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Published in:

PEDG 2023 - 2023 IEEE 14th International Symposium on Power Electronics for Distributed Generation Systems

DOI (link to publication from Publisher):

[10.1109/PEDG56097.2023.10215137](https://doi.org/10.1109/PEDG56097.2023.10215137)

Publication date:

2023

Document Version

Version created as part of publication process; publisher's layout; not normally made publicly available

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Guan, Y., Kang, W., Vasquez, J. C., Wijaya, F. D., Arumdati, N., Tenggara, W. N., & Guerrero, J. M. (2023). Quasi-SoC Balancing Control for Networked Ad-hoc Microgrids Against Natural Disasters. In *PEDG 2023 - 2023 IEEE 14th International Symposium on Power Electronics for Distributed Generation Systems* (pp. 1015-1020) <https://doi.org/10.1109/PEDG56097.2023.10215137>

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Quasi-SoC Balancing Control for Networked Ad-hoc Microgrids Against Natural Disasters

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Abstract—After natural disasters, mobile containerized renewable energy-based Ad-hoc microgrids could be an emergency solution to maintain power supply to critical loads. In this paper, a novel two-layer coordinated control for individual and networked Ad-hoc microgrids is proposed. The first layer deals with the internal coordination between RE and ESS to maintain a stable operation within an Ad-hoc microgrid by using bus frequency, thereby without communication links to reduce power consumption. When forming the networked Ad-hoc microgrids to a critical load with higher load demand, the regulations on the bus frequency from each Ad-hoc microgrid will result in instability. Therefore, a quasi-SoC balancing control strategy for the networked Ad-hoc microgrids is further proposed with only binary information exchanges to mitigate the interactions caused by the internal coordination control among the Ad-hoc microgrids. To verify the effectiveness of the proposed control approach, simulation results with Matlab/Simulink are presented.

Keywords—microgrid, networked Ad-hoc microgrids, coordinated control, Quasi-SoC balancing control, natural disaster.

I. INTRODUCTION

Natural disasters, such as earthquakes, tsunamis, and hurricane, are the major causes of large-scale power outages around the world. For example, the earthquake and tsunami occurred in Japan in 2011 caused 2.6 million households were without power supply [1]. In August 2019, an earthquake in Java Island, Indonesia resulted in a 9-hour blackout affecting 21.3 million 8620 customers including industries, mass rapid transit, and telecommunication system [2]. On 16th March 2022, the earthquake happened near Tokyo put more than 2 million homes in darkness [3]. Following the Turkey's earthquakes on 20 Feb. 2023, its southern province of Hatay has been plunged into complete darkness [4]. In 2021, a total of 367 major natural disasters occurred worldwide, affecting 127 countries and regions [5]. A resilient electrification system capable to deal

with natural disasters is highly desirable and renewables-based scalable and resilient microgrids can be a key solution in this regard. After a disaster, the main grid may blackout and gensets are shut down for security reasons. In this situation, low-power portable containerized microgrids can provide an emergency solution so that during two or three days, electricity and/or portable water pumps can be provided to relieve the damaged area.

Resilience and recovery in front of extreme grid faults are still a technical challenge for microgrids to deal with natural disasters. Several research works consider the microgrids operation, control, and energy management in normal operating conditions. However, microgrids performance during high impact low probability (HILP) events including natural disasters are not deeply investigated [6]. Recent works show that overall availability, robustness, and resilience of the power system can be enhanced via microgrids by a) service restoration [7], [8], b) reconfigurable network formulation [9], [10], c) robust control and flexible stability margins [11], and d) preventive self-healing and adaptability to the hazard environmental conditions [12]. For instance, [13] investigates the ability of MGs for restoring electricity services through islanded operation in case of HILP events, using advanced Monte Carlo simulations along with Markov's process on a standard IEEE-118 bus system. Similarly, [14] shows the enhanced resiliency of the power system to keep serving critical loads during extreme weather conditions via MG network formation.

