Protection Coordination of Properly Sized and Placed Distributed Generations–Methods, Applications and Future Scope

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Abstract: The radial distribution networks are designed for unidirectional power flows and are passive in nature. However, with the penetration of Distributed Generation (DG), the power flow becomes bidirectional and the network becomes active. The integration of DGs into distribution network creates many issues with: system stability, protection coordination, power quality, islanding, proper placement and sizing etc. Among these issues, the two most significant are optimal sizing and placement of DGs and their protection coordination in utility network. The proper coordination of relays with high penetration of DGs placed at optimal location increases the availability and reliability of the network during abnormal operating conditions.

This research addresses most of the available methods for efficient sizing and placement of DGs in distribution system (numerical, analytical and heuristic) as well as the developed protection coordination techniques for utility networks in the presence of DGs (Artificial Intelligence (AI), adaptive and non-adaptive, multi-agent, hybrid). This paper indicates the possible research gaps and highlights the applications possibilities and methods' limitations in the area of DGs.

Keywords: Index Terms—Distributed Generation; protection coordination; optimal DG location; optimal DG sizing

1. Introduction

Distributed generation (DG) has gained enormous popularity due to its modularity, ease of deployment, operation and control. The term DG is given to the production of electricity near the load center. The decentralized nature of distributed generation makes the basis for micro-grids, where the concept of centralized generation and control does not exist anymore and leads to the smart grid solutions [1]. DG technology mostly involves Renewable Energy Sources (RES) and cogeneration. The integration of DGs into distribution network may pose both positive and negative impact depending upon the characteristics of distribution network and the DG itself. The positive impacts of DG installation are: power loss reduction, voltage profile and reliability improvement, power quality enhancement, no need of new transmission lines installation, and postponement of substation capacity upgrade [2]. Moreover, the DG does not contribute to the greenhouse gases providing clean and efficient energy. The negative effects of DG application are: fault current level increase, discoordination of protection schemes, islanding, bidirectional power flows, and transient instabilities [3].

The optimal size and location of incoming distributed generation are preliminary factors to maximize the system support benefits. The size and location of DG can be decided on the basis of enhancement of one or more distribution network parameters in a way to improve the energy

efficiency and reduction of negative impacts of the installation [4]. Optimal size and location of DG improves also the performance and operation of whole network. The additional power delivered by DG significantly affects the bus voltage, load characteristics and reliability of the system [5]. Therefore, at the planning stage of distribution system, one of the most crucial and difficult task is to estimate the capacity and location of futures in the network. Different techniques are used for such estimations (e.g., numerical, analytical, and heuristic) and all of them were analyzed in terms of the efficient placement and sizing of DGs.

Since the main function of protection schemes in distribution networks is to immediately isolate the faulty part of the system from the healthy one for the fault occurrence. Thus, mostly overcurrent relays are used in such networks as primary and backup protection. The coordination of overcurrent relays is arranged in such a way that if the fault is not cleared by the primary relay then it should be backed by another relay.

With the introduction of DGs, the existing schemes for distribution network protection become inactive. The intensity of this discoordination depends upon the type, size and location of installed DG [6]. Since the radial utility networks are designed for unidirectional current flows so are protection schemes. With the DG installation, the distribution network forms a closed loop and current flows in both directions thus the existing relays do not protect the system effectively during the faults. One of the possibilities of solving this problem is use of directional overcurrent relays that are able to discriminate between upstream and downstream current flows [7]. Another option is to reset the Time Multiplier Settings (TMS) and Plug Multiplier Settings (PMS) of relays after integration of each DG [8]. However, Distribution System Operators (DSOs) are not in favor of changing the relays settings or network configuration manually. Many adaptive, non-adaptive, multi-agent, Artificial Intelligence (AI), hybrid, etc. techniques are evolved for proper and efficient coordination of relays.

This research addresses most of the available methods for efficient sizing and placement of DGs in distribution system (numerical, analytical, and heuristic) as well as the developed protection coordination techniques for utility networks in the presence of DGs (Artificial Intelligence (AI), adaptive and non-adaptive, multi-agent, hybrid). This paper indicates the possible research gaps and highlights the applications possibilities and methods' limitations in the area of DGs.

2. Methods for Location and Size of DG

The methods for location and sizing of DG are divided roughly into three categories: numerical, Analytical, and Heuristic.

2.1. Objectives

The objectives of different methods of Optimal Sizing and Location of DG (OSLDG) into distribution network include [9]:

(1) minimizing the power losses,
(2) enhancing the voltage profile of network,
(3) increasing the reliability of network,
(4) improving the loading capacity of network on the basis of voltage constraints,
(5) maximizing the economy of utility operator,
(6) maximizing the MVA capacity requirements of network.

2.2. Constraints

The single and multi-objective function of different methods of OSLDG involves many optimization variables with the following possible constraints [10]:

(1) power balance in the network,
(2) fault level and thermal limits,
(3) voltage limits,
(4) reliability and economic limits,

(5)   allowable number of DGs in the network,

(6)   power factor limits.

2.3. DG Technologies

The devices used for distributed generation include directly connected to the system rotating machines (induction or synchronous), as well as static and rotating devices, which are coupled to the network through electronic converters. Different DG technologies have various influences on the operation, control and stability of a system e.g., the inverter based DGs inject harmonics into the system while the rotating machines create issues for the protection coordination in the distribution network [11]. Most of the effects of distributed generation technologies depend solely upon the size and location of DG installation in the utility network.

2.4. Numerical Methods

Numerical methods are based on mathematical programming and analysis and they are listed below. The summary of presented methods is gathered in Table 1.

