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Islanding Operation-Based Under-Frequency Load Shedding Scheme Considering Analytical Hierarchy Process in Microgrid System

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Abstract: Microgrid power distribution systems require robust and adaptive control strategies to maintain stability under challenging operating conditions. This study proposes an advanced Under-Frequency Load Shedding (UFLS) scheme for isolated microgrids by integrating the Analytical Hierarchy Process (AHP) for systematic load prioritization. The method ranks loads based on their criticality and applies staged shedding during under-frequency events. Simulation results in MATLAB/Simulink show that, without the UFLS scheme, the system experiences severe under-frequency, diesel generator overloading, and eventual system failure. In contrast, the proposed UFLS scheme successfully restores frequency to nominal levels, prevents generator overloading, and maintains voltage within ± 5% of nominal values. These results demonstrate the ability of the scheme to enhance system resilience, maintain power quality, and safeguard critical services in isolated microgrids.

Keywords: Analytical hierarchy process, Isolated microgrids, Load shedding scheme, Renewable energy, Under-frequency

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1. INTRODUCTION

Isolated microgrids powered by renewable energy sources such as solar and wind are increasingly deployed worldwide to enhance energy access, reduce greenhouse gas emissions, and improve system resilience [1]–[3]. This growth is driven by falling renewable technology costs, policy incentives, and the need for reliable electricity in remote or disaster-prone areas. Reports from recent international projects show that microgrids are not only expanding in developing regions but are also becoming critical components in modern, decarbonized power systems in developed countries [2], [4].

While microgrids provide environmental and operational benefits, the intermittent nature of renewable generation presents significant challenges. Variations in solar irradiance and wind speed can cause supply–demand imbalances, leading to under-frequency events, voltage instability, and in severe cases, total system collapse [4], [5]. Addressing these challenges requires fast, accurate, and adaptive control mechanisms that can safeguard system stability under highly variable operating conditions.

Under-Frequency Load Shedding (UFLS) is a proven protection strategy that disconnects loads when system frequency drops below preset thresholds to prevent cascading failures [8]. However, conventional UFLS often relies on fixed settings and rigid staging, which may not be effective in high-renewable microgrids [5], [6]. To address these limitations, researchers have proposed adaptive UFLS schemes that incorporate real-time monitoring, dynamic threshold adjustment, and predictive control. For instance, Wang *et al.* [9] proposed a method that integrates objective and subjective load weighting, while Wu *et al.* [12] developed an adaptive UFLS strategy incorporating wind turbine and UHVDC participation, improving stability in renewable-rich systems.

In parallel, multi-criteria decision-making (MCDM) techniques such as the Analytic Hierarchy Process (AHP) have been applied to load prioritization problems, enabling systematic ranking of loads based on criticality, economic value, and operational flexibility [13], [14]. Recent works have integrated AHP with fuzzy logic [10], stability indices [11], hybrid ANN–ACO algorithms [18], and TOPSIS [19], offering more targeted load shedding decisions. Despite these advancements, most existing research treats UFLS and load prioritization separately, leaving a gap for a unified framework that combines real-time protection with structured decision-making.

Combining adaptive UFLS with AHP-based prioritization creates a scheme that not only reacts to frequency deviations but also intelligently selects the least critical loads for disconnection, minimizing operational and social disruption. This integration is essential for future microgrids, especially in isolated contexts where every load decision has significant consequences for stability and service continuity.

The main contributions of this paper are as follows:
1. Development of a UFLS scheme tailored for isolated microgrids, integrating frequency deviation detection and staged load shedding.
2. Incorporation of the Analytical Hierarchy Process (AHP) for structured load prioritization, ensuring minimal disruption to critical services during under-frequency events.
3. Comparative simulation analysis under various disturbances, demonstrating the effectiveness of the proposed scheme in enhancing frequency and voltage stability.

In summary, this work addresses a critical gap by delivering an integrated UFLS–AHP framework for isolated microgrids. By combining adaptive protection with multi-criteria decision-making, the proposed scheme enhances operational resilience, ensures continuity of essential services, and supports the reliable integration of renewable energy sources into modern microgrid systems.

2. METHODOLOGY

2.1 Project Framework

2.1.1 Overall Framework

Figure 1 outlines the block diagram outlines a structured approach to developing a smart microgrid system with an emphasis on under-frequency load shedding strategies. By leveraging tools like MATLAB/Simulink, and applying methodologies such as the Analytical Hierarchy Process, the project aims to design a robust system capable of effectively managing energy distribution in isolated microgrids, thereby enhancing grid stability and reliability.

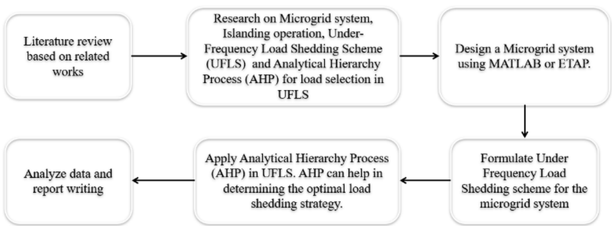

Figure 1. Block Diagram of Project Development

2.1.2 Simulation Flow

Figure 2 shows the flowchart of the simulation flow. To start the simulation process, a completely functioning microgrid model created with MATLAB/Simulink. To realistically show how an isolated microgrid works, the model includes important parts including generators, loads, control systems, and protection devices. After verifying a balanced generation–load state, three disturbance scenarios will be presented to test how well the microgrid works under diverse conditions. The first scenario examines the system's ability to withstand rapid changes in consumption by suddenly increasing the load requirement. In the second scenario, the microgrid is cut off from the main utility grid at a set time, so it must run on its own. The third scenario shows what happens when one of the power generators breaks down. This lowers the amount of electricity that can be generated and could make the system less stable. The simulation is run for each situation, and the system is monitored for errors or unstable response. If the simulation produces errors, such as non- converging result, or instability, the model is modified, and the simulation is run again until valid results are found.

Once valid simulations are obtained, the microgrid's frequency response under each disturbance is analyzed. The UFLS scheme is then optimized for staged, priority-based load shedding to maintain stability with minimal disconnection. System performance before and after UFLS is compared, focusing on frequency recovery, voltage stability, and system preservation, with findings summarized to highlight key benefits and areas for improvement.

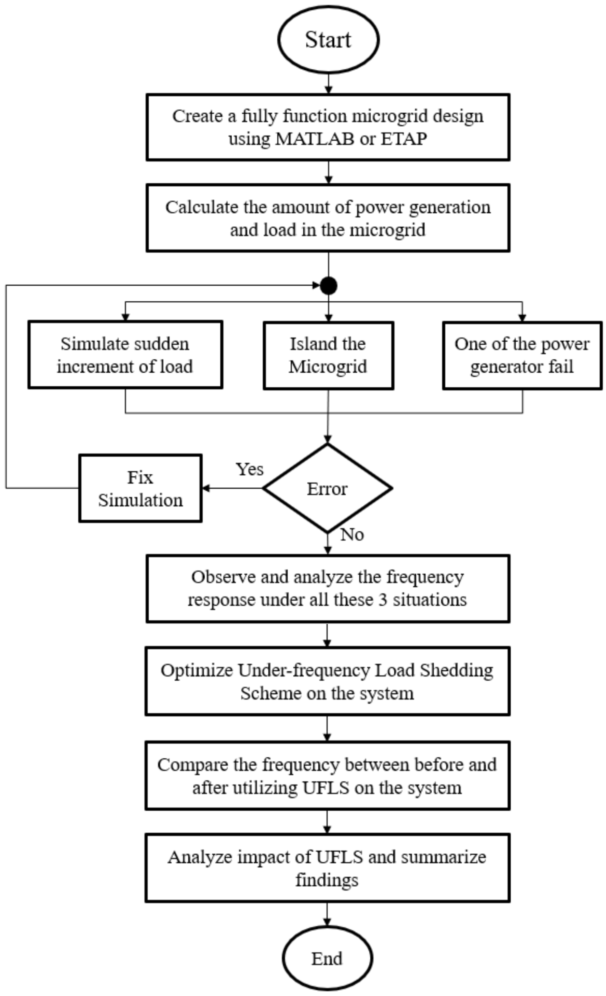

Figure 2. Flowchart of Simulation Flow

2.1.3 Under-frequency Load Shedding Scheme

Figure 3 explains how the UFLS Scheme works through a flowchart. It is supposed to be a fully automated control system that can detect the frequency thoroughly, and initiate UFLS automatically to restore under-frequency. The microgrid control system continuously monitors the frequency. If it drops below the normal threshold, indicating an imbalance between generation and load, a load-shedding scheme is activated. The system determines how much load needs to be shed and executes this in a predefined sequence to restore balance. Once the frequency returns to normal, the system resumes monitoring. If the frequency remains unstable after the initial shedding, the process repeats, shedding additional loads until balance is achieved between load demand and generation.