To maintain power supply to critical loads to avoid further losses of life, livelihoods, and services after natural disasters, Ad-hoc microgrids that are mobile, can be in situ deployed, and containerized to supply energy for emergency clinic support and clean water provision are a reasonable and feasible microgrid formation. The coordinated control for renewable energy resources (REs) and energy storage systems (ESSs) within an Ad-hoc microgrids is necessary to maintain a stable operation and to ensure a sustainable as well as a reliable power supply to the critical loads. Several coordinated control strategies for

state-of-charge (SoC) balance in a microgrid have been proposed [15]–[19] for centralized or distributed topologies by means of combining communication technology with hierarchical control. However, different from the existing studies in which only ESS units are considered, in the case of Ad-hoc microgrids, RE and ESS units are included in each Ad-hoc microgrid. Thereby, two layers coordinated control strategies for REs and ESSs within an Ad-hoc microgrid and for the networked Ad-hoc microgrids which are connected to a critical load need to be further investigated to avoid interactions between the internal coordination for RE and ESS and high-level regulations for networked Ad-hoc microgrids. Moreover, in the contexts of natural disasters, coordinated control methods without communication links or with limited communication loads are challenges by considering the potential damages on communication facilities and power consumption limitations.

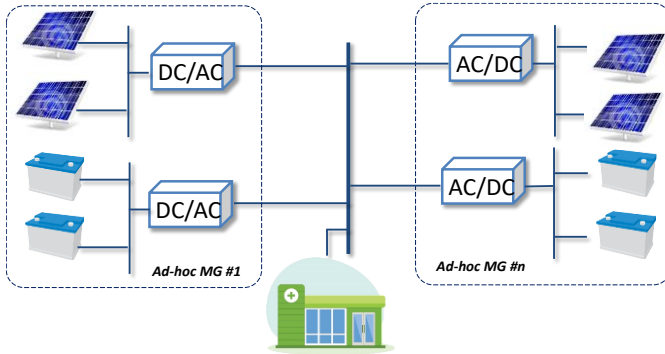


Fig. 1. Networked Ad-hoc microgrid case-study scenario.

In this paper, a novel two-layer coordinated control for networked Ad-hoc microgrids is proposed. The first layer deals with the internal coordination between RE and ESS to maintain a stable operation within an Ad-hoc microgrid by using bus frequency as the regulation signal, thereby without communication links. When forming the networked Ad-hoc MGs, the regulations on the bus frequency from each Ad-hoc microgrid may result in instability. Therefore, a quasi-SoC balancing controller for networked Ad-hoc microgrids is proposed to mitigate the interactions caused by the internal coordination control among the Ad-hoc microgrids. At the second layer, only binary information exchanged is needed with light communication load and low power consumption.

The paper is organized as follows. Section II introduces the configuration of the networked Ad-hoc microgrids. Section III presents the control strategy for a single Ad-hoc microgrid. Section IV introduces the proposed coordinated control strategy for the networked Ad-hoc microgrids to provide sustainable power supply to the critical loads against natural disasters by achieving quasi-SoC balancing among the Ad-hoc microgrids. Simulation results are shown in Section V in order to evaluate the feasibility of the proposed. Section VI concludes the paper.

II. NETWORKED AD-HOC MICROGRIDS CONFIGURATION

A photovoltaic (PV)-ESS-based networked Ad-hoc MG case-study scenario is shown in Fig. 1. Since Ad-hoc microgrids are expected to supply to the critical loads for at least three days where the utility grid is damaged after nature disasters, the Ad-

hoc microgrids will operate in autonomous mode. Each Ad-hoc microgrid composes of PV panels and ESS units and is mobile, can be in situ deployed. For a small clinic or a water purify camp, one Ad-hoc microgrid could be used. However, for a clinic or a water purify station with larger capacities, multi-Ad-hoc microgrids need to be interconnected to form the networked Ad-hoc microgrids to ensure an adequate power supply.

