

An Energy Management System for Disaster Resilience in Islanded Microgrid Networks

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Abstract—As disasters continue to become common around the world, the reliability of power systems is increasingly becoming critical. Researchers continue to explore the inclusion of distributed energy resources (DERs), specifically smart microgrids, into traditional power system designs to improve their reliability. Smart microgrids possess characteristic advantages of energy storage, off-grid operation, and control flexibility. In this regard, we explore load shedding of non-critical loads as a solution to extend the uptime of a group of interconnected microgrids that have been islanded after a disaster. Load shedding and Photovoltaic (PV) Curtailment are implemented as an addition to our previously proposed energy management systems (EMS) for each prosumer (PR) in the network. The proposed method shows that the proposed control methods can prolong uptime in the interconnected off-grid network of microgrids

Keywords— *Microgrid, Energy Management System, Business continuity plan, Electricity continuity plan, Photovoltaic Power, Storage battery, Resilience*

I. INTRODUCTION

Among the lessons learned from the Great East Japan Earthquake is the need for business continuity plans (BCP) in the demand-side network to better prepare facilities and businesses for a disaster. The BCP plan contains contingency measures to enable businesses to recover after disasters. An electricity continuity plan (ECP) is a major component of the BCP. This was suggested by Hirohisa in [1] who noted that despite the enormous disruption of power services from the earthquake that extended to areas beyond the disaster epicentre, the government had not seriously considered the implementation of BCP. However, a study on a resilient economy by a group of Japanese enterprises proposed an ECP where DERs and backup systems are installed as possible solutions to the disaster resilience question.

The authors in [2] also propose the inclusion of DERs consisting of smart microgrids into the design of demand-side network planning for smart cities to improve power security. As shown in Fig.1, power systems with existing ECPs can maintain uptime up to a certain percentage ($a\%$) of peak demand during a disaster occurrence. As a result, the disaster recovery time is also reduced by a time Δt . This is achieved with the help of distributed generation, back-up storage systems, shared power, and an effective energy management system (EMS).

The authors in [3]–[6] have explored load shedding as increasingly becoming important in disaster resilience studies as it can increase the uptime of islanded microgrids. The authors consider coordinated load shedding in a centrally

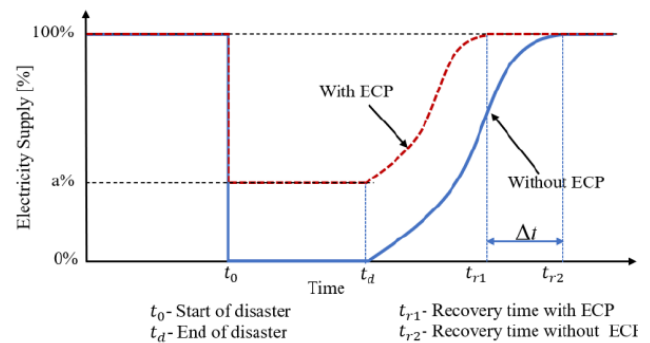


Fig. 1. Power System with ECP Vs Power System with No ECP

managed network. Some of the authors deliberate on the role of load shedding in stabilizing system frequency.

In our previous research, we proposed a switching EMS in [7]–[9] which sustains uptime for up to three days after a disaster occurs in a group of islanded interconnected prosumers based on the state of charge (SOC) of the storage battery (BT). This research takes advantage of the shared power and storage systems as critical resources for maintaining the uptime of the network of interconnected prosumers as a strategy for the ECP.

In this paper, the switching EMS is improved by adding load shedding of non-critical loads as an additional disaster resilience strategy. In effect, we consider a case where the power stored within the network is insufficient to support the load requirement of the entire network after it has been grid-disconnected, which is a typical case after disasters. Also, while three days is the average power service restoration time after disasters, it has been known to take even longer until restoration as we shared in [7].

Additionally, we implement PV curtailment (PVC) control to the EMS using the algorithm proposed by Marasini et al in [10]. PVC plays an important role in preventing PV power overgeneration that can lead to supply and demand mismatch, manifesting as frequency instability or over-voltage as discussed by the authors in [11], [12].

