# State-of-the-Art Microgrid Power Protective Relaying and Coordination Techniques

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***Abstract*—In recent years, a trend shifting from traditional power grids to modern smart grids has emerged formation of microgrids, connecting low voltage distributed generation (DG) units, loads and local storage apparatus to medium voltage distribution system. This revolution in power distribution systems has pledged ample advantages for customers including reliability, quality and efficiency of generated power, as well as eliminating the necessity to construct long transmission lines and excluding subsequent imposed power losses. In contrary to the benefits provided by microgrids, protection of these entities is an enormously perplexing procedure predominantly due to dynamic behavior of microgrids, bidirectional power flow, and high penetration of inverter-interfaced DG sources that has disrupted the conventional operation and coordination of protection relays. This paper presents an analytical appraisal on state-of-the-art protection techniques to address problems associated with microgrid protection. Advantages and disadvantages of each protection technique, as well as proper selection of protective relays suitable for each protection zone have been discussed. Recommendations on protection procedures and effective techniques be employed to resolve the microgrid protection issues have also been presented.***

***Index Terms*—Microgrid, Microgrid Protection, Power System Protection, Protective Relays Coordination, Distributed Generation**

## I. Introduction

In recent years, the employment of conventional power plants mainly operating on fossil fuels as a source of energy which is a great contributor to global warming has diminished and instead a tendency toward using renewable energies have escalated abundantly [1]. Moreover, the catastrophic environmental degeneration and electrical power losses in power transmission systems as a result of long distance between power generation plants and local load sites has attracted the use of Distributed Generation (DG), integrated to power grids and subsequently forming microgrids to not only provide adequate power to local loads and support the main grid in case of high power demand, but also eliminate the need for constructing long transmission lines and also exhausting conventional power plants running on destructive fossil fuels [2], [3].

There have been several definitions proposed for microgrids but a sensibly unanimous definition according to US Department of Energy (DOE), defines microgrid as a cluster of interconnected distributed energy resources, critical and non-critical loads, local power storage system within clearly demarcated electrical boundaries that acts as a particular controllable entity with regard to the grid operation mode, both grid connected or islanded mode [4]. A typical microgrid is illustrated in Fig. 1.

Microgrids are able to operate both in conjunction with distribution network (grid connected mode) or entirely independent (islanded mode). Microgrid is always connected to the grid during normal operation and consequently the loads are fed by both the generated power from grid and DGs, on the contrary, the microgrid operate in islanded mode during maintenance, abnormalities or any fault incidence in the grid side [5]. Microgrids are disconnected from the grid by a Static Transfer Switch (STS) at the Point of Common Coupling (PCC) and then the entire microgrid operates as an isolated grid from the rest of the network, as a result, the entire loads are fed by the DGs. The DGs connected to the microgrid are known as micro sources and typically operate at LV or MV voltage rating. These micro sources predominantly comprise of small scale wind farm, photovoltaic (PV), both synchronous and induction generators, CHP plants, fuel cells, flywheels, super capacitors, electric vehicles and battery energy storage system [6].

Despite numerous advantages purveyed by microgrids, several technical challenges exist that must be addressed and resolved by electrical engineers and one of the most crucial one is providing adequate and proper protection for microgrids. Microgrids, in spite of composing several DGs and loads, they operate as a net load or a power generating plant to the power grid with compliant characteristics, consequently having dynamic behavior inherently. Moreover, the DERs and loads are always disconnected and reconnected to the microgrid at any time, where such an unpredictable behavior, might cause the prior protection and control systems to be invalid and impractical. Microgrids during grid connected and islanded mode have different behaviors and possessing totally diverse level of short circuit current [7]. In grid connected mode, during the fault occurrence, the incoming short circuit current contributed by the main grid to the fault point is exceptionally large and the conventional power protection systems are able to operate and disconnect the faulty section. On the contrary, during the islanded mode, in the presence of fault in the microgrid, the fault currents instigating by DGs in the microgrid are severely less compared to the grid mode of operation as the protection relays are not able to distinguish between fault current and minor imbalances or disturbances in the grid. As a result, the existing overcurrent protection strategy is not valid anymore and new approaches must be devised and developed in order to provide microgrid with appropriate and suitable protection [8].

Another protection challenge after the emergence of microgrid is that, this phenomenon has changed the structure of distribution network from radial to loop, where this transformation result in improper operation of overcurrent relays in a way that they no longer are capable of protecting the new structures. Due to the reason that the level of short circuit current in grid connected and islanded mode is drastically different, the conventional single setting for protection relays is not applicable anymore and results in maloperation of relays in the presence of faults. [9] Furthermore, since a large portion of DGs in microgrids are inverter-based and the fault current contribution of these sources are only limited to 2-3 times of maximum load current thanks to the low terminal capability of their power electronics, it causes the protection relays to either not operate for some specific faults or take a very long time to trip and disconnect the faulty section in islanded mode of operation which is a drastically catastrophic issue that must be addressed and new techniques must be improvised [10].