(1)   **Gradient search**—this method, proposed in [12,13], is used to find the proper size of DGs in mesh networks while considering and ignoring the short circuit capacity limits of the network.

(2)   **Linear programming**—this method, evolved in [14,15], is used to find the optimal location of DG in the distribution network with maximum allowable penetration and energy harvesting from DGs.

(3)   **Sequential Quadratic Programming** (SQP)—it is a second order differential technique, presented in [16], [17], and [18], is used to find the optimal location and size of multiple DGs in distribution network, without considering the short circuit capacity limits of network. The main objective is to reduce overall power losses in the network.

(4)   **Exhaustive search**—a multi-object technique, used in [19–22], used for finding proper location and size of DGs with main focus on reliability improvement and loss minimization at fixed and variable load models. The time-varying behavior of renewable sources and loads were considered in [23].

(5)   **Ordinal optimization**—this method, suggested in [24], is used to find the optimal location and size of DGs in the distribution network making compromise between the power losses minimization and maximizing the allowable penetration of DGs.

(6)   **Dynamic programming**—this method's used to find the optimal size and location of multiple DGs, main objective is to maximize the economy of utility operator at different loading conditions [25].

(7)   **Nonlinear programming**—this technique converts probabilistic model with all network constraints into deterministic model using optimal load flow [26–28]. Mixed-Integer Non-Linear Programming (MINLP) is especially used for proper placement of multiple wind units simultaneously and can also be used for other types of DG but only for single units [29]. An interior point technique is used to find the maximum capacity of utility network for DG integration through optimal load flow analysis [30]. MINLP is used to determine the optimal location and size of inverter based DGs with main objective of enhancing the voltage stability margin of the network [31]. MINLP is used in [32,33] to determine the optimal location and size of DGs in distribution network while considering the variations in the market based energy prices. MINLP implemented in [34] is used during distribution system planning for investigation of the proper location and size of future DGs.

(8)   **Load model**—this method is used to locate and size the DGs in a distribution network having constant and variable power flows. Load models have great significance in stability studies. Three different voltage dependent load models i.e., residential, commercial and industrial are considered for investigation [35].

(9)   **Protection coordination index**—the integration of DGs greatly affects the protection coordination of distribution network. Protection coordination index (PCI) is an indicator which

represents the change of time coordination between the protection devices with change of penetration level of DGs into distribution network [36].

(10) **Contingency analysis**—this technique is used to analyze the impact of size and location of DG on distribution system after fault inception. Voltage profile of DG is investigated before and after the occurrence of fault to calculate voltage regulation of system. Based on loading conditions and network configuration the appropriate size and location of DGs can be decided [37,38].

Table 1. Summary of Numerical Methods for Placement and Sizing of DGs.

Technique	Main Features	Merits	Demerits	Network Configuration	Objectives
Gradient method [12,13]	Computing hessian of second order network matrix with and without faulty conditions	Fast convergence, easy implementation	Diverges at positive or small penetrations of DGs	6-bus meshed network	To reduce of active and reactive losses and loading on the buses
Linear programming [14,15]	Limiting voltage, thermal capacity, fault level and ratings of generator as linear constraints	Can be applied to any type of radial network	Does not produce effective results with changing network dynamics	5-bus radial distribution network	To maximize the generation capacity of DG
Fast sequential quadratic programming [17]	Formulating non-linear optimization function of network with nonlinear inequality and equality limits	Applicable to multiple DGs with unspecified power factors & takes least computation time	Not suitable for network with changing dynamics	69-bus radial distribution network	To minimize the system power losses
Exhaustive search [19]	Determining load conditions of network at different DG sizes	Simple, cost effective solution	Not suitable for multiple DGs	3 radial circuits	To reduce of power losses and improvement of system reliability
Ordinal optimization [24]	Making tradeoff between total energy losses and generating capacity of network on the basis of nonlinear power flow calculations	Less computational time	Rigorous calculations and analysis	69-bus distribution network	To minimize total energy losses and maximizing generating capacity
Dynamic programming [25]	Maximizing the economy of utility network while considering variable load models	Enhances voltage profile of system, reduces computation time	Not suitable for dynamic load conditions	8-bus radial network	To minimize power losses and improve reliability of network
Nonlinear programming [26]	Making compromise between the energy losses and generation capacity with optimal power flow	Applies to wind based DGs due to their time varying nature	Real time data of market prices is necessary as one of the variables	61-bus distribution network	To minimize total energy losses and maximizing generating capacity
Load model [35]	Maintaining the voltage at the buses under prescribed limits with variable active and reactive power	Suitable for complex networks with changing dynamics	Efficiency of model is very low when applied to ring-main distribution networks	38-bus radial distribution network	To reduce of power losses and MVA requirements of system
Protection coordination	Trying to keep the PCI on the lowest	Used for both synchronous	Not suitable for networks with	14-bus and30-bus	To reduce active and

index [36]	level possible as the changes in penetration of DGs affects the coordination timing between the relays	and static DGs. Helps utility operator to determine the maximum amount DGs that can be added to system	changing parameters	IEEE network	reactive power losses, improve voltage profile and restrict fault level and thermal limits
Contingency analysis [37]	Estimating the network voltage profile before and after faults with and without DGs	Suitable for network with varying load conditions and unbalanced power flows	Unreliable results on upstream buses	37-bus IEEE network	To enhance voltage profile of network

2.5. Analytical Methods

These methods are the combination of different techniques used to evaluate the characteristics of network qualitatively and quantitatively. Listed below techniques are based on mathematical expressions. The summary of presented methods is given in Table 2.

(1) **2/3 rule**—applied for the distribution networks with uniformly distributed loads. The rule states, the incoming DG should have 2/3rd capacity of existing distribution network and should be installed at 2/3rd length of a line [39]. Non-effective for non-uniformly distributed loads.