This paper describes the prosumer model, the control method and shares the results and conclusion of our simulation performed with MATLAB/SIMULINK Simscape Electrical Software.

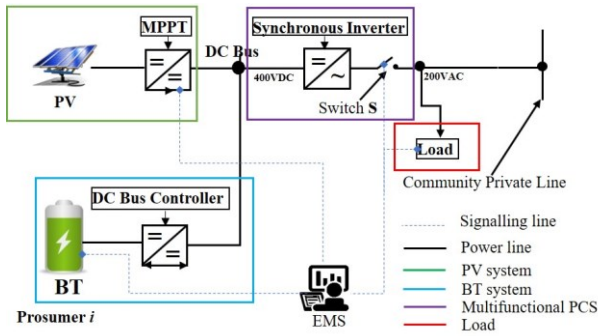


Fig. 2. Prosumer configuration.

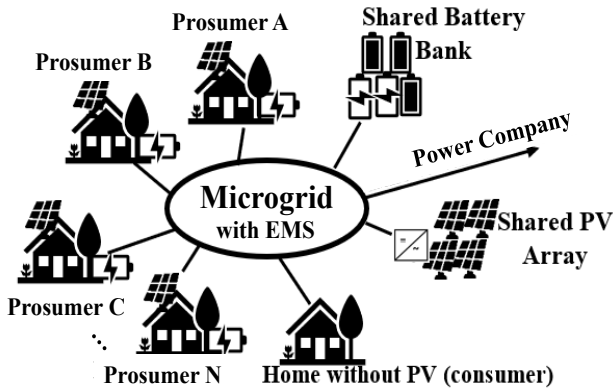


Fig. 3. Concept of Microgrid EMS Model.

II. THE PROPOSED PROSUMER MODEL

We consider each of the prosumers structure as in Fig. 2, already introduced by us in [7]–[9], [13], [14] containing:-

- PV system, which includes PV panels, PVC control tools, its maximum power point tracking controller (MPPT), and a DC-DC converter.
- The battery system, which comprises batteries, a bidirectional DC-DC converter with a DC Bus controller.
- Multifunctional power conditioning system (PCS), which includes a single-phase synchronous inverter (SSI) [15] with its PI controller.
- The dynamic load is divided into the critical and non-critical load which can be defined by the prosumer. The non-critical load is shed when normal load curtailment (load shedding) is implemented. (NLC)

This PV system, BT system, and Multifunctional PCS interconnect through the DC bus that is maintained at 400VDC by a PI controller contained within the BT system. The multifunctional power condition system (PCS) converts the DC voltage to an AC voltage of 200V at a frequency of 60Hz. The embedded PI controller maintains the 200V AC supply to a dynamic load.

Finally, the AC line connects to the community private line through an ideal transformer that steps up the voltage to 11kVAC. The community private line can interconnect various prosumers and consumers, as shown in Fig. 3.

The converters and inverters in this system are average value models to reduce simulation time and computational burden. This suits our experimental study which considers long simulation times of up to 72 hours.

III. PROPOSED ALGORITHM FOR CONTROLLING POWER-SHARING

The proposed algorithm achieves the following items.

1) By using the unique characteristics of PRs as input data, it is possible to analyze and evaluate the 3-day (72-hour) continuous system operation by flexibly sharing the BT stored energy in the microgrid.

2) Real-time curtailment of excess power generated by the PV system is curtailed based on input data and predefined PV power output limits. The accuracy of the PV curtailment method can be improved through weather prediction that will be considered in future research.

Each PR’s EMS automatically performs PVC control function implemented as in Fig. 4 and NLC control function in addition to power flow control using switch *S*. EMS control for each prosumer is controlled depending on the BT SOC as the primary parameter to effect power-sharing among the prosumers in the microgrid network.