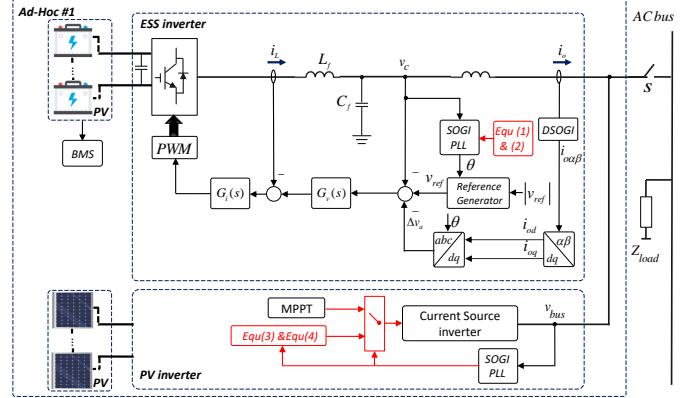


Fig. 2. Control strategy for a single-phase Ad-hoc microgrid

During daylight, the ESSs in an Ad-hoc microgrid, which operates as a grid-forming unit, can operate in charging or discharging mode to maintain power balance between the PV panels and local loads and supply to the critical loads during the power outage. To prevent operation failure of ESSs, coordinated controllers are required for the PV and ESS units within an Ad-hoc microgrid and then within the networked Ad-hoc microgrids respectively to maintain not only an adequate power but also a reliable power supply.

III. CONTROL STRATEGY FOR A SINGLE AD-HOC MICROGRID

Fig. 2 shows the overview of the control strategy for a single-phase Ad-hoc MG. As observed, the power stage consists of a two-leg single-phase inverter connected to a DC link, loaded by an L_f - C_f filter and an RLC load, and connected to the utility grid by means of a power line. A voltage reference signal composed of a constant voltage magnitude reference and the phase output from the second order generalized integrator (SOGI) synchronous reference frame-based PLL (SRF-PLL) is used.

Since an Ad-hoc microgrid operates in islanded mode after the natural disasters, the power exchange among RE units, ESS, and loads should be balanced inside the Ad-hoc microgrid in order to keep the stable operation. Therefore, a coordinated power control strategy is used based on the SoC of ESS, power available from the PV panels, and the power demand [20], [21]. In order to keep the minimum power consumption and reliable operation, communication-less control strategy is employed by using frequency as a bus-signal for the coordinated control. Therefore, only local measurements, which indicates a decentralized control manner, are needed for power distribution among Ad-hoc microgrid elements.

