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Regular Research Manuscript

Clustering Mini-Grids to Enhance Power Systems Reliability in Distributed Generation

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ABSTRACT

This study investigates the effectiveness of clustering mini-grids as a method to improve the reliability and operational stability of distributed generation systems in remote areas, particularly where renewable energy sources are predominant. As renewable resources like solar and wind are increasingly integrated into mini-grids, these systems face various challenges, particularly in maintaining stable voltage and frequency across interconnected networks. Such issues are compounded by the intermittent nature of renewable energy sources and the lack of extensive communication infrastructure in rural or resource-constrained settings. To address these control challenges, this study applies droop control techniques to two mini-grids in Uganda, utilizing modeling and simulation through Matlab/Simulink to evaluate the method's impact on system stability. Results demonstrate that, droop control strategy is effective in stabilizing frequency and enabling balanced distribution of active and reactive power across interconnected mini-grids, reducing the dependence on complex communication systems. The findings underscore the potential of droop control to enhance the resilience and adaptability of mini-grid clusters, making it a valuable solution for rural electrification in regions like sub-Saharan Africa, where the demand for sustainable and reliable energy solutions is rapidly growing (Chin & Hug, 2022; Joshal & Gupta, 2023; Tanomrug, 2022).

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INTRODUCTION

Mini-grids are decentralized energy systems that supply electricity to remote or rural areas with little connection to a central power grid by utilizing locally accessible energy sources including solar photovoltaic (PV), wind turbines, and battery storage (Aligbe *et al*., 2022). Distributed generation (DG) refers to connecting these renewable energy sources to a distribution network, which can enhance energy accessibility and reliability in such areas (Tkac *et al*., 2023). Recently, mini-grids have evolved from isolated, stand-alone systems to interconnected networks known as clustered mini-grids, in which multiple mini-grids are grouped and interconnected to form a single, coordinated power network. This clustering approach optimizes grid operations, supports the integration of renewable energy sources, and strengthens general system reliability by enabling mini-grids to share resources and balance loads (Chin & Hug, 2022; Tanomrug, 2022).

Despite the operational advantages, clustered mini-grids face considerable technical challenges related to control, stability, and resource management, especially when integrating renewable energy sources that produce intermittent power output. The key challenges in clustered mini-grids include frequency and voltage variations, power-sharing accuracy, and seamless mode transfers between grid-connected and islanded states (Issa *et al*., 2024; Joshal & Gupta, 2023). These challenges are intensified in clustered mini-grids due to the presence of multiple distributed generators (DGs) with diverse power sources, resulting in complex power management and control requirements (Aligbe *et al*., 2022). To address these issues, various control strategies have been developed, each with distinct advantages and drawbacks.

Among the commonly used strategies are model predictive control (MPC) and droop control. Model predictive control has the advantage of precise power flow regulation, often by adjusting the bus voltage within predetermined limits to maintain system stability and minimize frequency deviations. MPC is recognized for its adaptability in dynamic, multi-variable environments, as it forecasts future system states to optimize current control actions (Tkac *et al*., 2023). However, MPC requires substantial computational power and relies heavily on communication infrastructure for real-time data exchange between interconnected systems, which can be costly and complex to implement in remote mini-grid clusters (Senjyu, 2022).

Droop control, on the other hand, is a decentralized control strategy that manages voltage, frequency, and active/reactive power without relying on extensive communication networks. This method is particularly advantageous for mini-grids with distributed renewable energy sources, as it simplifies the integration of multiple energy sources while allowing inverters to share loads proportionally to their capacities based on local measurements of voltage and frequency deviations (Guerrero *et al*., 2016; Kushwah, 2017). Droop control is also less computationally intensive, which makes it a suitable choice for isolated or rural areas where communication infrastructure may be limited or unreliable. However, traditional droop control has limitations, such as reduced accuracy in active and reactive power sharing due to variations in line impedance among distributed generators, which can cause stability issues in larger or more complex mini-grid clusters (Keyvani-boroujeni *et al*., 2021).

