ISSN: 2278-4632
Vol-09 Issue-9 No. 1 September 2019

Integration of Distributed Generators with Grid

[1]**SUBASH CHANDRA MISHRA,** *Gandhi Institute of Excellent Technocrats, Bhubaneswar, India*
[2]**SUBHAM PRASAD SAHU,** *Spintronic Technology and Advance Research, Bhubaneswar, Odisha, India*

a b s t r a c t

The world is witnessing a transition from its present centralized generation paradigm to a future with increased share of distributed generation (DG). Integration of renewable energy sources (RES) based distributed generators is seen as a solution to decrease reliance on depleting fossil fuel reserves, increase energy security and provide an environment friendly solution to growing power demand. The planning of power system incorporating DGs has to take into account various factors such as nature of DG technology, impact of DG on operating characteristics of power system and economic considerations.

This paper put forwards a comprehensive review on planning of grid integrated distributed generators. An overview of different DG technologies has been presented. Different issues associated with DG integration have been discussed. The planning objectives of DG integration have been surveyed in detail and have been critically reviewed with respect to conventional and RES based DG technologies. Different techniques used for optimal placement of DGs have also been investigated and compared. The extensive literature survey revealed that researchers have mostly focussed on DG integration planning using conventional DGs. RES based DGs have not been given due consideration. While integrating RES, their stochastic behaviour has not been appropriately accounted. Finally, visualizing the wide scope of research in the planning of grid integrated DGs; an attempt has been made to identify future research avenues.

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Keywords:
Distributed generation
Grid integration
Planning objectives
Renewable energy sources

Contents

1. Introduction

The centralized power generation has been dominating power scenario for a long time. These systems utilize conventional energy resources for electricity generation. However, worldwide urge to reduce dependency on fossil fuels and mitigate climate changes has increased pressure to alter current generation paradigm. Distributed Generators (DG) which are small power sources connected near consumer terminals [1] are emerging as an attractive substitution to the expansion of central generating facilities. DGs offer a quick fix and more environment friendly option by providing enough opportunities for RES based technologies such as wind, solar, biomass etc. Alternative energy resources such as solar and wind are abundantly available in nature and therefore have attracted energy sectors to generate power on a large scale.

Integration of DGs affects system performance in multitude of ways such as reliability, losses and voltage profile [2]. Besides, environmental benefits offered by integration of RES based DGs are looked upon as a major driving force for increased inclination towards these technologies. Nevertheless, the intermittent nature and uncertainty associated with RES based DGs pose additional challenges in system planning. The literature on planning with DG sources is mostly focussed on conventional DGs. Amongst the literature on system planning incorporating RES based DGs, the intermittency associated with these sources has not been adequately accounted for.

The objective of this paper is to provide a comprehensive review on different planning aspects of DG integration. Considering global awareness to increase penetration of renewable energy sources, the review carried out in this paper particularly pays attention to RES based DGs. The objectives of DG integration and optimization techniques used for DG placement have been closely surveyed predominantly with reference to RES based DGs.

The remainder of paper is organized as follows: Section 2 provides an introduction to distributed generation. Various prevalent definitions of distributed generation have been surveyed. An overview of different distributed generation technologies has been presented. The technologies have been discussed along with their advantages and disadvantages. Further, benefits offered by DG integration have been reviewed. Section 3 presents major technical challenges encountered in integration of DGs. Section 4 elaborates various planning objectives as reported in literature. The planning objectives have been closely reviewed with respect to conventional DGs as well as RES based DGs. In Section 5, placement problem of DGs has been critically reviewed. Different optimization techniques used for DG placement along with their merits and demerits have been discussed. Section 6 provides an elaborate conclusion on planning of distributed generators. In order to provide a deep insight, research avenues have been critically discussed giving way to future research.

2. Distributed generation

Based on literature survey, it can be said that distributed generation has mostly been defined on the basis of capacity or location [1–7]. Table 1 presents a brief summary of different DG definitions from the perspective of capacity or location.

In this paper, authors have complied with the definition of distributed generation as proposed by Ackermann et al. [1] wherein distributed generation is defined in terms of location considering no restriction on capacity or type of DG technology used. Nevertheless, as suggested by Pepermans et al. [8] there can be various other criteria which can form the basis for defining DG. Some of these are depicted in Fig. 1.

The technological innovations and changing economic and regulatory environment have contributed to a global inclination towards distributed generation. As per International Energy Agency (IEA) [7], five major factors which have significantly increased interest towards distributed generation are as follows:

Table 1
Distributed generation definitions.

S. no.	DG definition	Perspective of DG definition	Reference
1.	Electric power generation source connected directly to distribution network or on customer side of meter	Location	Ackermann et al. [1]
2.	Small generating units installed close to load centres	Location	Borges and Falca~o [2] Griffin et al. [3] Kim et al. [4]
3.	Generation from a few kilowatts up to 50 MW	Capacity	EPRI [5]
4.	All generation units with a maximum capacity of 50 MW to 100 MW, which are usually connected to the distribution network and which are neither centrally planned nor dispatched	Capacity	CIGRE [6]
5.	Generating plant serving a customer on-site or providing support to a distribution network, connected to grid at distribution-level voltages	Location	IEA [7]
6.	Generation of electricity by facilities that are sufficiently smaller than central generating plants as to allow interconnection at nearly any point in power system	Capacity	IEEE [9]
7.	Electric power generation or storage (typically ranging from less than a kW to tens of MW) that is not a part of a large central power system and is located close to the load	Capacity and location	Dondi et al. [10]
8.	Small generation units of 30 MW or less located near consumer centres	Capacity and location	Chambers [11]

