Design and optimization of DC-grids power exchange

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***Abstract*—A dominance-based power exchange mechanism between DC grids has been presented and investigated to enable macro-optimization of power supply capacity. Furthermore, a MATLAB/Simulink simulation model is created to calculate the power loss and renewable energy ratio for the power exchange while taking transmission voltage and transmission power into account. As a result, the proposed power exchange method's effectiveness in terms of power exchange between on- and off-grids is demonstrated. Furthermore, adjusting the aforementioned parameters can lower the amount of power drawn from the utility grid, illustrating the significance of optimizing the parameters to optimize power exchange functioning.**

***Index Terms*—power exchange, microgrid, optimization**

I. INTRODUCTION

In recent years, in the context of global warming and natural disasters [1], and with the development of a smart society [2], there is a growing demand for low carbon emissions, flexibility, disaster resistance, and intelligence in power systems, and therefor there is an urgent need to reform existing power systems. Microgrids based on distributed energy resources (DERs) have attracted much attention due to their potential for power flexibility. A large number of papers have been published to promote the penetration and optimal management of these decentralized grids [3], and several countries and regions have implemented changes to the existing energy and market structures [4].

As a preliminary study to this paper, reference [5] proposes a new system concept that combines decentralized power systems with Information and Communication Technology (ICT) to achieve real-time, flexible, and more efficient control of DC grids through two control levels: autonomous decentralized coordinated control and centralized control. Microgrid groups are distinguished by Mobile Edge Computing (MEC) and a microgrid group usually contains one On-grid and several Off-grids. This power system differs from the market structure of the power system proposed in [6] in that it is a fresh paradigm of combining dispersed power users with the grid in a multi-layer manner. And since the autonomous control mechanism, its control system is less difficult. This research focuses on the optimal analysis of power sharing among microgrids based on this power system configuration.

The optimization analysis of power sharing is a very complex process due to its involvement in new technologies and business models [7]. Currently, there are numerous research assessments and pilot projects on power sharing between electricity producing and consuming customers (prosumers) [8]. However, due to technical constraints (such as the development of power routers [9]), research on power dispatching across microgrids is primarily theoretical, with little technical analysis, and the specific implementation techniques and quantitative evaluation of the effect not yet adequately documented.

Unlike power sharing in a microgrid [10], when power is exchanged between grids, the transmission losses become more significant and higher criteria for energy efficiency are imposed from a system perspective. As a result, in order to minimize transmission losses and maximize the use of renewable energy, a reasonable power exchange plan must be designed and implemented, including optimization of specific parameters such as power cables, transmission voltage, and transmission power.

So far, the autonomous distributed coordinated control (ADCC) of a DC grid based on renewable energy supply has been proposed which features by connecting the battery directly to the DC bus [11]. In this paper, a dominant-based approach for power exchange between such ADCC-based grids is designed, and the parameters to be considered in the power exchange process, such as transmission voltage and power, are further numerically analyzed and optimized in terms of losses and renewable energy use efficiency.

II. POWER EXCHANGE METHOD BETWEEN DC-GRIDS

One method for exchanging power between two DC grids is to increase the voltage of each DC bus and transfer it over a dedicated self-employed power line, as shown in Fig. 1. Bidirectional DC/DC converters are employed in this method to compensate for the voltage drop caused by long-distance power transmission on the one hand, and to reduce power losses caused by cable conductor resistance on the other by boosting the voltage or facilitating the delivery current. In general, while using self-employed power lines, the transmission

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voltage is set at a low voltage range to account for safety factors. As a result, transmission losses are not negligible for long-distance power transfer.

