Challenges of implementing protection systems in smart grids: a review

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ABSTRACT

Based on the emergence of increasingly advanced technology, the conventional power grid can be upgraded to a smart grid by adding bidirectional communication, computer algorithms, and equipment that uses artificial intelligence (AI). A smart grid is a revolution in the current electricity network that can control the two-way generation and transmission process by utilizing an intelligent system so that the distribution of electric power can be handled optimally and in real time. The challenge of the smart grid is that there are distributed generators and microgrids that must be controlled in real time with rapidly changing loads. To meet these criteria, several points are proposed, i.e., finding an effective procedure to construct self-healing capability; developing a protection system based on AI; and proposing a systematic procedure to realize self-healing and protection systems with the help of a multi-agent system (MAS). Multi-agent systems are one of the AI approaches. Each agent can work independently and can also communicate with one another and with other devices on the network. Agents used as models can be classified into several categories, such as grid component agents, distributed resource agents, end-user agents, failure control agents, data analysis agents, and graphical visualization agents.

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1. INTRODUCTION

The impacts of climate change are indisputable, i.e., the effects of global warming are increasingly felt. To address the negative effects, it is necessary to accelerate the implementation of clean energy. Power plants that use fossil fuels produce carbon dioxide (CO_2) emissions that account for around 40 percent of global greenhouse gas emissions. Thus, it is necessary to accelerate the use of renewable energy in power generation systems [1]–[3]. The electrical energy produced by the generator is delivered to customers via the power grid. The conventional power grid basically only provides unidirectional control and flow from the generation source to users [4]. An instant change in the network configuration, i.e., the addition of generators and loads, is difficult to handle for a conventional power grid. The smart grid is a revolution in the conventional power grid by adding bidirectional electricity and information, supported by the development of artificial intelligence (AI) in both equipment and control systems [5]. The smart grid concept is the integration of smart sensors, intelligent control methods, and advanced digital communications into the classic electricity network, both at the transmission and distribution levels [6], [7]. The main goal of a smart grid is to optimize production, transmission, and consumption from distributed and varied power sources [6].

To meet the energy needs of dispersed consumers, it is impossible to effectively use centralized energy sources. Therefore, power generation leads to the use of energy sources that are distributed in nature and spread in a certain area. These small-scale energy sources, such as solar panels, wind turbines, and micro-hydro, that are integrated into smart grids are called distributed energy resources (DERs) [1]. Because DERs cannot meet the energy needs of an area, when possible, they can also be combined with other renewable energy sources such as mini hydro, biogas, and geothermal. A combination of several distributed energy sources is also called a distributed generator (DG). The power generators and a group of loads in an area that form a self-contained network are called a microgrid. This microgrid can be connected to or disconnected from the smart grid. With several distributed microgrids, the smart grid energy supply will be more reliable. With the existence of a microgrid that can be instantly connected or disconnected from the smart grid, the response must be fast so that there is no disruption to the network [8].

Modern power grids continue to increase in size and operational complexity, requiring shorter response times and lower disruption levels [9]. To maintain network stability, guarantee safety from electrical accidents, protect equipment, and affirm the reliability of the electricity grid, a power protection system is needed. In principle, the protection system detects and isolates all abnormalities or disruptions that have the potential to cause damage to the network as quickly as possible, thereby minimizing disturbances in other parts of the network [10], [11]. However, there are several basic philosophies that distinguish between conventional protection systems and smart grid protection systems. For example, allowing DERs to integrate into a smart grid requires a special design for the protection system [11]. In other cases, when a relay is too sensitive and causes an unexpected trip, it can spread the failure in a cascade [2], [12]–[14]. On the other hand, it is the case that the relay is less sensitive because the current in the network exceeds the fault current, so the protective relay works very slowly, which causes disruption to the network [1].

The complexity of the smart grid involves a large system, and its application is still in its early stages [15]; thus, the proposed protection system is mostly still in the development stage. One of the protection developments with a smart system is the wide-area protection, control, and monitoring (WAPCAM) system [16]. In a smart grid system with a bidirectional flow of energy, independent equipment protection is insufficient. For example, a generator failure in an area can cause cascading failures that might lead to a blackout of the whole system when the system is not managed properly [17]. By using the WAPCS method, blackouts can be minimized when there is a fault in an area [18]. Therefore, the smart grid must be equipped with several protection schemes based on intelligent methods, with the aim of reducing the effects of failures and power outages [17]. Protection on a smart grid is called a smart protection system, which uses advanced methods, i.e., network reliability analysis, intelligent failure protection, state-of-the-art security, and privacy protection facilities [19]. Several studies that investigate the protection of smart grids with various methods and various faults are reviewed in this paper.

One of the most important aspects in the field of smart grids is self-healing, and it has received great attention from researchers [20]. Self-healing capability has two basic properties: first, detecting when the grid is not functioning properly; and second, carrying out restoration actions so that the grid functions normally without any human intervention. By leveraging a combination of advanced sensors, intelligent algorithms, real-time data analytics, and automated switches, the grid can detect disruptions within milliseconds. Once a fault is identified, the grid can quickly isolate it and adjust the route of electricity flow in such a way that the supply to customers is uninterrupted. With its self-healing capability, the electricity network has high performance, including reduced downtime and increased reliability. With increasing efforts to optimize power grid operations, in-depth research is needed to perfect self-healing capability procedures. The authors acknowledge that one article cannot offer a complete review of all the issues pertaining to self-healing capability. Hence, this survey paper presents research on self-healing capability and discusses challenges associated with different methods used to fulfill its functions in order to identify the most effective and efficient techniques. Additionally, it highlights potential research areas to achieve a well-functioning smart grid in the future.

