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Article

A Case Study on Increasing Microgrid Resiliency using Reserve Power Procurement Method

Halim LEE [1,*], **Gil-Seong BYEON** [2], **Jin-Hong JEON** [3], **Akhtar HUSSAIN** [4], **Hak-Man KIM** [5], **Anastasios OULIS ROUSIS** [6] and **Goran Strbac** [7]

[1] Korea Electrotechnology Research Institute, bulmosan-ro 10beon-gil, Seongsan-gu, Changwonsi, Gueongsangnam-do, Korea; halim@keri.re.kr
[2] Korea Electrotechnology Research Institute, bulmosan-ro 10beon-gil, Seongsan-gu, Changwonsi, Gueongsangnam-do, Korea; gsbyeon@keri.re.kr
3 Korea Electrotechnology Research Institute, bulmosan-ro 10beon-gil, Seongsan-gu, Changwonsi, Gueongsangnam-do, Korea; jhjeon@keri.re.kr
4 Incheon National University, Academy-ro 119, Yeonsu-gu, Incheon, Korea; hussainakhtar@inu.ac.kr
5 Incheon National University, Academy-ro 119, Yeonsu-gu, Incheon, Korea; hmkim@inu.ac.kr
6 Imperial College London, South Kensington Campus London SW7 2AZ, UK; a.oulis-rousis16@ic.ac.uk
[7] Imperial College London, South Kensington Campus London SW7 2AZ, UK; g.strbac@ic.ac.uk
* Correspondence: halim@keri.re.kr; Tel.: +82-10-9632-2894

Abstract: Power system decentralization has been an emerging topic for the past decade in an effort to improve power quality and environment protection via increased integration of renewable energy sources. Towards these objectives, decentralized microgrids have been proposed and thoroughly investigated in terms of technical capabilities and economic performance. In fact, the planning and actual operation of small-scale, decentralized microgrids has started in countries such as Canada, Japan, USA, UK and other countries. It is expected that the research in this area will progress and eventually take over the existing paradigm of large-scale power generation in the future. These small-size decentralized microgrids could be connected with nearby microgrids under normal operating conditions, but under special events, such as natural or man-made disasters, they would be disconnected and run in islanded mode. Under such high impact – low probability events, the microgrid must have resiliency to successfully re-connect with other microgrids and the main grid. In this paper, an Energy Management System (EMS) for a microgrid having a resiliency function, allowing to operate under islanded mode after an accident, is proposed. The proposed tool, called Resilient Energy Management System (ResEMS), aims at procuring reserve power into the microgrid's Battery Energy Storage System (BESS) effectively, by importing it from the nearby connected power system. The accident is assumed to be a predictable natural disaster, which means that the accident occurrence time, duration and level of damage can be estimated. The proposed ResEMS has been applied to a microgrid comprising of a BESS, a diesel generator and several photovoltaic devices. The simulation results verify its beneficial operation.

Keywords: energy management system; reserve power; resiliency; battery energy storage system.

1. Introduction

To reduce carbon emissions produced during the electric power generation process, the integration of renewable energy sources (RES) shall be increased. However, if their integration increases excessively in a bulk power system, the power system operation may be adversely affected by the abrupt power flow changes. Therefore, significant research has been focused in the effort to increase RES integration, while maintaining a stable electric power system. A way of doing so is the utilization of decentralized microgrids. Charlottetown, Hamilton, Winnipeg, Revelstoke of Canada, Shenzhen of China, Woking Borough Council of UK, Wildpoldsried, Sonnen Community of

Germany, Santa Ana of USA, Higashida of Japan are some examples of places integrating small-scale microgrids that operate in a stable manner [1], [2], [3], [4], [5], [6], [7]. These microgrids have the ability to self-produce power from their embedded resources and utilize this power to cover their loads. The excess of energy produced is typically traded with the nearby connected microgrids or the bulk power system, which eventually facilitates the power balancing amongst the various connected grids.

While the microgrid is operating in grid-connected mode, a natural disaster (e.g. typhoons, tsunamis), or man-made accidents can cause disconnection of the microgrid from others and lead to islanded operation. The disconnected or islanded microgrid must be able to withstand, and operate under emergency mode, until the accident that caused this disconnection is cleared, for successful re-connection and normal operation. When a microgrid changes its operation mode from connected to islanded, but still has the ability to deliver electric power to the loads consistently, and also has the ability to recover back to the connected mode, is characterized as resilient [8]. Significant research has investigated ways of increasing the resiliency of microgrids.

Research reported in [9], [10] and [11] proposed an electric power supply strategy using load shedding with renewable energy devices and battery energy storage systems (BESS). References [12], [13], [14] and [15] have introduced research utilizing diverse methods such as multi-agents, tabu search, genetic algorithms and graphical approach, in order to concentrate on restoration. At [16], using an electric vehicle as an electric power source has been studied. For preparation purposes against a resilient situation, [17], [18], [19] and [20] are suggesting several precautions such as line and microgrid cluster, and infrastructure hardening using a programmable network. The aforementioned research work has concentrated on hardening the infrastructure, and introducing control schemes that increase the resiliency of a microgrid.

