Integrated PV-Farm and Micro Hydro as Distributed Generation in The Distribution Network

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Intisari* – Energi terbarukan harus diimplementasikan dalam ukuran kompak yang sesuai untuk sistem pembangkit terdistribusi (DG) agar dapat memaksimalkan potensinya. Untuk utilitas sistem distribusi, mengintegrasikan banyak DG dapat menyebabkan beberapa masalah seperti regulasi tegangan dan pelanggaran pembebanan saluran. Kondisi ini akan menjadi lebih buruk jika DG tidak dimiliki oleh sistem distribusi karena tidak banyak pilihan kontrol. Untuk itu, metode optimasi untuk menentukan lokasi dan ukuran DG diusulkan berdasarkan minimalisasi rugi-rugi sistem tenaga. Model optimasi dikembangkan dengan menggunakan teknik algoritma genetika. Kasus nyata Sistem Distribusi 20 kV Feeder Godean nomor 4 yang memiliki beban puncak 5,11 MW digunakan sebagai kasus uji dengan opsi integrasi tenaga surya dan tenaga air skala mikro. Model sistem tenaga listrik dibangun dengan menggunakan DIgSILENT PowerFactory, sedangkan model optimasi dibangun dengan menggunakan Python. Tiga skenario, yaitu surya saja, hidro saja dan surya-hidro yang dioptimalkan, dikembangkan untuk menunjukkan efektivitas metode yang diusulkan. Dari hasil simulasi menunjukkan bahwa dengan memasang DG pada beberapa bus dan sumber daya yang berbeda dapat meningkatkan tingkat penetrasi sebesar 3,14, 2,24 dan 3,78 MW secara simultan untuk skenario surya saja, hidro saja dan surya-hidro teroptimasi. Selain itu, skenario surya-hidro teroptimasi juga menghasilkan pengurangan rugi-rugi yang lebih tinggi yaitu 7,27% dibandingkan dengan 6,85 (surya saja) dan 6,56% (hidro saja).

***Kata kunci* – pembangkit terdistribusi, optimasi, rugi-rugi sistem tenaga listrik, integrasi energi terbarukan**

Abstract – Renewable energy should be implemented in a compact size appropriate for a distributed generation (DG) system in order to maximize its maximum potential. For the distribution system utility, integrating a lot of DGs may cause some problems like voltage regulation and line loading violation. The condition might be worse if the DG is not owned by the distribution system since there are not so many control options. For that purpose, the optimization method for determining the location and size of DG is proposed based on the power system losses minimization. The optimization model is developed using a genetic algorithm technique. The real case 20 kV Godean Distribution System feeder number 4, having a peak load of 5.11 MW, is used for the test case with the integration options of solar and hydropower. The power system model is built using DIgSILENT PowerFactory, while the optimization model is built under the Python environment. Three scenarios, namely solar only, hydro only, and solar-hydro optimized, are developed to show the proposed method's effectiveness. From the simulation result, it shows that installing DGs in some buses and different resources may increase the penetration levels, which are 3.14, 2.24, and 3.78 MW, simultaneously for the solar-only, hydro-only, and solar-hydro-optimized scenarios. Furthermore, the solar-hydro-optimized scenario also results in higher loss reduction (7.27%) compared to 6.85% (solar only) and 6.56% (hydro only).

Keywords – distributed generation, optimization, power system losses, renewable energy integration

I. INTRODUCTION

Variable renewable energy penetration into the power system has become a common trend in the world based on the Kyoto Protocol [1] and Paris Agreement [2]. Indonesia has also committed to increasing the penetration of renewable energy as stated in [3]. Moreover, Indonesia is also hosting the G-20 meeting, one of the focus agendas of which is to strengthen the commitment to clean energy transition as presented in [4].