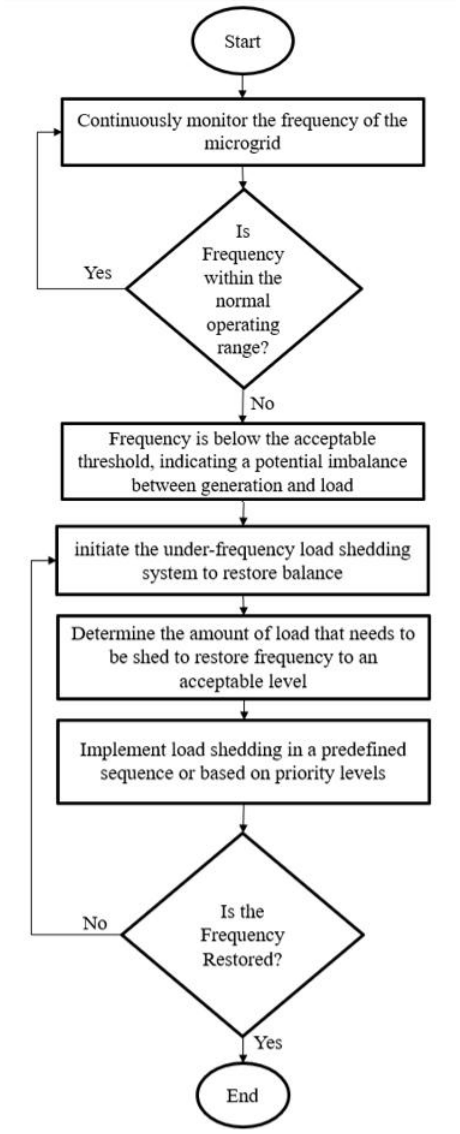

Figure 3. Flowchart of UFLS Scheme

Figure 4 illustrates the configuration and working principle of the frequency relay employed in the microgrid system. The relay block receives the microgrid voltage as its primary input, from which the system frequency can be derived. Since frequency is inherently embedded in the voltage waveform, the relay continuously monitors the variations of the voltage signal to estimate the instantaneous system frequency.

The measured frequency is then processed through a dedicated function block that compares the actual value with the predefined frequency thresholds. The relay output is represented as a binary signal, either high (1) or low (0), which is transmitted to the associated circuit breaker. Under normal operating conditions, when the system frequency remains within the specified threshold limits, the relay output stays high (1), allowing uninterrupted power flow between the source and the connected loads. However, if the system frequency deviates outside the permissible range, the relay output switches to low (0). This low signal acts as a tripping command that activates the circuit breaker, thereby isolating the load from the system to protect equipment and maintain system stability.

In this simulation, the nominal system frequency is set to 50 Hz. Both under-frequency and over-frequency settings are configured at 1% of the nominal value, corresponding to 49.5 Hz and 50.5 Hz, respectively. This narrow tolerance band ensures that even slight deviations in frequency are detected, allowing the relay to respond promptly. Such a setup is crucial in microgrid environments where frequency fluctuations are more likely due to the integration of distributed generation sources and variable load conditions. By implementing this relay mechanism, the system can prevent potential damage to sensitive equipment, enhance the resilience of the microgrid, and contribute to reliable operation during abnormal events.

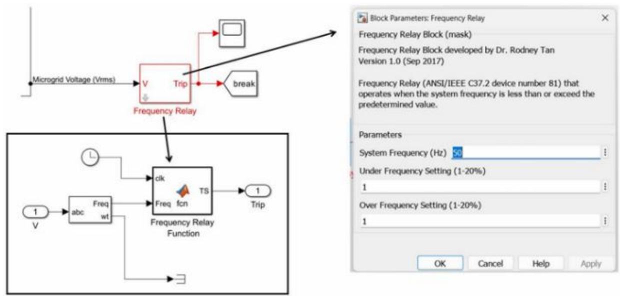

Figure 4. Frequency Relay Setup

Figure 5 illustrates the complete setup of the frequency relay system in the microgrid, where nine relays are installed and individually assigned to different types of loads such as residential areas, shopping malls, schools, factories, offices, universities, prisons, military bases, and hospitals. Each relay continuously monitors the system frequency and operates in a sequential manner, meaning that load shedding takes place step by step rather than simultaneously. This staged disconnection strategy ensures that less critical loads are shed first, while more important or sensitive loads are preserved for as long as possible, thereby maintaining stability and prioritizing essential services during frequency disturbances.

In addition, each relay is equipped with a light indicator that provides visual confirmation of its status. When a relay trips and disconnects its load, the corresponding indicator turns on, allowing operators to quickly identify which loads have been shed. This feature not only supports real-time monitoring but also assists in troubleshooting and post-event analysis by showing the order of disconnections. Overall, the system presented in Figure 5 highlights a structured and practical approach to frequency-based load shedding, improving both operational reliability and situational awareness in microgrid operation.

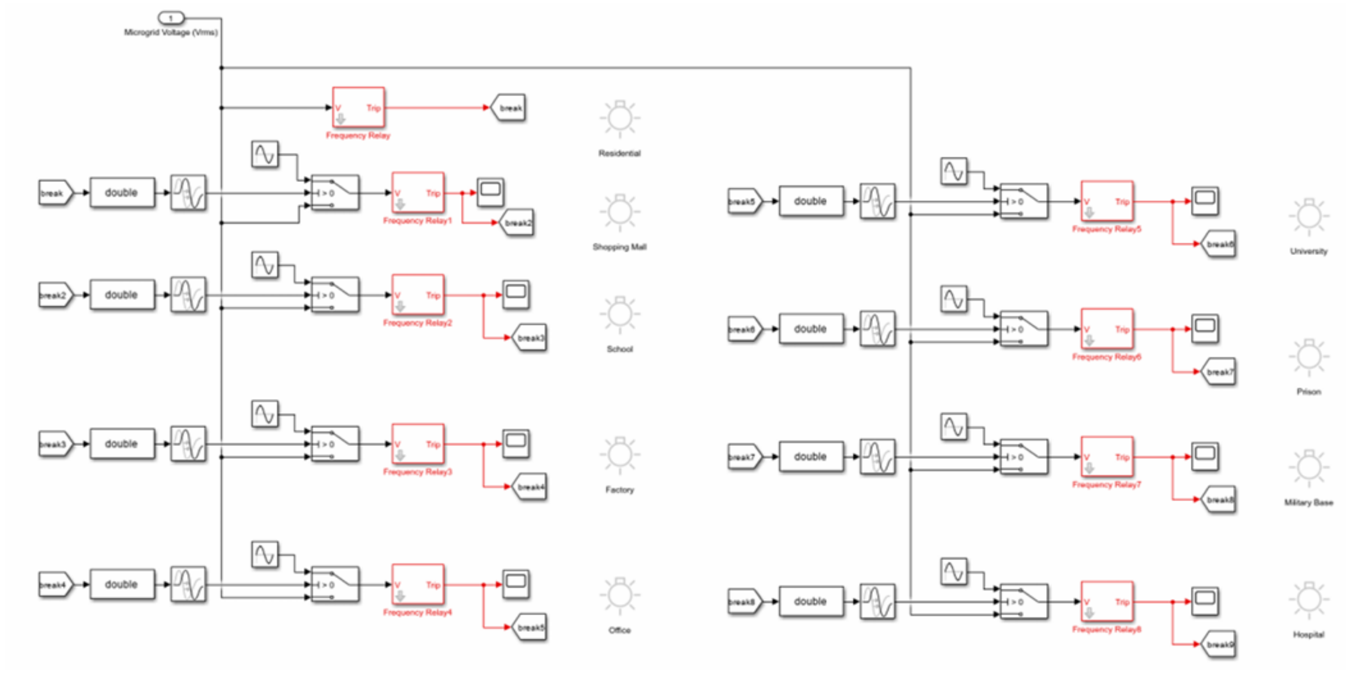

Figure 5. Complete Blocks of UFLS Control System

2.1.4 Analytical Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) was applied to determine the priority of loads for the under-frequency load shedding scheme. The process began by identifying the evaluation criteria which in this study, is the load importance.

A pairwise comparison matrix was then developed, in which each criterion was compared against every other criterion using Saaty's 1–9 scale, where 1 represents equal importance and 9 represents extreme importance of one criterion over another [13-15]. The comparison scores were based on expert judgment from experienced operators and academic sources relevant to load prioritization.

