Final report of the doctoral scholarship

“Control of the Smart Transformer in reconfigurable grids to improve the grid resilience”

of Gesellschaft für Energie- und Klimaschutz Schleswig-Holstein at the

Christian-Albrechts-Universität zu Kiel

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Acknowledgment of the project.

This final report describes the work accomplished during the funding period of 01.04.2022 to 31.04.2023 of the doctoral scholarship of Clara Rita Nájera-Alesón González at the Christian-Albrechts-Universität zu kiel by the Gesellschaft für Energie und Klimaschutz Schleswig-Holstein GmbH (EKSH).

The main goal of this research project titled "Control of the Smart Transformer in reconfigurable grids to improve the grid resilience" is to protect the climate by reducing energy-related emissions using technologies for energy storage and integration of renewable energies considering the impact on the state of Schleswig-Holstein, where it plays a key role on the green energy transition in Germany.

The preliminary proposal timeline of the doctoral research was of three years with funding from EKSH. This scholarship gives the possibility to decide after a year if it is extended for two more years regarding the situation of the research or the scholarship holder. After the first year, I have decided to pursue a career in the industry and I am extremely grateful to EKSH and the Chair of Power Electronics for giving me this opportunity to learn and grow as an individual and to have met and worked with incredible people on the way.

The results of this year have led to the following contributions: a conference paper for IEEE PowerTech 2023 titled "Smart Transformer-based Network Reconfiguration for Improved Resilience" with authors Hrishikesan V. M., C. Najera-Aleson, M. Langwaser and M. Liserre, And the bachelor thesis from Mohamed Abdelrehim titled "Resilience-oriented Analysis of ST-Based Microgrids".

1. Abstract.

This research focuses on enhancing the resilience of microgrids in the context of disturbances in a medium voltage (MV) grid connected to a low voltage (LV) distribution network with two main feeders. Specifically, the study investigates the resilience of the LV distribution network in islanded mode, with the goal of achieving a higher resilience index value. To achieve this goal, the research question asks how to determine the best method to enhance the resilience of the LV distribution network.

Furthermore, the dual-microgrid (DMG) scenario is considered to take advantage of the maximum control capability of the Smart Transformer (ST), considering normal and grid fault conditions. The change of conditions will demand a change in the operation of the different power converters changing from Grid Following (GFL) control to Grid Forming (GFM) or vice versa. The microgrid configuration was analyzed with the help of Pandapower, open source software for power flow analysis, the power simulation tool PSCAD and Matlab for controller tuning.

The findings of this research demonstrate the effectiveness of the proposed method in enhancing the resilience of microgrids. By improving the resilience index value, microgrid operators can better prepare for and respond to disturbances, ensuring continuous power supply to critical loads in islanded mode.

The resilience analysis considered how much critical loads can be supported without exceeding a 5% voltage deviation, which is necessary to maintain power quality. Through the analysis, the study discovers that adding a battery to the smart transformer and meshing the first buses together can achieve the desired resilience index value.

Keywords - Grid forming/following control, microgrid, renewable energy, resilience, smart transformer.

2. Introduction.

The electric grid is moving from centralized to distributed in response to the increased penetration of renewable energy sources. The integration of renewable energy is widely acknowledged as a crucial component for a sustainable future. However, as the use of renewables increases, concerns remain about their inherent variability, maintaining stability and sufficient energy supply to distributed and critical loads in case of an extreme event has been affected. In this context, power electronics assets like the Smart Transformer with integrated energy storage systems, which enables both DC and AC connections, play a vital role in ensuring a reliable power supply and offering greater control in the power distribution system.

Additionally, prioritizing system resilience is essential for a future power distribution system that heavily relies on renewable sources. Thus, apart from the specific outcomes mentioned earlier, this proposal aims to advance research on the resilience aspects of a power electronics-dominated grid in the future. As we transition from traditional synchronous generator-based grids to low-inertia grids dominated by renewables, it becomes crucial to study resilience in order to prevent power supply failures caused by fault events occurring within and outside specific grid areas. The proposed concept of Smart Transformer-based reconfigurable grids holds great promise in addressing this challenge. By leveraging the capabilities of Smart Transformers, these reconfigurable networks provide optimal solutions for normal and contingency conditions. The flexibility of ST converters allows for dynamic control transitions, enabling reconfigurable networks to adapt to specific objectives.

