Two-Stage Approach for the Assessment of Distributed Generation Capacity Mixture in Active Distribution Networks

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Distribution networks are limited with spare capacities to integrate increased volumes of distributed generation (DG). Network constraints and congestion, dynamic thermal limits, intermittent outputs, and the need for reduction in greenhouse gas emission increase the complexity of capturing optimal DG mixture that can safely permit the optimal operation. This paper investigates this problem in detail and proposes a two-stage approach for the quantification of optimal DG capacity mixture in an active distribution network. The approach is aimed at operational planning and takes into account dynamic thermal limits, network internal benefit, and network external benefit and then optimizes samples of DG mixtures through sequential simulation. A case study is performed incorporating Wind and PV generation as intermittent DG and diesel units as standing reserve units. Results suggest that specific operating conditions in an active distribution network can dominate the optimal DG mixture. Wind and diesel hybrid operation can be the most beneficial DG mixture compared to any other DG combination. Dynamic thermal limits of assets can potentially control the type of DG of the optimized mixture.

I. INTRODUCTION

Modern distribution networks are operated with intermittent distributed generation (DG) including wind and PV (Photo Voltaic). The traditional distribution networks are operated in the past as passive distribution networks because of their demand could be supplied by central power generation. The passive distribution networks became active with the integration of DG and their controls. The load demand in an active distribution network can be supplied by central generation as well as distributed generation, giving increased opportunities for new DG technologies to share the load demand.

With the increased integration of Wind and PV (Photo Voltaic) into active distribution networks, the firm power supplies to loads are challenging. However, the impacts of intermittency in supplying the demand can be mitigated with the integrated use of modern energy storage technologies and diesel units. Not all wind farms are in close proximity with large-scale storage solutions, which on the other hand, obstruct the level of reduction of output power variations. This barrier increases the need for the deployment of fossil-fuelled DG plants, such as diesels, to mitigate intermittent effects. Diesel units are also constrained with inefficient operation at lower output levels and greenhouse gas emissions. Thus, the resource optimization is challenging in an active distribution network. [1]

One can argue that the benefits of intermittent DG should be assessed by considering combined benefits that are associated with benefits internal and external to a network in balancing the environmental sustainability with efficient, economic, and secure supply of electricity to consumers. The internal benefits of an active distribution network include the benefits offered by DG for the efficient, secure, and economic operation of the network and their extensions to end users. The external benefits include the potential reductions in greenhouse gas emissions to the environment. The internal benefits can generally be quantified through the incorporation of life cycle costs (LCCs) to leverage the life cycle of equipment associated effects with start-up and network operating costs.

Life cycle costing is a process to determine the sum of all the costs associated with an asset or part thereof, including acquisition, installation, operation and maintenance, refurbishment, and disposal costs. Greenhouse gases (GHGs) are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth’s surface, the atmosphere itself, and by clouds.

Increased integration of renewable power generation into distribution networks also requires an adequate evaluation of their contributions to assess the environmental impacts, network impacts, and economics of the overall production and utilization lifespan, including the construction and operating stages of renewable plants. [2]

Distributed generation capacity and related impacts have been evaluated in many contexts and the published literatures evidence them. Reference [3] explores the long term transmission expansion problem as a mixed integer non-linear problem. Wind and PV hybrid system generators are sized in [4] using a basic numerical algorithm for a stand-alone operation. DG location and sizes are explored in [5] to minimize the power losses and to improve the reliability by combined application of discrete particle swarm optimization and genetic algorithms. Reference [6] investigates the optimal DG sizing problem as a nonlinear problem and explores the solutions by the application of sequential quadratic programming. Optimal DG location and sizes are further explored in [7] using the Kalman filtering algorithm and minimizing power losses. The maximization of DG size and reduction of power losses are investigated in [8]. Reference [9] investigates the optimal size of DG and their best location using genetic algorithms to maximize the system load margin. DG capacity investment is studied in [10] with cost-benefit analysis. Reference [11] formulate the DG optimization problem as a mixed integer nonlinear problem for the distribution network planning. An approach that maximizes benefits to DG owners and utility is proposed in [12]. In [13] the distribution network capacity is assessed using Monte Carlo simulation for the integration of wind power generation. Reference [14] proposes a bi-level programming model to solve a probabilistic optimal power flow problem for the distributed wind generation planning. A method is proposed in [15] to allocate different types of DG by formulating the problem as mixed integer nonlinear problem. Reference [16] proposes an approach to assess the security of supply with increased penetration of wind power while minimizing the level of shed loads. Reference [17] explores the state of art of methods and models used in optimal DG placement studies. Reference [18] assess the worth of DG installations taking into account differed investment, reduction in energy losses, and the reliability improvement.

This paper proposes a two-stage approach to determine the decisive operating conditions in an active distribution network and then quantifies the optimal size of DG mixture. The approach incorporates network internal benefits, network external benefits, dynamic thermal limits, intermittent effects of DG, load demand variations at sector customers, and then optimizes samples in sequential simulation to result optimal DG mixture. Network benefits are assessed by minimizing the costs to offer a reduced tariff to the electricity consumers. Life cycle costs of generation assets, start-up costs, and operating costs are incorporated for assessing the DG mixture that results the maximum internal benefit. External benefits are quantified with the metric of reduction in greenhouse gas emission volumes. Both types of benefits are added by converting the external benefits into the level of reduction in carbon tax to quantify the hybrid benefit of the optimal DG mixture.

The first-stage of the approach is proposed for the off-line identification of decisive operating conditions that can be used as agents to determine the optimal DG capacity mixture in the second-stage. The second-stage incorporates the decisive operating condition(s) for the operational planning of the DG mixture. First stage assessment is a one-off assessment unless the network undergoes expansions or reinforcements that involve structural changes.

The hybrid approach potentially benefits distribution network operators, DG plant developers, and electricity consumers directly or indirectly. However, the primary beneficiary of the approach can be seen as distribution network operators because they are to pay the carbon tax for generating electricity with conventional techniques. On the other hand, the reduction in carbon tax benefits electricity consumers because of the potential reduction in electricity tariff.

The approach advances the published methods by optimally capturing the DG mixture in the context of global benefits that include network internal benefits and the network external benefits through the use of dynamic thermal limits of network assets.

The remaining sections of the paper are organized as follows. The details of the approach are presented in Section II. Section III presents the details of the case studies, results, and analysis. Section IV gives the merits of the approach. Section V provides extended remarks of the approach. Section VI concludes the findings.

