SSEG Grid Impacts Assessment Support for Municipalities project report: Development of a feeder Hosting Capacity Tool for South African municipalities

B MOLEFYANE, L.L MBATHA, M RAMPOKANYO
Council for Scientific and Industrial Research
South Africa

SUMMARY

Some parts of South African metropolitan municipalities show an increasing rate in the deployment of small-scale embedded generation (SSEG). SSEG predominantly consist of photovoltaic (PV) modules and due to the variability of solar energy the output power does not always match the load profile. This can cause challenges to the distribution grid network and can sometimes violate the defined network operational limits. Network planners and operators can plan better for system upgrades when feeder hosting capacity limits are calculated. A feeder hosting capacity analysis tool is developed to enable South African distribution planners to determine the thresholds at which SSEG can be integrated into their distribution networks without undertaking network strengthening, and to determine locations for network improvements to allow for additional uptake of embedded generation capacity beyond this threshold. A stochastic hosting capacity method was implemented in DIgSILENT PowerFactory using DIgSILENT Programming Language (DPL). The method was assessed in terms of its advantages and disadvantages. The method was tested alongside the deterministic method using a South African municipal test network during which results were compared and used to assess functionality, capability, and to develop recommendations for improvements. Despite having a longer computation time, the stochastic hosting capacity method accounts for the probabilistic behaviour of SSEG installations observed in municipality networks, and thus would be the method more appropriate for calculating feeder hosting capacity.

KEYWORDS

Deterministic method, Grid Impact, Hosting Capacity Analysis, Optimal Method, Small Scale Embedded Generators, Stochastic Method, Streamlined Method.

1 INTRODUCTION

South Africa's (SA's) energy crisis has not only become an issue to the state government but has also pushed customers to now play an active role in deriving a solution to the problem. Load shedding has not only caused an inconvenience to customers but has also resulted in economic disruption of businesses, particularly small businesses. Residential, industrial and commercial customers have now opted to install owner supplies, termed as Small-Scale Embedded Generation (SSEG), which at the time of writing refers to a generation capacity less than 1 MW.

There is simultaneously a growing concern for the safety, reliability and quality of supply, which requires a proactive response from distribution network planners and operators. Several methods of analysis exist which can be implemented for interconnection and planning studies, one of which is a hosting capacity analysis. Hosting capacity is the amount of distributed energy resources (DER) that can be added to a network without compromising the power quality and reliability of the network under existing control configurations and without requiring network strengthening [1]. Control system upgrades, network strengthening or mitigation measures are required to safely integrate generation capacity above what the network can handle [2][3].

In addition to determining the generation capacity threshold of a network, hosting capacity analysis can help municipalities understand the impact of adding new SSEG to the electrical distribution system and further provide more information on the associated costs needed to upgrade the distribution network to accommodate more SSEG onto the network. Hosting capacity also provides information on optimal locations for SSEG interconnection, the trade-offs between cost and hosting capacity expansion for a range of possible distribution system upgrades that could be used to integrate SSEG [4].

This paper looks at four hosting capacity methods which exist, and are currently being utilised or being further researched. From the four methods, the stochastic method is selected to develop a hosting capacity tool for SA networks, implemented for a detailed analysis, and tested against the deterministic method on a metropolitan municipal network. A detailed analysis of the results is performed to assess the method, and develop recommendations on how it can be improved.

This paper includes the current introductory section followed by a review of hosting capacity methods in Section 2. Section 3 describes the development of the hosting capacity tool. The implementation and testing of the tool is discussed in section 4, followed by results and analysis in section 5. Section 6 concludes this paper with recommendations provided in section 7.

2 REVIEW OF HOSTING CAPACITY METHODS

2.1 Hosting Capacity Approach

The calculation of hosting capacity depends on a wide range of factors which include SSEG location, SSEG type, feeder configuration as well as assumptions and constraints applied for developing and testing a hosting capacity method [1]. Hosting capacity methods make use of impact factors to calculate a capacity of allowable generation. Within these impact factors, performance indices can be selected to calculate feeder hosting capacity and any single or combination of these performance indices can be used as a criterion. Table 1 below shows a list of the performance indices that can be used for assessing hosting capacity in distribution networks.

Table 1 : Performance indices for hosting capacity assessment

Voltage	Thermal overloading	Power quality	Protection
➢ Over-voltage ➢ Under-voltage	➢ Line/cable loading limits ➢ Transformer loading limits	➢ Voltage unbalance ➢ Harmonic distortion ➢ Reverse power flow	➢ Protection coordination

Most methods use a similar principle as seen on Figure 1 whereby SSEG penetration is increased in user-defined step sizes at a location while performance indices are checked at every iteration for violations. Once a violation has been detected, hosting capacity is obtained. All feeders will have a unique response to the interconnection of SSEG and therefore other impact factors of calculating hosting capacity can be the feeder capacity, PV deployments and specific utility established thresholds [5]. Hosting capacity is also time varying – i.e. a hosting capacity performed today, may be different to that performed 5 years back – as distribution networks are continually evolving in terms of topology and loading. It is therefore important to develop a method that will provide accurate information to distribution grid planners on where the SSEG can interconnect and where the network requires strengthening in anticipation of network growth [6].

