sustainable energy distribution system. This section critically evaluates the enabling technologies that facilitate control and automation in ADNs, with a primary focus on control and automation technologies themselves. The main operational goal of the distribution network is to deliver electricity of an adequate level of quality securely and reliably while ensuring economic, efficient, and environmentally sustainable operation. To facilitate the realization of this goal, the distribution network operator (DNO) makes use of a distribution management system (DMS). A DMS is essentially a set of functionalities (or applications) that facilitate the monitoring, control, and automation of distribution network operations. It acts as a decision support system utilizing which the DNO can have a real-time overview of the state of the network and initiate automatic or manual actions meant to maintain reliable and efficient system operation or mitigate anomalous network conditions. Reliability and quality of supply are ensured primarily by minimizing the occurrence of power outages, minimizing the outage time, and maintaining the system frequency and voltage magnitude at nominal levels throughout the network [62].

A distribution management system (DMS) can also be seen as an approach that unites primarily disparate facilities to operate the distribution system in an effective efficient and organized way. It has several functionalities to assist operators in managing and optimizing distribution networks through suitable decision-making. A DMS has two types of application functions which are the (i) real-time application functions and (ii) analytical application functions [63].

DMS is also required to perform a variety of on- and offline analyses to implement such functionalities as fault location, isolation service restoration, and network reconfiguration. A Supervisory Control and Data Acquisition (SCADA) system is an integral component of a DMS, which enables network monitoring, automation, and control. The architecture and key functionalities of DMS is seen in Figure 5. Among the key functionalities of the DMS, the following can be identified, some of which are also depicted the below.

Distribution system power flow (DSPF): The voltage phasors are computed on the nodes given the information of the grid characteristics and power dispatched, representation supply, and loads. Real-time DSPF employs forward/backward sweep for radial network and current injections for meshed distribution network [64,65].

Volt/VAR control (VVC): This is a DMS functionality that is mainly employed in managing voltage levels and reactive power flows throughout the network. Reactive power flows have a major impact on the network voltage profile. Devices employed for VVC encompass those that directly inject reactive power into the grid (e.g. shunt capacitors and shunt reactors), and those that more directly control voltage (e.g. load tap-changing (LTC) transformers and voltage regulators). Traditionally, LTCs, voltage regulators, and capacitor banks have been the primary devices used in implementing VVC. With the continued gradual increase in the amount of distributed energy resource technologies integrated into the distribution network, however, these are also anticipated to take part in VVC. Smart inverters, for example, can inject reactive power into the grid and thus constitute a good alternative VVC resource [66,67]. The VVC functionality facilitates the mitigation against excessively low or high voltages, which may not only impact the power quality but might additionally pose a threat to the safety of electrical equipment. Besides voltage regulation, VVC also plays an important role in minimizing system losses and relieving key network equipment (such as transformers and feeders) of excessive loading (by reducing the ampacity required to satisfy a given load demand).

Load shedding management: This is a DMS functionality that enables controlled balancing of supply and demand, where the demand exceeds the available supply. The main aim is to preserve the integrity of the entire distribution network by interrupting electricity supply to non-critical loads, to prevent a supply shortfall from cascading and threatening to cause the failure of the whole system. An automated load-shedding management application can detect predetermined trigger conditions that necessitate the initiation of predefined load-shedding control actions. If non-automated, operators have the responsibility to manually initiate the load-shedding operations, which should be done in a safe and controlled manner, to always maintain normal service to as large a part of the network as possible. Trigger conditions for load shedding, whether automated or manually initiated, include under-frequency load shedding, limit violations, and time-of-day-based load shedding [68].

Load balancing: This involves re-routing loads to other parts of the network to relieve certain distribution equipment of overload conditions. This is often achieved through network reconfiguration. A feeder load management unit in the load balancing functionality monitors the loads on the feeders and identifies possible areas of congestion that may be susceptible to overload conditions. Feeder reconfiguration may also be used for other network operation improvement measures, such as voltage profile improvement and loss reduction. Other benefits of load balancing include improved network utilization and reduced stress on key network infrastructure [68].

