Basic Sensitivity Analysis of Conversion Losses in a DC Microgrid

H. Kakigano, Y. Miura, and T. Ise

Division of Electrical, Electronic and Information Engineering
Osaka University
Suita, Japan

J. Van Roy, and J. Driesen

Department of Electrical Engineering
Research Group ELECTA, KU Leuven
Leuven, Belgium

Abstract—This paper presents a basic sensitivity analysis of the conversion losses in a dc microgrid by varying the system parameters. A simple residential apartment with 20 units with a photovoltaic (PV) system is taken for the analysis. The conversion losses are calculated with the measured electricity consumption and the estimated output of the PV system. Modelica, an object-oriented modeling language, was used as a simulation tool because of the flexibility in changing the system configuration and parameters. The simulation results show that the efficiencies of the converters in the system are almost directly proportional to the total system losses. Additionally, the rated capacity of the grid converter influenced the total losses linearly. It is also shown that the total rated capacity of the PV system has a relation to the advantages of dc microgrids compared to ac microgrids. These results reveal that the dc microgrid has an advantage regarding the loss reduction under suitable conditions. Additionally, this basic analysis will contribute to the design of system configurations and parameters for new dc microgrids.

Keywords—microgrid; dc distribution; conversion losses; sensitivity analysis; Modelica

I. INTRODUCTION

Renewable energy sources such as photovoltaic (PV) systems and wind turbines are becoming more important as future energy sources. The main reasons are the positive effect on the background of the greenhouse gas emissions, the rising fossil fuel price, and the denuclearization after the accident at the Fukushima Daiichi nuclear power plants. However, it is also well-known that the installation of many distributed generation (DG) sources can cause problems to the existing utility grids, such as a rise in voltage or frequency variation. Microgrids are a solution for introducing renewable energy sources into the utility grids seamlessly [1]. In most researched microgrids, ac distribution is adopted in the same way as normal electric power systems [2]. In the ac case, inverters are essential for the connection of dc output DGs (e.g. PV systems) to the ac system, and for some ac output DGs (e.g. gas engine cogeneration unit) to convert the generator's frequency to the grid frequency. Therefore, dc microgrids have been researched as emerging electric power systems because of their compatibility with dc output sources [3]–[5]. The authors have proposed “low-voltage bipolar-type dc microgrids” to supply high quality power and reduce ac/dc conversion losses [6]. A laboratory scale model is constructed and the fundamental characteristics of the system are examined [7]. The

experimental results showed that the system can supply stable power in preventing problems such as voltage sag or blackout of the utility grid.

In this paper, conversion losses in a dc microgrid are examined to clarify the priority to an ac microgrid. There have been previous studies about loss calculation in ac and dc systems. Ref. [8] and [9] show that the conduction losses in dc systems are lower than the losses in ac systems when the dc voltage is assumed to be about 325 V, which is the peak value of the ac voltage (230 V). Ref. [10] concluded that the losses in a dc system are 0.5 % higher than the losses in an ac system when the transformation and conversion losses are taken into account, but the internal losses caused by ac/dc conversions in the loads are not considered in the paper. The authors calculated the losses, including the conversion losses in the loads, in a previous study [11]. The conclusions are that the total losses in a dc system are 15 % lower, but the reduction effects depend on the system configuration and parameters.

Therefore, the authors have adopted a basic sensitivity analysis in this paper by varying the system parameters, in order to explore which parameters have a significant influence on the total losses in a dc microgrid, compared to an ac microgrid. A simple residential apartment building with 20 units and a photovoltaic (PV) generation system is taken for simplification of the analysis. The conversion losses are calculated with the measured electricity consumption and the estimated output of the PV system. The efficiencies of the load converters and the grid converter are considered as system parameters. In addition, the rated capacity of the grid converter and the PV system are also considered. Modelica, an object-oriented modeling language, is used as the simulation tool because of its flexibility in changing the system configuration and parameters. The results show that the efficiencies of the converters in the system are almost directly proportional to the total system losses. Additionally, the impact of the rated capacity of the grid converter on the total losses is linear. It is also shown that the total rated capacity of the PV system has an effect on the advantages of the dc microgrid. These results reveal that the dc microgrid has advantages regarding loss reduction under suitable conditions. Additionally, this basic analysis will contribute to the design of system configurations and parameters for new dc microgrids.

