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A Strategy to Balance Supply and Demand Fluctuation for RES-Based Microgrids in Isolated Area

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ABSTRACT

RES-based microgrids are often threatened by critical conditions due to variations in solar radiation in PV plants or wind intensity in wind turbines. This study provides a strategic framework to balance the supply and demand fluctuation for RES-based microgrids in an isolated area. By proposing the NILM, the load can be separately monitored for load shedding later when a critical condition occurs. NILM based on Data-Flow Programming (BDT) offers an appropriate NILM method to be applied to isolated areas. The infrastructure needed to implement the proposed method is related to building a monitoring station equipped with a set of computers and sensors so that the NILM algorithm can proceed. The load shedding and load priority algorithm are also presented in this study to achieve customer satisfaction. The method was developed by considering the limitations of infrastructure in communication, transportation, and other technologies in isolated areas. Therefore, it is necessary to have good cooperation between grid operators and consumers so that the proposed method can work properly.

1. INTRODUCTION

Indonesia has established several regulations regarding providing electricity based on Renewable Energy Sources (RESs) through the 2021-2030 Electricity Supply Business Plan (Rancangan Usaha Penyediaan Tenaga Listrik – "RUPTL") [1]. The future decision of the national electricity policy is to switchover from fossil fuel to RESs as a manifestation of clean and environmentally friendly energy. As the world's largest archipelagic country, Indonesia has many remote areas due to the spread of Indonesia's territory to several islands. This condition challenges electricity generation and electrical energy efficiency in those areas. In fact, renewable energy-based electricity generation in remote villages in Indonesia significantly reduces poverty and increases the number of small industries [2].

In line with the government's policy of increasing the use of renewable energy (RE) technology, among others, is to reduce fuel oil usage and increase the RE mix by 2025 to reach 23%. The conversion program of the diesel power plant to RE is one of the leading initiatives to reduce the use of imported fuel and increase generation efficiency, especially in isolated areas. Fossil fuel power plants will be replaced with RE generators, and RE technology will be utilized according to local energy potential. Employing local energy potential is predicted to reduce the time, effort, and costs required to transport fuel to the generating site.

The great benefits that will be felt by many parties, especially people in remote areas, after switching from diesel power to RESs, in addition to being environmentally friendly, 24 hours available electricity will open new economic development opportunities on a local scale. Several potential natural resources that are the mainstay of the region's commodities can continue to grow up because it is influenced by the availability of sufficient electricity to meet the local community's needs. While various RESs options can be considered for installing a microgrid in isolated areas, wind and solar power generation are the most suitable energy sources.

Wind and solar energy sources are inherently weather-dependent, so production rates vary locally. The energy system that carries the generator with these types of resources should be able to cope with the fluctuations. Compensation is conventionally done on the supply side by adjusting the production rates by conventional power plants. Managing both local power plants and consumers can provide additional compensation methods in energy management systems. Coordinating on both sides helps achieve the best results in energy efficiency and the resilience of the grid systems [3].

Distributed control as an approach to allow load-side participation has been proposed for various reasons, as listed in [4]. As part of frequency control, the concept of grid friendly appliances (GFA) is an essential enabler in distributed control. GFA becomes a specific standard to interface between individual loads and grid frequency. Several related research on GFA can be found in [5], [6], [7] and the references contained therein.

RESs and Demand Side Management (DSM) programs are vital for establishing a smart grid. DSM intends to efficiently manage electrical load consumption by engaging customers by offering price-based incentives

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and signals to change their consumption patterns or directly control their loads [8]. As a tool of DSM, Non-Intrusive Load Monitoring (NILM) can be employed in managing non-manageable renewable energy in some scenarios. NILM components refer to a single measurement point and software or algorithms to separate the energy consumption into individual loads or appliances. NILM is the best economical solution to solve the problem of monitoring electricity consumption [9].

NILM has been widely utilized to perform load shedding when the electrical grid is in a critical condition [10]. However, considering the limitations in remote areas, the architecture proposed in the previous study will not implement properly. The proposed technological infrastructure cannot be reached with suitable electrical conditions in remote areas.

In response to the electricity challenges in isolated areas, this study presents a strategy to overcome fluctuations in supply and demand using a NILM and load priority algorithm. The proposed strategy is specifically intended to be applied in remote areas. A method for prioritizing electrical appliances is also presented in this study.

The remainder of this paper is organized as follows. In Part II, the authors describe the supply and demand fluctuation in RES-based microgrids, followed by explaining the previous research in handling fluctuation in Part III. Part IV describes the proposed methodology. In part V, the study case is performed. Finally, the case study results are listed in Part VI, followed by the conclusions in Part VII.

2. SUPPLY AND DEMAND FLUCTUATION IN RES-BASED MICROGRID

Including Distributed Generation (DG) or microgrids on the utility grid presents another challenge to the electricity grid system. Excessive supply or penetration of the DG system into the utility power grid can cause various operational problems and violations, such as over and under voltage, excessive line losses, transformer and feeder overload, protection failure, and high harmonic distortion [11]. The main component of a microgrid is generation. Energy sources can be either renewable or non-renewable energy sources. An important note is that although RES-based microgrids (such as solar and wind) continue to increase, they cannot rely on 100% RE. It is due to the highly intermittent nature of both energies. Therefore, generation based on non-renewable sources (such as diesel units and micro gas turbines) is still being used.