To increase the proportion of renewable energy in a system, the variable renewable energy is integrated into the transmission systems as presented in the Java Bali System [5], [6] and Sulawesi System [7], [8]. Moreover, the integration of renewable energy was also done at the specific voltage level of the transmission level in Jordan [9]. However, the technology supporting the wind, solar, and hydro generation was also capable in small-scale systems like in the east part of Indonesia, as presented in [10]. In that situation, the resources and land availability were provided in the isolated area with small-scale electricity. For that purpose, the penetration level in the distribution/communal level was also considered as presented in [11]. In addition, the research to determine the solar farm penetration level in the distribution system was also done as presented in [12].

On Java Island, the population is relatively high, and there is no space left to install the mega solar farm. To optimize the full potential of renewable energy, small-scale PV farms and PV rooftops should be integrated into the distribution system as DG. In the traditional distribution system, most of the configuration is a radial power system, in which the load is distributed from the front to the edge of the network, making the power system distribution losses high. In this kind of situation, installing DG in the proper location might reduce the losses and increase the system reliability [13]. However, it would also change the voltage profile of the distribution system. Installing too many solar generations may cause overvoltage in the daytime so that the integration to the power distribution system should be limited.

Another giant resource is the hydropower generation (micro-hydro size), which can come from the irrigation system supporting the agricultural activities on Java Island. Different from the solar characteristic, hydropower can generate electricity for the whole day. This condition requires the performance of loss reduction and voltage regulation for a full 24-hour period. However, hydropower generation mostly depends on the season; in the dry season, water availability might be limited.

The research on how to find the hosting capacity has been discussed in the previous research. One of the research projects was done in feeder number 7 in the Bantul Distribution System by minimizing the system losses using a genetic algorithm (GA). The hosting capacity of DG might be installed in some buses as presented in [14]. Installing the DG distributed in some buses would decrease the power system losses. Similar works were also done in Purworejo using the partial swarm optimization (PSO), IEEE 30 buses using GA, and the IEEE 33 buses test system as presented in [15], [16], [17].

A typical distribution system is radial; the probabilistic approach to determine the HC in the radial system was developed. The probabilistic approach is needed to handle the time characteristic related to the renewable energy as presented in [18] The conventional way to determine the HC was done by dividing the feeder into head, middle, and end feeders as simulated in [19]. Moreover, the DG can also increase the voltage profile in the distribution system, especially in the distributed bus, as presented in [20], [21], [22].

In this research, the hosting capacity considering the voltage profile, losses, power factor, line loading, and reverse power to the upstream level is considered. The mathematical model is built using genetic algorithms. To demonstrate the effectiveness of the proposed method, the Godean Distribution System in Yogyakarta City, Indonesia, is used as the test system. Since the characteristics of all feeders are similar, feeder number 4 (GDN-04) is chosen. Moreover, near the feeder, there is potential to integrate solar and hydropower plants as distributed generation. There are some areas in the nearby villages that can be a PV farm. There is also the irrigation system from Kalibawang and the Progo River located in the Sendangmulyo and Sumberagung villages [23] where the hydropower can be installed. The DG is integrated into a 20 kV distribution system that consists of some scenarios that are solar only, hydro only, and solar-hydro optimized.

In the distribution network DG, the power system analysis to determine the maximum penetration level is required, especially with high penetration of non-dispatchable renewable energy. This procedure is called hosting capacity in a distribution network, which considers the power quality constraint for power system distribution customers. The constraint consists of voltage regulation, losses, line loading, and avoiding reverse power to the upstream network [24]. In the hosting capacity, the penetration level scenario can be determined, especially when doing the medium-long-time power system planning. The scenario can consider the environmental constraint to preserve the atmosphere, and the penetration point near the resources. Moreover, the distribution system characteristic depends on system parameters such as the transformer, voltage regulator, and distribution line. Consequently, the hosting capacity would be different for any distribution network.

