Valuing DER Location based on the Impact on Transmission Network: A Planning Tool

Sarangan Rajendran, *Student Member, IEEE*, and Visvakumar Aravinthan, *Senior Member, IEEE*
Electrical and Computer Engineering Department
Wichita State University
Wichita, KS, USA

Al Tamimi, *Senior Member, IEEE*, and Charles R. Yokley, *Member, IEEE*
Transmission Planning and Policy
Sunflower Electric Power Corporation
Wichita, KS, USA

***Abstract*—Distributed energy resources (DERs) are increasingly being considered as an attractive solution to the non-wire alternative problem, given their various benefits to the system. However, high levels of DER penetration can result in unanticipated electric grid operating conditions, as they are traditionally not considered in planning processes by the transmission utilities. Consequently, there arises a need to value DERs based on the impacts they have on the overall system as viewed from a transmission level. This paper presents three metrics to quantify the impacts caused by the addition of DERs to an existing system. The proposed approach employs a statistical approach to measure the shift of critical system parameters from normal operating conditions due to the addition of DERs. A test system developed based on the western Kansas region is used to analyze the impact of DERs and demonstrate the usefulness of the proposed method. The results provide additional insights on how value of DERs can be studied based on the candidate location of installation.**

***Index Terms*—non-wire alternatives, distributed energy resources, locational value**

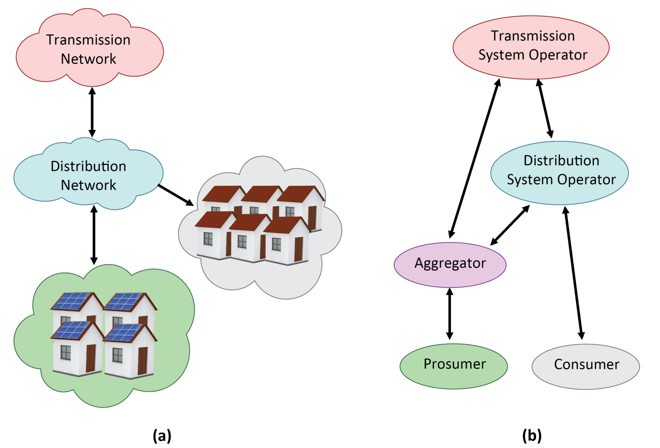

Fig. 1. DER Interconnection (a) Network Layout (b) Structural participation model

I. Introduction

Recent technological advancements have increased the possibility of differing or eliminating the need of constructing new transmission and distribution lines to meet the economic, reliability and policy goals. The National Council on Electricity Policy has defined five types of options [1]. These non-wire alternative solutions are: (i) improving end-user efficiency; (ii) end-user demand response; (iii) alternative generation including distributed generation; (iv) transmission system capability and efficiency improvements; and (v) storage technologies and plug-in electric vehicles. Some of these solutions directly reduce the demand, while others require alternate paths for power flow. The option of distributed generation as a non-wire alternative is particularly appealing to the system operators given the increasing number of rooftop solar installations nationwide and in the world [2].

Energy Systems Integration Group has identified three different structural participation models through which distributed energy resources (DER) can participate in wholesale markets, based on the nature of the interactions among the different market entities [3]. The most common among them is the DER aggregator model which is given in Fig. 1. As the DER penetration increases, it naturally leads to an increase in the number of aggregators who directly interact with transmission system operators. This in turn develops a need for the transmission system operators to include DER related studies as part of their planning.

Typical DER units are of less than 10 MW of power capacity, and can include fossil-fuel, renewable or energy storage technologies. When aggregated, the DER capacity that is connected to a transmission node in a network can be similar to that of small conventional generation sources. Well planned deployment of aggregated DERs can relieve congestions at distribution and transmission levels and improve the effectiveness of the power grid. However, when larger amounts of DERs are interconnected, the electric grid conditions might go beyond what it was originally planned and designed for [4]. With the increasing penetration of DERs, their combined effect becomes significant and has the potential to impact bulk system operations. By properly valuing DERs based on their location of interconnection, system operators will be able to anticipate critical scenarios and develop preventive measures against them.

