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A Review of Renewable Energy Based Distributed Generation in Electrical Power System

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Abstract- It is possible to describe distributed generation as power generation by small scale generating units installed in distribution systems. There is a steady growth in the penetration of distributed generation (DG) units into electric distribution systems. DG allocation is the process of finding the optimal type, location and size of DG units. The allocation of DGs is a hot research field and poses a difficult problem in electrical power engineering. This paper discusses the recent research work on the issue of DG allocation from the point of view of their optimization algorithms, targets, and decision variables, type of DG, implemented limitations and type of modeling of uncertainty used. In this research an overview of DG types and various DG technologies are highlighted. Some DGs challenges ahead with current drive towards smart grid networks is also discussed. The research gaps are defined on the basis of their views on current research work and some helpful suggestions will be made for future research on DG allocation. The author strongly believes that this paper could be beneficial in the related field for researchers and engineers.

Index Terms- Distributed generation, renewable energy, Solar, Wind, fuel cell.

I. INTRODUCTION

The climate change issue is becoming a big problem for the international community to face in this century. Over the last decade, the EU has made considerable efforts to establish a shared energy sector strategy. The replacement of fossil fuels with Renewable Energy Sources (RES) is considered to be an effective step for reducing global carbon emissions. The environmental benefits that go along with the increased use of RES for the production of electricity are generally known. In particular, multiple life cycle evaluation studies illustrate the great potential of renewable energy technologies to mitigate greenhouse gas emissions, as well as emissions that lead to regional environmental challenges, such as acidification. As a result, the EU, as well as different national governments, have set very ambitious goals for increasing the use of RES[1]. The EU strategy is that 22.1% of overall electricity usage could come from RES in 2010. In particular, Greece is aiming to raise the RES contribution to an indicative 20.1% [2].

In addition, rapid growth is expected for distributed generation of electricity [3]. The annual distributed electricity production is projected to rise by 4.2% between 2000 and 2030, reaching 35 GWh by 2030[4]. One of the key factors for Distributed Generation (DG) is the use of renewable energy (solar, biogas, wind and hydro) and Combined Heat and Power (CHP) to reduce greenhouse gas (GHG) emissions)[4,5].

In today's open energy market, distributed energy systems have an increasingly important role. Different definitions regarding Distributed Generation (DG) are used in the literature. According to Ackerman et al. [6] DG is an electric power source connected directly to the distribution network or on the customer side of the meter. Soderman and Pettersson [7] consider that a distributed energy system is a complex system comprising of a number of energy suppliers and consumers, district heating pipelines, heat storage facilities and power transmission lines in a region. DG should not be exclusively confused with renewable energy generation. Renewables can be exploited in DG and are very much encouraged by certain lobbying groups, though non-renewable technologies could also be considered in DG systems [10].

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II. TYPES OF DISTRIBUTED GENERATION TECHNOLOGY IN ELECTRICAL POWER SYSTEM

Traditionally, electricity is generated in large power stations, located near resources or at logistical optima; it is transported through a high-voltage transmission grid and is locally distributed through medium-voltage distribution grids. DG aims to add versatility of energy sources and reliability of supply and reduce emissions and dependence on fossil fuels (Figure 1 and 2). The goals of DG include the minimization of the environmental impacts of energy production and introduction of RES to the distribution network. In addition, DG can contribute to the reduction of transmission losses and help introduce new developments such as fuel cells and super-conducting devices [9].

Certain DG technologies are not new (e.g., internal combustion engines, gas turbines, etc.). On the other hand, due to the changes in the utility industry, several new technologies are being developed or advanced toward commercialization (e.g., fuel cells, photovoltaics, etc.). Figure 3 presents the different distributed generation technologies [10].

