2022 SAUPEC Conference, Durban, South Africa, January 25-27, 2022

DC system based bottom up grid extension for rural communities

Martial Giraneza
Electrical, Electronics and Computer Engineering Department
Centre for Power Systems Research
Cape Peninsula University of Technology
Cape Town, South Africa
giranezam@cput.ac.za

Khaled Aboalez
Electrical, Electronics and Computer Engineering Department
Centre for Power Systems Research
Cape Peninsula University of Technology
Cape Town, South Africa
aboalezk@cput.ac.za

Abstract— **Wordwide many people live without a connection to the electrical network service. The majority of them are in rural and remote areas from the utility network. Although off-grid electrification mode offers alternative solutions, grid extension is still the preferred mode of electrification for energy access to tier 4. On the other hand, the classic top-down approach for grid extension used by many utilities makes it difficult, even sometime impossible, for rural communities to connect to the grid. Thus need to find alternative approaches for the grid extension. This paper presents a network expansion strategy using a Direct Current system. The approach uses the swarm electrification concept and the existing off-grid solutions in rural communities to develop a grid extension from the end-users to the grid. The DC system is the backbone of the system. The proposed system is modeled and simulated in DIgSILENT PowerFactory environment. The simulation results indicate an efficient -interconnection of the generation units.**

Keywords— dc grid, swarm electrification, grid extension, microgrid, distribution, rural electrification, nanogrid

I. Introduction

The International Energy Agency report indicates that moreless 80 % of the population in Africa are not connected to the utility electrical power networks [1]. Some of the main factors contributing to that situation are the limited power resources, utilities in weak financial position, remoteness, and sparsity in population density[2]. The later factors make the grid extension technically and economically challenging. Utilities are reluctant to finance the grid extension towards rural areas because of the risk on the return on that investment considering the power purchase in rural areas. Consequently, individual power solutions such as solar home systems and diesel generators are extensively used in rural and urban areas. In Sub-Saharan Africa, diesel generators are the preferred solution in cities as well as in rural areas; it is an affordable solution for power shortages.

On the other hand, the deregulation in the electricity market has allowed independent power producers to emerge and the connection of distributed generation resources to the utility network. Furthermore, the resurgence of DC technology and the set in of the microgrid concept provided a new perspective towards the grid extension, consequently to energy access solution [3]–[5]. Moreover, with the change in the electricity market, a new type of energy users at the distribution level emerged: the prosumers. They are consumers and, at the same time, power producers with the option to inject power into the grid for a fee or other form of compensation and sell it to neighbors in peer to peer energy trading scheme. However, in third-world countries, especially in the sub-Saharan region, the utilities are still vertically integrated when it comes to grid extension with some variations in management where local communities are involved [6]. The review of recent research on microgrids in Sub-Saharan Africa [7] revealed an ongoing transition towards renewable energy-based microgrids in the region. The bottom-up grid extension concept of electrification using the swarm electrification approach provides an alternative solution to the centralized, top-down model for grid extension[8]–[10]. The swarm approach builds on the existing off-grid alternatives in the community, such as Photovoltaic(PV) Systems, generators, or small wind turbines.

Various researchers have focused on swarm electrification as a solution to energy access for all. In [11], the theory around swarm electrification is developed based on early observation of the first pilot application in Bangladesh. Furthermore, authors in [11] present a comparison of swarm electrification approach with other bottom approaches, such as PV system, microgrids, that provide energy to off-grid communities. The authors show that the swarm electrification-based bottom-up approach has the potential to reach high tiers of energy access. On the other hand, [12], in their study on swarm electrification in Yemen, noticed that improving energy access will not reach Tier 4 unless fossil fuel generators are used. In [13], the challenges surrounding various approaches for electrification in developing countries are explored. The authors highlight the minigrid interconnection as a fast, cost-effective, sustainable, and future-proof method to increase electricity access. However, as observed by the authors, there would be a need for a backup generation (diesel-generator) in case renewable energies are considered primary resources. In [14], a decentralized control method is presented for a cluster of interconnected nanogrid. In [14] the control technique used in the proposed method is the droop control. It uses the bus voltage and the state of charge of energy storage system, to coordinate the power-sharing between nanogrids. [15] investigated actual guidelines for interconnection of minigrid/microgrid for bottom-up electrification, as well as the technical challenges associated. The main challenge observed by the authors is the lack of synchronization process standards. This might result in technical issues such as frequency oscillation and other challenges associated with the generator's type. Moreover considering that most of research has focused on renewable energy based microgrids, while in most of remote communities in Africa the diesel generators