Four methods are reviewed, namely:

- Deterministic hosting capacity;
- Stochastic hosting capacity
- Streamlined hosting capacity, and
- Optimisation hosting capacity method.

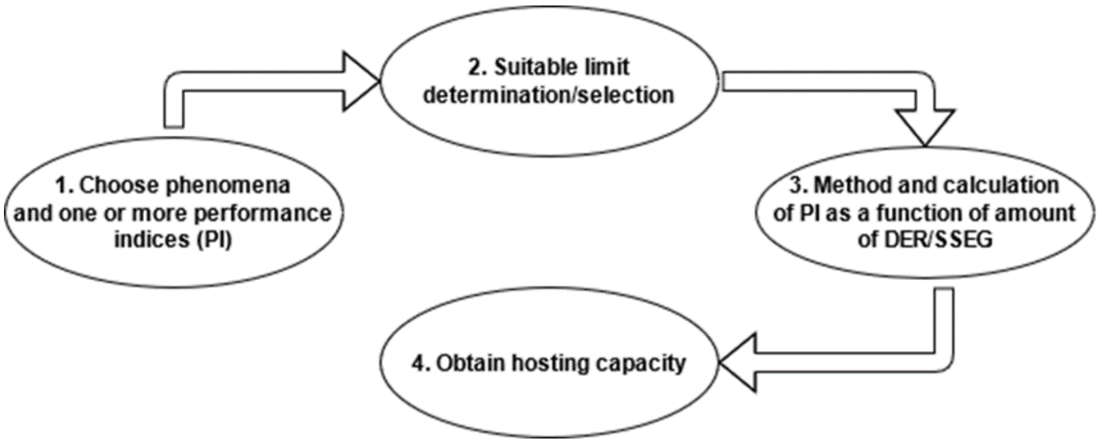

Figure 1 General methodology of feeder hosting capacity calculation [7]

2.2 Deterministic Hosting Capacity Method

The deterministic method requires known inputs such as the size, location, and properties of the embedded generation. It uses power flow analysis to determine the total installed capacity at a node (only part of the feeder). Generation capacity is increased at a constant rate at a specific node until violation of the operational limits is reached. The hosting capacity $P_{HC(i)}$ is the sum of current total capacity $P_{t(i)}$ minus previous total capacity$P_{t(i-1)}$ as shown in equation (1) below.

$$P_{HC(i)} = P_{t(i)} - P_{t(i-1)} \tag{1}$$

It is important to choose an appropriate constant increment in generation capacity to obtain a more accurate hosting capacity. A large increment can result in a more conservative hosting capacity, whilst a small value can require more computational time. The following data is required when performing a deterministic hosting capacity [7]:

- Network Model, this includes information on line impedances, loads and generation sources and how they are interconnected and configured
- Network equipment specifications (Transformer ratings, PV System maximum capacity, lines, protection equipment, reactive power compensation devices)
- Customer load consumption (a snapshot for constant deterministic method and load profile for time series deterministic method)

2.3 Stochastic Hosting Capacity Method

There are unknown variables when assessing the impacts of SSEG and these variables can be the number of customers who intend on installing SSEG, the size to be installed, location of installation, and the intermittent behaviour of renewable energy sources [7]. These unknown variables have an impact on the calculation of hosting capacity. The stochastic hosting capacity method uses a random function to account for the randomness of the aforementioned unknowns. There are well accepted methods which can be used to generate the random function, including [3][8]:

- Monte Carlo simulation (MCS),
- Random Distribution Energy Resources (DER) deployment,
- Sparse grid technique,
- Quasi Monte Carlo.

This paper illustrates how the Random DER deployment method can be implemented. The approach taken performs a baseline power flow analysis and optimises SSEG at random locations with random sizes (mainly based on the behaviour of customers in the area of study) and getting a result of a range of impacts, which are probable for future deployments of SSEG. It is important to note that the hosting capacity of a network is dependent on the on its loading, which in turn depends on weather patterns, seasonality, and mostly temperature [9][10]. Thus it is important to consider different loading conditions that a network experiences when conducting a hosting capacity analysis. The stochastic method illustrates a future planning scenario whereby SSEG is added at multiple locations across feeders [1].

2.4 Streamlined Hosting Capacity Method

One of the disadvantages identified for the Deterministic and Stochastic methods is the amount of computational time required when calculating hosting capacity [7]. The streamlined method uses algorithms and equations to efficiently perform analysis in a streamlined approach. Two types of streamlined method were identified during this research, the first is developed by Electric Power Research Institute (EPRI) [7] and the second being streamlined ICA method [1].

