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Multi-feeder minigrid loading index – a prequalifier to rigorous grid integration planning of minigrids

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***Abstract*—To achieve electricity access in developing countries, grid extension and off-grid energy solutions, such as minigrids, are employed. Recent evidence from Southeast Asia has indicated that the grid continues to expand and converges with minigrids beyond achieving electricity access. Such convergence is associated with policy, regulatory and technical challenges. For example, one of the technical challenges related to grid integration of minigrids is the lack of appropriate methods for their optimal planning. Previous research demonstrates that identifying an optimal point of grid infeed into a minigrid improves the loss reduction of the integrated network. However, the method for identifying grid infeed points requires a detailed power system analysis to be conducted for each minigrid integrating with the main grid. This paper introduces a loading index that can operate as a 'rule of thumb' for pre-assessing the need for a detailed grid integration study. The presented index is demonstrated for two case studies, and its accuracy on different minigrid conditions is also discussed.**

Keywords—minigrids, grid integration, DERs, SDG7, electricity access, convergence

I. Introduction

Sustainable Development Goal 7 (SDG7) is a United Nations initiative that aims to achieve universal access to affordable, reliable, sustainable and modern energy for all by 2030 [1]. To achieve SDG7, a mixture of grid extension and off-grid systems, such as minigrids and solar home systems (SHSs), are deployed in developing countries, like those in sub-Saharan Africa (SSA) where there are significant energy access issues [2], [3]. Evidence from Southeast Asia [4], [5] reveals that beyond achieving energy access through grid expansion and off-grid systems, the main grid continues to expand and, in time, converges with the off-grid systems.

The convergence of the main grid and offgrid systems can result in two general outcomes, as reported in [6]. Firstly, if the off-grid systems have not been deployed to grid standard, they are likely to be abandoned when the grid arrives [7], [8]. The abandonment favours the grid-supplied electricity which is more reliable, cheaper or can support productive uses of energy [9]. Secondly, if the main grid converges with a grid compatible minigrid, the minigrid may be integrated with the main grid [10].

The grid integration of minigrids presents policy, regulatory, and technical challenges highlighted in [10]. Some of the technical challenges, like the ability of formerly autonomous minigrids to operate in islanded and grid-connected modes, resonate with challenges associated with the operation of similar infrastructure in developed countries [11], [12]. Consequently, practitioners in developing countries can translate solutions from minigrid practice in developed countries to enable the duo-mode operation of minigrids that were initially designed to operate autonomously [13]. However, unlike the majority of minigrids in the global north, those deployed in developing countries are initially planned and optimised for autonomous operation in the absence of the grid. Therefore, new methods for planning the grid integration of minigrids are required for the best performance of the integrated network.

The authors in [14] propose that the grid integration of minigrids can be technically optimised by identifying an optimal point of grid infeed into each minigrid. However, this work had two main weaknesses. Firstly, the conclusion was justified using case study with a trunk and branch topology, and its application to hub-and-spoke minigrids was not presented (see [15] and [16] for minigrid topologies). Secondly, the presented method requires rigorous study every time a minigrid is present to integrate with the main grid. This may create a planning and resource burden for utilities when the number of minigrids requiring grid integration increase.

This paper addresses the weaknesses associated with [14] by presenting a novel multi-feeder minigrid loading index (MMLI) to pre-qualify the need for the rigorous methodology in [14] when planning the grid integration of minigrids in developing countries. In addition, the presented index is applicable across all possible minigrid topologies.

The rest of this paper is organised as follows. Section II defines the MMLI and its interpretation. Section III presents case studies for demonstrating the application of MMLI and establishing the effectiveness of the index in various minigrid conditions. Section IV presents the case studies' results, and Section V provide conclusions and future work.