This paper adopts the droop control technique as a control strategy for clustering mini-grids, as it offers a practical balance between reliability and scalability without the need for critical communication links. Through incorporating droop control into the clustering of two geographically close mini-grids in Western Uganda, this study aims to maintain voltage and frequency stability while enhancing the proportional distribution of power in response to load changes. The proposed droop control strategy is tested using modeling and simulation in Matlab/Simulink to verify its effectiveness in stabilizing system frequency, regulating voltage, and providing accurate power-sharing among interconnected mini-grids.

Case study

In this study, the case of mini-grids in the Kyenjojo District of Western Uganda is examined, specifically focusing on the Kanyegaramire and Kyamugarura mini-grids. These mini-grids, installed in 2015 with assistance from the Ugandan government and the University of Southampton, serve approximately 500 residents within a 3-mile radius, providing essential power for domestic use (Katre *et* *al*., 2019). Each mini-grid is designed to operate with a 13.5 kWp solar array, complemented by 38.4 kWh of battery storage and two 5 kW inverters. The mini-grids are managed by local cooperatives, which oversee their operation and maintenance, and supply energy for basic appliances, such as lamps, radios, and phone chargers.

By offering a dependable supply of electricity, these mini-grids have greatly benefited the community, but they also confront many difficulties, especially as energy demand rises. Like many mini-grids in rural and off-grid areas, the Kanyegaramire and Kyamugarura systems experience supply limitations that constrain their ability to meet the increasing electricity needs of the community. Originally designed to support a limited load profile, the grids are unable to fulfill the higher power demands that have emerged due to economic activities and household needs (Katre *et al*., 2019).

In addition to supply constraints, these mini-grids also encounter operational challenges related to system reliability and control. Renewable energy sources, particularly solar photovoltaics, introduce intermittent power generation that makes voltage and frequency regulation difficult, as fluctuations in solar output directly impact the stability of these small grids. As a result, the mini-grids in Kyenjojo District struggle to provide consistent and reliable power, especially during peak load periods or times of low solar irradiance. These reliability challenges are compounded by the limited battery storage capacity, which restricts the grids' ability to balance supply and demand effectively.

Moreover, the lack of centralized control mechanisms in these mini-grids poses additional control and stability issues. The mini-grids operate in an islanded mode, meaning they are disconnected from a main grid, which limits their ability to use external support for frequency and voltage regulation. This independence creates control complexities in balancing power flows among distributed generation sources, which often leads to frequency and voltage variations and reduces general system efficiency and reliability (Aligbe *et al*., 2022).

To address these challenges, clustering the Kanyegaramire and Kyamugarura mini-grids into a single network offers a potential solution by enhancing power-sharing capabilities and leveraging the combined generation resources and storage. Through interconnecting these mini-grids through a circuit breaker and implementing a droop control strategy, power distribution can be managed to improve reliability and system stability. Droop control, a decentralized approach, adjusts the output frequency and voltage of each inverter based on real-time measurements, allowing the interconnected mini-grids to share loads proportionally and dynamically in response to demand fluctuations. This clustering approach provides an effective solution for balancing load among the two mini-grids, reducing the impact of individual load surges, and maintaining frequency and voltage stability across the network (Guerrero *et al*., 2016)..

METHODS AND MATERIALS

Droop Control Algorithm

The droop control algorithm is a decentralized control approach used to regulate power sharing among inverters in multi-terminal voltage source converter (VSC) systems, ensuring stability without the need for extensive communication networks (Guerrero *et al*., 2016). The algorithm adjusts the output frequency and voltage based on power deviations, facilitating balanced load distribution.

Figure 1 demonstrates power flow between two voltage sources in an AC bus configuration

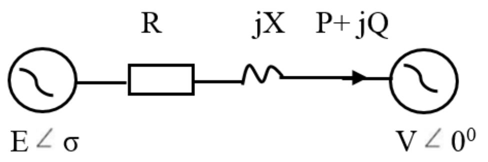

Figure 1: Power transfer between two voltage sources (Das et al., 2017)

where E ∠ σ and V ∠ 0^0 represent the inverter's output voltage and the common AC bus voltage, respectively and R + jX is line impedance (Z), then active (P) and reactive power Q transferred by the source is given as in equation (1) and (2) below also in (Das et al., 2017):

$$P = \left(\frac{VEcos\sigma}{Z} - \frac{V^2}{Z}\right)cos\theta + \frac{VE}{Z}sin\sigma\, sin\theta \quad (1)$$

$$Q = \left(\frac{VEcos\sigma}{Z} - \frac{V^2}{Z}\right)sin\theta + \frac{VE}{Z}sin\sigma\, cos\theta \quad (2)$$

where Θ is the phase angle for transmission line impedance.