For a bulk power system, when the electric power supply is less than its demand, there is a power imbalance, which if not dealt with might lead to a black out. To be prepared for such a situation, it is important to procure reserve power. This theory could also be applied to a small-size decentralized microgrid. When the microgrid changes its operation strategy from connected mode to islanded mode after an accident, the proposals from the aforementioned research could be a possible solution. In this case, heavy investments would be necessary, in order to have ordinary resilience. However, for predictable accidents, such as a natural disaster that can be forecasted, procuring reserve power to the BESS just before the accident occurrence expected time, would be a cheaper and more efficient solution.

In this paper, a reserve power procurement method has been proposed using ResEMS, assuming that an accident, which causes the microgrid to operate in islanded mode, is predictable. If the amount of procured reserve power is more than the one actually needed, the usage of generated power from renewable energy will be limited, when the SOC of BESS reaches the maximum value of capacity (i.e. after the microgrid returns back to connected mode). If not enough reserve power is procured, the microgrid will not be able to operate in islanded mode until it recovers back to connected mode, which would decrease its resiliency. Therefore, in order to increase the efficiency of electric power provided to microgrid's loads, an algorithm that calculates reasonable reserve power to be procured is proposed. The proposed algorithm is verified and analyzed by comparing the microgrid operation schedule calculated by a normal EMS, introduced in [10] and [11], and ResEMS, having a resilient function concentrating on reserve power procurement. After an accident occurs that changes the microgrid's operation mode from connected to islanded, the microgrid's loads are classified into critical and non-critical, and the power is supplied only to critical loads, as per [10] and [11]. Note that if the electric power is provided both to critical and non-critical loads, the necessary reserve power will be excessively large, which is not an optimal solution.

The paper is structured as follows: In chapter 2, the resiliency of a microgrid is explained. In chapter 3, the proposed ResEMS algorithm and optimization formulation is introduced and in chapter 4 a case study is presented to verify the proposed ResEMS algorithm. Finally, chapter 5 draws conclusions and future work.

2. Overall Outline of Resiliency

Resiliency from the perspective of a microgrid, is to have the ability to adapt to the grid's situation alteration, maintain the power supply after a disruption occurrence, and recover as soon as possible from the disruption [8]. Additionally, it has to be prepared for a disruption, even though it has low probability to occur but it comes with a high risk of damage to the microgrid. By summarizing all of this, the definition of a resilient microgrid is to have an ability to prepare, withstand, adapt to and recover from a disruption [21]. These capabilities are essential to increase the resiliency of a microgrid. If any of these capabilities do not exist in the microgrid EMS, it will be impossible for the microgrid to recover. In this paper the main concern is the ability to prepare before a disruption occurs.

According to [22], 44.4% of the blackouts in USA are caused by natural disasters. A natural disaster can be an earthquake, a tornado, a hurricane, a tropical storm, an ice storm, a lightning, a strong wind, heavy rain, intense cold weather and fire. Among these, predictable natural disasters are tornados, hurricanes, tropical storms, ice storms, strong winds, heavy rain and intense cold weather, which account for 43.6% of the reasons leading to blackouts. In other words, 43.6% of a disruption causing blackout can be predicted and it is possible to be prepared against these. If a microgrid had the ability to predict such a natural disaster, the proposed reserve power procurement algorithm, or ResEMS, could lead to a microgrid with stronger resiliency before an accident occurred, which would cause the microgrid disconnection. As explained earlier, procuring reasonable amount of reserve power is the key factor of ResEMS.

3. Algorithm and Mathematical Modelling

3.1. Proposed ResEMS Algorithm

In this paper, a ResEMS having reserve power procurement function, for increasing the microgrid resiliency, is proposed. A flowchart of the algorithm is illustrated in Figure 1. First, the input data including prediction data of critical load, non-critical load and photovoltaic device output is obtained together with microgrid status and device specific data. Then, in order to optimize the microgrid schedule using the exact operation mode, the algorithm examines whether an accident has occurred in the microgrid. Initially it is assumed that the accident did not occur, but predicted, which leads the microgrid to operate in grid-connected mode, or the proposed ResEMS algorithm. If the predicted accident occurs, the microgrid operation schedule is optimized for islanded operation. Each controllable device of the microgrid needs a set point to operate. Therefore, at the 'schedule optimization' step, the optimal set point of each device is calculated on a day-ahead basis. The set point for each time step is delivered to the respective device. The optimized day-ahead schedule is calculated for a 15-minute time step, which means there are 96 set points in total.