The most prevalent way of valuing DERs currently is

This work was partially sponsored by Sunflower Electric Power Corporation Grant.

through the net benefit method and its variations, which are used to calculate the compensation for the DER owners based on their excess production of energy which is sent back to the grid [5]. The locational marginal value framework, developed by Quanta Technologies and adopted by several utilities in multiple jurisdictions, calculates the value of DER on a feeder-node based locational and temporal basis in terms of grid avoided costs [5]. While these methods directly capture the power injected to the grid, they do not account for other system impacts that accompany that injection, such as bus voltage deviations and changing line flows. The value calculated through these methods is also highly dynamic in nature since it is mainly dependent on the load usage of the DER bus itself, and therefore is not suitable for steady state analysis, and finding a location-specific value.

In previously published literature, several researchers have come up with different methods to find a value for DER integration from the point of view of different entities in power systems. Reference [6] presents a method to rank utility feeders most suited for DER implementation, based on peak load reduction, increased system capacity, load-generation correlation, and feeder load growth. Reference [7] presents a statistical method to integrate the load and generation uncertainties in determining the value of DER. Reference [8] presents a method to value DERs as non-wires alternatives in the traditional distribution network planning process by identifying their locational marginal value. Reference [9] presents a method to value the installed DER capacity based on the support it provides to the capacity planning of a distribution network. While these presented approaches reduce the dynamic nature of the valuing method and allow capturing the value of the location by incorporating additional factors, they are implemented and calculated only at distribution level. The effects brought in by the DER interconnection on the transmission grid, and how they should be valued from the point of view of transmission system operators are not explored in literature.

This paper proposes a method to calculate a value for DER by performing steady state analysis of an existing network under a transmission utility with and without the DER and quantify its effect via three metrics. This approach captures the impacts on the system conditions so that it can be analyzed from a transmission level and enables the operator to associate a locational value for potential DER installations. Section II of the paper describes the metrics and the statistical approach through which they are derived. Section III of the paper presents a case study where a test system is subjected to simulations of DER installation at different locations and their impacts are analyzed using the metrics that were developed.

II. Evaluation Metrics

From a transmission system operator's point of view, the addition of a DER can alter the system conditions mainly in three ways: (i) change the overall system losses; (ii) increase or decrease the power flows in the system lines; and (iii) produce voltage deviations in the system buses. Therefore, to evaluate the impact of a particular DER installation on the overall system, it becomes necessary to see the extent of impact it has on all three of these parameters (losses, line flows, and bus voltages).

The system before the DER installation, and after the DER installation need to be considered as two different cases. For both cases, time series of the system parameters can be obtained by simulating over a certain period with the expected load and generation conditions. From the parameters, the evaluation metrics can be calculated by employing a statistical approach.

A. Loss Metric

The total losses in the system at any instance i is found by using (1) where P is the power injection / consumption in kW, G is the total number of generators in the system, and L is the total number of loads in the system.

$$X_{L,i} = \sum_{g=1}^{G} P_g - \sum_{l=1}^{L} P_l \tag{1}$$

When considering over a period of time, the losses can be obtained in the form of a vector $X_L = [X_{L,1}, X_{L,2}, \ldots, X_{L,n}]$ where n is the total number of hours in the considered period. The mean and variance of the distribution of the system losses can be found as given in (2) and (3).

$$\overline{X}_L = \frac{\sum_{i=1}^{n} X_{L,i}}{n} \tag{2}$$

$$s_L^2 = \frac{\sum_{i=1}^{n} (X_{L,i} - \overline{X}_L)^2}{n-1} \tag{3}$$

Through simulation, system losses can be found for the two cases: before and after DER, and the losses corresponding to both scenarios can be obtained as two vectors: $X_{L,NoDER}$ and $X_{L,DER}$. Both vectors can be considered as two sample sets of data from two different distributions with unknown population variances. Therefore, the shift in mean between both distributions can be statistically found by calculating the Welch's t-test score as in (4). Although t-test and its variations are conventionally applied for normally distributed data, they can also be used for heavily skewed data with a large sample size [10].

$$t_L = \frac{\overline{X}_{L,DER} - \overline{X}_{L,NoDER}}{\sqrt{\frac{s_{L,DER}^2}{n} + \frac{s_{L,NoDER}^2}{n}}} \tag{4}$$