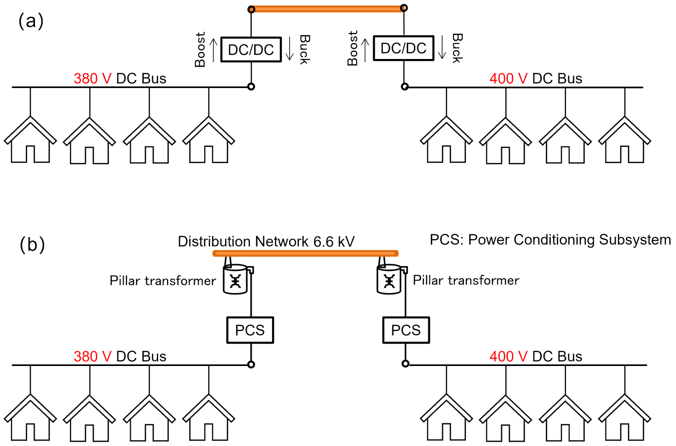

Fig. 1. Schematic diagram of power exchange (a) laying a self-employed DC power line and (b) using existing distribution power grid

Another method is to use the existing distribution power grid. In recent years, the separation of transmission and distribution has started in Japan, and when the 6,600 V distribution network is separated from the existing utility (power company) and operated by an independent company, it will be possible to use the present distribution power grid for power exchange. In this case, as shown in Fig. 1 (b), if power is transmitted from one DC grid to the distribution power grid through a PCS (power conditioning subsystem), and another DC grid connected to the distribution grid receives the same amount of power from the distribution grid at the same time, the supply and demand of power in the existing power grid is not affected. This allows the power to be flexibly transferred between different DC grids without affecting the power supply and demand in the existing power grid.

In contrast to the method of transmitting power via self-employed power lines, the high voltage of the distribution network allows power to be exchanged between grids separated by tens of kilometers. If a 500,000 V high voltage grid can be used, it is possible to transmit power over a much larger area of several hundred kilometers. However, even in this case, the tidal current associated with power exchange flows through the distribution network, so it cannot be used unless the distribution network has a sufficient capacity which means that various factors such as the contract with the power companies, the management, and delivery of power need to be considered. Besides, phase synchronization control is essential. As a result, it is not that simple to implement.

In comparison, in the case of a solution utilizing self-employed power lines, the exchange of power will be more flexible, and the conversion from DC to DC will not require phase synchronization. In addition, this scheme can be considered for connection to off-grid systems.

The advantages and disadvantages of these two methods are outlined in Table. I. In this article, employing the self-employed DC line for power exchange has been investigated based on the aforementioned analysis to develop microgrid networks.

TABLE I

COMPARISON OF THE ADVANTAGES AND DISADVANTAGES OF TWO METHODS OF POWER EXCHANGE

Method	Advantage	Disadvantage
Using self-employed DC power line	• Possible on between any grid (e.g. between off-grids) • Depending on the equipment, it is possible to transmit power freely regardless of the time and amount of power transmission	• Additional power distribution lines and related facilities are needed, which takes time and costs
Using existing distribution power grid	• Possible even at a distance of several kilometers. Further longer distances are possible with the high voltage power grid	• Limited between on-grids • Transmission capacity is limited so as not to burden the power grid

In general, when exchanging power between two DC grids, both grids must cooperate on the technique of exchanging power (when, how much power at what price, etc.). However, if the price is not as essential, like when transferring renewable energy generated power, one party may have the right to make power exchange decisions.

For example, when exchanging power between an on-grid connected to the utility grid and an off-grid independent of the utility grid, it seems reasonable to give the off-grid side the right to determine the power exchange method, given that it is difficult to stabilize the bus voltage due to sudden power load fluctuations and excessive power generation, and power outages are likely. Our proposed power exchange strategy is primarily intended to address the needs of the grid where power stabilization is more challenging, and the following two impacts can be anticipated.

1) Improve the quality of the grid on the demand side as well as the efficiency of renewable energy utilization.
2) Rationalize the distribution of power to all grids and minimize inefficient CO_2 emissions.