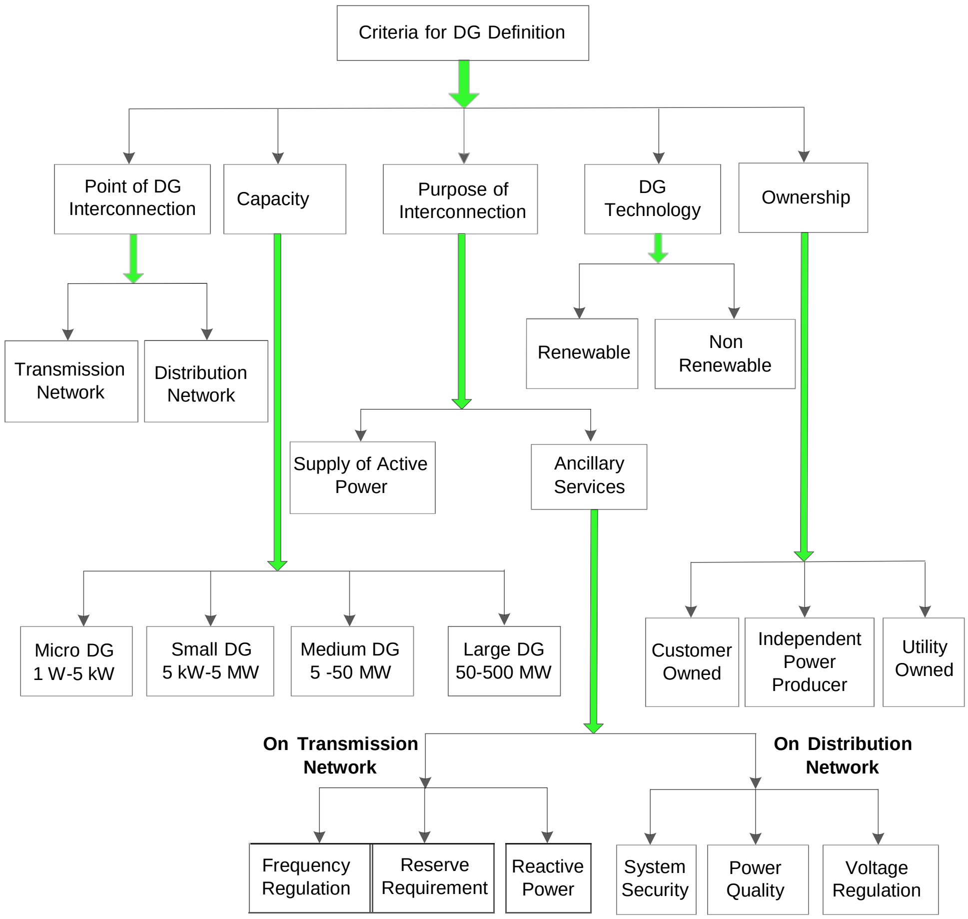

Fig. 1. Criteria for classification of DG.

- Development in DG technologies.
- Constraints on construction of new transmission lines.
- Increased customer demand for highly reliable electricity.
- Electricity market liberalization.
- Concerns about climate change.

Adequate combination of different DG technologies when connected to grid can impart high levels of reliability and security to power system. Fig. 2 illustrates the schematic of a grid connected hybrid power system employing DGs.

Overview of distributed generation technologies

Traditionally, diesel generators were considered synonymous to distributed generation due to their low cost and high reliability. However environmental issues and high fuel cost associated with diesel generators has always been a cause of concern. Over the years there has been a significant improvement in the development of broad array of other DG technologies. This section presents a brief overview of DG technologies. The DG technologies can be broadly classified as Renewable energy based, Non Renewable energy based and those which are not generating sources *per se* but facilitate efficient utilization of generated power. Electrical energy storage and load control strategies fall under last category [12]. Various DG [12–17] technologies are depicted in Fig. 3 and are discussed in following subsections.

Non renewable DG sources

The most popular DG technology based on non renewable sources is diesel generator which belongs to the category of reciprocating engines. Diesel generators are quite suitable for autonomous application. They can be started and shut down almost spontaneously owing to low inertia thus making them a viable choice for back up applications [13]. Technological developments over the last decade have given way to two new fossil fuel based technologies *viz.* micro turbines and fuel cell.

Micro turbines are mechanically simple, single shaft, high speed devices. Natural gas is the primary fuel used in micro turbines although biogas is also being pursued. It is a developing technology wherein an increase in efficiency and decline in operating cost is expected. Micro turbines are not very environment friendly owing to harmful emissions. Nevertheless, the emissions from natural gas are relatively lower in comparison with that of other fossil fuels.

Fuel cells are well suited for distributed generation applications. Fuel cells are fast gaining popularity since they are efficient and environment friendly [18]. There are many types of fuel cells currently under development including phosphoric acid, proton exchange membrane, molten carbonate, solid oxide, alkaline and direct methanol. The main difference lies in the electrolytic material of each type. Hydrogen is used as fuel which is extracted from hydrogen rich sources such as gasoline, propane or natural gas using a fuel reformer. Hydrogen can also be produced from water using electrolysis using power generated from RES in which case fuel cell can be regarded as RES based DG.

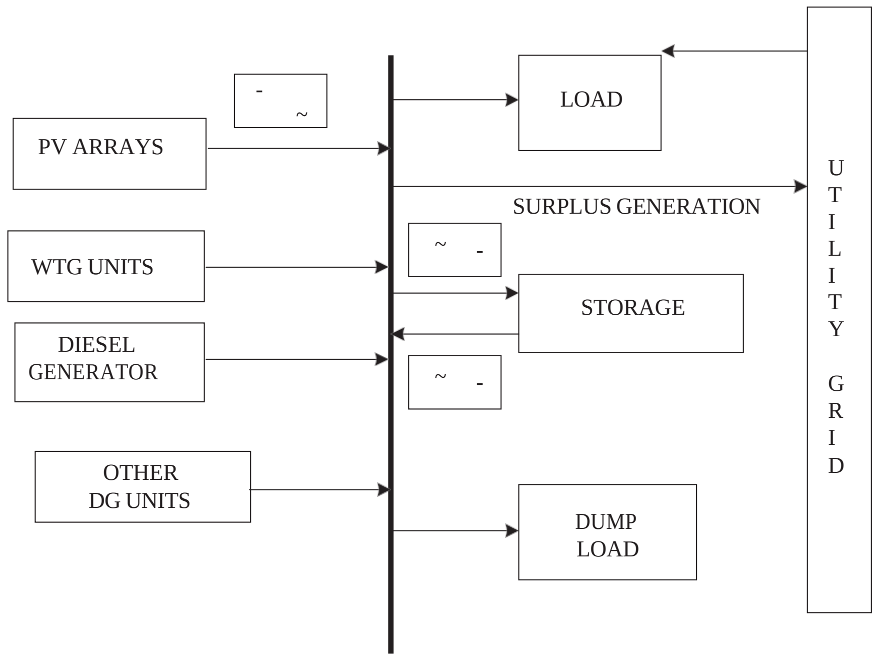

Fig. 2. Grid connected distributed generators.

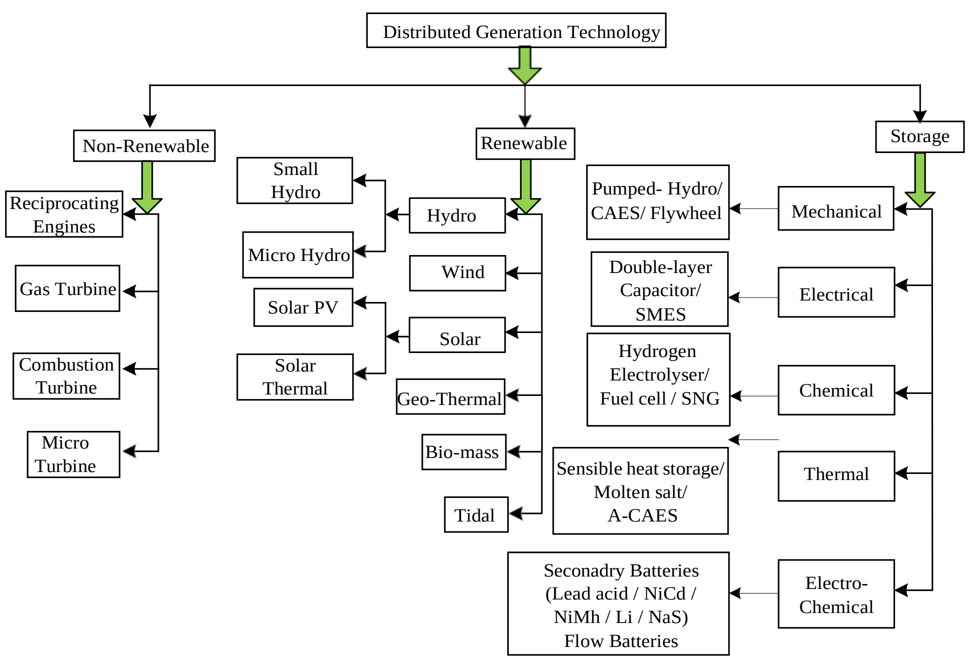

Fig. 3. Distributed generation technologies.