Inductive impedance $\theta = 90^0$

For a highly inductive line $\theta = 90^0$ hence Z= X and assuming σ to be small (Chen et al., 2015). For an inductive line, the power relation between the active P and reactive Q changes to:

$$P = \frac{VE}{X}\sigma \quad (3)$$

$$Q = \frac{VE - V^2}{X} \quad (4)$$

Equations (3) and (4) show that active power varies with a variation in power angle σ thus changes in frequency and reactive power vary with output voltage (V). Hence it can be derived from these relations that it is feasible to regulate active and reactive power by controlling frequency and output voltage respectively.

Considering the same relationship P-F/Q-V droop control (Active power – Frequency /Reactive power – Voltage droop control) is developed for inverter control of DG unit. The control scheme introduces droop in control parameters (voltage, frequency) to increase load demand making the inverter responsive to load change. The following correlation between frequency and active power, voltage, and reactive power is utilized for droop control of inverter units.

$$f = f^* - m(P - P^*) \quad (5)$$

$$V = V^* - n(Q - Q^*) \quad (6)$$

where m and n are the frequency and voltage droop coefficients, P* and Q* are the nominal active and reactive power, and f^* and V^* are the nominal frequency and voltage of the inverter operation. These coefficients are calculated from the following equations.

$$m = \frac{\Delta f}{P_{max}} \quad (7)$$

$$n = \frac{\Delta V}{Q_{max}} \quad (8)$$

where P_{max} and Q_{max} are the maximum active and reactive power supplied by the inverter respectively, and Δf and ΔV are the maximum allowable deviation in frequency and voltage as shown below in Figure 2 and Figure 3.The active power-frequency (P-F) and reactive power-voltage (Q-V) dropping characteristics are shown in Figure 2 and Figure 3, respectively.

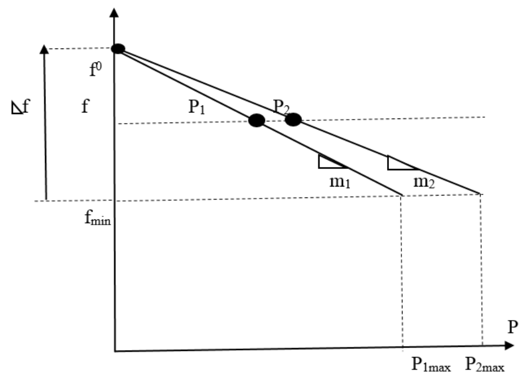

Figure 2 : Frequency droop characteristic curve.

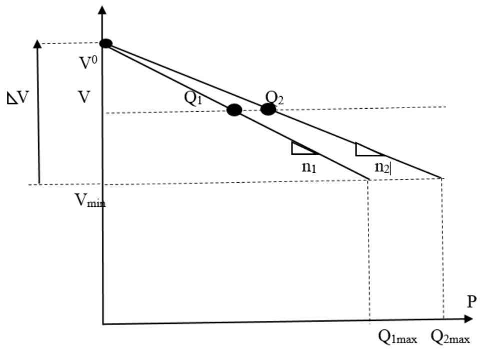

Figure 3: Voltage droop characteristic curve (Katre et al., 2019)

The f_{min} indicates minimum allowable frequency deviation, Similarly, V_{min} shows minimum allowable voltage deviation (Guerrero *et al*., 2016).

Resistive impedance $\Theta = 0^0$

For a highly resistive line, $\Theta = 0^0$ equations (3) and (4) may be written as follows:

$$P = \frac{V}{R}(E - V) \tag{9}$$

$$Q = \frac{EV}{R}\sigma \tag{10}$$

The inverter voltage amplitude controls active power P, while the power angle σ does not affect P, as demonstrated by formulas (9 and (10). Reactive power Q can be controlled by the power angle σ because the angle σ dominates the reactive power flow. The change in the inverter output-voltage amplitude E has minimal effect on Q.