There have been several studies conducted and new approaches were proposed to improve the protection of microgrids by addressing the acknowledged problems specifically in islanded mode of operation. However, the literature is still considerably limited and inadequate, the information provided is incomplete and diminutive, the reported works only verified by some simple simulation and the majority of them are just an idea rather than a practical solution. Therefore, a more comprehensive research must be conducted to resolve the aforementioned protection issues associated with microgrid both in grid connected and islanded mode of operations [11].

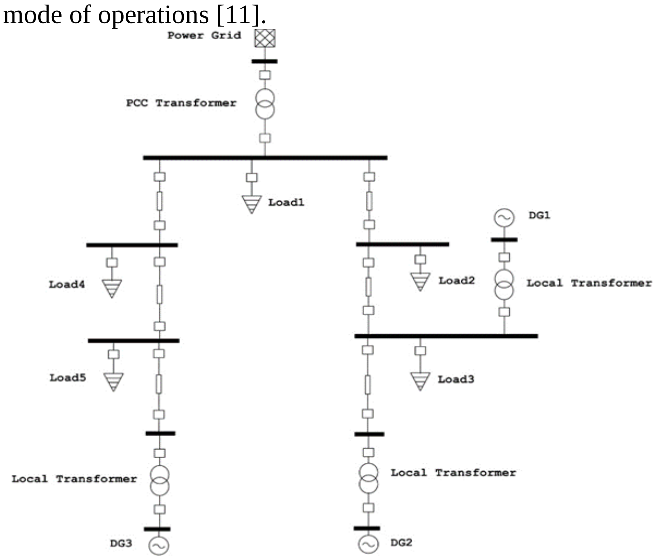


Fig. 1. A single line diagram of a typical microgrid.

## II. DETRIMENTAL EFFECT OF DG SOURCES ON PROTECTION DURING DUAL- OPERATING MODE OF MICROGRIDS

Microgrids are able to operate both in grid connected and islanded modes, In grid connected mode the microgrid including DGs and corresponding loads are all connected to the main grid whereas, in islanded mode the microgrid is entirely disconnected from the main grid and consequently, the loads are supplied by local DGs depending on their priority and significance [12]. Although this capability of microgrids is immensely desirable, it would compromise power system protection performance and cause several issues including miscoordination, malfunction, blinding and false tripping. Furthermore, microgrids are required to be protected from any type of faults that occur in any location. It is reasonable to classify fault location in two major categories: faults that occurs inside the microgrid, and the faults that take place adjacent to the main grid where the PCC is located (i.e. outside the microgrid). It is remarkably crucial to analyze the fault location in both microgrid operation modes, and its effect on overcurrent protection. Performance of microgrid protection with respect to the operation mode (either grid connected or islanded) and fault location is discussed as follows:

### *A. Protection relays performance during Grid connected mode*

In microgrids once a fault occurs during grid connected mode, the fault current contribution from DGs existing inside the microgrid negatively disturb the sensitivity, selectivity, coordination and operation of protection relays. Furthermore, based on the fault location, fault type and severity of the particular fault, the aggregate short circuit current could escalate while feeding fault current from the main grid could diminish. In other words, short circuit current contributed by the main grid and accordingly fault current detected by the protective relay is alleviated however, the total short circuit current is amplified. The larger the capacity of DGs are, the worse effect it imposes on the protection relays performance and signifies their deficient competency [13]. The major protection issues during grid connected mode are reported to be relays miscoordination, false tripping, blinding of protection and relay overreach.

Addition of DGs to microgrids has completely changed the pattern of conventional direction of fault current in microgrids where once a fault occurs during the grid connected mode, fault current can flow in two directions. This bidirectional fault current and power flow, causes miscoordination between protection relays. Moreover, false tripping occurs when a relay on a feeder connected to a DG trips for an impending fault for an adjacent feeder whether containing DG or not. This phenomenon causes a healthy feeder to be mistakenly disconnected and subsequently, resulting poor power quality and power generation provided for loads. The more DGs installed in a microgrid, the higher short circuit current is provided, and as a result, false tripping would occur more frequently which is extremely devastating for microgrid reliability [14]. Another common protection issue during grid connected mode is blinding of protection and it transpires when a relay on a feeder ignores to react to fault downstream from a DG. Since a large portion of DGs in microgrids are inverter-based and the fault current contribution of these sources are only limited to 2-3 times of maximum load current thanks to the low terminal capability of their power electronics, grid contribution to the fault never trigger a trip from relays to corresponding circuit breaker. It is also worth mentioning that, as a result of inadequate contribution of DG to a fault, the fault current provided from the main grid is diminished. Consequently, this results in escalation of voltage drop along the feeder and faulted bus which would imposes a smaller fault current from the grid. This is a catastrophe for protection relays specifically overcurrent relays, since they are sensitive to spike of excessive current, the massive current reduction caused in microgrid during grid connected mode will not trigger the relays and leaves a faulty section to be undetected and causes more perilous implications.