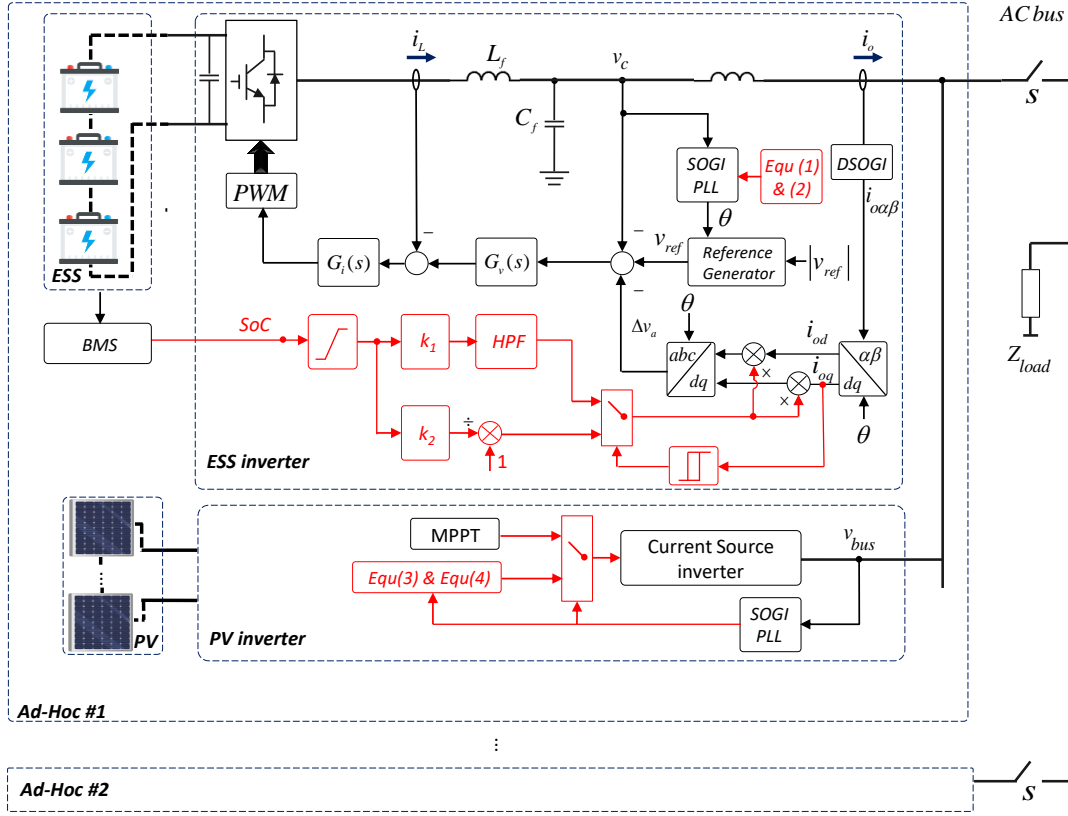


Fig. 3. Proposed control strategy for the networked Ad-hoc microgrids.

A. Relationship between SoC and frequency

As aforementioned, frequency is used as a bus-signal and a mathematical relationship is created to link the SoC variation with the bus frequency, as shown below [20], [21].

$$f = f_o + (SoC - SoC_{oMPP}) \frac{\Delta f_{\max}}{\Delta SoC_{\max}} \quad (1)$$

$$\begin{aligned} f_o &= 50\text{Hz}, \quad SoC_{oMPP} = 0.8 \text{ or } 1 \\ \Delta f_{\max} &= 0.2\text{Hz}, \quad \Delta SoC_{\max} = 0.175 \end{aligned} \quad (2)$$

f_o is the original bus frequency. SoC_{oMPP} is the SoC start point with the maximum power point tracking (MPPT) control at the PV side. Δf_{\max} is the maximum frequency deviation and ΔSoC_{\max} is the maximum SoC deviation. It can be derived from (1), when SoC increases, bus frequency f increases with the designed ratio. Therefore, bus frequency f can be used to indicate the SoC variations.

B. Relationship between SoC and frequency

A relationship between bus frequency and PV output current is created by using the following equations [20], [21].

$$\begin{aligned} i &= i_{MPP} - \frac{i_{MPP}}{\Delta SoC_{\max}} \frac{\Delta SoC_{\max}}{\Delta f_{\max}} (f - f_o) \\ &= i_{MPP} - \frac{i_{MPP}}{\Delta f_{\max}} (f - f_o) \end{aligned} \quad (3)$$

$$\begin{cases} i_{PV} = i_{MPP_PV}, & SoC < 0.8 \text{ or } < 1 \\ i_{PV} = i_{MPP} - \frac{i_{MPP}}{\Delta f_{\max}} (f - f_o), & SoC \geq 0.8 \text{ or } = 1 \end{cases} \quad (4)$$

It can be derived from (3) and (4), when SoC is below 0.8, the power generation of PV systems follows MPPT algorithm. When SoC is equal to or larger than 0.8, the PV output decreases according to the bus frequency. Since the bus frequency is changing according to the SoC, PV output links to SoC variations. Thereby, the variations of bus frequency can be measured to indicate the SoC changes, and then to further regulate the PV outputs in islanded operation to maintain a stable operation and to ensure a sustainable as well as a reliable power supply to the critical loads.