Distribution system state estimation (DSSE): It uses the state vector of the distribution network for estimation where the least square approach is used on redundant measurements [65] .The industrial sector requires premium power quality so either current or power methods are used to achieve high computational performance [69,70].

Optimal feeder reconfiguration (OFR): The main task of this function is to find ways to reduce generation losses by selecting the best radial system configuration. This is attained by solving an optimization that arranges the structure of the distribution network and has a load balance between feeders. The frequently used method due to the challenges of optimization is the switch exchange heuristic [63,71,72].

Distribution system short circuit computation (DSSCC): This function evaluates the capability of circuit breakers if they can perform adequately under maximum current operation conditions. It further checks on relay sensitivity under minimal current faults [64,73].

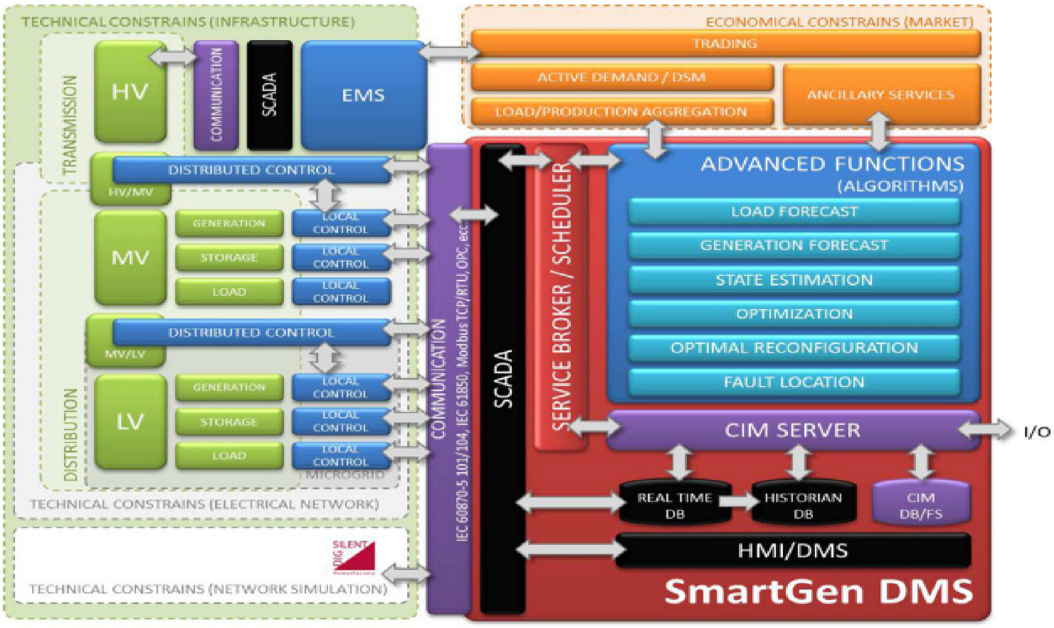

Figure 5. Architecture and key functionalities of a DMS [68].

Fault Locator (FLOC): It employs statuses of fault locators that communicate with DMS to locate fault branches in a network and then employs terminal impedance-based method approaches to precisely localize the faulty line [65,74].Fault Isolation (FISO**):** This is a method of isolating a fault by opening circuit breakers. It isolates a small portion of the distribution network by opening switches upstream and downstream of the fault [75].Service Restoration (SRE): Dispatches power to load nodes affected due to FISO via alternative feeders [72].

Load forecasting: This is a key component of the distribution management system that enables the system operator to assess the short-, medium-- and long-term expected load on the network, which then facilitates network planning and network infrastructure development. Short-term load forecasting is considered to have a duration of up to one day, medium-term load forecasting can consider a duration of up to one year, and long-term forecasting considers a longer duration, of up to 10 years. With the growing integration of distributed generation in the distribution network, generation forecasting is also becoming a key functionality of the DMS. This involves the analysis of weather patterns, seasonality, and other data, to estimate the output that can be expected from distributed generation, especially the weather-dependent intermittent renewable generation (e.g. photovoltaic and wind power generation). Effective load forecasting contributes greatly to reliable, economic, and efficient network operation [76].