The streamlined method developed by EPRI performs detailed stochastic studies on a range of feeders and then identifies commonalities which exist when interconnecting a particular type of SSEG (e.g., PV System) onto the feeders of that kind [7]. A series of sensitivity analyses are performed to produce three results for hosting capacity which are realistic, optimistic, and conservative. This method has already been developed and the algorithm is available in the Distribution Resource Integration and Value Estimation (DRIVE) [11]. The streamlined ICA method does not model the SSEG on a power system tool but uses a set of equations to observe impact. The method is developed to reduce the amount of computational time required when modelling a SSEG. The equations used to calculate hosting capacity can be found on PG&Es DEMO A/B report [1].

2.5 Optimised Hosting Capacity Method

The Optimised hosting capacity method also optimises both computational time and maximum generation capacity when determining hosting capacity. This method uses linear power flow equations which enable linear programming for the hosting capacity analysis, by doing so the method eliminates iteration as a traditional method. Using this method SSEG can be effectively integrated as it allows for dynamic changes to the model. All buses are simultaneously simulated and analysed for their hosting capacity [12].

3 DEVELOPMENT OF HOSTING CAPACITY ASSESSMENT TOOL

Developing an assessment tool to determine feeder hosting capacity is meant to assist South African municipal screening processes and planning for high SSEG penetration. The tool will better inform municipalities on the amount of SSEG a feeder can accommodate, and when to anticipate system upgrades to accommodate additional capacity. The stochastic hosting capacity method is selected for implementation. The selection of the methods depends on intended use. In this case the use may be based on customers' behaviour. From this perspective, calculating hosting capacity becomes more probabilistic where distribution network planners have no control on the location and size of installation. This method was implemented to provide better understanding and detailed analysis. The method was automated using DPL scripting in the DIgSILENT PowerFactory simulation tool [13] and studied in detail. The stochastic method is compared with the deterministic method for assessment purposes, but the development of the deterministic method is not discussed as it is not the focus of this paper. Implementation of the tool was such that the loading on the network was kept constant. This is done in order to assess functionality of the tool. A proper hosting capacity analysis requires that different loading condition be examined, as mentioned in section 2.3, and the lowest hosting capacity result be selected [9]. The lowest hosting capacity is obtained under minimum loading conditions when considering overvoltage violation, and under maximum loading condition when considering voltage unbalance [9]. Thus, the performance indices selected for the analysis have an influence on how loading conditions affect the results.

3.1 Stochastic hosting capacity tool

The stochastic hosting capacity analysis method implemented in DPL scripting uses a random number generator to introduce randomness in bus selection and capacity increase. The type of random number generator used is the Mersenne Twister, a type of random number generator classified as a strong pseudo-random number generator [14]. This means that this type of random number generator has a long period (number of random values generated before repeating a sequence) and uniform distribution of values [15].

Figure 2 shows a flow diagram that illustrates the algorithm used to carry out the stochastic hosting capacity analysis. The algorithm begins with a network model where the characteristic data (voltage and thermal loading limits) of the network, loads and generators are obtained. The algorithm then runs a load flow test to set the base case, where the distributed generators on the network (in this case, PV generators) connected to the buses of interest are set to some initial active power capacity. A bus corresponding to a distributed generator is randomly selected, then the algorithm continues to generate a random size with which to increase the generator capacity. For this case the capacity size increment ranges between 50 kW and 100 kW (chosen arbitrarily). After increasing the capacity on the selected bus, a load flow test is executed. The algorithm then checks for any voltage violations on all buses or thermal violations on all lines and transformers of the case file. The violation limits set in the code are:

- For voltages less than 500V, acceptable voltage deviation is ±10% and
- For voltages greater than 500V, acceptable voltage deviation is ±5%.
- Line and transformer thermal loading ≤ 100 % of continuous thermal rating

Voltage limits are from the requirements given in the NRS 048-2 [16]. If there are no violations detected, the algorithm loops back to randomly selecting another bus and runs through this process again. If a violation is detected, the algorithm subtracts the recently added capacity and records the current active power capacity on the bus as the hosting capacity of that bus. Once all buses of interest have been accounted for, the algorithm generates a list of hosting capacities.