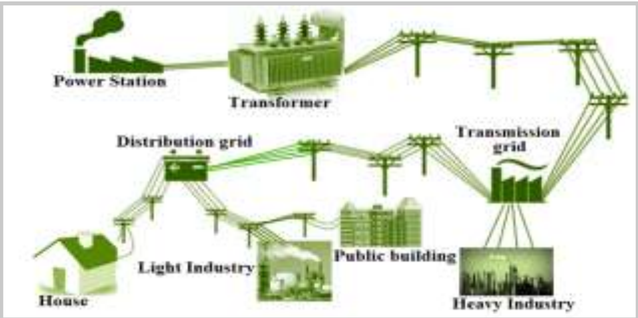

Figure 1: Schematic diagram of traditional central-plant model and DG- model

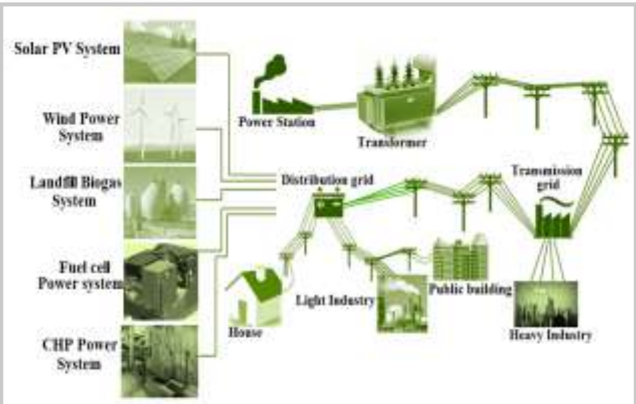

Figure 2: Schematic diagram distributed generation model

According to Ackermann [6], the DG as the installation of generating units of electric energy is connected directly to the distribution network or on the consumer side (low-voltage grid).

It is worth it to highlight that the above definition does not consider the size and the type of the generating sources, that is, the proximity to the load defines it. The same author divides the types of DG in four groups as a function of its installed power, which is shown in Table 1.

Distributed Generation is power generation technology that is close to the point of use, as opposed to the centralized production of energy.

The scale of the generated power is significantly lower, as the generator is usually designed to service a home, a building, a manufacturing plant or commercial facility or a small community. Distributed generation systems may be independent, connected to a pre-existing grid, or be connected to other independent distributed generation facilities to create what are called “micro-grids”.

Figure 3: Distributed generation technologies for power generation

Table 1 Classification of DGs in Terms of Power [12]

Categories	Power (kW)
Micro	Less than 5
Small	Between 5 and 5000
Medium	Between 5000 and 50,000
Large	Greater than 50,000

Another important characteristic to evaluate the impact of DGs in the distribution network is the interface used to connect it to the grid.

Table 2 shows all the sources mentioned above (renewable and nonrenewable) and its respective interface of connection to the grid.

Table 2 Power Sources and Their Main Connection Interfaces [12]

Technology	Connection Interface
Photovoltaic	DC-AC converters
Wind	Asynchronous generators and AC-AC converters
Internal Combustion Engine	Asynchronous generators and AC-AC converters
Micro turbines	AC-AC converters
Fuel Cells	DC-AC converters
SHPSs	Synchronous generators and asynchronous generators
Biomass	Synchronous generators

Types of Distributed Generator

Solar

The production of solar energy is one of the fastest growing and most promising renewable energy sources in the world. Solar energy is the conversion of solar radiation into electricity through the use of photovoltaic solar cells. This conversion takes place in the solar cell by photovoltaic effect. Normally, inputs are generated in the MW range. The power of the solar panel is converted into alternating current by the inverter.

Wind Turbine

A wind turbine uses the wind as an entrance. To turn this turbine, actuate a primary motor connected to the shaft a Generator. The generator provides an AC output voltage that depends on the wind speed. Since the wind speed is variable, the generated voltage must be transferred to DC and back to AC using inverters. The range of wind energy generated by wind turbines is several megawatts per turbine.

Fuel Cells

The operation of the fuel cell is similar to that of a battery, but it is continuously charged with hydrogen, extracted from any hydrocarbon source, this is the charge of the fuel cell together with the air (oxygen).The fuel cell uses the reaction of hydrogen and oxygen by means of an ionic conductor electrolyte to produce an induced DC voltage that is proportional to the number of fuel cells.

Micro Turbines

The micro turbines are based on the technology of very fast rotating turbines together with a generator to generate a high frequency voltage output. These micro turbines are usually powered by natural gas.