Table 1 shows an example of how the pairwise comparison works. The highlighted part is the value that the decision maker determines themselves while the non-highlighted part is the calculated value [13-15]. The decided values are then converted to the matrix.

Table 1. Pairwise Comparison Matrix [14]

	Criterion 1	Criterion 2	Criterion 3
Criterion 1	1	3	6
Criterion 2	$\frac{1}{C_{12}} = \frac{1}{3}$	1	5
Criterion 3	$\frac{1}{C_{13}} = \frac{1}{6}$	$\frac{1}{C_{23}} = \frac{1}{5}$	1

The pairwise comparison matrix was normalized, and the relative weight of each criterion was obtained by averaging the normalized values in each row. Consistency of the judgments was verified using the Consistency Ratio (CR), calculated as:

$$CR = \frac{CI}{RI}$$

where CI is the Consistency Index and RI is the Random Consistency Index. A CR value of less than 0.1 was considered acceptable [13].

After determining the criteria weights, the same pairwise comparison procedure was applied to the load groups to determine their relative importance with respect to each criterion. The final priority ranking was calculated by multiplying the criteria weights by the load group weights. This ranking was then used to determine the sequence of load shedding during under-frequency events in the simulation.

Figure 6 shows the flowchart of the process of how this method identifies the load shedding sequence. Firstly, decision-makers need to identify the criteria in the UFLS scheme. Then, conduct the pairwise comparisons between listed criteria. Matrices should be created based on pairwise comparisons, then derive priority vectors. Multiply the priority vectors by the original matrices to calculate the weighted sum for each criterion. Aggregate the weighted sum to obtain an overall score for each load shedding scheme and finally implement the chosen scheme in the microgrid. Make sure the scheme functions as expected, and if not, the process needs to be repeated until the desired result.

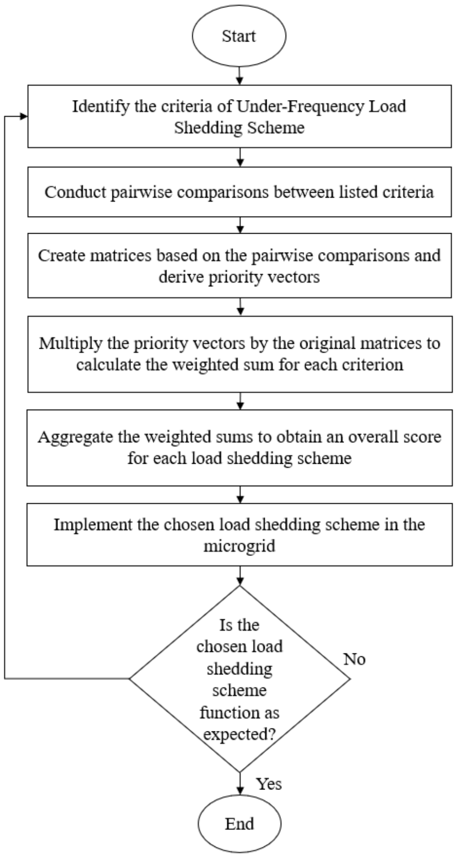

Figure 6. Flowchart of AHP

Figure 7 illustrates the overview of the decided goal, criteria and alternatives in this project. AHP is used for load selection in an under-frequency load shedding scheme. So, the goal of this project for sure is Rank of Load Shedding. Followed by the criteria, which are non-vital load, semi-vital load, and vital load. The alternatives are the loads under those criteria, which are shown in the figure. After thorough research and decision-making process, pairwise comparison matrix for the criteria is developed. The weight of importance of each criterion is determined by the calculation of AHP method.

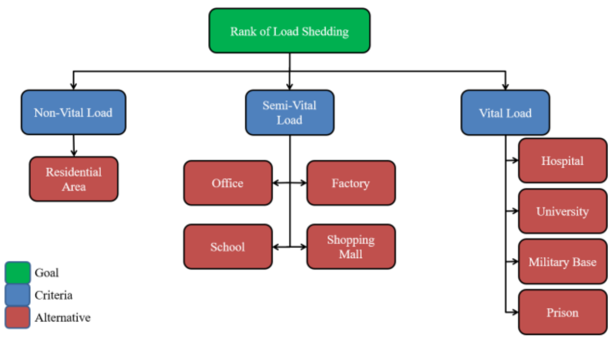

Figure 7. Analytical Hierarchy Process of the Project

The AHP method was selected over other multi-criteria decision analysis (MCDA) techniques such as TOPSIS, ELECTRE, or PROMETHEE because it allows for both qualitative and quantitative criteria to be integrated into a structured hierarchy, which aligns well with the load prioritization problem in under-frequency load shedding. AHP's pairwise comparison framework enables expert judgment to be incorporated directly into the decision process, while its consistency ratio check ensures logical coherence in the judgments [15], [16]. Furthermore, unlike ranking-based MCDA methods, AHP produces a normalized weight for each criterion and alternative, making it easier to directly integrate these weights into the control algorithm for the UFLS scheme [17-19].

2.2 Simulation Test System

Figure 8 illustrates the test system of this project simulation, which is a microgrid system, designed in MATLAB Simulink. The system is designed by referring to [20]. The system consists of four power generators which are main grid, diesel generator, photovoltaic, and energy storage system. There is a total of eighteen loads in this system, and it is divided into three categories, non-vital load, semi-vital load and vital load. A total of ten residential loads is categorized under non-vital load. Shopping malls, offices, schools, and factory are categorized as semi-vital load. University, prison, military base, and hospital are categorized under vital load.

There are ten circuit breakers in the system, each one has its own purpose. One is to isolate the system from the main grid, which is to create an islanding situation. Another is to break all ten residential loads, and the other eight are connected to each semi-vital load and vital load. If a tripping signal is sent to the circuit breakers, the load will break off from the system by the circuit breaker. This is to create a load shedding operation for the UFLS scheme.

Table 2 shows the simulation input data for power generation. The generation data are adopted from the simulation model described in [20]. Diesel generator has rated power of 1000kW, energy storage system provides a constant of 100 kW, while solar energy generates according to the equation in table. Basically, the generation of solar energy will change according to simulation time and has a certain time where it will constantly generate 250 kW. The overall generation amount of solar energy can be observed in Table 3.

Table 4 shows the simulation input data for load of microgrid system. Each resident in non-vital load is 50 kW, so the total residential load is ten times of it which is 500 kW. Total of semi-vital load and vital load is 350kW and 650 kW respectively. The total of all loads in the system is 1500 kW.

Table 2. Simulation Input Data of Power Generation

Type of Power Generator	Generated Power, kW
Diesel	1000
Solar	$P = 200\sin(50t) + 250$
Energy Storage System	100
Total	When $\sin(50t) = 1$ (Peak), Total = 1550 kW