The loss metric captures the elasticity of the shift by expressing t_L as a fraction of t_{L0} which can be found as given in equations through (5) - (7).

$$t_{L0} = \frac{\overline{X}_{L,NoDER}}{\sqrt{\frac{s_{L,NoDER}^2}{n}}} \tag{5}$$

$$\lambda_L = \frac{t_L}{t_{L0}} \tag{6}$$

$$\lambda_L = \frac{\dfrac{\overline{X}_{L,DER} - \overline{X}_{L,NoDER}}{\sqrt{\frac{s^2_{L,DER}}{n} + \frac{s^2_{L,NoDER}}{n}}}}{\dfrac{\overline{X}_{L,NoDER}}{\sqrt{\frac{s^2_{L,NoDER}}{n}}}} \tag{7}$$

A positive value for the loss metric score indicates that the DER has introduced more losses into the system, whereas a negative value indicates that it has absorbed part of the system losses that existed before.

B. Line flow Metric

The total line flows in the system at any instance i is found by using (8) where B is the total number of buses in the system.

$$X_{LF,i} = \sum_{f=1}^{B} \sum_{\substack{t=1 \\ t \neq f}}^{B} P_{ft} \tag{8}$$

The process of calculating the line flow distributions of both cases and the shift produced by the DER is similar to how it was derived for loss metric using (2) - (5).

The line flow metric is then derived to be as in (9).

$$\lambda_{LF} = \frac{\dfrac{|\overline{X}_{LF,DER} - \overline{X}_{LF,NoDER}|}{\sqrt{\frac{s^2_{LF,DER}}{n} + \frac{s^2_{LF,NoDER}}{n}}}}{\dfrac{\overline{X}_{LF,NoDER}}{\sqrt{\frac{s^2_{LF,NoDER}}{n}}}} \tag{9}$$

A lower value for the line flow metric indicates that the impact of DER on altering the system conditions is small and is therefore favored.

C. Voltage metric

The total bus voltages in the system at any instance i is found by using (10)

$$X_{V,i} = \sum_{b=1}^{B} V_b \tag{10}$$

The process of calculating the voltage distributions of both cases and the shift produced by the DER is similar to how it was derived for loss metric using the equations (2) - (5).

The voltage metric is then derived to be as in (11)

$$\lambda_V = \frac{\left|\dfrac{\overline{X}_{V,DER} - \overline{X}_{V,NoDER}}{\sqrt{\frac{s^2_{V,DER}}{n} + \frac{s^2_{V,NoDER}}{n}}}\right|}{\dfrac{\overline{X}_{V,NoDER}}{\sqrt{\frac{s^2_{V,NoDER}}{n}}}} \tag{11}$$

A lower value for the voltage metric indicates that the impact of DER on altering the system conditions is small and is therefore favored.

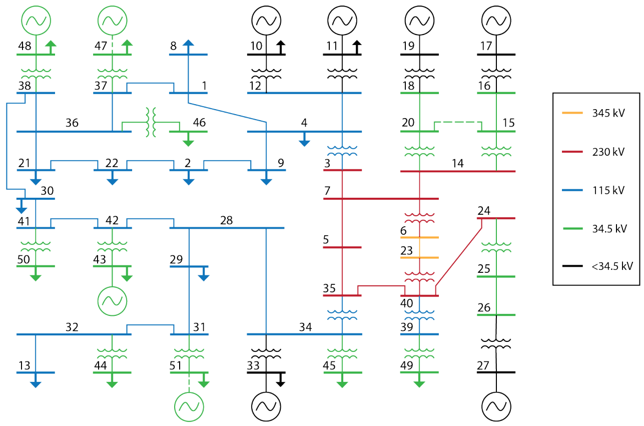

Fig. 2. Network layout of the 51-bus test system

III. Simulation and Results

A. Test System

To test the evaluation metrics, a test system was modelled from the grid data that overlaps part of the West Kansas region.[1] The network layout of the test system is given in Fig. 2. The test system consists of 51 buses and 53 lines, and it is supplied by 10 power plants including 3 wind farms. Buses with existing loads but without generators were assumed to be candidate buses for upcoming installation of DERs. In this test system, there were 13 such candidate buses.