Rotary Machines

Rotary machines are types of DG that include induction or synchronous machines such as induction and synchronous machines

Synchronous Generators

These machines use fuel as input to generate electricity, with different classifications from KW to a few MW. Rotary machines are mainly used as stand-alone systems or as backup generation systems. Generally Distributed generation resources are defined as those resources that are directly used in the generation of electric power for connection to distribution system. These sources include traditional and non-traditional such as renewable, non-renewable and energy storage technologies like batteries, flywheels, superconducting magnetic energy storage, to mention but a few as categorized in figure 1.0 with illustrations of various technologies. The traditional DGs are those generators that utilize combustion engines such as low speed turbines, reciprocating engine and gas micro-turbine. These resources even through are small in size but have wide spread geographically. On the other hand the Non-traditional DGs are those sources that produce power with zero emissions and are very friendly to environment. Most of these sources usually outputs DC power, therefore conversion to AC power is necessary before integration into an existing AC distribution network. For this reason sources such as photovoltaic and fuel cells uses power electronic converters (inverters) for grid interfacing as shown in figure 2.0.The traditional internal combustion engines (rotary machines) are mainly synchronous generators and are interfaced directly to the grid. Wind turbines are also considered as rotary machines and are mainly induction type generators which can be interfaced directly with the grid. In some wind applications as well as some combustion engines like micro-turbines, power converter/inverter devices are employed for grid interface as the benefits associated with the electronic interface justifies the additional cost and complexity involved. Therefore, the energy generated from the various DG sources is injected into the grid via synchronous Generators, static power converters or induction generators. The nature of operation of these generators or converters determines the models of DG to be employed in the power flow solution.

III. DISTRIBUTED GENERATION BENEFITS

1. Elimination of Transmission and Distribution Electrical Line Losses

It is generally accepted that around 7% of the electric power generated is lost during transmission from the central generation source to the final point of use. Electricity generated at a centralized station has to be stepped up for high power transmission, sent through miles of copper wire, then stepped down before being delivered to the end user. Each step has unavoidable inefficiencies in it that eventually build up to significant losses.

2. Improved Power Quality and Reliability

As discussed above, power quality is another benefit of distributed generation. For some applications, power interruption, voltage spikes, "brown-outs" and other power quality disruptions are simply unacceptable. Besides affecting the quality of life of ordinary electricity consuming citizens, such blackouts have affected manufacturing industries. One commentator has described the effect on the Mugher cement factory, and the result that had on the price of cement.

3. Reduction in Energy ($/kWh) and Electric Demand ($/kW) Charges
Peak shaving - choosing to get off the grid at times of peak demand when charges are high, or base loading - using your own DG resource to meet most of your needs and using grid supply for peak demand times only, are some of the strategies used to reduce overall utility electric bills.

4. Self-reliance: Potential Source of Emergency and High Reliability Standby Power
Beyond the reliability issues, locations that are far from a grid are better off generating their own power rather than facing the stiff capital costs associated with connecting to a remote grid line. Locations that ARE connected to the grid have the additional benefit of having reliable, high quality back up.

5. Environmental Cleanliness
DG technologies are generally designed from the ground up to be environmentally more benign, with little to no impact on air quality when compared to current centralized generation. For companies that can be exposed to stiff penalties due to pollutant emissions, this becomes an economic issue.

Challenges of Distributed Generation System
Despite their very valuable benefits, DG's may lead to some challenges. The challenges of DG's are listed out as below.

- Distribution systems were originally designed and constructed to handle unidirectional power flows from utility to end users, while the addition of DG units can lead to bi-directional power flows. This feature specially affects and disrupts the performance of protective relays.
- In DG-integrated distribution systems, the is landing may happen. Is landing may endanger the crew and public and may also cause over voltages [29].
- The control process for customer-owned DG's seems to be challenging.
- In renewable energy-based DG's such as PV and wind, the output power is a function of solar irradiation/wind speed, therefore, their output power is intermittent and they are non-dispatch able units.
- Some DG sources may lead to voltage flicker. For instance, in wind DG's, since the tower shades the blades for part of their rotation, voltage flicker occurs [30].
- If DG's are not properly sized and located, they may lead to over voltages and excessive power losses.
- DG's may inject harmonics into the electric system [14].
- Due to bi-directional power flows, DG's normally increase short circuit currents [31].
- Improper sizing or improper placement of DG's may cause stability issues.

IV. DG ALLOCATION PROBLEM

The research findings explicitly approve that the type, size and location of distributed generation units in distribution systems significantly affect technical, economical and environmental objectives of distribution systems [32–36]. Therefore, the best types of DG units with the best size should be installed at the best locations in distribution systems. The problem of finding optimal type, location and size of DG units in distribution systems is referred to as "DG allocation problem".