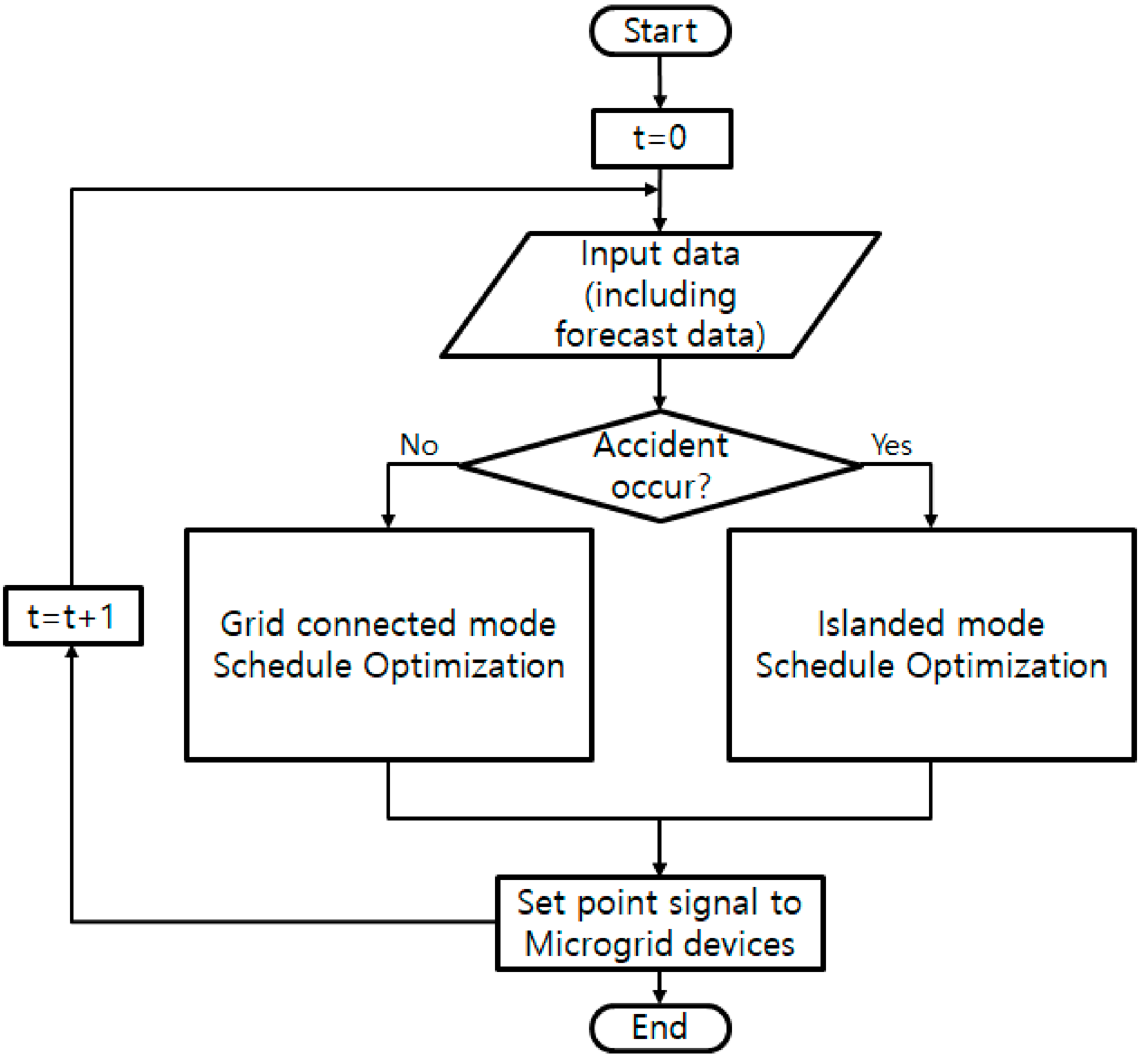

Figure 1. Overall ResEMS Algorithm.

The reserve power procurement algorithm, is applied and considered when the optimal schedule is calculated under connected mode through the ResEMS, right after an accident that causes disconnection between microgrids is predicted. By assuming that it is possible to predict a natural disaster, the proposed algorithm calculates the amount of the reserve power to be procured. Using the procured reserve power, the microgrid could survive and operate in islanded mode until it recovers back to connected mode. If the exact duration of recovery and re-connection is known, the reserve power will be calculated with less mismatch. However, in some cases, the expected duration time could last longer. Additionally, even when the duration time is as expected, it is possible that there is no sun light, causing the photovoltaic device prediction to have significant mismatch in the actual electric power generation. To prevent such a situation, this paper proposes to procure the reserve power as much to provide electric power to the microgrid until the next day's photovoltaic device energy production exceeds the critical load.