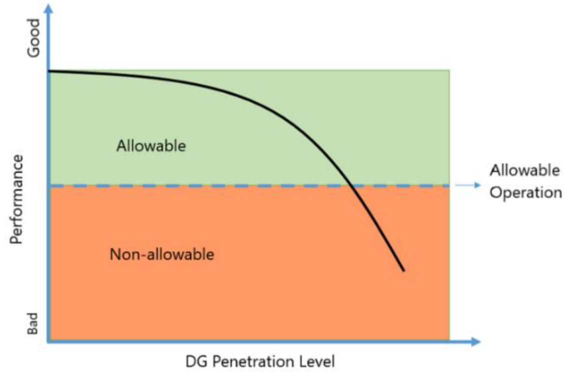

Figure 1. Correlation between DG penetration level and distribution system operation [24]

The hosting capacity illustration, which the trade-off to the distribution system operation presented, is presented in Figure 1. It is shown that the penetration level increment may worsen the system operation performance, which can be observed from the system variables such as voltage, power factor, and line loading as presented in [25]. The hosting capacity procedure might be formulated by an optimization procedure that has been described in [12].

II. METHODOLOGY

Integrating DG into the distribution system will also depend on the business process of the utility. In Indonesia, the distribution system utility manages the power from the upstream level. If the DG is connected to the distribution system, it is managed by the independent power producer. In this situation, installing so many renewable energy generations may cause operational problems since there are few control options. So that, the DG placement and sizing should be built from the point of view of the distribution system utility. For determining the hosting capacity, the research method presented in Figure 2 is proposed. First, identification of the potential for solar and hydropower is carried out in the GDN-04 area. Solar irradiation and waterway debit in the Kalibawang River data are collected. Then available areas for solar and hydro generation are identified to determine the maximum capacity. Then the transformer, line, and load parameters of the Godean Distribution System are collected, especially for feeder number 4. Moreover, the voltage, power, and line loading variables are also collected. The power system model is built in the DIgSILENT PowerFactory environment. For optimizing the potential of renewable energy in terms of DG, the mathematical model is formulated. The optimization is built under a Python environment and run into three scenarios to find the optimum location and size to minimize the power system losses.

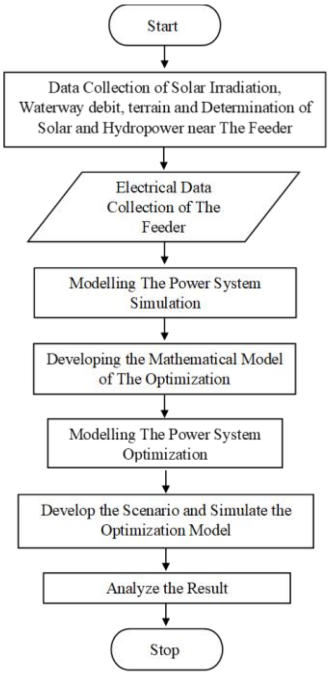

Figure 2. Research method of DG integration

The proposed optimization method is to minimize the system losses after penetration. The objective function is shown in (1) as follows:

Objective function

$$Min\ F = P_{lossDG}(P_{DG}^{T}) \quad (1)$$

Subject to

$$P_{lossDG}(P_{DG}^{T}) = \sum_{i=1}^{N}\sum_{j=1}^{N}[\alpha_{ij}(P_iP_j + Q_iQ_j) + \beta_{ij}(Q_iP_j - P_iQ_j)] \quad (2)$$

$$a_{ij} = \frac{r_{ij}}{V_iV_j}cos(\delta_i - \delta_j) \quad (3)$$

$$\beta_{ij} = \frac{r_{ij}}{V_iV_j}sin(\delta_i - \delta_j) \quad (4)$$

Equation (1) represents the objective function, $Min\,F$, which minimizes the active power losses in the network after DG penetration (P_{lossDG}). This objective function is chosen to ensure that DG integration has a positive impact on the system and enhances the efficiency of power distribution. With the losses formulation in (2)-(4) were simplified [26]. P_{lossDG} is defined as the active power of the network after DG penetration. P_{DG}^{T}, P_i and Q_i are the vector of DG size, active and reactive power injection in the network. V_i, δ_i and r_{ij} are the voltage magnitude, angle, and line resistant. While i, j and N are index and number of buses in power system.