The novelty and related contributions of this review paper are threefold. First, based on the results of the survey and discussion, a comprehensive picture of the direction of development of the protection system in the smart grid is presented. Second, various review papers have concluded that the self-healing capability of the smart grid is interesting for further research. In the discussion, the author proposes a systematic procedure to obtain an effective algorithm. Third, based on a review of several papers, the results highlight numerous challenges for further research.

2. PROTECTION ISSUES IN THE SMART GRID

A smart grid is a power grid equipped with sensors, control devices, and various other equipment, resulting in an automated digital grid. Several characteristics that differentiate smart grids from conventional power grids include self-healing capability, compatibility, resource optimization, computerization with intelligent algorithms, and integration of distributed energy sources. In general, a smart grid adopted by Sarathkumar *et al.* [21] can be illustrated in Figures 1 and 2.

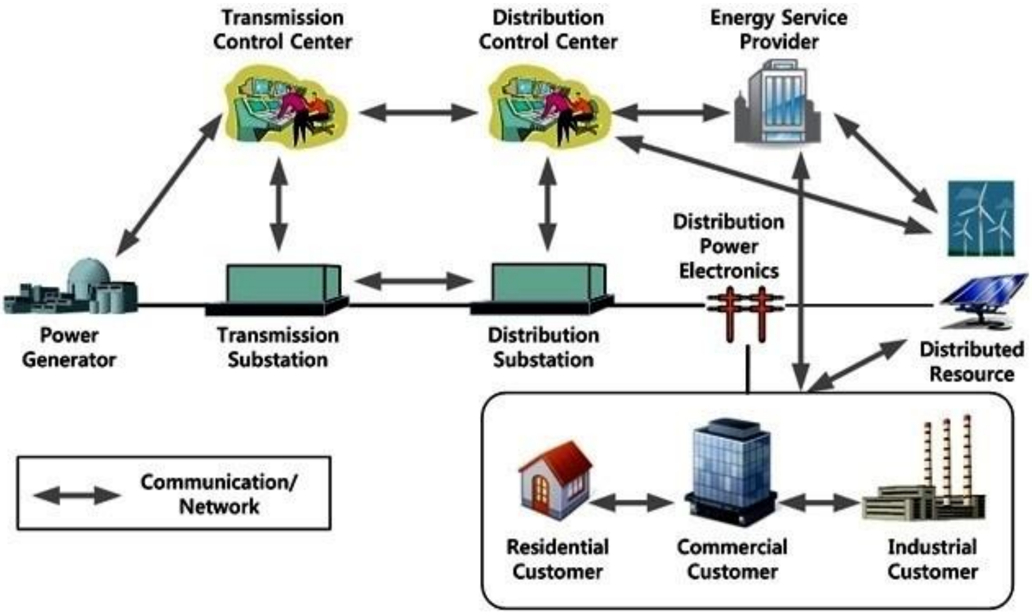

Figure 1. Illustration of a smart grid

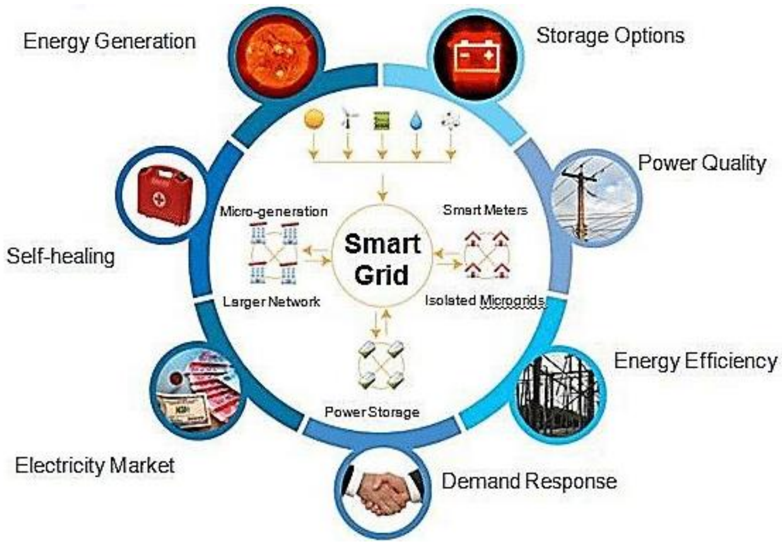

Figure 2. Some of the main features of a smart grid

2.1. Self-healing

Self-healing is a capability that allows the electricity network to reconfigure itself or automatically restore to normal operating conditions when a fault occurs, ensuring the uninterrupted flow of electricity [21]. When faults and power quality disturbances occur, the central network management system must initiate a self-healing process. By localizing the fault, other lines both upstream and downstream that are unaffected must have their service processes restored so that the customers do not experience major blackouts. The self-healing process involves a control system that is able to drive equipment so that the cognitive capability of the smart grid can reconfigure the network. Cognitive ability is defined as the process of collecting information from surrounding sensors to carry out analysis and make decisions. Reconfigurable capability means that the smart grid is embedded with equipment that can be reconfigured by controlling operating parameters in real time without any modification to hardware components. With a set of sophisticated algorithms, system effectiveness can be expressed in the process of preventing faults and coordinating proper generation [22].

