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Impact Of DG Installation On Voltage Profile And Reliability Improvement With Cost Consideration

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Abstract
This paper presents a methodology for optimal distributed generation (DG) allocation and sizing in distribution systems, in order to minimize the electrical network losses and to guarantee acceptable reliability level and voltage profile. Distributed generators (DGs) sometimes provide the lowest cost solution to handling low-voltage or overload problems. In conjunction with handling such problems, a DG can be placed for optimum efficiency or optimum reliability. Such optimum placements of DGs are investigated. The concept of segments, which has been applied in previous reliability studies, is used in the DG placement. The optimum locations are sought for time-varying load patterns. It is shown that the circuit reliability is a function of the loading level. The difference of DG placement between optimum efficiency and optimum reliability varies under different load conditions. Observations and recommendations concerning DG placement for optimum reliability and efficiency are provided in this paper. Economic considerations are also addressed.
Keywords: *Distributed Generation, Voltage improvement, Reliability indices, SAIFI, SAIDI, Cost consideration.*

1. Introduction

DG sometimes provides the most economical solution to load growth. Under voltages or overloads that are created by the load growth may only exist on the circuit for a small number of hours per year. There are many locations within the troubled circuit, or even in neighbouring circuits, that do not have overload or voltage problems, where the DG can be located and provide the necessary control. In this paper, it is assumed that it has already been justified that a DG provides the lowest cost solution to a circuit problem and is to be installed to provide the needed control. Then what is the best location in the system to add the DG? Many DGs are currently placed in or near the substation, probably due to convenience of installation. However, placing DGs further out on the circuit can lead to improvements in losses, reliability, or both. One of the criteria to find the optimal DG location is minimizing power loss. Several papers have been published that address the use of artificial intelligence algorithms to optimize DG placement [1]–[6] based on minimizing power loss. Reference [1] solves the problem by an exhaustive algorithm, [2] employs the Tabu search method, [3] uses a fuzzy genetic algorithm and analytical approaches are presented in [4]. Other papers consider the cost of power interruptions [5] and minimizing peaks [6], but power loss minimization is still the base strategy employed. All the simulations performed in [1]–[6] address a static load condition. Placing DGs to minimize loss based upon a single load point, such as the peak load, may not provide the same optimal solution as when the entire time-varying load pattern is considered. Applying DGs to a distribution system may also contribute to improving system reliability. So maximizing reliability can also be a criterion for seeking optimal DG location. This paper presents a reliability analysis based on set theory and discusses how the system load and additional generation (provided by DG) affect the system reliability. A cost analysis is performed relative to the differences in efficiencies. Since we are seeking economical solutions to load growth problems, and multiple DG installations lead to more expensive solutions that are not necessary to correct the problem, a single DG installation is simulated in this paper. We also assume a DG can be brought back online after the segment, to which it is connected, is switched to an alternate feed.

2. Definition

It refers to power generation at the point of consumption. Generating power on- site, rather than centrally, eliminates the cost, complex, interdependencies, and inefficiencies associated with transmission and distribution. Historically, DG means combustion generators (e.g. diesel equipment's). They were affordable and in some cases reliable, but they are not clean and continuous. Recently, solar energy has become one popular DG, due to its clean and continuous properties.

Distributed energy is generated or stored by a variety of small, grid- connected devices referred to as – **Distributed Energy Resources (DER)**.They are – mass- produced, small and less site- specific.
A brief summary of each definition is given below:
1. The purpose of distributed generation is to provide a source of active electric power. According to this definition; distributed generation does not need to be able to provide reactive power.
2. The location of distributed generation is defined as the installation and operation of electric power generation units connected directly to the distribution network or connected to the network on the customer site of the meter.
3. In the context of competitive electricity market regulations, only the legal definition for transmission and distribution systems provides a clear distinction between the two systems.
4. The rating of the DG power source is not relevant for our proposed definition.
5. The area of the power delivery is not relevant for our proposed definition of DG.
6. The technology used for DG is not relevant for the here proposed definition.
7. The environmental impact of DG is not relevant for the here proposed definition.
8. The mode of operation of distributed power generation is not relevant for the here proposed definition.
9. The ownership of DG is not relevant for the here proposed definition.
10. The penetration level of DG is not relevant for the here proposed definition.

