Assessment of Stress in Active Distribution Networks with Asset Dynamic Ratings

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Abstract—**Active distribution networks are vulnerable to random disturbances and the severity of stress of disturbances can be increased with dynamic rating of network assets, level of penetration of intermittent distributed generation (DG), and rise in customer demand. Increased stress in a distribution network can lead to major system disturbances including blackouts. This paper investigates this problem to assess how vulnerable the active networks to stresses arisen through random outages, dynamic variation of network asset ratings, demand rise, and high penetration of intermittent DG. The Monte Carlo simulation is the main driver of the assessment which incorporates dynamic rating of network assets through probabilistic modeling. The stress of the active network is recognizes as the product of network stress and the customer stress of not supplying the energy. A case study is performed and the results suggest that the active network stress can be buffered by the increased penetration of wind through strategic stations. The buffer is more effective at stressed operating conditions than the less stressed operating conditions.**

Keywords- ***active network operation, contingencies, intermittency, large system disturbances , Monte Carlo simulation***

I. INTRODUCTION

In the past, the distribution networks are operated as passive networks. With the introduction of distributed generation (DG) into distribution networks and active network management controls, the passive networks are transformed into active distribution networks. Active distribution networks are vulnerable to increased disturbances with the increased integration of intermittent distributed generation (DG). Majority of active network components which were in the past as passive network components, are reaching their end of life cycles. With the ageing network assets, significant change in weather patterns and severity, constrained opportunity for network reinforcements, reverse power flow effects and asset degradation, and random and frequent vulnerability to component outages can directly or indirectly affect the dynamic ratings of network assets. Dynamic variation of network asset rating can be a barrier for the network expansion planning and the knowledge of network stress with dynamic variation in asset ratings is also vital for strategic decision making in the presence of high penetration of DG.

Integration of intermittent DG such as wind and PV (photo voltaic) is beneficial for reducing greenhouse gas emission, which can also be considered as an off-line benefit. The network benefits with DGs can be explored through the planning and operational horizons and literature argued with mixed conclusions. However, the DG should not compromise the security of power supply to customers. On the other hand DG has the ability increase the availability of the generation even if the outages constraint the power supply from central generation. Role of DG is more valuable in highly stressed operating conditions than the less stressed operating conditions in a distribution network.[1, 2]

The literature addresses these issues in different spectrums [3-5]. Reference [6] discusses challenges of cascading failure and summarizes state-of-the-art analysis and simulation methods. A dynamic security or inverse of dynamic stress based linearized risk index is proposed in [7] for the detection of system security. Static security of supply is investigated in [8] using the successive elimination technique incorporating the investment deferral. Effects of the differed investment on the power system security are investigated in [9]. Security impacts with the large scale integration of wind power are explored in [10] using contingency analysis. Reference [11] proposes a multi objective probabilistic risk index to capture likelihood and consequences of events. Fuzzy and Monte Carlo simulation based hybrid technique is proposed in [12] for the power system risk assessment. Multiple objectives optimization based algorithm is proposed in [13] for the active distribution network planning taking into account uncertainties in distributed generation and demand response. Reference [14] proposes a probabilistic indicator to quantify the power system stress.

This paper investigates the network stress with dynamic asset ratings taking into account random contingencies, increased penetration of intermittent DG, and rise in system demand in an active distribution network environment. The stress is divided into network stress and the stress on electricity consumers. The core engine of the approach is the Monte Carlo simulation that incorporates complex probabilistic events and estimates the stress.

Increase in system demand can cause a rise in stress. Similarly increased penetration of intermittent DG can cause a rise in network stress at some of the operating conditions. Occurrence of random disturbances can increase the severity of the stress. However, the rise in demand does not necessarily rise the demand itself but also influential in affecting the dynamic rating of network assets. Similarly, increased penetration of distributed generation can even harness the potential stress at some of the operating conditions. Thus, the resulting stress is a byproduct of the combinatorial effects of stress caused by demand rise, intermittent DG harness, and random outages. Therefore, the research questions in this context would be how to model and quantify the resulting stress, at what level of DG penetrations and at which locations the network stress can be reduced, and how to better use DG to reduce total risk in an active distribution network. The proposed approach explores these questions in detail and critically analyses the avenues to mitigate system stress in an active distribution network.

