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Study of Power Wheeling Photovoltaic Generation Implementation With MW-km Method

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ABSTRACT — Efforts to mitigate carbon emissions within the electricity sector involve the implementation of environmentally sustainable renewable energy sources. Photovoltaic (PV) generation, functioning as a distributed generation (DG), represents a current trend in renewable energy installations. A distributed generation (DG) is situated near the load within distribution networks. When applied, a PV-DG influences the magnitude of power losses within existing electrical networks, subsequently impacting associated energy loss expenses. Additionally, adequate land availability is required for the PV-DG installation. The cooperation between PV-DG power providers and load partners is conducted remotely, resulting in distribution challenges. The construction of distribution lines by business actors to evacuate their electricity production is almost impossible. Distribution network rental emerges as an interesting solution, i.e., through a distribution network collaborative utilization scheme or power wheeling. This study seeks to examine the implementation of power wheeling of PV generation within the IEEE 33-bus distribution network system, by finding the location of the bus placement of the PV wheeling generation that results in the smallest total energy loss cost and distribution network rental cost. The MW-km method served as the basis for calculating network rental expenses. Moreover, this study incorporated the land availability associated with each bus. Findings indicate that positioning the PV wheeling generation at bus 8 yielded minimal total annual energy loss and distribution network rental costs. It indicates that the placement of a wheeling PV generation in arbitrary places does not necessarily result in the smallest total energy loss costs and distribution network rental costs.

KEYWORDS — Power Wheeling, Photovoltaic Generation, Distribution Network, MW-km.

I. INTRODUCTION

With dwindling fossil fuel reserves and escalating concerns over global warming and environmental degradation, nations worldwide actively seek opportunities to reduce carbon emissions across multiple sectors. The increasing electricity demand, predominantly sourced from conventional fossil-fueled power generations notorious for greenhouse gas emissions, underscores the significant role of the electricity sector in contributing to these emissions [1]. Thus, a transition from the use of fossil fuels to more environmentally friendly renewable energy in generating electrical energy is imperative. The Indonesian government is also striving to increase the implementation of renewable energy for its electricity supply by targeting the implementation of generation from new and renewable energy (NRE) by 23% in 2025 and increasing by 24.8% in 2030 [2].

Power generation using photovoltaic (PV) is one of the renewable generations that is trending today. A PV generation may be used as a distributed generation (DG) located close to the load on the distribution network. The increasing implementation of DG is driven by climate change factors and the abundance of renewable energy sources that are more environmentally friendly. In its implementation, PV-DG generation affects the amount of power loss on the existing network, thus also affecting the amount of energy loss costs. In addition, the installation of PV-DG also requires adequate land availability [3]. It causes cooperation between the business actors of the PV DG power provider and the load partner to be far apart, causing problems in the distribution process. The construction of distribution lines by business actors to evacuate their electricity production is almost impossible.

A solution to address this challenge is the implementation of a power wheeling scheme. Power wheeling utilizes the infrastructure of an electric power network provider for the transfer of power between entities, preventing the need for the power provider to construct additional infrastructure. This concept has emerged in developed nations following electricity deregulation, where the generation, transmission, and distribution sectors operate as distinct and independent entities [4]. Renewable energy generation that depends on the location of the primary energy source can utilize this scheme [5]. In Indonesia, regulations related to power wheeling are regulated in the Regulation of the Minister of Energy and Mineral Resources of the Republic of Indonesia Number 11 of 2021 concerning the Implementation of Electricity Business [6]. A power provider intending to establish electric energy generations in a region can leverage the transmission or distribution networks owned by an existing utility company for the electricity distribution process.

Several studies use power wheeling schemes for the implementation of generation from renewable energy sources such as PV and wind generation as well as the trend of using DG in distribution networks [7]–[9]. HOMER and DIgSILENT software have been used to conduct technical feasibility and financial feasibility studies based on levelized cost of electricity (LCOE) and net present cost (NPC) for the implementation of power wheeling of PV and wind generation in distribution networks in Nigeria and South Africa [7], [8]. The implementation of power wheeling for renewable energy DG impacts the current technical parameters of the network, including the voltage profile, disturbances, as well as active power losses, and reactive power on the transmission lines.