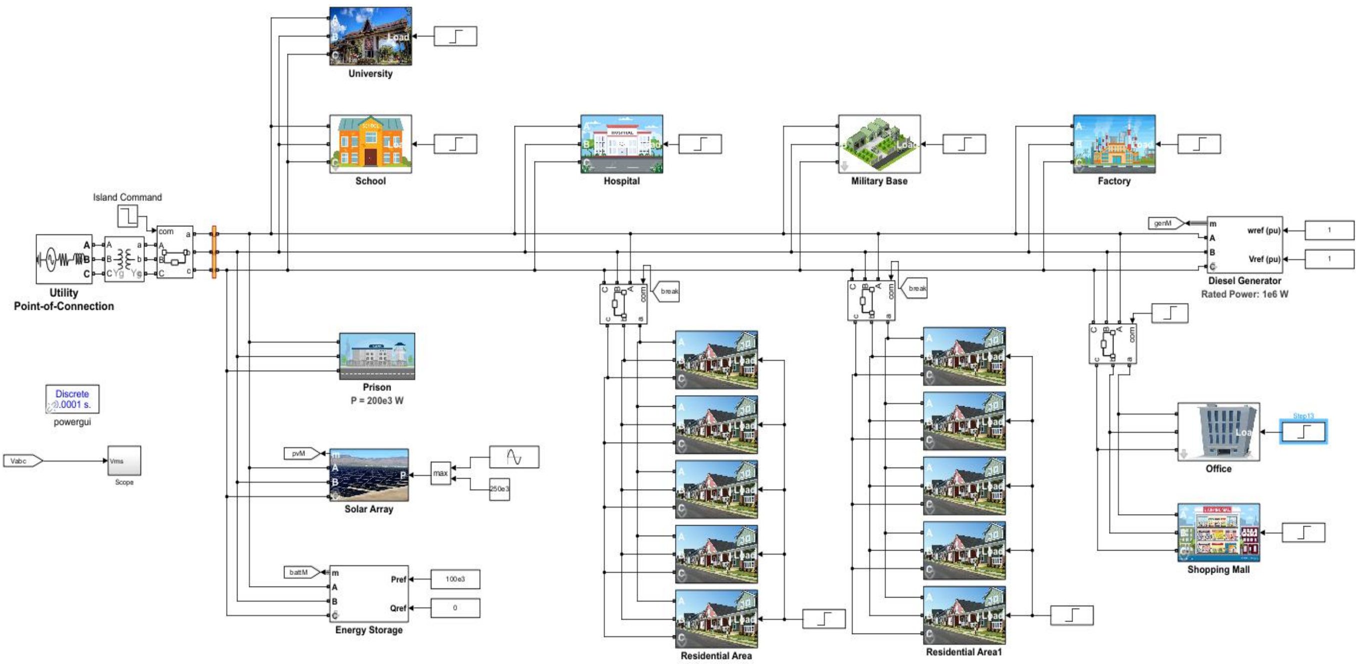

Figure 8. Test System of Simulation

Table 3. Solar Energy Generation

Time	Time in simulation (t), s	Power (kW)	From t = 14s to t = 24s (8pm to 6am)
7 am	1	297.5	Constant at 250 kW
8 am	2	342.4	
9 am	3	381.9	
10 am	4	413.8	
11 am	5	436.4	
12 pm	6	448.3	
1 pm	7	448.8	
2 pm	8	437.9	
3 pm	9	413.3	
4 pm	10	385.1	
5 pm	11	346.2	
6 pm	12	301.7	
7 pm	13	254.3	

Table 4. Simulation Input Data for Load

Type of Load		**Load (kW)**	**Total of each category**	**Total**
Non-vital Load	Residential	50	50 x 10 = 500 kW	1500 kW
Semi-vital Load	Shopping mall	100	350 kW	
	Factory	100		
	Office	50		
	School	100		
Vital Load	Hospital	200	650 kW	
	Prison	200		
	Military Base	100		
	University	150		

3. RESULT AND DISCUSSION

3.1 Formulating UFLS Scheme

Figure 9 shows the results of frequency relay during microgrid islanding from the main grid. Microgrid cannot meet the load demand using the remaining generators, so loads need to be shed to restore frequency stability. After tripping signals were sent, the frequency starts to recover and rise back to the system frequency, 50 Hz. After the frequency relay has output 0, it will not rise back to 1 to make sure the shed load will not be reconnected to microgrid. Frequency relay will only be reset for the next simulation. Table 5 explains the activity that happens in Figure 9.

Table 5. Discussion of Frequency Relay's Output

(1) Microgrid Frequency	(2) Frequency Relay
At T=5.1s, after islanding, frequency drops to 46.327Hz. Which is lower than nominal frequency (49.5Hz).	Tripping signal (0) is sent to circuit breaker at T=5.2s. This is due to the 0.1s delay set in the frequency relay.

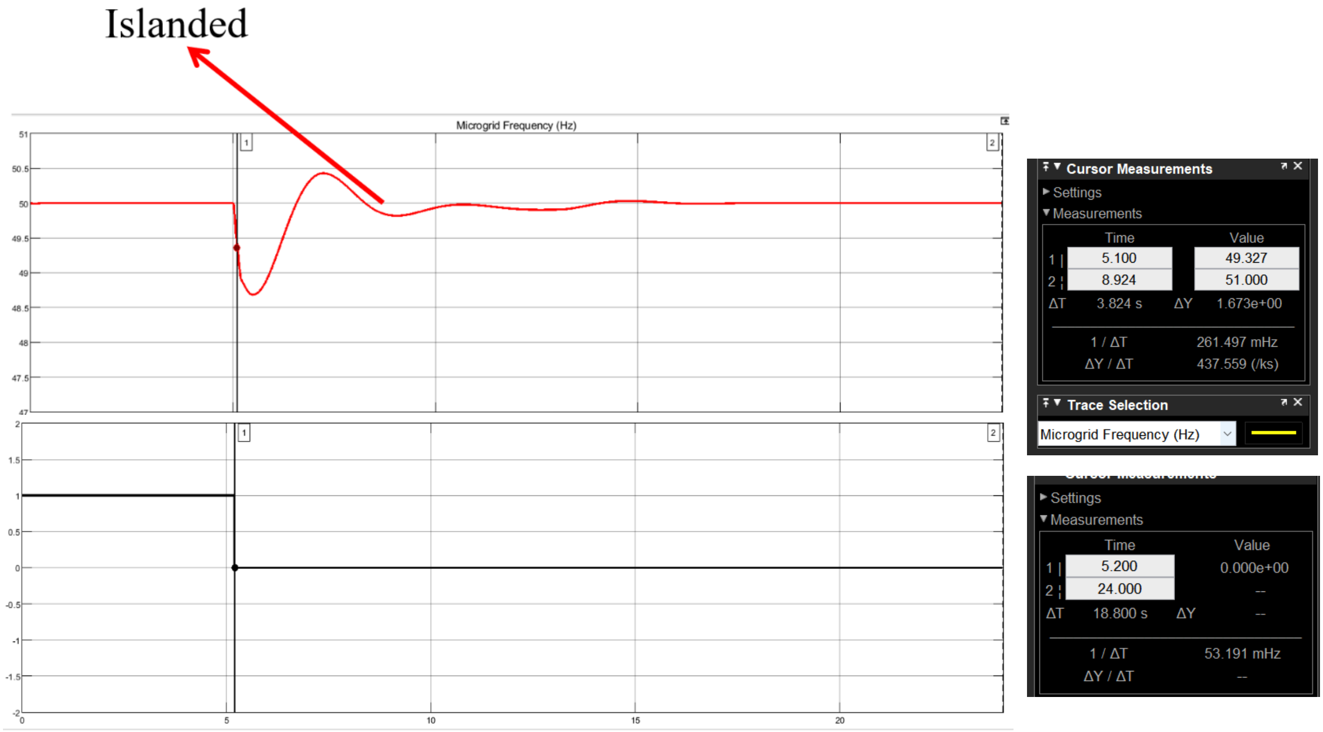

Figure 9. Output of Frequency Relay

3.2 Incorporating AHP for Load Selection

In this study, there are a total of three pairwise comparison matrixes. Table 6 shows the criterion in each of the matrixes. The first matrix is to determine the weight of importance between non-vital load, semi-vital load, and vital load. The second matrix is to determine the weight of importance between semi-vital loads. The third matrix is to determine the weight of importance between vital loads. Table 7, table 8, and table 9 illustrate the Matrix 1, Matrix 2, and Matrix 3 with their respective Consistency Ratio (CR). All the computed CR values are well below the recommended threshold of 0.1. This confirms that the pairwise comparisons are consistent, and the derived weights are reliable.

Table 6. Criterion in Each Matrix

Matrix	Criterion
1	Non-vital load, Semi-vital Load, Vital Load
2	Shopping mall, School, Factory, Office,
3	University, Prison, Military Base, Hospital

Table 7. Matrix 1

	Non-vital Load	Semi-vital Load	Vital Load
Non-vital Load	1	5	9
Semi-vital Load	1/5	1	3
Vital Load	1/9	1/3	1
CR	**0.0252**		

Table 8. Matrix 2

	Office	Factory	School	Shopping mall
Office	1	3	5	5
Factory	1/3	1	3	3
School	1/5	1/3	1	1
Shopping mall	1/5	1/3	1	1
CR	**0.0250**			

Table 9. Matrix 3

	Hospital	Prison	Military base	University
Hospital	1	5	3	7
Prison	1/5	1	1/3	3
Military base	1/3	3	1	5
University	1/7	1/3	1/5	1
CR	**0.0681**			

Table 10 shows the results of Analytical Hierarchy Process calculations using coding in MATLAB. The values shown are the weight of importance which sums into one. The higher the value, the more important the criterion. Same goes to the alternatives. The alternatives under the criterion of non-vital load do not need calculation since it has the same type of load, residential load. Figure 10 illustrates the hierarchy diagram of AHP with the weight of importance included.