The paper is organized as follows. Section II presents the approach of the paper. Section III describes the case study in detail and critically scrutinizes the results. Section IV concludes findings.

II. THE APPROACH

The entire approach is based on Monte Carlo simulation which incorporates random events through probability of occurrences. The network stress in an active distribution network can be quantified with several metrics. Network constraints including thermal and voltage limit violations can also be considered as an indication of the network stress. However, the severity of stress is not necessarily indicated by the constraint violations because of not all constraint violations last long and result a load shedding. This is because the network resources can rectify some of the violations to some extent depending on the operating condition and network resources. Therefore, they can be refereed as temporary stresses. Corrective actions in an active distribution network can eliminate constraint violations at most instances. The constraint violations that are unable to rectify and result load shedding or voltage collapse condition can be considered as permanent stresses. The proposed approach assesses the stress through permanent stresses and rectifies the temporary stresses using network resources through corrective actions.

The proposed approach considers level of curtailed load as the magnitude of stress. Duration of load shedding is an electricity customer stress for not supplying the electricity. Thus, the global stress can be defined as the product of magnitude of load shedding due to the network stress and duration of unsupplied electricity that results customer stress.

Fig. 1 shows the key steps of the approach. At first the network is modeled and network load growth is applied respective to the duration of the Monte Carlo simulation (MCS) period. Then, the dynamic asset ratings are modeled probabilistically which is described in section A. Next, the intermittent generation and load profiles corresponding to the sample of the MCS and the customer sector are applied to simulate the active network loading and distributed generation characteristics. Network component outages are modeled by generating random numbers for equipment in the network corresponding to the sample. The generated random number is then compared with the probability of failure of the equipment which is statistically determined based on existing data. If the random number is smaller than the probability of failure the equipment is considered as outaged. As the Monte Carlo simulation processes a significantly large number of samples to satisfy convergence criteria, the proposed way of probabilistically modeling random outage level of the equipment reach the statistically estimated outage levels of the equipment when it satisfy the convergence criteria of MCS.[3]

The approach incorporates A/C power flow solution to assess the power balance and then to monitor any thermal and voltage limit violations. Any constraint violation is rectified by applying corrective actions of re-scheduling the flexible generating units, shunt compensation, or load shedding in ascending order with the objective of reducing the network stress. Intermittent DG units are treated as base load plants, however, the existence of schedulable storage in the active network is also considered as a resource for corrective actions. Any divergence state of the load flow solution is rectified by minimal load shedding. Section B, gives the objective function, which is focused on minimizing the stress within the constraints.