II. SYSTEM CONFIGURATION

Fig. 1 shows a diagram of the apartment for the analysis. The apartment has 20 residential units: four floors and five residential units on each floor. The length, width and height of the building refer to a real residential complex in Japan. The apartment also has a PV system used for distributed generation of electricity. The rated capacity is assumed to be 30 kW, which is determined from the area of the rooftop.

Fig. 2 and Fig. 3 show the configurations of respectively the ac and dc system. The distribution line losses in the apartment are not considered in this study because the line losses are negligible compared to the conversion losses [9], [11]. The ac and dc distribution voltages are assumed to be 200 V and 400 V, respectively. Nevertheless, these voltages did not affect the results, because the line losses are not considered. It was assumed that the PV output power could be injected in the utility grid. Therefore, the PV system is operated for maximum power point tracking (MPPT). In the dc microgrid, the PV system does not include an inverter, but a grid converter is essential as a utility grid interface. Regarding the efficiency curves of the PV and grid converter, it is assumed that the efficiency curves of the ac/dc converter (Converter A) shown in Fig. 2 and the grid converter shown in Fig. 3 are equivalent. Similarly, the efficiency curves of the dc/dc converter (Converter B) are assumed to be equivalent. The details of the converter characteristics are described in the following section.

III. DATA FOR LOSS CALCULATION

A. Electricity Consumption

The electricity consumption of 20 residential units during one year was surveyed by Osaka University [12], [13]. In this analysis, monthly average data were used, which were taken every 30 minutes. Fig. 4 shows the total electric power consumption of 20 apartment units. Two peaks can be observed, because the residents are usually active at home in the morning and evening. When comparing monthly data, it can be observed that the power consumption becomes high in summer and winter, because of the use of air conditioners and heaters in these seasons, respectively.

B. Output Power from PV Panel

The yearly output power of a PV panel is calculated from the global solar radiation (total horizontal radiation) and the temperature of a real PV panel, which were measured in

Fig. 1. Diagram of the considered apartment.

Osaka University. Fig. 5 shows the method to calculate the total radiation on a tilted PV panel from the total horizontal radiation. First, the normal beam radiation and diffuse horizontal radiation are separated from the total horizontal radiation using the Erbs model [14]. The sky conditions are

Fig. 2. Configuration of ac distribution system.

Fig. 3. Configuration of dc distribution system.

Fig. 4. Total electric power consumption.

estimated from the normal beam radiation and the diffuse horizontal radiation, and secondly the diffuse horizontal radiation is divided into three elements using the Perez model [15]. Finally, the total radiation on a tilted panel is obtained.

The PV output power is obtained from the total radiation on a tilted panel, the panel temperature, and the PV panel parameters. The PV panel parameters were acquired from experiments performed on a practical PV system (2.7 kW). Fig. 6 shows a comparison of the estimated power with the experimental results. The estimated power is almost the same as the measured data. The estimated data were within $\pm 20\%$ of the measured data for 72.3 % of the total measuring duration, and the error of the total generation energy was -1.9 %. Hence, the accuracy of the estimated data is sufficient for this analysis. We assumed that the rated capacity of the PV system in the target system is 30 kW, as mentioned before. Therefore, the original PV output data (2.7 kW) is scaled.

C. Capacity and Efficiency of PV Converter

In the ac system, the converter of the PV system consists of an ac/dc converter and a dc/dc converter, as shown in Fig. 2. The rated capacity of the PV converter was set to be equivalent to the rated capacity of PV panel. Fig. 7 shows the efficiency curve of the ac/dc converter (Converter A), which is assumed to be a chain-link-type multilevel converter because of its high efficiency [16]. The efficiency curve is given by the following equation:

$$\eta = \frac{u}{0.004 + 1.002u + 0.018u^2} \times 100 \quad (1)$$

where η is efficiency, and u is the input power ratio. The coefficients are determined to fit the efficiency curve in [16].

Fig. 8 shows the efficiency curve of the dc/dc converter (Converter B), which is assumed to be a boost converter. The efficiency curve is given by the following equation:

$$\eta = \frac{u}{0.004 + 1.0017u + 0.007u^2} \times 100 \quad (2)$$

The coefficients in the equation are determined from

Fig. 5. Estimated flow of total radiation on a tilted panel.

efficiency curves of general boost converters.

In the dc system, Converter B is only used for the interface of the PV system. The efficiency curve is assumed to be equivalent to that of the dc/dc converter in the ac system, as shown in Fig. 8.