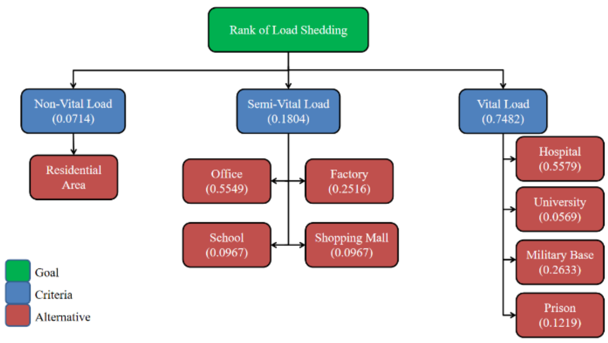

Figure 10. Hierarchy diagram of AHP

Table 10. Weight of Importance

		Weight of Importance	Total
Criteria	Vital Load	0.7482	1
	Semi-vital Load	0.1804	
	Non-Vital Load	0.0714	
Alternative 1 (Loads under semi-vital load)	Office	0.5549	1
	Factory	0.2516	
	School	0.0967	
	Shopping mall	0.0967	
Alternative 2 (Loads under vital load)	Hospital	0.5579	1
	Military base	0.2633	
	Prison	0.1219	
	University	0.0569	

With the information obtained, a ranking of load importance can be constructed. Table 11 shows the ranking of loads in the microgrid system, arranged starting by the least important load, residential area, to the most important load, hospital. The UFLS scheme should shed load according to this ranking.

Table 11. Ranking of Load Shedding

Type of Load	Load	Shedding Rank
Non-vital Load	Residential area	1
Semi-vital Load	Shopping mall	2
Semi-vital Load	School	3
Semi-vital Load	Factory	4
Semi-vital Load	Office	5
Vital Load	University	6
Vital Load	Prison	7
Vital Load	Military Base	8
Vital Load	Hospital	9

3.3 Analyzing System Performance

There are three different simulations that will be run to analyze system performance based on voltage magnitude and frequency response. First simulation runs without any condition or disturbances, just to show the voltage magnitude and frequency response of the microgrid system without any disturbances. The second simulation is to run the system and island it from the main grid. Simulation will be run with and without UFLS scheme. The last simulation has two disturbances, which are islanding and load increment.

3.3.1 Simulation 1: Simulation without disturbance

Simulation 1 is run without any disturbances, to see how microgrid system performs without disturbances. Figure 11 shows the result of this simulation, microgrid remains stable since there are no disturbances occurring in this simulation. The first row shows the microgrid frequency response, middle row shows the power generation by diesel generator, solar energy, and energy storage system. From the graphs, it can be observed that the microgrid frequency remains stable at 50 Hz, and the voltage waveform of microgrid stable at peak of ±5000 V.

3.3.2 Simulation 2: Islanding simulation

In Simulation 2, the microgrid islands from the main grid at T=5 s. The results are compared for two cases: with and without the Under-Frequency Load Shedding (UFLS) scheme. Figures 12 – 17 present the frequency, power generation, and voltage magnitude for both cases, while

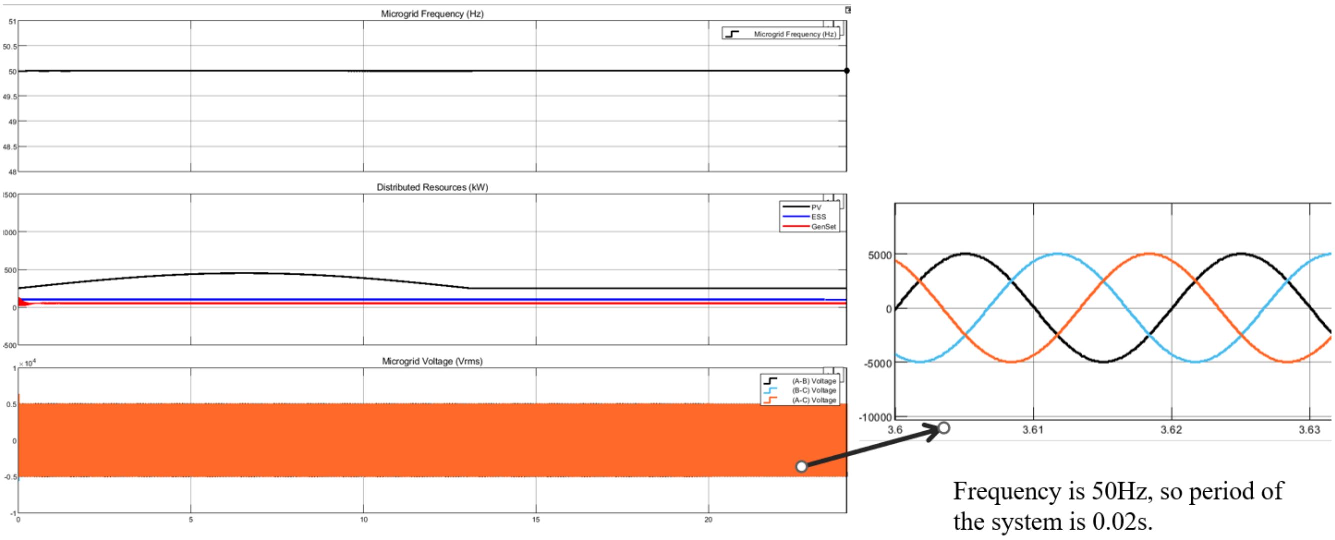

Figure 11. Result of Simulation 1

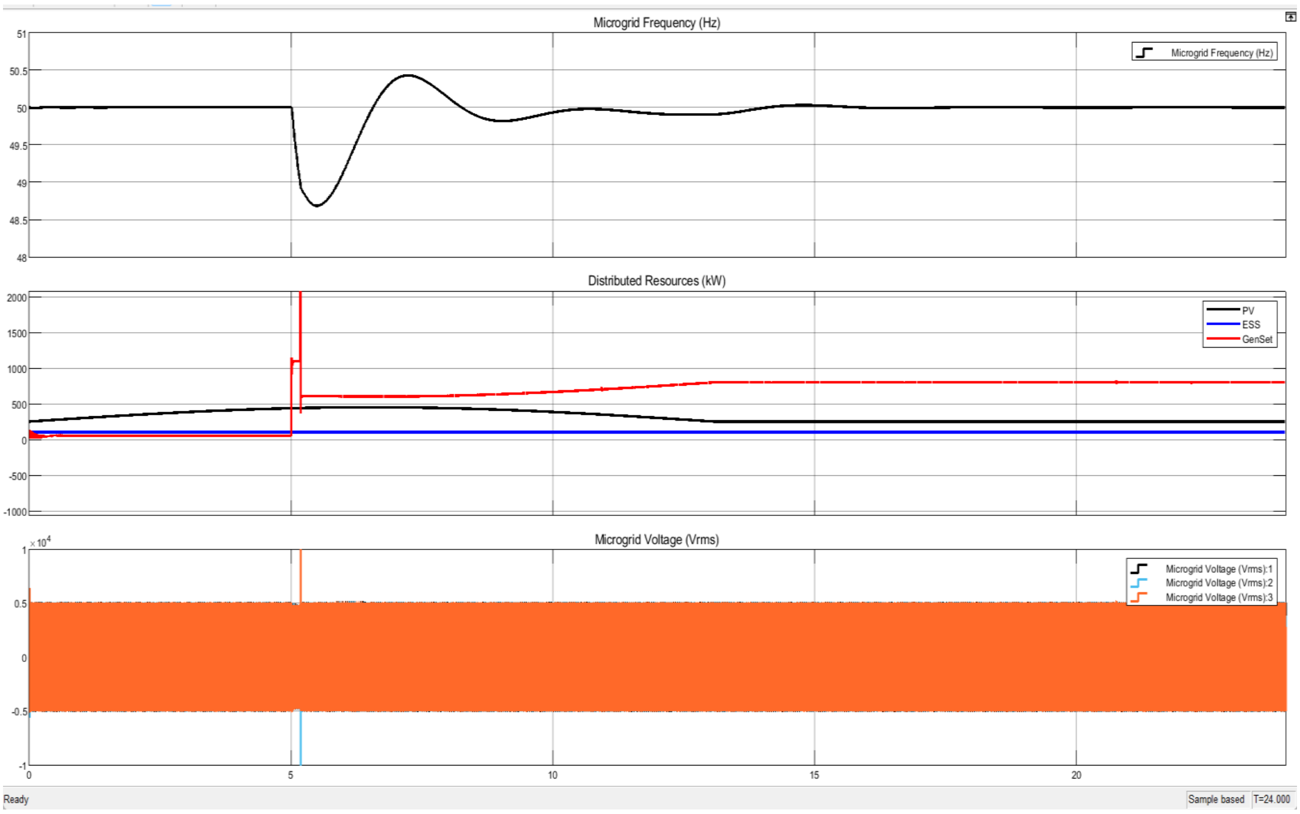

Figure 12. Result of Simulation 2 (Without UFLS)