2.1 Sample Benefits of Distributed Generation Systems [7]

1. Shorter construction times
2. Reduced financial risk of over- or under-building
3. Reduced project cost-of-capital over time due to better alignment of incremental demand and supply
4. Lower local impacts of smaller units may qualify for streamlined permitting or exempted permitting processes, reducing fixed costs per kW
5. Significantly reduced exposure to technology obsolescence
6. Local job creation for manufacturing, technician installers/operators
7. Higher local, small-business development and taxes vs. overseas manufacturing
8. Lower unit-cost, automated manufacturing processes shared with other mass-production enterprises (i.e., automotive industry)
9. Shorter lead times reduce risk of exposure to changes in regulatory climate
10. Significant reduction in fuel disruption risk (portfolio of locally produced fuels and **"fuel-less"** technologies—solar, wind)
11. Reduced fuel-forward price risk
12. Reduced trapped equity
13. Reduced exposure to interest-rate fluctuations
14. Potential for more modular, routine analysis for capital expansions
15. Multiple off ramps for discontinued projects, without same level of risk
16. Ability to redeploy portable resources as demand profiles change
17. Portability = Higher capacity utilization
18. Reduced site remediation costs after decommissioning
19. Higher system efficiency reduces ratio of fixed-to-variable costs (fuel)
20. Potential for lower unit costs for replacement parts when mass produced
21. Displaces that portion of customer load with highest line losses
22. Displaces that portion of customer load with greatest reactive power requirements
23. Displaces that portion of customer load with highest marginal energy costs
24. Weather-related (solar, wind) interruptions more easily predicted and of shorter duration than equipment failures at central plants
25. **"Hot swap"** capability – when one DG module (panel, tracker, inverter, and turbine) is unavailable, all other modules continue operating
26. Load siting reduces or eliminates line losses on electric transmission and distribution lines
27. Inherently improved system stability due to multiplicity of inputs
28. Reduced regional consequences of system failure
29. Improved transmission and distribution reliability due to reduced peak loading, conductor and transformer cooling
30. Fast ramping within the distribution system, ability to reduce harmonic distortions at customer's site.

2.2 Improvement of Voltage Profile

In the distribution systems, improvement of voltage profile is one of the significant factors to improve the overall efficiency of the power system. In this regard, DG allocation is one of the most well-known methods. DG units, considering their types, operation mode and network connection method can be modeled as PV or PQ bus.

A DG modeled as a PQ bus, may be modeled in three different types. In the first modeling type, DG units have a constant P and Q generation and modeled as a negative load. In the second modeling type, DG units have a specified value of P and power factor and modeled as a constant power factor machine and in the third modeling type, DG units are modeled as a variable Q generator .When DG is modeled as a PV bus, DG units have specified output real power and bus voltage magnitude. Also, DG units are modeled as a PV node using a dummy bus and dummy branch which injects reactive power to the specified bus to maintain the voltage in the specified value.

When a DG produces only reactive power, the phase angle of the DG output current is π/2 (radians) leading the phase angle of the local voltage. When the DG operates optimally (which means the ratio of real power injections of dg and reactive power injections of dg is equal to the sensitivity factors), the DG current is lagging the local voltage by $\tan^{-1}\left(\frac{1}{\text{sensitivity factors}}\right)$ radians. The DG operating condition, which represents the ratio of active to reactive power injection from the DG, is set to inject the optimal real and reactive power to maximize the voltage support.

A DG that is used for voltage support may only be required to operate several hours a week (during high demand periods) or during peak hours only. Thus, the DG capital cost may have much higher impact on the overall expenditure than its operating cost. In other words, if the usage of the DG is limited to a number of hours per year, the dominant cost will be determined by the DG kVA rating. Therefore, we have to find a DG with the minimum kVA rating, which would be just enough to support the required voltage levels. It has been found that in many cases, the injection mode of both real (P) and reactive (Q) power will result in a smaller value of kVA required (and thus smaller capital cost of the DG) than the DG size with the injection mode of reactive power only. Thus, the injection of both P and Q should have a lower total cost, although operating costs may become higher than that of the larger DG with the Q injection only. Therefore, we have to consider the injection of real and reactive power of the DG for voltage support at a fixed power factor.

2.3 Voltage Stability Index Improvement

DG is going to play a major role in power systems worldwide as a key function in active management; DGs must be able to face the contingency conditions, while playing a remedial role in the system security. Voltage collapse usually occurs in heavily loaded systems that do not have sufficient local reactive power sources and consequently cannot provide secure voltage profile for the system. This reactive power shortage may lead to wide-area blackouts and voltage-stability problems. The shortage can be alleviated by an increasing share of DGs in low-voltage (LV) distribution systems to improve voltage stability. These days, most DG technologies, such as synchronous machines, power-electronic interface Devices (e.g., photovoltaic cells and micro-turbines) etc., are capable of providing a fast, dynamic reactive power response. This capability can be used by the system operators to enhance system security and stability.