(2) **Kalman's filter algorithm**—used for finding the optimal size of multiple DGs in combination with Optimal Power Flow (OPF) technique [40]. OPF is used for finding the proper location of all the DGs in the distribution network,then Kalman's filter is applied to find their suitable ratings.

(3) **Loss sensitivity factor technique**—used for calculation of the equivalent current injections of all DGs on the basis of load flow analysis and for determination of their proper size and location. It employs matrix algebra [41].

(4) **Exhaustive load flow technique**—based on the power factors of DGs being connected to the distribution network. The computational process is done twice: firstly for losses calculation and secondly for losses reduction [42].

(5) **Improved analytical approach**—based on the Improved Analytical (IA) expression and used for finding the optimal location and size of multiple DGs. The IA expression is formed by taking into account the active and reactive powers, and power factors of all the DGs [43].

(6) **Exact loss formula**—analytical method used for development of an expression incorporating the exact relation between the network losses with proper placement and sizing of DGs. Nonlinear curves are obtained between optimal place and size of DG and the network losses [44].

(7) **Analytical approach with micro-generation**—technique proposed in [45], based on the loss contribution of micro-generators in LV networks at different load conditions. Method used for determination of size, location and number of DGs to be installed in the network based on quantity of avoided losses.

Table 2. Summary of Analytical Methods for Placement and Sizing of DGs.

Technique	Main Features	Merits	Demerits	Network Configuration	Objectives
2/3 rule [39]	Installing DG of 2/3rating of total capacity of network at 2/3 length	Simple, easy to implement	Not suitable for networks with non-uniform load distribution	33-bus IEEE network	To minimize the power losses
Kalman's filter algorithm	Considering total power loss in steady state and	Least computational times	Pre-processing data of system losses and DG	30-bus IEEE network	To minimize power losses

[40]	sorting out the best samples from entire sets of DGs size and location		rating are required		
Loss sensitivity factor technique [41]	Estimating the equivalent current injections of DGs	Easy, fast with desired accuracy	Cannot be applied to multiple DGs	12, 34 and 69-bus radial network	To minimize total power losses
Exhaustive load flow technique [42]	Executing load flow twice for loss calculation and reduction and for different configurations and power factors of DGs	Effective with variable load models	Restricted to local minimum value	16, 33 and 69-bus radial networks	To minimize total power losses
Improved analytical approach [43]	Maintaining balance of active and reactive powers in the network and analyze the optimal power factors of system	Can be used for any number of DGs and has least computational times	Protection coordination schemes becomes complex	16-bus, 33-bus and 69-bus radial networks	To minimize total power losses
Exact loss formula [44]	Generating search tables for different combinations of DGs and to analyze them by exhaustive load flow	Can be applied to complex networks	Not suitable for varying characteristics of network	30-bus, 33-bus and 69-bus radial networks	To minimize total power losses
Analytical approach with microgeneration [45]	Determining the amount of avoided losses on the basis of type of load distribution and penetration of micro-generation	Highly recommended for practical used	Cannot be applied to variable load models	34-bus distribution network	To minimize total power losses

2.6. Heuristic Methods

The heuristic methods are one of the optimization techniques, used to select the best possible solution among the set of different possible results. The summary of described methods is given in Table 3.

(1) **Genetic algorithm**—a biology-inspired algorithm which uses chromosomes built from genes to find out the optimal location and size of DGs. Using limits of crossover and mutation operator, the best possible solution is obtained [46]. GA used in [47] solves the problem of optimal location and size of DGs based on reliability constraints. GA is employed to solve the optimal location and size of DGs based on different load models [48,49]. In [50] GA is used to maximize the profit of utility operator by deciding proper size and place of DGs in distribution network. Considering power quality issues, GA in combination with decision variable theory is used to find the optimal location and size of DGs [51]. GA in combination with fuzzy theory is used to find proper location and size of DGs with main focus to minimize the power losses [52–55]. A technique with weights considering economy and merits of DGs is solved by GA for their

optimal location and size [56]. For maximizing the profits of consumers and suppliers GA is applied to find the proper size and location of DGs in distribution network [57]

(2) **Particle swarm optimization**—method based on natural phenomenon, inspired by social characteristics of bird flocking. The method has many similarities with genetic algorithm [58]. Based on the real and reactive powers injections of DGs, the PSO method is applied to find the proper location of DGs in distribution network [59], whereas based on the power factors of DGs, the PSO algorithm is applied to find the optimal location and size of DGs in distribution network at different load models [60]. Another possibility of considering the harmonic and protection coordination limit, the PSO algorithm is applied for finding the best location and size of rotating and static DGs [61].

(3) **Ant colony optimization**—method inspired by the behavior of ants which find shortest path to find food [62]. ACO algorithm suggested in [63], is used to find the optimal location and size of DGs while reducing network's active power losses.

(4) **Artificial bee colony**—technique inspired by the behavior of honey bees called swarms that have intelligent foraging characteristics [64]. ABC algorithm was used in [65] for finding the optimal location and size of DGs on the basis of their power factors and active power losses of network.

(5) **Differential evolution**—an evolutionary algorithm which optimizes the results in steps on the basis of defined constraints. It may also optimize the objective functions that are not continuous in nature [66]. Based on the voltage sensitivity of buses, the DE is used to compute the best location and size of incoming DGs [67].

(6) **Harmony search**—a music based heuristic method inspired by the characteristics of music searching for the perfect state of harmony [68]. The problem evolved by loss sensitivity factor technique for determining the proper location of DGs is further solved with use of HS algorithm for finding their optimal sizes [69].