A microgrid can operate independently (stand-alone/islanded microgrid) or be connected to the utility grid (grid-connected microgrid). Microgrids designed to operate independently are simpler in planning but susceptible to fluctuations with natural conditions when using RES in large portions. For this reason, microgrid operations connected to the utility grid are becoming an option in many places. In the case of a stand-alone microgrid, the difficulty in obtaining an energy balance between electricity demand and supply is indicated by fluctuations caused by intermittent both on the generation and consumption sides.

In residential-based microgrids, fluctuations on the demand side occur due to inappropriate load scheduling [12]. While on the generation side, RES-based microgrids have fluctuations that are much riskier due to interference from the wind when using wind turbines and solar irradiance when using photovoltaics [13]. Therefore, the use of 100% RES is still infrequent because it is intermittent from the aspect of the generation source.

An Energy Storage System (ESS) is used in the microgrid system to reduce the intermittent risk. The ESS system, such as using batteries and fuel cells, can increase the use of RE more effectively because energy generation units can be controlled. Controllable energy generation units and backup units such as diesel generators can efficiently balance the supply and demand of electricity in the microgrid integrated with RES.

3. STRATEGY IN HANDLING FLUCTUATION IN MICROGRID

The output voltage and frequency of the microgrid are maintained when parallelized with the utility grid. Therefore, stability studies for microgrids with small capacities are usually not required. On the other hand, when the microgrid is in islanded mode, it must maintain the balance of the supply and load fluctuations [14]. Many stability problems in microgrids have been classified, as shown in Figure 1.

Dynamic DMS has been developed and recognized as a strategic tool for achieving microgrid reliability. Various methods that have been offered widely can be implemented to achieve microgrid stability. One of the applications of dynamic DMS is the implementation of optimal load scheduling on electrical appliances at end-user premises [12]. By adjusting the on-time scheduling of the devices, a reduction in peak consumption can be realized to avoid the instability caused by the maximum capacity of the microgrid. In various studies, load scheduling also aims to minimize electrical energy costs [15] [16].

An IoT-enabled DSM has been developed, allowing electrical appliances to control and monitor [17]. The system gives users information about their energy consumption from a single platform. NILM was successfully applied to real-time data. The information is passed on to consumers via a smartphone. Because data is stored in the cloud, it is easily accessible and gives simplified data analysis. A system like this can assist the DSM program and make consumers aware of their energy use to increase energy efficiency. However, the infrastructure offered is unsuitable for application in isolated areas. Researchers in [10] presented fast and adaptive load control in innovative frameworks using IoT, Grid sense, and NILM technologies. Grid sense has been implemented as a pilot project in Jiangsu electricity grid, China. However, using a smart plug at every point consumes energy and needs additional infrastructure. In addition, determining the priority of the appliances automatically turned off when the critical condition was not performed.

Researchers in [18] have shown that adaptive Under Frequency Load Shedding (UFLS) is implemented in Lombok island, Indonesia. By tripping the biggest generator on the grid, this study resulted in the Lombok grid achieving a stable condition after 33.08 seconds at 49,988 Hz. However, there is no specific load selection in the load shedding scenario, so this scheme does not pay attention to customer needs and does not achieve customer satisfaction.

It is concluded from the cited works that a better scenario is needed so that the aspects in DSM are met to create grid reliability and customer satisfaction in isolated areas. Due to the many limitations, the proper infrastructure and technology can be well-developed to implement dynamic DSM in isolated areas.

4. METHODOLOGY

4.1 Proposed Method

Microgrids in remote areas generally have several layers, as shown in Figure 2. If possible, the utility grid or main power system will supply the microgrid system in an isolated area, which is desirable because connecting the microgrid to the utility grid will make it safer from stability issues. Layer 3 is a microgrid system divided into several district power systems. The district power system has the functions of dividing and distributing electrical energy to reach consumers who live in scattered areas. In layer 2, each district power system will provide electrical energy to several residents' houses. Furthermore, the last layer is layer 1, which is related to electrical loads or devices used in each house in isolated areas.

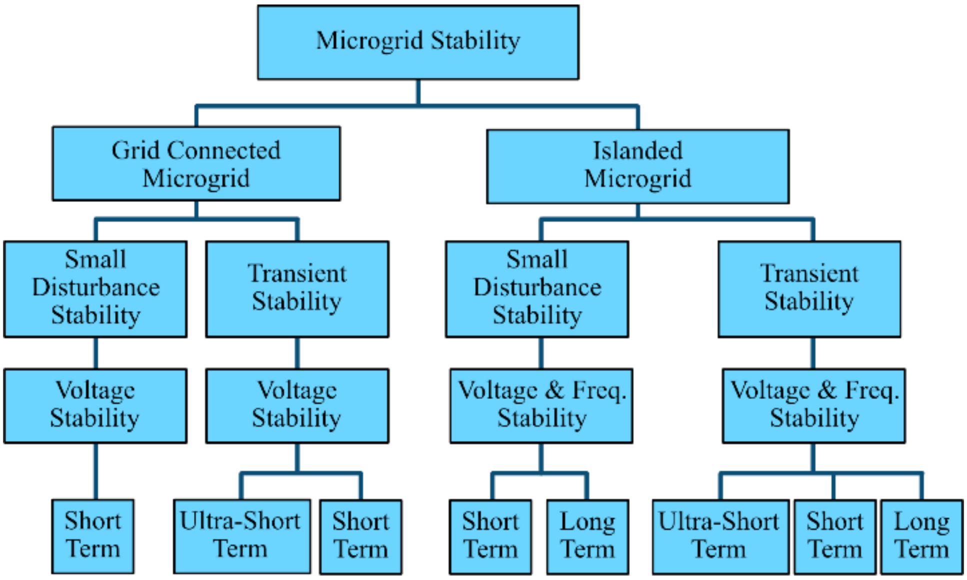

Fig. 1. Classification of microgrid stability.