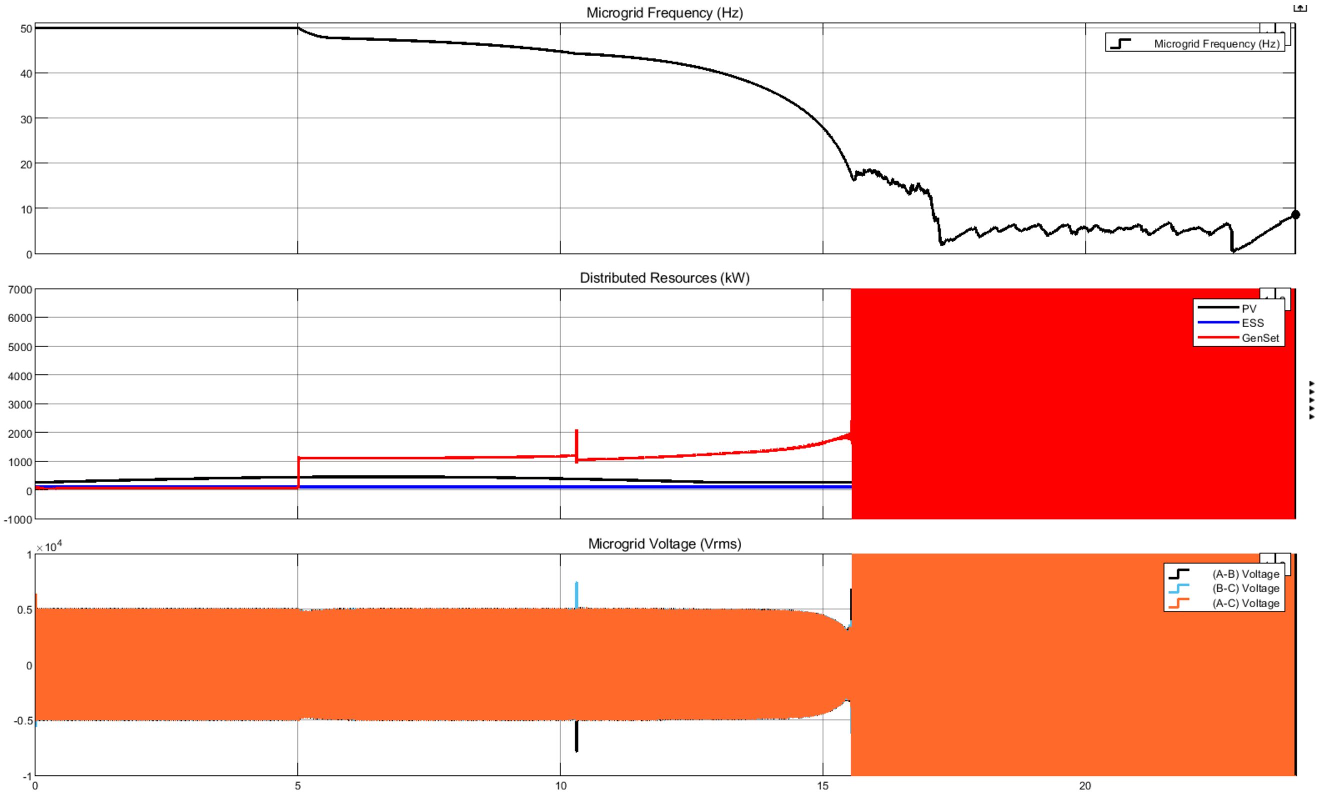

Figure 13. Result of Simulation 2 (With UFLS)

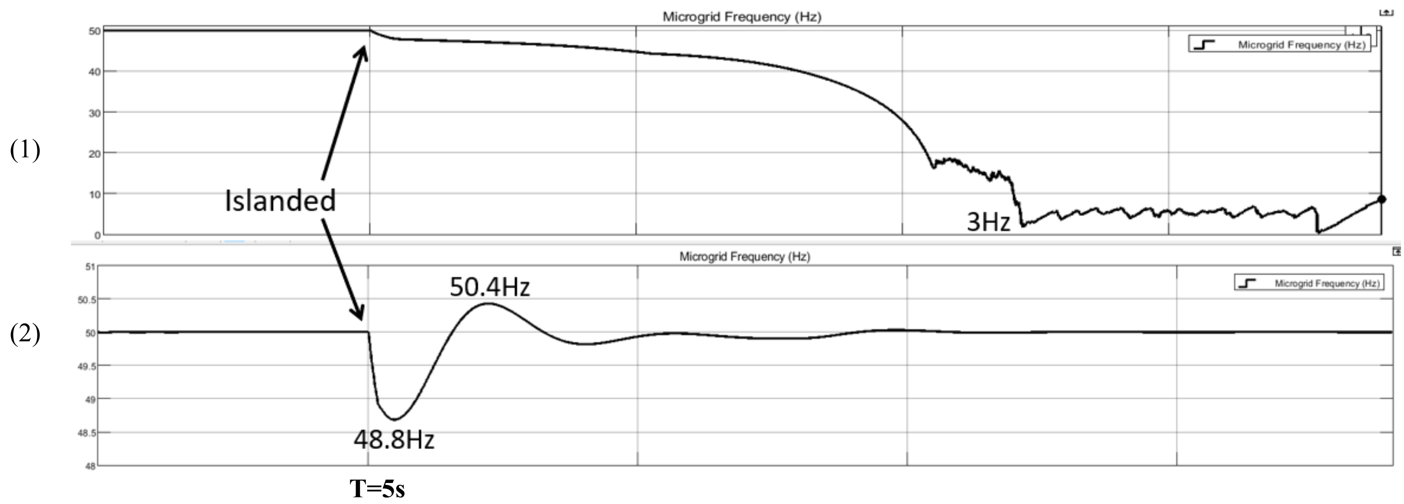

Figure 14. Microgrid Frequency Comparison

Table 12. Discussion of Frequency Comparison

(1) Without UFLS Scheme	(2) With UFLS Scheme
• After islanding, frequency starts to drop to 19 Hz. (From T=5 s to T=14 s) • Frequency proceeds to drop drastically to 3 Hz at T=15 s. From there, a zig zag pattern of frequency occurs until the end of simulation. • This indicates microgrids are facing underfrequency.	• After islanding, at T=5.1s, the frequency drops below 49.5 Hz. Frequency relay detected this and sent a tripping signal to circuit breakers. • Circuit breakers break connection between microgrid and certain number of loads. • Frequency takes time to recover, drops to 48.8 Hz at T=5.66 s overshoots to 50.4 Hz, then begins to settle down to 50 Hz.

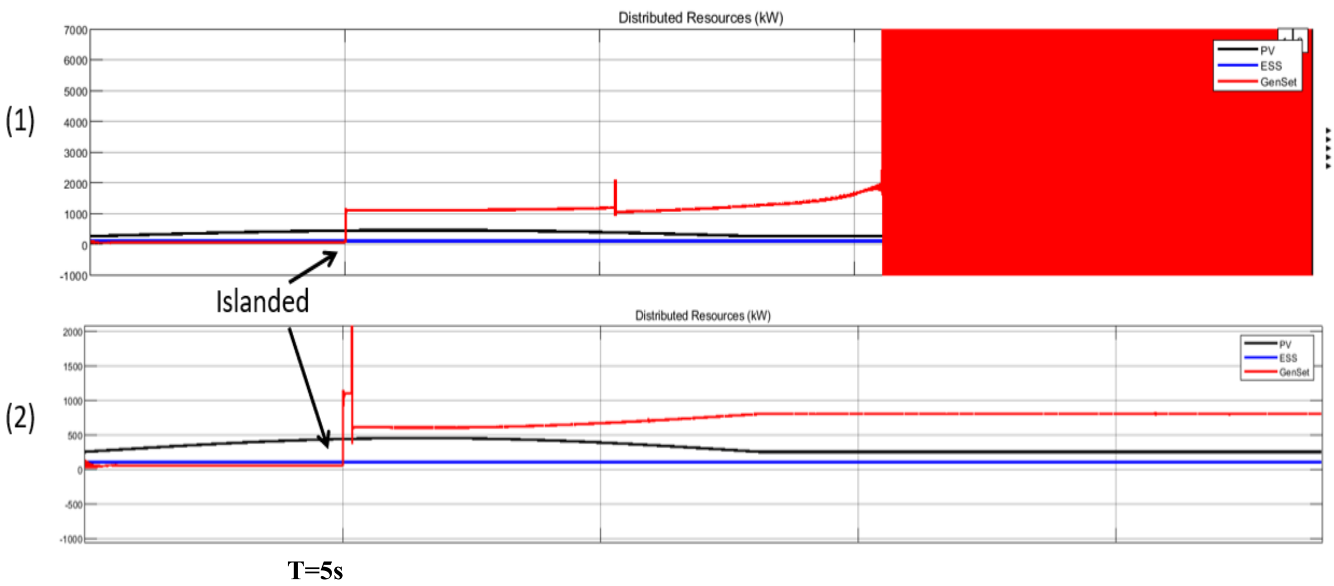

Figure 15. Power Generation Comparison

Table 13. Discussion of Generation Comparison

(1) Without UFLS Scheme	(2) With UFLS Scheme
• After islanding from the main grid, diesel generator tries to cover the load demand of microgrid system. Causes it to generate beyond its rated power. • This causes the diesel generator to fail. Fluctuations of diesel generator's power generation indicate that its system had failed.	• After microgrid islanded, at T=5.17 s, diesel generator generated more than its rated power to cover the load demand. • After the UFLS scheme shed loads from microgrid, diesel generators generate only the remaining amount of demand after PV solar and energy storage.