D. Capacity and Efficiency of Grid Converter

As shown in Fig. 3, a grid converter is needed for the interface of the utility grid in the dc system. The contract power of one residential unit is supposed to be 4 kW, resulting in a grid converter capacity of 80 kVA. The efficiency of the grid converter is equivalent to that of Converter A, as shown in

Fig. 6. Comparison of the estimated power with the experimental results.

Fig. 7. Efficiency of Converter A (ac/dc converter).

Fig. 8. Efficiency of Converter B (dc/dc converter).

Fig. 7.

E. Efficiency of Internal Conversion in Loads

Internal losses due to the ac/dc or dc/dc conversions in the loads are included in the total losses in this paper. Because there are many kinds of loads in the residences, the conversion efficiency is assumed to be constant, namely a 92 % ac/dc conversion efficiency and a 95 % dc/dc conversion efficiency. The details of the conversion efficiencies in the loads have been treated in an earlier study by the authors [11].

As described in the previous section, the measured consumption data are used, and the data include ac/dc conversion losses in loads. Nevertheless, in this study, the measured data were treated as internal consumption inside the loads as shown in Fig. 9 and 10. In other words, we took the measured data as internal load, and incorporate extra losses caused by ac/dc or dc/dc conversion.

IV. RESULTS

Numerical simulations are performed to evaluate the impact of the variation of the system parameters on the losses in a microgrid. Modelica, an object-oriented modeling language, developed by the Modelica Association, is used as an analysis tool for the loss calculations [17], [18]. The object-oriented approach enables an easier integration of previous modeling work and flexible system parameter settings.

The basic conditions of the study are shown in Fig. 9 and 10. The total yearly internal energy consumption is 84.4 MWh, and the peak power consumption is 18.5 kW (average for 30 minutes). In this case, the total yearly PV output energy is 27.6 MWh, and the peak output power is 25.1 kW (average for 30 minutes).

First, the losses of the system under the basic conditions are calculated as the reference scenario of this sensitivity analysis. Then, the impact of the following parameters is evaluated: the conversion efficiency in the loads, the grid converter efficiency, the PV capacity, and the grid converter capacity.

For the sensitivity analysis on the load conversion efficiencies, the grid converter efficiency and the grid converter capacity, the impact on the dc system losses is examined, in order to evaluate the minimal efficiency for the dc system to be advantageous compared to the ac system given the parameters of the ac system. For the sensitivity analysis on the PV capacity, the impacts on both the losses of the ac and dc system are examined.

The calculation step is 30 minutes, and the duration of the analysis is one year.

A. Losses in the Reference Scenario

Table 1 shows the results of the total losses in the reference scenario. The total losses in the dc system (7949.9 kWh) are 7.1 % less than the total losses in the ac system (8561.9 kWh). This is approximately half compared to the results mentioned in [11], which mentioned a decrease of losses of about -15 %. The reason for this difference is that the assumed system in [11] included a controllable DG unit, namely a gas engine cogeneration unit, which had an ac/dc + dc/ac conversion to convert the generator's frequency to the grid frequency, and the

losses of the dc/ac conversion was eliminated in the dc system. Hence, this shows that the loss reduction effect in dc microgrids depends on the configuration and the parameters of the system. In other words, the total losses in dc microgrids can even be higher compared to the losses in ac microgrids under certain circumstances.

B. Effect of Conversion Efficiency in Loads

A sensitivity analysis is performed to evaluate the effect of the conversion efficiency in the loads on the total losses in a dc

Fig. 9. Basic conditions of ac system.

Fig. 10. Basic conditions of dc system.

TABLE I
COMPARISON OF REFERENCE SCENARIO LOSSES
BETWEEN THE AC AND DC SYSTEM

	AC	DC
Losses of PV system [kWh]	1219.1	552.2
Conversion losses in loads [kWh]	7342.8	4444.3
Losses of grid converter [kWh]	—	2953.4
Total losses [kWh]	8561.9	7949.9

microgrid. Fig. 11 shows the relationship between the variation of the conversion efficiency of the dc/dc converter in the loads and the variation of the total losses in the dc system. A value of 0 % on the horizontal axis corresponds to the efficiency under the basic conditions (dc/dc efficiency of 95 %). Similarly, a value of 0 % on the vertical axis corresponds to the total losses in the dc microgrid under the basic conditions (total losses: 7949.9 kWh). Fig. 11 shows that the conversion efficiency has almost a linear relationship to the total losses. The total losses in the ac system under the basic conditions were 8561.9 kWh. If the internal conversion efficiency in the dc system is less than 94.4 % (or a decrease of more than 0.68 %), the ac system has an advantage over the dc system in terms of the total losses. As for the sensitivity, the slope of the first-order approximation line is -11.25, which means that a 1 % variation of the conversion efficiency causes more than a 10 % variation in the total losses.