B. Simulation

For this simulation, a fixed generating unit of 20MW was assumed to be the DER. An hourly time series data of all the loads in the test system was used to run the simulation over a period of one year. The process of obtaining the pre-DER and post-DER system parameters necessary for calculating the evaluation metrics as a time series was done by iterating through the following steps for every hour of load data.

- Optimal power flow is run with fuel cost minimization criteria using a power system simulation software, and generation dispatch of all 10 power plants is obtained. For wind power plants, the maximum generation capacity at each hour was capped by the actual wind generation recorded from that plant.
- The total generations, loads, line flows and bus voltages are calculated and are recorded as pre-DER system parameters.
- DER is added to one of the candidate buses and power flow is run using the power system simulation software while following the generation dispatch obtained in first step.
- The total generations, loads, line flows and bus voltages are re-calculated and are recorded as post-DER system parameters corresponding to the candidate bus.

[1]The test system was built based on proprietary data that was obtained through a Non-Disclosure Agreement.

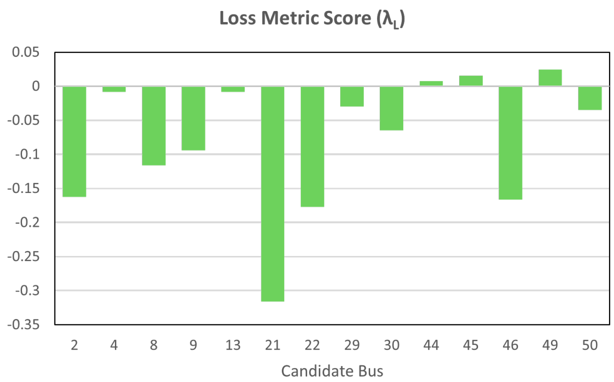

Fig. 3. Loss metric scores for the candidate buses

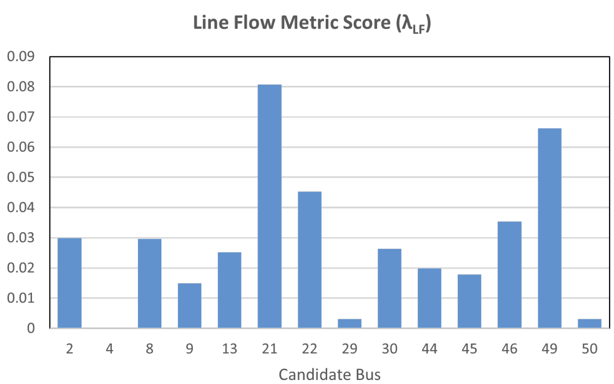

Fig. 4. Line flow metric scores for the candidate buses

Once the pre-DER and post-DER values are obtained for the whole year, the evaluation metrics were calculated using (1) - (11).

C. Results

The loss metric scores for the 13 candidate bus locations is presented for comparison in Fig. 3. Most of the locations have resulted in system losses being reduced from what they were before the DER installation. Bus 21 in particular has absorbed the most losses from the system when DER was installed. Buses 44, 45, and 49 however, have introduced more system losses.

The line flow metric scores for the 13 candidate bus locations is presented for comparison in Fig. 4. Since the added DER is of small capacity, the shift in the line flow distribution has resulted to be small as expected. Buses 4, 29, and 50 have negligible shifts, and therefore can be considered as good candidate locations with respect to the line flow metric.

The voltage metric scores for the 13 candidate bus locations is presented for comparison in Fig. 5. Magnitude of shift in the voltage distributions between both cases is much smaller compared to the previous two parameters. Given that the allowable voltage deviation limit itself is 5% for typical transmission buses, this behavior is expected. Buses 4, 45, and 49 show the smallest shifts compared to the pre-DER case, and therefore can be considered as good candidate locations with respect to the voltage metric.