The transition from passive to active distribution networks necessitates the development of advanced distribution management system functionalities that can handle the growing complexity of distribution network operation in the presence of a variety of active distributed resources, such as distributed generation, distributed energy storage, demand-side management, and demand response. The following subsection briefly discusses control and automation at the medium-voltage level of the distribution network.

5.1. Control and Automation at the Medium Voltage (MV) Level

The exponential rise of DG in distribution networks which takes place at the MV level means the distribution system operator (DSO) task becomes more complex. DSO will need to perform tasks in a well-coordinated control process for system stability which is the primary responsibility of a transmission system operator [77]. One paramount challenge is the voltage spikes at the DG connection point during the planning phase of the interconnections and future planning of the required operational limit of the future. The control of distributed networks is attained in three control phases: primary, secondary, and tertiary control as depicted in Figure 6. Each control level works at different grid levels and time responses but communication with high priority is connected between secondary controllers and tertiary [78].

Primary Control: This control employs measured values from devices and executes decisions autonomously in seconds. This is achieved by IEDs which control devices such as on-load tap changers (OLTC) that are controlled by automatic voltage controllers (AVC) relays in substations and reactive power compensation.

Secondary control: This is where the monitoring and control of substations happens with the assistance of a substation automation unit (SAU) which keeps network data and then computes state estimations and voltage control algorithms to decide on optimal network state. This information is then sent to controllers responsible for the distribution network [78,79].

Tertiary control: This control is at the control centre where the time response is from minutes to hours and it deals with network rearrangement and energy market decisions are decided here [80]

The primary objective of automation in electrical network is to improve fault management to reduce power outages and cost resulting in unsupplied energy and consequently improves the reliability of the system [81].