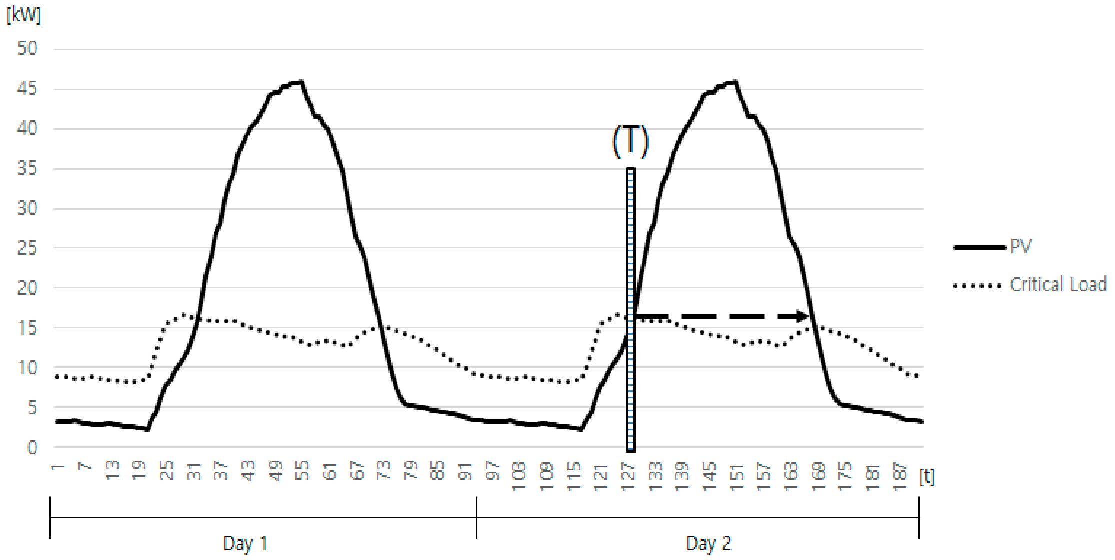

Figure 2. Reserve Power Procurement Concept.

Figure 2 illustrates the prediction data of photovoltaic device generation and critical load for two days, assuming a natural disaster will affect the microgrid only for day 1. It shows the proposed reserve power procurement concept. Looking at day 2, starting from time step 129, the predicted output of photovoltaic device exceeds the critical load. Despite the time the accident occurs (or the microgrid disconnection actually occurring on day 1) the reserve power must be procured to provide electric power to the critical load until time period 129 of day 2 in order to secure the resiliency of the micro grid. If the accident is cleared and the microgrid recovers back to connected mode before time step 129, the micro grid will operate normally with high resiliency. If the accident is not cleared until time period 129 of day 2, the critical load could also be supplied for some period of time, by using the energy production from the photovoltaic device. During this time, the BESS has an opportunity to store energy, until the photovoltaic device output is lower than the critical load, as in time period 169 of day 2. This stored energy makes it possible to provide the critical load for even longer time duration than expected, which allows more time for full recovery of microgrid connection. According to [23] and [24], the longest time for accident recovery was 1100 minutes. Which means in worst case scenario, the blackout could last for approximately 18 hours, and this must also be considered while calculating the amount of reserve power procurement.

The reserve power could be procured by purchasing power from the connected power system or by operating the diesel generator. However, since the optimization will be done by minimizing the total operating cost (i.e. explained in the following chapter) and also the cost for diesel generation is higher, importing electric power from the connected power system is more reasonable.

Figure 3 illustrates the flowchart of the reserve power procurement algorithm. Firstly, the algorithm searches for the time period of next day when the photovoltaic device output exceeds the critical load, and defines the time period as *T*. Then, the total amount of possible generation, sourced by both photovoltaic device and diesel generator, is calculated from the present time ①, or islanded mode start time *t*, until *T*. Also for the same time period, it calculates the amount of the critical load ②. For each time step, it compares ① and ②, and procures reserve power, by purchasing the lack of electric power from the connected power system, and storing it in BESS.