2022 30th Southern African Universities Power Engineering Conference (SAUPEC) | 978-1-6654-6887-9/22/$31.00 ©2022 IEEE | DOI: 10.1109/SAUPEC55179.2022.9730759

are largely used; thus the need to find a solution for the integration of those sources in a swarm electrification approach and at the same time overcome the technical challenges associated with the synchronization process.

Therefore, this paper presents a bottom-up grid extension using a DC network to integrate distributed energy sources in a swarm interconnection approach. The method overcomes the synchronization challenges and the associated frequency stability issues.The paper is organized as follows: the second section discusses of the DC system. The third section presents the proposed system. In the fourth section are discussed simulations and analysis of results. The fifth section presents the conclusion.

II. DC SYSTEM

The first electrical power, generation, and distribution system was based on a direct current voltage system. However, the shortcomings such as power losses, requirements to extend the network to long-distance, and safety associated with DC-based power distribution system; led to its abandonment in favor of Alternative Current (AC) systems[16]. Nowadays, the technological advancement in power electronics, protection, and control has made it possible to overcome the DC system's early challenges, on top of the ongoing increase of renewable energy resource's footprint in the utility network. Thus, the new paradigm towards using DC systems in power systems is gaining interest [17]. The operating voltage of DC systems are categorized as high for voltages range from 30kV_{DC} to 1500 kV_{DC}, as medium for voltage range from 1500 V_{DC} to 30 kV_{DC} and as low for voltages below 1500V_{DC}.The direct current low voltage systems falls under LVDC 72/33/EEC and LVDC2014/3/EU regulations[18], [19].Another category of the direct current system voltage is between 1,5 kV_{DC} to 3 kV_{DC} , it is considered as intermediate low voltage and it is oftenly used in raiway transportation[20], [21. However it also finding applications in regular electric power distribution networks due to its overall benefits[22]–[24].

III. THE PROPOSED SYSTEM

The idea is to build a network expansion starting from end users and considering pre-existing local nanogrids; the latter interconnections form microgrids, which are interconnected in the "Olympic rings" approach to expand the electrified areas and eventually meet the grid. The DC system is the backbone of the interconnection. Fig. 1 shows the proposed system. An evolutionary approach is used with 4 steps: (1) pre-electrification step, (2) microgrid development, (3) minigrid formation, and (4) Grid interconnection. In pre-electrification individual nanogrids are considered based on their respective proximity. The nanogrids are interconnected through AC/DC converters and networks to form a microgrid in step two. The AC/DC converters interface allows the integration of those nanogrids with different generator technology, and as in our case, as diesel generators are considered, the synchronization challenge is avoided. Note that power exchange among the nanogrids within the microgrid is possible and tapping for other consumers as well in peer-to-peer energy trading context. However, this paper does not discuss the control for power-sharing and peer-to-peer control. The LVDC network is used for interconnection. The use of DC lines has the advantage of low losses and reduced size of conductors. In step three, microgrids are interconnected through a DC system network for a minigrid formation The bi-directional DC/DC converters are used as an interface for microgrids. This scheme allows power-sharing between microgrids. The minigrid is connected to the grid through a medium voltage inverter in the last step towards the grid.