Renewable DG sources

In addition to being replenishable, the chief reason for popularity of renewable energy sources (RES) is its availability worldwide over wide geographical areas. This is quite unlike conventional resources (oil, natural gas) which are concentrated in specific countries. The RES comprise of photovoltaic (PV), wind, hydro, geo-thermal, tidal and bio fuel. Recent years have seen a significant increase in deployment of RES based DGs to grid. This is mainly attributed to two reasons [19]:

- The costs associated with RES based generation and storage is now on declining trend thus giving way to their large scale deployment on the grid.
- The traditional architecture of grid being based entirely on central generation is weakening, giving way to a modular architecture comprising of interconnected microgrids with distributed generation.

Majority of literature available on RES based DGs is focussed on PV and wind energy sources. PV is one of the most expensive DG technologies and has a fairly large footprint. High costs associated with PV systems make them a niche technology which is justifiable on the basis of inexhaustible energy from the sun and environmental benefits associated with them. Wind energy has shown tremendous worldwide growth in recent years and is considered as one of the leading carbon free technologies. Apart

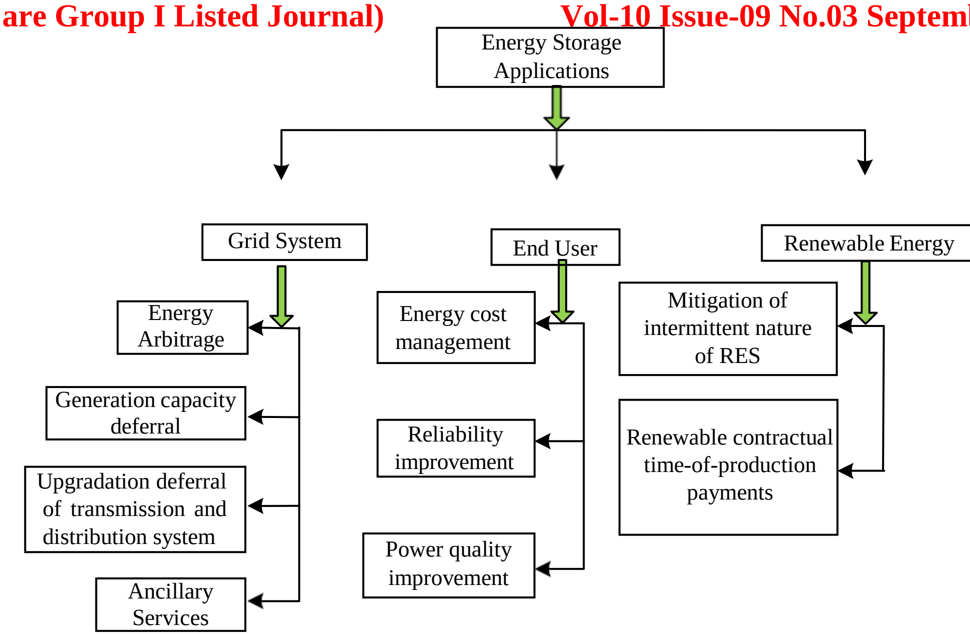

Fig. 4. Applications of energy storage.

from clean energy credentials, PV and wind also offer the advantage of providing a hedge against price volatility of fossil fuel based generation. However, intermittency is a major issue encountered with PV and wind energy systems making them less dispatchable and unsuitable for standalone applications. Efficient energy storage technologies have been seen as a viable option to suppress the mismatch between supply and demand.

Energy storage technologies

The power from RES such as PV and wind is dependent on meteorological conditions prevailing at that moment. Electrical energy storage can bridge the gap between power from these sources and load by supplying power during the periods of unavailability as well as storing the excess power during high periods of wind and sun. A wide range of storage technologies based on mechanical, chemical and physical principle are available. A classification of energy storage systems [14] based on energy form is shown in Fig. 3.

The integration of electrical energy storage offers multitudinous benefits to power utilities, transmission companies and end users. The major applications of energy storage are summarised in Fig. 4 [17,20,21].

The storage deployed to serve a specific application can be used to provide several other benefits. The selection of type of storage technology is based on the application which energy storage is required to serve. One of the major issues with energy storage is high cost associated with them. Apart from pumped hydro, other storage technologies need improvement both in terms of performance as well as cost.

Energy Storage offers an incredible technological solution to curb stochastic nature of RES without having to resort to fossil fuel based technologies for back up. Certain well established technologies such as pumped hydro offer an economical storage solution with substantial storage capacity. However specific geographical considerations and exhaustive infrastructure are required to install pumped hydro. Similarly compressed air energy storage (CAES) also has geographical restrictions besides low round trip efficiency. Other technologies such as Super capacitors, SMES and flywheel can be rapidly deployed but currently offer restricted capacity.

Battery energy storage is one technology that is now attracting considerable interest for autonomous applications as well as for large scale deployment on the grid. It can be used for load following applications thereby dealing with essentially intermittent nature of PV and wind sources.

Benefits of DG integration

DG integration fetches a lot of benefits which have been closely followed in various research papers. A broad classification of benefits is discussed in following subsections [22–29].

Technical benefits

- Integration of DG at strategic locations leads to reduced line losses.
- Integration of DG provides enhanced voltage support thereby improving voltage profile.
- Improved power quality.
- Enhancement in system reliability and security.

Economic benefits

- Deferred investments for up gradation of facilities.
- Certain DG technologies such as PV and wind have lower operation and maintenance cost.
- System productivity is enhanced due to diversification of resources.
- Integration of RES based DGs provides substantial environmental benefits. This results in an indirect monetary benefit in terms of reduced health care costs.
- Reduced fuel costs due to increased overall efficiency.
- Reduced reserve requirements and associated costs.
- Lower operating costs due to peak shaving.

Environmental benefits

- Reduced emissions of pollutants.
- Encouragement to RES based generation.

Table 2
DG benefits reported in literature.