The implementation of the power wheeling scheme imposes network rental costs on business actors. Reference [10] has compared power flow-based network rental cost calculation methods, namely MW-mile, MVA-mile, and current base methods on the implementation of power wheeling in the Java-Bali interconnection system. The calculation methods of MW-mile and MVA-mile network rental costs had more realistic results than the current base method based on electricity prices in Indonesia. Another study has determined the distribution network rental cost using the MW-mile method based on the difference in line power flow magnitude for the implementation of power wheeling in the distribution network system in Thailand [11]. The MW-mile method has also been used to evaluate the network rental costs associated with the use of the distribution network system in Australia for PV generation [9].

Building upon this premise, the present paper examines the implementation of PV generation power wheeling through simulation on the IEEE 33-bus distribution network system. The study aims to determine the optimal bus location for the PV wheeling generation placement, considering both total energy loss costs and minimal distribution network rental expenses, while also accounting for land availability at each bus location. Network rental costs were calculated using the MW-km methodology.

II. METHODOLOGY

The PV power wheeling scheme was applied to the IEEE 33-bus 12.6 kV distribution network system with a total line length of 20.35 km. The total load on the system was 3.71 MW [12], [13]. The minimum to maximum voltage limit was maintained at 0.9 to 1.1 p.u. [14]. Figure 1 illustrates the course of this research. The stage started with processing the data required and assumed in the research process, such as load parameter data, parameters of IEEE 33-bus distribution network lines, and financial data. In this research, the power flow study was conducted using the MATPOWER toolbox. Financial data including the price of electrical energy and the total cost of distribution network system lines were used to calculate energy loss costs and the distribution network rental costs using the MW-km method. In the subsequent stage, power flow simulation was carried out based on the preexisting condition and after the implementation of power wheeling in the IEEE 33-bus distribution network system to determine active power losses and differences in power flow used in the process of calculating the costs of energy loss and distribution network rental.

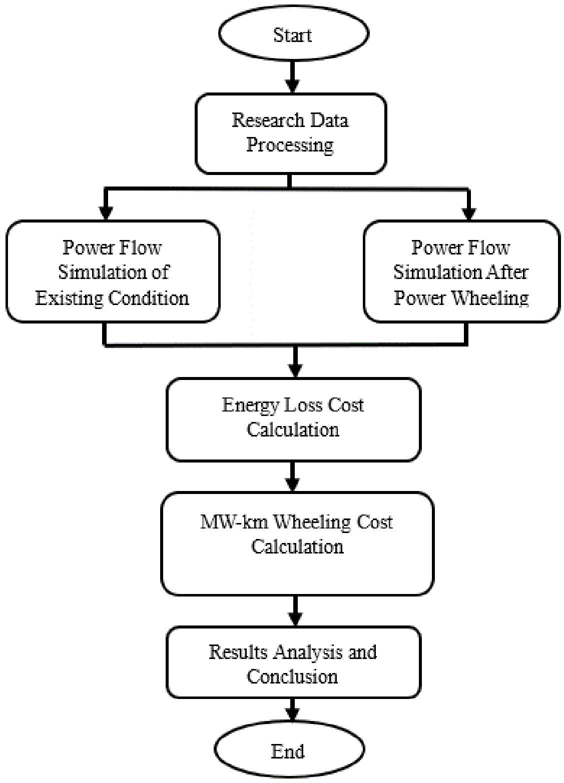

Figure 1. Research flowchart.

A. DISTRIBUTED GENERATION

DG is a power generation with renewable or nonrenewable energy sources applied to the distribution network or placed close to the consumer side [15], [16]. DG has become one of the trends in power systems used to help meet the increasing demand for electrical energy. DG can be categorized based on the nature of its power injection and its capacity [17], [18]. Based on the nature of the power injection produced, DG can be classified into four distinct types, namely:

- Type 1 DGs are those that generate only active power (P). Some examples include PV, microturbines, and fuel cell generations.
- Type 2 DGs are those that generate only reactive power (Q), such as a synchronous compensator.
- Type 3 DGs are those that can generate both P and Q, such as synchronous generations and wind turbines.
- Type 4 DGs are those that can generate P and consume Q, such as an induction generation.

