Minigrid integration in sub-Saharan Africa – identifying the ‘optimal’ point of connection

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Abstract — **Considering the effort and resources dedicated towards the Sustainable Development Goal number seven (SDG7) of "ensuring energy access for all", a post-2030 sub-Saharan Africa will be filled with a range of network solutions - main grids, minigrids and nano-grids. In time, some of the smaller networks will expand while others will be abandoned for better and resilient energy sources. However, such integration will pose technical challenges as most off-grid systems are designed and sized without any consideration of the main grid or other off-grid systems. This paper proposes that the identification of grid feed-in point into the minigrid network will be one of the critical decisions in integrating the main grid with once autonomous minigrids. Using power flow simulations of case study networks, results indicate that technical parameters such as losses and voltage drops on the local network vary significantly with choice of feed-in point, influencing the performance of the local network as well as its ability to accommodate more distributed energy resources in future. Based on these results, initial recommendations are made concerning the interconnection of such networks.**

Index Terms—**Hosting capacity, DER integration, interconnect, minigrid, grid extension, rural electrification, SDG7**

I. Introduction

By the year 2030, Sub-Saharan Africa (SSA) and many other regions like it will have an archipelago of active power networks. This shall be as a result of governments, private sector and international community efforts to meet SDG7 energy access for all targets [1]. Beyond 2030, it is expected that many of the isolated minigrid systems shall continue evolving; in many cases, neighbouring minigrids will interconnect to form clusters, and others will connect with the main grid, as it continues to expand [2-4]. Such interconnections will likely improve the quality of the energy service delivered by most of these isolated grids although some researchers have reservations on the possibility of integrating formerly isolated minigrids to the main grid [5, 6]. One of the main reasons for that is presented in [7] where small autonomous hydro-powered grids were marginalised and decommissioned upon the arrival of the main grid. However, most minigrids in SSA are powered by significant proportions of solar photovoltaic, whose operation is less complex than hydropower plants. Therefore, there is an increased optimism that such isolated minigrids can be integrated with the main grid to enable decentralized power system operation in SSA [6]. To ensure maximum benefits from such integration, there are technical, policy, regulatory and market related challenges that need addressing [2]. So far, most articles have addressed this issue from a policy and regulatory perspective [8, 9]. While such policy and regulation interventions are necessary to create a conducive environment, the actual integration is a technical undertaking which has received less attention in literature.

One of the first articles to discuss technical issues related to minigrid and main grid integration is [10]. The work focused on enabling the control and protection systems of different minigrid generation units to operate in grid connection mode. Though insightful, this work does not suggest or analyse the impact of such integration to the performance of the entire minigrid network. More recently, [4] analysed the impact of load shedding on the mode of operating a minigrid when the grid and minigrids meet. However, this analysis used HOMER software which does not model the electrical behavior of the minigrid generation and network, only load balancing [11]. In [12], feasibility of grid compatible minigrids in preparation for future grid integration is assessed. Although this work informs existing practices in minigrid designs, it is limited by the assumption that once a minigrid is grid ready, the future integration with the main grid will be seamless and optimal without requiring any analysis.

There is a significant shortage of comprehensive literature addressing the network related technical challenges associated with the post 2030 convergence of the grid and minigrids in SSA. An alternative way to understand these challenges is by observing the developments in power networks elsewhere and draw parallels with what is anticipated to happen in SSA. For example, in the global north, established power distribution systems are increasingly changing from being passive to active with the integration of various distributed energy resources (DERs) [13]. Optimal performance of these networks is realized by minimising costs while meeting a set of technical and environmental objectives [14]. Some of the technical objectives include loss mininisation, voltage profile improvement, improved reliability, maximising hosting capacity and load balancing [15]. One of the ways in which these objectives are met is by optimal sizing and placement of DERs [16, 17]. Such solutions are established relative to a fixed point where the local network connects to the wider grid.