Under typical grid conditions, reconfiguration offers numerous benefits, including improved voltage profiles, reduced losses, and alleviation of component overloads, thereby enhancing long-term reliability. During more severe and less frequent events, ST-based reconfigurations further enhance the power distribution system by optimizing the utilization of available renewable energy sources and storage, and ensuring uninterrupted power supply to critical loads. However, achieving these objectives requires further investigation into ST controls, with a particular focus on resilience. The interoperability between grid-forming and grid-following control capabilities of ST converters will be crucial for establishing a reconfigurable network configuration.

2.1 Objectives.

Resilience remains a rapidly evolving topic in the realm of microgrids. The study focuses on critically analyzing resilience terminology, and the results will demonstrate the improved resilience achieved through dynamic grid reconfiguration and the developed power management strategy for a future power distribution system with increased renewable penetration.

This study aims to develop a stable controller design for the ST-based reconfigurable network, incorporating both grid forming and grid following control modes. The designed controller will be adaptable to different grid configurations and enables a smooth transition.

3. Research project status.

3.1 Review on resilience.

Power system resilience refers to the ability of the system to effectively prepare for, respond to, and recover from significant disruptions caused by low-probability events [1]. Traditionally, enhancing resilience involves measures like replacing overhead lines with underground cables and reinforcing infrastructure to withstand severe natural disasters and ensure network stability. However, in modern power systems with a high penetration of renewable energy sources (RES) at the distribution level, the concept of microgrids is gaining attention as an alternative means to improve resilience [2]. Research [3] explores the feasibility of microgrids in functioning as local, community, and black start resources, emphasizing that the overall resilience relies on the collective response of various microgrids during major grid disruptions. Following a disruptive event, microgrids can operate independently from the main grid, forming interconnected networks [4], these interconnections are established by closing the normally open points (NOPs) in the network.

In this context, the smart transformer (ST) stands out as a power electronic transformer equipped with advanced control capabilities, making it a potential candidate for system reconfiguration and the formation of networked microgrids [5]. The ST's ability to create meshed networks has been studied using medium voltage (MV) dc link, low voltage (LV) dc link, and LV ac bus [5], [6]. Depending on the network's requirements, the ST's MV and LV ac interconnecting converters can operate in grid forming and following control structures [5], enabling network reconfiguration during disruptive events. Research [7] demonstrates the ST's transition capability during grid failure through the control transition from grid following to forming of the ST's MV ac-dc converter. Additionally, the ST can serve as a central component for black-starting multi-microgrid systems, thereby enhancing the network's resilience [8].

In this study, the ST can power up two different microgrids by restructuring its control configuration, effectively safeguarding a larger area from external events and reducing the immediate impact on the LV ac grid, hence increasing the network's resilience.

3.2 Preliminary resilience index and criteria.

Evaluating the resilience of power systems, due to several complexities, is a very controversial matter. However, this evaluation is required for the assessment of resilience enhancement strategies.

Resilience Index (RI) is a tool for measuring the resilience level of power systems. The appropriate evaluation of the resilience level of the power system leads to effective and rational resilience enhancement strategies, e.g., advanced control techniques to improve the resilience level of microgrids [9].

This document describes a grid resilience metric and the analysis method performed. The ideal resilience metrics would be simple to calculate; enable retrospective and forward-looking analysis;

be highly informative; and be highly consistent [10]. Considering these attributes, as preliminary resilience metric, since resilience focuses on survivability of the system, a simple measurement that accounts for the amount of loss of loads is used. Having less losses will result in a more resilient distribution system. The resilience measurement of a LV distribution network in islanded mode can be tested by simulating a disturbance in the MV grid. To measure these losses, the loads supplied before and after the fault has to be taken into consideration. The RI is a value between 0 and 1, being one the best scenario and 0 having no loads surviving the impact, this value comes from the ratio of critical loads that are supplied after the grid faults occurs over the total amount of loads in the system. This RI will provide us a measure on resilience that will allow us to compare the different loading and meshing conditions.