### *B. Protection relays performance during islanded mode*

In the case of any type of severe fault occurrence outside the microgrid, close to the main grid, the corresponding protection relays trips and command the STS at the PCC to disconnect the microgrid from the main grid to provide adequate protection for loads, utilities and DGs inside the microgrid. Although this behavior is satisfactory and desirable, it results in massive changes in the behavior of power flow and characteristics inside the microgrid and consequently creates chaotic impact on the protection relays performance which is all the result of drastic change in the topology of microgrid from grid connected mode to islanded mode of operation [15].

During islanded mode, DGs will be the only source of power generation for the loads in the microgrid therefore, the pivotal contributors to the short circuit current for impending faults originates merely from the DGs. Furthermore, since the majority of modern DG systems are inverter based, again similar to grid connected mode of operation, short circuit current generated by DGs are vastly circumscribed, subsequently causes protection relays not to trigger for the majority of fault types [16]. However, the microgrids that contain synchronous based DGs, since they are able to provide high fault current during abnormality, even single line to ground fault where the fault current is not exceptionally high, the fault current is high enough to trigger the protection relays and isolate the faulty feeder. Another protection issue that has been observed abundantly for microgrids during islanded mode of operation is that, during fault incidence, fault current and power flow would have bidirectional characteristic where current is flown in two different directions and causes miscoordination and malfunction of protection relays.

The entire observed protection relays issues in microgrids (which are predominantly the result of DGs addition to the microgrid and radial design of microgrid topology) during both grid connected and islanded mode of operation with respect to the fault location, have been tabulated in Table I.

TABLE I. MICROGRID PROTECTION RELAYS ISSUES WITH RESPECT TO FAULT LOCATION AND MICROGRID OPERATION MODE

| Microgrid Operation Mode | Fault Location | Protection Issues |
|---|---|---|
| Grid connected mode | - Downstream from DG connection point | - Overreach, lack of sensitivity and delayed operation of relays |
| | - Between main grid and DG | - Blinding, underreach and maloperation of protection relays |
| | - Faults on an adjacent feeder | - False tripping and miscoordination of relays |
| Islanded mode | - Between main grid and DG | - Loss of selectivity and lack of sensitivity of protection relays |
| | - Faults on an adjacent feeder | - Miscoordination and malfunction of relays due to bidirectional fault currents |

## III. EVALUATION OF PROPOSED TECHNIQUES FOR RESOLVING MICROGRID PROTECTION CHALLENGES

During design of microgrid protection system, some common protection criteria must be taken into consideration including selectivity, reliability, speed, simplicity, economics and also maintainability. In general, the proper protection technique for microgrids must be capable of providing adequate protection for the power apparatus, microgrid and main grid and also take action promptly against incoming faults occurring inside or outside the microgrid. The desirable response would be isolating the microgrid from the main grid during any fault in the utility grid side, and disconnect the smallest faulted area during any fault inside the microgrid. However, the existing protection schemes applied to provide protection for microgrid is considerably ineffective and nonfunctional. Therefore, new techniques and procedures must be proposed and developed to tackle the challenges associated with the protection of microgrid during both grid connected and islanded mode of operation in any fault location. A comprehensive review of the most significant proposed methods for microgrid protection has been compiled in the following sections as depicted in Fig. 2 below.

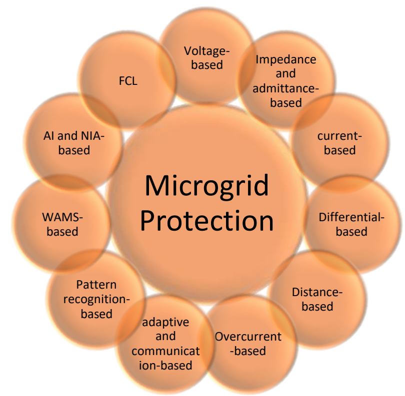


Fig. 1. Proposed schemes for microgrid protection.

### A. *Voltage-based Protection*

Voltage-based protection technique has been applied in order to protect microgrid against different types of faults specifically overvoltage and undervoltage abnormalities by employing extensive voltage measurement for some specific configuration of microgrids.

A voltage-based protection scheme has been developed for islanded operation mode by measuring the utility voltages and being transformed appropriately to detect the type of fault according to the voltage profile of the measured unit [17]. The authors demonstrated that the relay for a faulted zone is tripped when the fault voltage upsurges the threshold voltage corresponding to a fault. However, this technique is not only inaccurate and may cause relay to malfunction to some certain faults but also can be used for some specific configuration of small scale microgrids. Authors in [18], used voltage-based protection in conjunction with communication in order to exchange transfer voltage signals between two relays so they are able to detect any abnormalities in the islanded operation mode of microgrids for in-zone or out-zone impending faults. In this study, the voltage supplies are initially transformed from abc to dq frame to determine disturbance signal voltage. The magnitude of this reference voltage is used to distinguish between normal operation and existence of any disturbance in the power system. The signal voltage is then processed through low pass filter and hysteresis comparator in order to define the fault margin sensitivity. This scheme was reported to be more efficient than previous similar methods, however the proposed technique lacked adequate sensitivity for high impedance faults where the relays failed to trip properly. Park transformation voltage-based protection was also proposed in [19] to improve detection of fault or any abnormality in the microgrid which was successful and is applicable to various topologies of microgrids, however, it may not be suitable for larger microgrids where the calculations become largely complicated and congested.