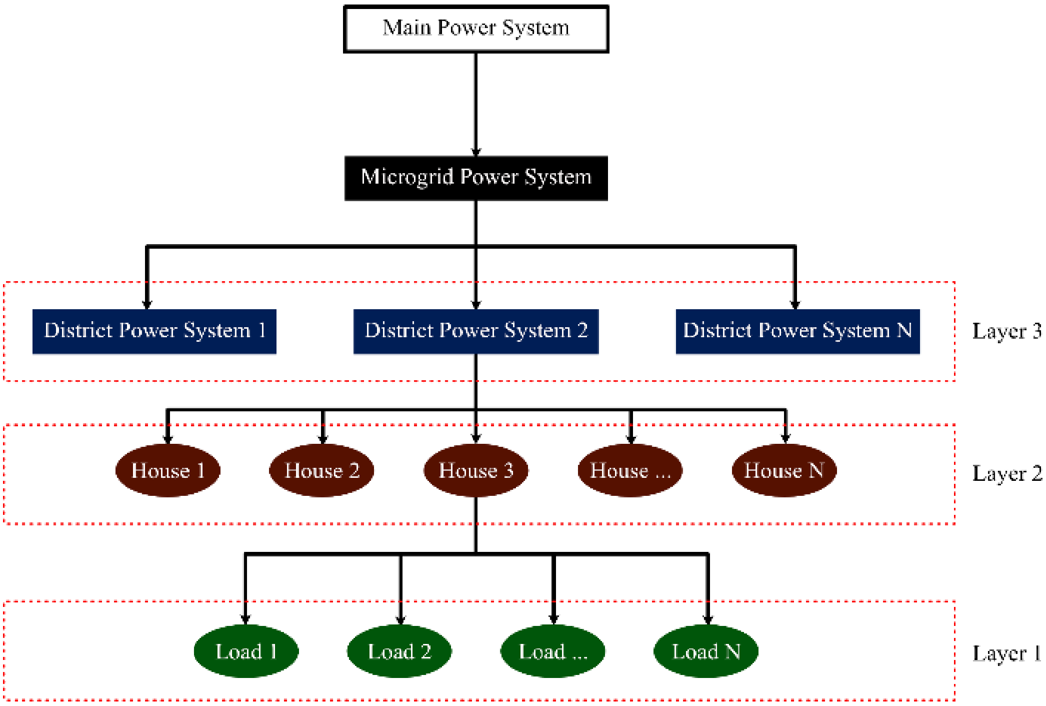

Fig. 2. Layers of microgrids. *Source: [31]*

The system architecture of the proposed method is shown in Figure 3. Three main parts of the electrification system in remote areas are generation, distribution, and consumers. Between the generation and distribution, there is a monitoring and controlling station. The monitoring station can monitor the generated electrical energy's performance and quality. It also controls the operation of the electrical system. There is an operator grid to play this role.

In the case of load shedding, the authors propose that the process is sequential from layer 1 to layer 3. In layer 1, NILM plays its function of disaggregating the consumer loads. Using NILM, electrical devices on or off can be identified using only a single meter in the monitoring station. Due to the technological limitation in the remote area, instead of using a smart plug as in [10], the load shedding process in layer 1 can only be done by consumers via notification from grid operators, especially when there is a critical supply on the microgrid. The communication method that can be used as an alternative is to send notifications via cellular networks or the internet to consumer smartphones. Therefore, this method needs good cooperation between the consumers and the grid operator.

In the lack of an internet connection case, as another alternative, Long Range (LoRa) technology can be used as a communication method between grid operators and consumers. LoRa allows very long wireless connections that can connect villages and cities. The LoRa protocol has been proposed as a low-cost and low-power messaging system [19]. LoRa can also be used to distribute information or as a media communication for disaster warnings in places lacking internet network infrastructure. However, in some instances, the LoRa network infrastructure's complexity creates another challenge and provides additional maintenance control and monitoring because it involves many components so that LoRa can be built [20]. Another solution widely applied in communication and monitoring devices is the Internet of Things (IoT). However, the development of this technology also requires an excellent internal network, which is usually challenging to find in isolated areas. LoRa can be combined with IoT to produce a communication system in rural areas with unstable network connections [21].

Layer 2 is the layer that involves every consumer's house. In the proposed scenario, there is no way to shut down an electrical house in the load shedding process. As a result, electricity in a house will be disconnected as a punishment if there is no good cooperation between a householder and the grid operator.