During the analysis, we considered the maximum voltage deviation from nominal value of 5%. This ensures that a proper power quality is maintained. The simulation results will be conducted with the LV distribution grid by using the power flow analysis tool of Pandapower [11] applying the Newton-Raphson Method.

The simulations consist of test cases where the load increases uniformly to determine how many critical loads can be supplied in each case. The RI value will be calculated for each test case using equation (1) below and the best case with the highest RI value will be selected.

$$RI = \frac{L_{Critical} \times 100}{L_{Total}} \tag{1}$$

Where $L_{Critical}$ is the total critical loads supported and L_{Total} is the total loads in the whole network. Once the best case with uniform load is identified, a set of new cases will be created to test its resilience with non-uniform load distribution and the RI value will be calculated again to determine how it changes under different loading conditions. The ultimate goal of the simulations is to design a resilient microgrid that can provide a reliable power supply to critical loads in islanded mode, even under adverse conditions.

3.3 Control operation of the Smart Transformer.

The dual-microgrid configuration in figure 1 [7] has been used as a case study for this research. Where two feeders are connected at a Point of Common Coupling (PCC) on the MV ac. One feeder is connected to a ST with a BESS coupled at the MV dc link through an isolated dc-dc converter whereas the other feeder has a Conventional Power Transformer (CPT) supplying a LV network. In the normal operation of an MV network, the smart transformer supplies power to loads connected to its low voltage side and injects power into the MV grid based on the available renewable energy sources and load demand.

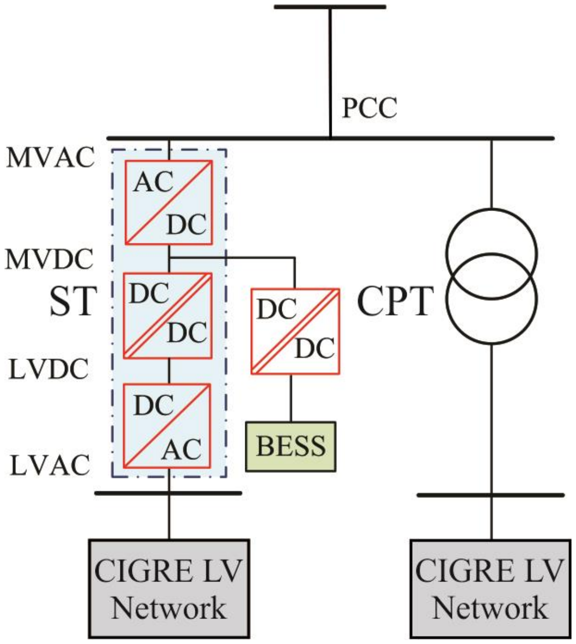

Fig.1. Dual microgrid configuration.

During faults in the medium voltage ac grid, the ST delivers power to sensitive loads that are connected to other feeders equipped with conventional power transformers and disconnects the PCC from the utility mains. In this situation, the distributed generation and storage integrated at the ST is the only source of power available to feed the critical loads. In this work, the mode of operation of MV rectifier is transferred from grid-following mode to grid-forming mode to maintain a constant balanced sinusoidal voltage at the MV terminal and provides power to the loads of other feeders connected through the CPT during the islanded operation.

This capability of the smart transformer to isolate from the utility grid and provide continuous power to sensitive loads on other feeders has the potential to greatly enhance the performance and resilience of the power system. Additionally, it is essential to integrate a reliable communication network into the smart transformer application in order to ensure stable and optimal operation of the power distribution system, both in normal conditions and during microgrid operation.

The control of the three stages of the ST when connected to the grid and the BESS is not connected:

- The inverter is working as GFL and controlling the MV dc link voltage at the capacitor.
- The dc-dc converter makes possible the power transfer between the MV and LV dc links and keeps the LV dc link constant
- The rectifier works as GFM, maintaining a balanced sinusoidal voltage with a constant frequency at the LV distribution system.

