Study on the impact of power sharing between microgrids on the usage of renewable energy and system stability

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***Abstract*—In order to satisfy the future growth of energy demand and to utilize the unstable renewable energy (such as solar, wind, tide, etc.) power generation more efficiently, it is important to improve the utilization of renewable energy. In this paper, we focus on the impact of power sharing between autonomic decentralized coordination control (ADCC) based microgrids on energy efficiency and on system stability (outage time) under two scenarios (power sharing between on-grid and off-grid, and between off-off-grid). We built a DC bus connection switch based power sharing model between close microgrids in MATLAB/Simulink and simulate the interconnection scheme. At the same time, we considered different voltage levels of existing DC microgrids and carry out the power sharing between microgrids of different voltage. As a result, we achieve about 3.3 MWh of power being used efficiently in the on-off microgrid power sharing scheme in a year and the overall system stability in the off-off microgrid power sharing scheme is improved.**

***Index Terms*—power-sharing, microgrid, renewable efficiency, autonomous-decentralized-cooperative-control**

I. Introduction

As the earth's population expands and developing countries industrialize, the demand for energy has reached unprecedented level. As of 2019, nearly 760 million people in the world still do not have access to electricity due to inadequate geographical and harsh environmental [1]. A reasonable solution is to expand the distribution of microgrids so that energy can be shared over a wider area. On the other hand, this method of energy sharing can also lead to more efficient use of unstable renewable energy. For a standalone photovoltaic system, excess solar energy is often discarded when it cannot be charged in batteries. In a power sharing system, this excess power can be transferred to other microgrids, and the shared power is used more efficiently for the whole system, thus improving the usage of renewable energy.

This research was supported by JST OPERA Prog. "Creation of R-EIC (Resilient-Energy-Information-Communication) Converged Network Infrastructure based on Overall Optimization of Autonomous Distributed Decentralized Cooperative DC Microgrids" (JPMJOP1852).

From the consumer's view, energy efficiency can be improved simply by reducing the amount of energy purchased to save money.

DC microgrids have been widely noticed for their proven advantages over AC microgrids in terms of reactive power flow and frequency synchronization. There is no standard voltage for DC microgrids, and the more commonly used voltage are 380 V [2], [3] and 400 V [4]. Maintaining the stability of the DC bus voltage of DC microgrid has been a challenging topic. The control methods of DC microgrids are classified into centralized control [5], decentralized control [6], and distributed control [7], etc. The ADCC based microgrid is a kind of DC microgrid control method proposed by our team [8], [9] (that can stabilize DC bus voltage by Li-ion battery which is directly connected to the bus without DC/DC converter), compared with the traditional control methods, this control method has many advantages such as better handling of single point fault, better control ability of the whole group, and simpler control operation. When the grid is connected to the utility grid (on-grid), loads that cannot be met can be supplied by the utility grid. When the microgrid is not connected to the utility grid (off-grid), the load can only be balanced by expanding the size of the battery or PV.

In this paper, we consider ADCC based microgrids with different bus voltage levels and discuss the improvement in energy efficiency and DC bus voltage stability of the two power sharing schemes (1. on-off grid power sharing; 2. off-off grid power sharing) based on power lines, respectively.

II. DC Microgrids Description

As shown in Fig. 1 (a), the ADCC based microgrid in which a combination of solar panels and Li-ion batteries is used to balance the load. For the ADCC based microgrid with DC bus of 380 V, the switching voltages are set to 360 V and 400 V.

Since in ADCC based DC microgrid, the voltage of DC bus is controlled according to the fact that the state-of-charge (SoC) shows nearly linear characteristics to the output voltage of battery. Fig. 1 (b) shows the discharge curve of 1-cell Li-ion battery. For a DC bus voltage of 380 V, about 120 Li-ion battery cells are required.