IV. COORDINATED CONTROL STRATEGY FOR NETWORKED AD-HOC MICROGRIDS

In case of a large capacity critical load demand which cannot be covered by only one Ad-hoc microgrid, for instance a water purify station, the networked Ad-hoc microgrids is necessary. In order to maintain both stable operation with the coordinated control between PV systems and ESSs within a single Ad-hoc microgrid and among the networked Ad-hoc microgrids, the above-presented coordinated control method needs to be further improved to achieve the coordinated SoC control and to avoid the potential instability caused by the simultaneous bus frequency regulation of the interconnected Ad-hoc microgrids. A Quasi-SoC balancing control is proposed in this paper to maintain the stable and coordinated operation for the networked

Ad-hoc microgrid, as shown in Fig. 3. The control strategy for the PV panel interfaced inverters maintains the same as the one in Fig. 2. However, the controller for the ESS units is improved with an adaptive virtual impedance loop which is linked with their SoC values. The proposed controller aims to regulate the virtual resistance of the Ad-hoc microgrids according to their SoC respectively ($V_{R1} * i_1 = V_{R2} * i_2$), thereby regulating the output power from each Ad-hoc microgrid.

A. Charging mode

The maximum power charging and quasi-SoC balancing control with only binary data communication link with insignificant power consumption is employed in the charging mode with the following control principles:

- the smaller the SoC, the larger the charging current, and the smaller the virtual resistance
- the larger the SoC, the smaller the charging current, and the larger the virtual resistance

The voltage raise caused by the virtual resistance can be restored by using a high pass filter to maintain power quality as shown in Fig. 3.

B. Discharging mode

In the discharging mode, the quasi-SoC balancing control is used with the following control principles:

- the smaller the SoC, the smaller the discharging current, and the larger the virtual resistance
- the larger the SoC, the larger the discharging current, and the smaller the virtual resistance

In addition, a hysteresis/delay is used to avoid interaction and frequent mode transition between charging and discharging modes.

V. SIMULATION RESULTS

In order to verify the effectiveness of the proposed control strategies for networked Ad-hoc MGs. The simulation model is developed based on Fig.3 in Matlab/Simulink. The simulation model is composed of two paralleled Ad-hoc MGs and a common load. Each Ad-hoc MG consists of a set of PV panels and a battery bank. The control parameters of simulation model are shown in the Table I. Clinic Mata Kuta in Lombok, Indonesia, is selected as the study case in this paper. The load profile is a combination of a typical clinic load profile with the maximum capacity of Clinic Mata Kuta.

A. Simulation results of an Ad-hoc microgrid supplying a critical load

Fig. 4 shows the simulation results of an autonomous operated single-phase Ad-hoc microgrid supplying a critical load. It's assumed that the natural disaster causes a power outage for three days, the designed single-phase Ad-hoc MG, which consists of a 30kWp PV panels and a 60kWh ESS with the minimum 20% SoC limit, operates as the solo power source to maintain stable power supply to the clinic Mata Kuta for three days. Fig. 4 (a) shows the power outputs from the PV panels during the three days. Fig. 4 (b) shows the load profile and Fig. 4 (c) shows the SoC of the ESS during the three days. It can be

seen that the battery and PV system can maintain stable power supply during the outage. Even though the PV output is limited on the third day, the ESS continuously discharges to supply the load demand and remains above the 20% minimum SoC limit.