The control structure when disconnecting from the MV grid and the BESS is connected:

- The inverter works in GFM mode to keep a balanced sinusoidal voltage at the PCC to maintain the continuity of the power supply to the CPT feeder.
- The BESS maintains the MVDC link voltage constant.
- The dc-dc converter and the rectifier work in the same manner, hence from the LV side point of view, there is no impact in the control mode when the MV grid is disconnected.

3.4 Simulation results.

The following subsections will first introduce the network topology used for the different meshed configurations. Secondly, the two different load profiles, uniform and non-uniform distribution of critical loads are explained and the impact on resilience is analyzed.

The uniform load refers to the homogeneous distribution of critical loads in the entire network, for example, if there is 10% of criticality on loads, then all the loads have 10% critical loads. In the opposite scenario, the heterogeneous distribution of critical loads, if means that the weight of criticality is not evenly distributed but there are loads that are more critical than others. To set a reference for which load is the most critical one, the one that after the study makes the system more prone to fail is chosen.

3.4.1 Grid configuration.

To create a microgrid with enhanced resilience, the Pandapower library was utilized to design an LV distribution network with two feeders. The LV network used has been a modification of the CIGRE-LV ac network [12] and it is shown in Fig. 2. It shows two feeders connected through a Normally-open point (NOP) making up the dual-microgrid configuration. The first feeder consisted of the ST, 19 buses, two Photovoltaic (PV) sources and 5 loads which drew their power from an MV grid. The second feeder is identical to the first one, where the main difference is that no ST was used, instead a CPT was implemented. The voltage levels of the MV and LV ac networks are considered 20 kV and 0.4 kV, respectively.

By having this dual feeder configuration, it is possible to study the impact of using the ST over a CPT and the different connection points.

The resilience index will be of importance when islanding operation occurs, disconnection from the main grid. In normal operation, is it assumed that all the loads are feed having sufficient energy supplied and that the system is stable, then using the RI aforementioned, the resilience is 1.

The case 1, is when no battery nor meshing is employed. The second case corresponds to the usage of the BESS. And in the following table, a summary of case 3, corresponding to the different meshed configurations is shown. More explanation is given in the next subsections.

Table I. LV grid meshed topologies and analysis performed.

Case 3	Meshing buses	Uniform load	Non-uniform load
Scenario 1	R1 – I1 (R0- I0)	Yes	Yes
Scenario 2	R5- I5	Yes	No
Scenario 3	R10 –I10	Yes	No

In the power flow analysis, the meshing at R0 and I0 by closing the NOP and the meshing at R1 and I1, case 3, scenario 1, are equivalent considering that the transformer is ideal. Then the results obtained can be extrapolated to the dual-microgrid in order to make full use of the ST converter capabilities.