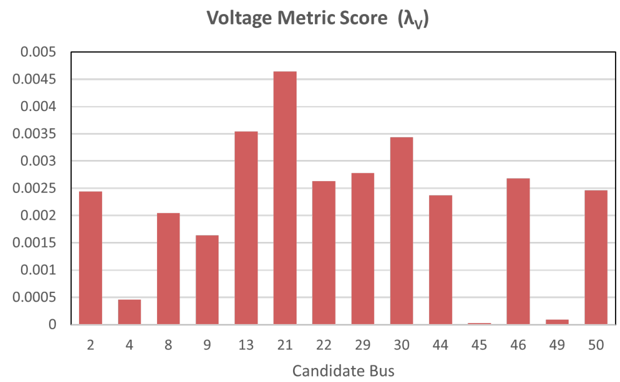

Fig. 5. Voltage metric scores for the candidate buses

It is evident when looking at all three metric scores, that no candidate bus location can be claimed as the one true ideal location for DER installation that will minimize the effects on the system with respect to all three parameters. However, since a system operator can prioritize which of the parameter shifts is more critical for them depending on their existing system conditions, it is advantageous to know which locations are good with respect to each of the parameters. This can be visualized geographically by using the following technique.

D. Map Visualization

Each parameter's metric score can be standardized to a value between 0 to 1 by accounting for the full range of the parameter metric scores obtained for all the candidate buses in the system. Since the lower values are better for the metrics, the standardized metric score can be written as in (12)

$$\lambda'_x = \frac{max(\lambda_x) - \lambda_x}{max(\lambda_x) - min(\lambda_x)} \tag{12}$$

The unified metric score can be obtained as the sum of individual standardized metric scores.

$$\lambda = \lambda'_L + \lambda'_{LF} + \lambda'_V \tag{13}$$

The unified metric scores of all 13 candidate buses are presented in Fig. 6. The best location for minimizing effects on the system with respect to all three system parameters is found to be Bus 4, which has a unified metric score of 2.0. Buses 13 and 21 are found to be generally poor locations for DER installations.

To visually present the metric score information on a map, each standardized metric score (λ'_x) was mapped to full range of each of the primary colors. The combined results of the primary colors is then assigned for the markers of the actual geographic locations as shown in Fig. 7. It can be interpreted that an ideal location that will minimize the effect on all system losses, line flows and voltages will be close to white

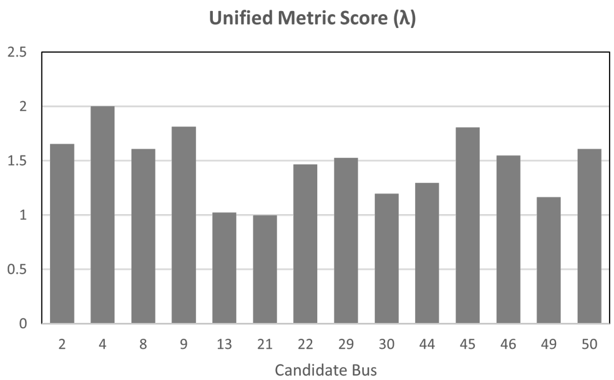

Fig. 6. Unified metric scores for the candidate buses

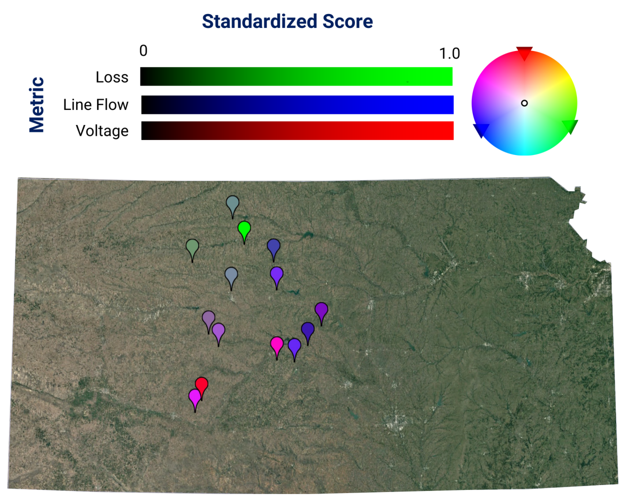

Fig. 7. Candidate bus locations with metric score color mapping

color, which is the combination of the three primary colors at their 100%.