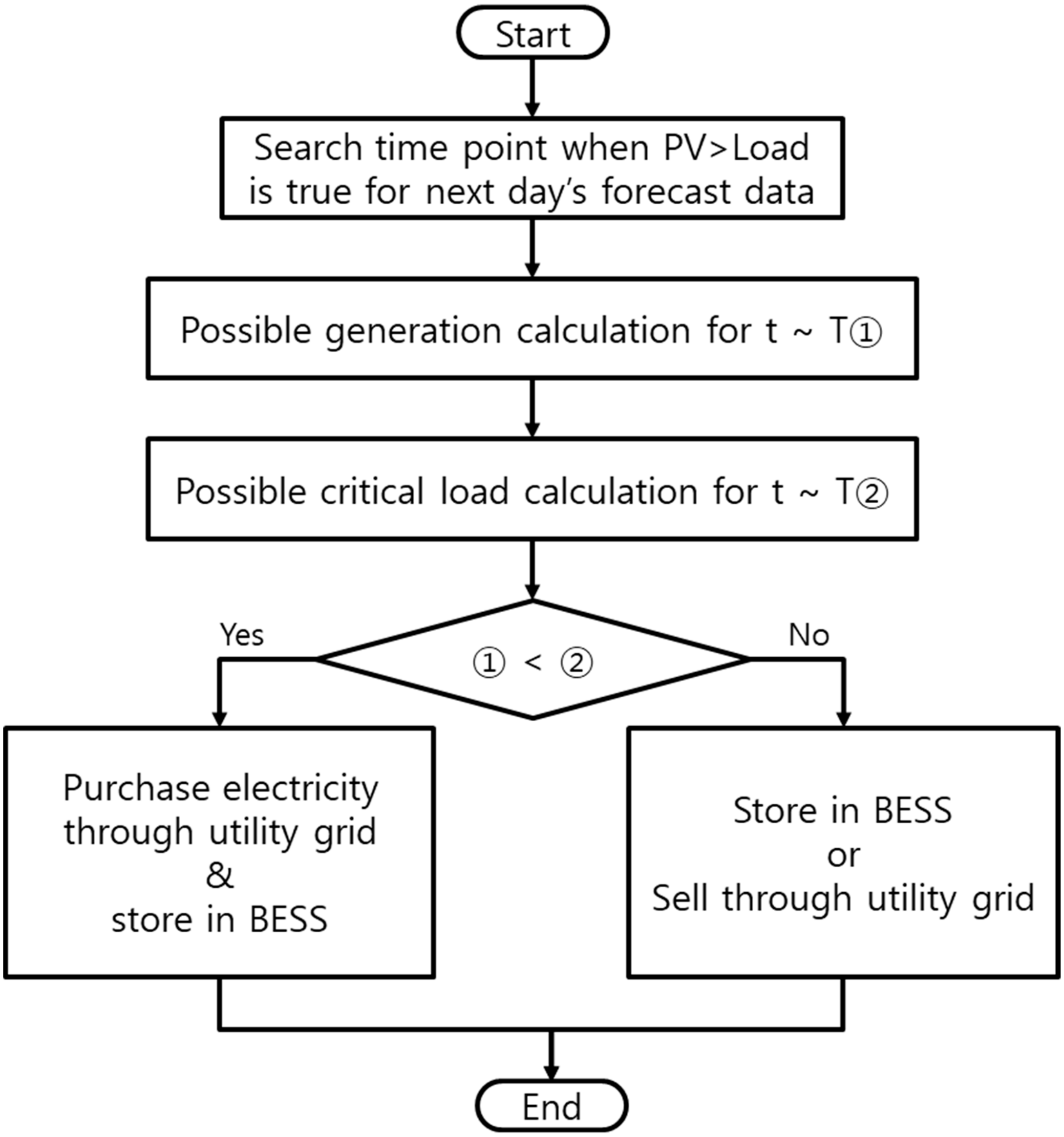

Figure 3. Reserve Power Procurement Algorithm.

3.2. MILP Optimization Formulation

In order to optimize the microgrid day-ahead scheduling, the objective function is set to minimize the generation cost, while maintaining the microgrid under stable condition. The critical load must be provided until the next day using the procured reserve power, stored in the BESS. The generation cost comprises of fuel cost and start-up cost of diesel generator and electric power purchase/sell fee from/to the connected power system.

A set of equalities and inequalities constitute the constraints of the optimization problem. An inequality is included for limiting the amount of the electric power that could be purchased from (2) or sold to (3) the connected power system. The amount of electric power produced by the diesel generator (4), amount of charge (5) and discharge (6) from the BESS's power conversion system (PCS), and the state of charge for BESS (7) are included as well. Additionally, inequality (8) is introduced to account for the total generation limit of the diesel generator considering a given amount of diesel fuel. Also, the total amount of electric power supplied to the microgrid must be greater than the amount of power charged/discharged from the PCS (i.e. represented by equality (9)). Finally, the energy difference between load and generation from photovoltaic should match the output from diesel generator, power purchased/sold from/to connected grid, charge/discharge power from PCS (10), for every time section *t*. When the microgrid operates in islanded mode, terms related to the connected power system, such as electric power purchase/sell fee, are ignored, since they should have no effect on the optimization process for the duration of time that no connection to another power system exists.

$$\min \sum_{t=1}^{T} (Cost_t^{GB} \cdot P_t^{GB} + Cost_t^{GS} \cdot P_t^{GS} + Cost_t^{DG} \cdot P_t^{DG} + Cost^{DGS} \cdot u_t) \tag{1}$$

Subject to:

$$0 \le P_t^{GB} \le P_{Max}^{GB} \tag{2}$$

$$P_{Max}^{GS} \le P_t^{GS} \le 0 \tag{3}$$

$$0 \le P_t^{DG} \le P_{Max}^{DG} \tag{4}$$

$$-P_{Max}^{B} \le P_t^{BC} \le 0 \tag{5}$$

$$0 \le P_t^{BD} \le P_{Max}^{B} \tag{6}$$

$$SOC_{min} \le SOC_t \le SOC_{Max} \tag{7}$$

$$P_{Tot}^{DG} \le P_{poss}^{DG} \tag{8}$$

$$SOC_{min} + R_{Tot} \le \ SOC_{ini} - P_t^{BD} - P_t^{BC} \tag{9}$$

$$P_t^{CL} + P_t^{NL} - P_t^{PV} = P_t^{BD} + P_t^{BC} + P_t^{GB} + P_t^{GS} + P_t^{DG} \tag{10}$$

In order to solve the optimization problem shown in the above mathematical formulation, a mixed-integer-linear program has been coded in Matlab environment [25]. By solving the optimization, the total day-ahead schedule data for the electric power import/export from/to the connected power system, input/output of the PCS and diesel generator, charge/discharge amount of BESS, and the electric power that critical and non-critical loads have absorbed, are obtained.

4. Simulation and Result

4.1. Simulation Assumption

The small-scale decentralized microgrid configuration shown in Figure 4 has been adopted for the simulations presented in this chapter. The critical and non-critical loads are mainly provided by the power generation from the photovoltaic device. When the power generation from the photovoltaic device exceeds the load, the remaining energy is stored in the BESS through the PCS. Otherwise, if power generation from photovoltaic device does not cover the load, the power balance will be achieved by importing power from the connected utility grid or by operating the diesel generator. However, the diesel generator will mainly be used when the microgrid is operating under island mode, as generally its generation cost is higher than the price of power imported from the connected power system.