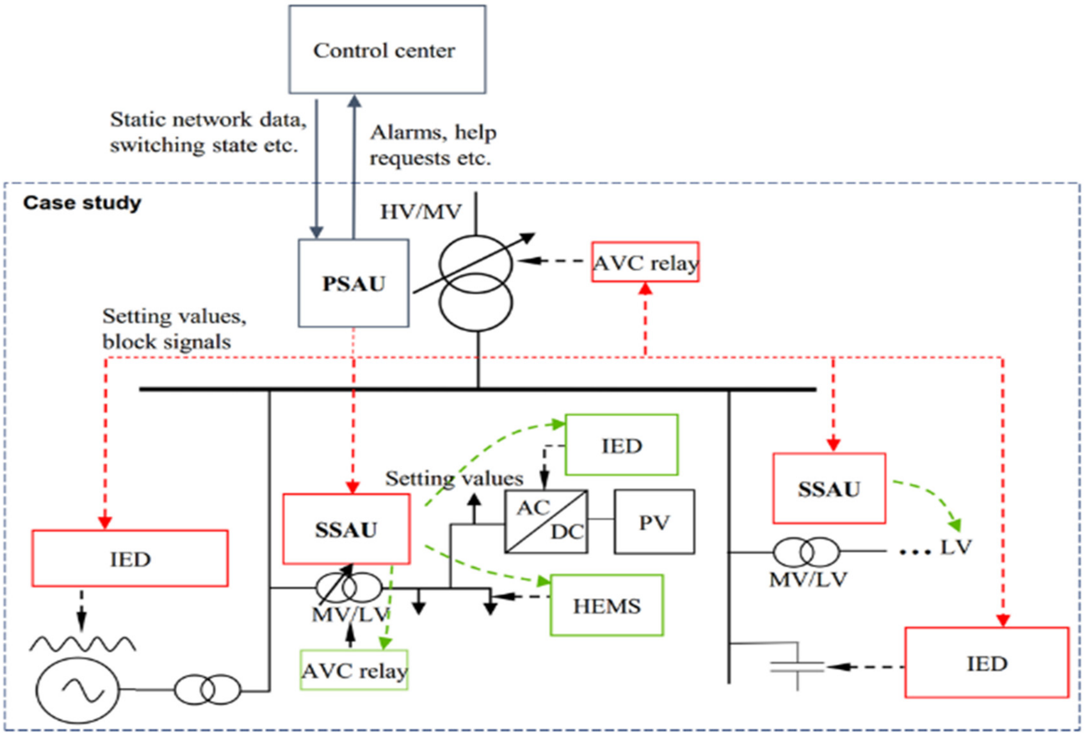

Figure 6. Distributed automation and control architecture [78].

5.2. Control and Automation at the Low Voltage Level (LV)

Electricity distribution is the end of the delivery of electrical energy after generation and transmission. The construction of MV and LV distribution systems is regulated by CEI EN 50160 standards [82]. CEI EN 50160 standard provides guidelines on acceptable voltage parameters and deviations. In LV the phase-to-phase voltage must not exceed 1000V [83]. The low voltage distribution system is prone to faults, malfunction, and human error. The automated system is the solution to those aforementioned challenges [84]. Artificial intelligence technology improves reaction time, judgment time, and acquiring information relative to human beings [85]. Distribution automation also assists in the reduction of operation and maintenance costs, improves power quality and the reliability of the system, and less equipment damage. The low voltage level distribution systems need online information, and remote administration for effective management of the system [84].

Low voltage level possesses the most complex application of distribution automation since it necessitates a high number of installation locations all of which must be economically feasible [86]. The following are necessary at the low voltage level.

Load Management: This is achieved by controlling consumer appliances. The utility-activated relay shuts down non-essential loads such as pool pumps.

Automated Meter Reading (AMR): This metering system is used by the electricity service provider to see the power usage and pre-ser consumption. These devices provide the ability to remotely reconfigure operational settings and schedules.

Demand side management**:** This is an extension of AMR with capabilities of monitoring power use and providing real-time pricing to the consumer depending on the time of use (TOU) to encourage behavior in consumption.

Quality of Service: This is the employed in the tracking of power outages and the duration thereof and also for monitoring of power quality issues [86].

The following which are detailed below are necessary in the automation and control of ADNs.

Information acquisition: The primary role of electrical automation control is data collection. This further needs precise comprehension of the running time, operational state, breakdown issues, and several more information to ensure personnel fully understands the system's operational state. This information must be accurate and timely throughout and when there is a failure, accurate and effective decisions are made and troubleshooted timely.

Information transmission: After information gathering, it is analyzed and instructions are conveyed to the terminals and then executed on the equipment based on that information [87].This data transmission is pivotal to attaining effective control. Information analysis: This is the process of implementing system control and monitoring. The data from equipment terminals and software is processed and analyzed then stored in the database. If the system is unable to interpret the data the operator, then takes over to coordinate numerous tasks of the system [85].

Table 3 summarizes and reviews the control and automation in ADNs and its impacts and limitations.

Table 3. Control, automation, impacts and limitations.

