Protection Challenges Under Bulk Penetration of Renewable Energy Resources in Power Systems: A Review

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***Abstract*—Among different sources of alternate energy, wind and solar are two prominent and promising alternatives to meet the future electricity needs for mankind. Generally, these sources are integrated at the distribution utilities to supply the local distribution customers. If the power generated by these sources is bulk, then they are either integrated at the distribution/transmission level or may be operated in an island mode if feasible. The integration of these renewables in the power network will change the fault level and network topologies. These fault levels are intermittent in nature and existing protection schemes may fail to operate because of their pre-set condition. Therefore, the design and selection of a proper protection scheme is very much essential for reliable control and operation of renewable integrated power systems. Depending upon the level of infeed and location of the renewable integration, the protection requirements are different. For low renewable infeed at the distribution level, the existing relay settings are immune from any small change in the network fault current from new incoming renewables. However, bulk renewable infeed requires modification in the existing protection schemes to accommodate the fault current variation from the incoming renewables. For bulk penetration of the renewable, the requirement of modified/additional protection schemes is unavoidable. Adaptive relaying and non-adaptive relaying schemes are discussed in the literature for protection of power networks, which are experiencing dynamic fault currents and frequent changing network topologies. This article presents a detailed review of protection schemes for renewable integrated power networks which includes distribution, transmission and microgrid systems. The merits and demerits of these protection schemes are also identified in this article for the added interest of the readers. The visible scope of advance protection schemes which may be suitable for providing reliable protection for dynamic fault current networks is also explored.**

***Index Terms*—Adaptive relaying, distribution systems, distance protection, doubly fed induction generator, microgrid, protection, renewable energy source.**

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I. Introduction

DESIGN and selection of proper protection schemes are very much essential for control and operation of power systems. It helps in better power reliability, less damage to power equipment and safety of operational personnel. The protection philosophy is well established for power systems which have conventional synchronous machines as their main fault feeding source. Their protection schemes are designed at the planning stage and reviewed from time to time whenever new fault feeding source(s) are connected with the network. The integration of renewables in the power system changes the fault level and also the infeed is intermittent in nature [1]. The protection schemes which were designed at the planning stage may operate reliably for low penetration infeed from a renewable energy source (RES). But large penetration of the RES leads to nuisance tripping of over current relays at distribution feeders and their impact may reach to the distance relays of the transmission system.

Penetration of the RES in power systems is steadily increasing and it has reached around 14% in India [2] and recommendations of the recent united nations framework convention on climate change (UNFCCC) in Paris have placed an urgency for 20% penetration of renewable energy in the electricity market by 2022. From the experience of the operator, the present protection challenges are not so serious and available protection techniques will be able to protect the system with the desired reliability. For universal energy access by 2030, the international energy agency projects 470TWh of RES power additions (primarily through renewables and diesel) against 368 TWh through grids (primarily from fossil fuels). The design of protection schemes for this bulk dynamic power penetration is a serious concern for the power system protection engineers. According to power produced (rating) by RES, these are broadly classified as micro RES (1 kW–5 kW), small RES (5 kW–5 MW), medium RES (5 MW–50 MW) and large RES (50 MW–300 MW) [3]. In the NREL Report [4], the large penetration of renewable issues are discussed on the USA based electrical networks. The penetration levels are considered as 30%–90% for a 2050 grid scenario. At present, the penetration levels of RESs are not more than 40 % of total system capacity. If penetration levels are more than 40% of system capacity, then we may consider it as a high penetrated RES.

Design of new protection schemes for bulk RES connected power systems is an emerging area. These schemes can be broadly classified as adaptive protection and non-adaptive protection philosophies. The relay settings need to be changed as per the changing fault level in the power systems. All the relays, switching devices and control centers must be connected through reliable bi-directional communication protocol for implementation of adaptive protection schemes [1]. In non-adaptive protection schemes, the fault current contribution from the RES is either minimized or blocked by placing external devices in the power circuit during fault periods [5], [6]. In this way, there is no requirement of changing the relay setting when the fault levels are varying in the power network due to intermittent operation of the connected RES. The high penetration of the RES may create under-reach or overreach problems on overcurrent relays and also it could affect the zone reach setting of the distance relays on upstream transmission lines and lead to mis-coordinated operation of the distance relays.

The future power system requires modified protection schemes. This requirement will be essential in case of an inverter based photovoltaic RES. The short circuit currents of these resources are extremely poor and protection devices may fail to discriminate the normal loading and fault condition due to the thin margin between them [7]. New protection schemes, which are suitable for a weak fault current feeding source need to be developed in the future. Particularly, the design of protection schemes for off grid/islands is an emerging research area in power systems. These power systems are either alternating current or purely direct current in nature, where protection schemes require extra consideration.

This review article discusses the merits and demerits of various existing protection schemes with the integration of RESs in power systems. The feasibility of these protection schemes for futuristic large scale penetration RESs in power systems is also discussed. The content of this review article is presented as follows, protection issues in RES connected distribution systems are presented in Section II and protection issues in RES connected transmission systems are presented in Section III and microgrid protection schemes are presented in Section IV. The conclusion and future scope of research in RES connected power system is also presented at the end of this article.

II. Protection Issues and Solutions in Distribution System with Large Scale Penetration of RES

Distribution systems are primarily protected with the help of current sensing devices such as overcurrent relays (OC), reclosers and fuses. These devices monitor the current flow through the protected element and generate trip signals to the circuit breaker if the fault current flow is more than the specified value. The protection philosophy of the distribution systems are designed based on the assumption that these are radial in nature and power flow is always unidirectional from the source to consumers [8].

In the case of a multi-generator/multi-loop system, the power flows are not unidirectional and fault currents will flow in either direction based on fault location. Directional overcurrent relay (DOCRs) are the best solution to avoid the sympathetic trippings in multi loop systems [9]. But in case of a large penetration of the RES, because of their intermittent nature, fault levels on the network will change with respect to the level of RES penetration. DOCR with fixed time dial setting (TDS) and plug multiplier setting (PS) will not protect the feeder from a large penetration of the RES. Particularly, the change in fault current primarily depends on the type, rating (penetration) and location of the RES integration in the network [5]. As shown in Fig.1, the fault is supplied from the grid as well as from the RES. For the fault near relay R2, the fault current seen by relay R2 will increase and it will decrease for relay R1 depending on the RES rating and RES impedance. The change in fault level seen by the relays will result in the under reach operation of the relays.

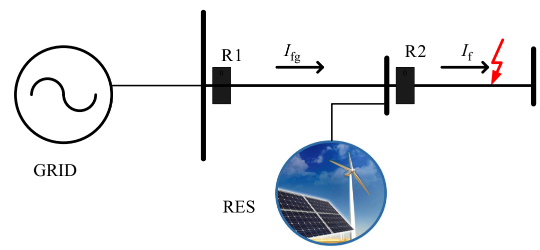


Fig. 1. RES integration into existing network.