Load shedding at layer 3 is the last option before shutting down the entire microgrid. This stage will only occur when specific load shedding in another layer cannot provide better grid conditions. This situation can occur when supply conditions are highly critical or there is no good cooperation between consumers and the grid operator.

The decision of the grid operator to turn off specific loads using NILM at critical supply conditions is based on some considerations. Therefore, a load priority algorithm has been built in this study. In addition, weather forecasting is also utilized as an input for decisions in the load shedding process. The load priority algorithm will be discussed further in the next sections.

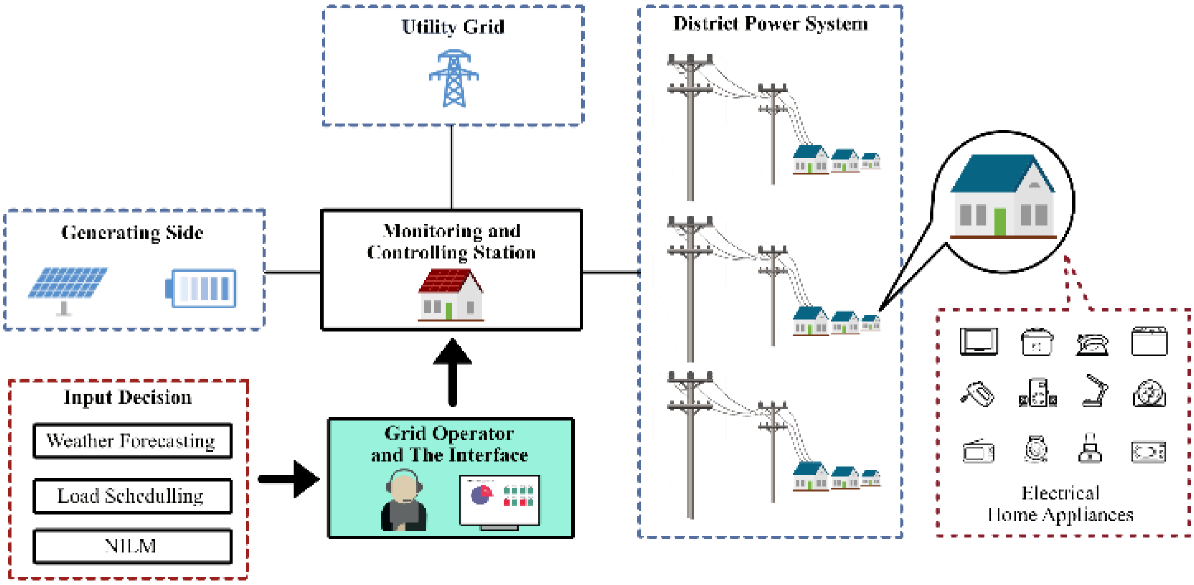

Fig. 3. The architecture of the proposed method.

4.2 Proposed NILM

The authors have proposed a NILM technique using the Bagging Decision Tree (BDT) algorithm based on Data-Flow Programming (DFP) method in [22]. DFP aims to reduce syntactic and cognitive barriers [23]. Therefore, this method has advantages in implementation in areas with limited human resources, especially in isolated areas. In addition, the use of DFP allows end-users to modify previously built programs. The performance of resulted NILM is good and competitive compared to other methods [24]-[26].

The power features are used in NILM: real power, apparent power, and reactive power. These features are detected from the NILM sensors installed in the monitoring station (Figure 4). When the on or off event occurs, the BDT algorithm processes the feature using DFP. The results will be displayed through the user interface and simultaneously monitor electrical parameters (Figure 5).