In summary, voltage-based protection is not reliable, efficient and comes down with various notable drawbacks including:

- Unable to apply universally to every microgrid as this technique can only be implemented to some specific configuration of small scale microgrids.
- Lack of sensitivity to high impedance faults and also grid connected mode of operation.
- maloperation and false tripping of relays due to any voltage drop in the microgrid.

### *B. Differential Protection*

Differential protective relays are usually used to provide protection for a single unit mostly employed for power transformers, however in microgrids since there is a necessity to provide adequate protection for different zones rather than only a single unit, differential zone protection including ideal numbers of relays and measurement sensors for each specific zone must be implemented. Differential protection operation is reliably fast usually close to 5ms, which can result in fast tripping and provide security for the microgrid for both grid connected and islanded mode of operation.

A distinct differential-based protection was implemented in [20] to secure microgrids during islanded operation mode. In this study a novel algorithm was developed to optimize the relays and sensors placement in order to minimize the number of relays and consequently reduce the cost. However, this study was only tested in simulation environment and was not validated experimentally. In reference [21] differential-based protection with the employment of overcurrent relays and communication links were studied in DigSILENT Power Factory software. The microgrid case study contained several types of DGs including converter-based and directly coupled model in order to ensure the effectiveness of the proposed method for modern microgrids. It was reported, although the differential-based protection was economically judicious, the results were not in terms of robust protection provision during unbalanced load conditions.

During designing the microgrid protection, it is exceptionally vital to devise backup protection for the primary relays so that in case the primary protective relay fails to trip due to any reason, the backup protection relay unit should trip accordingly after a short delay time set by coordination criteria. This phenomenon has been studied for differential-based protection in MV active distribution systems connected to microgrids in [22]. In this research, not only a primary differential protection was developed, but also a reliable backup protection was added to improve the integrity of the power system for 18 bus distribution system. Different types of DG comprising wind farms, PV, synchronous and asynchronous generators were designed for the microgrid in MATLAB software.

In summary, it is inferred that differential-based protection have the following drawbacks and challenges when implemented in microgrids:

- Unbalanced loads could impose serious maloperation and false tripping for protection relays as a result of transients during switching DGs.
- Requires extensive and expensive communication links to exchange data from several relays to each other and also to the corresponding circuit breakers.
- In case of communication failure and absence of backup protection, the reliability of whole microgrid protection would be severely compromised.

### *C. Overcurrent Protection*

The most efficient and commodious protection in distribution system is overcurrent protection by using overcurrent relays with directional elements to provide adequate security for the main grid, transmission lines, power apparatus, DGs, feeders and also loads, during disturbances and impending faults [23]. The operation of these relays is straightforward, simple and unpretentious; however, these relays are significantly effective and reliable. Overcurrent relays are sensitive to the measured current from current transformers in a way that if the current is higher than preset threshold value, then the relay will operate either instantaneously or with a delayed time based on Time-Current Characteristics (TCC) curve as depicted in Fig. 3 [24], and accordingly send a tripping signal to the corresponding circuit breaker to disconnect the faulty section immediately. There are three main categories of overcurrent relays which are: definite current, definite time, and inverse time relay which the latter is the most effective and prominent type in power system protection.

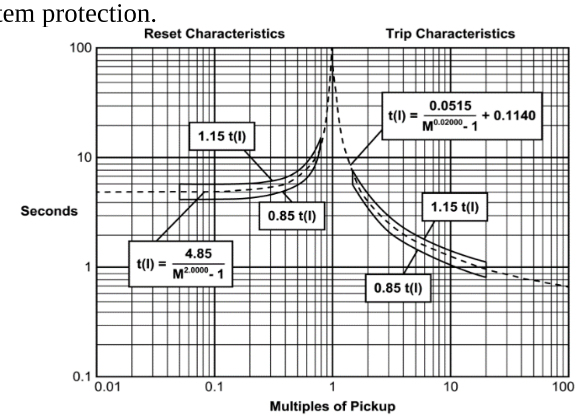


Fig. 3. TCC curve for a normally-inversed overcurrent relay according to C37.112-2018 - IEEE Standard [24]

The application of overcurrent relays and their coordination in microgrids is a drastically challenging task that have recently interested many researchers. Reference [25] employed overcurrent relays for a modified IEEE 13 bus power system where wind farms as DG, are the main power generation source, connected to the distribution system. The protection analysis results prove that the relays can operate properly for high current faults however, the effectiveness of the proposed protection for different circumstances is not clear as only three phase fault as the most severe scenario has been tested and just a small scale wind farm as the DG source has been considered in this research.

The coordination of duo directional overcurrent relay with the conjunction of differential relay have been studied in [26] for a small microgrid where synchronous generators are connected to this power systems. The protection results have been only analyzed for three phase faults where effect of renewable energy sources have been neglected. Although the relays operation has been satisfactory, the protection scheme is far from convincing since a microgrid topology includes DG sources comprising of intermittent sources including wind farm and PV, which can affect the operation of relays adversely.