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In comparison, an autonomous minigrid already has power sources comparable to DERs. These DERs are sized and placed to meet local demand without any consideration of a possible future connection to the wider grid [3]. Only once sufficient main grid expansion has occurred will the integration of autonomous minigrids be considered and, at this time, a point of grid connection will be introduced. The work reported in this paper identifies that a systematic selection of this point of grid connection has the potential to influence performance of the local network in the same way that the introduction of DERs affect established distribution networks. Using power flow simulations, the extent to which optimal identification of such a point would improve the performance of the local network is investigated. The remainder of this paper is structured as follows: Section II presents the options available for mini-grids when the grid arrives; Section III presents a brief theory behind distribution network analysis; Section IV presents the simulation studies conducted; finally, Section V and VI presents the results, conclusions and future work.

II. When Minigrids and the Main Grid Meet

According to [10], there are six options available to a mini-grid when the grid is extended into its territory. These are: small power distributor (SPD), small power producer (SPP), small power producer and distributor (SPP&D), side by side operation with the main grid (SSO), abandonment and mini-grid owner being compensated. This section will dwell on SPP&D, SPD and SPP as they are the only ones that involve integration of the grid and some infrastructure from the minigrid. The three are described as follows:

A. Small Power Distributor (SPD)

This option involves decommissioning the minigrid generation facilities and connecting the residual network to the main grid [10, 18]. The mini-grid operator retains energy trading rights to the minigrid customers and buys electricity from the utility company at a wholesale price. Due to environmental and cost reasons, this is the likely option for diesel-powered minigrids with grid compatible networks, as evidenced from cases in Cambodia [3]. However, with hybrid minigrids in SSA [1, 19], cost and environmental concerns will influence the decommissioning of any non-renewable component and retention of the renewable one. Consequently, SPD may be the least likely option to be observed in SSA when the grid and mini grids meet.

B. Small Power Producer (SPP) and Small Power Producer and Distributor (SPP&D)

The SPP option involves the national electricity utility company taking over the operations of the minigrid network; the mini-grid operator retains ownership of the generation facilities and sells all the generated energy to the utility company [10]. On the other hand, SPP&D involves continued operations of the mini-grid with the only difference being a connection to the main grid network that gives the mini-grid operator an option to export or import power [10]. These options are key to the continued utilisation of the renewable or distributed energy resources already present in the minigrids. For minigrids in SSA, this will likely be the norm as most of them are earmarked to have solar photovoltaic generation, either pure or hybrid.

The most likely options that will arise in SSA are SPP and SPP&D. In both cases, there will be a level of local generation and distribution network that the grid will be connecting to. However, the renewable technology of choice in SSA is considered PV, its unavailability during the nighttime means that the SPP&D option becomes a version of SPD. The presence of an already built network, and sized and sited DERs in the minigrid require proper consideration of the point of connecting the main grid for the SPP and SPP&D cases to make the most use of the available resources and infrastructure. Besides that, the diurnal availability of solar photovoltaic demands that the SPD case should not be spared from analysis as the SPP&D will transition to this case when PV is unavailable. This thinking is reflected in the selection of the scenarios presented in Section IV.

III. Integrating Minigrids and the Main grid

Based on an empirical assessment, there are two main options that would be considered as grid infeed points into an autonomous minigrid network. These are the node to which the primary minigrid generation source is already connected or any three-phase node that is nearest to the incoming main grid network. However, either of these options would not guarantee any technical optimality to the integration, they just facilitate the connection.

Consider the network in Fig. 1 representing an autonomous minigrid. G1 represents any combination of renewable and non-renewable generators satisfying demand connected to any of the nodes numbered 1 to 33. Total active and reactive power losses in the network will be given by (1) and (2) where n represents a branch of the network, j represents the receiving node of the branch, P_j and Q_j are the incoming active and reactive power to node j respectively, r_n is the resistance of the branch, x_n is the reactance of the branch and V_j is the voltage at node j and N is the total number of branches in the network which is also equal to the total number of receiving nodes, j.