In addition, based on its capacity, DG can be classified into:

- micro capacity, ranging from 1 W to 5 kW;
- small capacity, ranging from 5 kW to 5 MW;
- medium capacity, ranging from 5 MW to 50 MW; and
- large capacity, ranging from 50 MW to 300 MW.

One DG sourced from renewable energy is PV generation, characterized by its decentralized nature and absence of carbon emissions due to its nonreliance on fossil fuels. The energy generated by PV generations derives from a solar resource, which is infinite in quantity. In its implementation, the electricity output from PV installations is influenced by weather conditions [19].

B. ACTIVE POWER LOSS

Active electrical power flows from the generator to the load on the line in the power grid system. The process results in active power loss due to the resistance value in the system, resulting in energy loss costs [20]. The active power energy loss costs were calculated using (1).

$$C_p = P_{losses} \times C_E \times N \quad (1)$$

where C_p is the energy loss cost (IDR), P_{losses} is the active power loss (kW), C_E is the price of electrical energy (IDR/kWh), and N is the duration (hours).

C. POWER WHEELING

Power wheeling involves the collaborative use of an electric power transmission or distribution network, owned by a utility company, to facilitate electricity distribution for third-party entities. In its implementation, the cost of utilization or network rental is borne by the user of the electric power network [5]. The MW-mile or MW-km method is a technique employed to

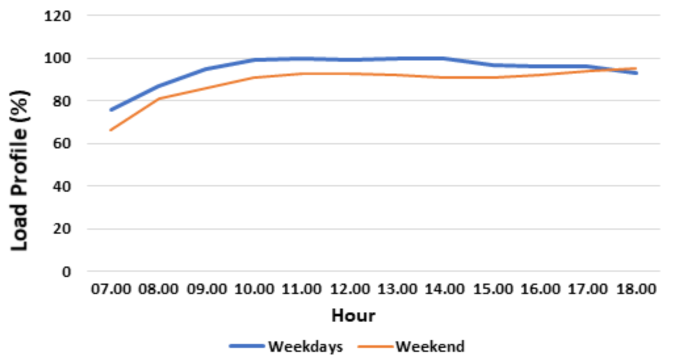

Figure 2. Variation of weekdays and weekend load profiles.

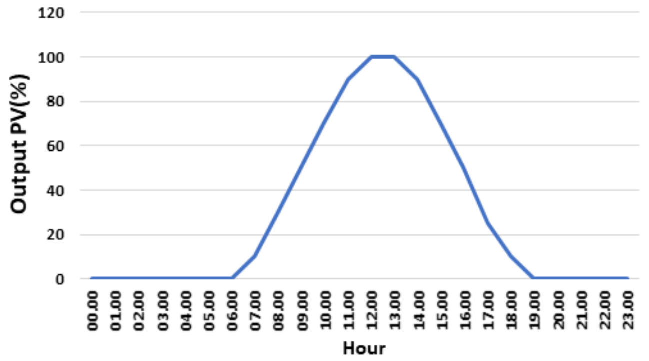

Figure 3. PV power output.

calculate distribution network rental costs, considering the actual utilization of the power network.

This method calculates the active power flow over the entire distribution line. The power flow is multiplied by the line length (L_k) and the cost per distribution line length (C_k), as presented in (2) [10], [21], [22].

$$MWkm_t = \sum C_k \times L_k \times MW_k. \tag{2}$$

Meanwhile, to calculate the allocation of wheeling transaction costs in the distribution network, (3) is used.

$$TC_t = TC \times \frac{dMWkm_t}{\sum MWkm_t} \tag{3}$$

where TC_t is the distribution network rental cost for network users (IDR), TC is the total cost of all lines (IDR), C_k is the cost per line length of the distribution network (Rp/km), L_k is the length of k lines (km), $dMWkm_t$ is the difference in MW-km between after and before the implementation of power wheeling (Rp MW), and $\sum MWkm_t$ is the total MW-km after the implementation of power wheeling (Rp MW).