II. Two-Stage Approach

Figure 1 shows the first-stage steps of the two-stage approach proposed to determine the optimal DG mixture, taking into account network internal benefits and benefits external to the network. The internal benefits are quantified through LCCs of generation assets, start-up costs, and operating costs of the network. The external benefits are quantified through GHG emissions. The approach considers diesel units are also as distributed generators that can buffer intermittent effects of renewable power generation to an extent.

A. First-stage of the approach

The first-stage of the approach is divided into four phases for the simplicity of explanations and to calculate the references of the optimal DG mixture. They are Phase A, Phase B, Phase C, and Phase D. Phase A, which is the base step, is used to model the base network with voltage and thermal limit constraints, and to perform A/C power flow analysis to determine the network health. Then, DG types and total capacities based on their geographical locations, network transport capacities at the deep end, and resource availabilities are inputted in addition to the costing data. Intermittencies of DG are modelled with time series of their output profiles. Time series of demand level variations and load growth of sector customers are also modelled by following the convergence of the load flow solution.

Next, the total costs are minimized for the operating conditions of samples. Samples are created to capture time related variations of demand. Thus, each sample captures a specific time period. Total costs are calculated by using the capital costs of needy plants, start-up costs, and operating costs of them to generate electricity. Capital costs at this phase are calculated using the investment costs of individual generating units without incorporating the life cycle cost components of them. The operating costs are calculated using costs of power generation resulting through the minimal energy losses followed up by minimal use of fossil fuel generation. The DG mixture is then calculated using the sequential simulation of optimised samples. The maximum DG capacity that results the minimum total costs by satisfying all operating conditions and constraints is considered as the base DG capacity of the network.

Then, dynamic thermal limits are applied onto the branches and the entire steps described above are repeated. The process provides two sets of results of which the first set is without dynamic thermal limits and the second set is with dynamic thermal limits. Both sets are separately taken into account for the remaining parts of the assessment.

During the sequential simulation, any violated operating condition is split into two groups. The first group considers a penalty cost for violating the operating limits that in turn added to the yearly running cost of the respective DG mixture. The second group discards entire DG combination of the sample, and assessment continues with remaining combinations of DG types.

Diesel generators of the network are operated only within the economic region of their outputs or in other words, diesel units are operated from 40% to 100% of their rated output capacities to minimise inefficiencies of the units. At each operating condition, the loading levels of diesel generators are monitored and if the output power of any unit is below 40% limit, then the generation of the operating condition is re-dispatched to reduce the output power of the other diesel units that are loaded more than 40%. If this attempt is not successful for the operating condition of the sample with all the network resources, then the corresponding unit is forced to shut down and the abilities of the remaining generating units to operate the network efficiently are determined. The load shedding is incorporated; however, it is the least priority option, and it is executed based on the availability of flexible loads (e.g. micro grid type loads) or loads contracted for the demand side management.

In Phase B, maximum DG mixture that gives the minimum total costs is determined based on the intermittent DG characteristics and an added objective of achieving the minimal cost of energy losses of the system. The cost of energy losses for the system is calculated by assuming that all the energy losses in the network are supplied by the diesel and other conventional generators of the network are centrally located. In other words, centrally connected conventional generators are assumed to generate an extra power to meet the power loses of the network. Thus, the approach minimises cost of conventional generation to reflect the minimal energy losses. This assumption provides the worst-case scenario because of the centrally connected conventional generators typically have the highest unit costs of supplying the energy to consumers through transportation barriers.

In phase C, LCCs of generation assets in place of capital costs of them are applied to determine the DG capacity mixture.

In Phase D, the same procedure as in Phase C is applied by additionally incorporating the greenhouse gas abatement provision of generation assets. Thus, the approach also minimises the GHG emission level to determine the optimal DG capacity mixture. Then, the carbon tax values are applied to the reduction in greenhouse gas emission tonnes, and the DG mixture for the network is calculated by integrating the costs result through network internal benefits and the external benefits. Equations (1) to (6) show the mathematical formulation of the problem to calculate DG mixture.

Min

$$F = \sum_{i \in NG} C_i (LCC_i) + \sum_{i \in NG} C_i (E_i) + C_{c-tax} \sum_{i \in NG} C_i (GHGT) \quad (1)$$

Subjected to:

$$P_i(V, \theta) = P_{G_i} - P_{D_i} \quad (2)$$

$$Q_i(V, \theta) = Q_{G_i} - Q_{D_i} \quad (3)$$

$$\left| S_{ij} \right| \leq S_{ij}^{\max} \quad (4)$$

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad (5)$$

$$P_{G_i}^{\min} \leq P_{G_i}(V, \theta) \leq P_{G_i}^{\max} \quad (6)$$

$$Q_{G_i}^{\min} \leq Q_{G_i}(V, \theta) \leq Q_{G_i}^{\max} \quad (7)$$

Where, $C_i(LCC_i)$ = life cycle cost of generators, $C_i(E_i)$ = cost of energy generation, C_{c-tax} = carbon tax, $C_i(GHGT_i)$ = greenhouse gas tonnes, NG = number of generators, P_i = real power injection at bus i, P_{G_i} = real power output of the generator connecting to bus i, P_{D_i} = the real power load connecting to bus i, Q_i = reactive power injection at bus i, Q_{G_i} = the reactive power output of the generator connecting to bus i, Q_{D_i} = the reactive power connecting to bus i, S_{ij} = power flow at a line from bus i to bus j, V_i = voltage magnitude at bus i, V = voltage, θ = angle, subscripts “min” and “max” give the lower and upper limits of constraints.