Due to the following reasons, efficient solving of DG allocation problem is very significant and important from technical, economical and environmental points of view.

- By proper allocation of DG's, there liability of power system is improved and power quality is enhanced.
- By proper allocation of DG's, the investment and operational costs are decreased.
- By proper allocation of DG's, the harmful environmental effects of power generation are mitigated.

From optimization perspective, DG allocation problem is a nonlinear, highly constrained, multi-objective, mixed-integer, multimodal optimization problem where in finding near global solutions is very difficult. The approaches that have been applied to DG allocation problem can be categorized into four main groups as below.

Classic Approaches:
In few cases, classic optimization algorithms, such as linear programming and non linear programming have been applied to DG allocation problem [37, 86]. In general, this group of approaches suffers from lack of flexibility; they usually entail pre-conditions such as convexity, linearity and continuity of objective functions which are not met in practice.

Sensitivity Analysis Based Approaches
These approaches are used to find the appropriate location of DG units. Based on a sensitivity index, they try to find the location that is the most sensitive. Although, these approaches offer low computational time, the degree of optimality of achieved solutions is unknown and they can only compute optimal location of DG units.

Metaheuristic- Based Approaches
They are usually population- based stochastic approaches that do not entail any pre-condition on objective functions or constraints [56–62]. They are effective in solving DG

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allocation problem and are the most common approaches for solving this problem [56, 23, 66, 67, 74, 75, 45-47, 82, 52, 63-73–89]. Despite all their merits, meta- heuristic optimization algorithms may converge into false local optima rather than global optimum, therefore a very high amount of research effort is being put to relieve their premature convergence problem in DG allocation problem [23].

Hybrid of sensitivity analysis and classic/metaheuristic-based approaches: In these approaches, first in order to reduce search space, sensitivity analysis is applied to find appropriate location(s) for DG unit(s),then a classic or metaheuristic optimization algorithm is applied to find optimal size of DG units [32,38]. The noticeable point is that since sensitivity analysis finds the location of DG's, the classic/metaheuristic optimization algorithm does not need to handle a mixed-integer optimization problem. Table 5 tabulates the main features of different categories of approaches applied to DG allocation problem.

Table 3 Main features of different categories of DG allocation strategies

Classic approaches	They require pre-conditions such as convexity, linearity and continuity of objective functions which are not met in practice
Sensitivity analysis based approaches	They offer low computational time, however, the degree of optimality of solutions is unknown and they can only compute optimal location of DG's.
Metaheuristic- based approaches	They require no pre-condition on objective functions or constraints. They are efficient in solving DG allocation problem and are the most popular approaches for solving this problem. Despite all their merits, they may converge into local optima instead of glob alone
Hybrid of sensitivity analysis and classic/metaheuristic-based approaches	In these approaches, first in order to reduce search space, sensitivity analysis is applied to find appropriate location(s) for DG unit(s), then a classic or metaheuristic optimization algorithm is used to find optimal size of DG units. The important point is that since sensitivity analysis finds the location of DG's, the classic/meta- heuristic optimization algorithm does not need to handle a mixed-integer optimization problem

Table 4 Existing research works on DG allocation problem from view point of used optimization algorithms, objectives and decision variables

Optimization algorithm	Objective(s)	Decision variables	Remarks	Ref
Sequential quadratic programming	Annual energy losses and energy cost	Size of DG modules and storage devices	The results show that biomass units are the most efficient in decreasing energy cost. The results also indicate that batteries are the most crucial component for standalones micro-grids.	[37]
Sensitivity analysis, hybrid of sequential quadratic programming and branch and bound	Copper losses	Location, real and active power	The proposed optimization scheme outperforms PSO and an analytical approach.	[38]
PSO	Copper losses, voltage profile	Location and active power of DG's	PSO outperforms grid search algorithm and an analytical approach	[68]
PSO with a new position update strategy and new inertia weight	Copper losses, voltage profile, capacity of DG's	Location and reactive power of DG's	The proposed multi-objective PSO scheme outperforms NSGA II and some other multi-objective evolutionary algorithms.	[75]