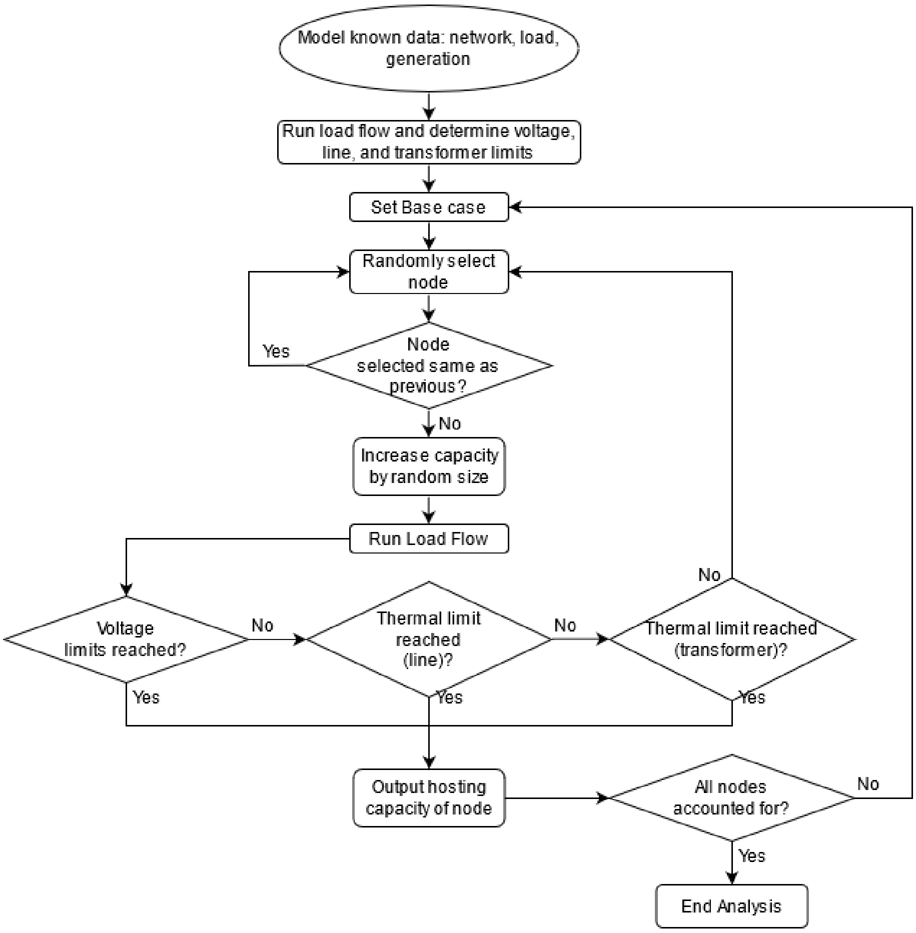

Figure 2 Flow chart illustrating stochastic hosting capacity algorithm

4 APPLICATION OF METHOD ON A METROPOLITAN MUNICIPAL NETWORK – SOUTH AFRICAN MUNICIPAL NETWORK

A practical metropolitan municipal network with three feeders (shown in Figure 3) is investigated for high penetration of PV systems. The network has a total maximum load of 3.36 MW, and the base case has six nodes with PV interconnection. The hosting capacity using the stochastic method is computed at for different loading cases (different load multipliers). Additionally, nodes are assessed in increments of two up to 30 nodes to assess the performance of the stochastic method. The whole distribution feeder model is implemented and tested using DIgSILENT (DIgSILENT | Power Systems Solutions, n.d.). This section takes a look at the performance of the method, however it is important to note that the exact outputs of the method would vary

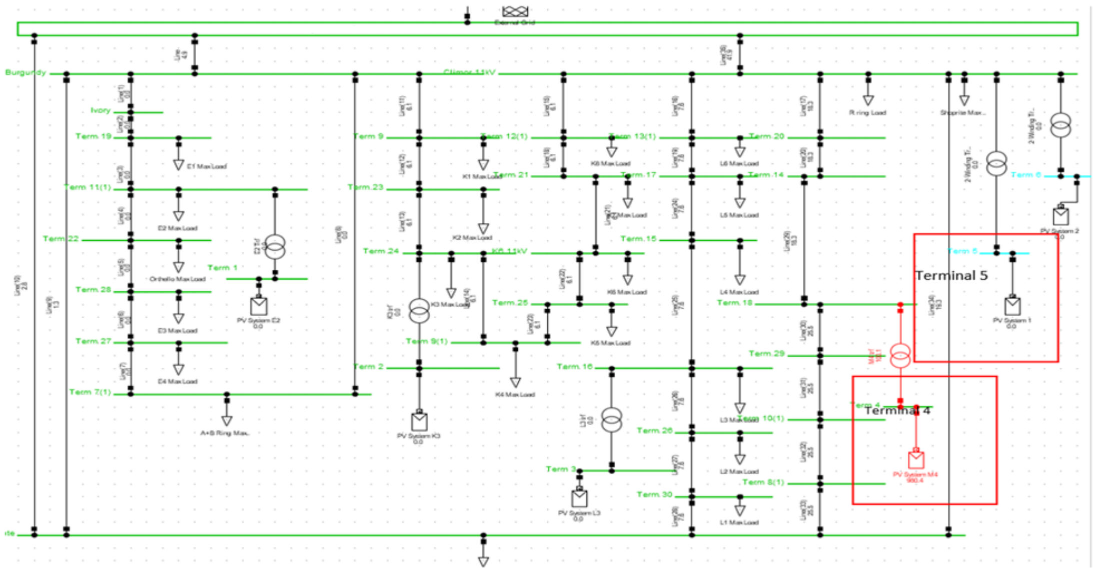

Figure 3 A practical metropolitan muncipal distribution feeder network

depending on the design of the study.

4.1 Implementation and testing of stochastic hosting capacity method

The stochastic method reflected reality in that generation capacity was increased at random location with random sizes (which was modelled to resemble the behaviour of installations on the network). The stochastic method is more complex to implement but it is valuable in educating the industry on impacts of SSEG. A range is provided (50 kW to 100 kW as mentioned in section 3.1) when increasing generation capacity and as a result it helps determine a range of possible impacts for future PV penetration.