Microgrids during grid connected and islanded operation mode have diverse fault current characteristics that causes dire performance on overcurrent protection. As a result, it is recommended to establish a communication with adaptive protection to change the settings of relays according to the microgrid mode of operation. This concept has been studied in [27] and developed a three stage communication assisted selectivity scheme. In this technique, at the first stage, fault current is detected by relying on local measurement from CT. Stage 2 is responsible for sending proper signal through an inter-breaker communication and finally stage 3 is developed to adapt the settings of the relays according to the microgrid operation mode. The results showed massive improvement for overcurrent protection relays performance. In a novel scheme developed by [28], a microprocessor-based relay was designed with directional element. The relays were designed based on definite time characteristics and the coordination between them were set in the zone starting from load side to the main microgrid connection point. The proposed technique was carried out without any communication links between relays and it was reported that the relays operated with a much longer delay for fault current in the DG zone however it may not cause any damage to the power apparatus.

In conclusion, overcurrent protection is a challenging task that although has been exceptionally successful in power distribution protection system, it has not achieved similar satisfactory results in microgrid protection. In order to improve the overcurrent protection performance for microgrids, all the relays must be equipped with directional element and communication between relays must be established to improve coordination and operation of relays. Moreover, adaptive protection techniques for overcurrent relays should be implemented so that the relays adapt their settings in response to the behavior changes of the grid, i.e. when the microgrid is in grid connected mode or islanded mode of operation. Since the state of DGs connection to the microgrid can also be changed randomly, the settings of relays must be adapted through either communication or adaptive preset settings for the relays accordingly as well. The main associated challenges with overcurrent protection are as the following:

- Capacity and size of DG affect adversely on the performance of protection relays and cause malfunction, miscoordination and false tripping.
- The fault current during grid connected and islanded mode of operation are vastly different and may cause insensitivity, blinding and maloperation of relays.
- Adaptive protection with proper communication is immensely required for robust overcurrent protection which would increase the costs. Also, in case of communication failure, if there is no backup protection established, the reliability of protection for microgrid would be compromised.

### *D. Adaptive and Communication-based protection*

As discussed before, due to nature of microgrid characteristics that can be operated in grid connected and islanded mode of operation and also because of the changes in operation status of DGs with their intermittent power generation features, protection relay settings should no longer be set offline but instead, their settings and coordination between them must be adaptive and corresponsive to the microgrids alterations [29]. Proper communication links between relays should also be developed to not only provide fast communication and data exchange between relays, but also to ensure robust protection and appropriate coordination is delivered by the protective relays [30]. In the modern power systems including microgrids and smart grids, extensive communication is required and in order to fulfil this necessity, the application of conventional protection relays will be irrelevant and impractical thus, only modern digital and microprocessor-based protection relays that are capable of programming and work on the concept of communication, must be employed [31].

The development of adaptive and communication-based protection scheme has been conducted by [32] where in this technique, a Microgrid Central Protection Unit (MGCPU) is developed to calculate and update the settings of protection relays by receiving faults currents measured from current transformers. In this research IEC 61850-70420 standard which is a common procedure standard employed for modern microprocessor-based protection relays. The proposed technique was shown to be successful for small scale microgrid however, the dynamic comportment of communication network has been disregarded. The other drawback was reported to be not being applicable for larger and complex microgrids. In another research done by [33], the adaptive protection was tested for a more complex microgrid containing three gas turbine generators and one CHP plant as main sources of DG. The entire design was simulated and tested in DigSILENT Power Factory software. Three phase faults having a low impedance of 0.05 Ω was imposed to the microgrid during both grid connected and islanded mode of operation to validate the reliability of the relays. An algorithm has been developed to detect the operation mode of microgrids and change the settings of the relays accordingly but measuring the fault currents. The attained results proved that by implementing adaptive protection, associated protection issues related to insensitivity, blinding and maloperation of relays can be successfully resolved and relays can reflect properly to the microgrid behavior changes.

A similar research [34] was done in PSCAD software for microgrid protection connected to electronically decoupled wind and PV DG plants. The authors proposed a feature that monitors the microgrid and update the settings of the relays accordingly based on the variations that occurs in the system. Automatic reclosers were also developed to ensure fast recovery from faults to improve the reliability and stability of the microgrid in the presence of abnormalities and disturbances. Although, the results proved the effectiveness of adaptive protection feature for relays but enormous memory is required store the entire settings for all protective relays and their coordination criteria, specifically for larger and more complex microgrids.

In summary, adaptive and communication-based protection is an essential scheme that should be developed for microgrid protection; however, it comes down with several drawbacks and challenges including:

- Communication infrastructure costs are drastically high and requires massive investment.
- Large memory storage is essential for the entire relay settings.
- All protection relays must be updated constantly for even small changes in the power system which may not be necessary.
- All possible configurations for microgrids should be known and considered before application of this technique.
- Short circuit current analysis is extremely demanding for complex microgrids.