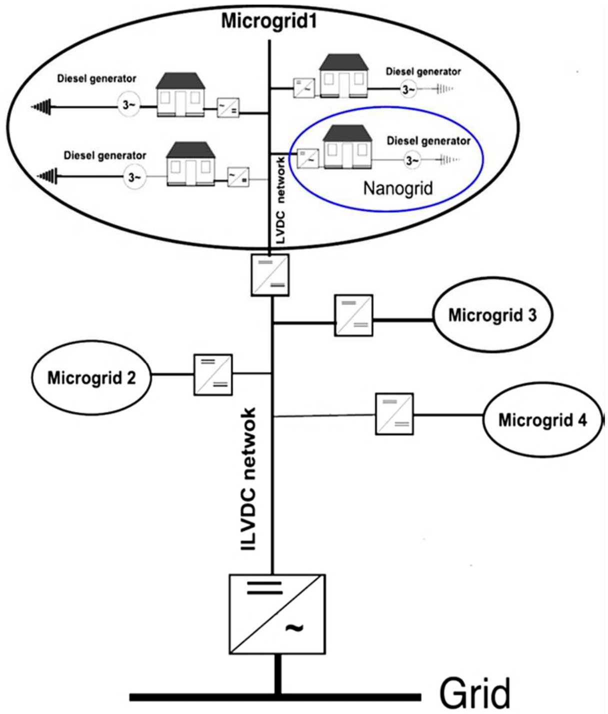

Fig.1. The proposed DC system for bottom-up grid expansion approach.

IV. SIMULATION AND RESULTS

The proposed DC system based bottom-up grid extension builds upon nanogrids interconnection to form 400 V_{DC} microgrids. In turn, the latter are interconnected through a 3kV_{DC} ILVDC network to form a minigrid and which eventually is connected to the grid. The system is modeled and simulated in DIgSILENT environment. Individual microgrids are simulated to analyze the behavior of each nanogrid participating in the interconnection. Three microgrids are considered: microgrids 1, 2 and 3.

Fig. 2 shows the microgrid 1model as developed in DIgSILENT environment. It consists of three nanogrids with diesel generators modeled as synchronous generators, nanogrid loads, and general loads. The latter represents other consumers that are connected to the microgrid through a peer-to-peer energy trading scheme. The nanogrids are expected to supply their local loads and support the general loads without overloading themselves. The three nanogrids installed power capacities are 33 kW for nanogrid_1, 31.5 kW for nanogrid_2, and for nanogrid_3 , 35.5 kW. On Table I is shown the power demand in microgrid 1. The cumulative local power demand is equal to 8.25 kW while the microgrid connected DC general loads amount to 36.5 kW. An individual nanogrid would not be able to support that load, therefore the need for nanogrids interconnection to form a microgrid. The load flow analysis results for the microgrid_1 are shown in Fig.3. The results show that the nanogrid 1, 2, and 3 generators produce 16 kW, 15.6 kW, and 17.6 kW, respectively. The interconnection benefit is observed in Fig.4 of microgrid1 nanogrid generators loading percentage. All generators are operating in the optimal range. The loading of the generator is 58 %, 58 % and 62%

for Nanogrid1, Nanogrid 2 and Nanogrid 3 generators, respectively.

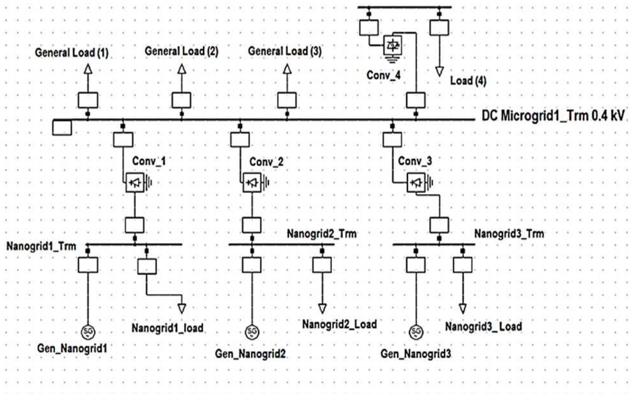

Fig.2. Microgrid 1 model.

TABLE I. MICROGRID_1 POWER DEMAND.

Load	Power (kW)
Load Nanogrid_1	2.25
Load Nanogrid_2	2
Load Nanogrid_3	4
General_Load_1	20
General_Load_2	9
General_Load_3	3
Load_4	4.75