The contribution of the fault level from a synchronous based RES (small hydro plants) is in the range of 5 to 6 times its rated current. In addition, an inverter based Photovoltaic RES has a poor contribution of fault current in the range of 1.1 to 2 times of rated current [10]. In this case, the existing over current relay fails to detect the weak fault current. In the later section of this review article, the authors(s) discuss new voltage and current based protection schemes which can effectively provide the protection for the inverter based Photovoltaic based distribution systems.

A. Main Protection Issues With Integration of a RES

1) Blinding of Protection

As discussed above in Fig. 1, fault current sensed by relay R1 will be lesser than without a RES connection. This reduction in fault current will result in no operation by relay R1 and is known as a blinding operation of the relay.

2) False Tripping or Sympathetic Tripping

Integration of large scale RESs in distribution systems results in the bidirectional flow of the fault current on most of the feeders/lines. A non-directional over current relay may fail to provide the desired protection for these networks during infeed from the RES. As shown in Fig. 2, for a fault, the relay R2 may trip in a reverse direction because of the forward operation of relay R1. These types of trippings are known as false trippings. In big interconnected distribution systems, a few relays may experience fault levels greater than their pickup value and may trip before the desired primary/backup relays which results in isolation of a larger portion of the network. These types of false trippings are known as sympathetic trippings.

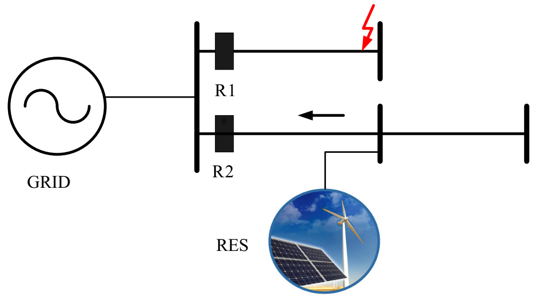


Fig. 2. Sympathetic tripping of relay R2 due to RES infeed.

3) Islanding Problems

As shown in the Fig. 3, if the fault current level sensed by R2 is sufficient to trip it, then it will lead to an islanding operation of the RES with its local connected load. The power imbalance in the isolated network may lead to unstable operation of the island network.

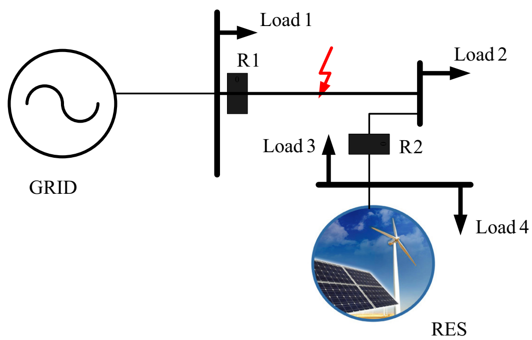


Fig. 3. Islanding problems due to RES connection.

4) Loss of Coordination

The false/sympathetic/blinding operation of the relays from downstream to upstream feeders leads to the sequentially false operation of the relays. This type of false tripping of the relay in a cascade manner is known as loss of coordination.

5) Auto Recloser Problems

As shown in Fig. 4, when the fault is partially cleared from the recloser bus, it still feeds the RES. The injected RES fault current may cause energization of the arc across the recloser and may convert a temporary fault into a permanent fault.

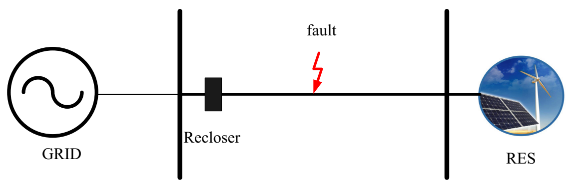


Fig. 4. Auto recloser problems with RES integration.

B. Protection Schemes for Distribution Systems With RES Integration

As discussed in the above section, the traditional protection schemes were not suitable for distribution systems with the integration of a RES. In this section different literature proposed protection schemes are discussed.

1) Point of Common Coupling (PCC) Voltage Based Protection Scheme

The main idea behind the design of this protection scheme is to reduce the fault current contribution of the RES during the fault periods. This can be achieved by monitoring the PCC voltage (V_{pcc}) by using the voltage control method [11]. During the fault periods, the converter reference current (I_{ref}) is controlled according to (1). During fault condition, if the voltage drop at the PCC bus is less than 0.88 p.u., then the reference converter current can be controlled from (1). It is a simple technique and no additional cost is required for implementation of this technique. But it fails to discriminate between the voltage drop during fault periods and the sudden voltage drop due to dynamic load changes in the transient periods. Moreover, if the fault is at the far end from the PCC bus and the voltage drop at the PCC bus is not noticeable, under such fault conditions this protection technique fails to reduce the fault current from the RES.

$$\begin{cases} I_{\text{ref}} = \dfrac{P_{\text{desired}}}{V_{\text{pcc}}} & \text{for } V_{\text{pcc}} \geq 0.88 \text{ p.u.} \\ I_{\text{ref}} = kV_{\text{pcc}}^{n} I_{\max} & \text{for } V_{\text{pcc}} < 0.88 \text{ p.u.} \end{cases} \tag{1}$$

where $I_{\max}$ is the maximum output current at $V_{\text{pcc}} = 0.88$ p.u., P_{desired} is the desired output power, k and n are constants.

2) Distance Protection on Distribution System

Distance relays are the main protected elements in a transmission system. Compared with the overcurrent relays, distance relays are less influenced by changes in network topology [12]. To overcome the false tripping of overcurrent relays in the distribution system with RES penetration, high set instantaneous (50 H or 50 NH) overcurrent elements were replaced by instantaneous quadrilateral characteristics, low set instantaneous (50 L or 50 NL) elements were replaced with an instantaneous mho element and time-over current (51 P) are replaced by mho elements [12]. Distance relay with mho characteristics is an inherently directional relay, so it can discriminate the forward and reverse faults. Fault resistance is not considered in [12], but it is also an important factor for distance relays in distribution systems, because distribution feeders are short in length and most faults are high impedance faults. For higher penetration, RES level distance relays may also face under reach or overreach problems in distribution systems.

3) Modifying Protection Scheme

A recloser-fuse coordination scheme was implemented with a distributed generation (DG) connection [13]. In this scheme, the lateral individual fuses with a RES were replaced with 3 phase reclosers and a relay is located at the interconnection point of the RES and network feeders. During a permanent fault condition, this additional relay will trip and limit the fault current from the RES. However, the disconnection of the RES during fault periods affects power reliability.

4) Limiting the RES Capacity

The protection coordination index (PCI) is evaluated in [5] and it is defined as the relationship between changes in the RES penetration power with respect to change in the coordination time interval.

In reported literature, attempts are made to penetrate the RES in the distribution system without compromising the existing protection setting of the network. This is primarily achieved by limiting the size of the RES penetration.

$$PCI = -\frac{\Delta P}{\Delta CTI} \tag{2}$$

This index (2) provides information about which are the safe locations or where protection coordination margins are less affected during penetration of the RES. The fall in coordination time interval is evaluated with respect to percentage penetration of the RES at the highest *PCI* node.

In this approach, the locations are provided by the network operators where the impacts of the RESs are at the minimal for maximum penetration of the RES power in the distribution systems. If the RES are customer based, then the size of the RES are optimized which will not impact the existing relay settings in the distribution systems. The application of PCI is also extended to multiple RES penetrations in a utility network [14].