Under this scenario, power sharing across parallel inverters may be achieved by the application of PV and QF droop control. As a result, we may describe the amplitude of the inverter output voltage reference and frequency as follows.

$$f = f^* + m(Q - Q^*) \tag{11}$$

$$V = V^* - n(P - P^*) \tag{12}$$

Clustering the two mini-grids

In this study, two geographically proximate mini-grids are interconnected to improve power reliability and facilitate efficient load sharing. These mini-grids possess similar characteristics, making them well-suited for clustering within a micro grid network. Both mini-grids primarily rely on renewable energy sources, specifically solar photovoltaic (PV) systems, which are supplemented by battery storage. Each mini-grid has two 5 kW inverters, a 13.5 kWp solar PV array, and 38.4 kWh of battery storage. This similarity in energy generation methods allows for compatible operational dynamics, simplifying power management and integration within the cluster (Guerrero *et al*., 2016).

Furthermore, the mini-grids demonstrate comparable load demand patterns. They experience peak loads at similar times of day, driven by the local communities' energy consumption patterns, which include lighting, domestic appliances, and small-scale commercial activities. This alignment in load demand ensures synchronized power fluctuations, which facilitates seamless operation when the mini-grids are clustered (Chen *et al*., 2015). The mini-grids in this study are also outfitted with inverters that use droop control to regulate voltage and frequency, each of which maintains a nominal voltage of 400 Vrms and a frequency of 50 Hz. Compatibility between inverter setup and control methods improves the system's capacity to distribute loads efficiently and adapt to demand fluctuations. This setup enables stable operation across the clustered mini-grids, as each system is able to adjust in response to load variations while maintaining the desired frequency and voltage levels (Keyvani-boroujeni *et al*., 2021).

The infrastructure of these mini-grids also includes similar network designs with both resistive and inductive loads, connected through a circuit breaker. This setup supports the smooth transfer of power between the two systems and enables them to collectively handle additional loads when required. Clustering these mini-grids offers a more resilient power supply, leveraging the combined generation and storage capacities to meet the communities' energy needs, particularly during periods of peak demand (Das *et al*., 2017). For power-sharing and increased power reliability, the inverters are linked via a circuit breaker. Droop control is incorporated to each inverter to maintain the frequency and voltage as shown in Figure 1. The system is kept at the nominal values of 50 Hz and 400 V_{rms} by the droop control. The DC power generated is connected to the inverter, and the output of the inverter is then connected to the LCL filter. Both mini-grids feature loads that are inductive and resistive and shared a switched load through the circuit breaker. Each mini-grid will efficiently supply its loads under typical operating conditions. Nevertheless, if a new load is introduced, each inverter should be able to produce enough power to meet the additional load in accordance with its capacity.