S. no.	Distributed generator benefit	Type of DG technology	References
1.	Loss reduction	Conventional	Borges and Falca~o [2]
		Conventional	Chiradeja and Ramakumar [22]
		Conventional	Chiradeja [23]
		Conventional and RES	Quezada et al. [38]
		RES	Atwa et al. [75]
		Conventional	Abou El-Ela et al. [79]
		Conventional	Acharya et al. [80]
		Conventional	Kashem et al. [81]
		Conventional	Maciel and Padilha [85]
2.	Reliability	Conventional	Borges and Falca~o [2]
		Conventional	Waseem et al. [26]
		Conventional	Neto et al. [51]
		Conventional	Pilo et al. [55]
		Conventional	Costa and Matos [57]
		Conventional	Pregelj et al. [58]
		RES	Atwa et al. [59,60]
		RES	Ming et al. [61]
3.	Environmental	Conventional	Chiradeja and Ramakumar [22]
		Conventional and RES (stochastic behaviour not considered)	Qian et al. [24]
		RES	Chedid et al. [42]
		RES	Wang et al. [43]
		Conventional and RES	Katsigiannis et al. [44]
4.	Economic	Conventional	Borges and Falca~o [2]
		Conventional	Gil and Joos [25]
		Conventional	Momoh et al. [27]
		Conventional and RES	Katsigiannis et al. [44]
		Conventional	Celli et al. [56]
5.	Voltage profile/power quality	Conventional	Borges and Falca~o [2]
		Conventional	Chiradeja and Ramakumar [22]
		RES	Carpinelli et al. [77]
		Conventional	Abou El-Ela et al. [79]
		Conventional	Maciel and Padilha [85]

With the integration of conventional fossil fuel based DGs, environmental benefits are indirectly obtained such as due to reduction in power generation resulting from reduced losses. On the contrary, the integration of RES based DGs fetch direct environmental benefits. This benefit has been greatly acknowledged and is the leading reason for worldwide popularity of RES based DGs despite of their capital intensive structure. Table 2 presents a summary of benefits reported in various research papers along with the type of DG technology considered in them.

As per a survey conducted jointly by Zpryme and IEEE Smart grid [30], the top three benefits of integrating DG are flexibility of interconnection, increased economic viability and improvement in system reliability. Fig. 5 offers a key insight into DG integration from the perspective of benefits.

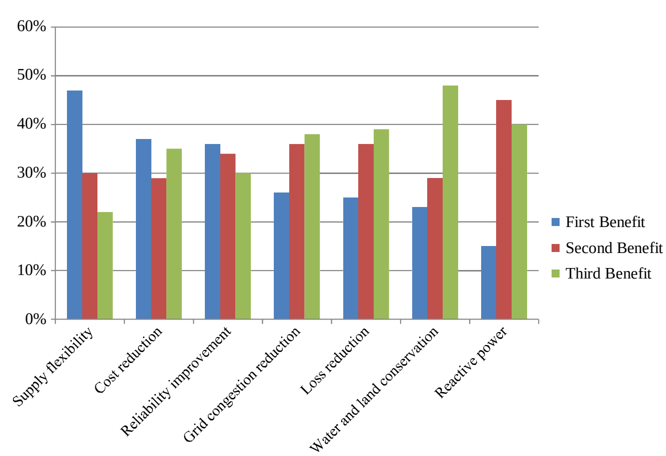

Fig. 5. Top three benefits of DG on the basis of survey conducted by Zpryme and IEEE Smart Grid [30].

3. Major issues with DG integration

Despite all advantages offered by DGs, impact of DG integration has to be carefully investigated in order to ensure optimum system performance. As suggested by Rodriguez and Alarcon [31] distribution networks have been designed to handle unidirectional power flow. Thus integration of distributed generation can result in voltage issues, problems in protection co-ordination and handling of reactive power [8,32,33]. Further if solar and wind based DGs are integrated; their stochastic nature can raise concerns regarding reliability of supply. High financial cost associated with RES based DGs can restrict their deployment on large scale. Lopes et al. [34] have classified DG integration issues into three categories viz. Technical, Commercial and Regulatory. Commercial and regulatory issues are affected by government policies and societal conditions and are not the focus of this review. Major technical issues associated with DG integration have been discussed in following subsections.

Impact on voltage regulation

The integration of DG can result in overvoltage issues. This need not be a problem when DG is connected to a system which is facing a low voltage problem. However, for weakly loaded systems, DG integration may result in high voltage problems thereby interfering with standard voltage regulation practices [2,35]. RES based DGs can further worsen the voltage conditions due to their intermittent nature and thus call for a thorough analysis before they are integrated into network.

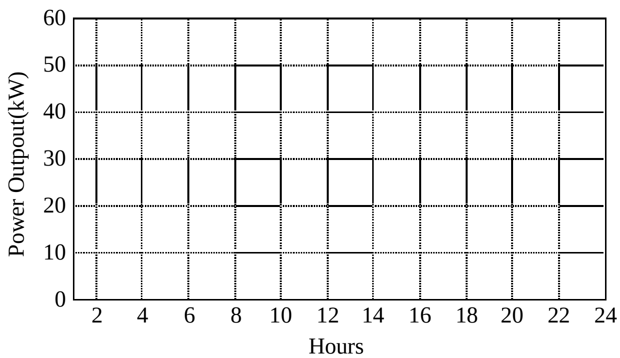

Fig. 6. Variation of output power generated by PV arrays over 24 h.

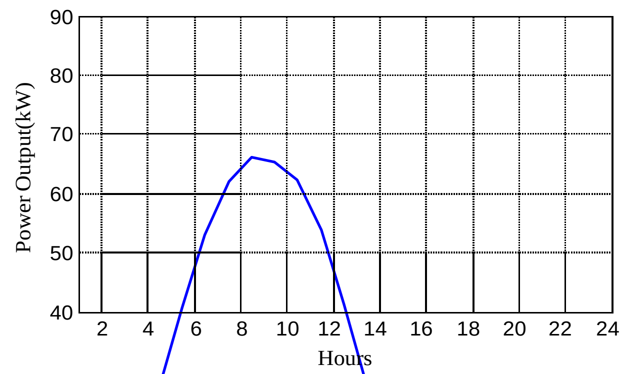

Fig. 7. Variation of output power generated by wind turbine generator over 24 h.

Masters [36] has presented an excellent discussion on voltage rise issues due to integration of DGs and has recommended following measures in order to handle the problem:

- Reduction of primary substation voltage.
- Installation of auto transformers and voltage regulators.
- Increasing conductor size.
- Shutting down of DG during light load conditions.

Impact on protection co-ordination

In present scenario, power grids are designed to operate for unidirectional flow of power from source to load. However DG integration can result in flow of power from load to source as well. This can affect protection system in following ways [2]:

(i) In presence of DGs, fault current is supplied both from power system and DG. This can result in increased short circuit current which can surpass breaker capacity.
(ii) Based on location of DG and fault, power flow from DG can result in a reduction in feeder current from substation. This may decrease relay sensitivity to operate during fault conditions.