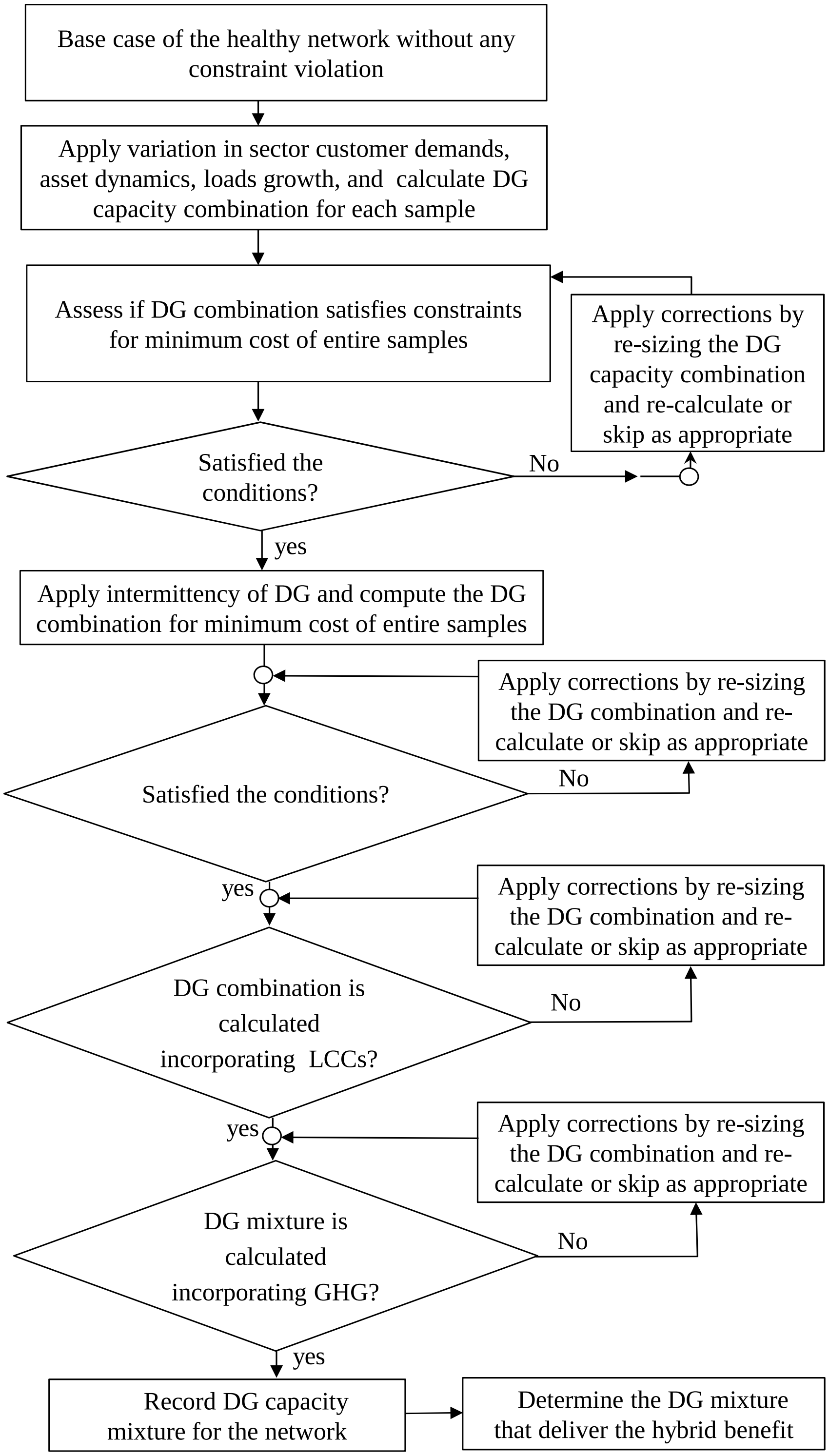


FIG. 1. Overview of the DG mixture assessment of the first stage

B. DG mixture with dynamic thermal limits (DTLs)

The approach classifies the samples in accordance with the dynamic thermal limits of branches and loading levels. As each sample represents a time duration which is continuously collated using sequential simulation, the optimized DG mixture comes out of the simulation also captures the dynamic thermal limits of assets. Depends on many factors including weather conditions, ambient temperature, operating temperature, humidity level, asset age, asset loading, frequencies of disturbances, and congestion, the dynamic thermal limits can either increase or decrease from the manufacturer specified limits. Taking into account these variations, the approach proposes three types of dynamic thermal limits. The first type uses the capacities of branches as the manufacturer specified limits. The second type considers the thermal limits are up rated by X% from the manufacturer specified limits. Third type considers the capacities of branches are de-rated by Y% from the manufacturer specified limits. Then, Z_1% of samples for DTL type 1, Z_2% of samples for DTL type 2, and Z_3% of samples for DTL type 3 ($Z_1\%+ Z_2\%+ Z_3\%=100\%$) are applied at each sample in the sequential simulation to quantify the optimal DG mixture for the network. In this process, at each sample, a random number between 0 and 1.0 is generated and it is compared with probabilities of experiencing type 1, type, 2, and type 3. Then, applying the Markov chain principle [19], the operating states of the assets (DTL type 1, DTL type 2, DTL type 3) are determined. In applying the Markov chain, the random number of the sample is compared with the probability of experiencing a particular state. If the random number is smaller than the probability of a state then the dynamic thermal type of this state is considered as the dynamic thermal limit of assets of the sample. For example, if the generator random number for the sample is R and the probability of experiencing an up-rated DTL is X, then if $R<X$, the network assets take the uprated DTL. Otherwise, the process continues through other states to find the DTL state for the assets of the sample. Similarly, the random numbers can be generated for each of the assets and then the dynamic thermal limits of each of the assets can be determined using the probabilities of states.

The level of up-rate or de-rate can be monitored by embedding smart sensors in the network assets. Such monitoring schemes are active in some of the pilot projects under the context of smart grids. The knowledge of the levels of uprated, rated, and de-rated thermal limits can be used to calculate the probability of states of dynamic thermal limits.

The first stage of the approach provides two major benefits. The first benefit is the quantification of the optimal DG mixture as described above. The second benefit is the identification of decisive sample(s) to use at the second stage of the assessment for operational planning.

C. Second- stage of the approach

The second-stage of the approach considers only the decisive operating condition(s) that could determine the optimal DG capacity mixture. This is because unless the network undergoes structural changes, the critical scenarios would not be affected. This argument was also validated by extended studies presented in Section III. The optimum DG mixture for increase or decrease in system demand or for different DG types can be calculated utilising the decisive sample(s). Thus, steps proposed in Sections IIA and IIB can be applied for the decisive samples to determine the optimal DG mixture corresponding to the varying load conditions of the network or for a change in DG type.

The second stage considers only the decisive sample(s) based operating condition(s) as oppose to the first stage, where entire samples of operating conditions are incorporated for the assessment. In this way, the processing time of the second stage of the simulation is significantly reduced and the distribution network operators can determine the optimal DG mixture periodically using the second stage steps.