The MW-km method has three distinct approaches for distributing line costs among network users: absolute MW-km, reverse MW-km, and dominant MW-km. Within the absolute MW-km approach, distribution network expenses are determined only by the power flow magnitude on the line, disregarding any counterflow. In the inverse MW-km approach, a reduction in distribution network rental costs is provided when the direction of power flow is opposite to the direction of power flow from the generation to the load. In the dominant MW-km approach, the counterflow in the distribution network system is ignored. Therefore, the rental cost of the distribution network is only calculated from the power flow flowing in the same direction as the power flow of the generation.

In this study, the cost of energy loss was calculated using the State Electricity Company (Perusahaan Listrik Negara, PLN) electricity tariff of IDR1,444.7 per kWh. The MW-km network rental cost calculation employed the absolute approach, with line expenses presumed to align with medium voltage operational costs, as per PLN's 2017 statistical data [23]. PLN's 2017 operating costs amounted to IDR275,474,094 million. It is assumed that the medium voltage fixed cost is 3% of the overall operating cost, so the operating cost for the medium voltage network is IDR8,264,222 million. With the total length of PLN's medium voltage lines being 401,959.41 km, the cost per length of the distribution line (Ck) is IDR20,559,844.14 per km per year or IDR2,347.01 per km per hour. In this research, the test system length for the IEEE 33-bus distribution network measured 20.35 km, resulting in a total distribution network line cost (TC) of IDR47,761.73 per hour. The power flow simulation was performed by considering hourly load variations based on the weekday and weekend load profiles of the IEEE 33-bus distribution network system shown in Figure 2 along with the PV power output in Figure 3 [24], [25]. The calculation of the costs of energy loss and network rental in the IEEE 33-bus distribution network system was carried out for a year, with 261 days of weekdays and 104 days of weekends.

III. POWER WHEELING IMPLEMENTATION SIMULATION

The study of the implementation of power wheeling of PV generations was simulated on an IEEE 33-bus radial distribution network system. In the radial distribution network system, the power flow direction is unidirectional, originating from the source bus (substation) and moving towards the load. It was assumed that a wheeling load of 0.5 MW was added at bus 11, which is in the middle of the IEEE 33-bus distribution network system. PV-DG type 1, which injected active power (P) with a small capacity category of 0.5 MW, was determined to be a wheeling generation or power wheeling actor. The location for the PV wheeling generation was determined based on the bus position, resulting in the least cumulative energy loss cost and network rental expenditure during power wheeling operations. Therefore, a power wheeling transaction is performed by placing PV wheeling plants on all different buses in the IEEE 33-bus distribution network system. As an illustration, Figure 4 shows the application of power wheeling in a 33-bus IEEE distribution network system with a PV wheeling generation at bus 15 and a load at bus 11.

Additionally, this study considered the land availability associated with each bus. It is assumed that a solar panel with a maximum power of 100 Wp has a panel area of 0.73 m2; therefore, a 0.5 MW wheeling PV generation requires a land availability of 3,650 m^2. Table I shows the land availability conditions at each bus in the IEEE 33-bus distribution network system for the placement of PV wheeling generations in this study.

IV. RESULTS AND DISCUSSION

A power flow simulation between preexisting conditions and conditions after the implementation of power wheeling has been carried out. The energy loss cost comparison between the two conditions is shown in Figure 5. The distribution network rental cost using the MW-km method is shown in Figure 6, while the distribution network rental cost and energy loss cost for a year are shown in Figure 7.