This is explained using the example of SOC operation management as shown in Fig. 5 and the PV curtailment controller flow chart in Fig. 6. Firstly, it is assumed that each

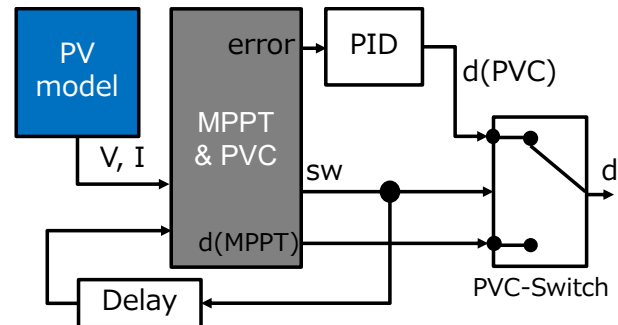


Fig. 4. PV Curtailment Controller.

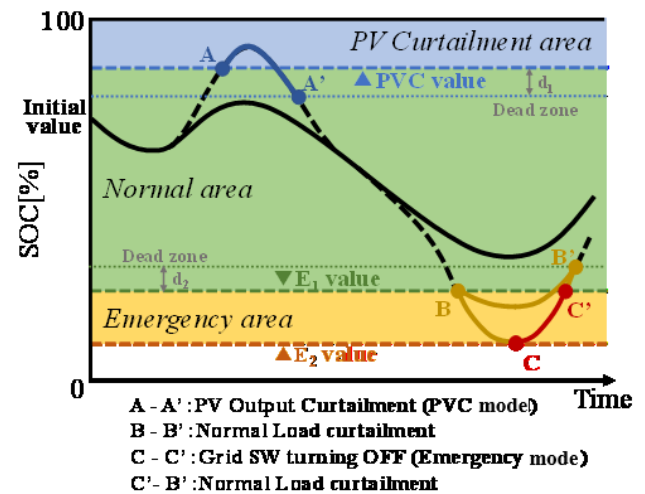


Fig. 5. PV Curtailment Controller.

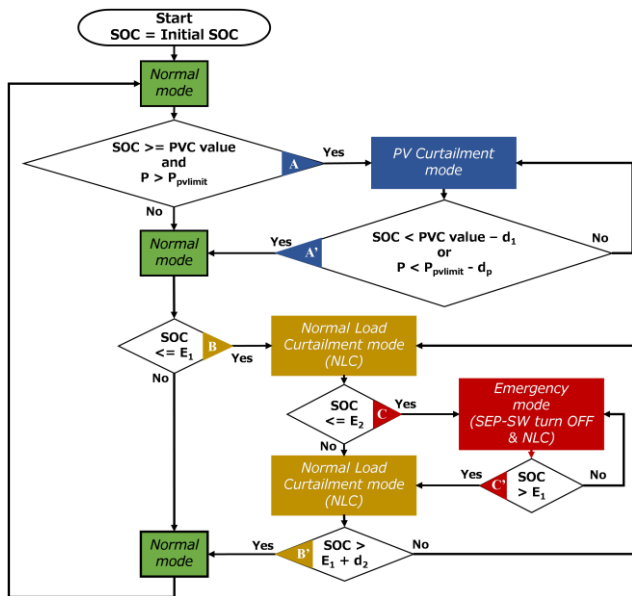


Fig. 6. PV Curtailment Controller Flow Chart.

PR has a predefined initial SOC value which is chosen through arbitrary logic.

As shown in Fig. 5, when the BT-SOC is in the green area (solid and dashed black lines), it is operating in normal mode. The PVC control function is implemented when the BT-SOC is in the range from point A to point A' (PVC Mode). The PVC control is performed when the PV output is larger than the pre-set reference value of PV output curtailment power ($P_{pvlimit}$).

In addition, the NLC function controls the NLC switch when the BT-SOC is in the range of point B to point B' (NLC Mode) as illustrated in Fig. 5. When the NLC function is active and the BT-SOC decreases and reaches the reference value E2, the Switch S is turned OFF (NLC control function mode), and the load demand is covered by the power-shared from other PRs during point C to point C' in Fig. 5 (Emergency area). The control procedures for the above conditions are shown in Fig. 6.