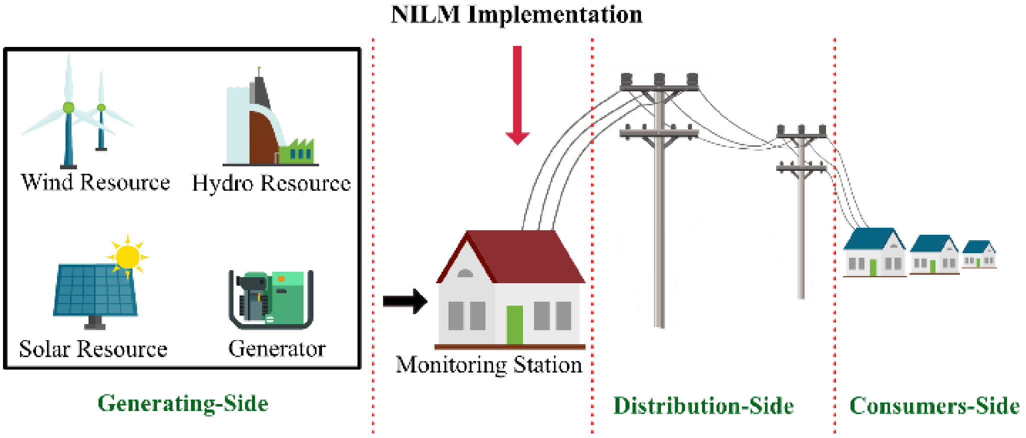

Fig. 4. NILM implementation. ***Source: [31]***

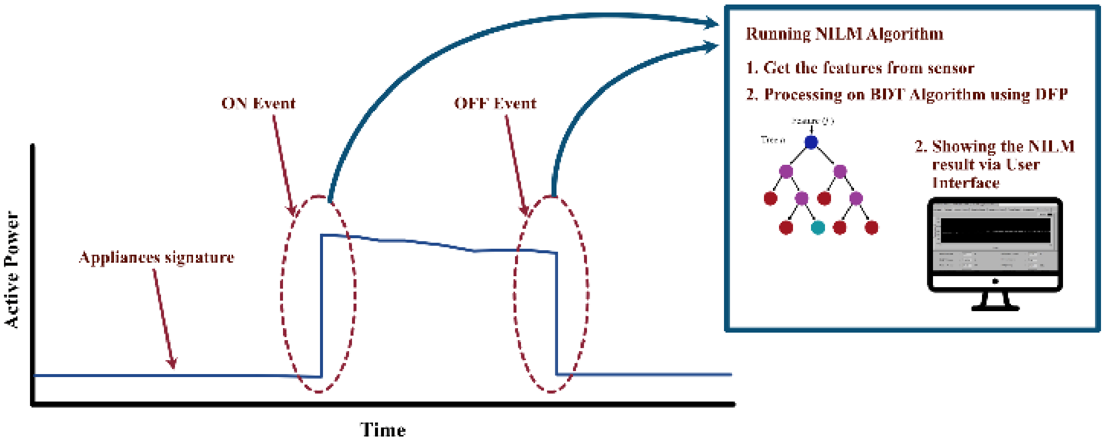

Fig. 5. Steps of proposed NILM.

4.3 Load Priority and Load Shedding

Equation (1), adopted in [27], is an objective function in this study and is formulated so that the load by the consumer must be less than or equal to the specified power limit. The power limit determination varies depending on the solar irradiance intensity and is determined by the grid operator. Moreover, the microgrid operational mode determines whether the grid is connected to the utility grid or operated in islanding mode.

$$A_u^T(t) \leq \left(\sum_{u=1}^{U} \partial * P_u^{(L)}(t) \right) \tag{1}$$

where,

$$\begin{Bmatrix} \partial = 1 & if, M \neq I \\ 0.5 \leq \partial \leq 0.9 & if, M = I \end{Bmatrix}$$

$A_u^T(t)$ is the total interruptible load T of user u at t time; U is the total users; I is the islanding operation in the grid; $P_u^{(L)}(t)$ is the power limit of user u at t time; ∂ is the limiting factor (provided by grid operator) and M is the operational mode of the grid.

In order to determine the type of loads in the process of load shedding decisions, electrical appliances are divided into several categories: essential, non-essential, and thermal loads [28]. Essential loads consist of fixed loads that are most needed and must be met at a specific time. Non-essential loads can be released in cases where the energy demand of the microgrid cannot be met. At the same time, thermal loads give grid operators the flexibility to shift or manage load profile characteristics on a day-to-day basis through the load scheduling process.

The essential loads can be changed to non-essential at any time and in any weather. For example, room and garden lights are an essential load in the evening but non-essential in the day. Fan and air conditioners are essential in hot temperatures but non-essential in the rainy season.

In the proposed method, the consumer carries out the determination of load priority. However, grid operators have the decision input to send turn-off commands to consumers about specific types of electrical home appliances that should be off in the load shedding process. The flow chart in load shedding is shown in Figure 6.

We must note that the electrical appliances most needed by customers are the highest priority. To find this out, grid operators can assume that the electrical devices that were last turned on during the islanded operation mode are the appliance most needed by consumers. Thus, turning off those electrical appliances can be avoided in this case.

The flowchart below is based on a load shedding scheme consisting of a Battery Energy Storage System (BESS) in a microgrid. The State of Charge (SoC) of BESS indicates the battery capacity. ΔSoC is the rate of changes in SoC. If the ΔSoC > 0, it means the battery is charged. Meanwhile, if the value decreases quickly, then most of the load consumes the battery without being balanced by charging the BESS.

The microgrid system will perform the load shedding in islanded mode and the critical condition generation. The SoC status of BESS will be a decisive step on whether the grid operator will shed the load. The load shedding process will be executed if ΔSoC < 0. By using NILM, the grid operator will know which devices are currently active so that the grid operator can request the consumer to turn off the load according to the criteria provided by the grid operator. The criteria are consecutive from non-essential loads, thermal loads, to essential loads. If the release of non-essential loads is sufficient to keep the grid stable, the load shedding process will stop. Nevertheless, if not, the load shedding process continues to turn off the district power system.