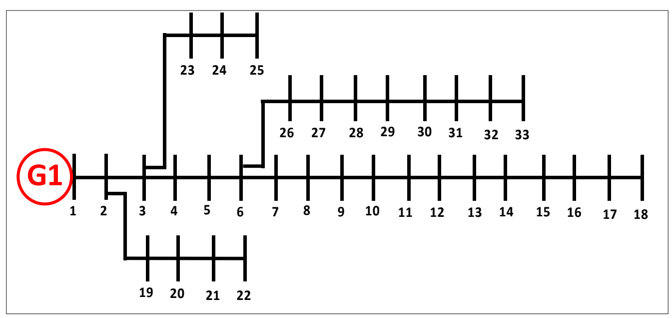

Figure 1 IEEE 33 bus network presented as a minigrid network

$$P_T = \sum_{n,j=1}^{N} \frac{r_n}{V_j^2}\left(P_j^2 + Q_j^2\right) \tag{1}$$

$$Q_T = \sum_{n,j=1}^{N} \frac{x_n}{V_j^2}\left(P_j^2 + Q_j^2\right) \tag{2}$$

When the main grid is connected to the minigrid network in Fig. 1, it becomes the reference node for all calculations and analyses in the local network. If the grid is connected to the same node with the original generation source of the minigrid (node 1 in this case), total active and reactive power losses in the network will still be given by (1) and (2). However, when the grid is not connected to the same node as the existing or decommissioned generation facilities in the minigrid, the flow of active and reactive power in the network will change. The total active and reactive power losses will be given by (3) and (4) where BG represents a set of branches whose power flow is affected by the local generation in the minigrid, P_g and Q_g are the active and reactive power generated by the minigrid generator respectively.

$$P_T = \sum_{n,j \notin BG} \frac{r_n}{V_j^2}\left(P_j^2 + Q_j^2\right) + \sum_{n,j \in BG} \frac{r_n}{V_j^2}\left((P_j - P_g)^2 + (Q_j - Q_g)^2\right) \quad (3)$$

$$Q_T = \sum_{n,j \notin BG} \frac{x_n}{V_j^2}\left(P_j^2 + Q_j^2\right) + \sum_{n,j \in BG} \frac{x_n}{V_j^2}\left((P_j - P_g)^2 + (Q_j - Q_g)^2\right) \quad (4)$$

Results from (3) and (4) will vary for different points of grid connection in the minigrid because it will influence the membership of the set BG. These variations are vital in identifying a technically optimal point for grid connection from the mini-grid's point of view. Such a point can be established by observing technical parameters such as power losses, voltage and hosting capacity.

A. Changes in Power and Energy Losses

When the grid is connected at the same node with the residual minigrid generation, power losses in the network remain unchanged. However, when the selected node is different, losses can go up or down according to (3). Power loss is a very important metric in distribution network planning such that minimizing them at a reasonable cost during the integration of minigrids to the main grid should signify a sense of optimality. When calculated over a period, changes in power losses can be quantified as changes in energy losses

B. Changes in Voltage Profile

Like losses, when the grid is connected to the same node as the minigrid generation, the voltage profile in the network will roughly remain the same. However, if the grid is connected to a different point, voltage profile can either improve or worsen. According to (3) and (4), different points of connection will result in varying active and reactive power losses, power flows and voltage drops. Depending on jurisdiction and local regulation, voltage is supposed to be within a certain limit for safety and power quality reasons. These limits may be in the range 0.95pu to 1.05pu which is stringent or between 0.9pu to 1.1pu which is light (for example in [20]).

C. Changes in Hosting Capacity

Changes in voltage profile will also influence the ability for the minigrid network to accommodate new generation. Although there are several factors that determine the hosting capacity of a network, it is recognized that voltage and thermal limit of equipment are the most significant [21]. As such, the maximum generation that can be accommodated on a node is given by (5) where P_{max} is the maximum capacity of distributed generator at a node, V is the voltage at that node, R is the Thevenin's resistance at that node and $\delta_{max} = \Delta_{max}/V$ is the relative voltage margin (in %) and Δ_{max} is the absolute voltage margin while respecting power limits of all equipment. In most cases, (5) is evaluated while respecting the thermal limits of equipment.