III. Case Studies

Figure 2 shows the active distribution network model that is used for the case studies. Network shown in Figure 2 is a typical distribution network model due to its inheritance of radial and meshed feeders embedded with distributed generation. It spans over three zones. The first zone is a 13 bus radial configuration which has active and reactive power loads of 12 MW and 3 MVAr respectively. Its nominal operating voltages are from 0.69 kV to 132kV. The first zone demand can be supplied by a wind farm and a diesel plant. The second zone is a 27 bus single and double line configuration, which has active and reactive power loads of 18MW and 2MVAr respectively. Its nominal operating voltages are from 0.69 kV to 132kV. The demand can be supplied by a wind farm and a diesel plant. The third zone is a 12 bus radial feeder configuration which has active and reactive power loads of 14 MW and 3 MVAr respectively. Its nominal operating voltage varies from 11kV to 132kV.The demand can be supplied by a PV system and a diesel plant. Annual load growth is not taken into account for the case studies; however time series of sector customer demand variations at each hour and annual wind and PV power generations are incorporated. A depreciation rate of 7 % was used to calculate the net present value of the costs at each year. Greenhouse gas coefficient of 1.38 kg CO2-e/kWh was considered for the assessment. The other key technical data used for the assessment as follows. The minimum and maximum voltage limits of busses were 0.94PU and 1.06PU respectively. The capital cost of diesel units was 5000 $/kW. Capital cost of wind units was 1000$/kWh. Capital cost of PV system was 2000$/kW. The project Life was 25 years. Case study considered weekly samples spanning over a year. Figures 3 & 4 show the time series profiles of PV and wind power generation outputs, where p.u. values give the output power normalized by the installed capacities of the units. Technical data were extracted from an Australian Context.

Diesel units are modeled as alternators considering the steady state model of synchronous generators. Wind and PV can be modeled in two ways. The first method considers the output power level of Wind or PV at the steady state as negative loads. The level of output power is determined through the time series profiles of output power. For example, if the installed capacity of a Wind unit is S (MW), and time series profile gives the output level for the sample as y p.u. then a negative load is implemented as –Sy (MW). The second method considers, static generator to simulate the wind generator in which the output power, maximum output power, and minimum output power are set as Sy(MW). In theory, both methods give the same answer in the load flow problem. Loads are modeled as constant power loads. The case study applied the second method.