The specific power exchange scheme changes depending on the two grids' properties. Using the previously described power exchange between on-grid and off-grid as an example, the on-grid is connected to the utility distribution grid, ensuring power supply and demand balance as well as bus-line voltage stability. Off-grid, on the other hand, necessitates an increase in the size of the equipment to ensure voltage stability, which results in excessive energy use and is thus assigned a prominent position. Therefore, when exchanging power, this paper focuses on the demand for power exchange at the off-grid and to transmit power from the off-grid after taking into account the losses.

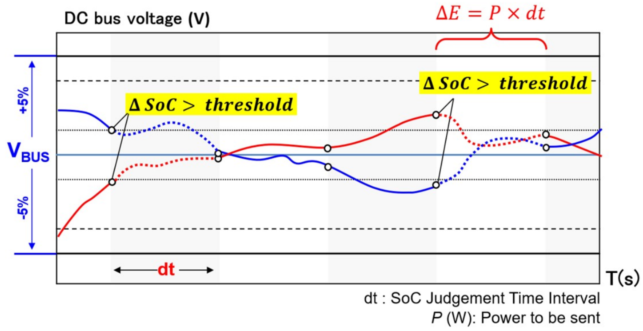

Fig. 2. Schematic of SoC-based power exchanging operation and corresponding baseline voltage performance

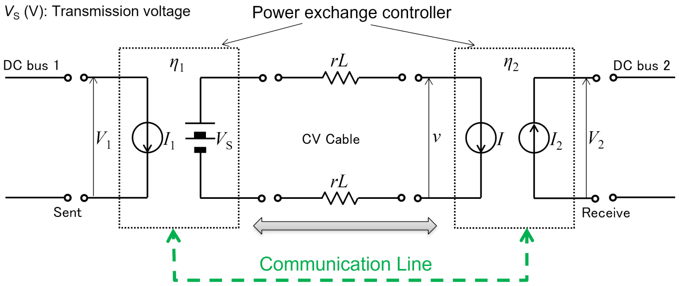

Fig. 3. Equivalent circuit of power exchange controller.

The proposed power exchange scheme is as follows: the power exchange occurs when the difference in state of charge (SoC) between the two batteries (ΔSoC) is greater than a certain constant (threshold) as shown in Fig. 2. This means that power flows will occur frequently, which has the advantage of balancing power conditions in real-time and is a good way to prevent power shortages due to unforeseen circumstances. For the power exchange between on-off grid, to ensure the stability of the bus-line voltage at the off-grid, the ΔSoC value at the off-grid is set to be higher than H (%) and lower than L (%) for the power exchange.

The voltages at the DC bus ports of both grids will be gathered and supplied to the power exchange controllers during the simulation. It is feasible to hypothesize about the SoC of the particular battery based on the voltage signal gathered in the controller (at one-hour intervals, for example), and the power exchange scenario is used to determine if power will be exchanged and in which direction the power will be delivered.

Fig. 3 depicts the equivalent circuit diagram of the power exchange process.

First, the dominant side in power exchange sends a power transmission or reception request to the other grid using some means of communication. Following that, the other grids begin transferring or receiving power in response to the request. Here, the power transmitted and received by the power exchange is represented by the current source model. When transmitting power, transmission loss occurs due to various factors in the transmission process. For example, in the case of DC/DC converters used for voltage conversion, the conversion efficiency varies depending on the model, but it is theoretically in the range of 94 to 98%. Furthermore, even with the same converter, the conversion efficiency varies depending on where the voltage is stepped up or down, the conversion ratio and the power of the load. As a result, an acceptable voltage conversion ratio and operational power range are required. Furthermore, when broadcasting over long distances, the transmission loss cannot be ignored if the transmitted power is large. Even with a very thick 200 SQ CV cable, the power loss can reach 1.7 kW when transmitting 10 kW of power over a distance of 10 km at a voltage of 400 V. In order to avoid the transmission loss, it is necessary to increase the transmission voltage or reduce the transmission power, however, lowering the transmission power will definitely influence the power exchange efficiency of the DC/DC converter, and increasing the transmission voltage may not be cost-effective. Therefore a reasonable choice of those parameters is important. We calculate by setting the parameter V_S as the transmission voltage, and the conductor resistance r per length, and the length L of the CV cable. The efficiency of the DC/DC converter can also be set by examining the table.