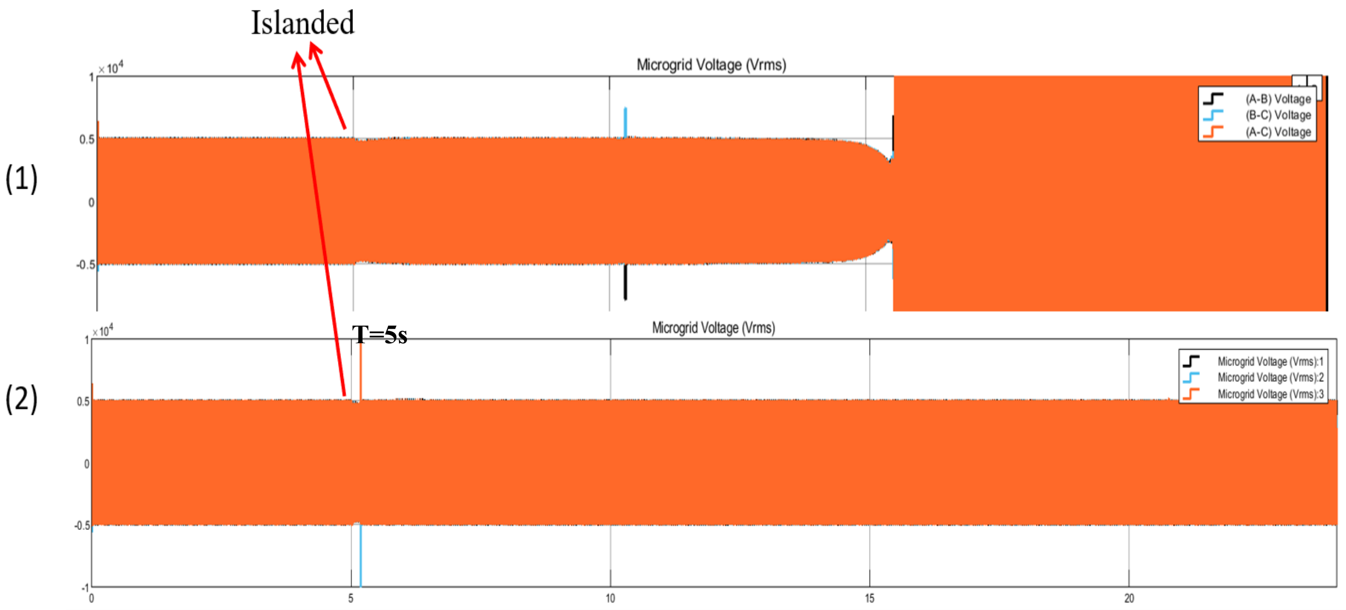

Figure 16. Microgrid Voltage Comparison Part 1

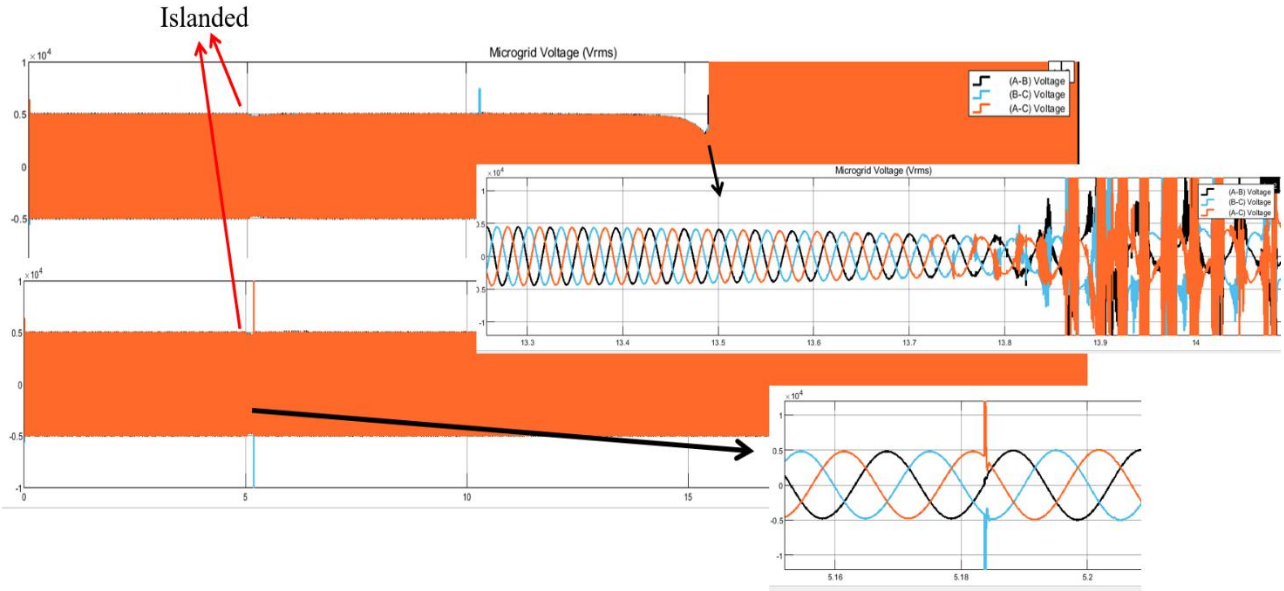

Figure 17. Microgrid Voltage Comparison Part 2

Table 14. Discussion of Voltage Comparison

(1) Without UFLS Scheme	(2) With UFLS Scheme
Voltage drops slightly to 3000V at T=13 s then proceeds to increase drastically to 10 kV and more. Since the voltage exceeds nominal voltage by 110 % - 120 %, this indicates that the microgrid is facing overvoltage.	At T=5.17 s, during island, the microgrid voltages shoots to more than 10 kV then instantly goes back to nominal voltage (5000 V) after load shedding operation. In the simulation of the UFLS control system, only the residential load was shed to restore microgrid stability after islanding. Figure 18 shows the frequency relay control system, where the light indicator for the residential area is turned on, indicating that the residential load has been disconnected. Since all other light indicators are off, the remaining loads remain connected to the microgrid.

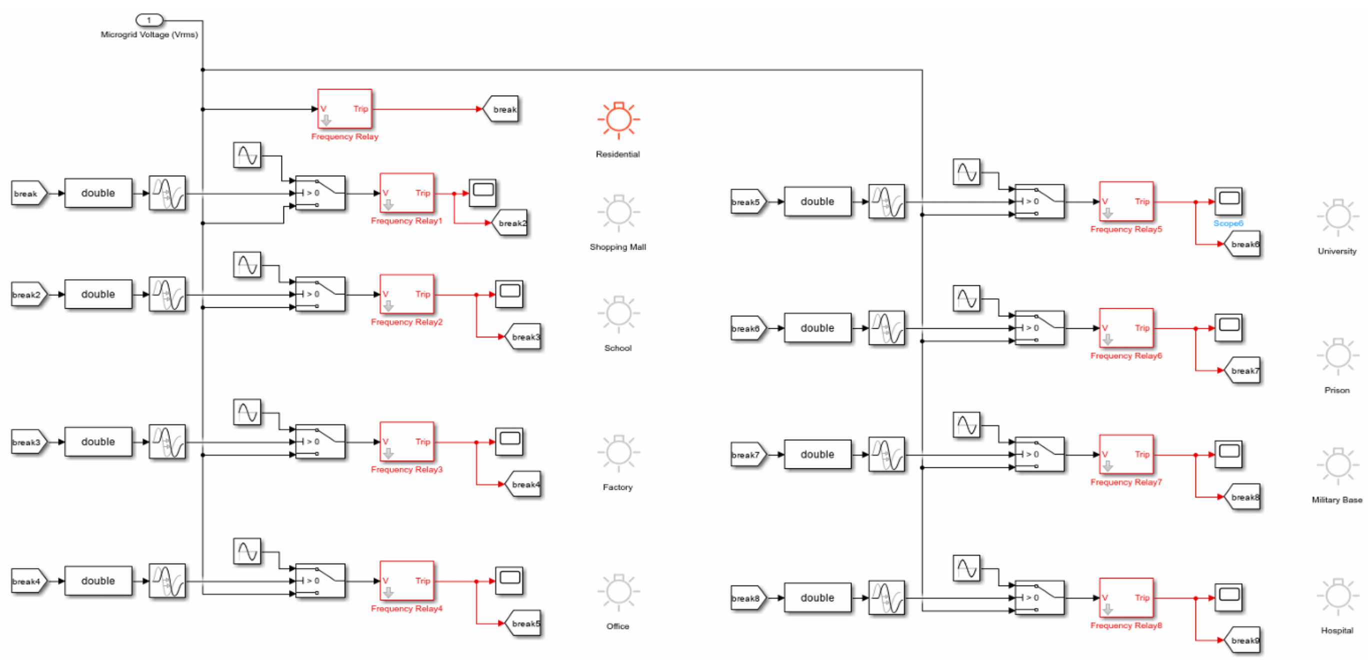

Figure 18. Result for Simulation 2 of Control System of UFLS Scheme

Tables 12 – 14 provide the corresponding discussions and numerical summaries.