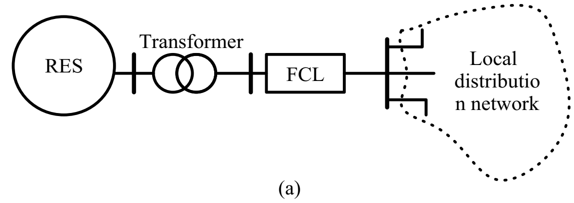
This index is also helpful for utilities for deciding the optimal location for the customer owned RES where, the customer can inject their RES power into the distribution system without effecting the existing operation and control of the existing system.

5) Using Fault Current Limiters

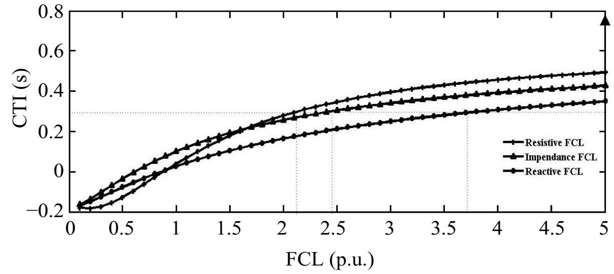
The philosophy behind this approach is to block the fault current from the RES during fault periods so that the relay setting decided at the planning stage without RES, remains valid for penetration of the RES. This is achieved by placing series devices with the RES, which offers low impedance during normal operations and high impedance value during fault conditions to block the fault currents [15]. The structure of the series fault current limiter (FCL) interconnection is shown in Fig. 5(a). Superconductivity based fault current limiters are envisaged to improve the switching speed and reduce the loss. However, high cost and big size are the main drawbacks which restrict their application for limited penetration of the RES. Different optimization techniques are used to minimize the size of the FCL for protection applications. In reference [16], a hybrid optimization scheme is used to size the FCL and to maintain the protection coordination in the power utilities. The hybrid approach is using both the FCL and partially changing the relay setting at the RES infeed bus. The optimal selection FCL for RES penetration at 33 kV buses in IEEE 30 system [17] is shown in Fig. 5(b) below.

The performances of the resistive types of FCLs are more effective than impedance/reactance based FCLs. The size of the FCL in this hybrid approach is relatively smaller than non-adaptive protection schemes [6].

Adaptive Protection Schemes: In the above mentioned techniques, the fault current from the RES sources are nullified/ localized or limited. In non-adaptive techniques, certain limitations are there with the higher penetration level of renewable sources. In adaptive protection schemes, the relay settings/ characteristics are adapted based on the prevailing condition of the network [17]. A simplex two-phase linear method is developed for finding the TDS settings for the relays [17]. An



(a)



(b)

Fig. 5. FCL placement and selection. (a) Series FCL interconnection. (b) Selection of FCL.

adaptive protection scheme for high DG penetration levels on a distribution system was presented in [1]. In this technique, the complete network was divided into separate zones (Zx), each zone has a reasonable amount of load and DG units. Each zone is separated by breakers (Bxy) as shown in Fig. 6. A central computer based main relay at substation (S/S) can control all these zone breakers and DG relays. During fault condition the main relay identifies the type of fault, fault location and it will give trip signals to corresponding zone breakers, so remaining zones can function as usual. The problem with this method is that for each zone, a separate protection scheme is required when the zone is operated in islanded mode and these schemes should not work under normal conditions (Grid connected mode).

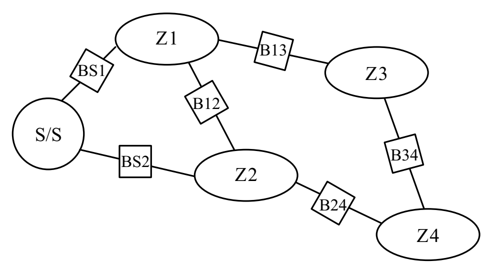


Fig. 6. Breaker divided zones of the distribution system.

An adaptive multi-agent protection scheme is proposed in [18]. The relay coordination is maintained by agents. It is shown in Fig. 7. Each relay, DG and elements (CT, breaker etc.) have agents (DG agents-DGA, Relay agent-RA and Elements agent-EA). All agents are communicated to each other. Every relay agents have multiple relay settings (without DG, with DG connected settings, etc.). When the DG is connected into the network, the DG breaker agents communicate to the relay agents and the relay agents pick up appropriate settings to maintain coordination.

In adaptive protection schemes, the relay settings will modify based on the network conditions. For every future installation of the DG unit, the overcurrent relay settings will

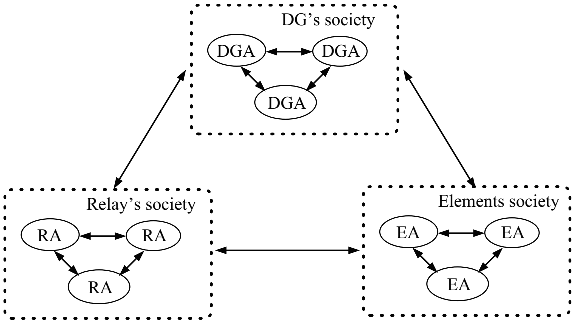


Fig. 7. Adaptive multi agent scheme for protection coordination.

change. Lukasz Huchel and Hatem H. Zeineldin proposed a method which is optimally identified by its unique overcurrent relay settings [19]. These settings are valid for all future DG installations. A simplex linear optimization technique is used to solve the optimization of overcurrent relay settings.

Renewable energy sources are intermittent in nature. Depending upon different seasons, the generation from these sources will increase or decrease by connection/disconnection of a few machines in a group of the RES. It will continuously modify the network topology. These are the challenging tasks for protection engineers to protect the system under high penetration levels of renewable sources. A dynamic adaptive protection scheme was presented in [20]. It is a two phase protection scheme and is shown in Fig. 8. In offline, the possible network topologies are identified which includes active network management (line outage & generator outage) and optimizes the relay settings by a differential search algorithm (DSA) nonlinear optimization method which are then stored in a group manner. In the online phase, the fuzzy based adaptive technique identifies the network topology group and communicates the corresponding relay settings to the individual relays. Similarly, a hardware in loop adaptive technique was presented in [21].

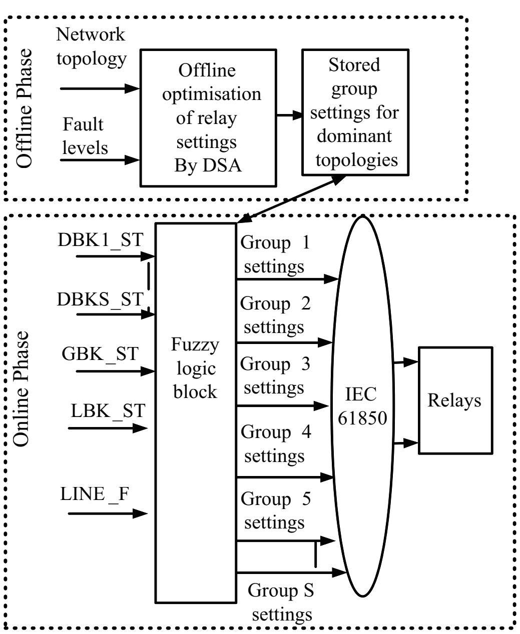


Fig. 8. A two phase adaptive protection scheme.