The stochastic hosting capacity method was tested on the municipal network and was compared against the deterministic hosting capacity method. The test involved assessing the computational time and differences in the results (mainly focussing on the hosting capacities calculated for the entire network, and the hosting capacity results for two buses for ease of observation) obtained when computing hosting capacities, as a function of the number of buses/nodes meant to be assessed. The outputs of the stochastic method are compared to those of the deterministic method to highlight the advantages and shortcomings of the stochastic hosting capacity method. The results and analysis of this evaluation are discussed in section 5.

5 RESULTS AND ANALYSIS

5.1 Hosting capacity of the test network

Applying the deterministic method in computing the hosting capacity of the test network yields the results shown in Figure 4. This figure shows the hosting capacity of 20 random buses (referred to as terminals in the figure) found on the test network. Through the deterministic method, the hosting capacity of a bus is determined assuming that no generation is connected anywhere else in the network. The main limitation with this method is that it does not provide information about the hosting capacity of the network as a whole.

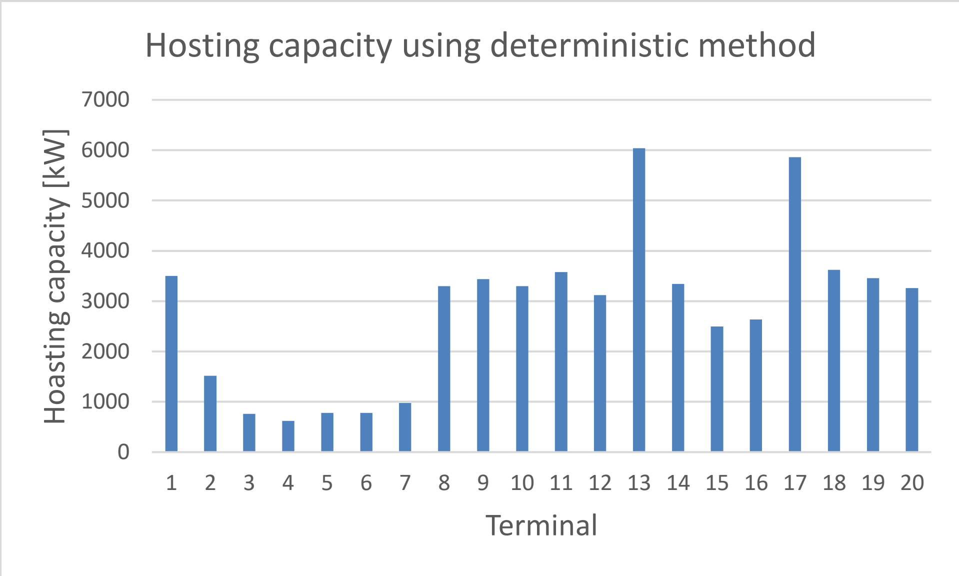

Figure 4: Deterministic Hosting capacity results of 20 random terminals in the test network

With the stochastic method on the other hand, the entire networks hosting capacity can be determined. Figure 5 shows the hosting capacity of the test network as a function of the load multiplier (i.e. as a function of the percentage of the total maximum load). This provides information on the networks hosting capacity for different loading conditions. The trend seen in Figure 5 shows that the histing capacity of the network increases with increasing network load. At 30% of the total maximum load (multiplier of 0.3) the network hosting capacity is ~6200 kW, and at 100% (multiplier of 1) it is ~8070 kW. Depending on possible loading conditions of the network, the lowest hosting capacity results achieved from the existing possible scenarios should be considered the hosting capacity of the network. Hence if we assume that all load multipliers considered in Figure 5 are possible loading cases for the test network, then the network's loading capacity is the lowest result, which is 6200 kW.

The stochastic hosting capacity method has an advantage of being able to determine the hosting capacity of the entire network in question. This is valuable information for a distribution system network planner since If 6200 kW is considered to be the hosting capacity of the test network, the system network planner would have to distribute this generation capacity across the different locations of the network. Only relying on the information provided by the determinist method as shown in Figure 4 could result in