The following part, using the aforementioned method, computes the power exchange between on- and off-grids as an example and numerically analyzes the effect of the power exchange in terms of transmit voltage and power conversion efficiency.

III. POWER EXCHANGE BETWEEN ON- AND OFF- GRIDS

Assuming that there is an on-grid and an off-grid (dominance), each equipped with solar panels (which is also known as PV) and batteries. The two girds are separated by a certain distance (assumed to be 1 km here) as shown in Fig. 4, And within each grid, it is assumed that the partial optimization of power is achieved by the autonomous decentralized coordinated control (ADCC) by the method described above.

Given that the majority of the DC bus voltage utilized in actual microgrid projects is 400 V [12]–[14], the DC bus voltage of both grids undergoing power exchange was specified in this model at 380 V and 400 V. According to the scales of both microgrids, the total annual consumption is 180 MWh, which is equivalent to the power consumed

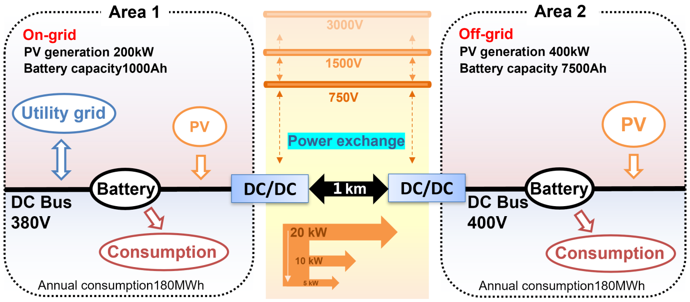

Fig. 4. Schematic diagram of power exchange between on- and off- grids.

by 50 Japanese households, where each Japanese household's electricity consumption is estimated as a series of random numbers based on a normal distribution (the mean is the refrigerator's electricity consumption and the variance of the distribution is set as 1/3 of other electricity consumption), based on the daily electricity consumption pattern.

Since the power assists from the grid are obtained, the total power generation ability of solar panels and battery capacity on the on-grid side are both relatively small, set to 200 kW and 1,000 Ah, respectively, while the total power generation ability of the solar panel and the battery capacity on the off-grid side are larger than those of the on-grid side and are set to 400 kW and 7,500 Ah respectively.

Due to the proximity of the regions of the two grids, we assume the same amount of solar radiation from both grids and calculate the solar power generation in real-time based on the amount of solar radiation in Sendai City, Japan, in 2019. After a year of simulation under these conditions, the off-grid side bus voltage is steady to within plus or minus 5% of the 400 V reference voltage, with no blackouts.

The primary goal of power exchange between on- and off-grids is to address power shortages and surplus power generation on the off-grid side, and the following two consequences can be anticipated.

1) Effective utilization of solar power generation mainly on the off-grid side.
2) Reducing the power received from the grid on the on-grid side.

Therefore, when the following conditions are satisfied, the power exchange operation is performed based on the request from the off-grid side:

1) When the state of charge (SoC) of the battery on the off-grid side falls below 20% or exceeds 90%, a power exchange request shall be issued.
2) When the difference between the SoC of the two grids (ΔSoC) is more than 20%, power exchange will be started.
3) When the exchange of the amount of power requested by the off-grid side is completed, the power exchange is completed.

The off-grid side has the right to decide the amount of power to be exchanged, and the on-grid side must transmit or receive the power required by the off-grid side taking into account the transmission loss.

IV. EVALUATION INDICATORS

To analyze the effect of power exchange more comprehensively, we have calculated and evaluated the following indicators based on the parameters described in table Table. II.