A multi agent system based protection and control scheme is proposed in [22]. It is a central controlled DG adaptive protection and control scheme. A basic three level control scheme, proposed for DG, relay and load agents, has three levels which include information collection, decision making and execution of commands and also communication to remote agents etc., is shown in Fig. 9. The authors assumed that the communication network is well developed in the distribution system. If any network changes are due to system reconfigurations or DG integration, depending upon the network prevailing conditions, the DG agents and other agents adopt their feasible control modes and relay agents will change the relay settings according to the network changes. A strong communication network is required to communicate with each of the element agents in the network.

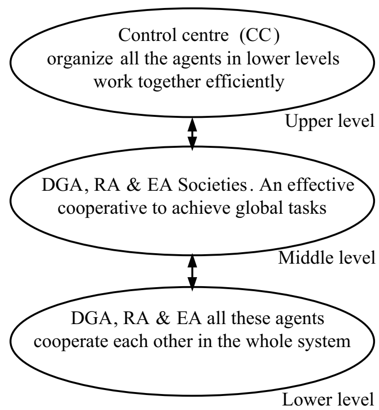


Fig. 9. Adaptive multi-agent scheme for protection coordination.

In [23], an intelligent coordinated protection and control scheme is proposed for a distribution network with wind generation integration. A cost based optimization algorithm is used to calculate the optimized present operating values for the relay. This scheme also minimizes the operational cost and risk of the control and protection scheme. In this scheme the operated network condition is defined based on the breaker status and controller (Wing generation controller) status. The proposed optimized cost based algorithm will identify the optimized group settings to relays and controller modes. And these new settings will communicate to the relays.

Due to unintended bulk tripping of the DG in the network, it will create severe disturbances in the network and it can further cause false tripping of the distance relays in the transmission network. In [24] the authors developed a support vector machine (SVM) based approach to prevent the distance relays tripping due to unintended DG tripping. The brief summary of distribution system protection schemes are listed in Table I.

III. Protection Issues and Solutions in Transmission Systems with Large Scale Penetration of the RES

Bulk wind farm based renewables are generally penetrated at the sub-transmission and transmission levels. In addition to the wind farm, bulk penetration of solar power is increasing in Megawatt size and preferably they are penetrated in the

TABLE I
SUMMARY OF PROTECTION SCHEMES FOR A DISTRIBUTION SYSTEM WITH RES INTEGRATION

Reference	Technique	Main Feature	Merits	Demerits
[25]	Fault current limiter (FCL) based	Optimization of impedance of SFCL (Superconducting Fault current limiter) in series with Wind-Turbine Generation System	Non optimization equivalent voltage source method used to solve the coordination problem.	Number & cost of FCL increase with more penetration of RES
[16]	Hybrid protection scheme with FCL	Using FCL to limit the fault current simultaneously changing the RES infeed relay settings	Size and cost of FCL will be reduced, compared with other FCL schemes.	Special scheme is required for changing RES infeed relay settings with the changing penetration levels of the RES
[26]	Harmonic restrained protection	Penetration is allowed until the harmonic penetration limit is not reached and protection is designed considering the harmonic constraints in addition to other requirements of protection.	This approach is highly suitable for inverter based RESs which are injecting high harmonics in utilities during their penetration.	This approach is not applicable for other types of RESs.
[27]	Protection under integrated optimal placement and sizing of RES in distribution utility (DN).	The RES placement and sizing optimized, so the existing relay setting need not be changed.	Original protection may hold well.	Optimal placement and sizing is a big concern for a site specific RES. For large penetration of the RES, these methods are not suitable.
[28]	Adaptive Relaying for DN.	The relay settings are adopted based on the changing network topologies/configuration. The configurations are identified based on status of interconnecting circuit breakers.	This method is applicable for wind farms and synchronous based RESs, where the changes in fault levels are measurable.	Communication and numerical relays are essential and design of protection schemes is expensive for small utilities/distribution systems.
[29]	Adaptive overcurrent based protection for DN.	It is a simple adaptive scheme; it continuously monitors local information (current & voltage) and re-calculates the relay characteristics based on network topology.	This technique is applicable for both Grid connected and islanded mode systems.	During dynamic conditions, such as sudden load change or transformer inrush currents, the performance is not good.
[30], [31]	A novel adaptive over-current protection of DN.	RESs are considered as current injection sources. Steady state fault currents are calculated from steady state equivalent reductions of the system. From these currents, the relay settings were calculated.	RES variable power is considered in the development of the protection algorithm	The algorithm run time increases with system size.
[32]	Adaptive-relay-recloser-fuse coordination.	In this scheme, the relay/recloser and fuse current are determined. If this ratio is less than unity, then the relay current is less when compared with the fuse current due to interconnection of the RES. Relay TDS is revised with the corresponding multiplication ratio of the RES current.	This method is applicable for both synchronous based DGs and Inverter based DGs	Sometimes it is not desirable to change the complete fast curve of the recloser .
[33]	Online-adaptive over current protection	It is an online based adaptive scheme. Based on the network condition, it will calculate the fault levels & relay settings will be updated by using HIL IEC 61850 communication.	Active network management (line outage) also considered in this scheme. This protection scheme is applicable for both grid connected mode and Islanded mode.	This approach does not address the performance during network transient conditions.
[34]	Fuzzy based protection scheme	A fuzzy logic can continuously monitor the status of the RES source, voltage phasor based on DFT technique and update the pickup & TDS settings based on the network changes.	This approach is suitable for limited network topologies	The identification of all potential network topologies is difficult.
[35]	Thevinen equivalent circuit parameter estimation adaptive scheme	Online calculation of fault currents under various system conditions by estimating the Thevenin equivalent circuit parameters. These currents will be used for relay setting calculations.	This method is applicable for both synchronous based DG and Inverter based DG.	Complexity will be more with the size of network and also separate offline optimization method is required for calculation of relay settings
[36]	Communication-assisted overcurrent protection	Ethernet communication is given in-between each primary and backup relay and also relays at each end of the line. Two definite settings given to each relay, one is immediate tripping and second one is time-delay tripping.	Highly communicated network, no need to change the settings of relays for each penetration level of the RES.	In this scheme authors considered studies for only synchronous based DGs. In case of multi-loop networks, communication links will create major problems.

transmission network [37]. But due to the variability nature of renewable sources, it affects the existing protection philosophy of transmission systems and the operator has to pay special attention for the design of protection schemes for transmission systems integrated with renewables. Particularly, the design of protection schemes for compensated transmission lines under these conditions becomes more complicated [38].

Various protection schemes have been used for transmission line protection, namely distance protection, overcurrent protection, differential protection and directional pilot protection. Distance protections are based on various relay characteristics like mho, quadrilateral and polygonal characteristics [39]. Distance relays with quadrilateral characteristics are predominantly used for protection of transmission lines. For fast protection of lines, the differential protection also provides a better result in conjugation with distance relaying schemes.