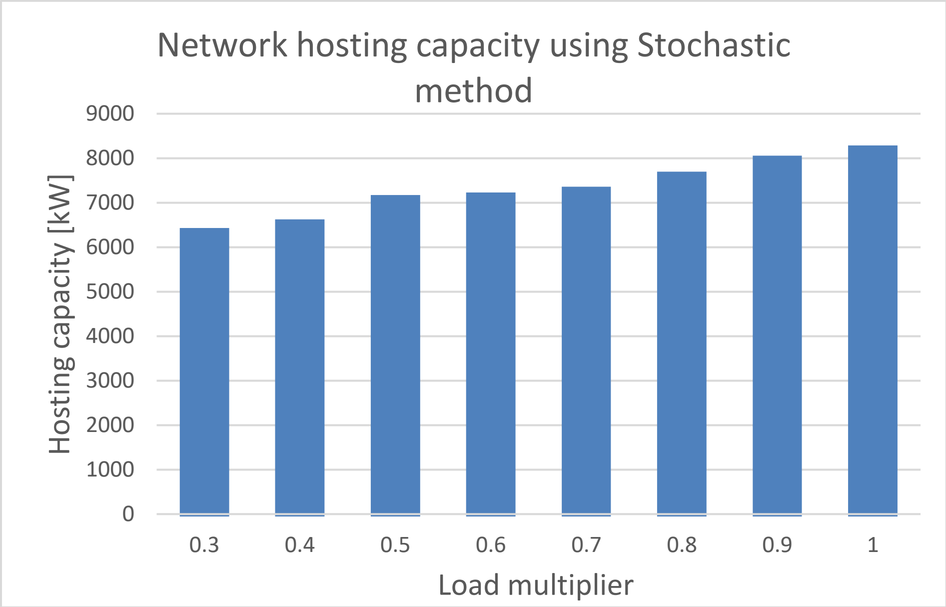

Figure 5: Stochastic hosting capacity results of test network at different loading conditions

the network's hosting capacity being significantly exceeded as the hosting capacity of terminal 13 alone is almost equivalent to the network's hosting capacity.

5.2 Hosting capacity results of two terminals

The hosting capacity analysis was undertaken for the stochastic method and compared to the deterministic method to observe functionality. Results were assessed for the metropolitan municipal feeder network. Hosting capacity was observed for two terminals/buses (hereafter referred to as node 4 and node 5) which had the largest hosting capacity values. These nodes are highlighted in red squares in Figure 3 above. At base case the hosting capacity value is approximately the same for both nodes when calculated using the deterministic and stochastic methods. The values begin to change when increasing the number of nodes assessed for only the stochastic method. The trends (linear graphs) at which the hosting capacity of nodes 4 and 5 decrease as

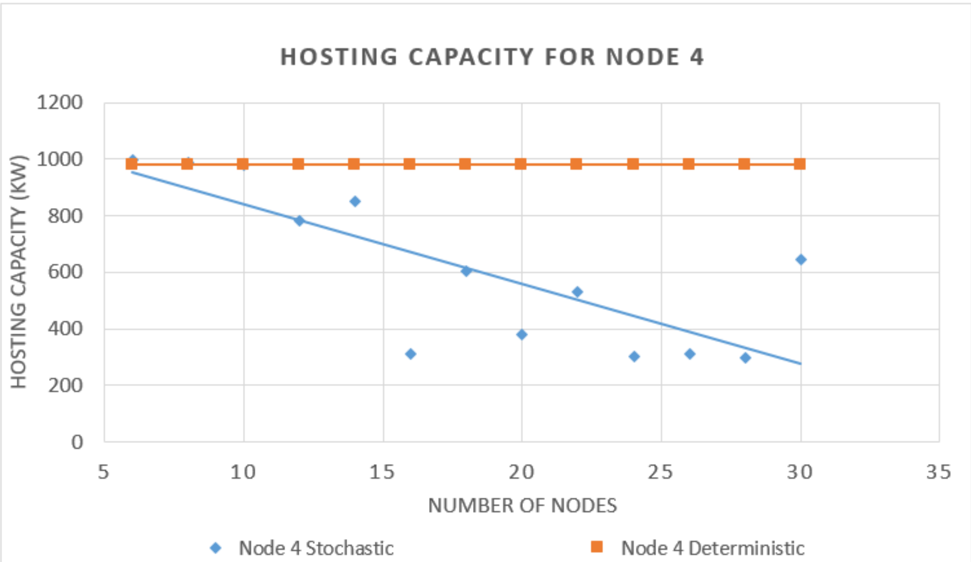

Figure 6 Hosting capacity for node 4 as a function of nodes assessed

a function of assessed nodes for the stochastic method are shown in Figure 6 and Figure 7 respectively. The points represent the actual values obtained during testing.