Voltage stability indices (VSI) have been introduced to evaluate the power systems security level from the point of voltage static stability. In a radial distribution system at first we have to identify the node, which is most sensitive to voltage collapse with the help of VSI. For stable the operation of the radial distribution networks, the node, at which the value of the VSI has lowest, is prone to collapse. The node with the lowest VSI is the weakest node and the voltage collapse phenomenon will start from that node. Therefore, to avoid the possibility of voltage collapse; the VSI of all nodes should be maximized with the help of DG & the DG should be connected to that bus which has the lowest VSI value.

2.4 RELIABILITY

The assessment of impacts that DG might have on the grid is complicated by several considerations, including the following ones -

• Main application of DG.
• Plans concerning the future development of the grid.
• The technology of DG.

Combination of the aforementioned factors determines the overall impact that DG can have on the system reliability. Let us examine qualitatively these factors. To simplify analysis, let us only consider distributed generators with fully controllable output power. That is, such DGs as photo-voltaic arrays or wind turbines are left outside the scope of the analysis. There are three main applications of DG, namely, providing back up power, peak load shaving, and net metering. It can be argued that the impact of DG on the overall system reliability depends on the application. For instance, DG installed with the purpose to provide backup power will certainly increase the reliability of power supply to the critical load it is protecting. However, the positive impact on the reliability of the power delivery to other customers will be only marginal. Positive impacts that DG can have on the grid are more expressed when the main aim of the DG is to reduce the

peak power demand. The positive impact originates from the fact that electric power is generated and consumed on-site thereby unloading the main feeder, which is likely to increase the overall system reliability due to a reduced rate of failures on the distribution grid. The impact of net metering on the overall system reliability can be two-fold.
On the one hand, net metering may contribute to peak load shaving and thus enhance reliability of power delivery. On the other hand, this application, in principle, causes bi-directional power flows, which under certain circumstances can depress reliability of the grid. In addition, the presence of such distributed generators can mask the load growth and therefore increase the number of customers which can be affected by power interruption due to a failure of the DG. For instance, if a distributed generator is installed in the middle of a feeder, then at the sub-station end of the feeder an increase of the load behind the DG may be difficult to recognize. This might lead to an increased number of customers affected by a fault on the feeder or the DG itself. In conclusion it can be stated that major impacts that DG can have on the system reliability is highly dependent on the DG characteristics, grid characteristics as well as the application of DG. The same DG technology utilized for different applications will affect system reliability in different ways, ranging from very positive impact (peak load shaving) to quite negative (load growth masking, changing the load flow pattern).It must however be stated that **"despite these conflicts, DG installations on utility distribution systems can nearly always be successfully engineered"**.

2.5 COST CONSIDERATION

Previously published different journal and conference papers shows how different reliability indices (like, SAIFI, SAIDI) can be formulated with respect to DG. Now, I can say that Voltage Profile can also be a pathfinder for those reliability indices. So, Voltage Profile can also be taken into consideration while discussing about various reliability constraints with respect to DG implementation.

Fitness function (F) = $\frac{\text{benefit (B)}}{\text{total cost (C)}}$

Where, Benefit (B) = Losses cost (before DG installation) – losses cost (after DG installation)

Total cost = investment cost + installation cost + maintenance cost

Losses cost = cost/kw * losses (kW)

The objective of protection devices and DGs placement in a radial feeder is to maximize the distribution network reliability under certain constraints.

The system average interruption index (SAIDI) and the system average interruption frequency index (SAIDI) are typically used to measure the average accumulated duration and frequency of sustained interruptions per customer.

$$\text{SAIDI} = \frac{\sum u_i N_i}{\sum N_i}$$

$$\text{SAIFI} = \frac{\sum r_i N_i}{\sum N_i}$$

Where, $N_i \rightarrow$ no. of customers of load point i

$r_i \rightarrow$ Failure rate

$u_i \rightarrow$ Outage time

For the purpose of Optimization, one can define a composite reliability index through Weighted Aggregation of these two indices.

$$C = [W_{SAIFI} * \frac{SAIFI}{SAIFI_T} + W_{SAIDI} * \frac{SAIDI}{SAIDI_T}]$$

Where, $W_x \rightarrow$ Weight for the corresponding Reliability Index

$T \rightarrow$ Target value

$$\text{Minimize Fitness} = A_1 * cost + A_2 * P_{loss} + \frac{A_3}{P_{sys}}$$

$$\text{Cost} = \frac{\sum_{j=1}^{s} cost_{DG}(j)}{\text{base cost}}$$

$$P_{loss} = \frac{P_{loss}}{P_{loss}^{base}}$$

$$P_{sys} = \frac{P_{sys}}{P_{sys}^{base}}$$

In this formulation, we incorporated desired values of both indices that are empirically justified. The smaller the value of the defined Reliability Index (i.e. Objective Function) is, the higher the system reliability becomes. Generally, constraints are taken as no. of DGs available subjected to it coupled with no. of candidate locations determined by the system configuration.