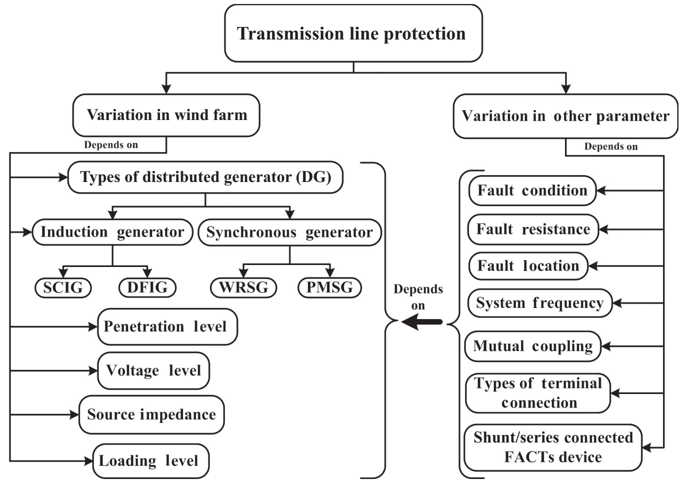


Fig. 11. List of various parameters impacting on the transmission line protection.

A. Main Protection Issue with Integration of the RES

Under reach/Overreach Issue: A single source transmission system with loads [40] is considered as shown in Fig. 10.

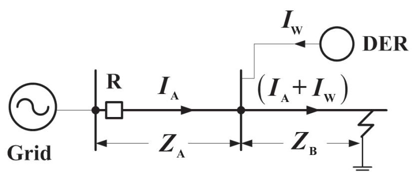


Fig. 10. Effect of the RES infeed on distance protection.

From Fig. 10, the fault at location F impedance (Z_{relay}) seen by the distance relay (R) is given in (3).

$$Z_{\text{relay}} = Z_{\text{A}} + Z_{\text{B}} + (\frac{I_{\text{W}}}{I_{\text{A}}})Z_{\text{B}} \tag{3}$$

The term $I_{\text{W}}/I_{\text{A}}$ is the perturbation. As the infeed current I_{W} depends on the speed of wind, which is variable in nature, it can cause overreach and under-reach issues.

The infeed current from the RES is variable in nature. In case this current is not considered for normal reach calculations of the distance relay, during fault conditions, the impedance seen by the relay will reduce because of the existence of the RES current. This may lead to under reach. In this case, the infeed current from the wind generator is considered for the relay trip zone setting and the relay may face an over-reach issue when the RES is absent during a fault condition.

B. Factors Affecting Distance Protection

Different factors affecting distance protection in an RES integrated transmission line are described below and can also be seen in Fig. 11.

1) Intermittent Nature of the Renewable Source

The variation in wind parameters significantly affects the reach of the distance relays set for transmission line protection. The effect due to wind farm loading on the trip boundary setting of the distance relay, having quadrilateral characteristics, has been discussed in [38], [41]–[45] in detail. As fluctuations in the wind speed causes variations in the voltage level of the local network buses, this leads to changes in the apparent impedance seen by the protective relay [38], [42], [46], [47]. This fluctuated impedance seen by the protection relay also causes changes in the reach setting of the relay [41], [43]–[45]. The effect of the source impedance on the performance of the distance relays is also investigated in literature [42].

2) Crowbar Protection

The effect of the new grid regulations of the fault ride through (FRT) capability, which states that the doubly fed induction generation (DFIG) must be connected with the grid during fault conditions, may cause damages to the converter, due to variations in the current. To protect the converter, crowbar protection is used which bypasses the converter. Due to the crowbar resistance, DFIG offers different values of the fault current compared to the normal conditions for certain periods [43], [48]. This causes reach issues in protection of the transmission line.

3) Types of Wind Generators

Wind farm based generation plants use different types of generators, namely induction and synchronous. Squirrel cage induction generators (SCIG) and DFIGs are induction based generators. Similarly, wound-rotor synchronous generators (WRSG) and permanent-magnet synchronous generators (PMSG) are based on synchronous generators [45], [49]–[54]. The short circuit behavior of induction generators is different than traditional synchronous generators which is an important factor for deciding distance relay characteristics [55].

4) Fault Characteristics and Nature of Faults

In wind based integrated systems, parameters like fault location, fault resistance, mutual coupling and power swing, also equally affect the performance of the distance relay protection. The impact of 3-phase short circuit faults in a DFIG connected transmission system is more severe compared to single line to ground faults [56]. In case of 3-phase short circuit faults, the combination of high crowbar resistance and rotor winding resistance, makes it a high impedance fault which is very difficult for the protective relay to detect [49], [52]. The zero sequence components, due to mutual coupling between parallel transmission lines and evacuating power from wind farms, also have an impact on the performance of distance relays [38], [43]. High penetration of the RES, which has significant impact on the power swing and operation of distance relays, is also investigated in [42], [43], [57].

5) Types of Terminal Connections

The effect of single terminal wind farms on relay trip boundaries are often compared to double terminal wind farm integrated grids [38], [42]. In this system, the fault resistance affects on distance relay performance, is discussed in literature [41], [44], [45], [51], [56]. The above mentioned factors affecting distance relay characteristics are shown in Fig. 12.

The design of protection schemes for wind based transmission lines requires consideration of variations in wind farms and variations in parameters outside wind farms. Different protection schemes have been proposed for the protection of bulk penetrated wind farms integrated with transmission systems. They are primarily distance based protection with adaptive features and modified differential relaying schemes. A brief summary of these two protection schemes are mentioned below.

C. Main Protection Schemes for RES Integrated Transmission Lines

1) Adaptive Distance Protection

In the proposed adaptive distance protection scheme [41], voltage and current phasors are collected from the RES connected bus. After collecting the voltage and current phasors, equivalent impedance of the RES side is estimated. Finally by computing the ratio ($I_{\mathrm{W}}/E_{\mathrm{A}}$), the positive and zero sequence distribution factors and error impedance is estimated. Now based on the error impedance calculation, new boundaries for the distance relay will be set.

2) Artificial Intelligence (AI) Based Differential Protection Schemes

In [58], a differential protection scheme is used with an AI technique. Signals received from the phasor measurement units (PMUs) are analyzed and various features are extracted from it using different transformations such as discrete fourier transform (DFT), Kalman Filter, etc. These features of both operating & restraining quantities will be sent to decision logic where the final relaying decision will be decided by an AI technique such as decision tree (DT), fuzzy logic, artificial neural network (ANN), etc. The brief summary of transmission line protection schemes are classified into different categories according to the characteristics of the relays which are listed in Table II below.