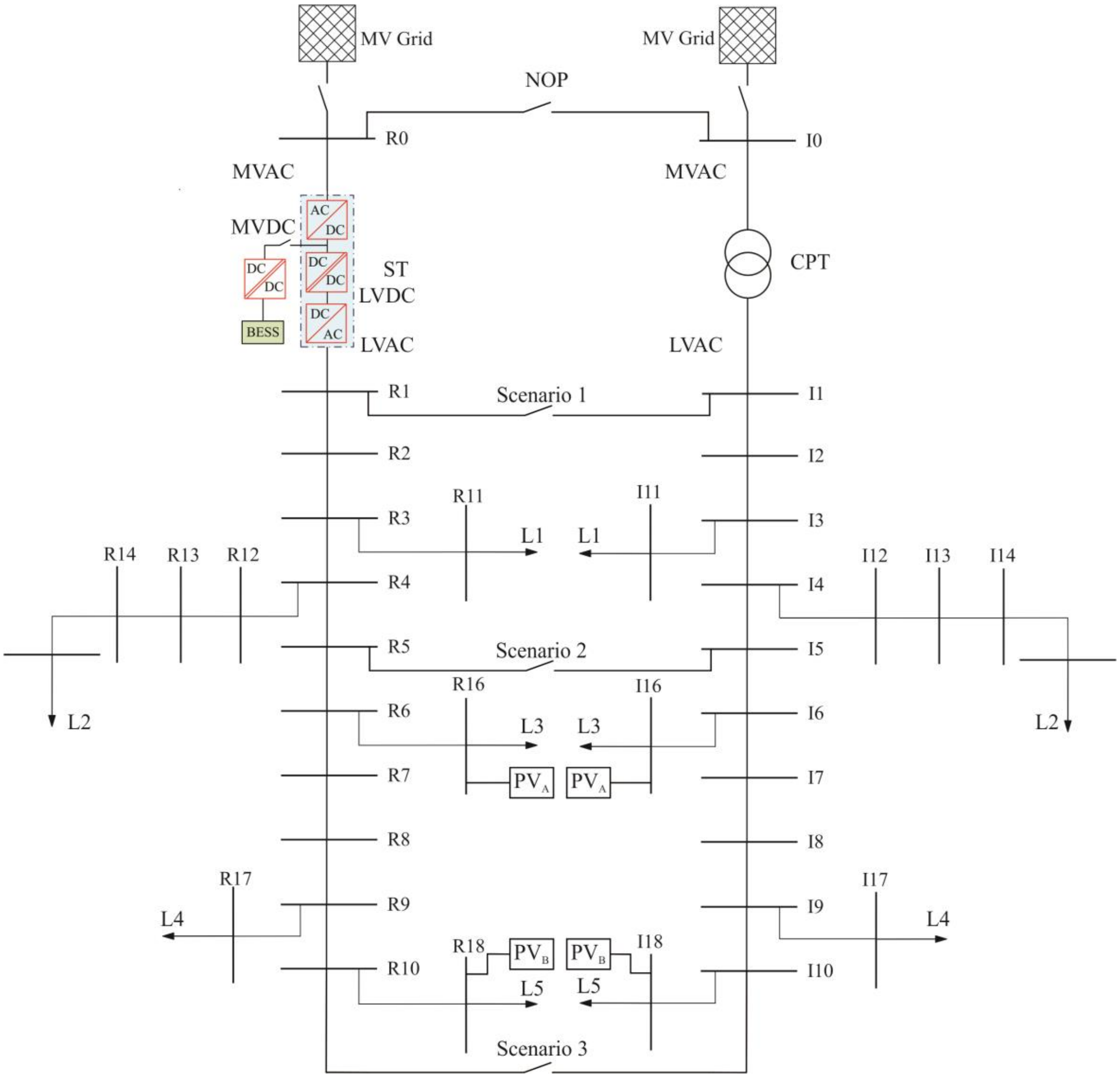

Fig 2. Grid configuration used for the different case studies.

3.4.2 Uniform load analysis.

Considering the first test case as a benchmark, when the BESS is disconnected and there is no meshing between feeders, all the connection points are open, the resilience index expected in islanded operation is null. If the ST is only used for supplying its own LV ac network, the CPT-fed feeder would be experiencing a complete outage resulting in a total loss of load irrespective of the PV penetration as the PV converters are not considered as grid forming units.

Case 2, the battery is connected thought the ST to the LV network without any meshing with the CPT feeder. The results shown in figure 3 that the battery can support 100% of the loads in the ST feeder as the voltage drop will be the same as the normal operation mode and still within our 5% voltage drop, which will result that the RI value is 0.5. The voltage drop at R15 is of 4.7%.