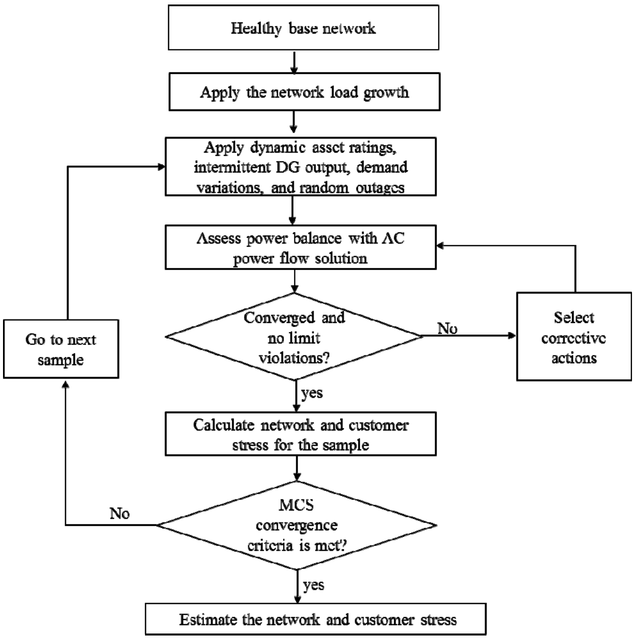

Figure 1: Basic steps of the approach with Monte Carlo simulation steps

With the network power solution converged and free from constraint violations, the network stress in terms of the magnitude of load shedding and customer stress in terms of unsupplied energy duration is calculated for the sample.

Monte Carlo simulation stops when it meets the convergence criteria which are based on the degree of confidence for the confidence interval of the resolution, and reaching the maximum number of samples. Then, the installed capacities of intermittent DG units are increased within the limits of distribution corridors and followed the above process. Next, system load growth level is applied and repeated the entire process described above.

A. Asset dynamics

Network asset ratings can be varied dynamically due to many reasons including weather patterns and conditions, maintenance cycles of equipment, loading levels and cycles, frequency of faults, insulation degradation, ambient and operating temperatures, frequency of susceptibility to intermittent and reverse power flow. Some of these causes are correlated each other and modeling of dynamic rating in an equipment is a complex and challenging task. However, it is not very challenging to monitor the equipment ratings dynamically with the help of smart sensors embedded in a power system. Such information is vital for online assessment of network stress. It is also likely to have a robust understanding of the varying range of the capacity of equipment. Such information is vital for the off-line assessment of the stress in an active distribution network. Alternatively, knowing the dynamic capacity range in equipment is useful for probabilistic modeling an asset dynamic rating. In a MCS simulation based probabilistic model, random numbers enable to determine the state of the rating of the equipment, which ultimately upon convergence captures the random variation of dynamic ratings of the network assets.

1) Thermal step based modelling of asset dynamic ratings

Consider a network in which each asset component undergoes different stages of life cycle due to external and internal effects as described earlier. For example, branches connected to consecutive bus bars may have different life cycles and dynamic thermal ratings. Although, network assets can be built in the same period, their dynamic ratings can be different due to the above said reasons including random disturbances, aging effects, and frequency of vulnerability to faults. Taking into accounts these facts, the network dynamic thermal ratings can be categorized as given in (1) and (2).

$$S_{\min}^{i} \le S_{dyn}^{i} \le S_{\max}^{i} \tag{1}$$

$$S_{step}^{i} = \frac{S_{\min}^{i} - S_{\max}^{i}}{l} \tag{2}$$

Where, i is the type of the network asset and $S_{\min}$ and $S_{\max}$ respectively are minimum and maximum dynamic thermal limit varying range from the manufacturer rated thermal limit. l is the number of dynamic thermal limit varying steps in the range in a time period. This step size can be set based on the type of equipment, vulnerability to dynamic thermal limit varying conditions, age, and the seasonal effects. S_{dyn} gives the manufacturer given thermal rating of the equipment in percentage.

$$S_{step}^{k-1} \le N_{rnd} < S_{step}^{k} \quad ; \qquad k = 1,\dots,n \tag{3}$$

Where, N_{rnd} and (S_{step}^{k} to S_{step}^{k-1}) are random number between 0 and 1.0 and dynamic thermal limit varying range at a particular time period of an equipment respectively.