(7) **Tabu search**—mathematical optimization technique used to find the best possible solution on the basis of user defined rules or search tables [70]. TS algorithm, used in [71,72], for uniformly distributed loads finds the optimal location and size of DGs with defined constraints of loss minimization and voltage profile enhancement.

(8) **Big bang big crunch algorithm**—is a method inspired from the two theories of the universe, big bang and big crunch. It produces random set of points in the big bang plane and distributes them to the big crunch plane through minimum cost function. BB-BC used in [73], optimally sizes and places the multiples DGs on the basis of performance indices of system.

(9) **Practical heuristic algorithms**—methods used for learning, solving and discovering solutions without the optimal solution guarantee. However, these techniques are suitable for instant results [74]. A heuristic approach was used in [75] for placing and sizing the DGs on the basis of market based economy and benefits provided to network at peak demands. The heuristic method suggested in [76] for placing only one DG on the basis of its power loss contribution to the network. A heuristic method used in [77] for placing the DG in the network by reducing the cost of network reliability. A heuristic method evolved in [78] was used for placing and sizing the DGs in steps by optimizing the variables of fitness function for maximizing the benefits from DGs introduction into the network.

(10) **Hybrid optimization algorithms**—many optimization algorithms can be combined together (e.g., PSO, GA, DE, ABC, ACO, etc.), to obtain the best possible solutions utilizing the benefits collectively [79]. A hybrid ACO and ABC was used in [80] to find the proper location and size of DGs by maximizing the economy and voltage stability of network and reducing power losses and emission rates of associated energy resources. A hybrid taboo search and genetic algorithm is suggested in [81] with major focus on maximizing the voltage profile and decreasing the power losses of investigated network was used for finding the optimal location and size of DGs. A hybrid GA and PSO algorithm, was used in [82] for finding the optimal location and size of multiple DGs.

Table 3. Summary of Heuristic Methods for Placement and Sizing of DGs.

Technique	Main Features	Merits	Demerits	Network Configuration	Objectives
Genetic algorithm [46,47]	Determining the cross over and mutation operator of fitness function for all possible sets	Robust and results are not restricted to local minimum solution	The convergence time is high when precise results are needed	14-bus IEEE network	To minimize power losses and to enhance voltage profile of network
Particle swarm optimization [60]	Determining the velocity of particle and updating its position in two dimensional space	Small computation time and ensure greater stability and loading of system	Protection schemes become complex	38-bus radial network and 30 bus IEEE mesh network	To minimize active and reactive power losses, improve voltage profile and maintain fault level of system
Ant colony optimization [63]	Chemical process based on the social behavior of agents to find the shortest path to efficient solution using composite reliability index	Highly recommended for protection coordination schemes	Economy of network is affected	69-bus &394-bus distribution network	To improve the reliability of network
Artificial bee colony [65]	Evaluating the optimization population on the basis of foraging behavior of honeybee swarm	Robust, Efficient and able to deal with nonlinear optimization problems	Tuning of parameters is necessary	33-bus&69-bus radial network	To minimize the active power losses
Differential evolution [67]	Formulation of continuous problem based on payback period and number of DGs	Considered load variations and can be applied to any number of DGs	Uncertainties about DGs' output was not taken into account	19-bus radial network	To maximize the economy of fuel
Harmony search [69]	Calculating loss sensitivity factor on the basis of voltage and current capacities of system	Suitable for simultaneous reconfiguration of network and installation of new DGs	Stability margin of network gets affected	33-bus&69-bus radial network	To reduce active power losses and to enhance voltage profile of network
Tabu search algorithm [71,72]	With known number of DGs and their total capacity, it determines their types and locations	Generates different possible solutions (neighbors)	Regression is required to be computed again and again	37-bus radial network	To minimize active power losses in distribution network
Big bang big crunch algorithm [73]	Determining the capacity and location of DGs based on the voltage and reactive power	Suitable for balanced and unbalanced networks	Only applicable for small DG units	37-bus& 69-bus IEEE network	To minimize the total power losses

	constraints with higher flexibility				
Practical heuristic algorithms [77]	Calculating weighting factors with Newton Raphson method	Robust and high precision	Does not consider the uncertainties about DGs' generation	6-bus, 14-bus& 30-bus IEEE network	To diminish the cost losses
Hybrid optimizati on algorithms [79]	Combining optimal power flow and genetic algorithm to find the best location and size of predefined number of DGs	Fast and high accuracy	Not suitable for simultaneous installation of multiple DGs and for variable power load models	69-bus mesh network	To minimize power losses, improve voltage profile and restrict fault level and thermal limits

3. Protection Coordination

Since, the integration of Distributed Generation into distribution network cause the bi-directional energy flow, the current levels during the fault inception increase in comparison to the ones without the DGs contribution. Therefore, the already existing, traditional protection schemes may fail to operate efficiently and may cause nuisance and false tripping [83]. Hence, as the efficient coordination of protection devices is necessary for correct operation of distribution network, the renewed relay settings are required after DG installation. The protection coordination issue limited to the downstream network is called a small scale problem while the extension to the upstream network is called a large scale problem [84].

For each incoming DG the settings of primary and back-up relays are required to be changed accordingly. Moreover, the directional element is integrated with overcurrent relays for distinguishing upstream and downstream faults after integration of DGs when power flow becomes bi-directional. Determination of the new relays settings is not an easy task, therefore many different adaptive and non-adaptive algorithms and techniques are used to do so. The new designed protection coordination techniques must be efficient for information monitoring, control and communication and are known to be global protection and control schemes [85,86].