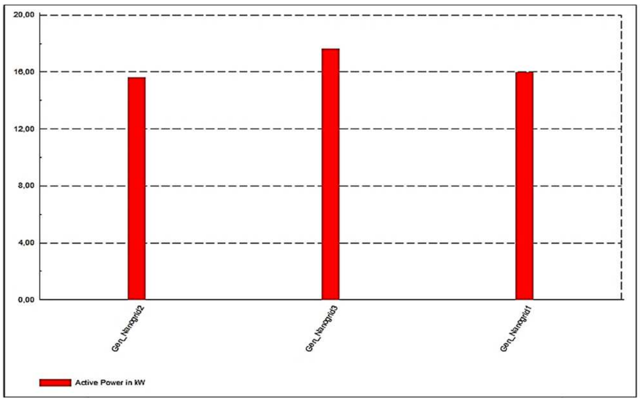

Fig.3. Power generated by nanogrids within microgrid 1

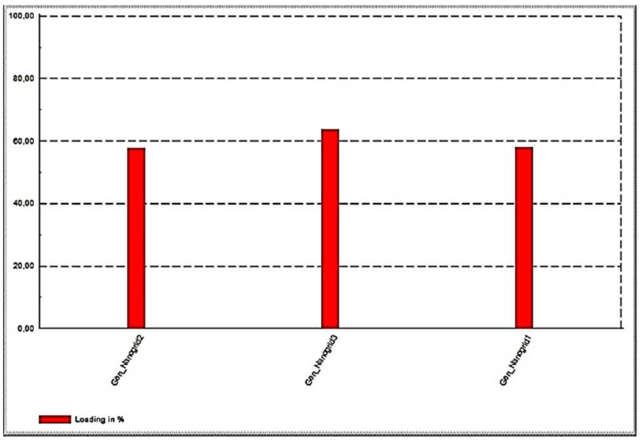

Fig. 4. Loading of nanogrid generators in Microgrid 1

Microgrid 2, as modeled in DIgSILENT is shown in Fig.5. Four nanogrids are considering for microgrid 2 formation through a 0.4 kV_{DC} network, and AC/DC converters are interfaced to nanogrids. The nanogrids considered are 21, 22, 23 and 24, with installed generating capacities of 35 kW, 30 kW, 35 kW, and 30 kW, respectively. Table II shows the power demand in microgrid 2. In Fig.6 are shown the results of the load flow analysis performed on microgrid 2. The results are as follows: Nanogrid21 (Gen_Nanogrid21) produces 17 kW, Nanogrid22 and Nanogrid24 generate 17.5 kW each, while Nanogrid23 generator generates 18 kW. All the nanogrids share equally the demand as shown in Fig. 7 the generator loadings are 62.7% for Nanogrid_21, 72.9% for Nanogrid_22, 73% for Nanogrid_23, and 72.9% Nanogrid_24.The above results show that the interconnection is successful and does not compromise the nanogrids generator's stability, rather it allows an equal distributed loading.

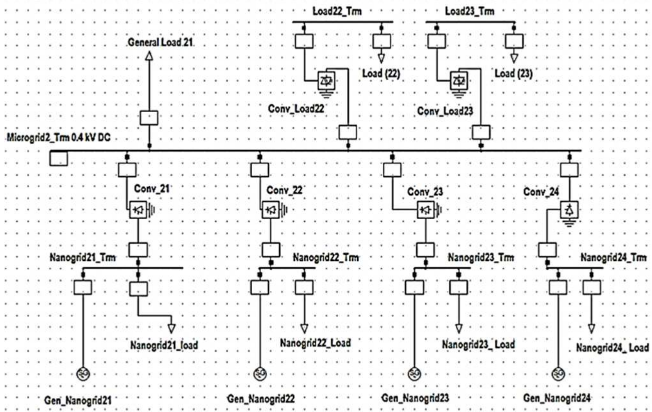

Fig.5. Microgrid 2 model.

TABLE II. MICROGRID 2 POWER DEMAND.

Load	Power (kW)
Load Nanogrid_21	1.5
Load Nanogrid_22	2
Load Nanogrid_23	2.5
Load Nanogrid_24	2
General load_21	18
Load 22	9
Load 23	28