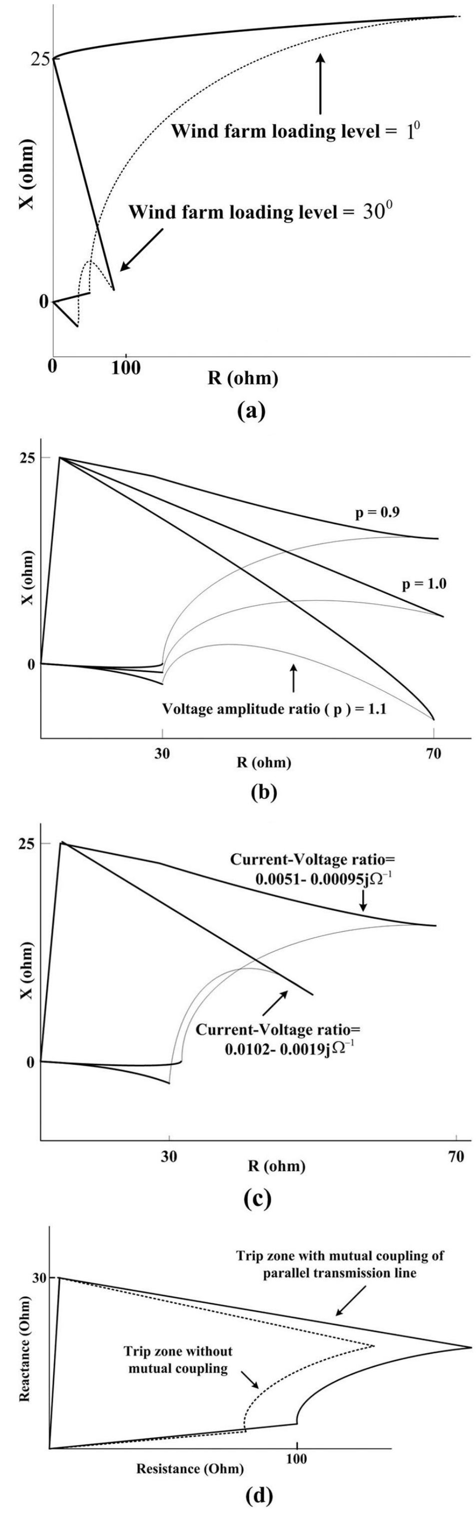


Fig. 12. Factors affecting distance relay characteristics. (a) Wind farm loading. (b) Voltage levels. (c) Current voltage ratio. (d) Mutual coupling.

IV. Protection Issues and Solutions in Microgrid

A microgrid is a small scale localized generating source and load, normally it will operate in an off-grid mode. It is connected to the grid when power generation is insufficient to meet its load [62]. A simple microgrid network is shown in Fig. 13. The main protection issues in a microgrid operating mode are listed below.

A. Main Protection Issue in Microgrid

1) Fault Current Level

Fault levels in the microgrid network are higher when it is operating with a grid connected mode as compared to an islanded mode of operation [63]. In an islanded mode of operation, only the RES sources are fault current feeding

TABLE II
SUMMARY OF PROTECTION SCHEMES FOR TRANSMISSION SYSTEM INTEGRATED WITH THE RES

Reference	Intelligent Technique/ Algorithm Used	Description of System With Focused Parameters	Merits	Demerits
		(A) Quadrilateral Characteristic Based Distance Protection		
[41]	Adaptive algorithm developed by taking current-voltage ratio and impedance of wind source	- Wind farm loading level, voltage level & source impedance - Fault resistance	Adaptive in nature	Mutual coupling effect is not considered
[42]	Algorithm developed according to the derived equation	- Wind farm loading level, voltage level & source impedance - Mutual coupling - Fault resistance (0 – 500 Ω) - Multi terminal line - Power swing	- Faster than mho relay - Adaptive in nature - The impact of various parameters has been considered	Compensated transmission line is not considered here
[38]	Algorithm developed according to the derived equation	- UPFC connected with transmission line - Wind farm loading level, voltage level & source impedance - Mutual coupling - Fault resistance - Power swing	- Reliable - The impact of various parameters has been considered - Adaptive in nature - Faster operating time	Complex calculation
[49]	Permissive overreaching transfer trip scheme based protection	- Types of generators used in wind farm - Analysis for balanced fault	Speed of operation is very fast	Communication wire is required
[59]	Scheme based on manual setting of relays using offline studies	Effect on protection system due to fault at the point of common coupling (PCC)	Eliminates chances of mal-operation	Not adaptive in nature
[24]	Support vector machine (SVM) based approach for protection	- Bulk penetration of DG - Different types of mal-operation conditions	Intelligently differentiates between mal-operation and fault	More costly
[60]	Algorithm developed according to the derived equation	- Flexible alternating current transmission system (FACTS) compensation - Wind farm loading level, voltage level & source impedance - Mutual coupling - Static VAR compensation (SVC) - Static synchronous compensator (STATCOM)	- Reliable, secure - Operating time is much less - Adaptive in nature	Implementation of logic circuit is more complicated due to complex calculation.
		(B) Polygonal Characteristic Based Distance Protection		
[46]	Artificial neural network (ANN) based approach for protection	- Distributed parameters of the transmission line is considered - Wind farm loading level	- Fast & accurate - Adaptive in nature	- Impacts of fault resistance have not been taken into consideration - Requires a large hard disk
[47]	Group setting based scheme using offline studies	- Offshore wind farm - Influence of wind ramp up - Influence of wind gust up - Fault resistance	- Provides a method to protect underwater transmission cables - Adaptive in nature	Impacts of wind farm loading level have not been taken into consideration
		(C) Modified Directional Pilot Protection		
[53]	Scheme based on voltage based phase selector	- Difference in current sequence coefficients - Mal-operating conditions have been taken into account	- Solved the mismatch problem caused by use of current based phase selectors	- Only a general idea has been proposed - Complete analysis is required
		(D) Differential Relaying Based Protection		
[44]	Wavelet transform and discrete Fourier transform based scheme	- UPFC connected with transmission line - Tapped transmission line - Gusts of wind - Wind farm source impedance - Mutual coupling - Fault resistance	- This method is dependable and secure - High speed of operation	Scheme is more costly for long transmission lines
[54]	Adaptive logic program for phase selection based scheme	- Starting element issue - Phase selection logic	- Avoids phase selection error - Proper action protective system - Adaptive in nature	Complete study is required
[61]	Decision tree-induced fuzzy rule-based differential relay protection scheme	- UPFC connected with transmission line - Very low fault current contribution by DFIG - Focused on speed of operation	- Differential features extraction - Accurate - Speed is more - Reliable for complex networks	Communication wire is required.
[58]	Data-mining based intelligent differential relay protection	- UPFC connected with transmission line - Focused on more accuracy and reliability - Focused on speed of operation - Differential features extraction - Decision Tree (DT) based logic	- Useful for modern smart grid protection -Extended Kalman filter phasor measurement unit has been used	Use of PMU increases cost

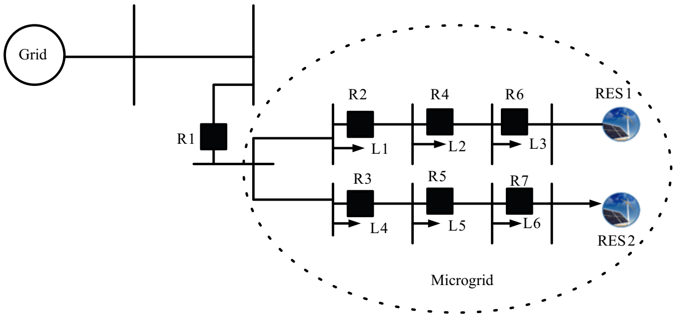


Fig. 13. A simple microgrid structure.

sources, which have limited short circuit capabilities. During these operational modes, the discrimination of fault levels from loading levels leads to nuisance tripping of the relays.