II. Definition and Application of Multi-feeder Loading Index (MMLI)

In established networks, loss reduction is achieved by reducing the current flowing in highly loaded branches of the associated network through, among other things, network reconfiguration [17] and placement of carefully sized distributed energy resources (DERs) [18]. Network reconfiguration can not be easily achieved in minigrids because they assume a radial design [15], [16]. On the other hand, DER placement and sizing in minigrids is primarily aimed at serving the local demand than reducing losses [4]. However, when integrating minigrids with the main grid, optimal placement of the incoming grid has been demonstrated in [14] to alter current flow in the minigrid network and achieve reduced losses.

The MMLI is a tool that assesses the distribution of demand in each minigrid feeder to indicate whether the optimal point of grid infeed is at, or close to, the generation hub or elsewhere in the network. Theoretically, MMLI is the maximum value of the set of ratios between the peak demand of each minigrid feeder and the sum of the peak demands of the rest of the feeders in the same minigrid network, as presented in (1).

$$\text{MMLI} = \max\left\{\frac{fd_1}{fd_T - fd_1}, \dots, \frac{fd_n}{fd_T - fd_n}\right\} \qquad (1)$$

Where fd_T is the sum of feeder peak demands in the minigrid as shown in (2).

$$fd_T = \sum_{n=1}^{N} fd_n, \qquad \forall fd_n \in \boldsymbol{FD} \qquad (2)$$

and $\boldsymbol{FD}$ is a set of peak demands of each feeder in a minigrid with N feeders emanating from a single minigrid generation hub.

The value of MMLI obtained from (1) will be interpreted such that if MMLI is less than or equal to 1, the minigrid does not have a dominant feeder; hence the incoming grid can be connected to the generation hub. However, if the value for MMLI is greater than 1, the generation hub is not the best point of grid infeed hence the need to identify another grid infeed point within the network using detailed study like that in [14]. The intepretation of MMLI values is summarised in (3)

$$MMLI \begin{cases} \leq 1 - \text{Optimal point of grid infeed is at} \\ \quad\quad \text{or near minigrid gen. hub} \\ > 1 - \text{Optimal point of grid infeed is} \\ \quad\quad \text{away from minigrid gen. hub} \end{cases} \qquad (3)$$

The MMLI can be applied on both single feeder (trunk-and-branch topology) and multi-feeder (hub-and-spoke topology) minigrid networks. For multi-feeder minigrid networks, the definition of MMLI in (1) applies directly. However, for a strictly single feeder minigrid, application of (1) may result in division by zero. Therefore, single feeder minigrid networks should be considered to have an MMLI of close to infinity, and according to (3), the optimal point of grid infeed is away from the generation hub. The methodology in [14] should always be used in planning their grid integration.

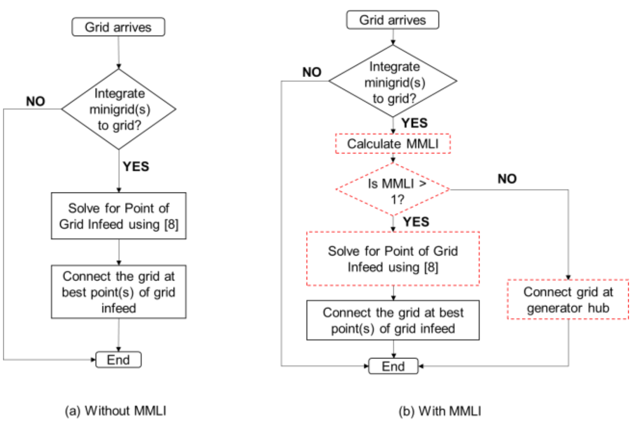

Fig. 1. Grid integration planning with and without MMLI

The incorporation of MMLI in planning the grid integration of minigrids is illustrated in Fig. 1(b) while Fig. 1(a) illustrates minigrid integration planning without MMLI. Without MMLI, in Fig. 1(a), a decision is made if the incumbent minigrid can be integrated with the arriving grid when the grid arrives. If the minigrid is grid compatible, a rigorous study is done to establish the optimal point of grid infeed. On the other hand, with MMLI in Fig. 1(b), the precondition for the rigorous identification of point of grid infeed is after obtaining an MMLI value of greater than 1.