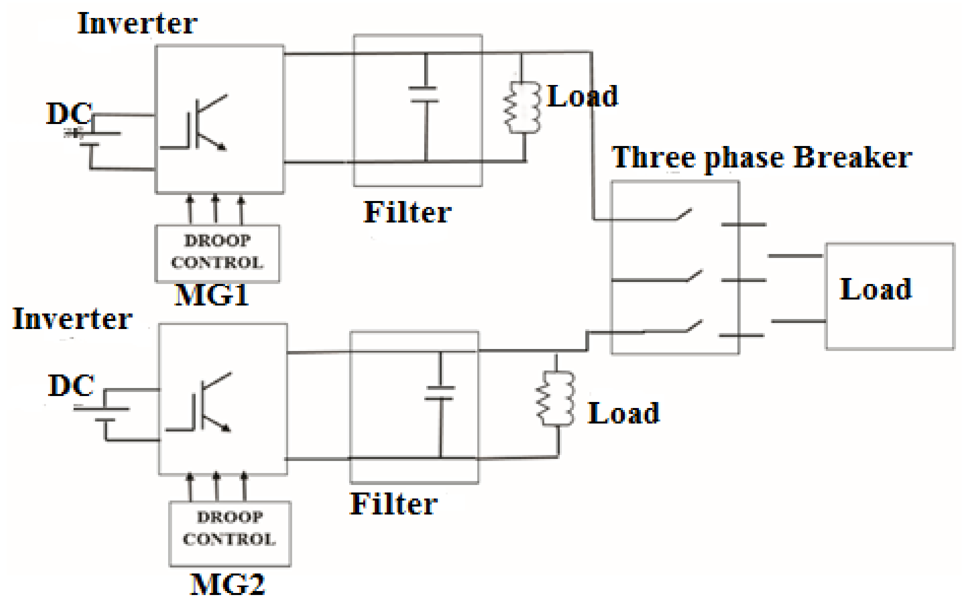

Figure 4: Two inverters connected in parallel through circuit breaker.

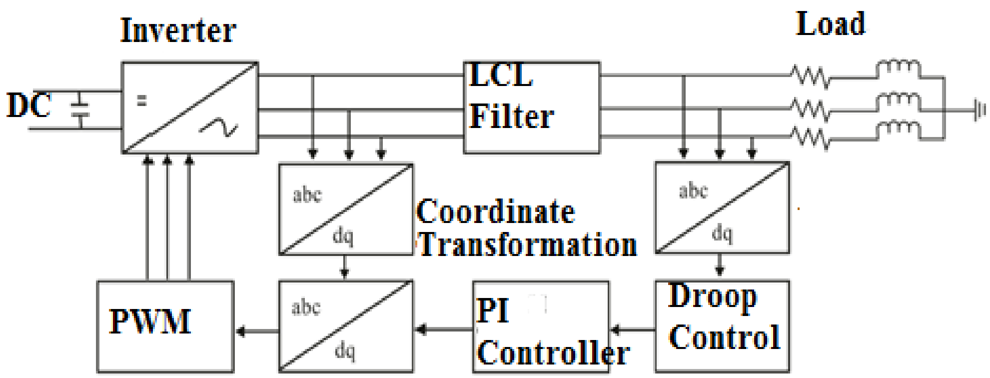

Figure 5: Inverter control mechanism in island mode with droop control.

Modeling and Simulation

The simulation, implemented in Matlab/Simulink, includes LCL filters for each inverter to attenuate higher-order harmonics and stabilize output voltage. Voltage measurements were taken after the filters, while current readings were pre-filter, ensuring precise transformation calculations and effective control.

In islanded mode with Voltage-Controlled Mode (VCM), the LCL filter aids in producing a more sinusoidal voltage waveform at the output, which is essential for maintaining stable voltage and frequency levels within the mini-grid. By placing the LCL filter between the inverter and the load, the system can effectively reduce the harmonic distortion that would otherwise compromise the quality of power supplied to local loads. This setup ensures that the voltage output remains consistent, which is critical in maintaining the overall stability and reliability of the clustered mini-grids in a decentralized power system.(Chen *et al*., 2015).

The three-phase line-to-line voltages are converted into two-phase alpha-beta to implement the controller Figure 5. The three-phase (abc) signal is transformed into a stationary reference frame *αβ0* by the *abc*/alpha-beta. The inverter output voltage and current are represented by V_{dq} and i_{dq}, respectively, after alpha/beta voltages are translated to d/q voltages using Park's transformation. The instantaneous active and reactive power may be calculated using (13) and (14) respectively.

$$P = V_d i_d - V_q i_q \tag{13}$$

$$q = V_q i_d - V_d i_q \tag{14}$$

Droop coefficient equations (7) and (8) use the computed active and reactive power as input for droop controllers m and n. The droop controller determines the operating frequency and the reference voltage. Using equation (5), the reactive power controller generates the reference voltage, and using equation (6), the active power controller generates the reference frequency. To determine the error, the reference voltage and the voltage V_{dq} are compared. The PI controller is particularly well-suited for systems operating in islanded mode, where voltage and frequency stability is critical and disturbances are relatively low-frequency in nature. Its effectiveness in minimizing steady-state error without requiring extensive computational resources makes it an optimal choice for the control strategy employed in this study.(Chen *et al*., 2015). Although Model Predictive Control (MPC) offers a more robust response, its complexity and computational demands make it less suitable for remote mini-grid applications. (Joshal & Gupta, 2023; Tumeran e*t al*., 2023)