Next, a random number between 0 and 1.0 is generated and it is compared with the probability of occurrence of (F_{th}^{w}) (dynamic thermal step S_{step}^{i} is multiplied by w and normalized by dynamic thermal range of the asset ($S_{\max} - S_{\min}$). Equation (4) gives the normalized dynamic thermal step fitting between 0 and 1.0. w^{i} gives the step number of the thermal step range.

$$F_{th}^{w} = \frac{S_{step}^{i} \times w^{i}}{S_{\max}^{i} - S_{\min}^{i}} \quad ; \qquad w^{i} = 1,..,l \tag{4}$$

For example, if $0 \le N_{rnd} < F_{th}^{1}$ then the dynamic thermal rating of the equipment i is set as $S_{\min}^{i} + F_{th}^{1} \times (S_{\max}^{i} - S_{\min}^{i})$. Inequality constraints shown in (5) give all the possible dynamic thermal steps of equipment.

$$\begin{aligned} &0 \le N_{rnd} < F_{th}^{1} \\ &F_{th}^{1} \le N_{rnd} < F_{th}^{2} \\ &. \\ &F_{th}^{r-1} \le N_{rnd} < F_{th}^{r} \\ &. \\ &. \\ &. \\ &F_{th}^{l-2} \le N_{rnd} < F_{th}^{l-1} \\ &F_{th}^{l-1} \le N_{rnd} < F_{th}^{l} \end{aligned} \tag{5}$$

In this way, random numbers are generated for each of the network asset that can be vulnerable to thermal rating variations and the dynamic state of the equipment is embedded into the Monte Carlo simulation in each sample.

B. Corrective actions

Corrective actions are used if the network sustained with constraint violations or leading to a divergence condition of the power flow solution. The network constraints considered in the approach are thermal limit of branches and voltage limits of busses. The thermal limit violations are corrected by re-dispatching generation taking into account economic benefits and flexibility of units. The generation is curtailed in accordance with economical merits and the flexibility. The loads are shed if any unstable and further damage to the network operation eminent and no other corrective action is feasible of controlling the operating condition within hard constraints. The loads are shed from the worst mismatch bus with the objective of minimizing the cost of generation of the bus within constraints (as relevant) and minimizing the resulting stress level as formulated below. [3, 15]

Minimize

$$\sum_{k \in ng} C_k P_k^{gen} + \sum_{k \in nld} W_k \left(P_k^{shed} \times t_{rest} \right) \tag{6}$$

Subject to:

Branch flow at a branch,

$$T_j = \sum_{k=1}^{nb} A_k^j (P_k^{gen} - P_k^{load} + P_k^{shed}); \; (j = 1, \ldots, nbr) \tag{7}$$

Power balance at a bus,

$$\sum_{k \in ng} P_k^{gen} + \sum_{k \in nld} P_k^{shed} = \sum_{k \in nld} P_k^{load} \tag{8}$$

Generation limit constraint (excluding non-flexible units),

$$P_k^{gen_{\min}} \le P_k^{gen} \le P_k^{g_{\max}}; \qquad (k \in ng) \tag{9}$$

Load shedding constraint,

$$0 \le P_k^{shed} \le P_k^{load}; \qquad (k \in nld) \tag{10}$$

Branch flow constraint,

$$\left| T_j \right| \le T_j^{\max}; \qquad (j = 1, \ldots, nbr) \tag{11}$$

Where P_k^{gen}, P_k^{load} and P_k^{shed} are the generation, load, and load shedding at the k^{th} bus respectively. A_k^j is the elements of the connectivity matrix between branch flows and power injections for the sample. T_j is the branch flow on the j^{th} branch. $P_k^{gen_{\min}}$ and $P_k^{gen_{\max}}$ are the lower and upper capacity limits of generation at the k^{th} bus respectively. $T_j^{\max}, W_k$, C_k, and t_{rest}, are the thermal limit of the j^{th} branch, weighting factor that reflects the importance of the k^{th} bus for load shedding (concerned with criticality), unit generation cost for the k^{th} bus generation, and restoration time respectively. nld, ng, nb, and nbr are the total number of load busses, generator busses (excluding busses with non-flexible units), busses, and branches in the network respectively.

III. CASE STUDIES

A. Network

The case study is aimed at determining the network and customer stress with varying thermal capacity of network assets when they experience outages, increased Wind and PV penetration, and rise in demand conditions. Fig. 2 shows a 23 bus active distribution network model used for the case study. The broken lines in Fig. 2 show the alternative wind and PV power generating stations. Site 1 is the first wind and PV power generation station whereas sites 2 to 4 give the other alternative generating stations.