The impact of DG integration on the protection coordination highly depends upon its type, location, and size. Moreover, the characteristics of DG and distribution network are also important factors to be considered while computing new settings for protection devices. It is worth mentioning, that the synchronous DGs contribute to large fault currents, irrespectively of the network configuration, while the inverter based DGs contribute to small fault currents [87].

3.1. Study Objectives

The prime objectives of the studies over the protection coordination are:

(1) maintaining the standard Coordination Time Interval (CTI),
(2) updating the Time Multiplier Settings (TMS) and Plug Multiplier Settings (PMS) of relays,
(3) ensuring selectivity, speed, reliability, cost, and simplicity of protection devices.

3.2. Popular Protection Devices for Distribution Network

The most popular devices used for protection of low voltage distribution networks are as follows:

(1) fuses,
(2) overcurrent relays:

    (a) directional,
    (b) inverse time,

(c) definite time,

(d) instantaneous.

3.3. Methods of Protection Coordination

Most of research in the area of protection coordination techniques, have been done for DGs tied to distribution network. Comprehensive summary of all the important methods discussed in different research papers are presented below and their summary is gathered in Table 4.

Expert system based protection coordination—expert system is a software inspired by the human behavior of solving issues or making rational decisions. Expert systems are used where the traditional data processing is not feasible. Operating on their knowledge database and expertise the expert systems, as a result, also give the reasons on the solution choice [88,89]. Expert systems are used in industrial networks for relay coordination after DG integration. Multiple relay settings were evolved for 22kV distribution network using expert systems [90], on the basis of load flow, and fault analysis. The general scheme diagram for expert system based protection coordination is shown in Figure 1[90].

The utilization of expert systems for coordination of the protection devices (i.e., relays, fuses and reclosers) in a 33 kV radial system for small scale DGs is suggested in [91]. Protection Device Coordination Expert System (PDCES) software is developed in [92] to help the utility operator evaluate the protection coordination issues. PDCES assesses the causes of mis-coordination, proposes solutions, and ranks the remedies, so that an appropriate action can be taken in accordance to the network characteristics. The potential usage of expert system in protection coordination studies is proposed in [93,94].
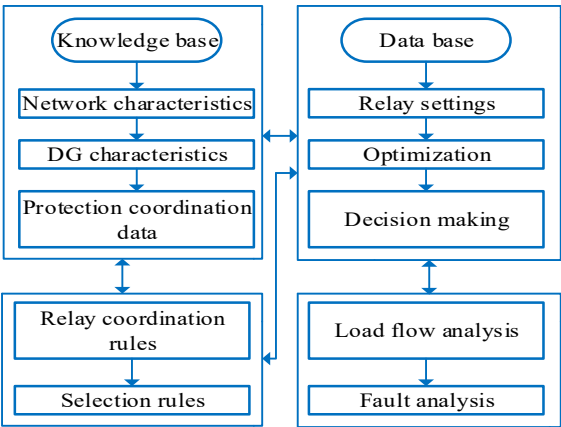
Figure 1. Expert System based protection coordination scheme.

Adaptive protection coordination—an emerging technique in power systems with low DGs penetration. It has ability to automatically process the data when conditions of the network changes with integration of DG. The defined rules and algorithms take the necessary actions accordingly, to achieve the high level of protection coordination in all the abnormal scenarios [95]. The adaptive technique used in [96], checks the relay settings after connection of every new DG on the basis of short circuit currents flowing through the protective devices. Adaptive scheme used in [97], evolves the coordination between protective devices on the basis of coordination time interval margin between their curves. An adaptive scheme suggested in [98] maintains coordination between the fuses in distribution network but all the DGs get disconnected at the instant of fault.

Fault current limiter (FCL) based scheme—integration of DGs into distribution system affects its overcurrent protection schemes and increase the level of fault current closer to the rating of protective devices [99]. The general scheme of FCL based protection coordination is shown in Figure 2 below.
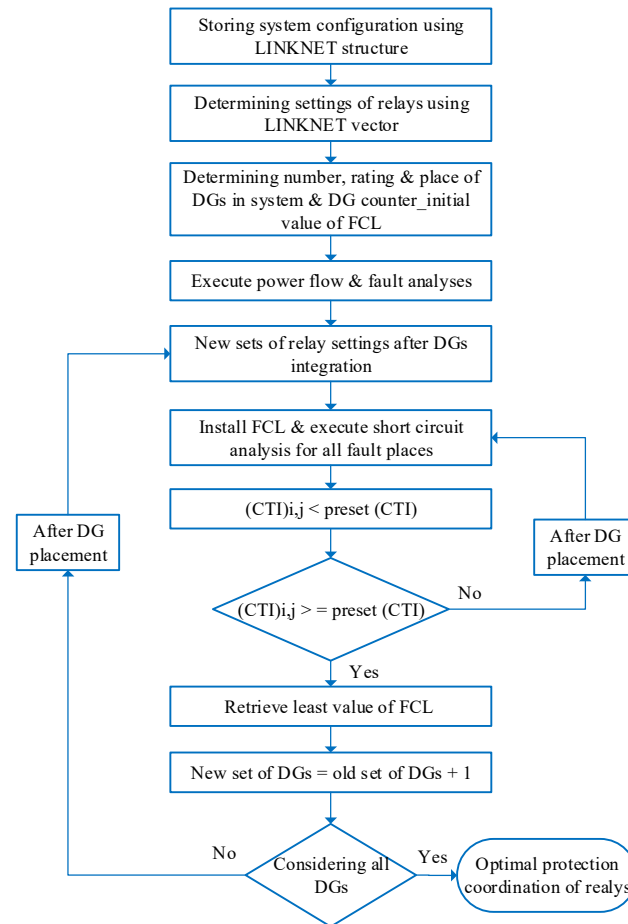
Figure 2. FCL based protection coordination.