2.6 Impact of distributed generation

Distribution systems are designed on the assumption that electric power flows from the power system to the load. Therefore, if output fluctuations or a reverse flow from generators occurs on the grid because of DG, there is likely to be some influence on the overall system in terms of power quality or protection and safety. The potential impacts of DG are [8]:

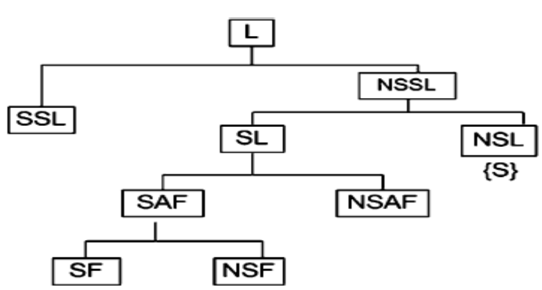
2.6.1 Losses and voltage profile

Distribution systems are usually voltage regulated through tap changing at substation transformers and by the use of voltage regulators and capacitors on the feeders. This form of voltage regulation assumes power flow circulating from the substation to the loads. DG introduces reversed power flows that may interfere with the traditionally used regulation practices [9]. For this reason, the inappropriate DG allocation can cause low or over-voltages in the network. On the other hand, the installation of DG can have positive impacts in distribution system by enabling reactive compensation, the voltage control, reduction of losses, besides contributing to frequency regulation and providing spinning reserve in main system fault cases.

2.7 Distribution system reliability analysis

The performance index used here to evaluate reliability of individual circuits or feeders is the system average interruption duration index (SAIDI) [10]. The method employed to calculate SAIDI is now explained for circuits with radial topologies. Here the power system is modelled in terms of segments. A segment is a group of components whose entry component is a switch or a protective device. The sectionalizing device for a segment groups components so that if any component loses power, all of the other components in the same segment will also lose power. The down times of all the components (e.g., line sections, transformers, capacitors, etc.) in a segment are identical, so the reliability analysis may be performed in terms of segments. In developing sets of segments, referred to as reliability analysis sets [11], the individual components that make up the segments do not need to be considered. Working in terms of segments as opposed to the individual components significantly enhances the computational speed.

Fig.1.Reliability analysis sets.

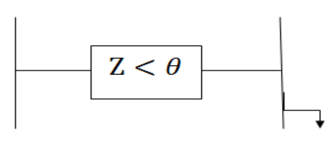


The reliability analysis sets illustrated in Fig. 1 are used to calculate the reliability of a given load point, the segment of interest. It is assumed that only one failure takes place at a time. Set L includes all segments that are not separated from the continuous path between the source (substation, generator, etc.) and the segment of interest S by a protective device. The L set represents the set of segments whose failure will cause a loss of power to the load point of interest. The L set is partitioned into the sets SSL and NSSL. The **NSSL** set consists of the segments that cannot be switched away from the continuous path between and the original source. The **SSL** set contains any segments separated from the continuous path by manually operated switches. If any element of this set fails, power to the segment of interest S can be restored from the original source before the failed component is repaired or replaced. Set NSSL can be partitioned into SL and NSL. The **SL** set consists of the segments that can be switched away from the segment of interest, so that if the failure occurs in the SL set, S may be fed by an alternate source. The **NSL** set consists of the segments that cannot be switched away from the segment of interest. That is the segment of interest itself, so this set only contains the element S. Set SL is divided into SAF and NSAF. For the **SAF** set, if the failed component lies in one of these segments, it is possible to restore power to S by an alternate source. For the **NSAF** set, if the failed segment belongs to this set, the segment of interest S cannot be temporarily restored from an alternate feed. Set **SAF** contains the segments that can be isolated from both the segment of interest and the alternative source, which make the temporary restoration topologically possible. Sometimes, system constraints may limit the restoration options; the alternate source may not have the capacity to support the particular load point of interest. So the set SAF consists of sets SF and NSF. If power can be restored to S from the alternative source with no system constraint violations, all the segments in SAF belong to SF. Otherwise, some or all segments in SAF belong to NSF (in this research, line section overloads and 6% below nominal voltage are regarded as constraint violations). Set L, including all the segments for calculating the reliability index, is decomposed as follows:

$$L = SSL \cup SF \cup NSF \cup NSAF \cup NSL$$

The detailed derivation of the above reliability analysis sets can be found in [12].