A self-healing grid can be explained simply as an intelligent network based on smart sensors that uses advanced communication to control the grid, which is capable of real-time self-configuration when there are unexpected faults [23]. In the self-healing process, apart from controlling the grid during disruptions, another main goal is to maintain the grid to prevent cascade effects when dealing with disturbances [24]. To fulfill this, several requirements must be met, which are described as follows [25]:

– Fault detection must be carried out quickly and accurately.
– The network must be reconfigured to eliminate negative impacts.
– The continuity of the energy supply must be guaranteed under all conditions.
– Failure recovery time must be minimized.

Ignoring the generation stage, the self-healing concept can be divided into three main grids: the transmission grid, the distribution grid, and the microgrid.

The self-healing capability of the smart grid manages all power distribution equipment, including sensors for data acquisition and intelligent software systems that are responsible for analyzing, making decisions, and carrying out control actions. The distribution flow illustrating the self-healing architecture of the smart grid adopted by Sarathkumar *et al.* [21] is shown in Figure 3. It monitors and processes data in real time, which is correlated with the function of the self-healing capability.

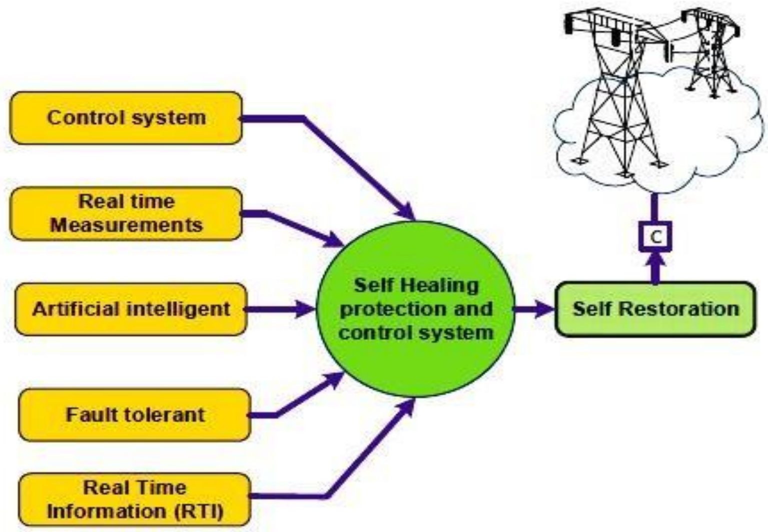

Figure 3. The architecture of a self-healing smart grid

2.2. Transmission grid self-healing

A smart transmission grid must have smart sensors, intelligent algorithms, and advanced communications networks deployed to monitor the performance of transmission lines, circuit breakers, and transformers [26]. The smart sensor is used to determine overhead conductor mechanical sag, predict probable insulator and tower failures, and determine the location of line faults. Self-healing in smart transmission is defined as the transmission system being able to return to a normal state after a fault occurs [27].

2.3. Distribution grid self-healing

The conventional distribution network protection systems only measure the magnitude of the current and compare it with the current time curve. When the current exceeds a failure threshold for a specific time threshold, the circuit breaker component trips. This results in a supply interruption for all network users downstream of the circuit breaker. To address changes in grid topology, adaptive overcurrent protection was developed [28]. When a fault occurs in an area with a DG as the source, the grid needs to be switched to island mode. Subsequently, load shedding is employed to restore the grid to its normal state, i.e., distribution grid self-healing.

2.4. Microgrid self-healing

Penetration of the use of DERs in power networks is growing rapidly. Generally, DERs combine renewable sources with fuel cells, which can reduce the negative impacts of fossil fuels [29]. In order to optimize power generation, it is proposed to integrate the widespread application of DERs through the use of microgrids [30]. A microgrid is a self-contained grid consisting of a group of generators, storage devices, and loads [31]. When DERs on a microgrid operate in an autonomous or island mode, the limited independent network can supply electricity to rural areas effectively and efficiently with minimum power loss [32]. Generally, DERs in microgrids are connected to the main grid, or grid-connected mode. However, when a fault occurs in the main grid, the microgrid can disconnect itself and change to island mode [8]. Integrating the microgrid into the main grid will increase customer participation in the energy market while also providing flexibility, reliability, and resilience to the main grid [33]. However, integrating the microgrid into the main grid leads to a unique set of challenges, especially in regard to protection. Microgrids have distributed generation and different inertial characteristics compared to conventional grids. Therefore, they require special protection methods to ensure system stability and reliability [29]. Self-healing in a microgrid is the ability to isolate faults in the microgrid, connect or disconnect the microgrid with the main grid, and maintain microgrid load generation [34].

2.5. Protection of microgrids

A microgrid is a small-scale combination of power sources and electrical loads on one electrically defined boundary that forms a self-sufficient network that is usually operated, connected, and synchronized with the main grid [35]. Microgrids have the ability to operate in two modes, i.e., island mode or grid-connected mode. When in island mode, the microgrid operates as an autonomous or independent network that provides on-site power generation with microsources and loads [36]. Microgrid protection techniques are the main requirement when operating networks must have reliability. The microgrid protection method must be able to ensure the grid works properly in grid-connected and island modes. There must be adequate protection techniques to guarantee the safe operation of the equipment, both on the network and in external circuits connected to the microgrid [37].