A. Transmission Efficiency

Transmission efficiency is defined as the proportion of total received power to the total transmitted power .

$$\eta_p = \frac{P_{in}}{P_{out}} = \frac{P^{in}_{ex,off} + P^{in}_{ex,on}}{P^{out}_{ex,on} + P^{out}_{ex,off}} \tag{1}$$

TABLE II
DESCRIPTION OF THE MAIN PARAMETERS IN THE POWER EXCHANGE PROCESS

Parameters	Description
$P^{potential}_{pv,off}$	PV generation potential of off-grid
$P_{cons,n}$	Power consumption at load, where n = 1 for on-grid and 2 for off-grid
$P^{k}_{ex,n}$	Exchanging power in terms of n (1 for on-grid and 2 for off-grid), where k=in or out
$P^{d}_{grid,on}$	Power changes between utility grid and on grid, where d=from for receiving power from utility grid and d=to for sending power to utility grid

$$P_{loss} = P^{out}_{ex,on} - P^{in}_{ex,off} + P^{out}_{ex,off} - P^{in}_{ex,on} \tag{2}$$

where, the η_p includes the conversion efficiency of the converter as well as the losses caused by CV cables.

B. Power received from the utility grid

Power received from the local grid includes power generated by fossil fuels. In Japan today, this percentage is about 80%. This value is expected to improve in the future toward the achievement of carbon neutrality in 2050, but at this time, we will analyze and evaluate using this value.

C. Renewable energy ratio

The renewable energy ratio is defined as the proportion of electric energy generated by renewable energy in the total energy consumed by loads in both grids. Its calculation formula is as follows:

$$P^{total}_{re,ratio} = \frac{1 - P^{from}_{grid,on}}{P_{cons,on} + P_{cons,off}} \tag{3}$$

D. Renewable energy utilization rate

This variable is defined by the ratio of the amount of power actually generated and used against to the power generation potential of the solar panel. In the case of off-grid, if the SoC of the battery is full and there is no storage capacity, the solar panel may be able to generate power but must be stop power generation. In this case, the renewable energy generated power will not be utilized and will be discarded. Here we need to subtract the loss that occurs during the transmission of the power generation.

$$P^{total}_{re,utilization} = \frac{P_{pv,on} + P_{pv,off} - [P^{to}_{grid,on} + (P^{out}_{ex,off} - P^{in}_{ex,on})]}{P_{pv,on} + P^{potencial}_{pv,off}} \tag{4}$$

V. INFLUENCE OF TRANSMISSION VOLTAGE AND POWER

Transmission losses are smaller at higher transmission voltages and lower transmission power if the power cables to be used are specified. However, since the highest withstand voltage of a typical CV cable used in a microgrid is around 3,000 V, it was assumed that the power would be transmitted at