Hence integration of DGs requires protection co-ordination capable of sustaining bi-directional power flows.

Impact on harmonics

In order to integrate RES based DGs with feeder, power electronic interface may be required which may result in injection of harmonics in the system. The type and severity will depend on power converter technology and interconnection configuration. IEEE 1547 interconnection standards [37] specify limit for harmonic distortion caused due to DG interconnection. Nevertheless, improved converter design along with efficient filters can be used to limit harmonic distortion considerably.

Impact on reactive power management

Reactive power management can be an issue with DG units which are incapable of providing reactive power (For e.g. traditional wind farms employing asynchronous generators) [38]. However DG units with power electronic interfaces are capable of delivering reactive power. Based on inverter technology used, DG units can both supply and consume reactive power as and when required. Nevertheless, sophisticated control techniques are required in order to ensure smooth mechanism.

Predictability of power output with RES based DGs

The RES based DGs such as photovoltaic arrays and wind turbine generators have highly intermittent nature making prediction and commitment of output power very difficult. Thus increased penetration of RES based DGs can make system less reliable [39,40]. For example, Figs. 6 and 7 show output power obtained from a PV array rated 80 kW and wind turbine generator rated 150 kW over a period of 24 h on a typical day in the month of January. As can be observed from Fig. 6, output power from PV arrays is not available for nearly half of the time. Also, it can be obseved from Fig. 7 that output from wind turbine generator is highly intermittent in nature. Thus, unlike conventional DGs which can provide a designated amount of power all the time, output from RES absed DGs is weather dependent.

The main challenge encountered in deployment of solar and wind based DGs is the impact of intermittent nature of these sources on various issues such as reliability, losses, voltage profile and cost.

4. Objectives of DG integration

Optimal resource integration and utilization should allow DGs to best compete in market. Integrating DG in distribution network does offer lots of benefits, but at the same time it presents many restrictions and limitations. Installing DG in distribution system will increase system planning problem complexity. These limitations and problems must be solved before choosing DG as a planning option [41]. The objectives reported in literature which form the basis of planning for integration of DGs are discussed in following subsections.

Maximization of renewable DG penetration

Integration of DGs to grid offer an opportunity to reduce reliance on fossil fuel based generation if DGs are based on RES. One of the most sought after benefits from renewable DG penetration is the environmental benefit obtained due to reduction in green house gas emissions. Renewable energy based technologies such as solar and wind are extremely clean and environment friendly. In fact environmental policies and regulations is one of the key drivers for increasing renewable energy penetration.

Chedid et al. [42] and Wang et al. [43] have used emission as one of the decision variables in determining optimal sizing of RES based DGs. Katsiagnnis et al. [44] formulated a multi objective optimization problem comprising of economical and environmental objectives. An interesting analysis has been presented by Doherty et al. [45] wherein the impact of variation of carbon tax

Table 3
DG modes of operation and corresponding impact on reliability.

Mode	Back-up source	Micro-grid	Parallel operation with utility grid
Operation	DGs operate in the event of failure of utility supply	DGs feed load autonomously. Excess power is injected into utility network	DG units can be modelled as [2]: • Constant active and reactive power injections • Negative load • Controlled voltage sources
Reliability benefits	Yes	No	Yes

in determining least cost generation portfolio has been analyzed. The work also asserted on role of increasing wind energy penetration in reducing emissions in least cost manner considering increasing fuel price scenarios. Qin et al. [46] performed an emission reduction analysis considering different DG technologies.

In coming years, increasing renewable energy penetration is expected to stay in forefront of DG planning owing to growing environmental concerns.

Maximization of system reliability

Customers are becoming increasingly aware of reliability of supply. In fact IEA [7] recognizes the provision of reliable power as most important future market niche for distributed generation. However, distribution system is designed to operate in radial fashion. Thus integrating DG sources can affect protection system. Thus IEEE 1547 standard [37] has established a criterion for interconnection of DG sources. The present standards do not allow islanded operation of DG owing to following reasons [35]:

- Development of an island during a standard reclosing operation may result in islanded DG units drifting out of phase during the dead period. This will result in utility connecting out of phase during reclosing.
- Islanding may also raise voltage and frequency issues.
- Islanding may pose issues regarding safety of operating personnel during utility repair operations.

Thus during events of fault, the current practice is to de-energize all DG sources connected to network and stay put disconnected until the fault is cleared. This practice hampers reliability benefits offered by DG integration [33,35,47]. The system reliability can be greatly improved, if DGs are allowed to operate in islanded mode. This goal can be achieved by coordinating intentional islanding of DG units [48]. Thus recent work on DG integration takes into consideration the islanded operation of DGs and its consequent impact on system reliability. Analyzing from the perspective of reliability, three different modes of DG operation are compared [49] in Table 3.

Borges et al. [2] determined reliability benefits obtained through DG installation by modelling DGs as controlled voltage sources. Brown [50] examined reliability in presence of DGs for different load duration curves representing different sectors. Reliability benefits through DG integration have also been reported in [51–53]. A composite reliability index comprising of weighted aggregation of SAIFI and SAIDI has been used as objective function [54]. Pilo et al. [55] have pointed out that intentional islanding could offer substantial benefits for nodes where alternative energy routes due to fault on main feeder are not available. However this is subjected to capability of DG being able to feed load of the island. The authors carried forward the work [56] where the DG location has been optimized to find a network arrangement in order to fetch maximum reliability benefits to customers.

Costa and Matos [57] have explored possibility of operating microgrids in isolation from upstream network and consequent reliability benefits offered to internal as well as some external customers. Pregelj et al. [58] demonstrated that placement of protection devices in DG enhanced feeders can have significant impact on reliability and determined optimal recloser positions through Genetic algorithm (GA). Wang and Chanan Singh [54] also determined optimum recloser position for fixed DG location using Ant Colony Optimization.

Thus reliability benefits of system in presence of DGs have been greatly acknowledged by researchers. However aforementioned references investigate reliability benefits in presence of conventional DG units only which ensure firm generation. The assessment of reliability impacts of conventional DGs can be easily done since output from these units is predictable. On the contrary, RES based DG units require exhaustive modelling as output available from these units is strongly correlated to weather conditions.

Pregelj et al. [58] have asserted that if only renewable DG with random energy input is placed in an island, it could not be relied upon to support its local load. This can lead to deterioration of reliability. Atwa et al. [59,60] have performed adequacy assessment studies by integrating RES based DGs into system. The impact of DG integration on reliability has been demonstrated by comparing operation of DG in anti-islanding and islanding mode. However, impact of different penetration level of DGs on system reliability has not been investigated. The system reliability in presence of wind based DGs considering intermittent nature of RES has also been investigated by Ming et al. [61]. The reliability evaluation has been carried out using MCS.

These references though take into account intermittent nature of RES based DGs, do not demonstrate the impact of intermittency on system reliability. The possibility of reliability enhancement with increased penetration of RES based DGs has also not been investigated.