The EHV (extra high voltage) represents the utility grid. Grid serves as the artificial energy storage for the excessive power generation from wind and PV. Grid and diesel plants provide standby power for intermittent cycles as necessary and relevant. Primary standby power is drawn from grid if that is feasible with the operating condition. If the grid is unavailable or constrained with exporting power then the diesel units provide the standby power. The total peak active and reactive power demand of the network of the base case are 14MW and 3MVAr respectively. Base installed capacity of Wind and PV generation from each site is 2.6MW of which 0.6MW of installed capacity is from PV units. There are two existing wind farms in the South part of the network. Each load bus consists of four sector customers; residential (contracted) residential (non-contracted), industrial, and commercial. The load varies in accordance with the hour of use and the type of the sector. The wind and PV generation outputs vary at each hour in accordance with wind speed and insolation respectively.

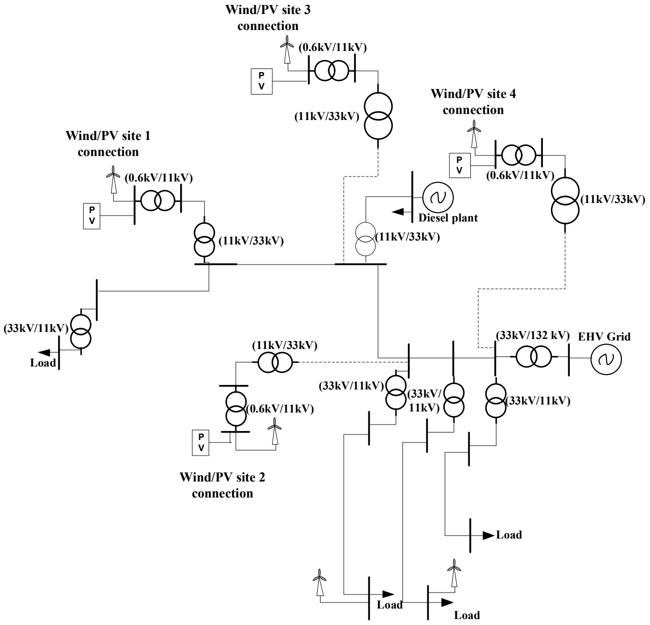

Figure 2. Active distribution network model with wind and PV power generating sites

Then, the approach proposed in section II is applied by integrating one Wind and PV generating site at a time basis.

B. Scenarios

The scenarios are established to investigate the impact of asset dynamic ratings, increased penetration of wind and PV, and rise in system demand on the network and customer stress. There are four scenarios considered in this assessment. Scenario 1 uses base case which does not incorporate dynamic ratings of network assets or wind and PV from sites 1 to 4. Scenario 2 uses same operating condition as in Scenario 1 but incorporates dynamic rating of network assets. Scenario 3 uses same operating conditions as in Scenario 2, but increases the installed capacity of wind and PV systems regularly by 2MW and 0.6MW steps respectively. Scenario 4 uses same operating conditions as in Scenario 3 but for each of the wind and PV incremental step the system demand (active and reactive power demand) is also increased by 10% to 50% of the base case loading.

C. *Results and Analysis*

Fig. 3 shows the reduction in global stress (sum of network stress and electricity consumer stress) compared to non-incorporation of asset dynamic ratings for the Wind/PV penetration through Site 4. The stress values are given as annual stress values. Each scenario carries base case load. The results suggest that the incorporation of dynamic asset ratings can marginally affect stress of passive network operating conditions given as "zero" in Fig. 3. However, in the case of active distribution networks (base to quadruple penetration of Wind and PV generation) the impacts can be significant at some of the penetration levels. The case with "base" level of penetration of Wind/PV through Site 4, gives the highest growth in stress against varying dynamics of network assets.