III. Case Studies and Scenarios

The MMLI theory and application, presented in Section II is demonstrated using three feeder hub-and-spoke minigrid topologies whose base network data is from low voltage networks presented in [19]. Due to the lack of standard minigrid test networks, the networks in [19] are applicable for investigating the problem at hand, which is akin to SSA for two main reasons. Firstly, the IEEE test feeder [20], which can be used to investigate microgrid (or minigrid) related problems [21] is originally from [19]. Secondly, SSA minigrids and secondary distributions systems are operated at 50Hz within the voltage range 220V to 240V, for example, in Malawi [22] and Nigeria [23], which is similar to the European standards on which [19] is based.

A. Demonstrating the application of MMLI

The application of MMLI is firstly demonstrated on two minigrid networks presented Fig. 2. Minigrid X has a peak demand of 345kW and that of Minigrid Y is 210kW.

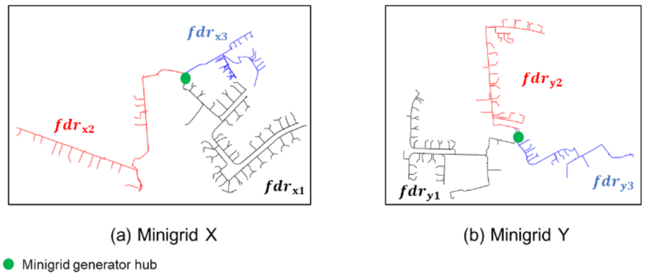

Fig. 2. Two minigrids requiring grid integration

The peak demand for each feeder within the minigrids in Fig. 2 is presented in TABLE I.

TABLE I. Feeder Load Details of Minigrids X and Y

Minigrid ID	Feeder ID	Feeder Demand (kW)
X	x1	250
	x2	60
	x3	35
Y	y1	80
	y2	90
	y3	40

Both approaches to minigrid integration presented in Fig. 1 are applied for on Minigrids X and Y, and the results are compared. For each minigrid and planning exercise, there are three different minigrid DER technologies: photovoltaic (PV), photovoltaic with storage (PV + Storage), and conventional generator. The penetration of each of these DERs, with respect to minigrid peak demand, is varied from 0 to 100% in steps of 25%.

B. *MMLI on several mnigrids*

Up to 220 three-feeder minigrids were used to investigate the application of MMLI on minigrids with a variety of distribution of demand among feeders and DER scenarios. For each minigrid network, the MMLI value was calculated, and the actual grid integration planning method is applied without using MMLI (as in Fig. 1(a)). The rigorous analysis outcome is compared to the expected result if MMLI was used.

Similar to the case study in Section III.A, each minigrid network has three DER scenarios (PV, PV + storage, and conventional generator). For each DER scenario, the DER penetration is increased from 0% to 100% in increments of 25%. Then, the accuracy of the MMLI as a pre-assessment tool for minigrid integration planning is evaluated using the confusion matrix in TABLE II. and (4).

TABLE II. CONFUSION MATRIX FOR ASSESSING THE PERFORMANCE OF MMLI

		Full minigrid integration study [14]	
		LR = 0	LR > 0
MMLI outcome	MMLI≤1, LR=0	TP	FP
	MMLI>1, LR>0	FN	TN

Where LR is loss reduction as a percentage of the losses if the main grid was integrated at the minigrid generation hub, TP is true positive, where the full integration analysis in leads to a loss reduction of 0% while the MMLI is less than 1. TN is true negative where the rigorous integration study leads to a loss reduction of greater than 0% while the MMLI is greater than 1. FP and FN are false positive and false negative, respectively, using the same criteria. The accuracy of using MMLI, A_{MMLI}, is given by (4).

$$A_{MMLI} = \frac{TP + TN}{TP + TN + FP + FN} \qquad (4)$$

IV. RESULTS AND DISCUSSIONS

This section presents the results and discussions from the case study scenarios defined above.