Authors	Type	Implementation	Impacts	Limitations
[88]	Power flow management (distribution power flow)	Employment of series voltage source converters for load balancing in medium voltage distribution network. The control is based on a modified synchronous reference frame, and it can autonomously dispatch active and reactive power between distribution feeders.	Increases the capacity in feeders without grid reconfiguration and more DG can be employed to mitigate congestion **[Test bench and simulation]**	
[89]	Real-time reactive power control for voltage regulation (Volt-Var control)	The use of grid forming converters is utilized where reactive power is injected at affected nodes to regulate voltage within nominal values. This control is made up of two layers, the cybernetic and the physical layer. The model is implemented in Typhoon HIL to track active from SCADA and reactive power reference from VVC to regulate voltage violations	Mitigate voltage fluctuation caused by increased DER and it is adaptable to for implementation on any distribution network **[Simulation]**	IEC61850 protocol not considered
[90]	Modular multilevel converter (Calculation of Short circuit current)	This is applied in the DC distribution system to investigate two types of faults: inter-pole faults and single grounding faults. The Modular multilevel converter in inter-pole short circuits proposes a linearized model based on common and differential mode transformation for calculating single grounding short circuit	This new model has been demonstrated to be dependable and conservative and can assist in grid planning and equipment selection **[Simulation]**	Complex multi-terminal DC distribution networks were not investigated. This method can flexibly transform the network topology and has a much faster calculation speed than simulation
[91]	Kruskal's maximal spanning tree algorithm (Optimal feeder reconfiguration)	Kruskal's algorithm is employed to compute, obtain, or derive an optimal radial network (optimal maximal spanning tree) that provides improved voltage stability and the highest loss minimization among all possible radial networks obtainable from the DG-integrated mesh network for different time-varying loading scenarios.	It can quickly compute the optimal radial configuration that mitigates power losses and provides supreme voltage stability with load fluctuations. **[Simulation]**	It is slow to converge when the topology changes which could introduce erratic choices.
[92]	Power system status estimation (PSSE) using Phasor measurement unit (PMU) (Fault Locator)	This utilizes the combination of PMU and PSSE by initially combining data before and after the fault with PSSE. The goal of incorporating the PMU in the PSSE problem is to estimate the voltage and current amounts at the branch point and across the whole network once a failure occurs. For each network portion, branch node quantities are computed using the PMU and the governing equations of the line model, and the problematic part is identified based on a comparison of the obtained values.	The benefits are simplicity and step-by-step implementation, applied to different faults such as short circuits.	Power system state estimation is heavily subjected to measurement error, which comes from the noise of measuring instruments, communication noise, and some unclear randomness.

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6. Optimization techniques for demand-side resources in Active Distribution Networks

The integration of demand-side resources (DSRs) into active distribution networks has gained significant attention in recent years due to the increasing need for more sustainable and efficient energy systems. Thus, it is important to explore the optimization techniques employed to harness the full potential of DSRs within active distribution networks, with a particular focus on the modeling of these resources. The effective utilization of DSRs can enhance grid reliability, reduce energy costs, and promote environmental sustainability.The subsections below classifies and details the different optimization strategies that have been employed in DSRs and Table 4 outline the various optimization methods in literature and their limitations.

6.1. Optimization strategies and Models used in Demand-Side Resources

Optimization techniques for demand-side resources in active distribution networks are essential for achieving a more resilient, efficient, and sustainable energy system [93]. Accurate modeling, load forecasting, demand response programs, and the integration of distributed energy resources are key components of effective DSR optimization. Multi-objective optimization and real-time control systems further enhance the capabilities of active distribution networks.

The foundation of effective optimization techniques for DSRs lies in accurate modeling. To optimize DSRs in active distribution networks, accurate load forecasting is critical. There are different load forecasting techniques, including statistical methods, machine learning algorithms, and hybrid approaches. The integration of weather data and historical consumption patterns enhances the accuracy of load forecasting, enabling better DSR optimization. Demand response programs play a pivotal role in optimizing DSRs. The demand response strategies include time-based pricing, direct load control, and incentive-based programs. The optimization techniques for DSRs should consider the integration of distributed energy resources (DERs) like rooftop solar panels, energy storage systems, and electric vehicles. Exploring modeling approaches and optimization strategies enables to effective management of the interaction between DSRs and DERs [94].To maximize the economic and environmental benefits of these resources, the coordination and control algorithms must be considered. Multi-objective optimization techniques are essential to balance conflicting objectives, such as minimizing costs and reducing carbon emissions.

Different multi-objective optimization algorithms exist, which include genetic algorithms, particle swarm optimization, and Pareto-based methods [93]. Additionally, real-time control and decision support systems are crucial for the dynamic management of DSRs. Advanced control strategies are developed to enable real-time decision-making and control of DSRs, these include various controls such as model predictive control (MPC), and the integration of advanced sensors and communication networks [95].