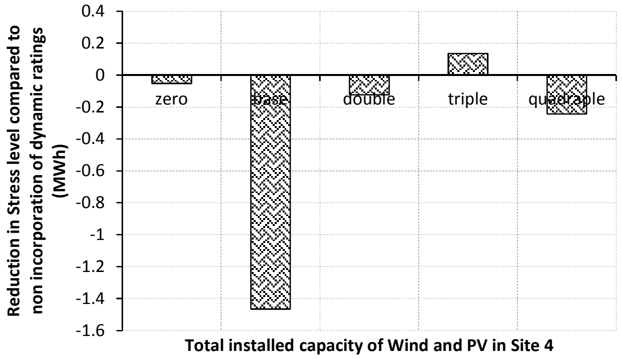

Figure 3. Reduction in stress level with asset dynamic ratings

Fig. 4 to 7 show the reduction in stress level compared to zero Wind and PV integration incorporating asset dynamic ratings at each case and increasing the system load from 10% to 50% of the base case load.

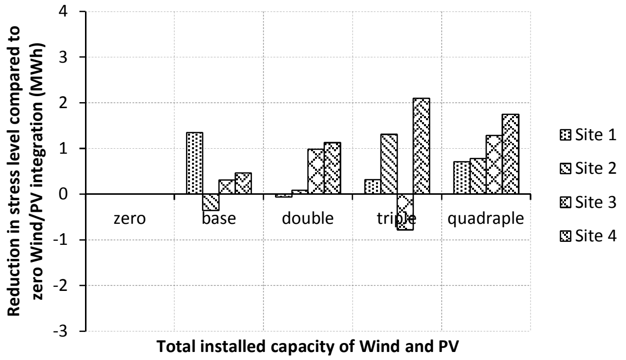

Figure 4. Stress level compared with zero Wind and PV integration . All the scenarios carry base case load. Positive values indicate a reduction in stress compared to zero wind/PV integration.

The results suggest that the increase in system load increases the system stress (network and customer stress) however the presence of Wind and PV power genertaion from strategic locations can buffer the increase in system stress arrisen through the increase in system load. The level of buffer also depends on the level of penetration of Wind and PV and the geographical location of Wind and PV sites. A quantitaive analysis enables to identify the stretegic locations and level of buffer offered by the Wind and PV regemies in an active distribution network. On the other hand, at extreme opertaing conditions of Wind and PV generating sites where their outputs become zero, the active distribution network can significantly suffer from stresses unless the sufficient reserve and operating margins are allocated at the network operational planning stage.

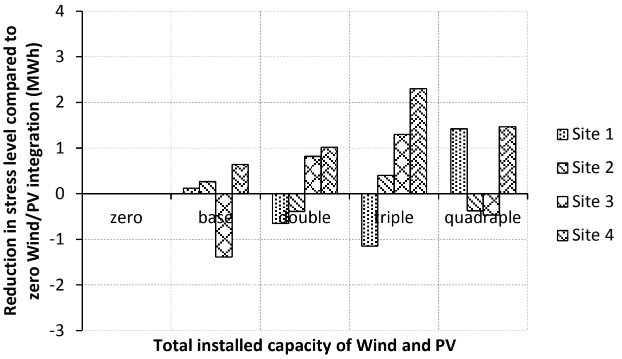

Figure 5. Stress level compared with zero Wind and PV integration . All the scenarios carry 110% of base case load.

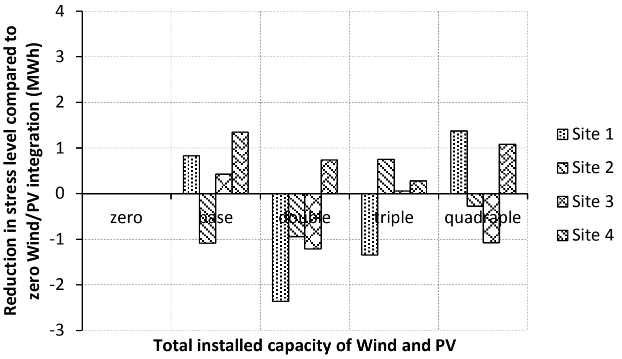

Figure 6. Stress level compared with zero Wind and PV integration . All the scenarios carry 120% of base case load.