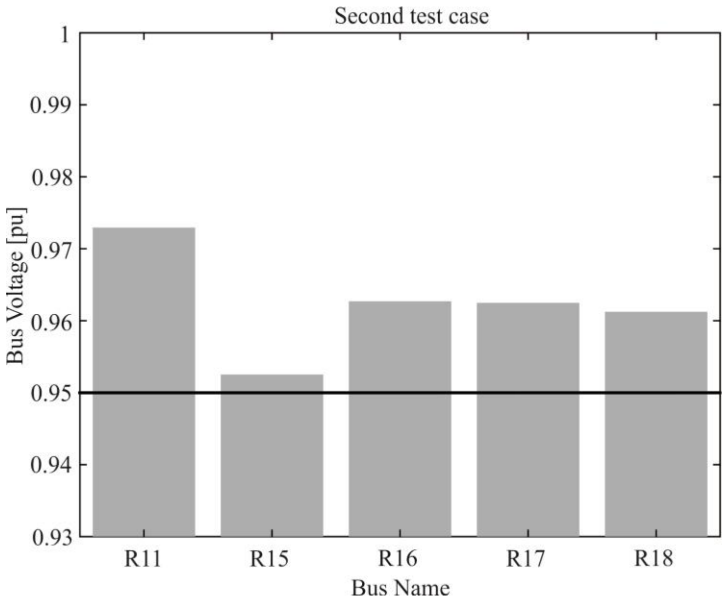

Fig 3. Test case 2 bus voltages.

Case 3 is split into three scenarios; the BESS is operating and the meshing with the CPT feeder will occur in three different locations.

- Scenario 1, the battery is connected to the ST and the ST and CPT feeders are meshed together from BusR1 and BusI1. The battery can support 75.3% of the loads considering the voltage drop to make it still within the 5% voltage drop, which will result that the RI value will be 0.753.
- Scenario 2, in this case, the battery is connected to the ST and the ST and CPT feeders are meshed together from BusR5 and BusI5. The results obtained show that the battery can support 59% of the loads considering the voltage drop to make it still within the 5% voltage drop, which will result that the RI value will be 0.59.
- Scenario 3, the two feeders are meshed together from BusR10 and BusI10 resulting in 0.41 resilience index.

This comparison in Fig. 4. shows that the third uniform load case (1st Scenario) is the most resilient one. The plotting is used for 41% of criticality of all loads, when the scenario 3 fails, since it is the least resilient. This way it can be seen the voltage drop all the other cases that are fully supported by the battery, such as scenario 1 and scenario 3 having the lowest voltage drop at 2.5 % and 3.2%. (0.975pu and 0.968pu)

This is due to the fact that if a fault occurs, the closer the meshing to another stable energy source the less the voltage drop at the point of connection. The further the connection is from a stable voltage source, the higher the voltage drop through distribution the line. This result was to be expected using uniform loads, then it is important to see how using non-uniform loads can also alter the resilience.

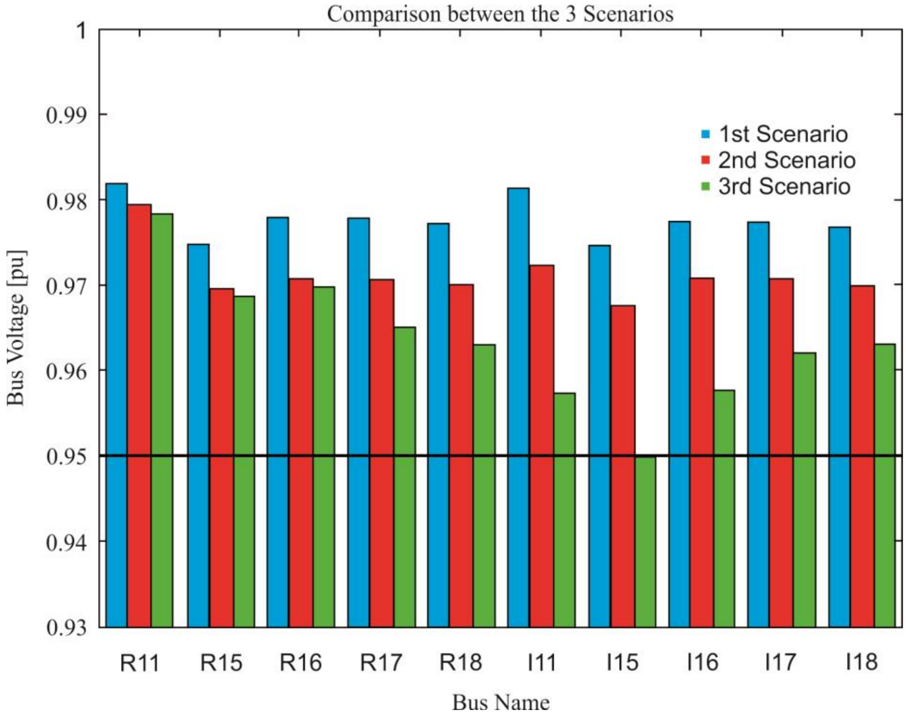

Fig. 4. Comparison of bus voltages with 41% of critical loads.