A. COSTS OF ENERGY LOSS

Figure 5 shows the graph of the comparison results between the total energy loss cost in the IEEE 33-bus distribution

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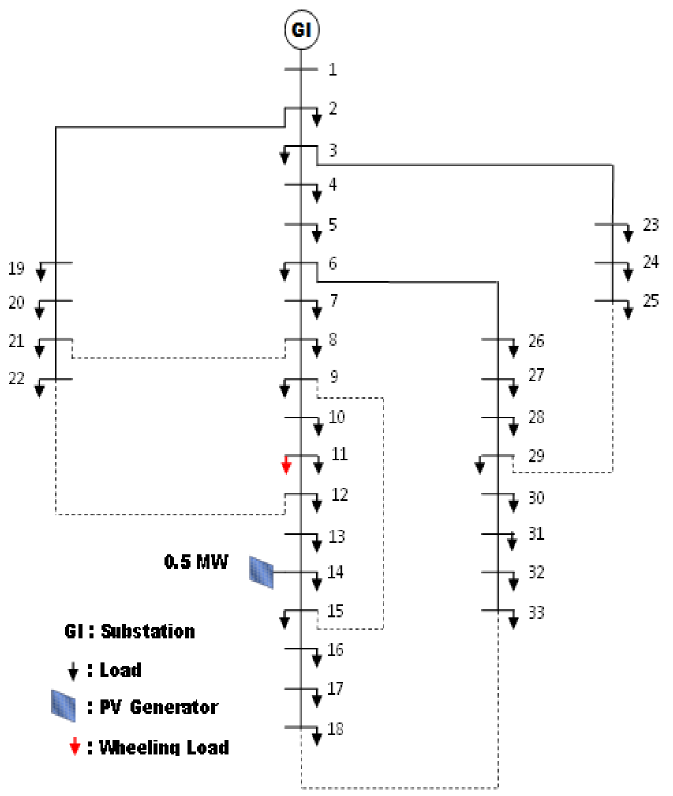

Figure 4. IEEE 33 bus distribution network system with PV wheeling generation implementation.

TABLE I
LAND AVAILABILITY

Bus	Land Availability	Bus	Land Availability
2	Available	18	Available
3	Not available	19	Not available
4	Not available	20	Available
5	Available	21	Available
6	Available	22	Available
7	Available	23	Not available
8	Available	24	Not available
9	Not available	25	Available
10	Not available	26	Available
11	Not available	27	Not available
12	Not available	28	Available
13	Not available	29	Available
14	Not available	30	Available
15	Not available	31	Not available
16	Not available	32	Not available
17	Not available	33	Available

network system for the existing condition and the condition after the implementation of power wheeling, with load variations on weekdays and weekends and the placement of wheeling PV generations in each bus.

On weekdays, the energy loss cost under existing conditions was IDR3.16 million per day. After the implementation of power wheeling, the placement of a power wheeling PV generation in bus 15 resulted in the smallest energy loss cost on the system, which was IDR3.48 million per day. The wheeling PV generation placement in bus 2 resulted in the largest energy loss cost, which was IDR4.23 million per day. Meanwhile, at weekend, the existing condition energy loss cost was IDR2.74 million per day. After the implementation of power wheeling, the placement of a power wheeling PV generation in bus 15 resulted in the smallest energy loss cost to the system, which was IDR3 million per day. The placement of the wheeling PV generation in bus 2 resulted in the largest energy loss cost, which was IDR3.68 million per day. It is evident from the obtained results that energy loss expenses increase subsequent to the installation of power wheeling in comparison to the preexisting conditions.

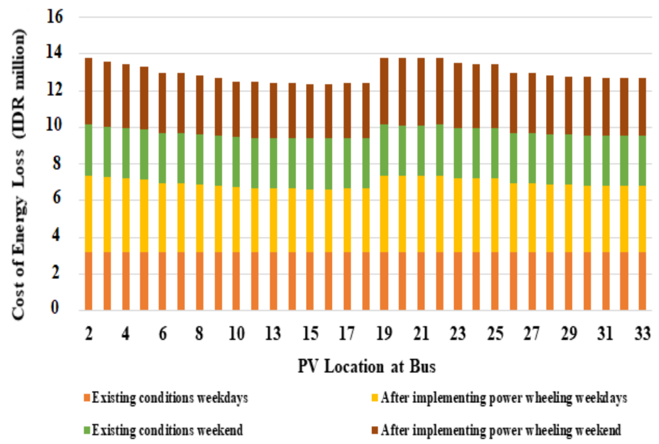

Figure 5. Energy loss costs.