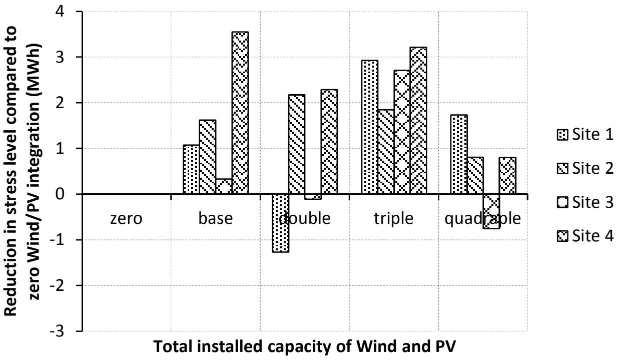

Figure 7. Stress level compared with zero Wind and PV integration . All the scenarios carry 150% of base case load.

Fig. 8 shows the reduction in stress level compared to base case load. It is evidenced from the results that the increase in loading in an active distribution network can increase the global stress exponentially. However, there are sites which act as startegic sites in reducing the stress compared to others in all loading conditions. Identification of such sites enables to reduce the stress of active distribution networks to some extent and enables differred investment provision. However, due to the intermittent nature of wind and PV power generation, the co-exitance of rise in demand and high penetartion of wind and PV generation through strategic sites can be low. If those operating conditions arrise then they can be mittigated by the use of energy storage technologies at startegic sites taking into account cost and benefits assesment within them.

These finding increase the need for weighted penetration of wind and PV generation through sites for the increased benefits of DG and reducing the system stress.

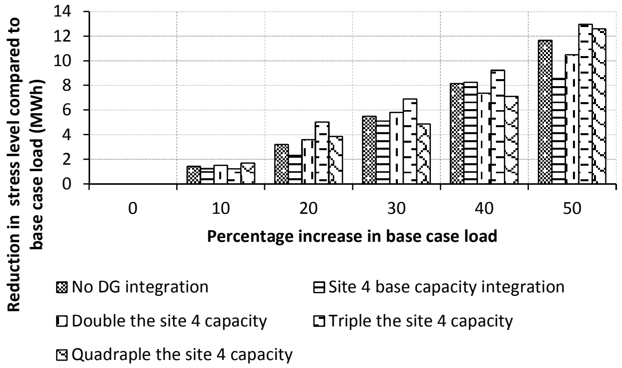

Figure 8. Stress levels compared to no wind and PV integration through site 4. Base integration capacity of Site 4 DG is 2.6MW.

IV. CONCLUSION

The paper proposes an approach to assess network and electricity customer stress of an active distribution network incorporating dynamic rating of network assets, random outages, and intermittent effects of distributed generation in Monet Carlo simulation.

The investigations through case studies suggest that the influence of asset dynamic ratings on system stress can be significant at some of penetration level of Wind and PV. Intermittent distributed generation can buffer the system stress if they are penetrated through strategic sites considerably. Increased system demand resulting stress can be substantially reduced by the high penetration of wind and PV generation through strategic sites.

Strength of reducing system stress of each wind and PV site is non-linear against the level of penetration of wind and PV generation and growth of system demand. The weighted penetration of wind and PV generation through sites can be an alternative for increased benefits and reducing the system stress.

With the increased integration of distributed generation into active distribution networks the network assets operate closer to the operating margins. The proposed approach can be used to assess the dynamic stress of such networks, to relieve the congestion, and to mitigate frequency and severity of blackouts in an active distribution network.

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