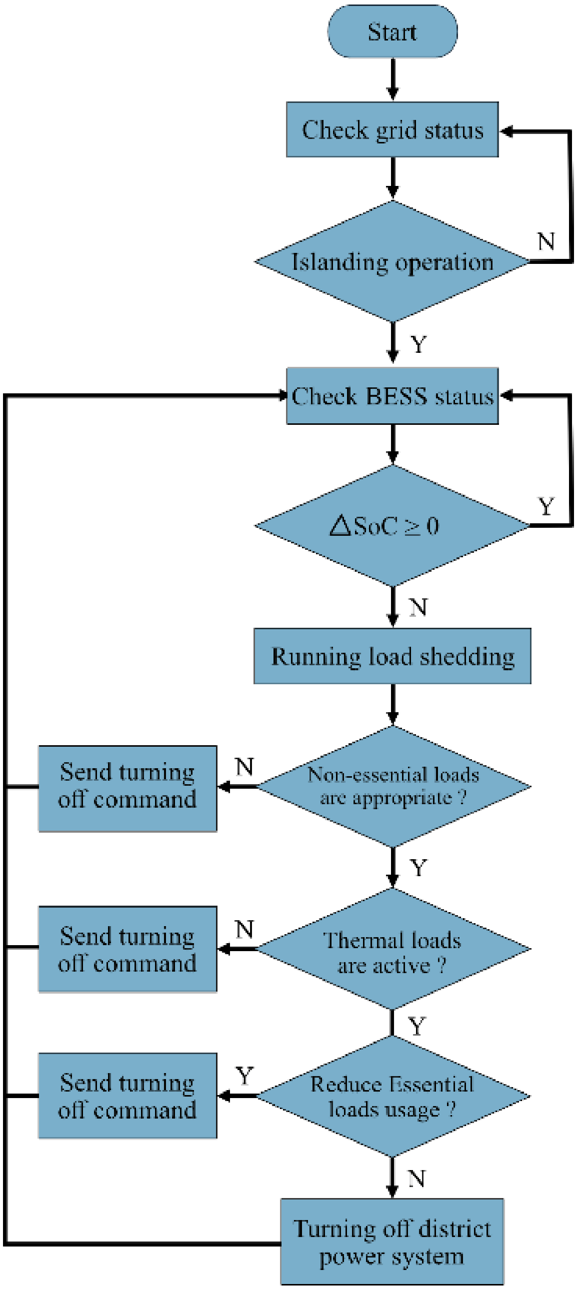

Fig. 6. The flowchart in load shedding. ***Source: [31]***

5. CASE STUDY

A case study on load shedding that corresponds to a fluctuating critical condition in Indonesia is presented. This experiment was conducted according to the microgrid configuration consisting of the utility grid, a PV plant, a BESS, inverters, transformers, and loads. The scheme is when islanding occurs, meaning the microgrid is not connected to the utility grid. Figure 7 describes the microgrid configuration and its specifications in this case study.

The analysis is carried out using Typhoon HIL software which can simulate according to actual conditions. Solar irradiance data is needed as input to the PV plant. Based on a solar report from the World Bank Group, Indonesia has good solar radiation potential, as in Figure 8 [27]. The solar irradiance data is then employed in the simulation. This simulation analyzed the microgrid performance based on the average Global Horizontal Irradiance (GHI) and minimum GHI data. Afterward, the microgrid condition is simulated before and after load shedding according to the architecture and framework proposed in this study.