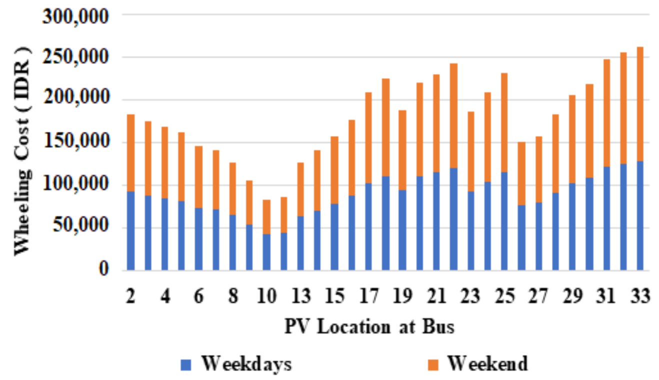

Figure 6. Distribution network rental costs.

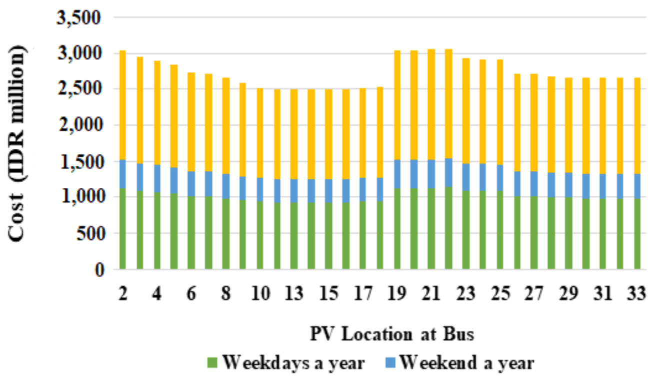

Figure 7. Distribution network rental costs and energy losses for a year.

B. DISTRIBUTION NETWORK RENTAL COST

The network rental cost is charged to the power-wheeling actor as the user of the distribution network. The implementation of power wheeling impacts the IEEE 33-bus distribution network system lines. The placement of the power wheeling PV generation on different buses for each power wheeling implementation affects the amount of distribution network rental costs. The calculation of distribution network rental costs was carried out using the MW-km method.

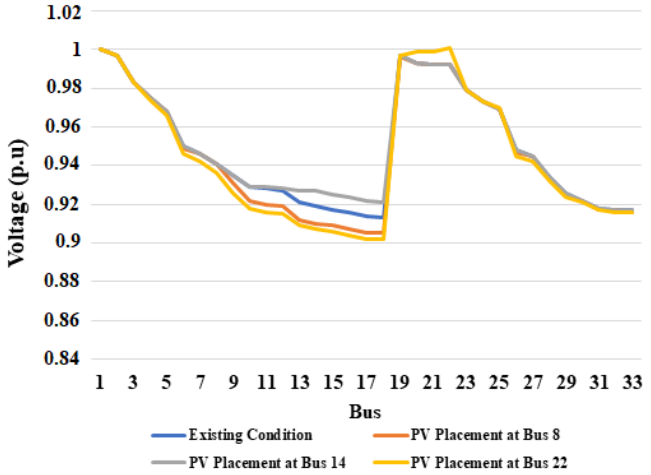

Figure 8. Voltage profile.