TABLE I. CONTROL PARAMETERS OF SIMULATION

	Parameters		Value
		Description	
ESS inverter	V_{dc}	DC Voltage	400 V
	L_f	Filter Inductance	0.4 mH
	C_f	Filter Capacitance	3.3 μ F
	C_{bat}	Capacity of ESS	130 AH
PV inverter	L_{if}	Inverter side Filter Inductance	0.2 mH
	C_f	Filter Capacitance	3.3 μ F
	L_{gf}	Inverter side Filter Inductance	0.1 mH
Controller (ESS)	k_{pv}	Voltage proportional term	0.01
	k_{iv}	Voltage resonant term	3
	k_{pi}	Current proportional term	0.0025
	k_{pPLL}	PLL proportional term	32.5
	k_{iPLL}	PLL integral term	438.3
	ω_{HPF}	Bandwidth of HPF	5 rad/s
	k_1	Virtual resistance (charging)	5.5 Ω
Controller (PV)	k_2	Virtual resistance (discharging)	0.1 Ω
	k_{pi}	Current proportional term	0.003
	k_{ji}	Current resonant term	0.03
	k_{pPLL}	PLL proportional term	32.5
Secondary	k_{iPLL}	PLL integral term	438.3
	$k_{p\omega_{inv}}$	Sync. proportional term for ω	1e-4
	$k_{i\omega_{inv}}$	Sync. integral term for ω	5e-4
	$k_{pE_{inv}}$	Sync. proportional term for E	10
	$k_{iE_{inv}}$	Sync. integral term for E	20

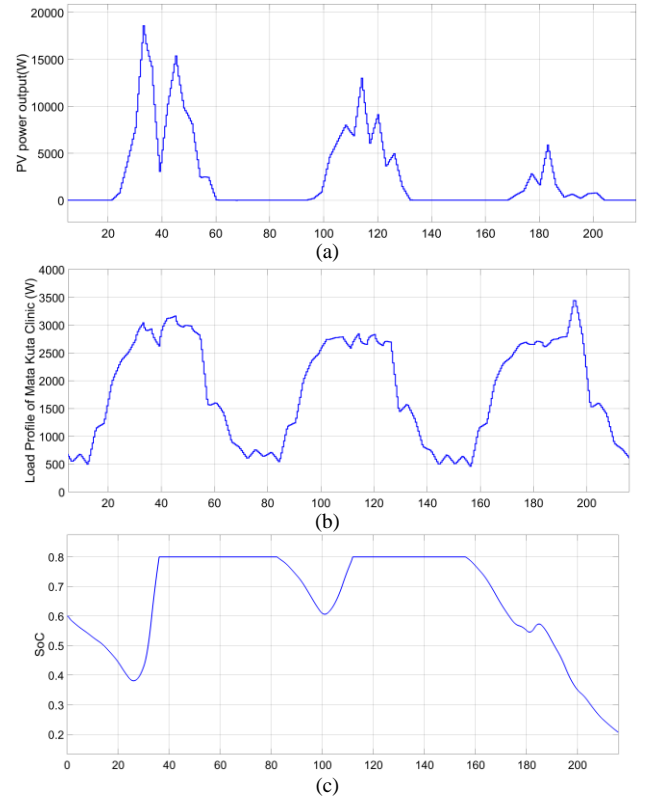


Fig. 4. Simulation results of an Ad-hoc microgrid supplying a critical load for three power outage days. (a) power outputs from the PV panels; (b) load profiles; (c) SoC of the ESS.