With growth in renewable energy penetration, it is imperative to look for options to store energy during high periods of wind and sun which can be put to use later. This is vital in order to decrease mismatch between variation of renewable energy resources and electricity demand. Thus storage has been seen as a key enabler in increasing penetration of RES based DGs. Asserting on importance of integrating storage with RES based DGs, Paliwal et al. [62] have proposed an analytical technique for reliability evaluation of systems incorporating RES based DGs and storage. The authors have further implemented the developed technique [63] in conducting reliability constrained optimal sizing studies based on techno-socio-economic criteria.

The reliability assessment studies during islanded mode, incorporating RES based DGs and storage has not been reported in literature. With increasing interest of utilities worldwide in RES based technologies, it is essential to analyze impact of RES based DGs along with storage on reliability benefits for efficient and effective system planning.

Minimization of investment and operational cost

Economics has been one of the most important criteria in planning studies [64–67]. Though DG integration offers various benefits, it also incurs additional costs. Thus an optimised integration of DG units calls for an in depth cost–benefit analysis. El. Khattam et al. [64] have formulated objective function based on supply model chain. The objective is to minimize investment and operating costs of candidate local DGs, payments toward purchasing the required extra power by the DISCO, payment toward loss of compensation services as well as the investment cost of other chosen new facilities.

Celli et al. [56] have formulated a multi objective problem for DG planning and have proposed a methodology which permits system planners to decide the best compromise between cost of network upgrading, cost of power losses, cost of energy not supplied, and cost of energy required by served customers. The cost of deferred investment however cannot be considered relevant in respect of RES based DGs due to uncertainty in power provided by them. Borges et al. [2] formulated an objective function which is the ratio of benefits obtained due to cost of loss reduction to the investment and installation cost incurred in DG installation. An interesting approach to economic analysis has been put forward by Gautam et al. [68] wherein two distinct objective functions namely social welfare maximization and profit maximization have been formulated. Social welfare maximization takes into account consumer's perspective on the other hand profit maximization takes into account utility's perspective.

The references discussed above have carried out economic analysis considering integration of conventional generating units. However planning studies with RES based DGs require a more comprehensive economic analysis due to capital intensive structure of these technologies. As pointed out by Chedid et al. [42] if grid is available, integration of RES could only be justified on the grounds of reducing environmental emissions. Thus it is essential to incorporate cost of emissions while performing economic analysis.

Amongst the literature considering economic evaluation of systems considering RES based DGs, Chedid et al. [42] and Wang et al. [54] have proposed a multi objective formulation for determining optimal allocation of solar and wind energy based DGs and storage batteries for a grid connected hybrid power system. The multiple objectives of minimizing annualized capital cost while maximizing reliability and minimizing emissions have been targeted.

In majority of work reported in literature, economic analysis has been carried out considering conventional generating units only. The benefits offered through DG integration are sufficient enough to justify cost of integrating conventional generating units. However, scenario is different when RES based DGs are to be integrated. The RES based DGs have high capital costs associated with them. They win over conventional generating units when compared on the basis of operating costs and environmental benefits associated with them.

Besides, economic evaluation of integration of RES based DGs in conjunction with storage units has not been adequately dealt in literature. The global scenario is now in favour of maximizing RES penetration and storage is emerging as a strong solution to overcome the issues associated with intermittency of RES. Thus an exhaustive economic evaluation considering different planning scenarios is required in order to facilitate an in depth understanding of associated costs and benefits.

Reduction in system losses and improvement in voltage profile

One of the major benefits offered by DG integration is the reduction in electric line losses. Due to their proximity to load centres, DGs can positively contribute towards reduction in line losses particularly if the feeder is heavily loaded. However inappropriate size and location can lead to increase in losses and deterioration of voltage profile. Thus planning from the perspective of line loss reduction is a sizing as well as locational issue. There has been significant contribution by researchers in determining optimum size and location of DGs for line loss reduction. Following scenarios have been reported in literature:

- Determination of optimum DG size for a fixed location [22].
- Determination of optimum location for a fixed DG size [69,70].
- Determination of both optimum DG size and location [2,71–73].

Most of DG planning studies targeting loss reduction consider conventional DG units only [2,22,69–74]. However with renewable energy penetration on increasing trend, it is essential to analyze the impact of integration of RES based DGs on losses.

Carpinelli et al. [66] have considered a set of scenarios of power production from wind based DGs with their probabilities of occurrence. However the correlation between load and RES has not been considered. An effective analysis has been put forward by Quezada et al. [38] wherein effect of different DG technologies, penetration levels, DG dispersion and location and reactive power control strategies on system losses has been examined. It has been examined by the authors that wind turbines have least positive impact on losses due to their highly intermittent nature. Energy from PV, though unavailable for more than half of the time over a day, follows daily load variations more efficiently. The authors have also examined the impact of reactive power control capabilities of DG on system losses. However, penetration level as defined in work does not ensure that for every considered time interval, penetration of DG units will be equal to the defined one. This is significant in context with RES based DGs due to their stochastic nature. Besides, although authors have asserted the impact of DG placement on system losses, optimal placement of DG has not been targeted in this work.

In a recent work proposed by Atwa et al. [75], a methodology for optimally allocating different types of RES based DGs for loss reduction has been proposed. The methodology is based on generating a probabilistic generation model that combines all possible operating conditions of RES based DGs along with their probabilities of occurrence. An optimal generation mix which serves maximum loss reduction has then been obtained. The authors have considered penetration level as a percentage of peak load and impact of intermittency on penetration level has not been examined. The DG locations have also been assumed to be fixed and locational impact of DG units has not been examined.

Integration of DGs can have significant impact on voltage profile of distribution grid. The presence of DG may raise system voltage slightly [35]. This will not create any problem, if the consumers connected to network had been experiencing low voltages wherein DG integration will provide required voltage support and will contribute towards a flat voltage profile. However, if consumers had a normal voltage profile earlier, the DG integration may cause voltage to even cross defined upper limit. Thus based on existing network and loading conditions, voltage profile has been used as an objective [76–79] or a constraint [2,52,75,78] in DG planning problem.

Chiradeja and Ramakumar [22] have proposed two alternate approaches to quantify benefits offered by DG integration on voltage profile. The first approach uses weighting factors based on importance and criticality of different loads to evaluate voltage profile improvement index. The second approach calculates index based on how close the voltage profile is in comparison with the nominal voltage levels. Abou et al. [79] have formulated a multi objective problem wherein improvement in voltage profile has been considered as one of the objectives. The weighting factors associated with each of the objectives is chosen based upon degree of improvement desired.

Table 4
Comparison of different techniques.