Above the SOC lower limit, switch S is turned ON, and the load is supplied by its PV output and BT output power under normal mode.

Furthermore, when the SOC continues to decrease and reaches the lower limit, the switch S is turned off, the load is disconnected from the PV and the BT, and utilizes the power supplied by other PRs from the community private line. This is called the "emergency mode".

IV. SIMULATIONS

A. Simulation Conditions

In this paper, a community consisting of 4 PR houses is assumed. The input to the PV system is solar radiation [W/m^2] and the air temperature [$^{\circ}C$] which are measured at the experimental research A1 building of Hiroshima University using 1-minute interval data as shown in Fig. 7.

The load is divided into the normal load (non-critical and controllable) and critical (uncontrollable) load as illustrated in Fig. 8. The critical load is assumed to be constant whereas the normal load is considered variable. The total load is the sum of the two types of loads. We considered only resistive load

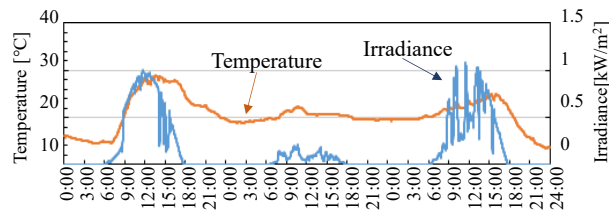


Fig. 7. 3-day Temperature and Irradiance Data.

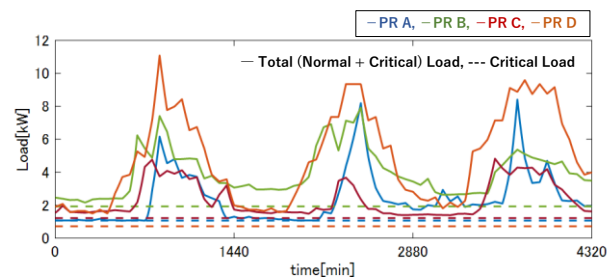


Fig. 8. Electrical load profiles.

TABLE I. SETTING OF SOC FOR EACH PROSUMER (PR)

PR	Initial Value [%]	PVC Value [%]	E ₁ Value [%]	E ₂ Value [%]
A	80	80	65	60
B	50	80	45	40
C	80	80	25	20
D	50	80	25	20

for this simulation, therefore unity power factor was assumed at a system frequency of 60Hz.

The SOC reference values are listed in Table I. The PVC reference value is set to 80 [%] for all PRs, and the power is controlled to be 5 [kW] when the output is curtailed. The dead zones d_1 and d_2 in Fig. 5 and d_p in Fig. 8 are set to 1 [%], 1 [%], and 75 [W], respectively.

The total output power of the PV system is 7.5 [kW] using 13 units in series and 3 in parallel. For the BTs, a lead-acid type is assumed, the output capacity of the BT system is 28 [Ah] (5-hour rate), the nominal voltage is 48 [V], the rated discharge current is 17.4 [A/unit].

The simulation was run in MATLAB/SIMULINK Simscape Electrical software with a simulation sampling time, $t = 1ms$, using the fixed step auto solver.

B. Simulation results

The simulation results are shown in Fig. 9, where the supply and demand status of each PR for 3 days are illustrated.

For all the figures, PV output, BT, load, Power flow (shared power), and DC bus voltage curves are shown, corresponding to each prosumer. Positive power flow corresponds to power purchase whereas negative power flow implies that power is sold to the community private line. negative values of BT power indicate that the battery is charging, and positive values imply it is discharging.