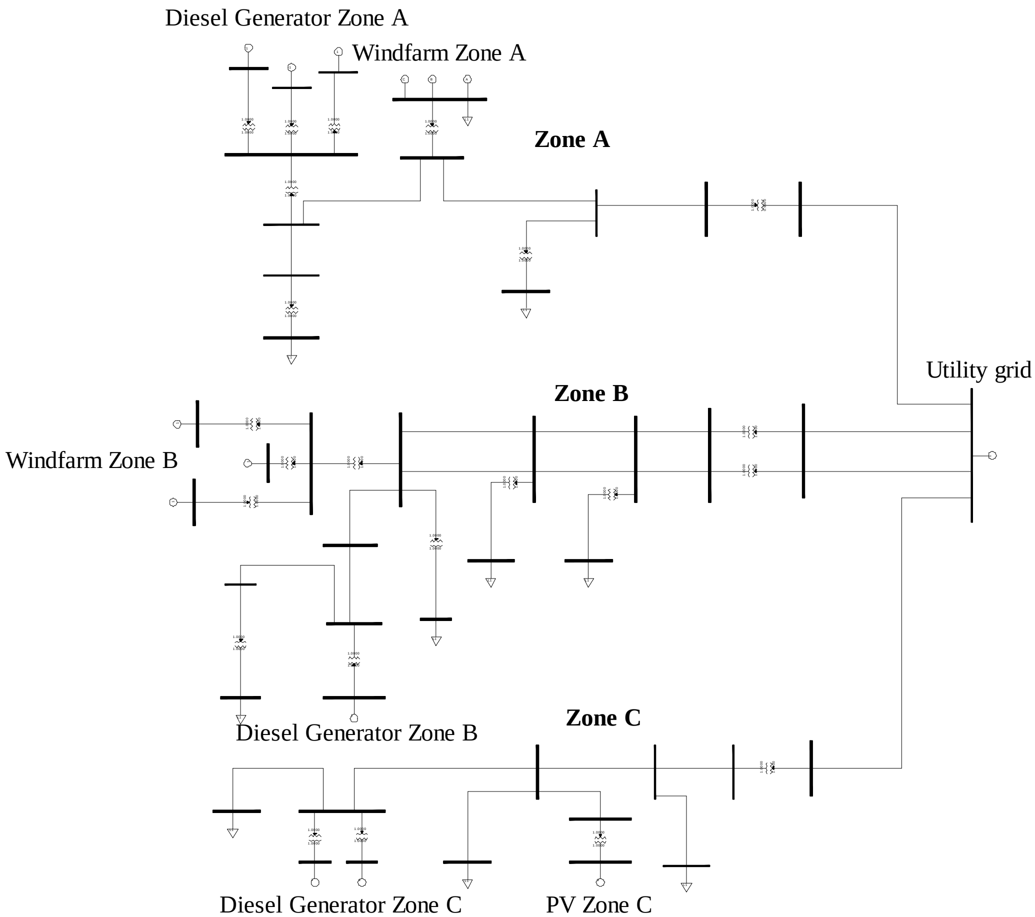


FIG. 2. Single line diagram of the active distribution network

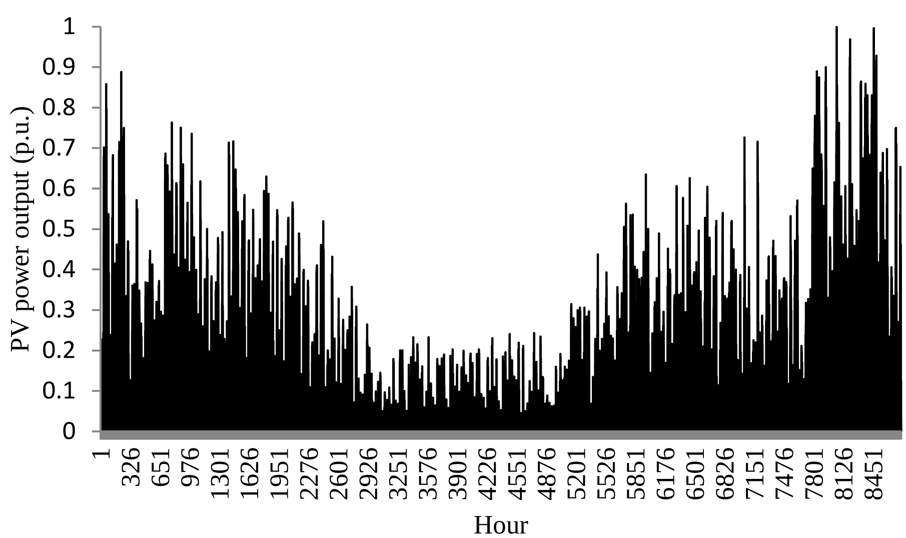
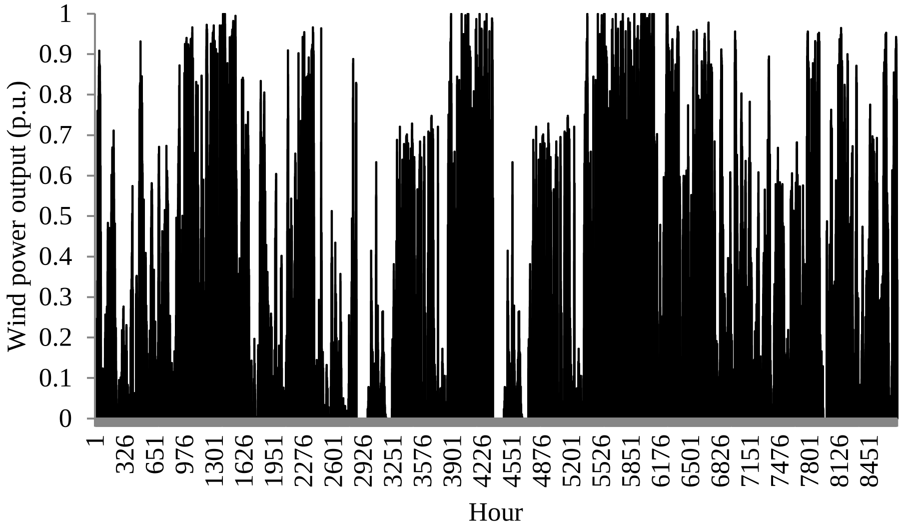


FIG. 3. Output characteristics of PV power generation in a typical year



FG. 4. Output characteristics of wind power generation in a typical year

A. DG mixture with varying loads and without GHG provision

Figure 5 shows the total installed capacities of Wind, PV, and diesels against variation in system loads without incorporating GHG provision. The variation in sample DG capacity mixture is due to the variation in system load and characteristics of output powers of intermittent generators. Such variation is realistic because of a week can have a lower wind gust requiring higher capacities of wind turbine units to serve the loads. Results further depict that the installed capacity combination at the 47th week is the best DG combination that minimizes the total costs while satisfying all operating conditions of the network. Thus, the operating condition of the 47th week is the operating condition of the decisive sample that can be used for the second-stage of the assessment to determine the optimal DG mixture for change in conditions other than structural changes of the network.

Figure 6 shows the total installed capacities of Wind, PV, and diesels with the rise in system demand in percentages of the base case load. The results depict that the magnitudes of installed capacities of generating units are varying for the entire range of loads, although the size of the most economic generating unit combination is yet to be determined by the sample operating condition of the 47th week. The scenario with the 90% of the base case load gives the largest installed capacity requirement of Wind compared to all other cases to meet any operating condition of the year. Beyond the 90% of the base case load, the system can be operated with lower installed capacities of wind because of the increased utilization of diesel generation, which delivers firm power outputs.

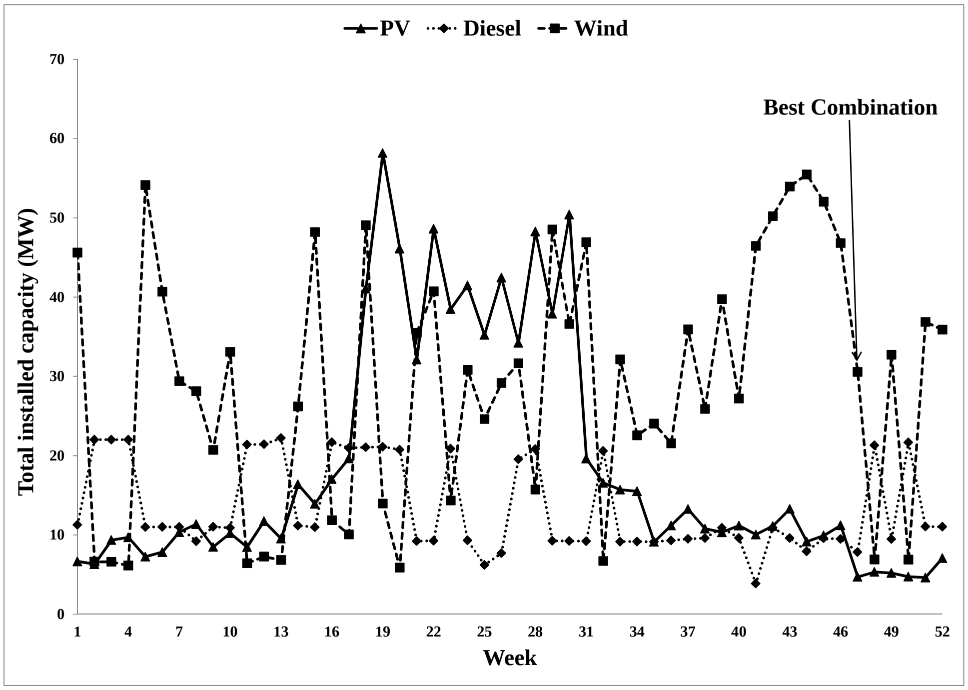


FIG. 5. Total capacities of DG needed to meet weekly operating conditions

At 90% of the base load demand, the penetrations of Wind and PV are more than the penetration levels of 100% load demand due to the level of wind gust and the insolation of the samples. This situation demands a comparatively larger DG capacity at this loading level. The loadings from 30% to 80% of the base case load follow a linear variation of total installed capacities of Wind, PV, and diesels. In addition, 80% of the base load gives the most economical DG mixture out of the scenarios of 30% to 80% of the base case load. The entire results in Figure 6 also suggest that the 47th week sample also captures the optimal DG mixture at the second-stage of the assessment.