Equation (5) explains the active power injection in the buses after DG penetration.

$$P_i = P_{gi} - P_{Li} + \sum P_{DGi} \quad (5)$$

with P_{gi}, P_{Li} and P_{DGi} are upstream active power, injected active power load and DG active power, respectively.

Equations (6) and (7) present the load flow formulation

$$P_i = \sum_{j=1}^{N} Y_{ij}V_iV_jcos(\theta_{ij} + \delta_i - \delta_j) \quad (6)$$

$$Q_i = \sum_{j=1}^{N} Y_{ij}V_iV_jsin(\theta_{ij} + \delta_i - \delta_j) \quad (7)$$

$$0{,}9 \le V_i \le 1{,}05 \quad (8)$$

$$P_{min} \le P_{DG\,i} \le P_{max} \quad (9)$$

$$I_i \le 0{,}8\ x\ I_{max,i} \quad (10)$$

The voltage, DG power and line loading constraint are presented in (8), (9) and (10), respectively. Y_{ij} and θ_{ij} is the magnitude and angle of Ybus element matrix. While I_i and $I_{max,i}$ are the line current and line current limit.

$$\sum P_{DGi} \le \sum P_{Li} \quad (11)$$

To limit the DG power not to flow back to the upstream level, the (11) is formulated.

The optimization method used in this study is GA. The genetic algorithm (GA) is an optimization method inspired by natural selection. It begins with an initial population, consisting of multiple individuals, where each individual represents a potential solution to a given problem [27].

Each individual undergoes a fitness evaluation, determining its effectiveness in solving the problem. Based on this evaluation, an individual selection process takes place where the best candidates are chosen for reproduction. These selected individuals undergo crossover and mutation, generating a new population that evolves over successive generations. This iterative process leads to population convergence, ultimately finding the optimal solution. The block diagram illustrating the GA cycle is shown in Figure 3.

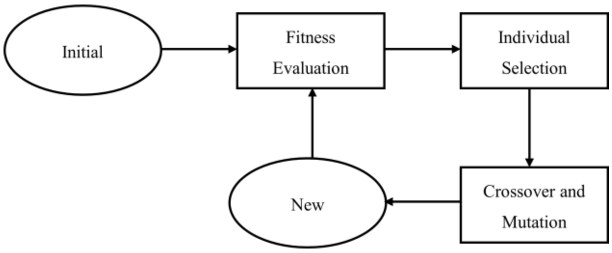

Figure 3. Genetic algorithm cycle [27]

Godean distribution system has two main transformers. The 30 MVA transformer supplying feeder GDN-01, GDN-02 and GDN-03 (feeders 1 – 3) while the 60 MVA transformer supplying feeder GDN-04, GDN-05, GDN-06 and GDN-07 (feeders 4-7). The proposed method then simulated into 20 kV feeder 4 test with the system configuration is presented in Figure 4. feeder has 5.11 MW dan 2.48 MVAr with the distribution in each bus are presented in Table 1.

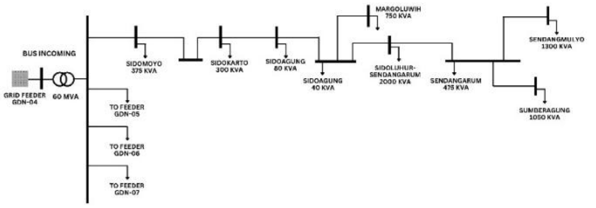

Figure 4. Simplified GDN-04 feeder test system

There is a village and river map presented in Figure 5 that is developed from [28] to show the potential of hydro and solar generation. For the solar farm, there are 21.5 ha of land that is available. That is a solar irradiation of 3.8 kWh/day/m² so that the maximum 42.8 MWp solar farm can be installed in that area [29]. For the hydro, Kalibawang waterway has 29 potential locations. Based on the secondary data [23], [30], the average debit of the water is 58.5 m³/s, with the maximum being 331 and the minimum being 12 m³/s. So that, the maximum installed capacity is 3.3 MW. The load profile and solar irradiation characteristics in that area are presented in Figure 6 [29], [30]. The maximum capacity of the DG is set at 10 MWp [31], [32], and the minimum is zero.