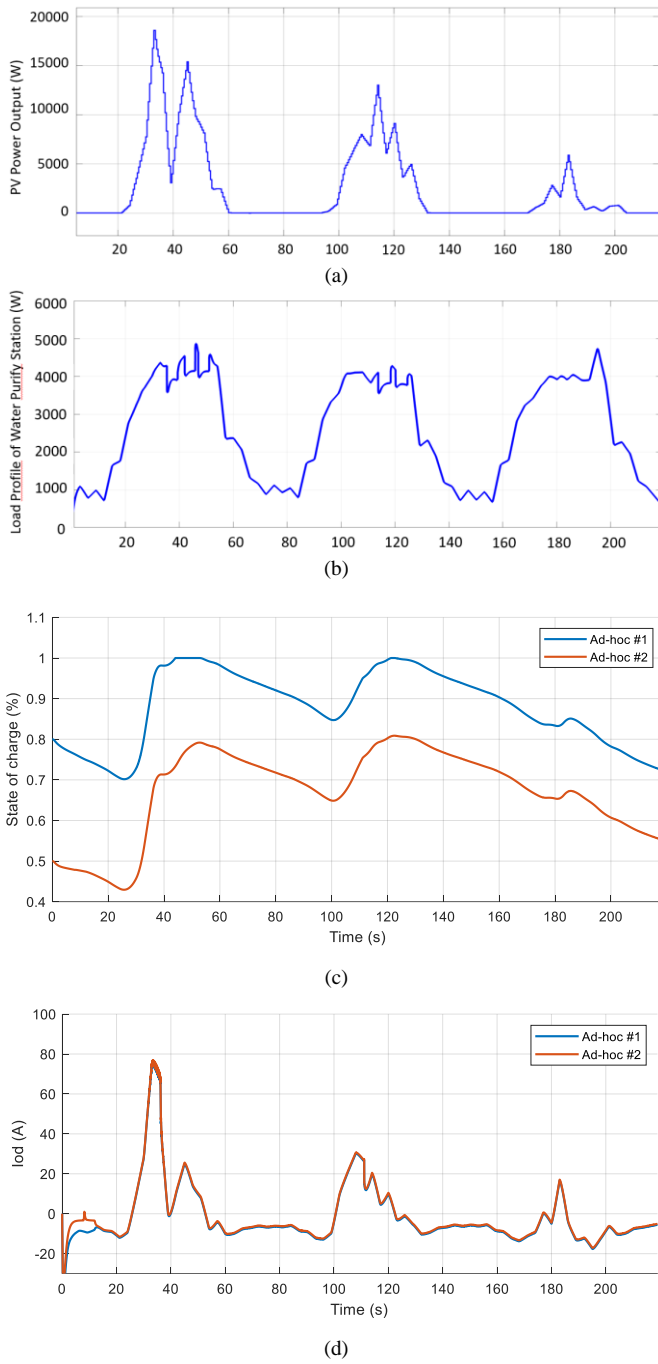


Fig. 5. Simulation results of the networked Ad-hoc microgrids supplying a critical load for three power outage days without the proposed quasi-SoC balancing control. (a) power outputs from the PV panels; (b) load profiles; (c) SoC of the ESS units; (d) d-axis current outputs.

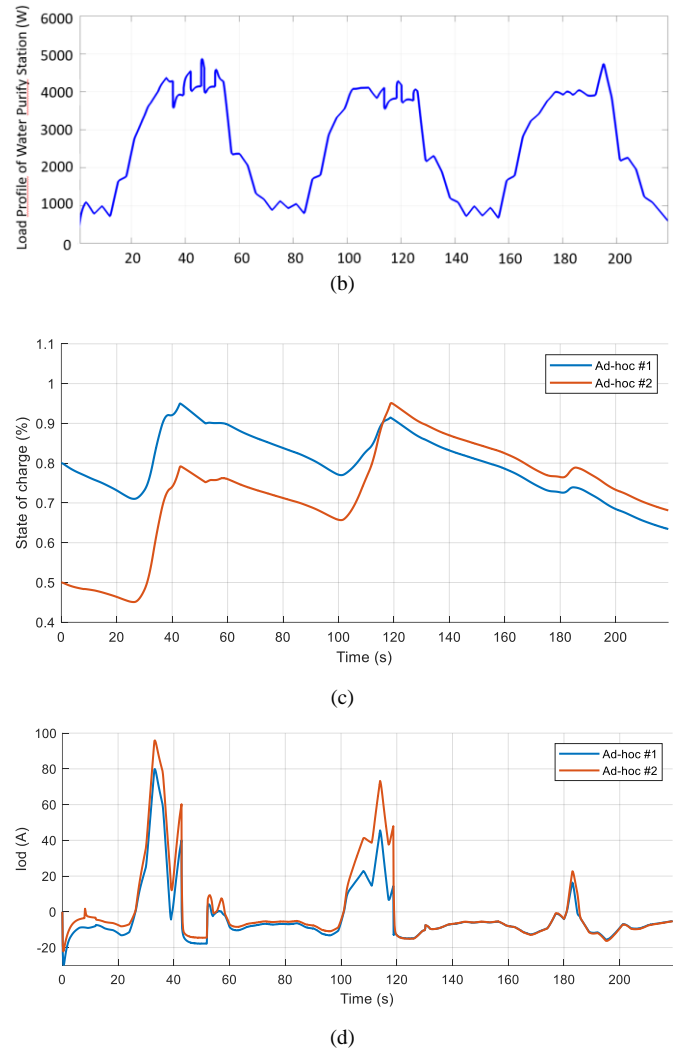
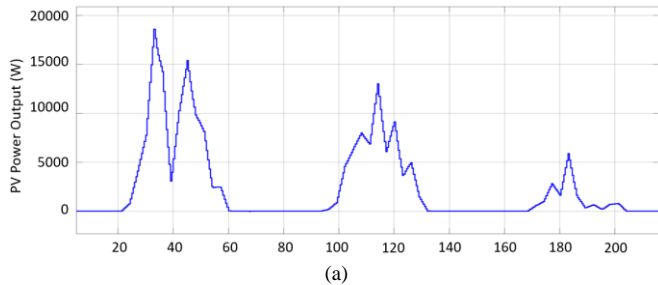