For a microgrid to operate successfully, proper planning is needed regarding the operation, control, and protection of the microgrid. Microgrids have limited capabilities, so conventional protection designed for conventional grids is not suitable for application to microgrids. When a microgrid is connected to the main grid, the current from the microgrid is inherently much lower than the current from the main grid. Faults in microgrids when grid-connected cannot be anticipated by conventional protection systems. Microgrid implementation on the main grid must consider protection coordination because a fault in any part can cause the entire system to trip, resulting in energy loss throughout the network. The differences in various microgrids are mainly in capacity, so the protection system must be designed specifically for each microgrid. In conventional grids, it is very easy to distinguish between fault current and main current; however, in microgrids, the relationship between the capability of generating equipment, load, and faults requires more complicated protection procedures to be implemented. Depending on the operating conditions (grid-connected mode or island mode), a dynamic protection system strategy based on an understanding of the associated risks and a dynamic fault propagation analysis is required. When the microgrid is disconnected from the main grid and starts in island mode, the current entering the network can cause significant deviations in system frequency and voltage. When the generator in the microgrid is not properly protected, this can result in a power outage. For a smooth transition between grid-connected mode and island mode, special mitigation techniques are required to ensure the reliability of the microgrid through careful design and a comprehensive understanding of the system. Load changes that exceed the microgrid capacity must be anticipated, especially during island mode, because this can disrupt network stability.

DG, according to the IEEE 1547 standard, are allowed to be connected to the main grid, but when a fault occurs, they must be disconnected. When the power contribution from the disconnected DG is large enough, this disconnection will endanger the main grid. In a survey, several protection schemes have been designed for the successful operation of microgrids. Several topics that are discussed to obtain potential solutions to protection and control problems in microgrids include [32]:

- Reciprocal power flows: in a traditional distribution system, the power flow is unidirectional, i.e., from the generator to the loads. The integration of DGs on the main grid results in a bidirectional flow, so reverse power flows are possible. Therefore, the traditional protection methods will not be able to handle the fault in the main grid [38].
- Short circuit range limitations: the fault current in the inverter-based DGs is limited to a maximum of 2 p.u. As a result, the traditional overcurrent relay is unable to detect the fault [38].

- Stability problems: the control system in the microgrid system allows local oscillations to arise. Therefore, to guarantee the stability of the microgrid, it is necessary to carry out an analysis using the small signal stability theorem, which is ensured by the transient response results [39].
- Low inertia: traditional power grids have high inertia; on the other hand, microgrids have low inertia characteristics, especially for inverter-based DGs. When disconnected from the main grid, serious frequency deviations may occur, so a special protection and control system is needed [39].
- Discontinuous power: some microgrids use photovoltaic or wind as intermittent renewable energy resources. This distributed generation produces intermittent power sources. As a consequence, there is a need for coordination between DGs and storage devices [32].

2.6. Protection of active distribution networks

Active distribution networks that combine microgrids (MG) with the penetration of DER create challenges for the protection system [40]. Conventional protection systems are very risky to use on this network. Conventional protection systems usually use current detection to determine the fault location. With changing grid configurations, it is necessary to innovate fault detection methods by combining voltage-based and overcurrent-based protection systems. Optimizing this method becomes the most important contribution, leading to an increase in the speed of the protection system and its selectivity problems [41].

In general, microgrids can be grouped based on the type and location of the feeders connected to them [42], including i) urban microgrids, ii) rural microgrids, and iii) off-grid microgrids. In addition, microgrids can be grouped based on the type of power transfer, including: i) AC microgrids; ii) DC microgrids; and iii) hybrid microgrids, which are a combination of AC and DC sub-grids [43]. The conventional overcurrent protection based on local measurements can lead to incorrect decision-making and, often, a lack of coordination with other relays. Many protection techniques are designed for active distribution networks, including: forming a group of relays that are set in a coordinated manner [44]; intelligent current differential protection [45]; advanced differential impedance techniques [46]; and smart differential energy-based algorithms [47].

2.7. Progress of an adaptive protection technique for the smart grid

The adaptive protection system is a protection method in which the protection relay settings are adapted according to changes in network configuration (topology, DG connections) using smart algorithms [48]. Due to the immensely growing electricity network, changes in grid configuration will occur frequently. Conventional protection systems with fixed parameter settings will be unable to handle fault issues on systems with varying configurations. Adaptive protection methods that can change real-time setting parameters based on the operating state and system conditions continue to grow rapidly because they can handle fault issues even as the grid configuration changes [49]. The use of such adaptive protection will improve the drawbacks of conventional protection systems so that it can make the protection system better, i.e., enhance reliability, sensitivity, and speed of fault handling [50].

The smart grids have a dynamic topology, which means that to protect against faults occurring on the network, an adaptive protection system is needed. Network resilience relies heavily on adaptive protection that can deal with dynamic faults that often occur within the network. By using large amounts of data generated from advanced sensors, adaptive protection schemes can be developed. Protection systems are very important to protect critical equipment and ensure that consumers are not injured or killed when a fault occurs on the network. Stable, reliable, transparent, and easy-to-interpret protection algorithms are necessary to ensure the reliability of protection decisions. In addition, the protection decisions must be simple, fast, reliable, consistent, selective, and sensitive to faults. To face this challenge, this section will focus on adaptive protection schemes [51]. The growth of adaptive protection methods is rapid due to their ability to adjust the protection scheme with real-time settings based on the system operating state and system conditions. Due to the complex challenges of adaptive protection systems, a significant number of schemes have been developed and implemented over the past few years [49].