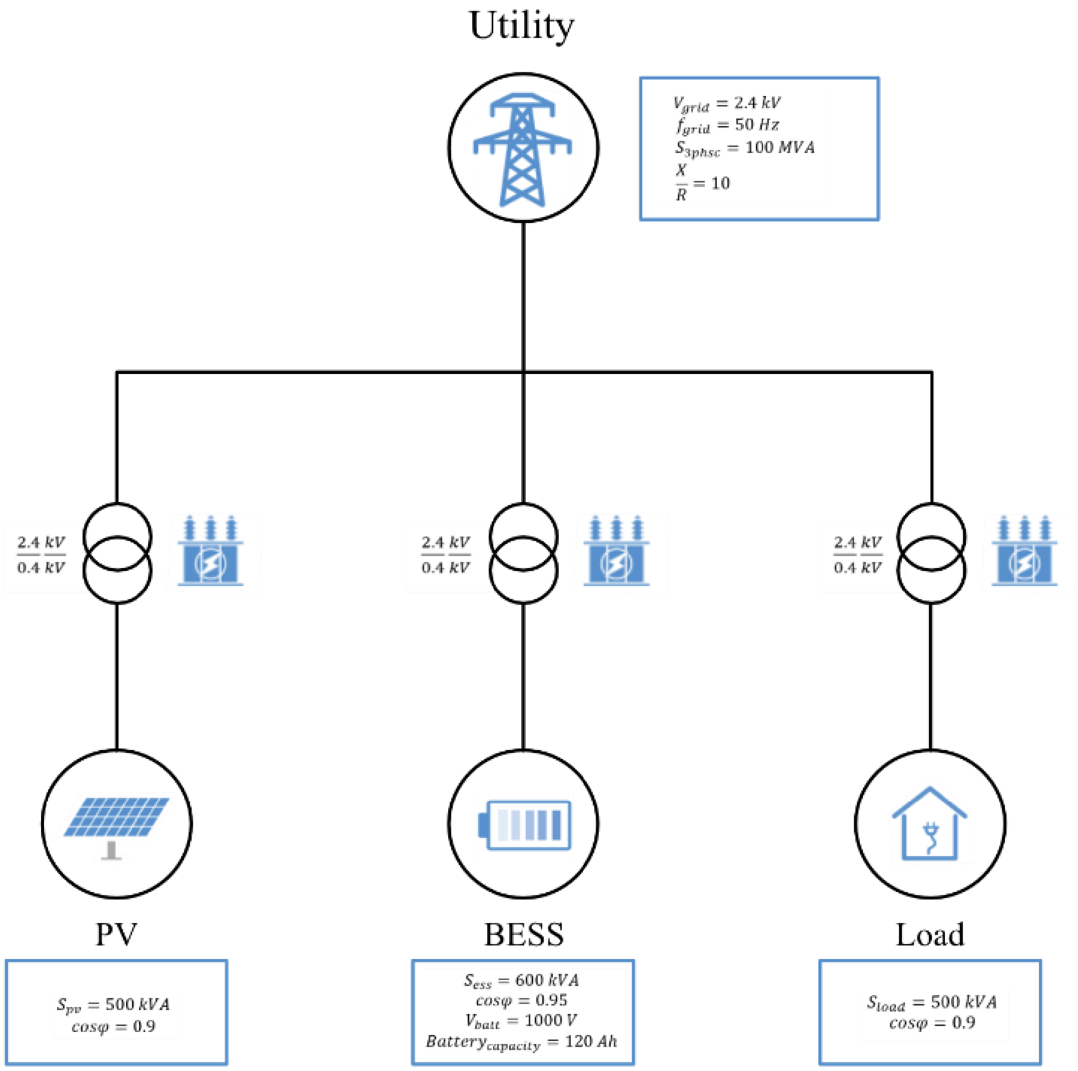

Fig. 7. The microgrid configuration.

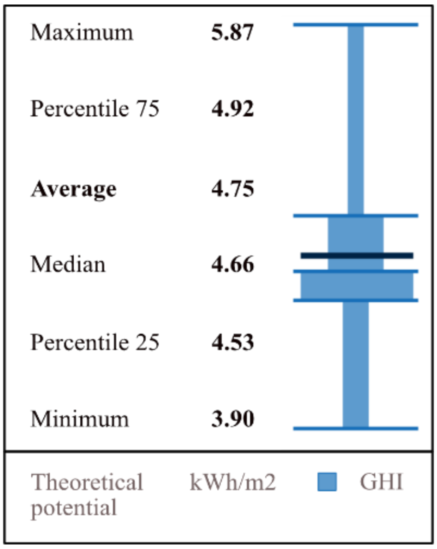

Fig. 8. GHI potential in Indonesia

6. RESULTS

During running the simulation, several parameters need to be set. In BESS and its inverter, the operation mode used is droop instead of grid following and isochronous. This simulation starts at the SoC BESS at 22%, while the State-of-Health (SoH) of BESS is 90%. Ultimately can be seen in Table 1.

In the PV plant and its inverter, it is necessary to input data regarding solar irradiance and temperature. Previously, data regarding the potential of GHI had been known. The average and minimum GHI data are utilized in this simulation. The data unit needs to be transformed from kWh/m^2 per day to W/m^2 (see Table 2).

Table 1. Parameters in BESS and inverter.

	Value
Operation mode	Droop
Frequency droop coefficient	0.5%
Voltage droop coefficient	1%
Active power reference	0.5 p.u.
Reactive power reference	0.0 p.u.
Frequency power reference	0.0 p.u.

Table 2. Parameters in PV plant and inverter.

Parameter	Value
Active power reference	0.2 p.u.
Reactive power reference	0.2 p.u.
Temperature	27°C Minimum 33°C Average
Irradiance	162 W/m^2 Minimum 200 W/m^2 Average

Table 3. Parameters in load.

Parameter	Value
Active power	0.2 p.u.
Reactive power	0.2 p.u.
Consumption dependencies	none

The load on the grid system is 500 KVA and cos phi 0.9. During the simulation, the values listed in Table 3 are employed. The loads then vary to 50%, 60%, 80%, and 100% of the initial value to perform the different conditions of the simulation.

Figure 9 compares the simulation results in average and minimum GHI conditions. The orange line shows the BESS condition at the average GHI. In comparison, the blue line shows the BESS condition at the minimum GHI. The simulation results show that the SoC of BESS can still survive to supply the loads (ΔSoC = 0) when the GHI is in average condition. Thus, load shedding is not required.

On the other hand, when GHI is at its minimum, the SoC of BESS decreases rapidly and hits the minimum limit (10%). So that the grid is not allowed to operate. In this condition, ΔSoC is < 0, so the load shedding scheme must be performed.

The load shedding comparison is shown in Figure 10. The simulated load shedding varies from 20% to 40% to 50% of the initial load. The blue line shows 100% load usage when the minimum GHI conditions result in a drastic reduction in SoC from BESS. The green line is the simulation result when 20% load shedding is performed. With a reduced load of 20%, ΔSoC > 0 but still risky due to slow charging. The yellow and grey lines are the simulation results when 40% and 50 % load shedding are performed, respectively.

In 100% load usage conditions, the grid will last approximately 45 minutes. Then, the grid will blackout because the SoC of BESS is set to operate at a minimum condition of 10%. The load priority algorithm and the grid operator will determine the load reduction. Then, certain conditions using the proposed method will be reached. The more significant the reduction in load is carried out, it will undoubtedly increase the resilience of the microgrid. Due to the balanced load and solar intensity, the grid condition will be stable with a 20% load reduction in the case study.