Fig. 6. Simulation results of the networked Ad-hoc microgrids supplying a critical load for three power outage days with the proposed quasi-SoC balancing control. (a) power outputs from the PV panels; (b) load profiles; (c) SoC of the ESS units; (d) d-axis current outputs.

B. Simulation Results of the Networked Ad-hoc Microgrids Supplying a Critical Load without the Proposed Quasi-SoC Balancing Control

Fig. 5 shows the simulation results of the parallel connected Ad-hoc microgrids supplying a critical load without the proposed method. It can be seen that the ESS units and PV systems can maintain stable power supply during the outage in this case. However, it needs to be noted that instability may occur without the proposed coordination control if an increased frequency regulation ratio is employed. As observed in Fig. 5 (c), the SoC values of the two ESS units of the interconnected Ad-hoc microgrids are maintain in parallel. It is because that the direct current outputs (I_{od}) of the interconnected Ad-hoc microgrids are the same as shown in Fig. 5(d). The Ad-hoc microgrid #2 with smaller initial SoC has to be shut down firstly once it is out of power, which may result in operation fault caused by the overload of the remaining Ad-hoc microgrid #1.

C. Simulation Results of the Networked Ad-hoc Microgrids Supplying a Critical Load with the Proposed Quasi-SoC Balancing Control

Fig. 6 shows the simulation results of the parallel connected Ad-hoc microgrids supplying a critical load with the proposed quasi-SoC balancing control. It can be seen that the ESS units and PV systems can maintain stable power supply during the outage. As observed in Fig. 6 (c), the SoC values of the two ESS units of the interconnected Ad-hoc microgrids are progressively converged in both charging and discharging modes by regulating the virtual impedance and current outputs thanks to the proposed quasi-SoC balancing control. As observed in Fig. 6 (d), the direct current outputs (I_{od}) of the interconnected Ad-hoc microgrids are different as they are dynamically adjusted depending on the regulatable virtual resistances and the SoC values of the Ad-hoc microgrids.

VI. CONCLUSIONS

Two-layer coordinated control strategy for single and networked Ad-hoc MGs are proposed in this paper to maintain stable and sustainable power supply to the critical loads after natural disasters. A quasi-SoC balancing control is proposed for the networked Ad-hoc microgrids to achieve the coordinated SoC control and to avoid the potential instability caused by the simultaneous frequency regulation. Simulations results validate the effectiveness of the proposed control methods.

ACKNOWLEDGMENT

This work was supported by Tech-IN project (Granted by Danish Ministry for foreign affairs and supported by Danida Fellowship Centre Under grant #20-M06-AAU); www.energy.aau.dk/tech-in.

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