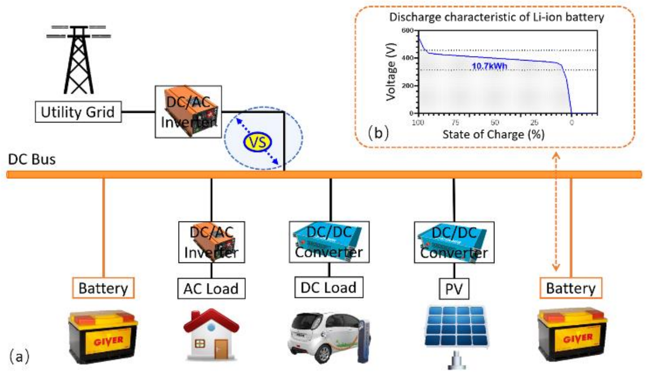

Fig. 1. (a) DC bus with distributed-loading batteries and (b) Discharge characteristic of 1-cell Li-ion battery.

III. Power sharing operation using DC bus connection switch

The proposed schematic diagram of power sharing operation between two microgrids in close proximity is shown in Fig. 2. For two microgrids with different bus voltages connected by power lines, one at 380 V and the other at 400 V, a few kilometers apart, some rules must be followed at the DC bus connection switch which will be discussed in the follow sections.

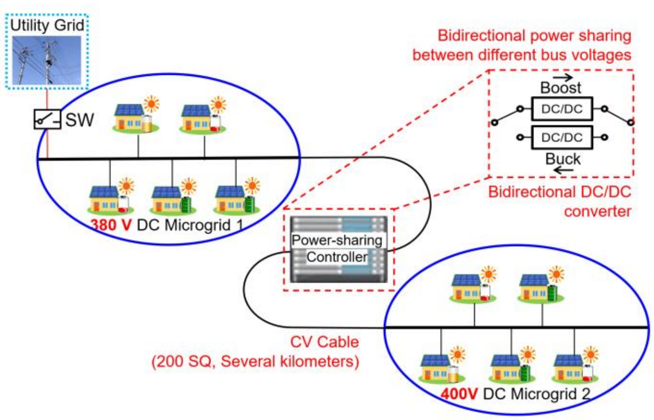

Fig. 2. Schematic diagram of power sharing between two microgrids in close area.

A. Power-sharing Controller

In a power line based power sharing scheme, bidirectional DC/DC converters need to be used to match the voltage and compensate for the voltage drop due to the power line in order to share the power between different DC bus voltages.

Fig. 3 shows a simple current source model of the DC bus connection switch. For example, in order to transfer P_1 from Bus1 to Bus2, a current of $I_1 = P_1/V_1$ is drawn from the port on the Bus1 side of the switch, and a current of $I_2 = \eta P_1/V_2$ flows into Bus2 from the port on the Bus2 side. η represents the transmission loss. The switch operates to transmit power between grids only when a certain threshold value is reached.

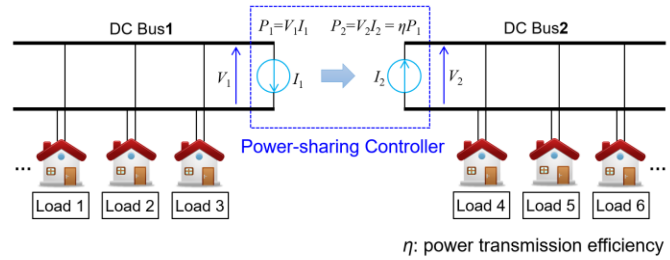

Fig. 3. Control scheme of power tide to or from the local grid

B. Transmission loss

Since the power transmission is operated at a low DC bus voltage (between 350 and 400 V), the transmission loss cannot be negligible over long distances. For example, even if a very thick CV cable with a core cross-sectional area of 200 SQ (permissible current: about 500 A) is used, its resistance is about 0.12 Ω/km. When the power of 10 kW is transmitted at a voltage of 380 V, the transmission loss about 170 W will occur over a distance of 1 km, and about 1.7 kW over a distance of 10 km will be lost as joule heat. Therefore, the practical limit of power sharing using a CV cable is about a few kilometers. As for the power conversion efficiency of bi-directional DC/DC converters, the conversion efficiency of such devices on the market is 98% for good and 95% for bad. Therefore, the conversion efficiency is assumed to be 90% considering above situations.