A. *Demonstrating the application of MMLI*

Upon evaluating the grid integration planning for Minigrids X and Y with an without MMLI, the results are presented in two main categories. Firstly, the actual values of MMLI for minigrids X and Y and their expected implications. Secondly, the comparison between the outcomes of planning grid integration of a minigrid with and without MMLI.

a) Minigrid MMLI values

The MMLI values for Minigrids X and Y are 2.63 and 0.75 respectively. Using the interpretation of MMLI in (3), these MMLI values suggest two main things. Firstly, Minigrid X has a dominantly loaded feeder hence has loss reduction potential that can be realised through a detailed grid integration planning exercise. Secondly, the results show that Minigrid Y does not have a dominantly loaded feeder and will not require a detailed grid integration planning study.

Therefore, the point of grid integration for Minigrid Y should be expected at or near the minigrid generation hub, while that of Minigrid X is likely to be away from the generation hub. The conclusions drawn from the values of MMLI are further supported and discussed in the subsequent subsection.

b) Points of grid infeed and loss reduction

After applying the minigrid integration planning method with and without MMLI, as shown in Fig. 1(a) and (b), the point of grid integration for minigrids X and Y are shown in TABLE III. Due to the location of the points of grid infeed for Minigrid Y being close or at the minigrid generation hub, there is no significant loss reduction. However, the loss reduction corresponding to the grid infeed points for Minigrid X is presented in Fig. 3.

TABLE III. POINTS OF GRID INFEED INTO MINIGRIDS X AND Y

DER Pen. (%)	Minigrid X		Minigrid Y	
	Without MMLI	With MMLI	Without MMLI	With MMLI
PV Only				
0	$20_{fd_{x1}}$	$20_{f_{x1}}$	1	1
25	$46_{f_{x1}}$	$46_{f_{x1}}$		
50	$46_{f_{x1}}$	$46_{f_{x1}}$		
75	$46_{f_{x1}}$	$46_{f_{x1}}$		
100	$20_{f_{x1}}$	$20_{f_{x1}}$		
PV + Storage				
0	$20_{f_{x1}}$	$20_{f_{x1}}$	1	1
25	$46_{f_{x1}}$	$46_{f_{x1}}$	1	
50	$46_{f_{x1}}$	$46_{f_{x1}}$	$3_{f_{y2}}$	
75	$46_{f_{x1}}$	$46_{f_{x1}}$	$6_{f_{y2}}$	
100	$46_{f_{x1}}$	$46_{f_{x1}}$	1	
Conventional generator				
0	$20_{f_{x1}}$	$20_{f_{x1}}$	1	1
25	$46_{f_{x1}}$	$46_{f_{x1}}$	$6_{f_{y2}}$	
50	$46_{f_{x1}}$	$46_{f_{x1}}$	1	
75	1	1	1	
100	1	1	1	

Notes: 1 = Node 1 of either minigrid X or Y

$20_{f_{x1}}$ = Node 20 of feeder f_{x1} within minigrid X

The results in TABLE III. and Fig. 3 demonstrate that MMLI can indeed prequalify the need for a rigorous minigrid integration study. For example, TABLE III shows that for the majority of scenarios, the point iof grid infeed into Minigrid X is away from the minigrid generator hub (Node 1). This is also supported with an MMLI value of greater than 1 and corresponding loss reduction reported in Fig. 3, loss reduction potential of up to 69% depending on the residual DER and their penetration.

In TABLE III, the points of grid infeed are all located in feeder x1, which is the most loaded feeder within Minigrid X according to feeder details provided in TABLE I. This observation suggests that for an MMLI value greater than 1, within the minigrids. This observation can be noticed in Fig. 4 (c), (f) and (i), where the DER penetration level is 100%, but the loss reduction levels are dimished compared to lower DER penetration levels. An extreme case is even reported in Fig. 4(i) where there is barely any loss reduction. The effect of DER on loss reduction demonstrates that MMLI values should not be used in isolation from observing the presence or absence of DERs in the minigrid.