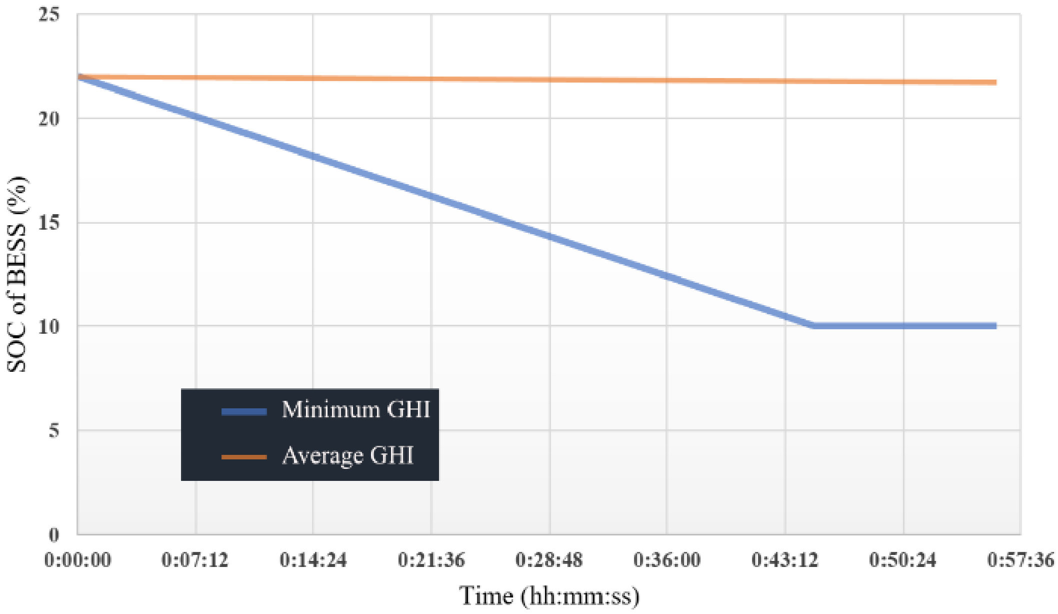

Fig. 9. SoC of BESS in average and minimum GHI.

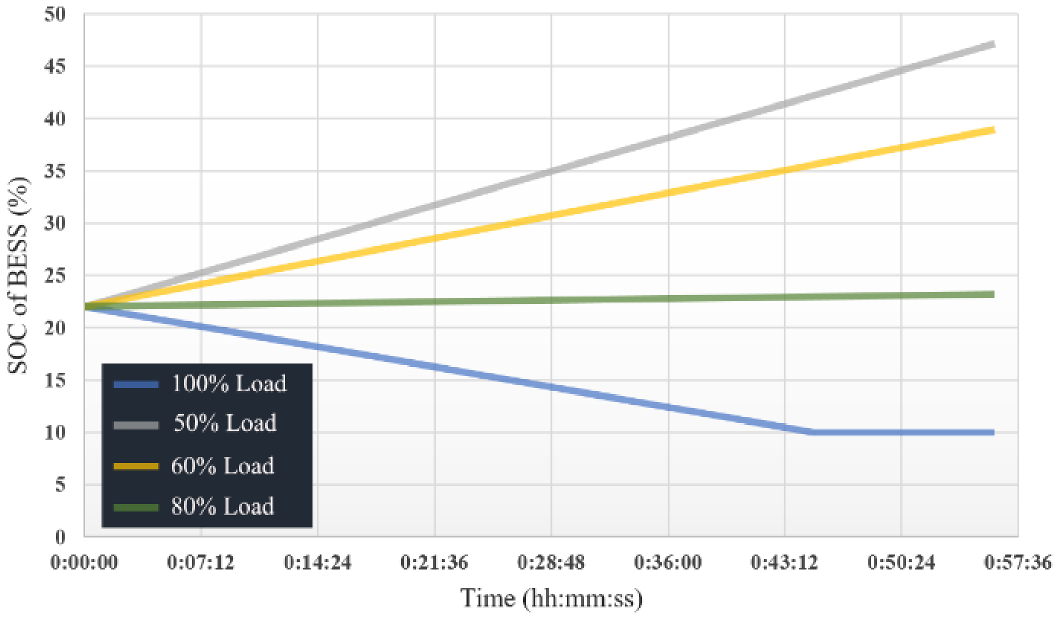

Fig. 10. SoC of BESS before and after load shedding.

7. CONCLUSION

This study proposed a strategy to balance supply and demand fluctuation for RES-based microgrids in isolated areas. The proposed case study is in a microgrid configuration consisting of the utility grid, a PV plant, a BESS, inverters, transformers, and loads when islanding occurs. Several technologies are proposed, including the use of NILM techniques to disaggregate loads. The BDT algorithm processed in DFP offers an appropriate NILM method to be applied to isolated areas. The infrastructure needed to implement this method is related to building a monitoring station equipped with a set of computers and sensors so that the NILM algorithm can proceed. The sensor should be able to read several electrical parameters according to the required NILM algorithm, namely active power, apparent power, and reactive power.

Load shedding and load priority algorithm have also been built in this study. The method was developed by considering the limitations of infrastructure in the form of communication, transportation, and other technologies in isolated areas. Therefore, it is necessary to have good cooperation between grid operators and consumers so that the proposed method can work well.

A case study in Indonesia, with a minimum GHI of 3.9 and an average of 4.75, a microgrid system consisting of PV capacity with 500 kVA and 600 kVA BESS successfully supplied a 500 kVA load using the proposed method with a 20% load reduction.

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