$$P_{max} = \frac{V^2}{R} \times \delta_{max} \quad (5)$$

IV. Simulations

Due to lack of standard minigrid network models, the IEEE 33 bus network (shown in Fig. 1) and a modified low voltage network from [22] (in Fig. 2), were used to carry out this investigation. The IEEE 33 bus network demand is beyond that of most existing mini grids but it allows the theoretical approach to be demonstrated. The Low Voltage (LV) network in Fig. 2 is based on a real UK distribution network and it is parameterized to represent a minigrid by changing the ratings of cables and loads. This network helps to establish that the theoretical approach presented in this paper can be applied on existing networks that are akin to a minigrid. For both networks, the minigrid generation is lumped together as that is the case in all existing minigrid networks [23]. Typically, there is a generation hub from which the network emanates in either a hub and spoke or trunk and branches fashion [23, 24]. This investigation focuses on the trunk and branch networks.

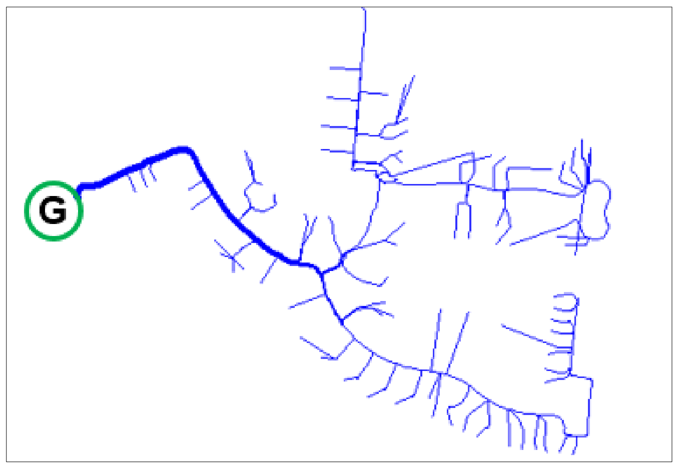

Figure 2: Low voltage network used in the simulations (adapted from [22])

The effect of varying point of grid connection was investigated under four different scenarios presented in TABLE I. Each scenario represented a different amount of residual generation in the minigrid whose percentage is calculated with respect to the demand in the network. The peak demand in the IEEE 33 bus network is 3,715kW while for the LV network is 240kW. The simulation involved running static as well as time dependent power flows to obtain voltages, power losses, energy losses over 24hr period and hosting capacity of the network local network. In each simulation, the point of connection of the grid (slack bus in this case) is changed to evaluate its effects on the local network. The lower and upper voltage limits imposed in these simulations are 0.95pu and 1.05pu respectively.

TABLE I: SCENARIOS INVESTIGATED

Scenario No.	1	2	3	4
DG Penetration	0%	33%	66%	100%

V. RESULTS AND DISCUSSION

A. Changes in Losses

Fig. 3 and 4 show that both networks exhibit a similar pattern in losses. It is observed that different points of grid infeed into the minigrid result in different values for power losses in the local network regardless of the amount of residual generation in the minigrid. This observation is vital because it illustrates the need for a systematic way to evaluate and decide on the point of grid connection as any random selection of grid infeed point does not guarantee optimal operation of the network. For example, in Scenario 1 of Fig. 3, if the grid is connected to the same point as residual minigrid generator, there are power losses of 200kW. However, connecting the grid to node 6 reduces the losses by 50% while node 18 increases the losses by over 200%. A similar trend is also observed in Scenario 1 of Fig. 4 though in this case, the reduction is significant than the increase in losses. However, as the amount of residual generation increases, the incremental gain in loss reduction is reduced. For example, there is much less variation in losses in Scenario 4 of both networks.

For the specific cases in SSA, initial local generation penetration of up to 100% is least expected during integration with the main grid. This is because most of these minigrids will have a composite of renewable and non-renewable energy sources. On integration with the grid, the non-renewable energy sources, for example diesel generators, is expected to be decommissioned for cost and environmental reasons. Consequently, the initial amount of local generation during integration with the grid will be lower than the demand. Therefore, the choice of grid in-feed point will significantly influence the power losses in the local network which is of interest to whoever ends up operating the network – be it the previous minigrid operator or the power network company.