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Hybrid GA–ICA	PSO and support vector machines	Fuzzy-based multi-objective PSO (MOPSO)	An enhanced version of PSO wherein the particles are repelled from the worst particle.	Hybrid of GA and PSO (GA for sitting, PSO for sizing)
Voltage stability index, copper losses and voltage deviations, even distribution of power among branches, benefit	Copper losses, voltage profile	Copper losses, voltage stability, even distribution of power flow among feeders	Investment, reinforcement and operation costs, cost of purchased power, copper losses	Hybrid of GA and PSO (GA for sitting, PSO for sizing)
Location and size of DG's	Location, active and reactive power of DG units	Active power, reactive power and location of DG's	Capacity, location, installation year	Location and generating power of DG units
The proposed hybrid GA and ICA outperforms GA and PSO.	The proposed multi-objective strategy outperforms some other multi-objective optimization	The proposed fuzzy MOPSO outperforms non-dominated sorting genetic algorithm (NSGA) and strength Pareto evolutionary algorithm (SPEA),	The simulation results show that the proposed hybrid PSO–DE scheme significantly outperforms12otherschemes.	The proposed optimisation strategy outperforms GA and PSO
[52]	[50]	[20]	[47]	[45,46]

V. LITERATURE REVIEW FROM VIEW POINT OF RENEWABLE DG TYPE AND ALLOCATION PROBLEM

In this section, the existing research works on DG allocation problem are classified from the view point of DG type, applied constraints, uncertainty modeling and used case study. Furthermore, for each research, it is stated whether it includes storage devices or not. Table 5 presents the classification of some existing research work on DG allocation problem from view point of DG type, constraints, uncertainty modeling and used case study. From the perspective of used DG type, P-type DG's are the most commonly used type [32,34,70,72,73,44,78,80,49,51,64-67,85,86], although, Q-type DG's [43] and PQ type DG's [25,28,38,56] have also been used. A very notice able point is that although renewable energy based DG's are very effective in reducing emissions, they have only been used in few works [16, 37,85–55, 66, 68, 81, 83].

To have realistic solutions for DG allocation problem, the uncertainties of renewable energy- based generating units such as PV's and wind units and also the uncertainty of loads must be considered and modelled. However, only in a few research works, the uncertainties have been taken into account. Actually, only in [16,20,36,50,53–55,66,68,83], uncertainties have been considered.

In [54], uncertainty sets have been defined to take the uncertainty of loads, PV modules and wind DG's into account. In [16,55], the uncertainty of electricity price is modeled by fuzzy theory. The uncertainty of solar and wind DG's has also been considered .In [36], uncertainties of loads and electricity market price have been modelled.

In [53], the uncertainties have been modeled by time series. In [20], uncertainty of loads has been modeled by fuzzy theory, however, the uncertain nature of DG units has not been modelled. In [50], chance constrained stochastic programming has been used for handling and modeling of uncertainties.

In [83], the uncertainty of loads and generated power has been modelled. In [66], Weibull probability function is used to model output power of wind turbines. Probabilistic load flow takes the uncertainty of loads into account. In [68], uncertainties of solar and wind DG units and also uncertainties of fuel and electricity price have been considered and modelled. Reyleigh distribution function models the uncertainties of winds peed and solar irradiance.

Although using storage devices can help to smooth the output real power of generating units, only in few research works, they have been used in concert with DG units [16,37,53,55].

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Table 5 Classification of research works from view point of DG type, constraints, uncertainty modeling and used case study.

DG Type	Wind, biomass, photovoltaic	PV, wind	Multiple DG types including solar, wind, diesel generator, fuel cell, micro-turbine.	Renewable DG's (PV, wind)	Different type of DG's including photovoltaic (P type), combined heat and power (PQ type) and synchronous condensers (Q type)	Renewable including biomass, wind and solar
Storage	Battery	No	Battery	Yes		No
Constraints	Voltage magnitude of buses should be bounded to[0.94, 1.06] pu. Apparent power of branches are limited, power of DG's are confined within a certain range. Power discharged by batteries at any hour should not be more than the demand of that hour.	No Voltage magnitude of buses should be confined within a certain range and power of feeders should be bounded.	Minimum and maximum power of DG's, minimum and maximum allowable charge for batteries and the ramp up limit for output power of DG's should not be violated.	Dumping energy is not allowed if the load demands are not properly met. The excess energy of micro-grid cannot be sold back to the grid, since regulations do not permit DER injections into the grid	Voltage magnitude of buses should be within [0.9,1.04] pu, thermal limit of branches, power factor of DG's, active and reactive power of DG's should be bounded to specified ranges.	Voltage magnitudes of buses should be bounded, the real and reactive power of DG's should be confined within a certain range.
Modelling uncertainties	No	Yes, uncertainty sets have been defined to take the uncertainty of loads, PV and wind DG's into account	The uncertainty of electricity price is modelled by fuzzy theory. The uncertainty of solar and wind DG's has been considered.	Modelled by time series.	No	Yes, the hourly loads and generating power of DG's are provided
Case study	31 bus system	A micro-grid with 33 load nodes	A micro-grid with a battery and multiple DG's	16 bus generic UK distribution system	IEEE 33 and 69 bus systems	IEEE 33, 69 and 118 bus systems
Ref.	[37]	[54]	[16,55]	[53]	[81]	[83]