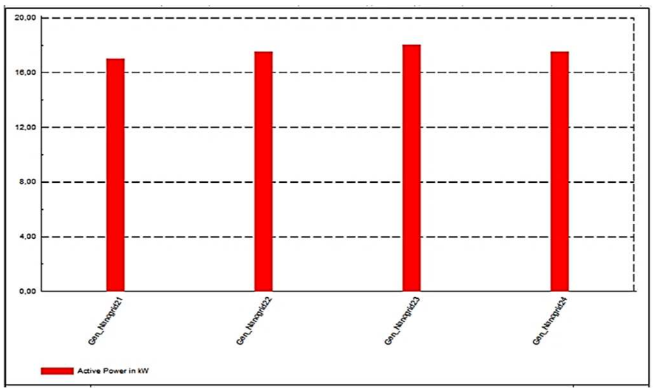

Fig. 6 . Power generated by nanogrids within microgrid 2

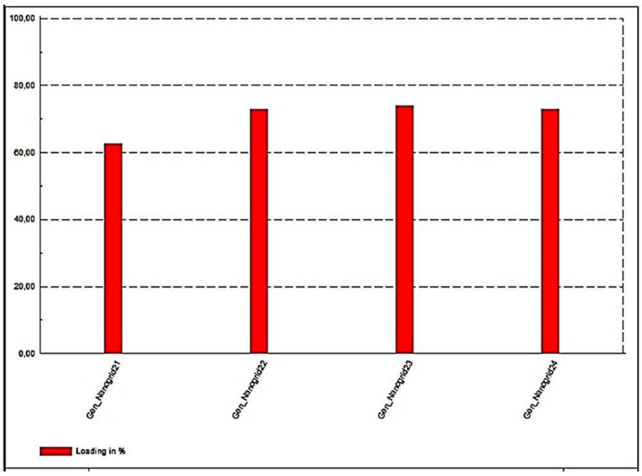

Fig. 7. Loading of nanogrid generators in Microgrid 2

Microgrid 3 model formed with three nanogrids is shown in Fig 8. The three nanogrids are namely Gen_nanogrid31, Gen_Nanogrid32 and Gen_Nanogrid33 with generating capacity of 45 kW, 35 kW and 15.5 kW, respectively. The nanogrids generators are supplying their respective loads namely the load of Nanogrid_31,the load of Nanogrid_32 and the load of Nanogrid_33,and as well as Load_31 and Load_32 connected to the microgrid. The nanogrids power is exported to the microgrid through the power converter _31, converter_32 and converter 33. Table III shows the power demand in microgrids 3. In Fig.9 are shown the results of the load flow analysis performed on microgrid 2, the results are as follows: Nanogrid 31 produces 6.1 kW, 5.8 kW for Nanogrid32 and 8.8 kW for Nanogrid33. The nanogrids are sharing equally the power demand from the load 31 and 32 by supplying 3 kW each. The loading of the nanogrid is shown in Fig. 10.

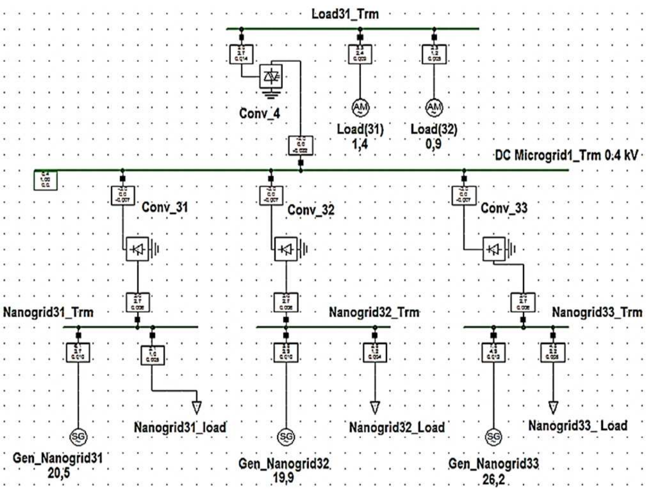

Fig.8. Microgrid 3 model

TABLE III. MICROGRID 3 POWER DEMAND.

Load	Power (kW)
Nanogrid_31_load	2.5
Nanogrid_32_load	2
Nanogrid_33_load	4
Load_31& 32	8.5