2) Coordination and Selection of Protection Devices

Selection of the protection device depends on the operating speed, voltages and fault current. The RES integrated terminal bus voltage is highly variable due to the intermittent nature of the RES [64]. The topology (Grid mode/islanded mode) of the microgrid will affect the magnitude and directions of the fault currents in the microgrid network. Reliable coordination of the relays, fuse and recloser in the microgrid is a complicated protection challenge. Other protection issues, such as nuisance tripping, relay blinding operation, islanding detection, etc. are already listed in section II.

B. Protection Schemes for Microgrids with RES Integration

In present practice, these small power generated resources are disconnected during the fault periods in order to save them against the reverse fault current from the main system [65]. For protection of these independent systems, we require a sensitive protection scheme which can accurately differentiate between close faults and load currents. The designed protection scheme must be able to provide a reliable protection in both grid connected and islanded modes of operation. The review of different types of microgrid protection schemes discussed in literature is shown in Fig.14.

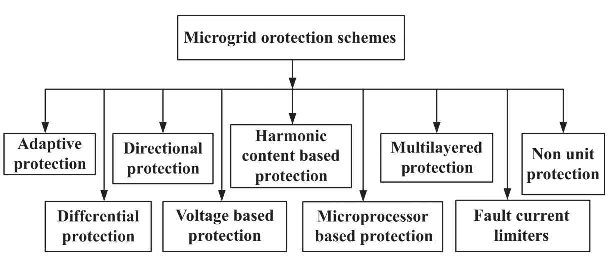


Fig. 14. Results in literature of microgrid protection schemes.

Fault Current Limiter Based Over Current Protection: The fault current contribution from an incoming RES in a microgrid can be blocked by application of the FCL. These schemes are similar to the RES integrated distribution system. Generally in case of distribution networks, the location of the FCL is either connected in series with infeed RES or interconnected at optimal locations in the network. In case of microgrid networks, the optimal FCLs are placed at the PCC buses [66]. In [67], the FCLs are placed in series with the power line/point of common coupling. The sizing, location identification and tuning the parameters of the FCL are challenges for the operational engineers. Increasing the penetration level of the incoming RES in the microgrid may require a big size for the FCL and their cost as well as placement is a big constraint at small sized substations.

Differential Protection Scheme Using Symmetrical Components: A differential protection scheme is based on comparing the magnitudes of the local fault current across the protected power component. In [68], a refined data mining approach is used to calculate the relay settings for which the symmetrical components, total harmonic distortion, magnitude and phase angle of the current & voltage parameters are used. The discussed differential protection scheme is based on the differential measurement across the point of common coupling rather than local measurements. The advanced signal processing technique which is used in this protection scheme strengthens it by providing better communication for detecting small fault currents contributed by the invertor based RES. The differential current components are deployed to detect the faults that occur in the sub stream zone of protection, whereas symmetrical components of the current are used to detect the single line to ground fault in the downstream zone of protection and the line to line faults in all zones of protection.

Differential Energy Based Protection Scheme: In [69], spectral energy content of the fault current signals retrieved at both ends of the feeder using time frequency transformation (S-transformation) and then differential energy is computed to register the fault patterns. The threshold limits of the differential energy are set for both grid connected and off grid for issuing the trip signals. However, this protection scheme is only applicable for shunt and high impedance faults, as series faults are symmetrical in nature and their differential energy cannot be computed.

Harmonic Content Based Protection Scheme: The invertor based RESs are rich sources of voltage harmonic microgrids. In [70], a fast fourier transform (FFT) is applied to extract the total harmonic distortion (THD) from the voltage in the microgrid operation. This scheme has two stages. In the first stage, it identifies the type of fault by computing the THD and in the second stage it will differentiate between the faulted zone and healthy zone. These types of faults will be identified whenever there is a deviation from the fundamental frequency [70], [71]. This protection scheme fails when the size of the RES is not uniform and its performance also diminishes when the dynamic loads proportion increases with respect to the static load.

Voltage Based Protection Scheme: In [72], a voltage based protection scheme is presented in which the source voltage is transformed into DC using a d-q frame. Any disturbances in the source output voltage due to the fault will be directly reflected in the d-q values. This technique can distinguish between a fault which is either internal or external to a protected zone of the microgrid. Basically it depends on communication between the relays and microgrid structure. This protection scheme fails to detect a high impedance fault. Later in [73], a proposal was made for a new fault algorithm based on detecting the positive sequence component of the fundamental voltage such that it can provide reliable and fast detection of different types of faults in the microgrid. In this method, the transformed DC voltage is compared to the amplitude of the fundamental positive sequence voltages in the d-q coordinated system. Any voltage drop within the microgrid may lead to mis-operation of the protection devices.

Overcurrent and Overload Protection Schemes: Time inverse over current relay fails to maintain the coordinated operation in the microgrid due to limited fault current contribution from the weak RES. The operating time of the relays in the microgrid is enhanced by adding a voltage function to the time-inverse over current relays [74]. During the fault periods, the terminal voltages of the RES fall below their ratings and there will be small increases in the fault current. The operating region of this voltage based current-time inverse relay is shown in Fig.15. These attributes of the microgrid enhance the operating time of the voltage current based time inverse over current relays.

In [75], two add-on features for the voltage control protection scheme for over current and over load protection with RES integration are discussed. The proposed protection schemes detect the fault and limit the output current from the RES unit and restore the microgrid to its normal operating conditions subsequent to fault clearance. The overload protection scheme detects overload conditions based on voltage measurements, and limits the output power by assigning appropriate voltages to the interface terminals of the voltage sources controller of the RES unit. The voltage controlled protection scheme is faster than the conventional overcurrent relay protection scheme.

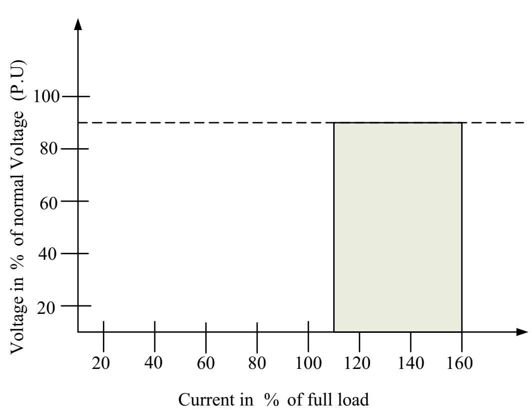


Fig. 15. Operating region of voltage based current-time inverse relay.