### *E. Pattern Recognition-based Protection*

Pattern recognition is a stellar technique categorized into machine learning systems that is applied for recognizing patterns and provide predictabilities in a large data based on supervised or unsupervised classification [35]. This technique can also be used in power system protection to detect faults in microgrid, recognize the fault location and fault type which could enhance the performance of protection relays to operate reliably and vigorously [36].

Application of Pattern recognition-based protection for a medium voltage microgrid containing converter-based DG sources has been studied in [37]-[38]. In these researches, Stockwell Transform (S-transform) based on a novel differential energy protection system in conjunction with time frequency scheme was introduced. The application of this technique is very straightforward and focuses on analysis of spectral energy density content of contours which are produced through S-transform originated from measured current at each bus bars in the power system. By conducting this technique, fault patterns can be simply recognized and according to preset threshold value for current instigated on the differential energy, a tripping signal is sent to the circuit breaker. The efficiency of this technique has been tested for various fault types and fault locations where the results was promising. However, the entire system was developed through simulation software and was not tested on real time and practical microgrid to challenge the reliability of this technique.

Unfortunately, there have been a staggering limited research accomplished on application of pattern recognition-based protection for microgrids and the effectiveness of this technique for various topologies of microgrid with different types of DG sources, has not found to be convincing yet. The major drawbacks of this technique are as the following:

- Not practically feasible for microgrids as the machine learning system and patterns are trained through simulation and not real cases.
- Both frequency and time data from the entire microgrid must be provided to properly train the system which may be significantly complicated for complex larger microgrids.

### *F. Wide Area Measurement-based protection*

Wide Area Measurements (WAMS) technology has been gradually flourished to a point that is being implemented in most power systems to improve the performance of protective relays and ensure faster fault elimination. The basic structure block of this technology is Phasor Measurement Unit (PMU) that is installed at each bus bar to provide real time information of voltage, current, phase angle and etc. from each designated location [39]. In this technique, Intelligent Electronic Devices (IEDs) are utilized and perceptibly, comprehensive communication links should be installed to deliver fast communication of electrical information from various locations of the power system to the protective relay [40].

The application of WAMS for microgrid was carried out in [41] where a novel backup protection system was developed by considering fault component voltage distribution. In this research several PMUs, Local Backup Protection Center (LBPC), System Backup Protection Center (SBPC) and control breaker units were developed which are accounted for the general configuration schematic of the developed technique. PSCAD/EMTDC software was utilized to test the effectiveness of the proposed method by introducing both symmetrical and asymmetrical faults for IEEE 39 bus system containing 10 synchronous generators as DG source. The results showed WAMS can be successfully applied for microgrid protection and the advantage of the proposed method is offering high flexibility and providing simple settings for protection relays. In another study done by [42], adaptive protection in conjunction with WAMS and extensive communication have been proposed for microgrid with high DG penetration. A central protection unit was developed to communicate with the relays based on IEC61850-7-420 standard and update the settings of relays by exchanging data from PMUs located at the microgrid. The simulations were done in OPNET software to evaluate the message latency of the proposed scheme. Although the results were reported to be promising, the application of this technique is drastically expensive and may not be applicable for large microgrids.

WAMS technology offers ample improvement for performance of protection relays however the robustness of this technique has mainly been studied and tested for microgrids containing PV and synchronous generators. Thus, more research must be done to prove the efficiency of this scheme for various types of microgrids. There are several flaws and drawbacks associated with employment of WAMS in microgrids as mentioned in the following:

- Requires extensive communication infrastructure which is drastically costly.
- Communication failure may cause catastrophic problems for microgrid protection if no backup protection is devised.
- Communication delays and latency of measurement restricts the application WAMS for large microgrids where high speed protection functions are required.
- PMU provide an approximation of the fundamental frequency component, hence components associated with transients comprising harmonics and dc offset are not obtainable in WAMS.

### *G. AI and NIA-based Protection*

Artificial Intelligence (AI) and Nature Inspired Algorithms (NIA) have been used vastly in recent years in power system protection specifically for optimization purposes [43]. Optimal coordination of overcurrent relays is extremely demanding and are considered as a highly constrained nonlinear programming problem specifically for complex microgrids which this hindrance can be affluently solved by employment of proper AI techniques. The most prominent methods that have been successfully implemented to improve the performance of protection relays in distribution systems are shown in Fig. 4, [44]-[45]. Researchers have frequently applied GA, PSO, GWO and COA for power system protection, relays setting optimization and optimal coordination due to their fast operation, effectiveness, reliability and robustness.