C. Power-sharing Method

The process of power sharing operation is shown in Fig. 4. First we measure the voltages of the two DC bus at a time interval (Δt) and this message will be sent to the power-sharing controller. Then, the SoC status of the overall batteries in two grids is assumed and compared based on their bus voltages. When the difference in SoC between the two grids is greater than the threshold value (ΔSoC), power will be shared from the bus with the higher SoC to the bus with the lower SoC in Δt. The power to be transferred was set to be proportional to the difference in SoC between the grids ($P = P_0 \times |\Delta SoC|$), and no power sharing operation is performed when this condition is not satisfied. A similar process will be operated in the next time interval.

D. Evaluation Indicators

To compare more comprehensively the utilization of renewable energy in different scenarios and the stability of the DC bus voltage, we defined the following three indicators.

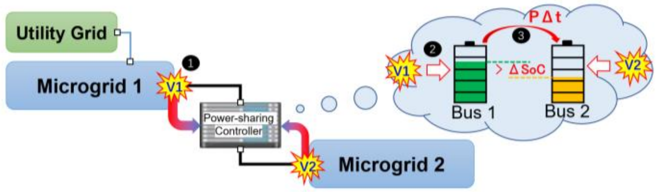

Fig. 4. Algorithm of the power sharing operation

1) Renewable energy ratio $\left(\eta_{RE,n}^{prop}\right)$*:* Renewable energy ratio represents the proportion of power consumption that is accounted for PV arrays where n represents the microgrid number (1, 2). For on-grid, the load demand (P_{cons}) is mainly satisfied by the utility grid (P_{from}) and solar energy. Therefore, this value can be defined as the proportion of the load demand excluding the portion from the utility grid as in (1). For off-grid, this value is 1.

$$\eta_{RE,n}^{prop} = \frac{P_{cons}-P_{from}}{P_{cons}} \quad (1)$$

2) Renewable Energy Utilization $\left(\eta_{RE,n}^{usage}\right)$ *:* Renewable Energy Utilization is defined as the percentage of power generated by PV arrays that is consumed in the local DC grid as shown in (2). In the case of power integration, it is also necessary to consider the amount of power transmitted to the adjacent grid. P_{used} represents a different meaning in the on-/off- grid. The unused solar energy in on-grid is sold to the utility grid, while the excess PV generation in off-grid is discarded.

$$\eta_{RE,n}^{used} = \frac{P_{used}}{P_{PV}^{potential}} \quad (2)$$

The P_{used} in the equation represents a different meaning in the on-/off- grid. The unused solar energy in on-grid is sold to the utility grid, while the excess PV generation in off grid is discarded.

3) Outage time $\left(T_{o,n}\right)$*:* Here, the Outage time $\left(T_{o,n}\right)$ is defined as the number of hours that the load cannot be satisfied (outage occurs) in a year (8760 h), taking into account the differences in generation and power consumption in different seasons as shown in (3). This can also represent the stability of the DC bus voltage.

$$T_{o,n} = \sum_{h=1}^{8760} U(h) \quad (3)$$

Where, $U(h)$ represents the number of hours in which outage occurs (h).