2.8 DG can be used as – Reactive Loading Index



Sending end voltage - $V_S < \delta_S$

Receiving end voltage - $V_r < \delta_r$

Current - I_r

Complex power - $S_L = (P_L + j.Q_L)$

$S_L = V_r.I_r^*$

$$I_r = \frac{(P_L - j.Q_L)}{V_r^*} = \frac{(P_L - j.Q_L)}{(V_r < -\delta_r)}$$

$$I_r = \frac{(V_r - V_r)}{Z} = \frac{(V_S < \delta_S - V_r < \delta_r)}{Z < \theta}$$

If, we compare the last two equations, we get the following relation –

$$(P_L - j.Q_L) = \frac{[V_s < \delta_s - V_r < \delta_r]}{Z < \theta}.V_r < -\delta_r$$

By simplifying the above equation, we get the following form of equation –

$$(P_L - j.Q_L) = \left[\frac{V_s.V_r}{Z}.\cos(\theta - \delta_s + \delta_r) - \frac{V_r^2}{Z}.\cos\theta\right] - j.[\frac{V_s.V_r}{Z}.\sin(\theta - \delta_s + \delta_r) - \frac{V_r^2}{Z}.\sin\theta]$$

So, value of reactive power will be –

$$Q_L = [\frac{V_s.V_r}{Z}.\sin(\theta - \delta_s + \delta_r) - \frac{V_r^2}{Z}.\sin\theta]$$
$$= [\frac{V_s.V_r}{Z}.\sin(\theta - \delta) - \frac{V_r^2}{Z}.\sin\theta]$$
$$(Q_L - Q_G) = [\frac{V_s.V_r}{Z}.\sin(\theta - \delta) - \frac{V_r^2}{Z}.\sin\theta]$$

To get the maximum value, we have to differentiate the above equation –

$$\frac{d(Q_L - Q_G)}{dV_r} = 0$$

After simplification, we get the following relation –

$$[2.\frac{V_r}{V_s}.\sin\theta - \sin(\theta - \delta)] = 0$$

Now, at no load condition, $V_r = V_s$ and, $\delta_r = \delta_s$

So, $\delta = 0$

So, main equation will be –

$\sin\theta = 0$

However, at the maximum reactive power $(Q_L - Q_G)$, the equality sign holds and thus, the equation becomes zero.
Hence, the left hand side of the main equation is considered as a reactive loading index with Distributed Generation $(L_{Q\,dg})$ of the system that varies between $\sin\theta$ (at no load) to zero (at maximum modified reactive power).
Thus,

$$L_{Q\,dg} = [2.\frac{V_r}{V_s}.\sin\theta - \sin(\theta - \delta)]$$

Here,

$$0 < L_{Q\,dg} < \sin\theta$$

3. Conclusions

This paper presented a method for optimal DG units' allocation and sizing in order to maximize a benefit/cost relation, where the benefit is measured by the reduction of electrical losses and the cost is dependent on investment and installation. Constraints to guarantee acceptable reliability level and voltage profile along the feeders are incorporated. The method can be used to test alternative DG allocation solutions or to find automatically the best solution. Conclusions from this work are summarized as follows.

Improving reliability and efficiency in a single circuit

- Often, DGs are placed at substations for convenience. However, placing a DG further out on a circuit as opposed to locating the DG at the substation can enhance circuit reliability and reduce power losses.
- Often in industry, decisions are based on power flow analysis run for the peak load. Placing a DG where only the peak load condition is evaluated may not provide the best location for minimum loss or reliability improvement.

Improving reliability in a system of circuits

- If DGs are to be shut down when circuits experience outages, for the best improvement in system reliability, DGs should be placed in circuits that have the lowest failure rates.
- If DGs can be quickly restarted following switching operations with alternate feeds, the circuit component failure rate is not a determining factor in considering optimal DG placement for reliability improvement.

System reliability is influenced by loading patterns

- If all the circuits in a system exhibit the same loading pattern, then applying a DG may help to enhance system reliability more during light load periods than during heavy load periods.
- If the circuits in a system exhibit different loading patterns, adding a DG may yield the largest improvement in system reliability during periods of high load.

Comparing minimum loss with maximum reliability

- The optimal DG placements for minimum loss and maximum reliability are different during light load conditions and close to one another during heavy load periods.
- The cost of improvements in reliability can, in part, be evaluated by the trade-off with the cost of the losses in efficiency.

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