Optimization technique	Benefits	Drawbacks	Objective function	DG technology	Reference
Analytical technique	• Computing time is short • Easy to implement • Non-iterative in nature • Unlike other techniques, does not pose convergence problems	• When problem becomes complex, assumptions used in order to simplify problem may override accuracy of solution • Lacks robustness	Loss minimization	Conventional and RES	Wang and Nehrir [69]
			Loss minimization	Conventional	Gozel et al. [71]
			Loss minimization	Conventional	Acharya et al. [80]
			Loss minimization	Conventional	Kashem et al. [81]
			Minimization of loss, line loading and reactive power	Conventional	Rau et al. [82]
Genetic algorithm	• Can rapidly locate solutions, even for large search spaces • Works with discrete and continuous parameters • Bad proposals do not affect end solution negatively as they are discarded • Very useful for complex and loosely defined problems • No derivatives needed	• Repeated fitness function evaluation for large and complex problems may be time consuming • May not suggest best solution always, possibility of trapping into local optima • Lack of accuracy, not suitable when a high quality solution is required	Benefit/cost ratio maximization	Conventional	Borges and Falca~o [2]
			Service quality improvement	Conventional	Teng et al. [53]
			Voltage profile improvement, maximizing spinning reserve, loss and power flow minimization	Conventional	Abou et al. [79]
Tabu search	• Has explicit memory • Allows non-improving solution to be accepted in order to escape from a local optimum • Applicable to both discrete and continuous solution spaces • Effective for larger and complicated problems as compared to other approaches	• Too many parameters to be determined • Number of iterations could be very large • Global optimum may not be found and largely depends on parameter settings	Loss minimization	Conventional	Nara et al. [84]
			Loss minimization voltage regulation short circuit level	Conventional	Maciel and Padilha [85]
Particle swarm optimization	• No overlapping and mutation • Simplified calculation • Adopts real number code and it is decided directly by solution	• Cannot work out problems of scattering and optimization	Voltage profile improvement, minimization of loss and emissions	Conventional and RES	Jain et al. [41]
			Power quality	Conventional	Raj et al. [86]
			Loss minimization	Conventional	Wong et al. [87]
Ant colony algorithm	• Inherent parallelism • Positive feedback accounts for rapid discovery of good solutions	• Theoretical analysis is difficult • Sequences of random decisions (not independent) • Probability distribution changes by iteration • Research is experimental rather than theoretical • Time to convergence uncertain (but convergence is guaranteed)	Maximization of reliability	Conventional	Wang and Chanan Singh [54]
			Cost minimization	Conventional	Falaghi et al. [88]
Simulated annealing	• Ease of implementation • Ability to provide reasonably good solutions for many combinatorial problems • Robustness	• Large computing time	Loss and emissions minimization	Conventional	Sutthibun and Bhasaputra [89]
Hybrid approaches	• Higher efficiency • Higher possibility of global optima • Less computational time	• Increased complexity	Bellman-ZadehþFuzzy logic	Loss minimization voltage profile improvement cable loading	Conventional	Barin et al. [52]
		Genetic algorithmþsimulated Annealing	Loss minimization	Conventional	Gandomkar et al. [90]
		Genetic algorithmþ Herford Ranch Algorithm	Loss minimization	Conventional	Gandomkar et al. [91]
		PSOþShuffled frog leaping algorithm	Loss minimization voltage profile improvement transient stability improvement	Conventional	Nayeripour et al. [95]

Based on literature review it can be concluded that though impact of integration of conventional DG units on line losses and voltage profile has been widely studied, majority of studies fail to acknowledge the impact of intermittency of RES based DGs on line losses. With regards to studies analyzing the impact of variation of penetration level on system losses and voltage profile, it has been observed that penetration level as defined in literature does not take into account the stochastic nature of RES.

Besides, given the intermittent nature of RES based DGs, integration of storage has been found essential in order to provide firm support to renewables. With the increasing inclination of RES, storage integration is expected to gain increasing importance in near future. However, none of the analyses consider the impact of adding storage units along with RES based DGs on system losses.

Thus a more exhaustive formulation is needed in order to effectively investigate the impact of RES based DGs and storage on system losses and voltage profile. Moreover, in context of RES based DGs, the penetration level corresponding to a time segment is a function of meteorological conditions of that particular time segment. Hence the assessment of repercussion of penetration level on system losses has to be investigated on hour by hour basis.

5. Placement of distributed generators

The installation of DG at optimum location boosts the performance of distribution system as well as presents a cost effective solution thereby giving a new dimension to distribution system planning. The positive impacts of optimal DG placement are reflected in terms of improved distribution system reliability, reduced customer interruption costs, reduction in losses and improvement in voltage profile as well as power quality at the consumer terminal. In order to enable electric utilities to obtain maximum benefits, the placement problem calls for state of art optimization techniques capable of handling multiple objectives simultaneously in order to present best feasible solution. DGs can have both negative and beneficial impact, depending on their size and location. With the advent of restructuring and performance based rates, it is critical for utilities to minimize the negative impact and maximize the positive impacts of DG.

Acharya et al. [80] have analyzed that inclusion of DGs beyond a particular capacity and at an unsuitable location can have a reverse impact on losses. Similarly, the effect of adding DG on network security and reliability will vary depending on its type and position and load at the connection point. Consequently, one or more sites on a given network may be optimal. Other technical, economic and environmental benefits also seek optimum siting and sizing of DG. Various techniques have been used for tracking optimal location of Distributed Generators.

Analytical technique has been used by Gozel et al. [71] with the objective of loss minimization wherein the impact of variable DG size has been taken into account. Various load models have also been considered. The placement problem considers only conventional DGs. Using the same technique Kashem et al. [81] have performed sensitivity analysis to determine size and location for minimization of losses. Acharya et al. [80] have made use of exact loss formula for determining optimal location from the perspective of loss minimization. With the similar objective, heuristic search has been employed [3] using B loss coefficient. Classical second order approach has been used [82] for determining optimal locations of distributed resources in a network to minimize losses, line loadings, and reactive power requirement.

Ghosh et al. [83] have used a conventional iterative search technique along with Newton Raphson load flow for DG placement in order to optimize cost and losses using weighting factor. The work also focuses on optimization of weighting factor. Tabu search (TS) has been used for DG placement for targeting both single and multiple objectives. Nara et al. [84] have used TS in conjunction with decomposition/co-ordination technique for placing DGs for loss minimization. Maciel and Padilha [85] have used multi objective Tabu search (MOTS) with objectives of loss minimization, short circuit level and voltage regulation. MOTS has been compared with NSGA-II (Non Dominated Sorting Genetic Algorithm) and has been found to be superior in terms of time and pareto sets.

Particle swarm optimization (PSO) has been widely used for solving DG placement problem. Raj et al. [86] have employed PSO for identifying optimum DG capacity and location for enhancing power quality while Wong et al. [87] have focussed on reduction in power losses subjected to constraints on voltage limits.

Ant colony optimization (ACO) has been used by Wang and Chanan Singh [54] for optimum placement of reclosers and distributed generators. A composite reliability index is used as objective function in the optimization procedure. ACO has also been compared with GA and has shown encouraging results. Falaghi et al. [88] have modelled DG as constant power source and have employed ACO for minimization of total costs associated with DG integration. Simulated Annealing has been used by Sutthibun and Bhasaputra [89] for DG placement with objective of minimization of power loss and emissions. The results obtained have been compared with TS and GA and have been found better in terms of computational time.