The profile of the BT-SOC and the operation state of PR are shown in the bottom graph of each figure. In these figures,

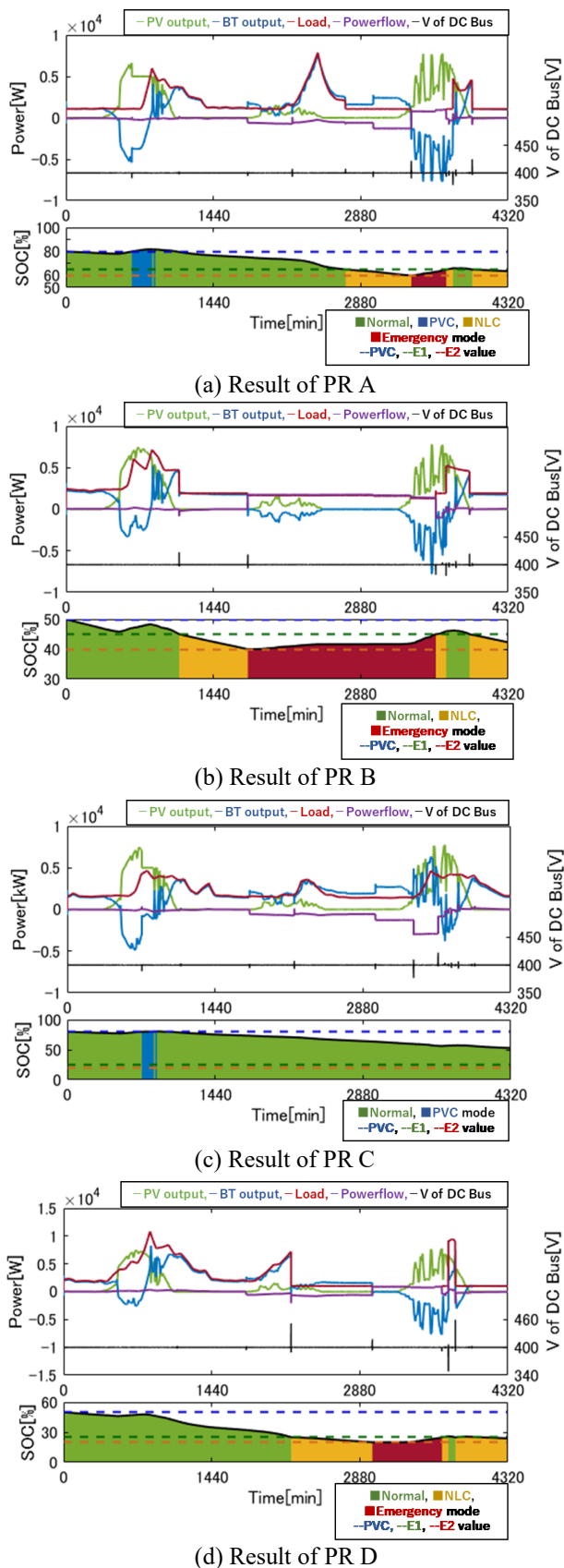


Fig. 9. Results of 3-days system operation

the green background color is normal mode operation, blue indicates PVC control mode while yellow and red correspond to NLC mode where switch S can be turned off to allow for buying of power from the private line.

It is observed from Fig. 9 that the PV output is curtailed to 5 [kW] when PVC is active. Similarly, the load is reduced when the NLC is active. In addition, the PRs cooperate in power-sharing which corresponds to the aim of our research.

Our proposed system successfully maintained uptime over a 3-day simulation period which is sufficient to support service restoration after a disaster and allow time for relief service to be delivered.

V. CONCLUSION

In this paper, a control algorithm for power-sharing in a local community consisting of four prosumers with PVs and BTs is simulated while the case for the electricity continuity plan (ECP) is validated.

With respect to the BT-SOC value, stable operation using our proposed EMS method was maintained for 3 days. The use of this simulator can lay the foundation for the optimum design of the EMS model suitable for ECP. It can be a useful tool for the operators that build local microgrid communities in virtual power plant (VPP) designs that are gaining popularity.

Contrary to the assumption in this research, the critical load can also be controllable. Therefore, We are currently working on additional research for a more flexible load-curtailment control method that can perform ECP even under bad weather conditions supplemented by load and weather prediction using neural network techniques in an energy trading environment.

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