6.2. Defining Objectives and Constraints of Optimization

The foundation of any optimization technique lies in the clear definition of objectives. There are diverse objectives associated with DSR optimization, such as cost minimization, demand response, grid stability, and environmental sustainability. There is the necessity to prioritize objectives based on specific use cases and stakeholder goals. For instance, utilities may focus on cost reduction, while policymakers emphasize carbon emission reduction. Optimizing DSRs in active distribution networks necessitates a thorough understanding of constraints. Constraints can arise from technical, regulatory, or operational aspects. There exist different constraints that need consideration, including network capacity, voltage limits, DSR availability, and regulatory requirements. Recognizing and modeling these constraints is vital to ensure the feasibility of optimization solutions.

To translate objectives and constraints into actionable optimization strategies, mathematical models are indispensable. The mathematical modeling approaches commonly used in DSR optimization include linear programming, mixed-integer linear programming, and nonlinear optimization (Liao, 2019). In many cases, DSR optimization involves conflicting objectives. Multi-

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objective optimization techniques are explored to strike a balance between these competing goals [96]. Methods such as Pareto-based optimization, weighted sum methods, and evolutionary algorithms are essential in handling multiple objectives. Managing constraints effectively is essential to ensure that optimization solutions adhere to real-world limitations. Therefore, it is necessary to investigate various constraint-handling techniques, including penalty functions, barrier methods, and feasibility-based approaches. This investigation however further focuses on how these methods address different types of constraints, ensuring that optimization solutions are both optimal and feasible. Emerging technologies like artificial intelligence and machine learning are increasingly being applied to DSR optimization [27]. In the context of optimizing DSRs within active distribution networks, it is important to explore the role of these technologies in enhancing objective definition and constraint management. The subsections below outlines and investigates the frequently employed optimizations methods employed in DSRs.

6.3. Classical/Deterministic Optimization Methods

Classical or deterministic optimization methods are a cornerstone of problem-solving across various domains, from engineering and economics to logistics and operations research. These techniques provide systematic and structured approaches to finding the best possible solution for a given problem within a set of constraints. Classical or deterministic optimization methods play a pivotal role in optimizing demand-side resources (DSRs) within active distribution networks. These methods are indispensable for effectively integrating and managing DSRs to enhance grid reliability, efficiency, and sustainability.

Table 4. Optimization methods and limitations.