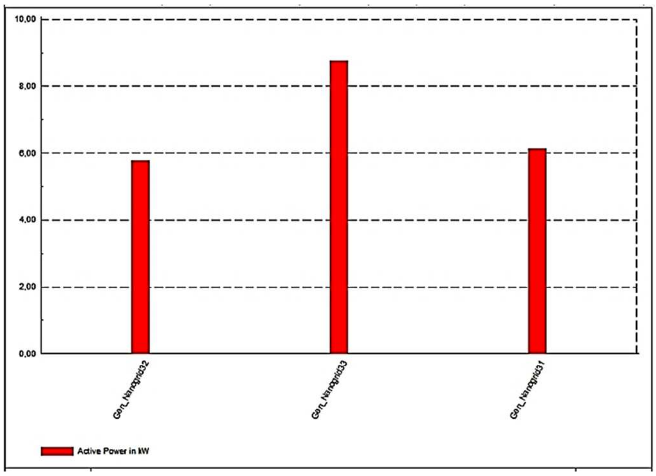

Fig.9. Power generated by nanogrids within microgrid 3

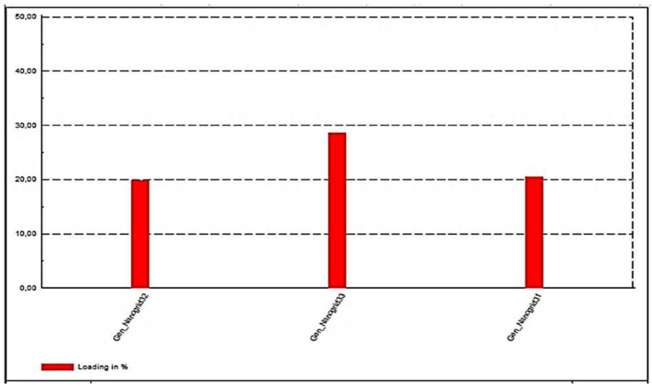

Fig.10. Loading of nanogrids generators in Microgrid 3

The minigrid is developed from the interconnection of the three microgrids through an ILVDC network. The voltage adopted for the interconnection is $3kV_{DC}$. Fig.11 shows the minigrid as developed and simulated in DIgSILENT Power Factory and its connection to the utility. An AC/DC converter interfaces the DC network system to the 3 kV AC utility bus bar; and a general utility load is also connected on the utility bus through a distribution transformer.

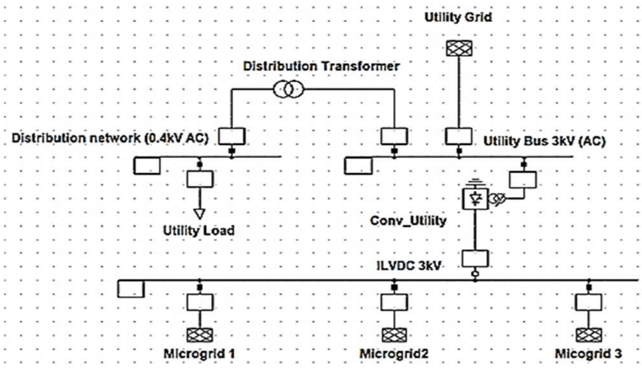

Fig. 11. Microgrid interconnection model

Load flow simulation of the minigrid is performed and results are shown in Fig. 12 shows the minigrid bus voltage profile resulting from the three microgrids integration. A voltage of 3.1 kV_{DC} is observed at the interconnection bus.The voltage is in the range prescribed by the standars. This demonstrates a successful iminigrid formation. Fig.13 shows the loading of all the generators within the minigrid after the interconnection.It shows that in this particular case, the loading of interconnected generators is not affected as the microgrids are self sufficient; thus no power exchange observed.