Figure 6 is a graph of the distribution network rental cost calculation results during weekdays and weekends using the MW-km method to place the wheeling PV generations in each bus on the IEEE 33-bus distribution network system. On weekdays, the placement of the wheeling PV generation on bus 10 resulted in the smallest distribution network rental cost in the system, which was IDR42,537.81 per day or IDR12.24/kWh. The wheeling PV generation placement at bus 33 resulted in the largest distribution network rental cost, which was IDR128,687.63 per day or IDR37.03/kWh. On weekends, the placement of the wheeling PV generation at bus 10 resulted in the smallest distribution network rental cost on the system, which was IDR40,415.20 per day or IDR11.63/kWh, while the placement of the wheeling PV generation at bus 33 resulted in the highest distribution network rental cost, which was IDR134,096.97 per day or IDR38.59/kWh. Based on the results obtained for the network rental cost calculation, it is concluded that the placement of the wheeling PV generation in bus 10 has the smallest distribution network rental cost during weekdays and weekends.

C. BUS LOCATIONS OF WHEELING GENERATION PLACEMENT

Figure 7 shows the total cost of energy loss and distribution network rent calculated for a year based on the placement of a wheeling PV generation in each bus of the IEEE 33 bus distribution network system.

Placement of the PV wheeling generation at bus 14 resulted in the smallest total energy loss cost and distribution network rental cost for a year, which was IDR1,247.49 million. Meanwhile, placement of wheeling PV generation at bus 22 resulted in the largest total energy loss cost and distribution network rental cost for a year, which was IDR1,530.34 million. Based on the total cost calculation results for a year, bus 14 was the placement location of the wheeling PV generation for implementing power wheeling in the IEEE 33-bus distribution network system. However, based on the land availability data in Table I, there was no land available for the placement of wheeling PV generation at bus 14. Therefore, bus 8 was selected as the placement location of the wheeling generation because land was available at that location. In addition, bus 8 had the smallest total cost for a year, which was IDR1,327.54 million.

Figure 8 shows the voltage profile comparison graph between the existing condition and the condition after the power wheeling implementation, with the wheeling PV generation placement at bus 8, bus 14, and bus 22 during full load usage. It can be seen that after the implementation of power wheeling to the existing conditions, there had been a change in the voltage profile, namely the improvement of the voltage profile and voltage drop. The voltage profile after the implementation of power wheeling with the placement of wheeling generations in bus 8, bus 14, and bus 22 remained at the minimum and maximum guarded voltage limits of 0.9 to 1.1 p.u., so the placement of wheeling PV generation at in bus 8 could be applied.

V. CONCLUSION

The implementation of power wheeling has resulted in an increase in energy loss costs against the existing condition of the IEEE 33-bus distribution network system, based on the placement of a wheeling PV generation in each different bus. Placement of wheeling PV generation on bus 15 during weekdays and weekends resulted in the smallest energy loss cost. The smallest energy loss cost during weekdays was IDR3.48 million per day, and during weekends, it is IDR3 million per day. In calculating distribution network rental costs using the MW-km method, the placement of wheeling PV generations in bus 10 for weekdays and weekends resulted in the smallest distribution network rental costs, namely IDR42,537.81 per day and IDR40,415.20 per day. The placement of the wheeling PV generation on bus 14 resulted in the smallest total energy loss cost and distribution network rental cost for a year, which was IDR1,247.49 million. Considering land availability and voltage profile, placing the PV wheeling generation on bus 8 had the smallest total cost of energy loss and distribution network rental for a year, which was IDR1,327.54 million.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest in preparing this research entitled “Study of Power Wheeling Photovoltaic Generation Implementation with MW-km Method,” neither personal interests that might be interpreted to affect the representation nor interpretation of the research results.

AUTHORS’ CONTRIBUTIONS

Conceptualization, Muhammad Bhayu Bramantyo and Sasongko Pramonohadi; research themes, Muhammad Bhayu Bramantyo; software, Muhammad Bhayu Bramantyo; validation, Muhammad Bhayu Bramantyo, Sasongko Pramonohadi, and Sarjiya; formal analysis, Muhammad Bhayu Bramantyo; parameter data, Muhammad Bhayu Bramantyo; writing-original drafting, Muhammad Bhayu Bramantyo and Sasongko Pramonohadi; writing-reviewing and editing, Muhammad Bhayu Bramantyo, Sasongko Pramonohadi, and Sarjiya.

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