Authors	Type	Implementation	Resources	Limitations
[97]	MILP (Classical)	Reduced annualized cost by optimally selecting several system components and renewables on a smart grid.	Grid-tied with microgrid with solar PV, CHP, backed-up boilers, and load [Simulation based]	Struggles to handle the optimization of multi-input and output systems.
[98]	Multi-objective framework using MILP(Classical)	Avoid power export by optimizing the multiple cogeneration systems such as combined heat and power in microgrid residential areas. An operational planning model to mimic energy loss characteristics between storage tanks and a hot water calculating model regarding energy loss on network pipes was developed using MILP. This resulted in a reduction in residential units involved in the hot water supply network.	Grid-tied with microgrid residence cogeneration system, gas-fired boiler, storage tank, and load (hot water demand) [Simulation based]	Struggles to handle the optimization of multi-input and output systems. It struggles to handle the system with high disturbances.
[99]	Fuzzy logic-based decision-making framework (Heuristic)	Optimize power dispatched to the grid through storage systems. Maximize electricity generation through renewables and revenue to microgrid owners during time-varying electrical costs.	Grid-tied microgrid with renewable energy sources battery storage, and loads [Simulation based]	Slow in transient and systems with a high volume of dynamics.
[100]	MILP(Classical)	Investigates how the combination of electrical and thermal storage can reduce energy cost by enabling the microgrid to improve using its power produced inhouse.	Grid-tied with microgrid solar PV, geothermal heat pumps, solar thermal energy plant, thermal energy storage, battery storage, and load [Simulation based] (Real data)	However high investment costs made them not profitable at the current price condition.
[101]	Improved teaching learning-based optimization (Heuristic)	Minimize the impact of intermittency and fluctuation of renewables by controlling DG output power, altering network topologies, and managing demand side load.	Grid-tied microgrid with wind turbines, solar PV, and loads [Simulation based]	Inability to predict the future behavior of the system.
[102]	Advanced model prediction control (Heuristic)	Maximize the high penetration of renewables in the microgrid and minimize the running cost by solving optimization problems at each sampling time while meeting the demand and accounting for technical and physical constraints.	Grid-tied microgrid with battery storage, fuel cell, wind turbines, hydrogen electrolyzer, solar PV, hydrogen tanks and loads [Simulation based]	Scalability, complexity, and controllability challenge.
[103]	MPC (Heuristic)	Minimize energy cost and maximize battery lifespan by employing a microgrid central controller to optimally choose the adequate pattern for charging and discharging.	Grid-tied microgrid with energy storage, wind, and solar PV [Simulation based]	Slow in handling fast transient systems.
[104]	Fuzzy logic adaptive prediction control (Heuristic)	Tuned the input parameter on a cost function from the diesel generator and fuel cell to optimally regulate frequency in the microgrid.	Standalone microgrid that is made up of fuel cell, diesel generator, wind turbine battery storage, and loads [Simulation based]	The high number of input variables affects model formulation leading to more computational power needed.
[105]	Stochastic receding horizon control	Minimize uncertainties from renewable energy sources by employing simplified Z-Bus with sequential linear programming to linearize non-linear system dynamics. The controllable DG, switchable shunt capacitor, storage unit, and on-load tap changing transformer are jointly optimized to reduce cost, and constraint violations are mitigated.	Grid-tied microgrid with solar PV, wind turbines, and loads. [Simulation based].	Slow in handling fast transient systems.
[106]	Enhanced Model predictive control (Heuristic)	Minimize consumption from the grid, improve battery lifespan, and increase renewable sources' participation in catering for the load	Grid-tied with microgrid PV, Battery ban, and load [Simulation based].	Accuracy of models is a challenge.
[107]	Adaptive predictive control (Heuristic)	Minimize frequency fluctuations in the existence of disturbances and mitigate oscillations caused by external disturbances on tie line variation.	Grid-tied microgrid with a diesel generator, flywheel, battery storage, fuel cell, wind turbines, hydrogen electrolyzer and loads. [Simulation based].	The model becomes complex when handling a large number of controls.

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6.3.1. Principles and Different Methods used in Classical Optimization

Classical optimization methods operate on the assumption that the objective function and constraints are deterministic and known with certainty. The core principle is to identify the optimal solution by systematically searching through the feasible solution space. Key elements of these methods include mathematical modeling, objective function formulation, decision variables, and constraints. The foundation of classical optimization methods lies in mathematical modeling. It is crucial to know how optimization problems related to DSRs are represented mathematically. It represents the formulation of objective functions, identification of decision variables, and incorporation of constraints. An accurate mathematical representation is critical for developing optimization models that reflect the unique characteristics of DSRs.

Linear Programming is particularly well-suited for optimizing DSRs in active distribution networks where objectives and constraints are linear [108]. LP models can be used to minimize operational costs, such as energy procurement costs or grid infrastructure investments while adhering to constraints related to capacity, voltage limits, and DSR availability. LP provides valuable insights into cost minimization and resource allocation. The integration of discrete decisions into DSR optimization is addressed by Mixed-Integer Linear Programming [109]. MILP models are beneficial for problems that involve both continuous and discrete decision variables, which are common in DSR management [110]. Examples include determining optimal load-shedding strategies during demand response events or selecting the best time to charge electric vehicles (EVs).

Deterministic optimization methods are instrumental in load scheduling for DSRs. Classical techniques such as linear programming and mixed-integer programming are used to optimize the timing and magnitude of electricity consumption for various DSRs, including industrial processes, HVAC systems, and residential loads. These methods ensure efficient energy utilization while meeting operational and economic objectives. Classical optimization methods are employed in demand response (DR) programs, where the goal is to optimize DSR participation to balance supply and demand [111]. These models allow utilities to maximize the economic benefits of DSR participation while ensuring grid stability.