One way to overcome the issue of mis-coordination between protection devices after DG integration might be a replacement of the existing scheme for a new one with higher rating, but this would be a costly option. Another way is to limit the value of fault current to the acceptable level so that the existing schemes may operate effectively [100]. The fault current limiters are connected in series with distribution lines to limit the amount of fault current contributions from the DGs. However, fault limiters cause small amount of loading and contribute to the power losses during normal conditions [101]. The LINKNET is type of data structure used to determine the set of random variables.

Directional overcurrent protection coordination—the directional element is added to the conventional overcurrent relays to deal with the bidirectional power flows caused by integration of DGs. This ideas used in [102–104] to isolate internal and external faults in the microgrid. The scheme of operation is based on directional overcurrent relays with additional communication and is relatively expensive. The directional protection scheme with master-slave concept is suggested in [105] to protect the micro-grid system against the external and internal faults. The proposed scheme has communication ability to detect the direction and location of fault. The directional protection scheme using microprocessor based relays proposed in [106] is used to protect the connected grid and also islanded DGs. This proposed scheme does not require communication link and is independent on the level of fault current values and the operation mode of DGs. The limitations of directional overcurrent protection have been identified in [107]. It is pointed out that the unintentional and frequent connection and disconnection of DGs affects the network configuration and the settings of protection devices.

Time-inverse protection coordination—when the fault occurs in a radial utility network, the prime source of fault current is a supply side. There is a huge difference between the magnitudes of

fault current and load currents so the overcurrent relays are able to distinguish between faulty and normal conditions. However, after the installation of DGs, the margin between the load current and fault current is small and thus the relays cannot efficiently discriminate between them [108]. A method based on voltage-current inverse characteristics is proposed in [109–111] to discriminate between the faulty and normal conditions.

Selection of DGs location and size—the location and size of DG have significant importance in the protection coordination study. The optimal sizing and placement of DG would cause small disturbances in coordination schemes of distribution network. The general scheme of such a method is shown in Figure 3.
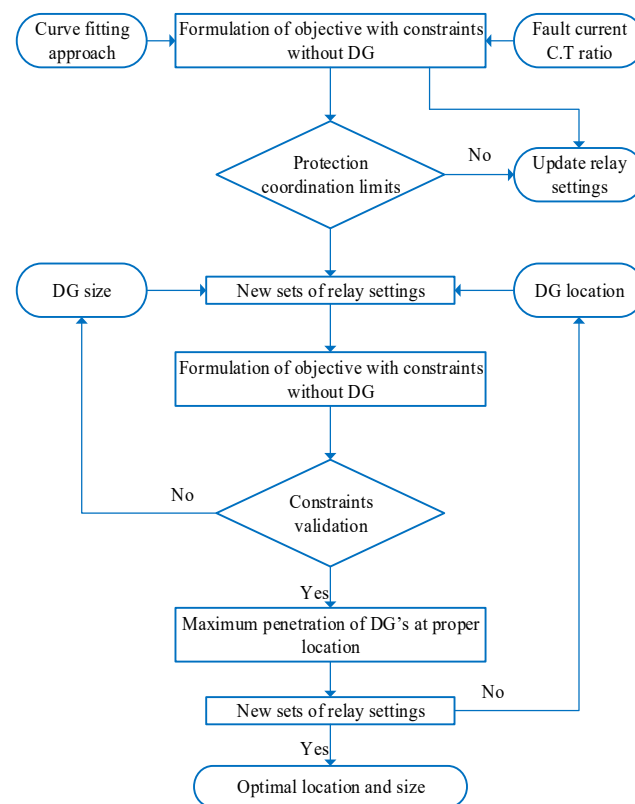
Figure 3. DGs location and sizing based relaying scheme.

The protection coordination scheme discussed in [112] evaluated the effect of size and location of DG on the overcurrent network protection based on fault current in upstream and downstream networks. In [113] the limitations for DGs' penetration are suggested to maintain coordination between conventional protection devices. The effect of size and location of DG on the coordination time interval (CTI) margin of inverse time overcurrent relays is analyzed in [114]. The sensitivity of relays in upstream and downstream network at different DGs location and size is also discussed.

Neuro-fuzzy based protection coordination—with the growing popularity of Artificial Intelligence in the power system applications the protection coordination methods are using fuzzy logic and neural network approaches [115]. Multi-Layer Perceptron Neural Network (MLPNN) based protection coordination scheme is being suggested in [116, 117]. However, this method is not robust due to training and complex structure of neural networks. The protection coordination scheme based on fuzzy logic approach proposed in [118] minimizes the operational time of primary and backup relays and evolutionary algorithm is used to optimize them. In order to add the decision making ability the fuzzy logic is adapted. Three stage neural network based protection coordination scheme is suggested in [119]. The first stage determines the distance to the fault point and the second stage identifies the exact location of fault while the third stage is used to isolate the faulty part from the network.