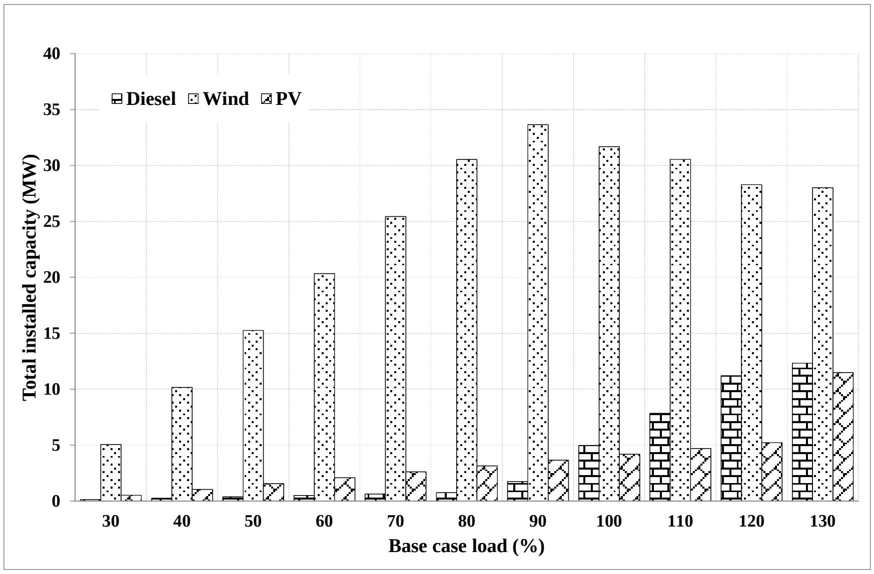


FIG. 6. Sum of the generating unit sizes vs. rise in system demand

When the demand is increased beyond the base case loading (100%), the load shares of diesel units increase due to the reduced generation of electricity from Wind and PV units. Another cause behind the change in load share patterns in Figure 6 is the excessive capital cost requirements at the higher installed capacities of Wind and PV plants to meet the entire range of operating conditions.

B. Effects of dynamic thermal limits without GHG provision

This part of the study considered the probabilities of experiencing DTL type 1, 2, and 3 respectively as 0, 1.0, and 0. Figure 7 shows the total costs of the mixtures of diesel/wind, diesel/ PV, and wind/ PV/ diesels systems with dynamic thermal limits of assets and varying demand levels for yearlong operating conditions. The GHG provision is not incorporated into the assessment. Results indicate that the hybrid operation of Wind and diesel generators give the lowest total costs out of all scenarios. The lowest cost is achieved at the thermal limit and load level of 110% and 100% respectively. In this network, the wind/ diesel hybrid system operation is less sensitive to the dynamic thermal limits and demand rise effects compared to the diesel/PV and diesel/PV/wind system operation.

Figure 8 shows the optimal benefit of DG mixture taking into account dynamic thermal limits and varying load conditions. The results suggest that the diesel/wind system operation is 22% less expensive than diesel/PV/wind system operation, and 36% less expensive than diesel/ PV system operation of this network.

C. Costs of DG combinations excluding GHG provision

Figure 9 shows the total costs of DG combinations of wind, PV, and diesel generators excluding GHG emission provision corresponding to weeks of the year. The results suggest that the optimal DG mixture can be determined by the 47th week operating condition if the GHG reduction benefits are excluded from the assessment. The DG mixture corresponding to the 47th week has a greater power generation from wind and PV and less power generation from diesels. This scenario also meets the annual demand of the network without violating constraints and offers the lowest total costs.