P type DG's, gas turbines, fuel cells and wind turbines	Multi-type DG's including wind, PV, gas turbine, micro-turbine, diesel engine and fuel cell have been used. The DG's are considered of P-type.
No	No
Voltage magnitudes of buses and active power of DG's are bounded.	DG penetration level is limited. Maximum capacity of wind and PV units is 2 MW and the maximum capacity for other used DG's is 1 MW. Voltage magnitudes of buses are bounded within [0.9, 1.05] pu.
Weibull probability function is used to model output power of wind turbines. Probabilistic load flow takes the uncertainty of loads into account.	Yes, uncertainties of solar and wind DG units, uncertainties of fuel and electricity price have been considered and modelled. Reyleigh distribution function models the uncertainties of wind speed and solar irradiance.
IEEE 33 and 69 bus systems	9 bus system
[66]	[68]

VI. CONCLUSION

After reviewing the existing research works on DG allocation problem, the followings are provided as shortcoming of the existing works and directions for future research.

- Although a lot of research effort has already been put to develop efficient and powerful metaheuristic optimization algorithms for solving DG allocation problem, there is still room for improvement. Developing more efficient metaheuristic optimisation algorithms with strong capability in discovery of global optimum is recommended for future research.
- For a realistic formulation of DG allocation problem, the technical, economical and environmental objectives should be considered, while in a large portion of existing research works [1–19], the economical or environmental objectives have not been considered. In particular, the consideration of environmental objectives due the world wide global warming and pollution concerns seems imperative.
- To provide a realistic solution for DG allocation problem, all the related technical, economical, environmental and geographical constraints must be taken into account, while in a large portion of existing research works, some of constraints are neglected. For example, in most of cases, right of way issues do not allow the installation of DG units in certain buses of distribution systems, while in most of research works, such a constraint has been simply ignored.
- While the addition of storage devices along with DG units can provide smooth output power and relieve intermittency of renewable energy-based DG's, they have been rarely used in existing research works. Using storage devices in concert with DG units and fully investigation of their effects on solutions of DG allocation problem is highly recommended.
- Since the output power of solar and wind DG units depend on the solar irradiation, temperature and wind speed, they have probabilistic/uncertain nature. However, most of the existing research works have not taken the uncertainties of solar/wind DG units into account. Due consideration of the uncertainties of solar/wind units lead to more resealistic solutions for DG allocation problem.
- While real-life distribution systems are usually of very large scale and include a large number of buses and branches, in most of the existing research works, the optimisation schemes for DG allocation problem has been validated on very small scale distribution systems.
- Using renewable energy resources as DG units can be very effective in improving technical, economical and especially environmental characteristics of distribution systems. However, in a small portion of existing research works, they have been utilised.
- Although a lot of research effort has been put to develop modern DG allocation strategies and there exist efficient DG allocation strategies, in practice, utilities mostly use traditional experience based strategies rather than modern strategies for allocation of DG's. Even in some countries, in particular developing countries, the power generation is totally provided by centralized power plants and distributed generation is not used. Awaring utilities in different countries of the benefits of distributed generation and encouraging them to use modern DG allocation strategies is highly recommended.
- Among renewable energy-based distributed generation resources, the resources such as biomass have been rarely used in DG allocation. Using new renewable energy-based distributed generation resources in DG allocation and assessment of their impact on DG allocation solutions and objectives and comparing their effects with other distributed generation resources is recommended.

- Almost all existing research works, attempt to optimize steady state characteristics of distribution systems, while transient and dynamic issues of the system can also be considered in DG allocation. In particular, enhancement of transient/dynamic stability of the system by optimal allocation of DG units is recommended.

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