To determine the error, the output voltage is compared with the reference voltage generated by the droop control algorithm. The PI controller processes this error to produce the reference current. Mathematically, expressed as follows:

$$I_{ref} = K_p e(t) + K_q \int e(t)dt \tag{15}$$

where I_{ref} is current, $e(t)$ is the error between the reference and actual output, Kp is the proportional gain and Kq is the integral gain.

The reference current is then compared with the actual inverter output current. Any discrepancy between these values is fed back to the PI controller to adjust the reference voltage. This reference voltage is subsequently transformed from the reference frame back to the frame, making it compatible with the Pulse Width Modulation (PWM) technique used to control the inverter switching signals. PWM enables the inverter to follow the reference signals closely, ensuring accurate control over the inverter output.(Keyvani-boroujeni *et al*., 2021).

The droop control algorithm adjusts the voltage and frequency references based on the active and reactive power deviations, which are fed into the PI controller. The PI controller then calculates the necessary corrections, resulting in a reference voltage that aligns with the desired power-sharing and stability goals.

RESULTS AND DISCUSSIONS

Initially, the mini-grid both supports a base load of 5kW. Which reflects the standard power demands of the connected community. After 0.5 seconds of operation, the load in both micro-grids increases to 3KW.This new load increases the total demand across the system, prompting the inverters to adjust their output accordingly to meet the higher power requirement.
Figure 6 displays the load profile, illustrating the initial load and the increased demand due to the added load at the 0.5-second mark.
With the added load, the total power required from the system increases, and both inverters respond by scaling their outputs to satisfy the new demand. Figure 6 and Figure 7 shows the adjustment of active and reactive power levels in both mini-grids. The added load is evenly split between the two inverters, as they are rated with equal capacity and can distribute power proportionately. This balance in contribution is crucial for maintaining system stability and ensuring that each mini-grid effectively shares the burden of the added load (Chen et al., 2015).
The contribution of each mini-grid to the common load is represented in Figure 6 and Figure 7 where it can be seen that the active and reactive power output from each inverter increases in response to the added load. With both inverters having the same capacity, they share the power demand equally, each supporting approximately half of the new load. This proportional distribution aligns with the principles of droop control, which allows the inverters to self-regulate their output based on real-time power needs.

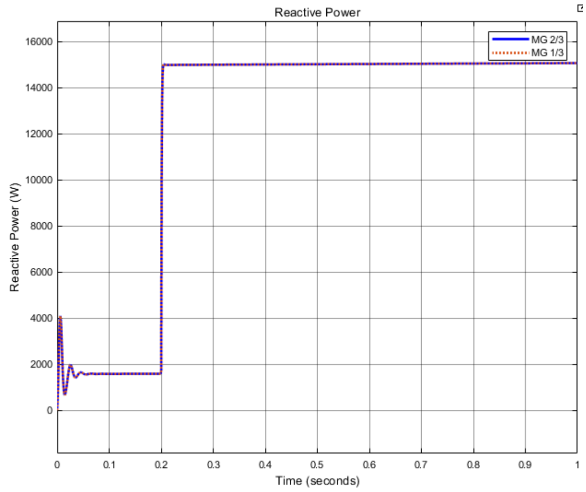

Figure 6: illustrates the reactive power adjustment before and after the additional load is connected.

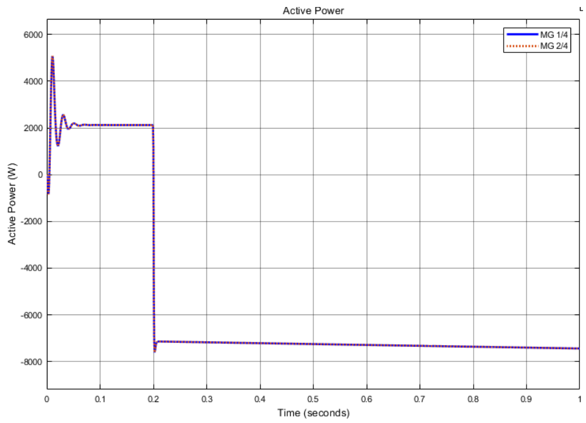

Figure 7: Illustration on active power adjustment before and after the additional load is connected.