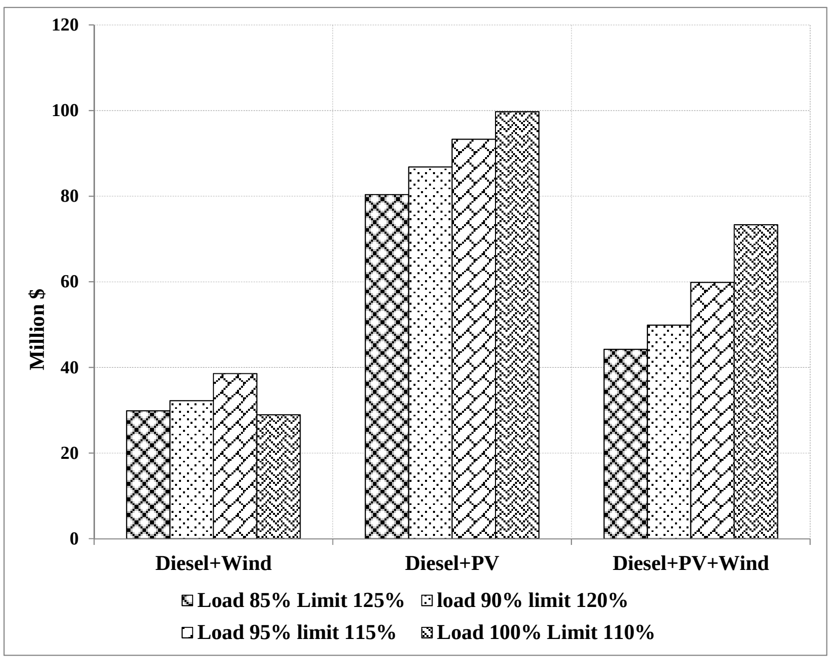


FIG. 7. Sensitivity of cost variation with dynamic thermal limits

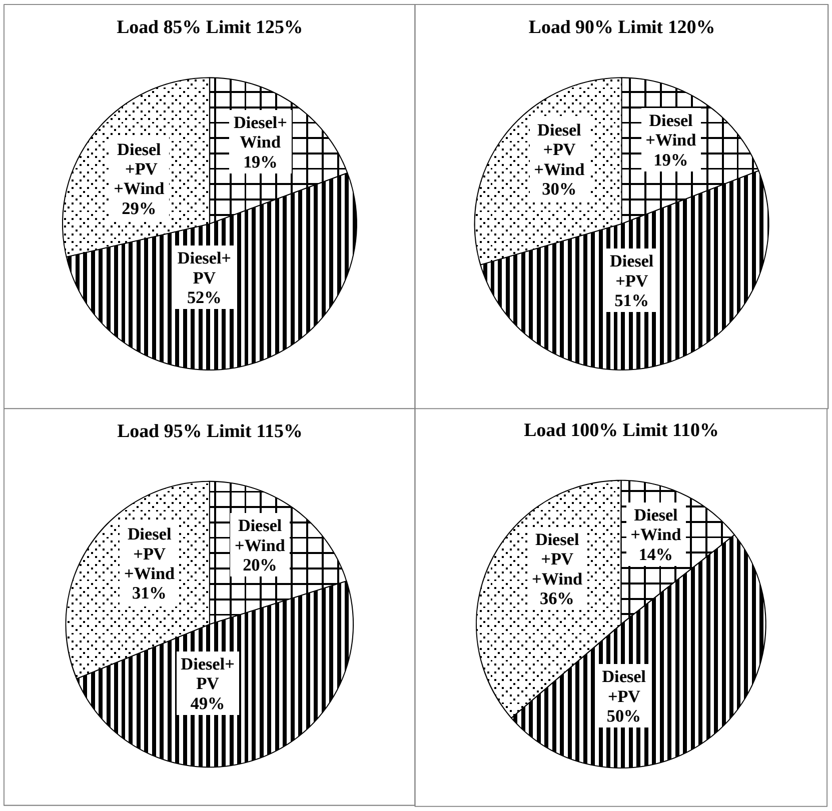


FIG. 8. Optimal benefit of DG mixture with dynamic thermal limits and varying load conditions

D. GHG emission of DG combinations

Figure 10 shows the greenhouse gas emission of the equivalent of CO_2 weights in tonnes against weekly scenarios of Figure 9. The results suggest that the DG unit combination corresponds to the 29th week configuration has the lowest GHG emission. Therefore, the operating condition at the 29th week can be considered as the operating condition of the scenario that determines the most beneficial DG unit combination with regard to benefits external to the network.

E. Ranking of costs of external and internal benefits

Figure 11 shows the costs ranks with internal benefits. The lowest-cost rank of internal benefit results at the operating condition of the 47th week. Figure 12 shows external benefit cost ranks corresponding to weekly combinations. The lowest rank is resulted at the operating condition of the 29th week.

F. Combined benefits

The cost ranks by combining internal and external benefits suggested that the most beneficial DG unit combination arises at the 41st week operating condition; however, it is not the best combination if either cost of internal benefit or cost of external benefit is considered separately. Detailed investigation of results suggested that the DG unit combination resulting through the 41st week operating condition shares a lower load with diesel units and much higher load with wind units.

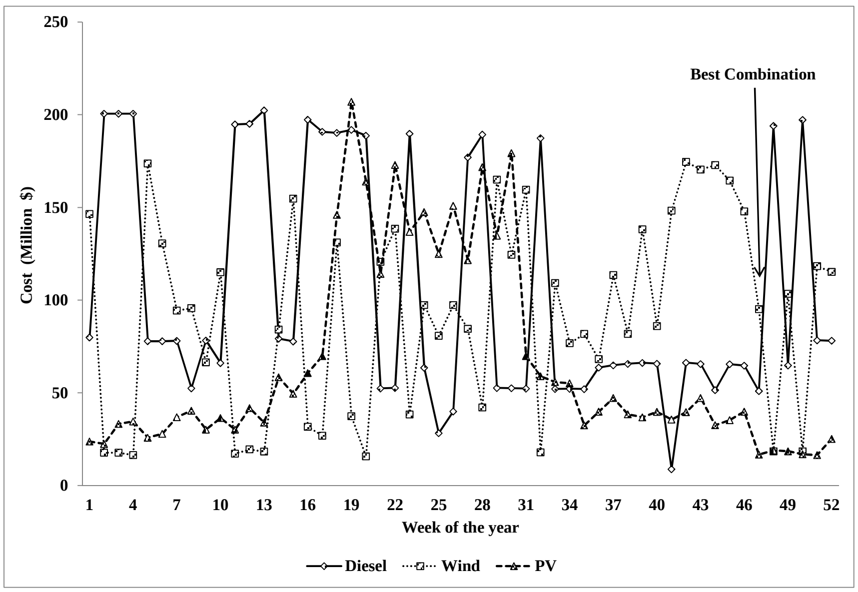


FIG. 9. Costs of DG combinations excluding GHG resulting cost

The optimised DG mixture that provides the maximum internal and external benefits arises with 46MW wind, 10MW PV and 4MVA diesels. If the objective is to prioritise only the internal benefits, then it could be achieved with 31MW wind, 5MW PV, and 8MVA diesels. Thus, having 15MW of wind and 5MW PV can replace the use of 5MVA diesel generation of the particular distribution network. Therefore, one can argue that only a significantly high volume of intermittent DG can take the place of firm power generating units in an active distribution network, even with dispersed connections.

G. Extended studies with internal benefits

Case studies are extended to assess the variation in total costs of internal benefits of the system when combinations of generation technologies are varied to supply the same demand of the load. In these scenarios, the most economical combination resulted at the hybrid system with diesel and wind units. This combination offers 12% less cost than the combination of diesel, wind, and PV. The results further suggest that the wind/diesel operation is 22% economical than that of PV/diesel operation for the particular network.