2.8. Detection and position determination methods for high-impedance faults

The high-impedance fault (HIF) produces a fault current that is relatively small compared to the nominal current. HIF often occurs in an electrical power distribution system [52]. When contact occurs between the conductor and a tree or ground with high impedance, it will trigger HIF. The energized fallen conductor jeopardizes public safety because of the possibility of contact with humans and the potential to cause an arc to ignite wildfires [53]. Therefore, it is important to proactively detect and localize energized fallen conductors, which will help protect people from safety hazards and reduce the occurrence of wildfires. However, HIF detection using conventional protection systems is difficult because the resulting fault current level is usually too low compared to the nominal current [54].

According to surveys, HIF account for between 5% and 10% of overall system faults [55]. When most faults in the electrical network endanger electrical equipment, HIFs could also have an impact on human safety and lead to legal issues. People may accidentally come into contact with the energized fallen conductors or energized surfaces [56]. In forest areas or areas with an accumulation of flammable gas, HIFs can cause fires or explosions [57]. HIFs are one of the biggest ongoing challenges in the field of power distribution protection. Using traditional protection systems, it is very difficult to detect the occurrence of HIFs, with failure rates reaching 32% [58]. To develop an accurate protection system, it is crucial to comprehend the phenomenon of HIFs [59].

A HIF occurs when an energized conductor encounters a quasi-insulating medium, such as a tree, structure, or piece of equipment, or when a fallen energized conductor touches the ground. The characteristics of HIFs are mainly determined by the materials in contact with the energized conductor, which results in different voltage-current properties [60]. HIFs are nonsymmetric and random, and the fault current is inherently nonlinear, so no one method will be able to detect all HIFs [61], [62]. HIFs can be grouped into two classifications, i.e., the first is the active HIFs, which are usually accompanied by an arc current, and the current flowing is much less than the specified protection unit, while the second is the passive HIFs, which do not cause an electric arc. Both are very dangerous and threaten the lives of people and animals because of the possibility of touching them or causing wildfires [60].

Doria-García *et al.* [63], an impedance-based HIFs protection scheme was designed to estimate the location of faults on transmission lines. This protection scheme can be used to find high-impedance and low-impedance faults by setting specific features of a HIF model using simple input parameters. The method is easy to apply with an uncertainty of less than 80 m for almost 90% of all possible fault scenarios, which is equivalent to less than 0.1% of the line length.

Hao [64], a comprehensive review of arcing-HIF detection using AI based on distribution network models is presented. First, an analysis is carried out to describe the characteristics and model of arcing-HIF, and then an arcing-HIF database is built, which is the fundamental work for arcing-HIF detection. Furthermore, the AI-based arcing-HIF detection scheme is explained in detail, including data acquisition, feature extraction, and classifier selection. Additionally, to demonstrate the reliability of the arcing-HIF detection algorithm, a test was conducted using a set of criteria. Finally, a comprehensive overview is provided to examine future trends and challenges related to arcing-HIF detection.

As discussed in [59], an AI-based pattern mapping method to diagnose HIFs involves collecting data, extracting features, and training. The data processed by AI, according to [65], [66], are a pair of absolute values and phase angles of current and voltage. To make the data more specific in mapping HIF patterns, feature extraction was carried out. One method of feature extraction is wavelet transform (WT). Research by Narasimhulu *et al.* [67] shows that the multi-wavelet transform (MWT), an extension of the scalar WT, can provide information on faults during a specified time. This information can be utilized in a decision-making algorithm. Training on AI-based pattern mapping systems is necessary. Some researchers use neural networks (NNs), which are trained based on patterns of feature extraction results. The acquisition data is used by MWT to extract the relevant features, and then the NNs act as classifiers based on the extracted features. From the research results in [68], excellent performance is demonstrated in terms of accuracy, security, dependability, safety, and sensitivity. It can be concluded that the use of NNs in determining the location of HIFs is very satisfactory in terms of its performance.

2.9. Development of wide-area protection, control and monitoring systems

WAPCAM is a method that utilizes synchronized measurement technology (SMT) to take preventive and corrective action with the aim of avoiding the cascading effects of large disruptions. The WAPCAM system can overcome large blackouts, thereby enhancing the stability, reliability, and security of the electricity grid [69], [70]. To obtain smart sensor-based data, a sensing device called the phasor measurement unit (PMU) has been developed in recent years. A PMU is a measurement device that monitors the magnitude and phase angle of an electrical phasor quantity, such as voltage or current, using multiple time-synchronized sensors. The data from a PMU is processed using smart methods so that it can be used for wide-area measurement systems as a basis for monitoring and controlling smart grids. Data from the PMU is very important because when the supply from the network is not sufficient for demand, it will result in frequency imbalances and, therefore, cause stress on the network, which has the potential to cause power outages [71]. A wide-area measurement system (WAMS) uses data from a PMU to monitor the real-time status of a critical area and prevent overloads and instabilities that lead to power blackouts [72]. The WAPCAM works based on WAMS and various control and protection algorithms, which are designed to reliably predict and coordinate actions capable of eliminating or preventing wide-area disruptions. By using the WAPCAM system for real-time protection and control, faults can be detected quickly, allowing control actions to be carried out, resulting in the self-healing process [69].