Besides that, solar photovoltaic (the dominant renewable energy resource in SSA) is only available during the day and it is variable in nature. Therefore, through the course of any 24-hour period, after integration with the grid, the local network will experience varying levels of penetration from the residual generation. Taking this into consideration, Fig. 5 and 6 show the spread of energy losses over a 24-hour period for each of the penetration levels. Like the power losses, these results also show that different points of grid in-feed influence the energy lost in the local grid. Although the results from the power losses show a relatively smaller loss reduction in Scenario 4, the variation in energy lost per day cannot be considered trivial.

B. Changes in Voltage Profile

Fig. 7 and 8 show the changes in the average voltages in the two networks when the grid is connected at different points. As with the losses above, there is both acceptable and unacceptable voltage behavior in the network depending on the location of grid in-feed into the network. Similarly, the occurrence and severity of unacceptable voltage behavior is reduced with increased penetration of generation in the local network.

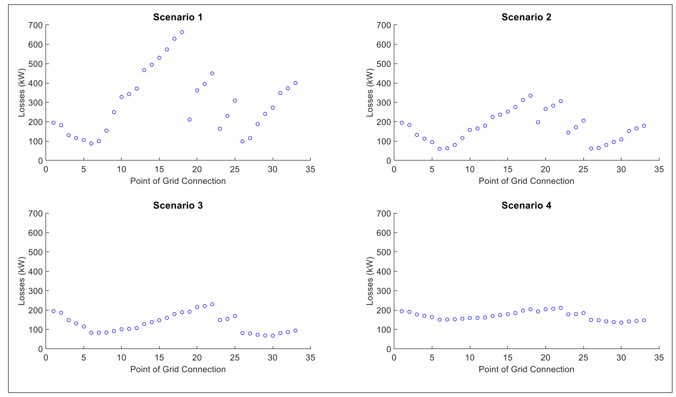

Figure 3 : Variation of power losses in the 33 bus network

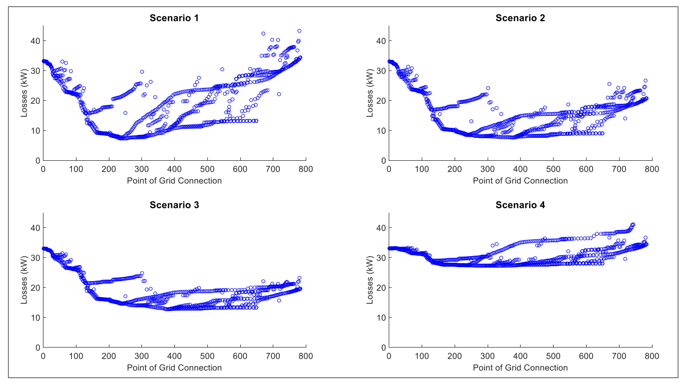

Figure 4 Variation of power losses in the LV network

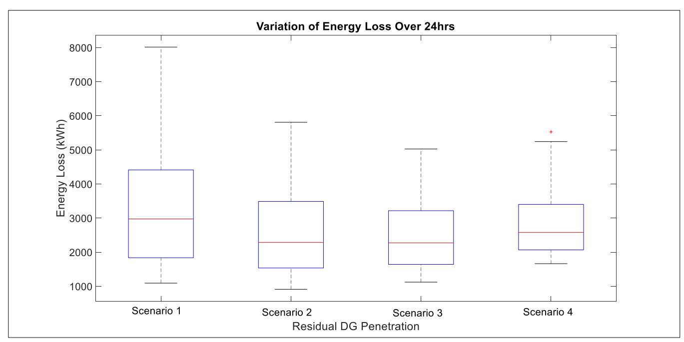

Figure 5. Spread of energy losses in the 33 bus network

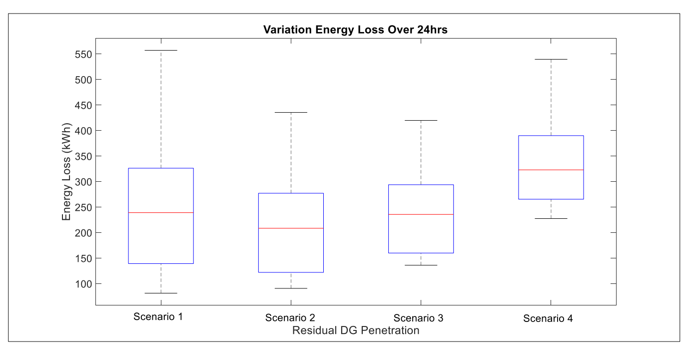

Figure 6. Spread of energy losses in the LV network

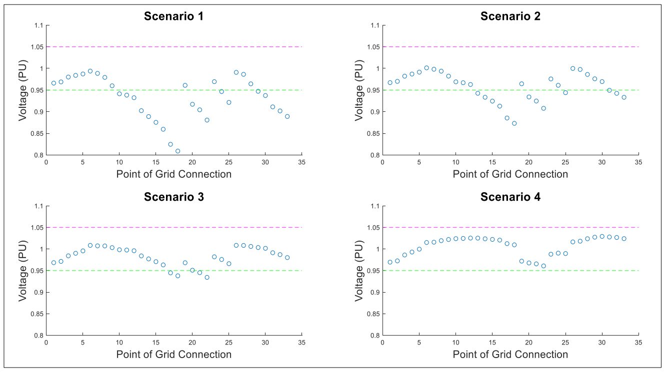

Figure 7: Network average voltage in the 33-bus network

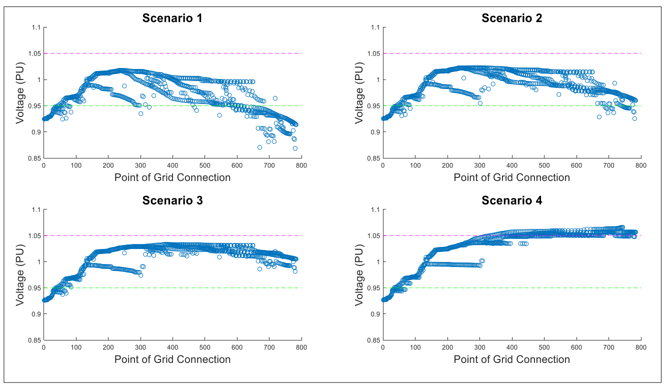