IV. Power Sharing Between On- and Off- Grids

Two ADCC based DC microgrids with bus voltages of 380 V and 400 V powered by solar panels are assumed as shown in Fig. 2. Each microgrid contains five three-person households with an average monthly electricity consumption of 300 kWh. The power consumption of the load is a sequence formed by random numbers satisfying a regular distribution. The grid with a bus voltage of 380 V is an on-grid that is connected to the utility grid, and each of the five houses is equipped with a PV with a rated output of 4 kW and a Li-ion battery with a capacity of 15 Ah. The grid with a bus voltage of 400 V is an off-grid with no connection to the utility grid processing a PV of 7 kw and a battery of 150 Ah as listed in the following Table Ⅰ. For an off-grid, a 150 Ah battery which ensures 6-days load consumption is a very large battery, comparable to an EV car battery. However, this value is necessary to ensure the DC bus stability. It is noticed that for a distance of a few kilometers, the irradiance of the two grids can be considered to be the same. For off-grid, excess generation discarding and load shedding will be held to ensure the stability of the DC bus voltage. Regarding the parameters of power sharing, we set the ΔSoC threshold to a relatively large value of 20% and set P_0 to 10 kWh, considering the rapid change of SoC in on-grid.

TABLE I
Simulation parameters of power sharing between on-and off-grid

	PV	Battery	Load	DC bus voltage
off grid	7 kW	150 Ah	No. 1-5	400 V
on grid	4 kW	15 Ah	No. 6-10	380 V

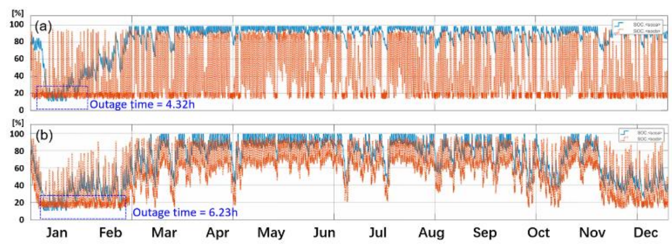

Fig. 5. Changes in SoC of both grids with (a) no power sharing and (b) power sharing based on DC bus voltage presumption.

Changes in SoC based on DC bus voltage presumption of both grids with (a) no power sharing and (b) power sharing are shown in Fig. 5. The blue curve shows the SoC change in 400 V off-grid, and the orange represents that in 380 V on-grid. In the off-grid without power sharing as shown in Fig. 5 (a), the PV generation is surplus most of the time with the battery maintaining a high level of SoC, the PV is forced to stop generating power. Power outages tend to occur at the beginning due to the lack of power generation in winter. For on-grid with a small battery, the SoC changes relatively frequently, and the loads are often supported by the utility grid in either form of receiving or sending power. In the case of power sharing as shown in Fig. 5 (b), the SoC of both grids are equalized and change slowly, and the surplus power from PV generation on the off-grid side will be used on the on-grid side. In terms of outage time, it is evident that the power sharing has increased the hours of outage occurs, because off-grid has transferred power during winter even when there is a shortage of power generation.

TABLE II

COMPARISON OF ANNUAL ELECTRICITY CONSUMPTION OF THE TWO OF THE ON- AND OFF- GRIDS WITH AND WITHOUT POWER SHARING

		Without power sharing [MWh]	With power sharing [MWh]	Difference [MWh]
on grid	PV Generation	18.64	18.64	0
	Load consumption	17.17	17.17	0
	Power from utility grid	4.63	1.78	-2.85
	Power to utility grid	5.93	7.88	+1.95
	Share in power	0	5.62	5.62
	Share out power	0	0.83	0.83
off grid	PV Generation	18.63	23.94	+5.3
	Load consumption	18.58	18.51	0.07
	Share in power	0	0.73	0.73
	Share out power	0	6.24	6.24

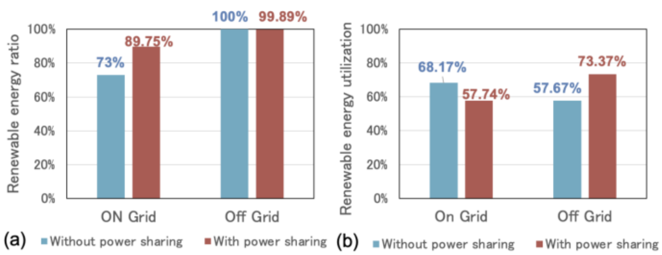

Fig. 6. (a) Renewable energy ratio and (b) Renewable Energy Utilization Ratio in the two ACC based microgrid without and with power-sharing.