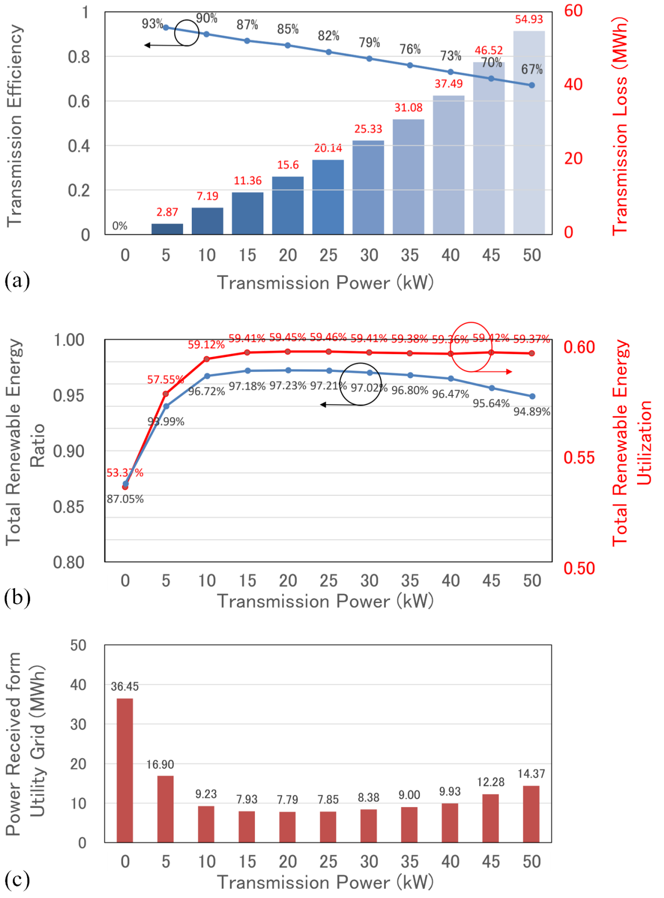

Fig. 5. Impact of transmitted power on power exchange operation regarding (a) transmission losses (b) ratio and utilization of renewable energy (c) power received from the local grid when the transmitted voltage is set as 750 V.

a voltage lower than that. Therefore, the transmission voltage was set to be from 400 V to 3,000 V. Simulations were also performed for transmission power ranging from 5 kW to 50 kW, as well as numerical evaluations for the aforementioned indicators. Here the power conversion efficiency of DC/DC converters is assumed to be 98% for both boost and buck. To explore the effect of the transmission power on the power exchange, we first assume that power is delivered at 750 V, and the results are shown in Fig. 5.

As can be seen from Fig. 5 (a), the transmission loss during the power exchange process increases with increasing transmission power, so the transmission efficiency decreases almost linearly from 93% at 5 kW to 67% at 50 kW. At this time, the annual loss is as high as 55 MWh.

Despite the decreasing efficiency, the overall renewable energy ratio tends to rise and peaks at 20 kW, and then decreases as efficiency increases. At the stage when the renewable energy ratio increases with the increase of transmission power, the effect of the power exchange becomes more significant although the transmission efficiency decreases so that the power received from the utility grid tends to decrease. With the further increase of the transmitted power, the large transmitted power will increase the power variation between the two grids, and therefore the power exchange between the on-grid and the utility grid will be more frequent, which means that more power will be received from the utility grid and the corresponding renewable energy ratio will also become smaller.

In terms of the renewable energy utilization rate, it rises at first as the power increases and keeps stable with a small fluctuation after about 15 kW. In the beginning, as the power transmission becomes larger, the off-grid PV generation will generate more power, which is partly consumed by the load in the on-grid and partly sent to the utility grid. As the power increases, when the load is satisfied, a larger proportion of the power will be sent to the utility grid. When the PV generation is balanced with the amount of power sent to the utility grid and transmission loss, the utilization rate will remain stable.

Compared to the case without power exchange, the renewable energy ratio and utilization rate under the above-mentioned power exchange operation are increased by a maximum of about 10% and 6%, respectively, which proves the effectiveness of the proposed power exchange method. It also shows that when the transmitted power is 20 kW, the power received from the local grid reaches the minimum, which means that the carbon emission is the minimum at this point. It can be seen from Fig. 5 (c) that up to 28 MWh can be saved per year (equivalent to 7.8% of the total load consumption) in terms of the power received from the utility grid in the proposed power exchange method compared to no power exchange.

Based on the optimal solution obtained above, the transmission power is then fixed at 20 kW and the effect of the transmission voltage on power exchange operation is investigated. We investigated 400 V, 750 V, and 1,500 V of the low-voltage zone, as well as the relatively high voltage of 3,000 V, and the results are shown in Fig. 6.

With the increase of the transmission voltage, the conversion efficiency can be increased at most from 56% at 400 V to 95% at 3,000 V, and the total losses are reduced by about 48 MWh, as shown in Fig. 6 (a). The renewable energy ratio and the renewable energy utilization in Fig. 6 (b) also increase with the increase of the voltage. However the results at 1,500 V and 3,000 V are very close with about a 0.01% (0.02%) difference, and the improvement from 750 V to 1,500 V is also very limited. It can also be seen from Fig. 6 (c) that although the result at 3,000 V is the best, it may be reasonable to set the transmission voltage at 1,500 V or even 750 V if the economic benefits are considered.