From the map illustration it becomes easier to infer about the value of each location geographically. Most of the locations have performed better when it comes to minimizing the change in line flows, resulting in a lot of blue shaded map markers. Locations that are higher up north tend to perform better when it comes to absorbing more system losses, resulting in more green shade; whereas locations that are more down south tend to perform better in minimizing bus voltage deviations, resulting in more red shade. Visualizing this way enables the system operators to easily identify which bus locations are favorable for their particular system.

IV. Conclusion

In this paper, a novel method is presented to value the location of a DER interconnection from the point of view of transmission system operators. The method processes the change in system losses, line flows and bus voltages effected by the addition of DER to the original network and statistically obtains three metrics to evaluate the impact of DER on the overall system. The three metrics can be either interpreted individually depending on the network priorities of the system operator, or as a single standardized score to value a particular location as a potential DER candidate. The method was tested on a 51-bus test system modelled based on western Kansas region, where the locational value of DERs was found for 13 candidate locations and compared. The corresponding results show that the method can be employed as a planning tool by system operators to identify the locations which are favorable and which are not favorable for future DER installations. Since the method is not dependent on the type of DER, the approach can also be extended to include beyond distributed generating sources, such as electric vehicles and battery storage.

References

[1] M. Keogh, J. Rowlett, B. Flansburg, P. O'Connor, A. Spahn, M. Brown, "Updating the electric grid: an Introduction to non-transmission alternatives for policymakers," The National Council on Electricity Policy, USA, Sep. 2009. [Online]. Available: https://www.energy.gov/oe/downloads/updating-electric-grid-introduction-non-transmission-alternatives-policymakers

[2] K. Ardani *et al.*, "Solar futures study," Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, Sep. 2021. [Online]. Available: https://www.energy.gov/sites/default/files/2021-09/Solar Futures Study.pdf

[3] M. McDonnell, J. Gorman, F. Kahrl, L. Kristov, J. Keeling, P. Sreedharan, "DER integration into wholesale Markets and Operations," Distributed Energy Resources Task Force, Energy Systems Integration Group, Reston, VA, USA, Jan. 2022. [Online]. Available: https://www.esig.energy/der-integration-series-wholesale-markets-and-operations/

[4] T. S. Basso, "System impacts from interconnection of distributed resources: current status and identification of needs for further development," Technical Report, NREL TP-550-44727, Jan. 2009. [Online]. Available: https://www.nrel.gov/docs/fy09osti/44727.pdf

[5] R. Masiello, F. Farzan, E. Ntakou, "An analytic framework for evaluating the value of distributed energy resources," Quanta Technologies, Apr. 2020. [Online]. Available: https://quanta-technology.com/report/value-of-der-framework/

[6] B. Kroposki, P. K. Sen and K. Malmedal, "Selection of distribution feeders for implementing distributed generation and renewable energy applications," in *IEEE Transactions on Industry Applications*, vol. 49, no. 6, pp. 2825-2834, Nov.-Dec. 2013, doi: 10.1109/TIA.2013.2262091.

[7] M. Shahidehpour, H. Nasiri, S. Bahramirad and E. A. Paaso, "A methodology to evaluate the value of DER to the distribution network considering uncertainties," *2019 IEEE Power and Energy Society General Meeting (PESGM)*, 2019, pp. 1-5, doi: 10.1109/PESGM40551.2019.8973848.

[8] P. Andrianesis, M. Caramanis, R. D. Masiello, R. D. Tabors and S. Bahramirad, "Locational marginal value of distributed energy resources as non-wires alternatives," in *IEEE Transactions on Smart Grid*, vol. 11, no. 1, pp. 270-280, Jan. 2020, doi: 10.1109/TSG.2019.2921205.

[9] H. Nasiri et al., "Networked-constrained DER valuation in distribution networks," in *IEEE Transactions on Smart Grid*, vol. 11, no. 6, pp. 4809-4817, Nov. 2020, doi: 10.1109/TSG.2020.3002425.

[10] M. Fagerland, "T-tests, non-parametric tests, and large studies: a paradox of statistical practice?", *BMC medical research methodology*, vol. 12, Jun. 2012, doi: 10.1186/1471-2288-12-78