Table Ⅱ records the amount of PV generation, power consumption, power from and to utility grid, and power transferred between the two grids without and with power sharing operation. Based on the 2019 irradiance data for Sendai City, PV generation rated at 4 kW and 7 kW will have an annual generation potential of 18.64 MWh and 32.6 MWh, respectively. The annual power transfer between the two grids is about 7 MWh, which means that the off-grid side transmits most of the excess power to the on-grid due to the large amount of off-grid PV generation in summer, this leads to about 5.3 MWh additional PV generation. On the other hand, on the on-grid side, the power to utility grid increases by 1.95 MWh due to the power sharing operation, but at the same time, the power from utility grid decreases significantly to about 2.85 MWh. The evaluation indicators related to energy efficiency are calculated as shown in Fig. 6. On-grid power sharing increases the renewable energy ratio by 16.75% (from 73% to 89.75%, equivalent to 2.6 MWh), while in off-grid, this indicator slightly decreases because about 20 kWh of the power transferred from on-grid power sharing is non-renewable. On the other hand, the renewable energy utilization decreases by about 10% (1.94 MWh) in on-grid because a part of the power received is not used but sent directly to the utility grid. However, PV utilization in off-grid is about 16% (5.3 MWh) higher. Thus, in total, about 6% (3.3 MWh) of PV generation is effectively utilized by the power sharing operation.

V. POWER SHARING BETWEEN OFF- AND OFF- GRIDS

In this section, to investigate the power sharing performance between off- and off-grid, simulation is held with the following parameters as shown in Table Ⅲ. Here, a relatively small ΔSoC threshold (10%) is set due to the slowly changes in SoC and P_0 is set to 20kWh to ensure the same shared power.

TABLE III

SIMULATION PARAMETERS OF POWER SHARING BETWEEN OFF-AND OFF-GRID

	PV	Battery	Load	DC bus voltage
off grid 1	7 kW	150 Ah	No. 1-5	400 V
off grid 2	7 kW	150 Ah	No. 6-10	380 V

TABLE IV

COMPARISON OF ANNUAL ELECTRICITY CONSUMPTION OF THE TWO OF THE OFF- AND OFF- GRIDS WITH AND WITHOUT POWER SHARING

		Without power sharing [MWh]	With power sharing [MWh]	Difference [MWh]
off grid 1	PV Generation	18.64	18.68	+0.04
	Load consumption	17.17	18.86	+1.49
	Share in power	0	0.11	
	Share out power	0	0.08	
off grid 2	PV Generation	17.18	17.23	+0.05
	Load consumption	17.17	17.17	0
	Share in power	0	0.07	
	Share out power	0	0.13	

TABLE V

COMPARISON OF OUTAGE TIME AND RENEWABLE ENERGY UTILIZATION OF THE OFF- AND OFF- GRIDS WITH AND WITHOUT POWER SHARING

		Without power sharing	With power sharing	Difference
off grid 1	Outage time	4.32 h	2.13 h	-2.19h
	Renewable energy utilization	57.13%	57.26%	+0.13%
off grid 2	Outage time	0 h	0 h	0 h
	Renewable energy utilization	52.66%	52.81%	+0.15%

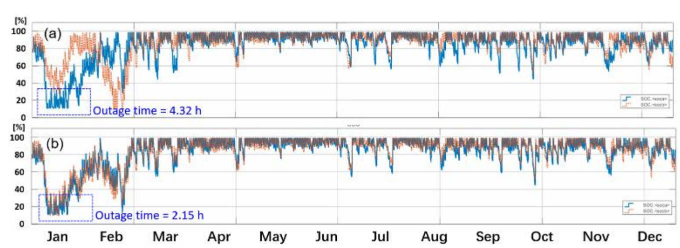

Fig. 7. Changes in SoC of off- and off- grids with (a) no power sharing and (b) power sharing.