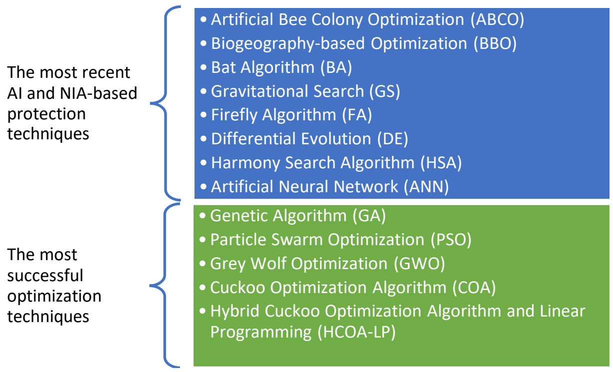


Fig. 4. The most recent and successful AI and NIA-based protection for microgrids

In a study [46], [47]conducted for improved protection of DFIG-based wind farm connected to a microgrid, GA and GWO optimization techniques was employed to improve the overcurrent relays operation and enhance the coordination settings by optimizing the TMS values. Coordination of relays was first carried out according to IEC standard by using conventional nonlinear time-current relay curve optimization method and then GA and GWO techniques were developed in MATLAB software to optimize the relay settings. The results were compared to the conventional nonlinear optimization method and showed a staggering improvement in performance of relays operation time with respect to faster operation time as a result of optimized TMS. Various fault types in different locations were introduced to examine the effectiveness of the proposed method.

In a recent novel research carried out in [48], a hybrid Cuckoo Optimization Algorithm and Linear Programming (COA-LP) with the purpose of optimizing directional overcurrent relays in a microgrid with high penetration of DGs during both grid connected and islanded operation mode were proposed. This technique was accomplished specifically for addressing the effect of DGs on coordination of directional overcurrent relays. It was found that hybrid COA-LP is capable of solving the miscoordination criteria of relays are achieved better results that GA and PSO in terms of speed and operation time of directional relays. Various fault types in different locations for a Canadian distribution system case study was simulated and the results of relays operation were satisfactory.

The main advantage of AI and NIA-based protection techniques is when applied correctly based on the proper objective function formulation and appropriate selected constraints for microgrid, they are capable of attaining optimal results specifically for optimizing the coordination of the relay settings which is drastically crucial in power system protection [49]. The other advantage is that application of these techniques does not require any communication links and adaptive approaches to update the relay settings online. They can be implemented when offline settings are required for best possible results. However, the main disadvantage is that, they may not be able to achieve optimal results for every case study in power system protective relaying. Also, they can be used as only backup protection for microgrid when communication links, adaptive and/or WAMS protection are required.

## IV. COMPARATIVE ANALYSIS AND RECOMMENDATION FOR FUTURE RESEARCH

The underlying criteria and attributes of power system protective relaying are reliability, selectivity, sensitivity, speed, simplicity, cost and maintenance. However, it may not be feasible to have all these characteristics in a single protection approach due to availability of diverse microgrid topology, bidirectional behavior of current flow and most significantly, detrimental impact of high penetration of DGs on protective relay performance. Moreover, conventional overcurrent relay is no longer applicable due to complex structure of microgrid, and coordination of relays is considerably scrambled and challenging due to bidirectional power flow and impact of inverter-based DG units during islanded operation mode. Thus, each protection technique discussed earlier may be applicable to only a specific designed microgrid with particular topology and DG technology. A summary of underlying disadvantages and drawbacks of each technique is illustrated in Table II.

Based on the numerous protection techniques studied for microgrids, adaptive protection in conjunction with proper communication infrastructure based on IEC 61850-7-420 is recommended to be implemented since it has the capability of incorporating the dynamic changes in the status of microgrid operation mode, DG connection status and subsequently update the relay settings according to the power system dynamic changes as depicted in Fig. 5. Conventional mechanical-based relays should be outdated and instead, microprocessor-based protection relays must be employed which are suitable for adaptive and communication-based protection and are able to operate faster and provide reliable protection for microgrid. As a backup protection strategy in case of adaptive and communication failures, AI and NIA-based optimized settings and coordination for protection relays can be deployed to ensure maximum security for the microgrid as well as robust and reliable power quality during disturbances by minimizing the disconnected area at the shortest possible time. Adaptive and communication-based protection should also be prepared for abnormal malicious hackers, manipulating relay settings instigating catastrophic damage to power systems and compromising personnel safety. Undoubtedly, cyber security will be significantly more crucial in the near future as hacker attacks are being increasingly more prominent, subsequently proper countermeasures must be devised to avert any plausible complications.

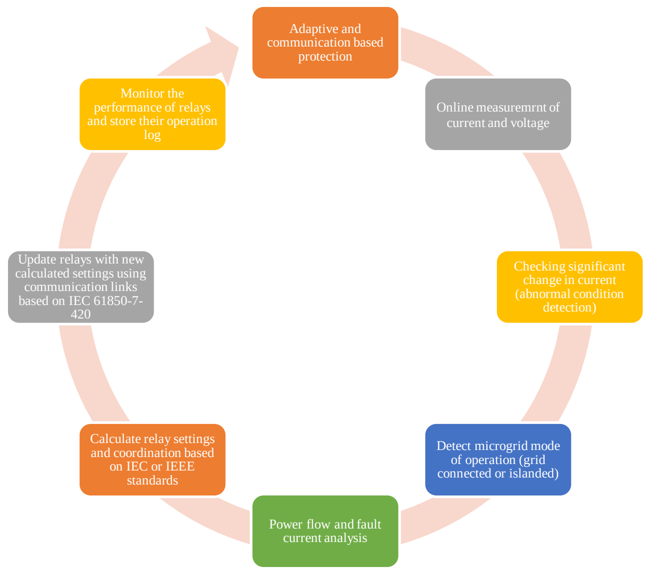


Fig. 5. Efficient adaptive and communication-based protection for microgrids.