Intelligent electronic devices (IEDs) implemented in the power sector, such as circuit breakers, transformers, and capacitor banks, are equipped with control and automation functions. IEDs that can be used as smart sensors are a more modern alternative to, or complement to, setups with conventional remote terminal units (RTUs) [73]. Based on data from the IED or RTU as well as time-referenced data synchronized by the global positioning system (GPS), the smart grid system can utilize the WAPCAM system [16]. With the sophistication of WAPCAM, data or information, such as system-wide bus voltage, angle, active and reactive power flow, etc., is analyzed to estimate whether the system is under stress or not. With coordinated control actions, the electricity network can be protected from total blackouts or, at least, eliminate the cascade effect of disruptions in one area. WAPCAM systems, like SCADA systems, also have various hierarchical levels to carry out preventive control actions, such as the local feeder level, substation level, and central/regional level. Combined data from WAPCAM and SCADA can be used to analyze the electricity network system as a whole so that, when necessary, control actions can be taken manually.

WAPCAM consists of multiple sub-systems, including wide-area protection and control (WAPC), which is further divided into system integrated protection schemes (SIPS) and remedial action schemes (RAS) through an advanced communications infrastructure, among others. Another sub-system is wide-area stability and control (WASC), which includes power system stabilizers (PSS) and on-load tap changers (OLTC). By combining WASC and the wide-area monitoring and control (WAMC) system, it can be used for self-healing in the smart grid, thereby eliminating the impact of wide-area disruptions. An optimal bus-splitting scheme and an optimal island mode scheme are also included in the WAPCAM subsystem. Even when stressful conditions occur in the power system, such as transient angle instability, voltage instability, and/or frequency instability, the self-healing properties of the WAPCAM must be able to restore the network to a normal condition using real-time control action. With these various capabilities, WAPCAM can overcome global blackouts to enhance the stability, reliability, and security of the smart grid.

2.10. Implementation of artificial intelligence in protection systems

With the help of advanced sensors and a robust data infrastructure, the implementation of AI in the protection system will provide the best solution because it can be adapted for various network configurations with high accuracy and result in a faster response than conventional protection [74], [75]. Based on data from various sensors and measurements, AI methods can be used to diagnose faults, i.e., determine fault locations and classify them. Furthermore, based on network configuration data, load variations, and fault locations, AI algorithms are utilized to optimize protection settings in real time.

The protection system in a smart grid is very complicated because there are more and more microgrids and DGs that are sometimes connected and sometimes disconnected. To increase the reliability of the smart grid, it is crucial to perform real-time fault detection and determine their location. This allows for automatic network reconfiguration by promptly disconnecting the faulty line segment. The protection system must be able to locate faults quickly and precisely, even as network reconfiguration occurs. Thus, it is very important to design a flexible, safe, fast, and reliable protection system for the proper operation of a smart grid [76]. To ensure the performance of the protection system, fault detection must be intelligent and require the integration of hardware, software, and sophisticated analysis. By thoroughly analyzing the network condition, fault detection combined with a proper control system can enhance grid reliability and resilience. Conventional local protection systems with constant settings and parameters must be updated to handle electrical networks with changing configurations. Leveraging advanced AI algorithms that are capable of analyzing various sensors and measurements throughout the electricity network to detect faults, such as short circuits or line failures, and classifying them according to their type and location, allows for faster response times to protect equipment, decreasing downtime and mitigating damage [77]. Here are some things that can be handled using AI algorithms:

- Adaptive real-time protection based on network conditions, load variations, and fault location helps improve system reliability while reducing the possibility of unnecessary disruptions or power outages.
- Fault event data is analyzed in detail, which can help engineers enhance system protection schemes by examining the root causes of disruptions.
- Accurate fault location estimation reduces the time required to repair the faults.
- Integration with IoT or IED-based sensors installed throughout the electricity network will play an important role in real-time monitoring to enhance protection capabilities.

A robust data infrastructure, accompanied by cybersecurity measures and thorough testing, is essential for the application of AI-based protection systems to guarantee the reliability and security of the electricity network [78]. Furthermore, compliance with standards and regulatory guidelines ensures adherence and interoperability. This includes ensuring that organizations and individuals adhere to specified rules and guidelines to fulfill quality, safety, security, and legal obligations. AI-based electricity network protection can result in a power grid revolution that increases resilience and efficiency, thereby reducing downtime and increasing overall network reliability [79].

3. DISCUSSION

Self-healing is a fundamental feature or basic capability that must be present in a smart grid [80]–[82]. The philosophy of self-healing capability is to increase reliability by ensuring that the supply of electricity to customers is uninterrupted. The main objective of self-healing has two functions: the first is prevention by detecting faults to ensure that customer service functions are not disrupted by hidden troubles, and the second is self-reconfiguration by restoring faults as quickly as possible [81], [83]. The self-healing algorithms require powerful and real-time computing systems that monitor and determine the extent of their state towards a fault state with prognostic analytics. When faults occur, they make quick decisions to diagnose, find, and isolate faults, as well as reform and redirect power flows [21]. In self-healing stages or procedures, the first step is modeling in the form of an algorithm equipped with a fault detection mechanism. The model must describe network behavior as a whole so that when there is an abnormality that may be a fault, it must be detected as quickly as possible. At this stage, there are several papers that need to be discussed.

Yang *et al*. [81] and Yongjie *et al.* [84] divide the self-healing model into four steps. The first step is to create a model that describes the behavior of the network. In the second step, the limits of the system status values must be determined between those that are normal and those that show symptoms of disruption, so that a safety margin model can be developed [81]. In the third step, based on the first and second models, it is necessary to build a model of the maximum power supply recovery capacity of the normal operating feeder. Finally, based on the existing model, it is necessary to develop algorithmic steps that can be implemented to form a self-healing procedure [84].