3.4.3 Non-uniform load analysis.

For this comparison also three cases have been considered but they are performed a different way, now the meshing topology used is scenario 1, the most resilient meshed grid where the comparison was shown in Fig. 4. And just the criticality of load changes, no other modifications are done. By having a closer look to the plot, the load that makes the system fail is the one connected to R15 and I15 in the blue bars. Then changing the critical percentage of this load will considerably impact on the resilience measurement.

The first non-uniform case is having 20% of critical load in all the loads except the two aforementioned. The result is that the battery can support 100% for load R15 & load I15 and the rest of the load are supported with 20% considering the voltage drop to make it still within our 5% voltage deviation, which will result that the RI value will be 0.36.

The second non-uniform case, similar to previous one but considering 40% criticality. Once again, the battery can support 100% for load R15 & load I15 and the rest of the load are supported with 40% considering the voltage drop to make it still within our 5% deviation, which will result that the RI value will be 0.52.

The third and last case, is when the battery cannot fully supply all the loads, this happens when 60% of all loads but R15 and I15 are critical. Then the battery can support 90% for load R15 & load I15 and the rest of the load are supported with 60% considering the voltage drop to make it still within our 5% voltage drop, which will result that the RI value will be 0.66.

After these results, it is important to notice how the correct battery sizing and load profiles impact on the resilience, so further research on these factors is a matter to consider.

4. Conclusion.

In conclusion, the development of microgrids requires a keen focus on resilience. The inclusion of communication networks, distributed energy supplies, and effective control systems are all critical components that can enhance the resilience of microgrids. These factors play a vital role in creating microgrids that can withstand disruptions, recover from them quickly, and continue to provide power under challenging conditions.

Several simulations were conducted using the Pandapower library, utilizing a power flow analysis to determine the number of critical loads that could be supported in each scenario. These simulations included test scenarios where the load increased incrementally. The 3rd Test Case (1st Scenario) was identified as the best-case scenario, as it involved a Battery Energy Storage System (BESS) connected to the ST, a mesh linking the two feeders from R1 to I1, and the network operating in islanded mode. The supply in this case was 75.3% for both feeders with RI value of 0.753 when considering a 5% voltage drop. The third load case was also identified as having a higher level of resilience, with a RI value of 0.66 when a 5% voltage drop was considered.

In summary, the development of microgrids that are resilient to disruptions is critical for ensuring an uninterrupted power supply under challenging conditions. Effective communication networks, distributed energy supplies, and control systems are essential components that contribute to the resilience of microgrids. The Pandapower library offers a valuable resource for designing and evaluating microgrids, and simulations using this library can provide valuable insights into the resilience of microgrids under various scenarios. The findings of this study highlight the importance of considering resilience in the development of microgrids, and the potential benefits of incorporating BESS and mesh networks in these systems to enhance their resilience.

4.1 Future Work.

Based on the findings of this study, there are several potential areas for future research related to microgrids and resilience. First, future research could be conducted to evaluate the effectiveness of different communication networks, distributed energy supplies, and control systems in enhancing the resilience of microgrids. Further exploration of the design and implementation of these components could provide valuable insights into how to create microgrids that are even more resilient to disruptions.

Second, additional research could investigate the potential benefits of incorporating other technologies into the analysis, such as renewable energy sources or advanced energy storage systems. This could include exploring how the integration of renewable energy sources could impact the resilience of microgrids and evaluating the effectiveness of different energy storage systems in enhancing their resilience.

Finally, future research could explore the economic feasibility of different microgrid designs and configurations, considering the cost of implementing various resilience-enhancing components and optimization. This could include assessing the cost-effectiveness of different control systems, communication networks, and energy storage systems, as well as evaluating the potential return on investment for microgrid owners and operators.

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