## V. CONCLUSION

Microgrid protection is a substantially challenging task where conventional microgrids are no longer practical and suitable for protecting microgrid against impending faults and disturbances. Inverter-interfaced DGs, Bidirectional power flow, inheritably dynamic behavior of microgrids as a result of intermittent nature of DGs and dual operation mode grid connected and islanded mode, has a significantly detrimental impact on protection relay performance, consequently new approaches must be employed to solve the associated problems with protection relays in microgrids. In this regard, a comprehensive and analytical appraisal on the proposed techniques and approaches has been perpetrated and it was inferred that some techniques can be only applied to some certain microgrids with specific topologies and DG technology. Moreover, the majority of the proposed techniques were only developed in software and was never tested on authentic real case microgrids. Implementation of some methods can be costly, or just simply an idea where can never be practically done. Therefore, there is still a necessity for more research to be done to address protection issues specifically overcurrent relay and coordination problems to ensure robust protection is provided for microgrids. Also, some protection standards for microgrids should be revisited and updated to improve the performance of relays in both operation modes with high penetration of DGs.

According to the literature and comprehensive study done in this paper, it is recommended to employ adaptive and communication-based protection technique in conjunction with microprocessor-based protective relays since it is drastically successful to react to dynamic behavior of microgrids and update the relay settings and coordination criteria based on constant changes occurring in microgrid. As a backup option, AI and NIA-based optimization techniques for protection relay settings can be developed to ensure robust and reliable protection for microgrids. Furthermore, cyber security should also be considered when adaptive and communication-based protection is applied, in which it should be considered as a critical topic in the future protection studies.

TABLE II. A SUMMARY OF ASSOCIATED DRAWBACKS WITH EACH PROTECTION TECHNIQUE

| Protection Technique | Drawbacks |
|---|---|
| Voltage-based | • Applicable to only some specific small scale microgrids<br>• Lack of sensitivity to high impedance faults<br>• maloperation and false tripping due to any voltage drop |
| Impedance and admittance-based | • Requires extensive communication links which is highly costly for large microgrids<br>• Communication failure would endanger the integrity of the microgrid due to absence of backup protection system |
| Current-based | • Maloperation of relay due to a fault in another feeder<br>• False tripping and miscoordination of relays in a feeder connected to a DG as result of bidirectional power flow during fault incidence |
| Differential-based | • False tripping and maloperation of relays for unbalanced loads as a result of transients during DG switching<br>• Requires extensive and expensive communication links<br>• Communication failure could severely compromise the reliability of microgrid due to absence of backup protection |
| Distance-based | • Inaccurate measurement for fault impedance from the relay to the fault location as a result of harmonics and transient<br>• Inaccurate and challenging measurement of fault impedance in microgrids that have noticeably short lines<br>• Insufficient sensitivity for downstream DG infeed fault current<br>• Distance protection is mostly restricted to only transmission lines |
| Overcurrent-based | • Capacity and size of DG affect adversely on the performance of protection relays and cause malfunction, miscoordination and false tripping<br>• The fault current during grid connected and islanded mode of operation are vastly different and may cause insensitivity, blinding and maloperation of relays<br>• Adaptive protection with proper communication is immensely required for robust overcurrent protection which is costly for large microgrids |
| Adaptive and communication-based | • Costly communication infrastructures<br>• Requires large memory storage for the entire relay settings<br>• Necessity for relays to get updated constantly for even small changes in the power system which may not be necessary<br>• All possible configurations for microgrids should be known and considered before application of this technique<br>• Demanding short circuit current analysis for complex microgrids |
| Pattern recognition-based | • Not practically feasible for microgrids as the machine learning system and patterns are trained through simulation and not real cases<br>• Complicated to train the system for large and complex microgrids since frequency and time data from the entire microgrid should be measured |
| WAMS-based | • Requires extensive communication infrastructure which is drastically costly<br>• Communication failure may cause catastrophic problems for microgrid protection if no backup protection is devised<br>• Communication delays and latency of measurement restricts the application WAMS for large microgrids where high speed protection functions are required<br>• PMU provide an approximation of the fundamental frequency component, hence components associated with transients comprising harmonics and dc offset are not obtainable in WAMS |
| AI and NIA-based | • Applicable as only backup protection when offline settings are required<br>• Infeasible optimal results for every case study in microgrid protective relaying |
| FCL as external device | • Extremely challenging to find the optimal impedance value for FCLs in the microgrids with high DGs penetration<br>• May cause miscoordination for directional overcurrent relays if the impedance value is not correctly calculated<br>• Certain types of FCLs as an external device, are costly for large microgrids |

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