This observation is further illustrated in TABLE IV where the point of grid infeed is likely to be located in the most loaded feeder of the minigrid. Therefore, instead of running the grid integration planning method on all the nodes in the minigrid, the search for an optimal point of grid infeed can be restricted to the nodes in the highly loaded feeder, hence reducing the computation effort needed.

B. *MMLI over several minigrids*

Among the 220 three feeder minigrids used in this investigation, 104 minigrids had an MMLI of equal to or less than 1, while 116 minigrids had an MMLI of greater than 1. Fig. 4 shows the relationship between MMLI and loss reduction for each DER scenario, where two main observations can be drawn.

Firstly, Fig. 4 shows that there is a positive correlation between loss reduction and MMLI values. Therefore, for any two minigrids with the same peak demand capacity, the one with a higher MMLI value should be expected to have greater loss reduction potential than the one with a lower MMLI. As MMLI increases, more and more of the system load is located on a dominant feeder and potential to reduce losses by grid connection to that feeder increases. Once 50% of the load (MMLI = 1) is located on the dominant feeder, gains in loss reduction start to decline, plateauing at about MMLI of 2.

Secondly, Fig. 4 shows that regardless of the MMLI value, higher penetration of DERs reduce the loss reduction potential

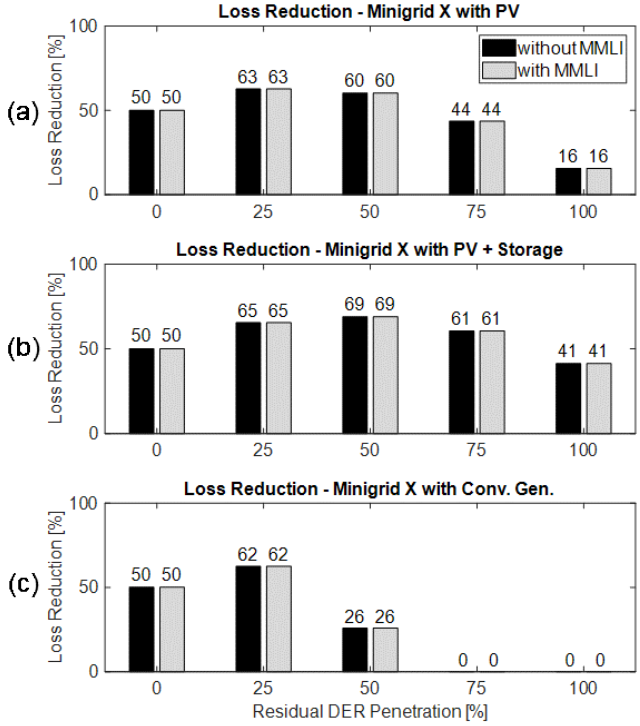

Fig. 3. Post grid integration loss reduction for Minigrid X

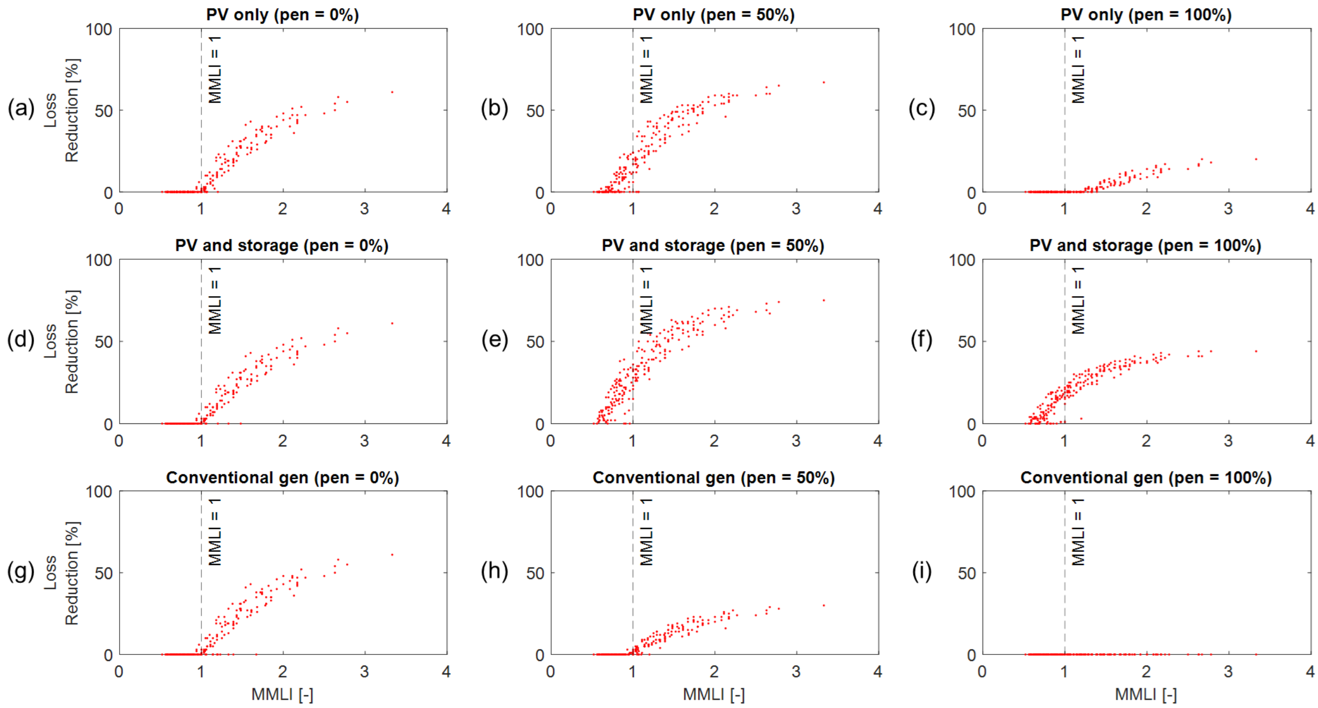

Fig. 4. Relationship between loss reduction and MMLI