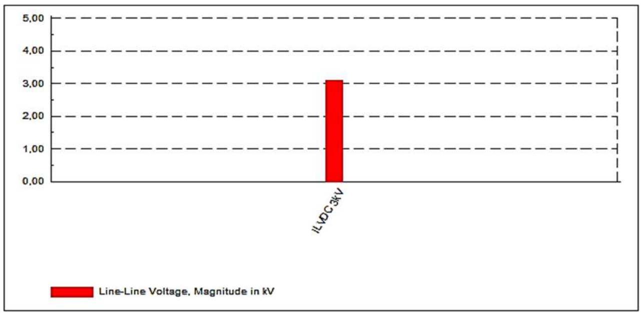

Fig. 12. Minigrid bus voltage profile

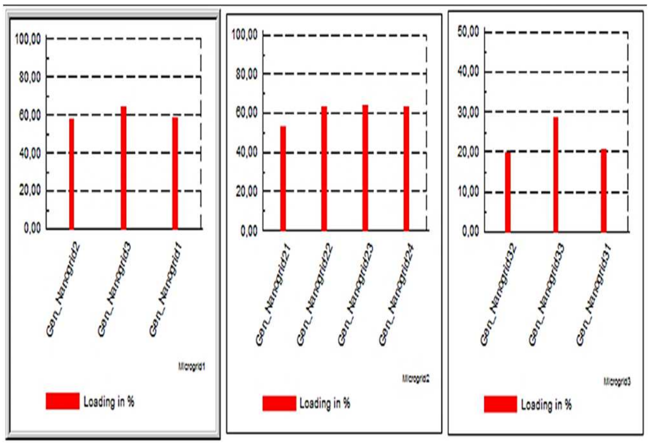

Fig. 13 Loading of all generators after interconnection

V. Conclusion

The lack of access to energy is a challenge in many rural off-grid communities. The alternative or off-grid solutions are insufficient to achieve tier 4 energy access. The grid extension is still the preferred mode of electrification. However, the existing top-down grid extension approach is not efficient. Therefore the need for new approaches for grid extension in rural areas. Thus, this paper presents a DC system for bottom-up grid extension for rural communities. The system uses the swarm electrification concept to interconnect the pre-existing local power resources (nanogrids) micogrids to create a pool of energies that eventually interconnect in "olympic rings" approach to connect to the utility grid. The DC system is the backbone of the interconnection. The system is modeled and simulated using DIgSILENT software.The interconnection consists of three microgrids , which are made up by nanogrids generators and local loads. The generators are modelled as synchronous machines.Analysis of load flow simulation results were carried out for every microgrid in the minigrid formation. The evaluation of microgrids performance using bus voltage profile and generator loading as criteria was conducted. The overall analysis of the results shows a successful interconnection of microgrid through the developed DC system.

References

[1] IEA, "World Energy Outlook 2020 – Analysis," 2020.

[2] B. Rawn and H. Louie, "Planning for Electrification: On- and Off-Grid Considerations in Sub-Saharan Africa," *IDS Bull.*, vol. 48, no. 5–6, 2017, doi: 10.19088/1968-2017.161.

[3] V. Motjoadi, P. N. Bokoro, and M. O. Onibonoje, "A review of microgrid-based approach to rural electrification in South Africa: Architecture and policy framework," *Energies*, vol. 13, no. 9, 2020, doi: 10.3390/en13092193.

[4] P. Buchana and T. S. Ustun, "The role of microgrids & renewable energy in addressing Sub-Saharan Africa's current and future energy needs," in *2015 6th International Renewable Energy Congress, IREC 2015*, 2015, doi: 10.1109/IREC.2015.7110977.

[5] M. M. Gironaa, M. S. Peraltab, M. Lazopoulou, E. K. Ackomd, X. Vallveb, and S. Szabóa, "Electrification of Sub-Saharan Africa through PV/hybrid mini-grids: Reducing the gap between current business models and on-site experience," *Renew. Sustain. Energy Rev.*, vol. 91, pp. 1148–1161, 2018.

[6] S. C. Bhattacharyya and D. Palit, "A critical review of literature on the nexus between central grid and off-grid solutions for expanding access to electricity in Sub-Saharan Africa and South Asia," *Renewable and Sustainable Energy Reviews*, vol. 141. 2021, doi: 10.1016/j.rser.2021.110792.

[7] Q. Liu, K. M. Kamoto, and X. Liu, "Microgrids-as-a-service for rural electrification in Sub-Saharan Africa," *Comput. Mater. Contin.*, vol. 63, no. 3, pp. 1249–1261, 2020, doi: 10.32604/CMC.2020.05598.

[8] M. . Groh, S.; Koepke, "A System Complexity Approach to Swarm Electrification," in *International Symposium for Next Generation Infrastructure Conference Proceedings*, 2015, pp. 283–290, doi: 10.14324/000.cp.1469412.

[9] B. Soltowski, D. Campos-Gaona, S. Strachan, and O. Anaya-Lara, "Bottom-up electrification introducing new smart grids architecture-concept based on feasibility studies conducted in Rwanda," *Energies*, vol. 12, no. 12, 2019, doi: 10.3390/en12122439.