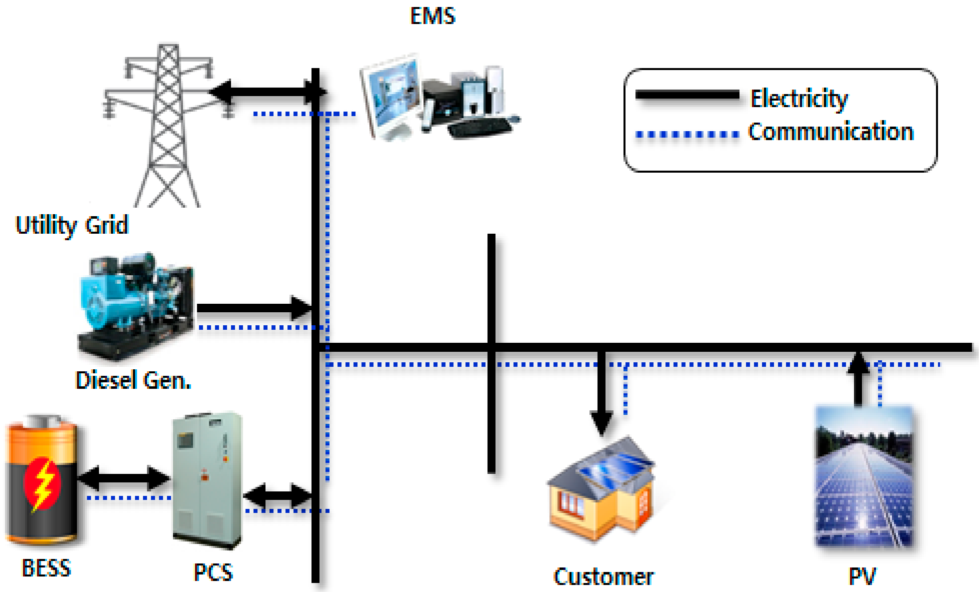

Figure 4. Example of Micro Grid Configuration.

The capacity of the photovoltaic device is 75 kW, peak value of critical and non-critical loads is 16.65 kW and 25kW respectively. The generation capacity of the diesel generator is 100 kW and there is sufficient amount of fuel to generate 250 kWh for the microgrid. The electric power import/export from/to the grid is limited to 80 kW. The BESS has the storage capacity of 400 kWh, and the maximum charge/discharge power for PCS is 100 kW. The specific data for the BESS is shown in Table 1.

Table 1. Specific Data for BESS.

Parameters	Specific Ability
Capacity (kWh)	400
Efficiency (%)	95
Initial SOC (%)	50
SOC Range (%)	0 ~ 100

Figure 5 is the assumed prediction data that has been used for the simulation. The simulation time step is considered to be 15 minutes, which has 96 time steps for the calculated day-ahead schedule. When an accident is predicted to occur within the microgrid, leading to islanded mode, the reserve data must be procured in advance, for the microgrid to maintain resilient operation. In this case, the next day prediction data is assumed to be the same as the first day prediction data, since it is always possible that under severe circumstances (such as the natural disasters investigated here) the prediction device could have been damaged or the prediction system could struggle to provide an accurate forecast.

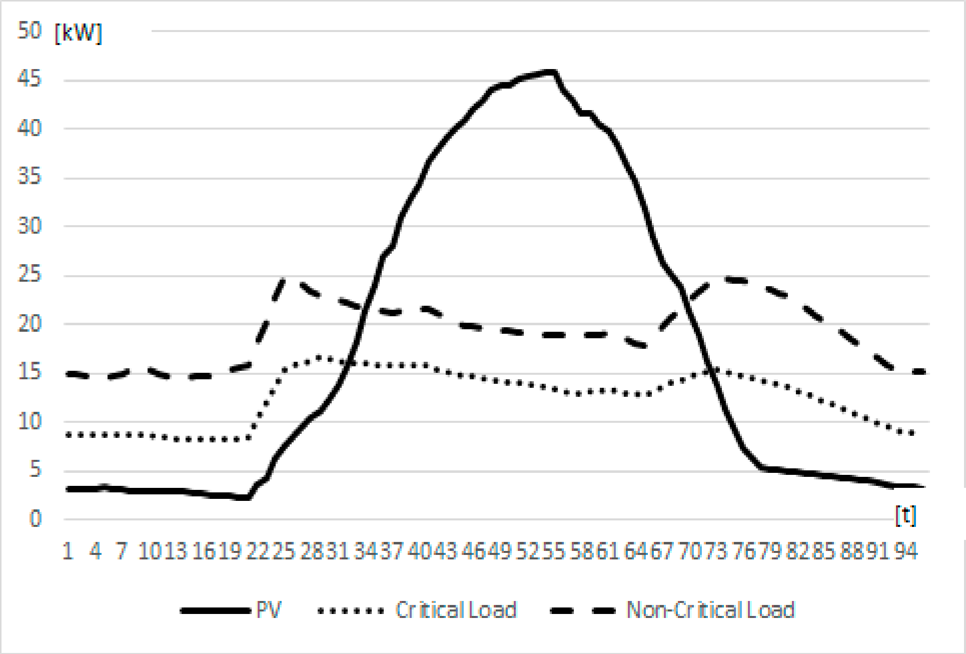

Figure 5. Prediction Data.

Two different simulation cases have been assumed in order to verify the proposed resilient EMS algorithm.