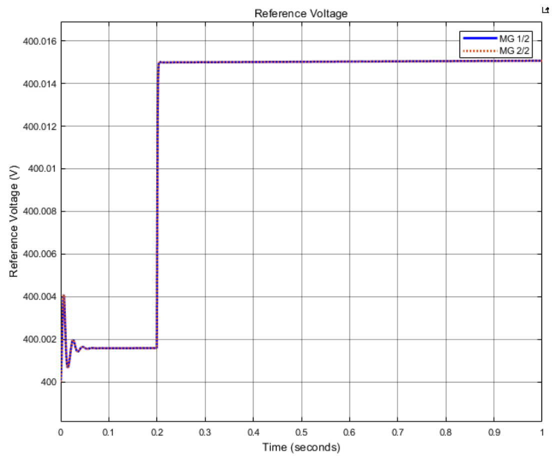

Figure 8: Illustration on reference voltage before and after the additional load is connected, the reference voltage is maintained around 400 V

Regarding the reference voltage, the droop control mechanism does not directly produce it but instead adjusts the voltage and frequency setpoints to match the desired operating conditions. In this case, the reference voltage is maintained at around 400 V as shown in Figure 8, which serves as the target voltage for the inverter output. The droop control algorithm modulates this reference to stabilize the voltage despite fluctuations in load (Keyvani-boroujeni *et al*., 2021). When the additional load is connected at 0.5 seconds, the droop control enables the system to maintain nominal operating frequencyas seen in Figure 9, showcasing the droop control's effectiveness in maintaining system stability under load changes.

Figure 10 provides insight into the voltage and current waveforms before and after the additional load is introduced. Upon connection of the new load, the voltage is observed maintained at the desired level however there is an increase in current. This change is indicative of the system’s response to the higher power requirement, as the inverter output adjusts to meet the demand by increasing current to sustain the additional load at the target voltage level.

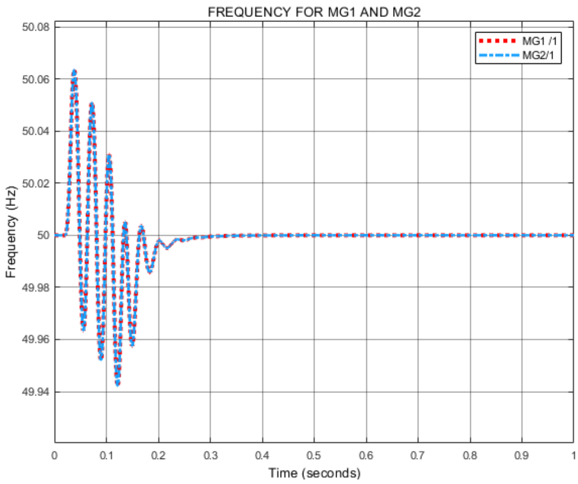

Figure 9: Showing frequency for both mini-grids one (MG1) and mini-grid two (MG2) before and after the additional load is connected

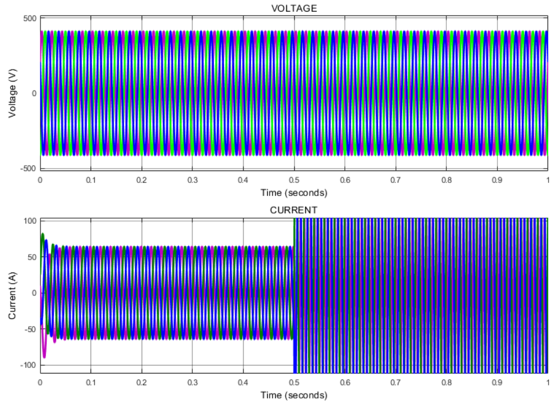

Figure 10: Voltage and current waveforms before and after the additional load is introduced.