In the simulation for both off-grids, we used the exact same parameters except for the load consumption variations and the comparison of annual power consumption between the two grids with and without power sharing is shown in Table Ⅳ.

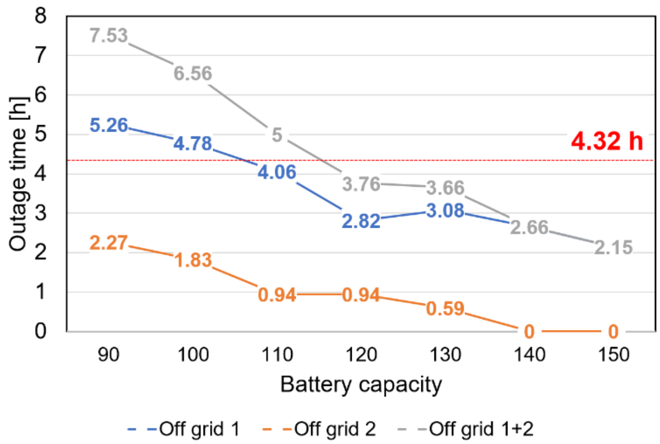

Fig. 8. DC bus voltage stability versus Li-ion battery capacity

The energy efficiency improvement is very limited due to the low power exchange of a few hundred kWh, with an average improvement of 0.14% as shown in Table Ⅴ. From the SoC variation of the two microgrids (as shown in Fig. 7), the battery power is kept at a high level except in winter because of the insufficient PV generation and heavy load demand. The power sharing operation between the two grids also occurs mainly during the winter. Currently, off-grid 1, which was originally unstable, becomes more stable under the effect of power sharing. For off-grid 2, the SoC becomes relatively low in winter but still remains stable. The outage time of the two microgrids are 4.32 h and 2.15 h respectively, where the stability of off-grid 1 is improved by 2.19 h.

Considering the large battery capacity used in the off-grid microgrid and the impact of power sharing on the outage time, we can assume that the battery capacity can be further reduced to make the system more economical while maintaining an acceptable system stability. For off-grid 1 and 2, we measured the outage time by gradually reducing the battery capacity in 10-Ah intervals to obtain a battery capacity comparable to the total outage time for a 150 Ah battery without power sharing operation (4.32 h). The DC bus voltage stability versus Li-ion battery capacity is recorded as shown in Fig. 8. The blue and orange curves represent the outage time of off-grid 1 and off-grid 2, respectively, and the grey curve represents the sum of both. From this figure, it can be found that the outage time of both grids decreases as the battery capacity decreases. At a reduced battery capacity of about 115 Ah, the outage time is close to that of 150 Ah without power sharing (4.32 h). The inflection point at 130 Ah may be due to the fact that the increased outage time at off-grid 2 instead reduces the amount of power that needs to be supplied from off-grid 1. Therefore, it can be concluded that the implementation of power sharing between off- and off-grid can effectively reduce the outage time, on the other hand, the economic efficiency of the system can be improved by reducing the capacity of the batteries while ensuring a certain outage time.

VI. SUMMARY

In this paper, the renewable energy ratio, renewable energy utilization and outage time were calculated and evaluated in two scenarios: on-off-grid and off-off-grid power sharing using power-sharing controller.

In the case of on-off-grid power sharing, the ratio and utilization of renewable energy are significantly improved (about 3.3 MWh of PV power is utilized more efficiency), but the outage time is increased by about 2 h. Power sharing between off- and off- grids offers a smaller improvement in renewable energy share and utilization but can significantly improve system stability by reducing outage time from 4.32 h to 2.15 h. Based on this characteristic, we ensure an acceptable outage time by reducing the battery capacity and find that the stability when the battery capacity is reduced to approximately 115 Ah is consistent with that at 150Ah without power sharing.

In general, the effectivity of power sharing operation on the usage of renewable energy and system stability is demonstrated in both scenarios mentioned above.

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- **The below form will not be published, but it is necessary to help with the review process.**

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