C. Effect of the Grid Conversion Efficiency

Fig. 12 shows the relationship between the variation of the grid converter efficiency and the variation of the total losses in the dc system. The variation of the grid converter efficiency has almost a linear relationship with the total losses. In this case, if the decrease of the efficiency of the grid converter is larger than 0.8%, the total losses in dc system become higher than the ac system. The slope of the first-order approximation line is -9.61. The effect of the grid converter efficiency on the total losses is smaller than the conversion losses in the loads, but both values of the first-order approximation are close to -10. Thus, the efficiency of the grid converter also has a large effect on the total losses of a dc system.

D. Variation of Grid Converter Capacity

As shown in Fig. 7, the efficiency of the grid converter becomes small in the low output region, especially when the input is less than 20 % of the rated capacity. Consequently, if the rated capacity of the grid converter becomes smaller, it tends to operate in the high-efficiency region. Fig. 13 shows the relationship between the variation of the grid converter capacity and the variation of the total losses in the dc system. The value of 0 % on the horizontal axis corresponds to 80 kVA. From this result, the total losses in the dc system vary with the rated capacity almost linearly, and the total losses become small when the rated capacity is small. However, the grid converter needs sufficient capacity to handle large load peaks. As described previously, the peak of the internal consumption in the loads is 18.5 kW in this study, but it is an averaged value, not an instantaneous value. As for the sensitivity, the slope of the first-order approximation line is 0.29, which shows a weaker relationship than the previous analyses. Yet, the rated capacity of the grid converter still affects the total losses in the dc system, so the design of the grid converter capacity is important for the total system efficiency.

E. Variation of PV System Capacity

Fig. 14 shows the relationship between the rated capacity of the PV system and the total losses in both the ac and dc systems. These results show that the dc system has an advantage compared to the ac system, when the capacity of the PV system is larger than approximately 11 kW. However, the relationship is not proportional, as in the previous results. In

particular, the ac system has an advantage in the region where the PV capacity is less than approximately 11 kW. The plot of the dc system is not linear in the region where the capacity of the PV system is less than approximately 20 kW because the grid converter losses increase in this region.

V. CONCLUSION

DC microgrids have several advantages over ac microgrids, and one of them is their low conversion loss because of their lower number of ac/dc conversions. In this study, a basic sensitivity analysis has been presented to evaluate the results of the variation of several system parameters. To make the results clear, a simple system configuration was assumed in this study. The results from this analysis are summarized as follows:

- The conversion efficiency inside the loads has a large effect on the total losses, and these two quantities have a proportional relationship. The slope of the first-order approximation line is -11.25, which means that a 1 % variation of the conversion efficiency causes more than a 10 % variation in the total losses. Under the basic conditions, the conversion efficiency in the loads of the dc microgrid has to be higher than 94.4% to have lower total losses compared to an ac microgrid.
- The efficiency of the grid converter in the dc system is also an important factor for loss reduction, and the efficiency has almost a linear relationship with the total losses. The slope of the first-order approximation line is -9.61. Under the basic conditions, the efficiency of the grid converter needs to be no lower than -0.8 % of the original efficiency to hold an advantage over the ac system.
- The rated capacity of the grid converter affects the total losses in the dc system, but the slope of the first-order approximation line is only 0.29.
- The dc system has an advantage regarding the total losses when the capacity of the PV system is larger than approximately 11 kW. The relationship is not proportional, as in the previous results.

If the system includes other DGs with controllable dc output, the loss reduction effects of the dc microgrid should be higher. In particular, energy storage devices are expected to have a large effect on the losses in dc microgrids. Hence, the next study will evaluate the influence of dc output devices under basic conditions. In this case, the operating algorithm should have a great influence on the calculation results. For this reason, additional sources were not included in this research in order to obtain the fundamental characteristics of the system.