6.4. Heuristic/Non-Deterministic Optimization Methods

Heuristic and non-deterministic optimization methods have gained prominence in optimizing demand-side resources (DSRs) within active distribution networks. These methods offer valuable tools for solving complex, non-linear, and computationally intensive DSR optimization problems [112]. Heuristic and non-deterministic optimization methods are characterized by their ability to handle complex and computationally challenging problems. Unlike classical optimization methods, they do not guarantee globally optimal solutions but provide near-optimal solutions within a reasonable computation time. These methods are particularly well-suited for DSR optimization in dynamic and uncertain environments [113].

Metaheuristic algorithms, such as genetic algorithms, and particle swarm optimization, are widely used in DSR optimization [114]. Genetic algorithms mimic the process of natural selection to evolve potential solutions to optimization problems [115]. They are effective in optimizing DSRs by exploring a diverse solution space and iteratively improving solutions. Genetic Algorithms (GAS) have been applied to DSR management problems like load scheduling and demand response planning, often yielding near-optimal solutions in complex scenarios. Particle Swarm Optimization (PSO) is inspired by the social behavior of birds flocking or fish schooling. It optimizes DSRs by iteratively adjusting potential solutions based on both individual and group performance. PSO has been applied in DSR optimization to tackle problems involving distributed resources, such as distributed energy generation and load control [116].

7. Conclusion

This paper provides an overview of control, automation, and optimization of demand-side resources in active distribution systems. The literature survey is based on several developments in the distribution network which is a linchpin of electric distribution power supply. The fundamental differences between passive and active distribution networks were investigated and their differences are presented with ADN providing a unidirectional flow of power which is beneficial to both the utility and the consumer in terms of financial benefits and provides more energy stability and grid resistance. The planning and design of the traditional grid were looked at and the role of DNO, network security, and reliability with performance indicators such as LOP, LOLE, reserve margin, and EENS. The study also investigated the planning and design of ADN which is influenced by energy markets and technology innovation.

The innovation in the information technological space, growth of DG, and deregulation of the electric power supply industry fast-tracked the concept of active distribution systems. The volume of information exchange between different players in the active distribution network required adequate protocol to standardize data models in the electricity system equipment and provide operational specifications such as interoperability which is why the IEC61850 standard is implemented. The high information exchange results in vulnerabilities and attacks through attaining access to substation automation controls such as GOOSE flooding and intrusion of SMV which poses as a major challenge in communication and data exchange. Moreover, this also affects the smart metering technologies through the generation of the interfering signal and high frequencies on the communication line, but different mitigation measures are taken such as integrated anomaly detection and data collected from simulated attacks, employing software-defined network(SDN) switch eliminates possible paths of intrusion and network data overload and intrusion detection system as a countermeasure.

The optimization techniques of demand-side resources in ADN such as the deterministic optimization methods and non-deterministic methods were citically studied. The work concludes that IoE is becoming a major player in ADS which assists reduction of faults due to human error, fast responses, and improved stability of power supply. It is also worthy to note that automatization and control also have financial benefits to the consumer due to the bidirectional flow of power. In DRs, at a low voltage level the challenge becomes the privacy of their information, how to claim compensation from the markets is still not vivid enough, and the accuracy of the measurements from the consumer to the ISO. Cyber threats and security breach are also and will still be a continuous challenge that needs frequent evaluation and mitigation measures so as not to collapse the power supply system. Multi-input and output systems is a major challenge to both the classical optimization techniques and heuristical one. ADN is made up of complex non-linear systems whose requirements need techniques that respond timely, effectively, and adequately to different configurations.The classical optimization however can not handle such complexities. In heuristic techniques, the high frequency of change in system dynamics affects the model formation of MPC due to the complexities and requires high computational power to run such simulations. The introduction of artificial intelligence (AI) could further improve the performance of techniques such as MPC in microgrids and also deep learning could deal with unprecise models.

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