Figure 8: Network average voltage in the LV network

Fig. 7 and 8 also show that under voltages (rather than over voltages) are a major concern during the integration of the main grid and minigrids. This is contrary to the integration of distributed generators in established networks where voltage rise is the major issue. Comparing these results with the ones for losses, it is noticeable that the same nodes that lead to poor voltage performance of the system also lead to high losses. For example, node 18 leads to the greatest losses in Fig. 3, Scenario 1 and it is the same node that leads to significant under voltage in Fig. 6, Scenario 1. This can also be noted when we compare Fig. 4 and Fig. 8 for the LV network. This behavior should be expected in these networks because almost the same parameters that affect power losses (1) also affect reactive power losses (2), hence exacerbating voltage drop in the network.

C. Changes in Hosting Capacity

Fig. 9 and 10 show that the ability of the local network to absorb additional distributed generators is influenced by the point of grid infeed. However, unlike for voltages and losses, in which Scenario 1 produces some of the worst and best performance (depending on the point of connection), this is the best Scenario for hosting capacity. From both Fig 9 and 10, connecting the grid to any node leads to a high hosting capacity. This is logical as Scenario 1, does not have any residual distributed energy resources. However, the presence of any centralized residual generation begins to reduce the amount of generation that the local network can absorb as shown by Scenarios 2, 3 and 4. Increase in DG penetration restricts the best performance to connecting the grid to nodes that are close to the residual centralized generation.