- EMS case (base case): EMS without resiliency function. Calculate the day-ahead schedule for the microgrid regardless of accident occurrence.
- ResEMS case: EMS with resiliency function. Calculate the day-ahead schedule considering the reserve power procurement when an accident is predicted.

Both cases have been simulated and compared in order to verify the effect of the resiliency function. Through the simulations, day-ahead schedule for the following decision variables will be obtained:

- Import/export electric power from/to the connected power system.
- Power output of diesel generator.
- Charge/discharge power from PCS.
- SOC of BESS.

Using the calculated values of the variables, the effect of resiliency function will be verified by comparing whether the reserve power is sufficient to supply the critical load until the designated time period of next day, *T*. The process follows the steps mentioned below:

- Calculate the reserve power stored in the BESS for every time step.
- Calculate the critical load provision time, from *t* to *T*, using the stored energy in BESS, diesel generator's possible generation amount (i.e. in kWh) and prediction data of critical loads and photovoltaic device for day 1 and 2.

As it can be observed in Figure 5, at time step 33, the predicted value of photovoltaic device exceeds the critical load. Therefore, for the EMS base case, it is expected that electric power will not be provided to the critical loads until time step 33 of the next day, when the accident occurs. In contrast with the base case, when using the ResEMS strategy, it is expected that the microgrid has sufficient reserve power to cover the critical loads until time step 33 of next day, regardless of the accident.

4.2. Result

The results of the simulation are as shown in Figures 6-(a), 6-(b) and 6-(c). The calculated day-ahead schedule of the import/export electric power from/to the bulk power system, charge/discharge value of the BESS and the SOC of the BESS optimized by both the EMS and ResEMS algorithms are depicted. It can be observed in Figure 6-(a) that, at the early part of ResEMS scheduling, the electric power import value is larger than the scheduling result calculated by EMS. It is obvious that ResEMS has to import more electric power from the bulk power system, since additional reserve power must be procured. The specific reason for importing power early within the day relates to the electric power price, which is cheaper during this period. The difference between the EMS and the ResEMS schedule for the charge/discharge output and the SOC value of BESS is also affected by this fact, as illustrated in Figures 6-(b) and 6-(c).

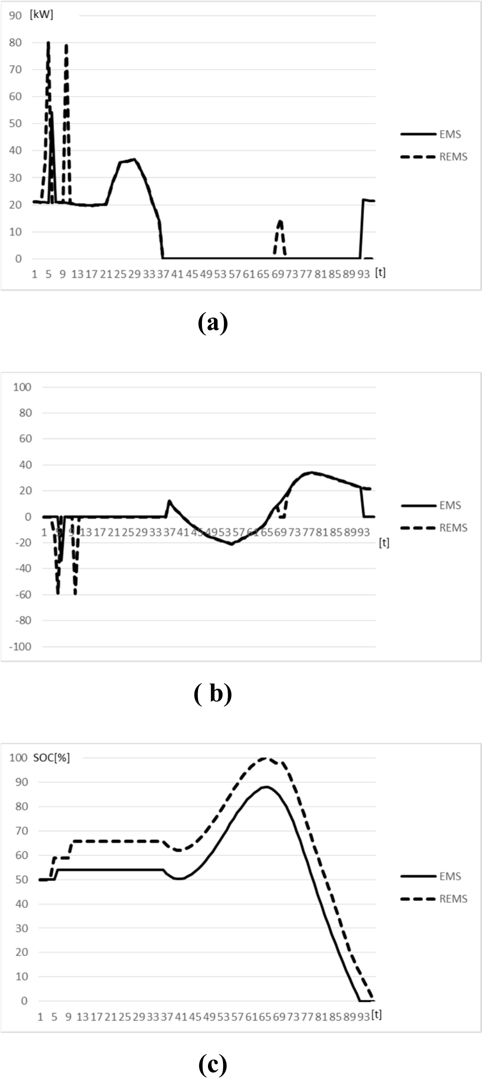

Figure 6. Optimized schedule of EMS and ResEMS for: (a) Electric energy import/export value; (b) Charge/discharge value of BESS; (c) SOC of BESS.

4.3. Analysis

Figure 7 indicates the total time period the electric power from the main grid could supply the critical loads after the accident occurrence. At time step 33 of day 2, from Figure 5, the photovoltaic device power output exceeds the critical loads. This means that the microgrid should procure reserve power to supply critical loads until time step 33 of day 2 (i.e. time step 129 if 96 time steps are added from day 1). Looking at Figure 7, the optimized schedule calculated by the ResEMS enables the microgrid, while in islanded mode, to survive until time period 129, regardless of the accident occurrence time. Therefore, when the accident occurs at day 1, the critical loads will be covered successfully until time step 129 according to the schedule of the ResEMS. However, when the base case EMS is utilized and an accident occurs in specific time steps 71 to 91, the critical loads cannot be supplied until time step 129. In simpler words, this means that the EMS scheduling algorithm leads to a less resilient microgrid.