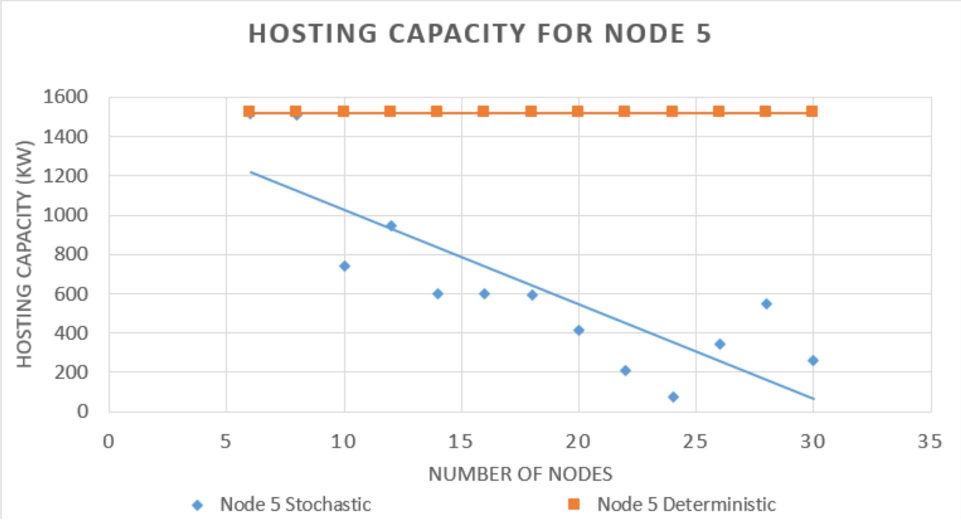

Figure 7 Hosting capacity of node 5 as a function of nodes assessed

5.3 Results for Computational time

The computational times for the stochastic and deterministic methods are compared in Figure 8. The figure shows the trends (linear graphs) of increasing computational time for the two methods as a function of nodes assessed. Again, the points represent the actual values obtained during testing. Figure 8 shows that the computational time for the stochastic method increases faster than that of the deterministic method. To emphasise this observation, compares the computational time for the minimum and maximum number of nodes assessed for both the stochastic and deterministic methods. The computational time for the stochastic method is about twice that of the deterministic for six nodes. At 30 nodes, the stochastic method's computational time grows to approximately three times that of the deterministic method. This observation is a result of the stochastic nature of the algorithm and the amount of information required to perform the hosting capacity analysis. However, given the advantages that the stochastic method provides (discussed in section 5.4), the added computational time can be considered an acceptable trade-off.

Table 2: Computational time for the minimum and maximum number of nodes assessed for both methods

Number of nodes	Deterministic method	Stochastic method
6	~30 s	~60 s
30	~200 s	~600 s

5.4 Analysis of results

The deterministic hosting capacity method computes the hosting capacity of a single node at a time, assuming that no generation capacity is installed elsewhere. The result is a hosting capacity for a node that remains constant regardless of the number of nodes examined as seen in Figure 6 and Figure 7. This method caters for the highly unlikely case of generation being connected at a single point on the network. In reality, installation of SSEG happens at multiple locations at random. As a result, the hosting capacity of a specific node could be reached due to the threshold of a component

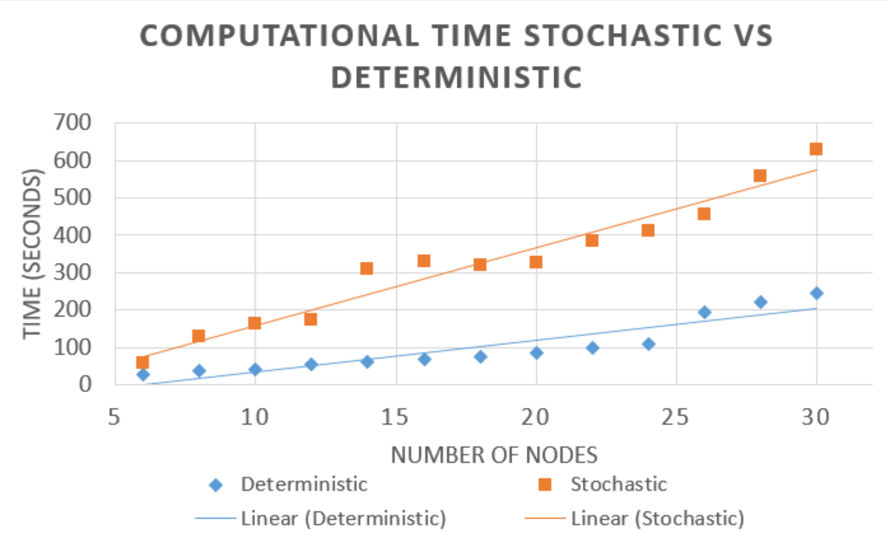

Figure 8 Computational time as a function of nodes assessed

connected elsewhere in the network. The stochastic method accounts for this and provides results based on the likelihood of generation being installed at multiple points in the network. This method also provides information on the hosting capacity of the entire network and not just a specific node. This is seen in Figure 7 and Figure 8 where the hosting capacities of nodes 4 and 5 decrease with increasing nodes assessed, showing that the hosting capacity of any node depends on generation at other nodes, and the hosting capacity of the network limits how much generation capacity can be connected at any node provided there are other connections made elsewhere in the network. The stochastic method also provides more insight into crucial points in the network that require upgrading to increase the overall hosting capacity.

A limitation with the stochastic method is its lack of precision. Observations of results from tests conducted suggest the possibility of a weak correlation between hosting capacity outputs and depicted trend of the stochastic method seen in Figure 6 and Figure 7. This suggests that the likelihood of getting the exact same results from multiple tests is low. This is due to the random nature of the algorithm employed. Additionally, the stochastic method is computationally intensive. From Figure 8 it can be seen that the stochastic method has a long computational time that increases at a higher rate with increasing nodes as compared to the deterministic method. However, depending on the intended use of the tool and the size of network being studied, longer computational times might not be an issue.