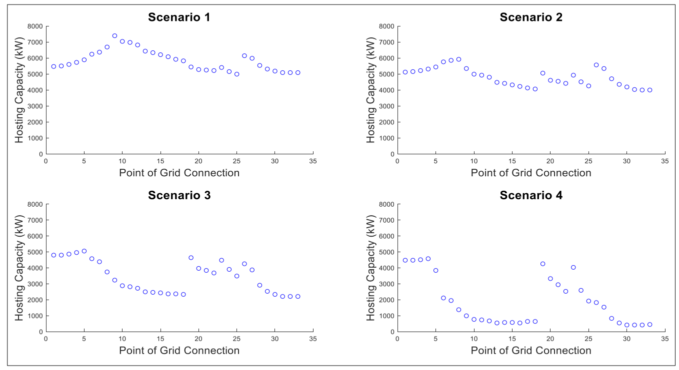

Figure 9: Hosting capacity in the 33 bus network

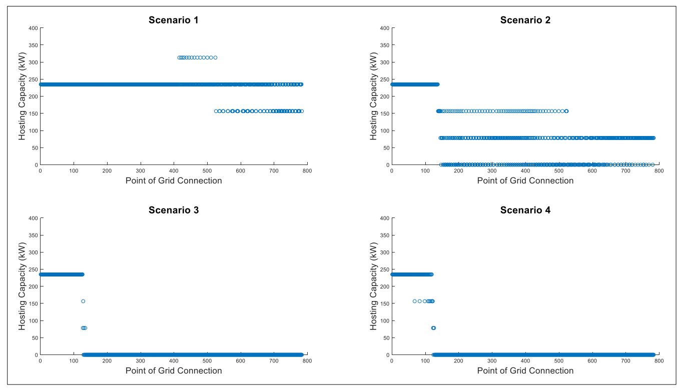

Figure 10: Hosting capacity in the LV network

This is the case because the further the grid in-feed is from the residual generation, the greater the path resistance R in (5). For any fixed P_{max} (already installed before the grid arrival), the change is voltage may go beyond the allowable change in voltage δ_{max}. Therefore, the centralized generator raises the average voltage of the network such that any additional distributed energy resources would not be accommodated except for the application of some smart control techniques which are not investigated in this study.

VI. Conclusions and Future Work

Using the IEEE 33 bus and an adapted LV network, this study demonstrates that determining the optimal location of grid infeed point is vital in the integration of minigrids to the main grid in SSA. Such decision will allow for the maximization of the usage of the residual generation resources, better network performance and possibility of future integration of distributed generation in the local network. However, existing literature does not present any framework, methodology or tool that can be used to achieve this. Without such appropriate decision support tools, the post 2030 utility in SSA will use intuition to connect minigrids to the main grid. However, this paper has demonstrated that the intuitive approach is unlikely to deliver optimal outcomes.

The results presented confirm that the selection of grid in-feed node is a multi-objective problem. While other objectives like losses and voltage profiles may positively correlate, other objectives like hosting capacity and cost (which has not been included in this study but is very key in network integration) may create a contrast. The multi-objective nature of this problem compares very well with other distribution planning problems such as distributed generation placement and sizing, and network reconfiguration. This creates an opportunity to adapt some of the techniques used in solving the related problems in specifying the framework and tools for optimal location of grid infeed point into a previously autonomous minigrid.

This preliminary study gives new technical insight to minigrid and main grid integration, especially relevant to the emergent grids in SSA but further work in this area is still required. Apart from specifying the framework and developing tools stated above, there is a need to include comparison of investments required for different grid connection options. Furthermore, this study has quantified the technical benefits from a deterministic simulation which may not be robust for systems with stochastic generation sources like solar photovoltaic. Therefore, stochastic or probabilistic time-series approaches need to be investigated. Future research will therefore focus on advancing the work presented in this paper to specify a framework and develop a tool that can be used for optimal selection of grid in-feed point when integrating the grid with minigrids in SSA. The framework and tool will also be extended to analyse the interconnection of islanded minigrids.

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