3.3.3 Simulation 3: Islanding simulation with Load Increment

The Simulation will run for 40 seconds with two disturbances. Microgrid islanding at T=5 s, and load increment at T=15 s. Figure 19 is the result of this simulation. At T= 15s, the total load increases to 2100 kW. At T=5 s, after islanding, the frequency drops and recovers back to 50 Hz, same as in simulation 2. However, at T=15 s, after increment of load, the frequency drops again, and it takes longer to recover. The lowest point of frequency is at 48.2 Hz, then the frequency starts to rise and settles to 50 Hz. For power generation, the diesel generator tries to cover the load demand both during islanding and load increment. It generates normally right after load shedding took place. The microgrid voltage spikes up to more than 10 kV during islanding and load increment, then the voltage waveform is back to normal after load shedding.

Figure 20 shows the load that has been shed from microgrid system. 14 loads have been shed from microgrid, which are ten residential areas, shopping mall, school, factory, and office. Only the vital loads remain in microgrid system, which are university, military base, prison and hospital.

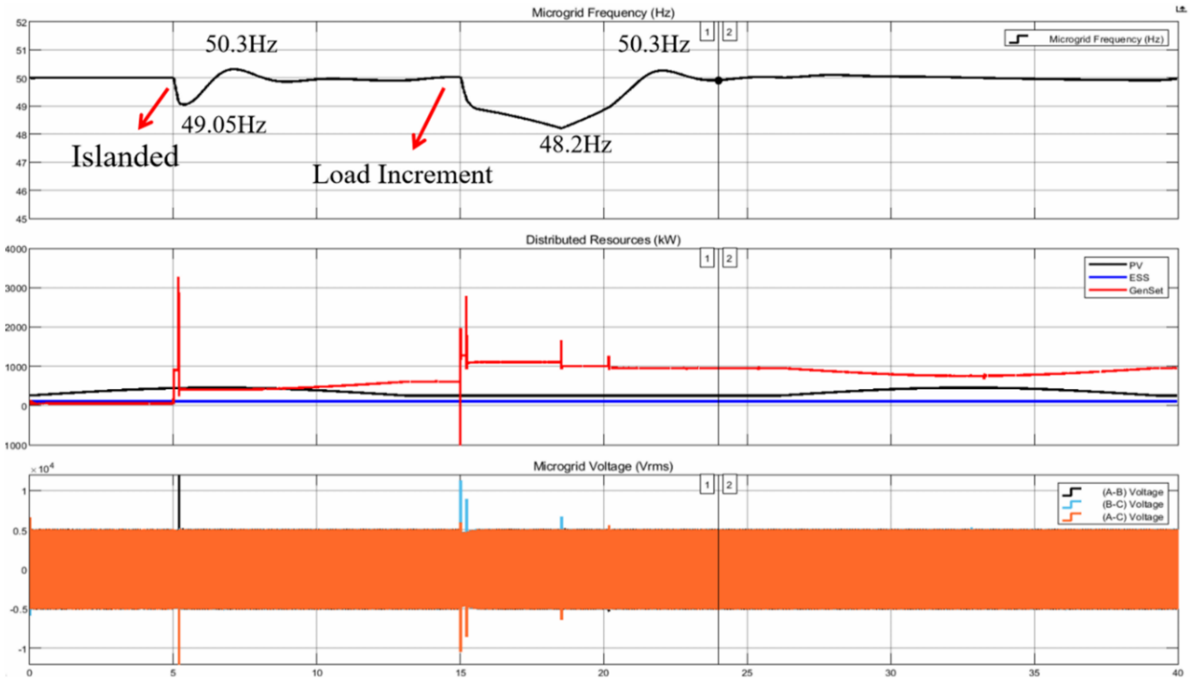

Figure 19. Result of Simulation 3

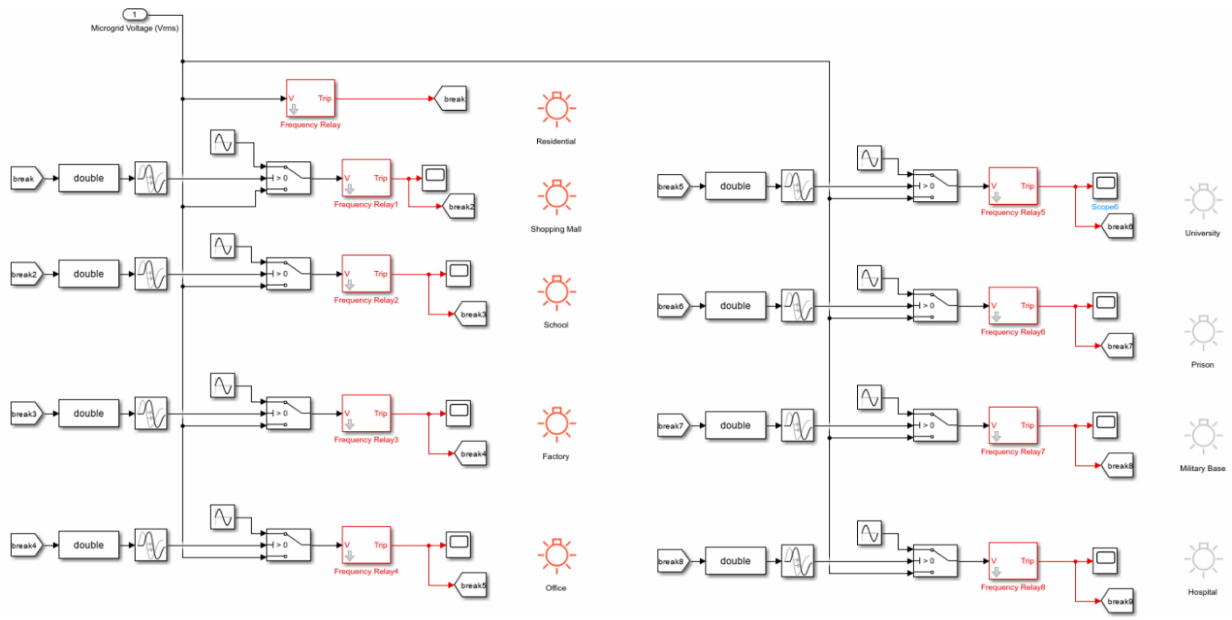

Figure 20. Result for Simulation 3 of Control System of UFLS Scheme

4. CONCLUSION

This study presented a UFLS scheme for isolated microgrids that integrates the Analytic Hierarchy Process (AHP) to systematically prioritize loads based on their criticality. The proposed approach ensures stable operation during under-frequency events while safeguarding vital services, thereby contributing a structured decision-making framework for microgrid load management. Simulation results demonstrate that, with the UFLS scheme, the microgrid can maintain operational stability during islanding events, avoiding system collapse that occurs in the absence of such a scheme.

Unlike conventional UFLS strategies, this method combines adaptive control with a multi-criteria prioritization process, offering both improved resilience and practical applicability for microgrid operators. The integration of AHP allows for transparent and justifiable load-shedding decisions that can be tailored to the specific operational priorities of different microgrids.

The practical implication of this work is the provision of a flexible UFLS framework that can be readily implemented in real-time control environments, supporting microgrids with varying demand profiles and critical service requirements. Future research could focus on scalability to larger and more complex microgrid configurations, integration with high-penetration renewable sources and variable storage systems, and experimental validation in a real-time simulation or hardware-in-the-loop environment.

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