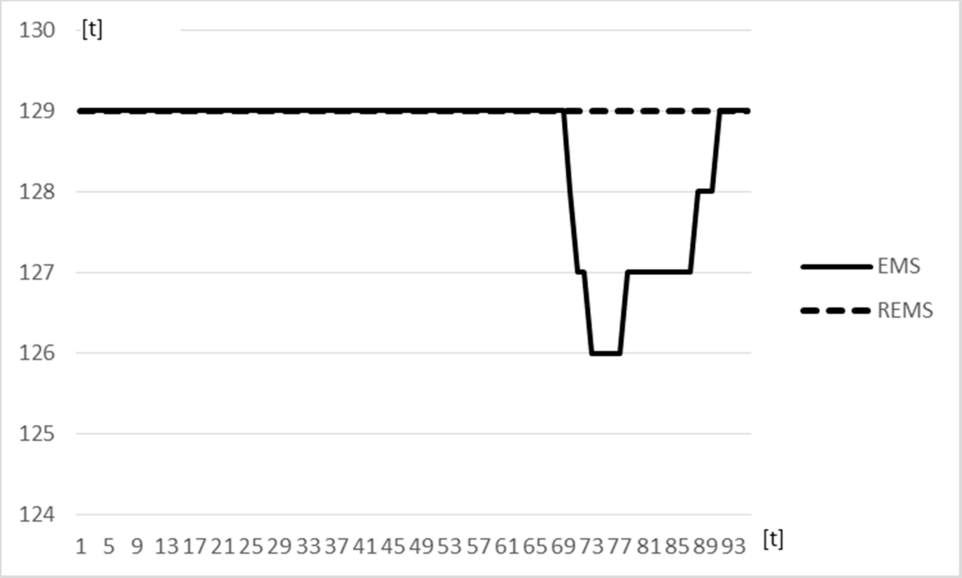

Figure 7. Critical load supply time duration after accident occurrence.

It should also be noted that if the critical loads could be supplied until time step 129 (i.e. by using the reserve power procured by the resilience function of ResEMS), then the critical load could also be supplied after time step 129 by using the power generated from the photovoltaic device. In this case, while the photovoltaic device output exceeds the critical loads for day 2, or after time step 129, the surplus power will be stored in the BESS. This energy stored will conversely be used, when the photovoltaic device power output does not exceed anymore the critical loads.

5. Conclusion and Future Study

5.1. Conclusion

In this paper, a resilient EMS or ResEMS algorithm has been proposed, whose main goal is to increase the resiliency of a small-scale, decentralized microgrid by procuring reserve power effectively. If a predictable accident, such as natural disaster, occurs in the microgrid, the connection between other microgrids could fail or be damaged causing malfunction. In this situation, the microgrid must operate in islanded mode. While operating in islanded mode, the microgrid should be able to provide electric power to critical loads, until the microgrid can recover back to connected mode. To enable this, the proposed ResEMS procures reserve power stored in a BESS. It has been demonstrated through the case studies that by using the optimized schedule calculated by the ResEMS, the microgrid's resiliency is strengthened.

5.2. Future Study

To improve the proposed algorithm, additional constraints are necessary to reflect an actual microgrid in reality. For example, looking at the graph of Figure 7 calculated by the EMS, when the accident occurrence time is not between time steps 71 to 91, additional reserve power does not need to be procured. Therefore, it is not necessary to import any electric power from the connected bulk power system. The resilient function of the ResEMS determines the additional procurement of reserve power at every time slot, which may not be necessary at certain time steps and leads to increased costs. Additionally, the prediction data for the day after the microgrid disconnection must be improved, since during any natural disaster the weather conditions would change considerably and the forecast precision would be low.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

$Cost_t^{GB}$: Electric power purchase fee at time *t* [$]
$Cost_t^{GS}$: Electric power sell fee at time *t* [$]
P_t^{GB} : Purchased amount of electric power from connected power system at time *t* [kW]
P_t^{GS} : Sold amount of electric power from connected power system at time *t* [kW]
$Cost_t^{DG}$: Fuel cost for diesel generator at time *t* [$]
P_t^{DG} : Generated electric power from diesel generator at time *t* [kW]
$Cost^{DGS}$: Start-up cost of diesel generator [$]
u_t : Diesel generator status variable {0, 1}
P_{Max}^{GB} : Maximum value of electric power that could be purchased from connected power system [kW]
P_{Max}^{GS} : Maximum value of electric power that could be sold from connected power system [kW]
P_{Max}^{DG} : Maximum value of electric power that could be generated from diesel generator [kW]
P_t^{BD} : Amount of power discharged from BESS at time *t* [kW]
P_t^{BC} : Amount of power charged from BESS at time *t* [kW]
P_{Max}^{B} : Maximum value of power that could be discharged or charged from BESS [kW]
SOC_t : State of charge at time *t* [%]
SOC_{Max} : Maximum value of state of charge [%]
SOC_{min} : Minimum value of state of charge [%]
R_{Tot} : Total amount of reserve power that has to be procured [kWh]
SOC_{ini} : Initial value of state of charge [%]

P_t^{CL} : Value of critical load at time t [kW]
P_t^{NL} : Value of non-critical load at time t [kW]
P_t^{PV} : Value of photovoltaic device generation at time t [kW]
P_{Tot}^{DG} : Total amount of diesel generation production [kWh]
P_{poss}^{DG} : Possible amount of diesel generation production [kWh]

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