the MMLI is most accurate at lower DER penetration levels. However, this accuracy decreases and shows an inconsistent trend with increasing DER penetration. The decreasing accuracy of MMLI and emergence of inconsistent trend with increasing DER penetration should be expected because the presented MMLI formulation in (1) only focuses on demand and does not include any effects of incumbent minigrid DERs.

TABLE IV. ACCURACY OF MMLI UNDER DIFFERENT CONDITIONS

DER Pen.	PV Only	PV + Storage	Conv. gen
0%	0.95	0.95	0.95
25%	0.80	0.75	0.69
50%	0.72	0.55	0.94
75%	0.82	0.53	0.47
100%	0.82	0.61	0.47

V. CONCLUSION AND FUTURE WORK

As minigrid deployment continues in developing countries, their interactions with the main grid beyond achieving electrification should not be neglected. Previous work has demonstrated a rigorous planning process for identifying an optimal point of grid infeed into formerly autonomous minigrids.This paper adds to that work by presenting an index for anticipating whether such a process is needed or not for any minigrid. The index can help minimise the time and resources required to plan the grid integration of numerous minigrids in developing countries.

The paper has also presented the accuracy of the proposed index under different minigrid integration scenarios and concluded that the index is accurate at lower DER penetration levels. However, from these initial results, he accuracy of MMLI decreases and does not present a consistent trend with higher DER penetration. This should be expected because the present formulation of the index assumes a passive minigrid network and does not adequately consider DERs. Therefore, further advancement of this work shall include the effect of DERs on the proposed index.

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