GA is one of the most popular approaches for DG placement problem owing to its simplicity. A multi objective optimization problem has been formulated by Abou et al. [79] using weighted sum technique. The results have also been compared with conventional linear programming approach. Borges and Falca~o [2] have used GA for optimal DG units allocation and sizing in order to maximize a benefit/cost relation, where the benefit is measured by reduction of electrical losses and cost is dependent on investment and installation. Constraints to guarantee acceptable reliability level and voltage profile along the feeders are incorporated. Value based DG placement for overall improvement in service quality has been obtained through GA by Teng et al. [53]. GA has been found to be very effective in area of DG allocation; however it is not very efficient in determining the absolute optimum. Therefore it is not the obvious choice when the high quality solutions are desired. To overcome this drawback, GA is hybridised with other techniques in order to improve its efficiency. Gandomkar et al. [90] have used GA in conjunction with simulated annealing and have demonstrated its ability to produce high class solutions in comparison with classic genetic algorithm. In order to overcome the defects of existing simple genetic algorithm (SGA), Hereford Ranch Algorithm (HRA), has been used by Gandomkar et al. [91] and Kim et al. [4] to search optimal site and size of DG in distribution feeders. HRA uses sexual differentiation and selective breeding in choosing parents for genetic string. A multi-objective approach based on Bellman–Zadeh algorithm and fuzzy logic has been used to evaluate qualitative and quantitative criteria to determine appropriate DG site by Barin et al. [52].

Thus, a wide variety of techniques have been used to solve DG placement problem. Analytical techniques, though computationally efficient, might not be suitable for complex problems. Metaheuristic and heuristic approaches can offer a more feasible and simplified solution. However this may lead to a compromise in solution quality and computational time.

Majority of placement problems reported in literature [2,52,54,71,79–89] focus on placement of conventional generating units. Very few references are available for placement of RES based DGs. Amongst the literature on placement of RES based DGs, Chiradeja and Ramakumar [92] have put forward a probabilistic approach for analyzing impact of addition of WTG units on voltage profile improvement. Probabilistic modelling of WTG units has also been considered by Carpinelli et al. [66]. Atwa et al. [75] have proposed a mixed integer non linear programming based approach to determine optimal generation resource mix and their respective locations for RES based DGs. Wang and Nehrir [69] have used analytical technique for DG placement in both radial and networked systems for minimization of power losses subjected to voltage constraints. Both time invariant and time variant DGs have been used in the analysis. Jain et al. [41] have used a multi objective PSO for DG placement targeting multiple objectives *viz.* improvement in voltage profile, reduction in environmental emissions and line losses, minimization of investment cost associated

Table 5
Summary of literature survey.

Inference drawn from literature survey	Authors' critical comments
Planning is focused on DG integration using conventional DGs	Increasing share of RES in power sector calls for refined planning models for integrating RES based DGs
Integration of RES based DGs to the grid does not consider possibility of ensuring firm capacity addition from these resources	Without ensuring firm capacity addition, capacity deferral cannot be achieved
Planning of grid connected RES based DGs in collaboration with storage has not been adequately dealt in literature	Integration of storage becomes essential at higher penetration levels. Thus impact of storage on technical and economic parameters has to be carefully investigated
Reliability benefits offered by DG integration mostly focus on conventional DGs	Due to stochastic behaviour of RES based DGs, the reliability assessment becomes much more complicated. Impact of RES based DGs on system reliability in grid connected and islanded mode has to be analysed
Conventional reliability indices have been used in reliability evaluation studies	Conventional indices fail to acknowledge stochastic behaviour of RES and energy limited capabilities of storage
Cost evaluation is focused on DGs employing conventional generating units	Cost evaluation with RES based DGs and storage has to take into consideration their capital intensive structure and stochastic nature
Placement problem is primarily focused on conventional DGs	Placement of RES based DGs requires special consideration due to their stochastic behaviour
Placement of storage units has not been considered	Storage exhibits dual nature posing as load or source based on charging/discharging mode. Thus planning of storage integration calls for increased attention

with DG units. The wind and solar based units have been used by authors. However, uncertainties associated with these resources have not been considered.

Thus, placement problem of RES based DGs has not been duly addressed. Besides, none of the placement problems consider placement issues associated with storage units. With storage emerging as a prime solution to intermittency associated with RES based DGs, adequate mathematical models are required to address placement problem. The storage is an energy limited source and availability of energy is dependent on excess energy available from DGs. The major problem encountered in placement of storage is due to the fact that storage behaves as a source when it is in discharging mode and behaves as a load when in charging mode. This can become particularly significant in systems with high DG penetration wherein the power drawn and supplied by storage is quite high. DG placement techniques have been thoroughly reviewed by Tan et al. [93]. A comparison of different approaches [94] has been shown in Table 4.

6. Conclusion

In this paper a comprehensive review on various issues related to planning of grid integrated distributed generators has been presented. Various DG technologies have been discussed with their associated merits and demerits. The benefits associated with DG integration along with a current survey on the weightage being given to each benefit have been presented. The assessment of popularity of benefits helps system planners in formulating planning problem more efficiently. A well formulated planning problem begins with a clear understanding of objectives. Hence in this paper an attempt has been made to investigate current status of research on different planning objectives.

DG placement problem forms an important area of power system planning. Inappropriate DG location may result in non optimal use of DG integration. When placed inappropriately, DG can have negative effect on system performance in terms of increased losses and degraded voltage profile. Various techniques used for DG placement problem have been investigated and a comparison of different approaches has also been presented.

It has been found from literature survey that the research is mostly focussed on DG integration planning using conventional DGs. However owing to growing environmental concerns, countries across the world are resorting to clean and sustainable renewable energy sources. The literature available on integration of RES based DGs does not give adequate treatment to stochastic behaviour of these resources.

The available literature does not report any systematic evaluation of benefits served by integration of DGs. The impact of integration of DGs on system reliability, losses, emissions, voltage profile and cost has to be carefully investigated in order to come up with an optimum system planning. The system planning studies conducted for analysing grid integration of DGs mainly focus on following issues:

i. Effect of DG integration on cost of network up gradation, power purchased from grid, emissions and reliability.
ii. Effect of DG integration on system losses and voltage profile.

Most of the system studies do not acknowledge the effect one parameter can have on the other. For instance, increasing grid penetration of RES based DGs has a positive impact on environmental factors. However when increased beyond a certain level, it can have detrimental effect on system reliability due to stochastic behaviour of RES. Similarly, increased penetration can also worsen system losses and voltage profile. Thus, system planning studies based on only few parameters can actually worsen scenario for the other. Hence there is a need for carrying out optimal planning studies considering various parameters in totality in order to ensure a well planned system and enhanced system performance. The authors' critical comments from literature survey have been summarised in Table 5.

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