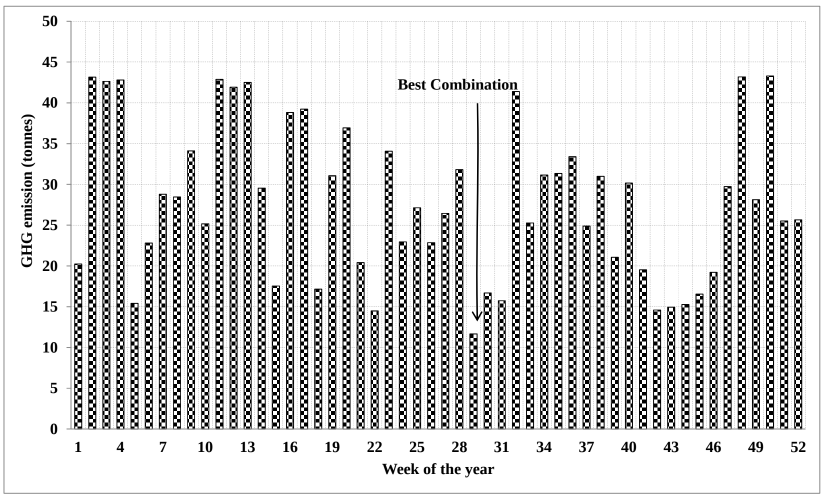


FIG.10. GHG emission of DG in FIG. 9

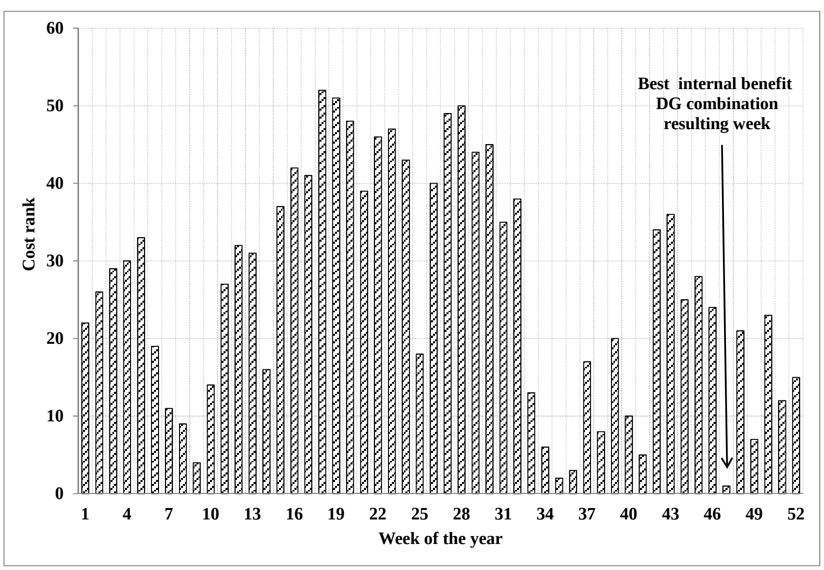


FIG. 11. Internal cost ranks based on internal benefit provision

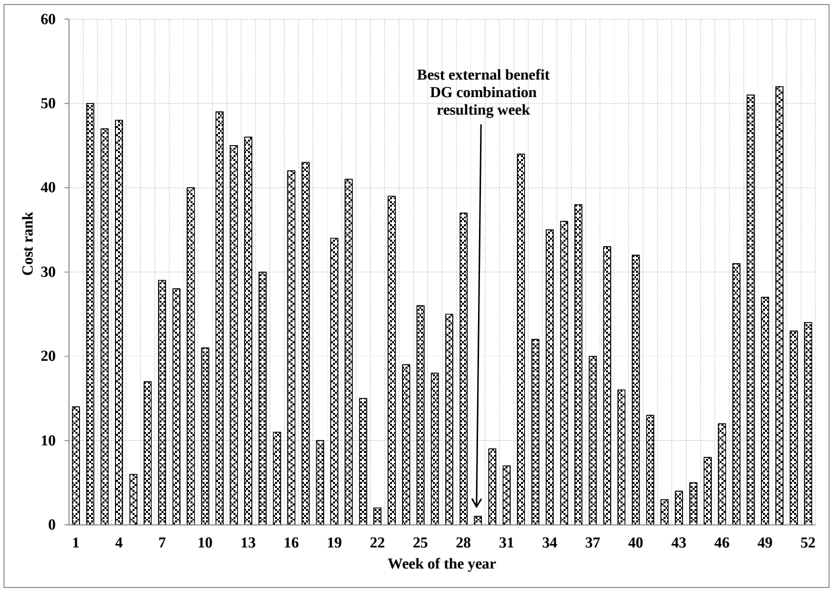


FIG. 12. External cost ranks based on external benefit provision

IV. MERITS OF THE APPROACH

The proposed approach takes into account dynamic thermal limits of assets, uncertainties, LCCs, and GHG abatement provision for determining the optimal DG mixture for an active distribution network. Because of the active power networks are embedded with a significantly large number of uncertainties, single stage optimal sizing of DG mixture can take a considerable processing time, which may not always be a sufficient solution for operational planning. In the short term operational planning, timely availability of optimal DG mixture does not only offer an accurate view of the distributed generation requirements but also offers the time to mitigate unexpected impacts from random penetration of intermittent DG.

In an active distribution network, the sector customer demand of the system can be varied randomly while different DG types are connected to the network. Having the second-stage of the approach to determine the closer view of the optimal DG mixture in a smaller processing time facilitates preparation of remedial actions in case of emergencies occur.

The proposed approach has several advantages over other approaches published in the literature. At first, the distribution network operators need to apply the first stage once and then the second stage for any change in demand level or availability of new DG types. Since the second stage takes a significantly smaller processing time, the users of the approach benefit from significantly lower processing times to determine optimal DG capacity mixture. Published literature explores DG capacities based on internal benefits in a limited scope; however this paper showed that capturing only the internal benefits does not necessarily capture true benefits that offer realistic values for the embedded generation. The third benefit is the extension of the traditional optimization problem to capture dynamic thermal limits through state random sampling. The approach also fits into smart grid environment in which the dynamic thermal limits play a key edge in optimizing the asset utilization.

V. EXTENDED REMARKS

The case studies can be enhanced further by taking into account forecasting data of loads, growth rates of intermittent generators, and expansion planning horizons of the network, in particular, the planning leads to structural changes. The approach can also be used to predict the feasible DG capacities that would mitigate short term operational planning challenges associated in an active distribution network.

VI. CONCLUSION

The paper proposes a two-stage approach for the assessment of optimal DG mixture that provides global benefits. The approach leads the published methods by comprehensively capturing the optimal DG mixture through internal and external benefits of an active distribution network, incorporating dynamic thermal limits, and improving the efficient operation of network assets. It takes into account costs of generating electricity, startup costs, LCCs of assets, GHG abatement effects, and dynamic thermal limits and then optimizes samples in sequential simulation. Case studies suggest that DG types and capacities in an active distribution network can be determined by specific operating conditions of the network. The DG mixture that provides internal benefit differs from the mixture that provides external benefit. Internal or external benefit offered DG mixture does not necessarily offer the combined benefits.

Case studies also depict that the wind and diesel unit hybrid operation can be cost less than the combined operation of diesel, wind, and PV units. The wind and diesel system operation can be more economical than PV and diesel system operation for the same operating condition. Dynamic thermal limits can control the DG type in an optimized mixture. Variation in system load does not necessarily affect the optimized DG mixture, although DG capacity levels can potentially be affected.

Optimal integration of DG is vital for active distribution networks in balancing the network internal and external benefits. In that context, the proposed approach provides a platform to benchmark distribution networks against hybrid benefits.

VII. References

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