Elgenedy *et al.* [23] and Gomes *et al.* [85], the self-healing model is implemented using the multi-agent system (MAS), which can be categorized as an AI approach. Each agent can work independently and can also communicate with each other as well as with other devices in the network. The agents used as models can be classified into several categories [86], such as grid component agents, distributed resource agents, end-user agents, failure control agents, data analysis agents, and graphic visualization agents. The working principle of a MAS can be illustrated in the form of a block diagram, as shown in Figure 4. In Figure 4, the interaction between two active agents in the MAS is depicted. These agents have the capability to analyze data from distributed objects and utilize it for control actions.

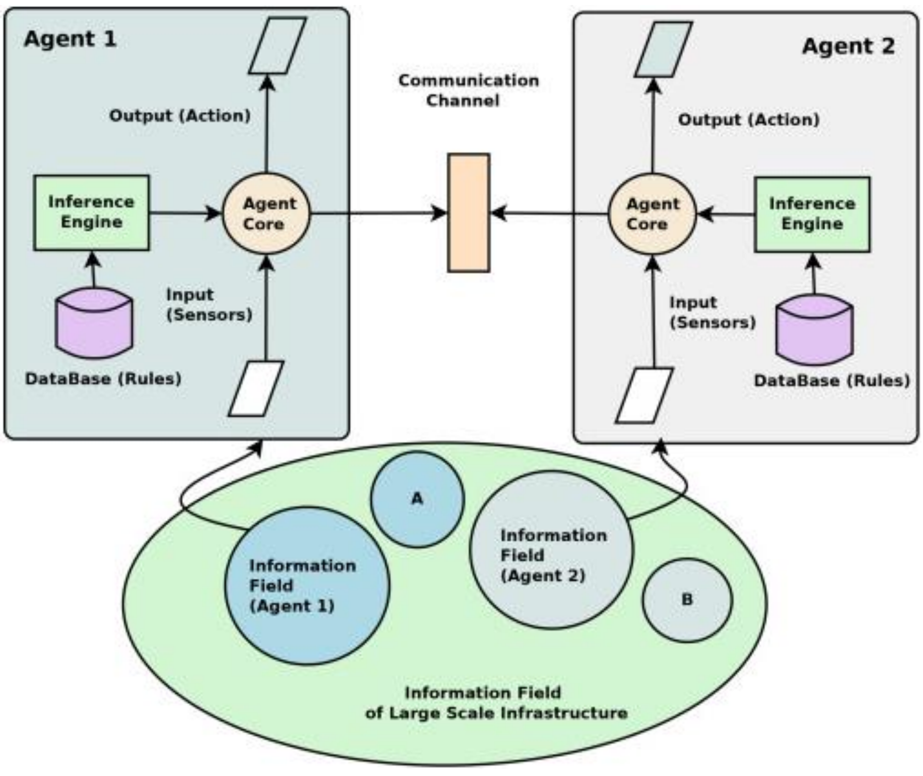

Figure 4. Block diagram of a MAS

Yuan *et al.* [87], a self-healing method called edge computing-assisted intelligent decision models (EC-IDM) was introduced. In this method, coordination techniques are arranged hierarchically to optimize local object models. Local objects are based on data collected from sensors located in a specific area using optimization techniques to form load patterns, detect fault issues, and simulate a wide range of conditions in order to maximize network efficiency.

Jiao *et al.* [88], a self-healing method was designed based on data obtained from the WAPCAM method. The WAPCAM is designed based on a hierarchical protection and control system, which can be used to form a self-healing method. Based on data from sensors, the detection algorithm is divided into three levels: the local detection center, the substation-integrated detection level, and the wide-area detection level. The success of this three-level self-healing method must be supported by the synchronization of the substation communication network and the integrated wide-area communication network.

Smart grids are modern power grids that are becoming increasingly complex and have a lot of data to be processed in protection and self-healing systems. The self-healing capability can function properly when it can process large amounts of data quickly and accurately. Classical computing methods make it very difficult to handle vast amounts of data. Therefore, implementing AI approaches in smart grids is an increasingly necessary technique [89]. Various AI-based research has been conducted to synthesize self-healing procedures, taking advantage of the ability of AI approaches to process large amounts of data quickly and accurately. One of the functions of the self-healing procedure is fault detection.

Shafiullah *et al.* [90] determined fault locations based on the extreme learning machine (ELM) method in a network with input data in the form of useful statistical features extracted by WT. They stated that the results were more accurate compared to methods based on support vector regression plus WT (SVR-WT) or artificial neural network plus WT (ANN-WT). Fazai *et al.* [91] designed a machine learning model based on gaussian process regression (GPR) and then detected faults using the generalized likelihood ratio test (GLRT) to enhance the accuracy of fault detection (FD) in photovoltaic (PV) systems. Sirojan *et al.* [92] used a sustainable deep learning-based method to apply high-impedance fault detection (HIFD) in the power grid, achieving a higher detection accuracy of 98.67 percent. A protection scheme for HIFD using extreme learning machines (ELM) based on wavelet packet transform (WPT) is proposed by AsghariGovar *et al.* [93]. Zhang *et al.* [94] captured the features of multi-sourced data by using long short-term memory (LSTM) networks and classified them using support vector machines (SVM) to predict line trip faults. To achieve a higher level of accuracy in predicting line trip faults, Haq *et al.* [95] extracted features using discrete wavelet transforms up to nine levels and classified them based on double-channel extreme machine learning. Wang *et al.* [96] synthesized a stacked sparse autoencoder (SSAE) neural network trained using a deep learning method with input features based on principal component analysis (PCA) and classified using SVM. The results showed high accuracy when applied to real-world data.