Further, in order to investigate the characteristics of other transmission power, all transmission power and voltage combinations were calculated and the results are given in Fig. 7.

At voltages of 400 V, data for powers above 20 kW are not available because the transmission losses at this point exceed 100%. At voltages other than 400 V, 20 kW is the optimum transmission power. It can be seen that the difference between the maximum (5 kW, 400 V) and minimum (above 20 kW, 3,000 V) power obtained from the power system for

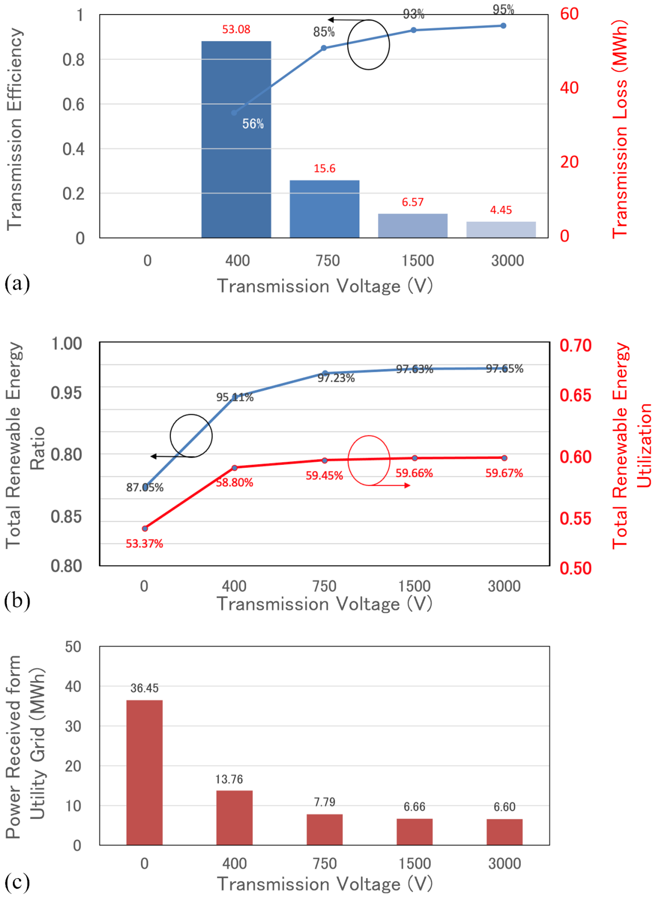

Fig. 6. Impact of transmitted voltage on power exchange operation regarding (a) transmission losses (b) ratio and utilization of renewable energy (c) power received from the local grid when the transmitted power is set as 20 kW.

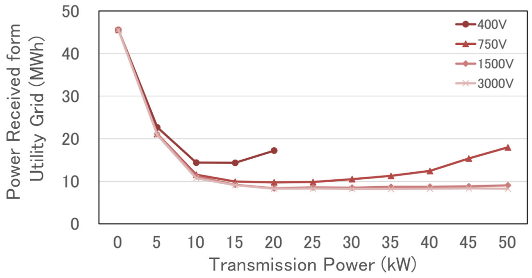

Fig. 7. Power received from the utility grid at different combinations of transmission voltage and power

the combination of transmission power and voltage we set is about 13 MWh per year (equivalent to 3.6% of the total annual power demand of 360 MWh in a year), which demonstrates the effect of parameter optimization.

VI. SUMMARY

In this paper, the modeling of the dominance-based power exchange mechanism is developed and established in MATLAB/Simulink. And its effectiveness has also been investigated in the on-off-grid power exchange scenario. The proposed power exchange approach improves the renewable energy ratio, utilization rate, as well as the received power from the utility grid. Additionally, the impact of transmission voltage and power on power exchange operation is simulated and examined. The proper transmission voltage and power are demonstrated based on the simulation results of the optimization parameters to improve the efficiency of the power exchange.

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