Lastly, Figure 11 and 12 shows the reactive and active power outputs from both mini-grid one (MG1) and mini-grid two (MG2) before and after the additional load is connected. It is evident that both mini-grids produce similar active and reactive power levels, ensuring balanced contribution towards the added load. The even distribution of power between the two mini-grids reflects the system’s capacity to share loads effectively, facilitated by the equal ratings of the inverters. This proportional adjustment exemplifies how droop control enables the system to self-balance and respond to increased demands while maintaining overall stability and consistent power quality.

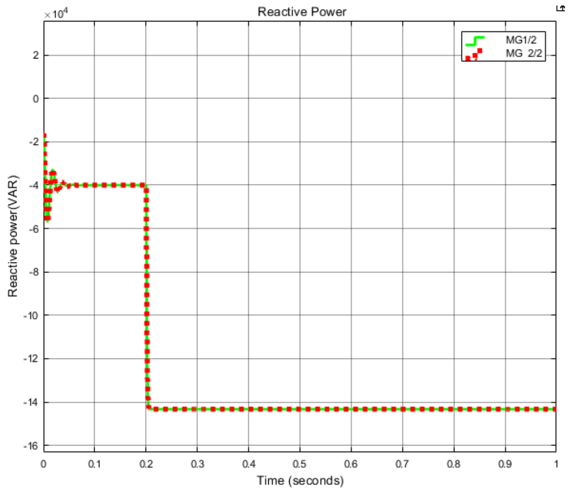

Figure 11: Reactive power management and mini grid contributions before and after load changes.

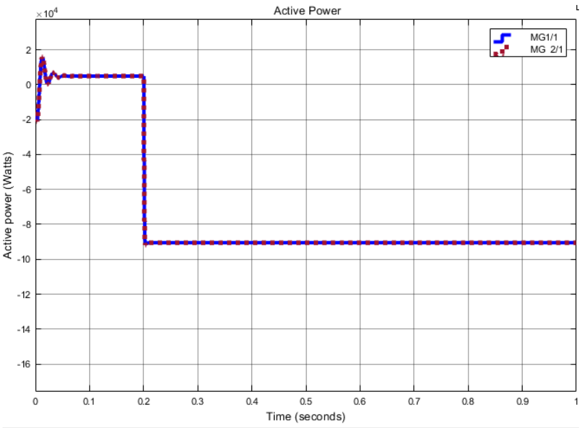

Figure 12: Active power management and mini grid contributions before and after load changes.

Results demonstrate that the droop control effectively, maintains system stability, ensures proper power sharing, provides good reference tracking, and manages frequency and voltage regulation and handles load changes smoothly.

CONCLUSION

An overview of droop control techniques used in mini-grids has been discussed. Two mini-grids close to each other geographically are clustered together. It is proposed to connect these two mini-grids with their inverters connected in parallel, each of which has a built-in droop control.
The analysis of the droop control strategy for clustered mini-grids demonstrated its effectiveness in maintaining proportional load sharing and frequency stability, essential for reliable mini-grid operations. The results showed that when the two inverters with droop control are connected in parallel, it is observed that the inverters automatically adjust their outputs based on system frequency, ensuring that power is shared among them in a balanced manner. Any fluctuations in load can be absorbed by the mini-grids connected in parallel. Consequently, droop management, a recommended control approach, greatly improves the efficiency and reliability of parallel-connected mini-grids. It plays a crucial role in stabilizing system frequency, providing proportional accurate sharing of active and reactive power and voltage regulation as demonstrated by the results presented.
Though the government of Uganda has proposed upgrading the two mini-grids (Kyamugarura and Kanyegaramire) applying this strategy after upgrading will further improve their power reliability and efficiency. Practical ramifications of these results highlight the necessity of ongoing assessment and modification of control schemes to meet the changing requirements of clustered mini-grids.
Future work should focus on exploring hybrid control approaches that combine droop control with advanced techniques, such as Model Predictive Control (MPC), to balance simplicity with enhanced performance. This combination could offer improved system response, greater resilience, and more efficient power management in interconnected mini-grids.

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