In this paper, based on the survey results, more in-depth research is required to address the challenges of developing self-healing algorithms. First, the data from the sensor is packaged using a standard database using the WAPCAM method, and then the first function of the self-healing capability is designed in the form of a fault detector. The detection algorithm is divided into three levels [97]: the local detection center, the substation-integrated detection level, and the wide-area detection level. At the local detection center, a model must be created that is able to capture the features of local network conditions. Therefore, it can detect various types of faults. At the substation-integrated detection level, the model must be able to integrate the backup of various protection systems and also function as substation control, such as automatic reclosing, automatic bus transfer, and circuit breaker failure protection. Both the protection system and control system at the substation-integrated detection level are based on data and information that cover the entire work area of the substation-integrated detection level. At the wide-area detection level, the model must be able to combine the backup of various protection systems from the entire system and also function as a central control system. The model must also be able to integrate protection and control into one optimal combined system. Thus, all models, both at the local detection center, at the substation-integrated detection level, and at the wide-area detection level, must have self-healing capabilities. The modeling method must be AI-based, which will result in the protection system being able to detect faults quickly and accurately. It is necessary to research various AI algorithms that produce the best performance.

The most effective algorithm for synthesizing self-healing capabilities is to utilize a MAS, resulting in the importance of each issue being modeled in the form of an agent. These agents must be able to classify local network conditions and determine how close they are to the possibility of a fault occurring. Other agents must also be able to predict component conditions that can cause faults. When a fault occurs, an agent must be designed to manage the network by disconnecting the location of the fault and rerouting (changing the configuration), resulting in an uninterrupted energy supply to customers while optimizing energy sources. Once the fault has been repaired, the self-healing algorithm must perform a second function, which is to normalize the network as quickly as possible. All these algorithms must be managed properly, both by the substation and by the WAPCAM control center, based on data from sensors.

Some challenges that still need further research but are not discussed in too much depth are the following:

- The complexity of modern power grids causes a transition from conventional electricity networks to smart grids, resulting in more uncertainties and issues in this complicated environment. With the increasing development of renewable energy, which is integrated into the smart grid, there are many challenges. This is due to the highly diverse and unpredictable nature of renewable energy [98].
- The communication network in a smart grid is built on a network with very large data flows and high variability, which is a challenge in itself that must be handled appropriately [89].
- Robustness and adaptiveness in the use of AI algorithms in smart grids require extensive research [99].
- Another challenge that needs to be explored further is the robustness of big data, which needs to be stored and analyzed quickly and accurately [89].
- The availability of large amounts of data required for the learning process of neural networks based on deep learning methods, which will be used in self-healing algorithms, is one of the main challenges in smart grid analysis. Transfer learning is an alternative to overcome this situation, which motivates researchers to use it in the case of self-healing algorithms.
- It is a challenge to research the existence of data anomalies that will be processed by self-healing algorithms, whether caused by cyberattacks or sensor failure. LightGBM is a highly efficient gradient boosting decision tree (GBDT) that is effective for classification and regression processes. It is necessary to examine the pattern recognition process to detect data anomalies using the LightGBM technique.
- Rerouting or reconfiguration actions, which are one of the functions of self-healing procedures, can be carried out effectively when utilized with a distributed intelligence approach. This phenomenon is another challenge that requires further research.

4. CONCLUSION

Reconfiguration of a power grid with the integration of microgrids is a particularly challenging task because these grids are intermittent, adding complexity. Therefore, the integration of microgrids with the power grid requires advanced protection schemes to avoid unwanted tripping, and such protection schemes are complex to adapt and, in some cases, cannot be adapted to these changes. These disadvantages can only be overcome through a complicated update process to the protection settings. In addition, the smart grid requires self-healing capabilities, i.e., the ability to reconfigure quickly while maintaining system reliability. Microgrid protection requires special methods, i.e., it is necessary to design a suitable protection method for the microgrid to protect it from any disruptions that could occur in both grid-connected mode and island mode. Modern grids are active distribution networks, which require coordination between protection relays to prevent incorrect decision-making. With the dynamic configuration of the modern power grid, an adaptive protection system is needed that is able to protect the grid when a fault occurs, even as the configuration changes. HIFs are a big challenge because the fault current is relatively small compared to the network current. Advanced methods must be developed for the accurate detection of HIFs. With the increasingly complex electricity network, there is a need for comprehensive coordination within the grid so that protection, control, and monitoring can carry out their duties properly. Therefore, the WAPCAM system was developed. With the increasingly sophisticated development of AI technology, various types of protection systems developed for smart grids can utilize AI to increase resilience and efficiency, thereby reducing downtime and increasing overall network reliability.

Our conclusions from the survey results can be summarized as follows: i) self-healing capability is a crucial feature of the smart grid, and finding effective procedures for it poses a significant challenge; ii) the protection system in the smart grid is still extensive and requires further research and development; and iii) this survey is expected to generate interest among both authors and readers, encouraging further research on protection systems in smart grids.

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