[10] X. S. Musonye, B. Davíðsdóttir, R. Kristjánsson, E. I. Ásgeirsson, and H. Stefánsson, "Integrated energy systems' modeling studies for sub-Saharan Africa: A scoping review," *Renewable and Sustainable Energy Reviews*, vol. 128. 2020, doi: 10.1016/j.rser.2020.109915.

[11] M. Koepke and S. Groh, "Against the Odds: The Potential of Swarm Electrification for Small Island Development States," in *Energy Procedia*, 2016, vol. 103, pp. 363–368, doi: 10.1016/j.egypro.2016.11.300.

[12] M. M. Hoffmann and D. Ansari, "Simulating the potential of swarm grids for pre-electrified communities – A case study from Yemen," *Renew. Sustain. Energy Rev.*, vol. 108, pp. 289–302, Jul. 2019, doi: 10.1016/j.rser.2019.03.042.

[13] J. Bowes, C. Booth, and S. Strachan, "System interconnection as a path to bottom up electrification," in *2017 52nd International Universities Power Engineering Conference, UPEC 2017*, 2017, vol. 2017–Janua, pp. 1–5, doi: 10.1109/UPEC.2017.8232018.

[14] M. Nasir, Z. Jin, H. A. Khan, N. A. Zaffar, J. C. Vasquez, and J. M. Guerrero, "A Decentralized Control Architecture Applied to DC Nanogrid Clusters for Rural Electrification in Developing Regions," *IEEE Trans. Power Electron.*, vol. 34, no. 2, pp. 1773–1785, 2019, doi: 10.1109/TPEL.2018.2828538.

[15] M. Z. Degefa, J. R. A. Klemets, S. D'Arco, P. C. Sekhar, and A. Gupta, "Review of Grid Interconnection Requirements and Synchronization Controllers for Dispersed Minigrids," in *2021 IEEE PES/IAS PowerAfrica*, 2021, pp. 1–5, doi: 10.1109/powerafrica52236.2021.9543220.

[16] G. F. Reed, B. M. Grainger, A. R. Sparacino, and Z. H. Mao, "Ship to grid: Medium-voltage dc concepts in theory and practice," *IEEE Power Energy Mag.*, vol. 10, no. 6, pp. 70–79, 2012, doi: 10.1109/MPE.2012.2212613.

[17] C. An and J. Chen, "Analysis of the Development of DC Distribution Network with Renewable Energy and Flexible Energy Storage," *J. Phys. Conf. Ser.*, vol. 1087, no. 4, p. 42015, Sep. 2018, doi: 10.1088/1742-6596/1087/4/042015.

[18] EU, "Directive 2014/35/EU," *Off. J. Eur. Union*, no. February 1973, pp. 357–374, 2014.

[19] K. Smith, D. Wang, A. Emhemed, S. Galloway, and G. Burt, "Overview paper on: low voltage direct current (LVDC) distribution system standards," *Int. J. Power Electron.*, vol. 9, no.

3, p. 287, 2018, doi: 10.1504/IJPELEC.2018.093354.

[20] A. Verdicchio, P. Ladoux, H. Caron, and S. Sanchez, "Future DC Railway Electrification System - Go for 9 kV," in *2018 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles and International Transportation Electrification Conference, ESARS-ITEC 2018*, 2019, doi: 10.1109/ESARS-ITEC.2018.8607304.

[21] P. Simiyu and I. E. Davidson, "MVDC railway traction power systems; state-of-the art, opportunities, and challenges," *Energies*, vol. 14, no. 14, 2021, doi: 10.3390/en14144156.

[22] J. J. Justo, F. Mwasilu, J. Lee, and J. W. Jung, "AC-microgrids versus DC-microgrids with distributed energy resources: A review," *Renewable and Sustainable Energy Reviews*. 2013, doi: 10.1016/j.rser.2013.03.067.

[23] D. Hur and R. Baldick, "An economic analysis of potential cost savings from the use of low voltage DC (LVDC) distribution network," *J. Electr. Eng. Technol.*, vol. 9, no. 3, pp. 812–819, 2014, doi: 10.5370/JEET.2014.9.3.812.

[24] N. K. Sharma, S. R. Samantaray, and C. N. Bhende, "VMD-Enabled Current-Based Fast Fault Detection Scheme for DC Microgrid," *IEEE Syst. J.*, 2021, doi: 10.1109/JSYST.2021.3057334.