Multi-agent protection coordination—a method gaining popularity in protection coordination studies. An agent is an intelligent system which performs the defined autonomous functions in order to achieve desired objectives. The task performed by agents exist in predefined environment and their infrastructure contains communication and interface links [120]. The general scheme of multi-agent protection coordination is shown in Figure 4 [121]. An efficient protection coordination scheme using multi-agents for distribution networks with DGs connected is proposed in [122–124]. A multi-agent based protection coordination scheme proposed in [125] coordinates the overcurrent relays via communication link to enhance the efficiency of protection coordination and to decrease the operating time of relays. The multi-agent protection scheme proposed in [126] divides the system into various protection zones. This protection scheme has distributed control but makes coordinated decisions. Then, a peer-to-peer multi-agent protection coordination is suggested in [127]. A multi-agent approach is also used in cases where the operational timing of relays is longer due to small fault currents in the network. The inverter based DGs connected to low voltage network contribute small amount of current to the fault points [128,129]. Also, a communication based protection coordination scheme using synchro-phasors is used in [130].
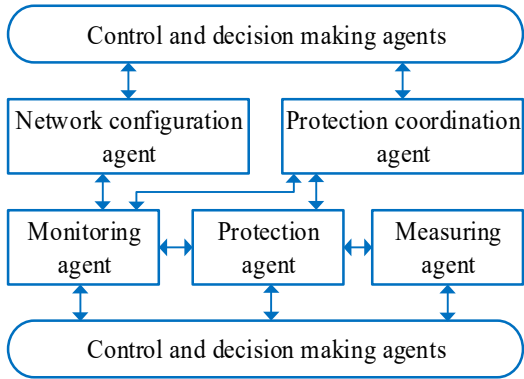
Figure 4. Multi-agent relaying scheme.

Table 4. Summary of Methods for Protection Coordination of DGs.

Technique	Main Features	Merits	Demerits	Network Configuration	Objectives
Directional overcurrent element [131]	Discriminating upstream and downstream currents.	Significant discrimination between fault and load current	Problem with phase and ground directional elements	4 bus radial network	To avoid false tripping and to halt system at increased fault level than predefined value
Adaptive inverse-time overcurrent protection [132]	Clearing overcurrent, under-voltage and symmetrical faults without considering upper and lower operating time limits while maintaining coordination time	Higher selectivity, smart, robust, adaptive and reliable	Does not perform well during changing conditions of network	13 bus IEEE network	To calculate new PMS for relays by using information of overcurrent, zero sequence fault current and voltage drop in network
Optimal location and sizing of DG [133–136]	Sizing and placing DGs so that have low effect on protection scheme of network	Economical results in least outage duration, does not require network modifications	Not efficient with high penetration of DGs	RBTS Bus 2 system/15 bus IEEE system	To reduce total outage time and energy costs
Time coordination method [137]	Achieving most of optimal protection settings with least disturbance and	Generates various possible solutions (neighbors)	New relay settings are required to be generated each	Ring-fed distribution system	To achieve zero supply failure rate and interruption

	failure timings		time with new DGs		frequency
Solid state unidirectional fault current limiter (SSUFCL) [138]	Restricting fault currents within defined zones used as an interface between upstream and downstream networks.	Suitable for DGs with storage system and converter technology	Unable to provide discrimination between upstream and downstream relays close to DGs	7 bus test system	To optimize the time and current settings of overcurrent relays and characteristics of SSUFCL
Adaptive differential current protection [139]	Changing values of fault level and network configuration are required for relay coordination in both grid-connected and islanded mode DGs	Applicable to MV network with inverter based DG technology	Cannot be applied to synchronous DGs	3 bus radial network	To avoid false fault detection based on differential current with least frequency deviations between supply and load
Multi-agent adaptive protection coordination [140,141]	Deciding settings of digital overcurrent relays on the basis of condition of agents and communication between them	Used for complex networks with frequent changing dynamics	Continuous communication between overcurrent relay agents, feeder agents and display agents are required	2 bus radial network/4 bus radial network	To determine relays settings through learning algorithm and communicate with its neighboring agents
Directional protection with fault current limiter (FCL) [142]	Determining settings of FCL through algorithm that limits the fault current	Eliminates complexity in control strategies, ensures reliability and safety of network at the lowest costs	Connection and disconnection of DGs may affect the values of FCL and relay settings	30 bus IEEE system	To minimize the cost function at zero values of FCLs
Voltage sag coordination technique [143,144]	Disconnecting DG from the system when voltage falls below 0.5 p.u in less than six cycles and coordinating relays on the basis of specific energy as the function of time.	Can be applied to both synchronous and static DGs with different ratings	More laborious, limited to small DGs	1 bus radial network	To maintain standard coordination time margin
Adaptive protection coordination [145]	Calculating time dial and plug multiplier settings of relays on the basis of varying parameters/configuration of the network	Extremely flexible to maintain the coordination among overcurrent relays and distance relays	Communication and numerical relays are required for obtaining best settings	8 bus test system and14 bus IEEE network	To avoid nuisance tripping of overcurrent and distance relays at distribution and transmission levels respectively
Directional inverse time overcurrent protection [146]	Estimating the direction of fault current on the basis of its angle with polarizing voltage in both forward and reverse directions for relay settings	Used for complex power networks and for systems with changing dynamics	Additional nonlinear multi-variable function is used which only works for continuous first derivatives of the system	30 bus IEEE network	To diminish the coordination delay between relays while maintaining protection coordination limits
Centralized adaptive scheme	Optimizing the relay setting on the basis of network	Automatic online coordination, desired selectivity	For every change in the network	6 bus interconnected network	To minimize the primary and backup