Adaptive Protection Scheme: The adaptive protection scheme has the ability to change the relay setting/protection requirement as per the network prevailing conditions. In the microgrid and grid connected modes of operation, the network conditions are sensed by external sensors. Two sets of relay settings are discussed for maintaining the coordinated operation of the relays in [75], when a microgrid is operating in grid connected mode as well as in the islanded mode of operation. In this article, directional over-current relay functionality of the numerical relay is used to adopt different relay settings for different network operating topologies. A communication based adaptive protection scheme is discussed in [76]. This adaptive scheme determines the relay communication protocol/communication infrastructure for interacting among the relays and master controller. The master controller senses the topology of the microgrid and communicates the updated settings to each relay. The proposed scheme is shown in Fig.16. For implementation of an adaptive protection scheme without communication, a voltage based protection algorithm is discussed in [77]. This algorithm utilizes the voltage response during short circuit and overload conditions for changing the protection. The magnitude of the voltage drop during the short circuit period is greater than the overloading period. Accordingly, a voltage based fault detection algorithm is employed to discriminate between voltage drops in the short circuit and over loading conditions.

Another adaptive protection scheme has been proposed in [78], based on digital relaying and advanced communication techniques. In this scheme, the protection settings were updated periodically by the microgrid central controller for different operating conditions of the microgrid.

In [79], an impedance based adaptive protection scheme is discussed. The system impedance at various buses is continuously determined using the bus voltage and line currents. This system impedance changes for grid connected and microgrid modes of operations. The relays installed at various buses automatically update their settings based on the change in the system impedance. The brief summary of microgrid protection schemes are listed in Table III.

The futuristic power systems may have highly dynamic fault levels depending on the level of integration of the RES. The adaptive based protection schemes will be more effective for protection of such power networks. Apart from the conventional relaying schemes, the logic based protection schemes may also be reliable solutions. The use of reliable communication protocol for enabling the communication based protection schemes are also gaining momentum across the globe for protection of RES based power networks.

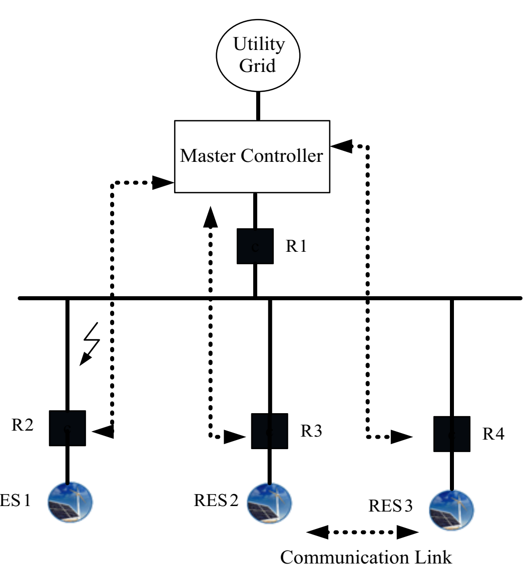


Fig. 16. Communication based adaptive scheme.

TABLE III
SUMMARY OF PROTECTION SCHEMES FOR THE MICROGRID

Reference	Schemes	Description	Merits	Demerits
[70]	Harmonic content based protection	Utilizing FFT and THD to detect the type and location of the fault.	Can be used as a backup for main protection devices, where the network have several dynamic loads.	May fail under different levels of penetration of the DER sources.
[71]	Voltage based protection	abc-dq0 transformation of DGs output voltages.	Applicable for both grid connected and islanded mode operations of the Microgrid.	Fails to detect high impedance faults. May not be favorable for microgrids with different structures.
[80]	Multilayered protection scheme	Four layer based protection 1) Adaptive over-current protection, 2) Differential protection 3) Backup protection 4) Anti-islanding protection	Increases the efficiency, reliability and flexibility of power delivery systems.	To maintain coordination between the different layers, a large communication Link is required.
[81]	Multi-agent system for micro grid protection coordination	Micro grid is composed with foundation for intelligent physical agents (FIPA) 1) Calculation agent, 2) Circuit breaker (CB) agent 3) Intelligent electronic devices (IED).	In case of failure of main CBs, CB agent will send trip signal to backup protection CBs. More reliable.	Any interruption in sending and receiving information will lead to failure of total protection system coordination. More no. of relays are required. It will be expensive.
[82]	A non-unit protection scheme based on local measurement	Using local measurement by calculating the impedances for DC microgrid.	This scheme is simple, fast and suitable for grids without interruption of the normal operation of the grid.	Applicable for only DC microgrid protection Not applicable for different microgrid topologies.
[83]	Microprocessor based	Using microprocessor based relays with directional elements in low-voltage microgrids. Primarily independent for magnitude of fault current and modes of operation.	Applicable for both grid connected mode and islanded mode microgrid operations. Communication links are not required.	Does not operate satisfactorily for medium voltage networks. Having complex logic structure which takes more time to meet selection requirements.
[84]	Differential protection	Using digital relays. Works on Kirchhoff's current law.	Considers all microgrids. Applicable for both grid and islanded mode operations of microgrid.	Very costly Greater number of relays are required. Some problems may come during connection and disconnection of DGs.
[85]	New directional element protection	Magnitude and angle of negative sequence impedance to detect the direction of asymmetrical faults. Magnitude with current and torque angle of negative sequence impedance for symmetrical faults.	A new directional element scheme is presented that is not influenced by inverter based and induction machine based microgrid fault currents.	Different topologies of microgrid operation are not considered.
[86]	Adaptive protection scheme	Comparing programmable logic method and setting group method	Validated for different structures of microgrid. Relay settings are changing. Applicable for both grid and island mode of microgrid operations.	Complexity of switching relay settings (PSM & TDS) in between different structures of microgrid operation will increase with the size of the network.

V. CONCLUSION

Protection schemes for a renewable integrated power network are an important evolving research area in power engineering. The highly variability and intermittent nature of renewable results in different network topologies causes variation in fault levels. The relays which are set for the fixed fault level for pre-defined network topology, will experience different fault levels. This will lead to losses in the coordinated protection of the relays.

The impact of renewables on the network protection schemes are broadly classified into three categories in this review article. In the first category, when the renewables are penetrated at the distribution level and over current relays which are predominantly used for protection of distribution systems, losses occur in their coordinated operation. Depending upon the level of infeed, the impact may reach to sub-transmission levels and result in loss of coordination operational distances and over current relays. Different over current relaying based protection schemes are discussed in this article which may be suitable for protection of renewable integrated distribution systems. In the second category, when the bulk megawatt renewable are integrated at the transmission level, the reach of the distance relays become affected and result in under reach operation of the distance relays. For a large number of integrated renewables, it is manually not feasible to set the reach of each distance relay for different renewable infeeds. Adaptive distance and intelligent technique based differential relaying protection schemes are discussed in this review article which can adapt the protection setting of the relays as per the network operational requirements. In the third category, the renewables are allowed to feed the local network in the islanded mode of the operation, the protection requirements for such systems are different from the other two categories. The fault levels in the islanded mode of the operation are weak as compared to the grid tied connection and it further decreases for a photo voltaic generation based islanded network. The protection schemes for such systems require a highly sensitive protection which can provide reliable protection against weak faults in islanded operations as well as for grid faults during grid tied operations. This review article discusses both the merits and demerits of various existing protection schemes for low feed renewable penetration in power systems.

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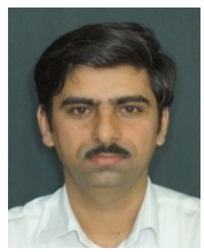

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