REFERENCES

- [1] "Microgrids," *IEEE Power Energy Mag.*, vol. 6, no. 3, pp. 26-94, 2008.
- [2] Lawrence Berkeley National Laboratory, Microgrid Symposium Website [Online]. Available: URL: <http://der.lbl.gov/microgrid-symposiums>
- [3] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. Vicuna, and M. Castilla, "Hierarchical Control of Droop-Controlled AC and DC Microgrids – A General Approach Toward Standardization," *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 158-172, 2011

Fig. 11. Relationship between variation of the conversion efficiency in the loads and variation of the total losses in the dc system.

Fig. 12. Relationship between the variation of the grid converter efficiency and the variation of the total losses in the dc system.

Fig. 13. Relationship between the rated capacity of the grid converter and the total losses in the dc system.

Fig. 14. Relationship between the rated capacity of the PV system and the total losses.

- [4] A. Kwansinski, and C. N. Onwuchekwa, "Dynamic Behavior and Stabilization of DC Microgrids With Instantaneous Constant-Power Loads," *IEEE Trans. Power Electron.*, vol. 26, no. 3, pp. 822-834, 2011
- [5] A. Kwansinski, "Quantitative Evaluation of DC Microgrids Availability: Effects of System Architecture and Converter Topology Design Choices," *IEEE Trans. Power Electron.*, vol. 26, no. 3, pp. 835-851, 2011
- [6] H. Kakigano, Y. Miura, T. Ise, T. Momose, and H. Hayakawa, "Fundamental Characteristics of DC Microgrid for Residential Houses With Cogeneration System in Each House," in *Proc. IEEE PESGM*, 08GM0500, 2008
- [7] H. Kakigano, Y. Miura, and T. Ise, "Low-Voltage Bipolar-Type DC Microgrid for Super High Quality Distribution," *IEEE Trans. Power Electron.*, vol. 25, no. 12, pp.3066-3075, 2010
- [8] A. Sannino, G. Postiglione, and M. H. J. Bollen, "Feasibility of a DC Network for Commercial Facilities," *IEEE Trans. Ind. Appl.*, vol. 39, no. 5, pp.1499-1507, 2003
- [9] K. Engelen, E. Leung Shun, P. Vermeyen, I. Pardon, R. D'hulst, J. Driesen, and R. Belmans, "The Feasibility of Small-Scale Residential DC Distribution Systems," in *Proc. IEEE Industrial Electronics Society (IECON)*, pp.2618-2623, 2006
- [10] D. Nilsson, and A. Sannino, "Efficiency analysis of low- and medium-voltage dc distribution systems," in *Proc. IEEE Power & Energy Society General Meeting*, 2004
- [11] H. Kakigano, M. Nomura, and T. Ise, "Loss Evaluation of DC Distribution for Residential Houses Compared with AC System," in *Proc. The 2010 International Power Electronics Conference (IPEC-Sapporo)*, pp.480-486, 2010
- [12] K. Tsuji, M. Mizuno, O. Saeki, H. Sano, and T. Ueno, "Reports on the Monitoring of End-Use Demand for Residential Houses in the Kansai Science City (Vol. 1)," Distributed Autonomous Urban Energy Systems for Mitigating Environmental Impact, JSPS "Research for the Future" Program, 2001 (in Japanese)
- [13] K. Tsuji, M. Mizuno, O. Saeki, H. Sano, T. Ueno, D. Shimazaki, and K. Chihara, "Reports on the Monitoring of End-Use Demand for Residential Houses in the Kansai Science City (Vol. 2)," Distributed Autonomous Urban Energy Systems for Mitigating Environmental Impact, JSPS "Research for the Future" Program, 2002 (in Japanese)
- [14] D. G. Erbs, S. A. Klein, and J. A. Duffie, "Estimation of the Diffuse Radiation Fraction for Hourly, Daily and Monthly Average Global Radiation," *Solar Energy*, vol. 28, no.4, pp.293-302, 1982
- [15] R. Perez, P. Ineichen, R. Seals, J. Michalsky, and R. Stewart, "Modeling Daylight Availability and Irradiance Components from Direct and Global Irradiance," *Solar Energy*, vol. 44, no. 5, pp.271-289, 1990
- [16] MITHUBISHI ELECTRIC, "Release Information about Chain Link type Multilevel Converter," 2007 (in Japanese) <http://www.mitsubishielectric.co.jp/news-data/2007/pdf/1004.pdf>
- [17] Modelica and the Modelica Association, <https://modelica.org/>
- [18] Peter Fritzson, *Principles of Object-Oriented Modeling and Simulation with Modelica 2.1*, IEEE Press, 2004