6 CONCLUSION

In developing a hosting capacity tool for South African municipalities, four methods were investigated. Of the four, the stochastic hosting capacity method was used as the basis for a hosting capacity analysis script developed using DPL due to the method's implementation strategy and ease of development. The tool was tested on the Morgen Gronde distribution network and results were compared against those obtained from using the deterministic method.

The tool will potentially be rolled out to municipalities through online resource portals hosted by organisations such as the Council for Scientific and Industrial Research (CSIR), Sustainable Energy Africa (SEA) and South African Local Government Association (SALGA).

An analysis into this evaluation shows that the stochastic method reflects realistic scenarios and accounts for the contribution of generators at different locations to the hosting capacity computed. The behaviour of hosting capacity when increasing interconnections points shows that the hosting capacity at any one location decreases when increasing embedded generators at different locations. The stochastic hosting capacity method also gives the user more information on the impacts on the overall network when increasing embedded generator to the network. However, the stochastic hosting capacity method has a long computational time and low precision in terms of results obtained. Depending on the intended use of the tool, the stochastic method would be ideal when calculating hosting capacity as it provides more information in determining hosting capacity the impact of increasing SSEG to the distribution network.

7 RECOMMENDATIONS

To improve on the limitation of precision for the stochastic hosting capacity method, the relationship between output precision and capacity size increment range of the method could be explored to determine an optimal increment range that provides better precision. Also, currently the method only considers scenarios where the load is assumed to be constant. To account for the randomness introduced in the loading of the distribution network, the loading could be modelled using stochastic means such as using Monte-Carlo simulations (MCS) [8]. This will produce results that reflect realistic events more accurately, however, this will increase computation burden of the analysis.

BIBLIOGRAPHY

[1] M. (EPRI) Rylander, J. (EPRI) Smith, and L. (EPRI) Rogers, “Impact Factors, Methods, and Considerations for Calculating and Applying Hosting Capacity,” *Integr. Distrib. Energy Resour.*, p. 72, 2018.

[2] A. Mikulec and V. Mikulicic, “Influence of Renewable Energy Sources on Distribution Network Availability,” *Int. J. Electr. Comput. Eng.*, vol. 2, pp. 37–48, 2011.

[3] M. Zain ul Abideen, O. Ellabban, and L. Al-Fagih, “A Review of the Tools and Methods for Distribution Networks ’ Hosting Capacity Calculation,” pp. 1–25, 2020.

[4] NREL, “Hosting Capacity Analysis for DEVELOPERS,” p. 2, 2019, [Online]. Available: www.nrel.gov.

[5] Elerctric Power Research Institute, “Distribution Feeder Hosting Capacity: What matters when planning for DER,” 2015.

[6] D. Gahl and R. Umoff, “Hosting Capacity : Using Increased Transparency of Grid Constraints To Accelerate,” no. September, 2017.

[7] E. Mulenga, M. H. J. Bollen, and N. Etherden, “A review of hosting capacity quantification methods for photovoltaics in low-voltage distribution grids,” *Int. J. Electr. Power Energy Syst.*, vol. 115, p. 105445, 2020, doi: https://doi.org/10.1016/j.ijepes.2019.105445.

[8] J. Chihota, B. Bekker, and T. Gaunt, “A Stochastic Analytic-Probabilistic Approach to Distributed Generation Hosting Capacity Evaluation of Active Feeders,” 2020.

[9] A. Dubey, S. Santoso, and A. Maitra, “Understanding photovoltaic hosting capacity of distribution circuits,” *IEEE Power Energy Soc. Gen. Meet.*, vol. 2015-September, 2015, doi: 10.1109/PESGM.2015.7286510.

[10] N. Chabouni, Y. Belarbi, and W. Benhassine, “Electricity load dynamics, temperature and seasonality Nexus in Algeria,” *Energy*, vol. 200, p. 117513, 2020, doi: 10.1016/j.energy.2020.117513.

[11] M. (EPRI) Rylander, “Distribution Resource Integration and Value Estimation (DRIVE) Tool User Group,” p. 2, 2020, [Online]. Available: https://www.epri.com/research/products/000000003002020018.

[12] M. Alturki, A. Khodaei, A. Paaso, and S. Bahramirad, “Optimization-based distribution grid hosting capacity calculations,” *Appl. Energy*, vol. 219, pp. 350–360, 2018, doi: https://doi.org/10.1016/j.apenergy.2017.10.127.

[13] DIgSILENT GmbH, “PowerFactory 2019 - User Manual,” pp. 1–1269, 2019.

[14] DIgSILENT GmbH, “PowerFactory 2019 - DPL Function Reference,” p. 1269, 2019.

[15] Y. Tan, “Chapter 10 - GPU-Based Random Number Generators,” Y. B. T.-G.-B. P. I. of S. I. A. Tan, Ed. Morgan Kaufmann, 2016, pp. 147–165.

[16] NRS Working Group and Eskom, *NRS 048-2: Electricity Supply - Quality of Supply Part 2 : Voltage characteristics , compatibility levels , limits and assessment methods*. 2017.