[147]	conditions, using SCADA server that retrieves the network data and perform load flow, contingency analysis and sensitivity analysis.	and sensitivity	conditions, the process is repeated	operation time of relays while retaining desired selectivity
Neuro-fuzzy protection [148]	Deciding the optimal settings of IDMT relays based on the status of DG and network conditions. With Fuzzy inference The results are optimized through neural network with voltage and current phasor based DFT algorithm	Applicable to networks with changing parameters and with multiple DGs' integration. Better performance in terms of speed and efficiency	Complexity is high, computational times are large	34 bus IEEE system	To ensure desired coordination time in closed loop system
Expert System protection coordination [90,149]	Using expert system as decision tool to investigate the effect of DG integration and proposes protection coordination settings for relays	Simple, robust and suitable for system with multiple coordination settings	With changing configuration of network, computation processing time is large	22-kV test system	To identify the maximum and minimum fault currents in the protection zones
Communication assisted digital relay scheme [150]	Providing under-voltage and overcurrent protection with grouped relays based on short circuit capacity of system	Used for high impedance faults and integration of multiple DGs	Complete knowledge of entire configuration and parameters of network is difficult and security of communication link is necessary.	6 busand 13 bus loop network	To optimize location and number of relays according to network configuration and characteristics of DGs
Coordinated backup protection [151]	Analyzing different faults based on coordinated substation which works on differential principle and acts as backup for master station	Suitable for network with varying power flows, does not require complete information about system	Communication protocol between master station and coordinated station is required to be secure	14 bus IEEE system	To minimize the probability of protection failure

4. Future Scope and Recommendations

In this article, authors have identified the possible future scope and challenges for protection coordination schemes and DG location and sizing methods.

4.1. DG Location and Sizing Methods

(1) The optimal sizing and placement of DGs, proper placement of capacitor banks and the network reconfiguration are the three best options for minimizing the power losses in distribution systems. The coordination planning of all these three options results in economical results. Therefore, during the network reconfiguration, proper placement and sizing of DGs, capacitor banks and protection devices should be carried out simultaneously.

(2) New model of DGs placement and sizing using information of voltage sag distribution network with objective of minimizing losses is aim of future research.

(3)   The optimizations methods used for optimal sizing and location of DGs are based on trial and error methods. In order to improve their performance and efficacy, their objective functions should be evaluated adaptively and automatically.

(4)   The stability of distribution system should be considered after large penetrations of DGs because the system becomes active then. Moreover, the energy management strategy during transient operation of network should be designed with available distributed generation.

(5)   The effects of new DG installation on the characteristics of existing DGs in distribution network should be analyzed. The dynamic model for proper placement and sizing of DGs will be an effective solution.

(6)   With the installation of DGs, not only voltage of network is rised up but also the power quality is significantly being changed. With the online monitoring and control of distribution network, the capacity of network to accommodate new DGs can be determined, the new relay settings can be deduced and the cost of integrating DGs can be calculated. The Online Management System (OMS) integrated with model of DGs placement and sizing is the work of future research.

(7)   The different parameters of objective functions of DGs placement and sizing algorithms are uncertain such as; output power of distributed sources, future power demand, fuel costs, market trends, charging and discharging characteristics of electric vehicles, future investments, availability of fuel reserves, etc. Therefore, deterministic and evolutionary algorithms should be used to deal with such uncertainties.

4.2. Schemes of Protection Coordination

(1)   High penetration of DGs at distribution levels affects the reach of upstream distance relays at transmission level. Therefore, during installation of multiple DGs, not only relays settings of downstream distribution system but also relays at upstream transmission level should be considered.

(2)   Since the relays are coordinated while considering the lower limit of CTI and neglecting its upper limit. Thus, in case of low fault current contributions from DGs, the operation of backup overcurrent protection is delayed. Therefore, in order to achieve optimal operation of overcurrent relays during such scenarios, time inverse current relay characteristics should be applied in relay coordination schemes.

(3)   Installation of DGs influences the configuration of distribution network and hence directional relays are installed to distinguish between the upstream and downstream fault currents. In such situations, the selection of relays settings for backup protection becomes more complicated and thus simple curve fitting techniques are ineffective to do so. Therefore, modern communication based techniques are required to solve such issue for highly complex systems.

(4)   Integration of photo-voltaic systems into power system makes the protection schemes more complicated due to their small fault current contribution. Under such conditions, the accuracy and robustness of protection schemes is a challenging task. Using voltage sag characteristics of system, protection schemes for distribution with PV system can be designed.

(5)   With high penetration of DGs, the communication based coordination schemes with distributed adaptive techniques become inactive. In future coordination studies, this issue should be considered.

(6)   In [142], Author used the information of voltage sag for protection coordination of relays and in [145], Author coordinated the relays using fault current angle. Since, with high penetration of DGs into distribution network, not only the magnitude of voltage is affected but also its angle, during the steady state as well as during the transient conditions. Therefore, a new protection scheme can be designed on the basis of both parameters of voltage sag (magnitude+angle), which is ongoing research of Authors

(7)   Due to interconnection of highly loaded distribution systems and the installations of DGs, the short circuit capacity of network changes adversely and causes sympathetic tripping of relays.

Such issue should be considered while integrating DGs into distribution network during steady state and dynamic conditions of system.

5. Conclusions

This article presented the detailed review of protection coordination schemes and placement and sizing methods of DGs in distribution networks. The integration of DG into distribution system creates many protection coordination issues. The sensitivity of these issues highly depends upon the place and rating of incoming DG. Therefore, different methods and optimization techniques for optimal placement and sizing of DG were discussed. The most common objective among all the techniques was the reduction of losses and enhancement of voltage profile. The most frequently used methods for proper placement and sizing of DG are Genetic Algorithm (GA) and different practical heuristic algorithms.

After the DGs are optimally sized and placed then issues arise with bidirectional power flows in distribution networks. The existing protection schemes fail to clear the faults correctly. This article addressed various protection coordination methods. The application of different protection schemes were based on the characteristics of network and installed DGs. The protection coordination problems were formulated as linear and non-linear problems and were then evolved by different optimization methods to determine their optimal protection settings. All the discussed protection schemes were based on restraining the adverse effects of DGs and updating their protection characteristics.

This article also discussed possible research gaps, applications and limitations of different protection coordination schemes and DG sizing and placement methods.

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