Table 1. Distribution of load in GDN-04 buses

Bus Number-	Villages	Active Power (kW)	Reactive Power (kVAr)
T1	Sidomoyo	54	26,22
T2		432	209.22
T3	Sidokarto	378	183.1
T4	Sidoagung	126	61
T5		36	174
T6		396	191.8
T7		108	52.3
T8	Sidoluhur	36	17.4
T9	Sidoluhur and	342	165.6
T10	Sendangarum	720	348.7
T11		36	17.4
T12		216	104.6
T13		216	104.6
T14	Margoluwih	702	340
T15		18	8.7
T16		216	104.6
T17	Sendangarum	72	34.9
T18	Sumberagung	36	17.4
T19		396	191.8
T20	Sendangmulyo	72	34.9
T21		36	17.4
T22		468	226.7

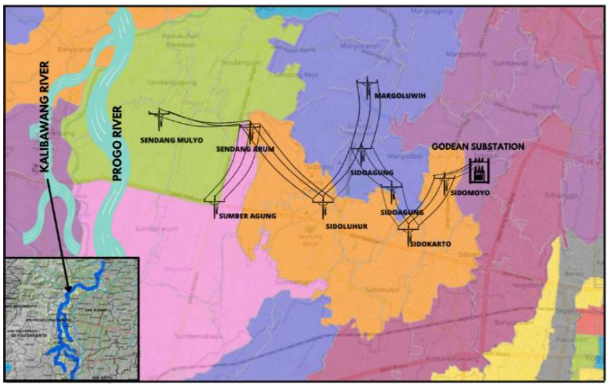

Figure 5. Illustration of terrain in the feeder 4 area [28]

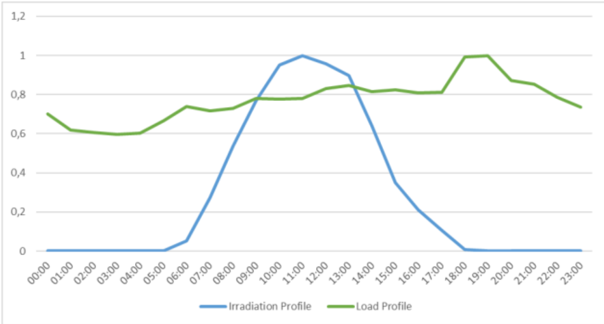

Figure 6. Load profile and solar irradiation characteristic in per unit [29], [30]

III. RESULTS AND DISCUSSION

For showing comprehensive analysis to find the optimum location and size of solar and hydro generation, there are three scenarios. The scenarios are solar-only, hydro-only, and solar-hydro optimized scenarios.

A. Scenario 1: Solar Only

In this scenario, the solar generation candidates are in areas Sidomoyo, Sidokarto, Sidoagung, Margoluwih, Sidoluhur, Sendangarum, Sumberagung, and Sendangmulyo, which are near the GDN-04 feeder, and are optimized to minimize the power system losses. The simulation is executed using the load profile at 11:00 to simulate the maximum possibility of solar generation. Then, for verification, the simulation would also be done from 8:00 to 16:00.

Based on the proposed method, the simulation result shows that the PV farm should be installed on the bus T17 in Sendangarum Village with a maximum penetration of 3.14 MWp. In this size and location, the power system losses are minimum.

To validate that the result is not violating the constraint, the bus voltage in the existing and after penetration are shown in Figure 7. In both simulations, the voltage profile is still in permissible constraint. Furthermore, the system losses on 11.00 would decrease from 49.93 kW to 46.51 kW (6.85% decrement).

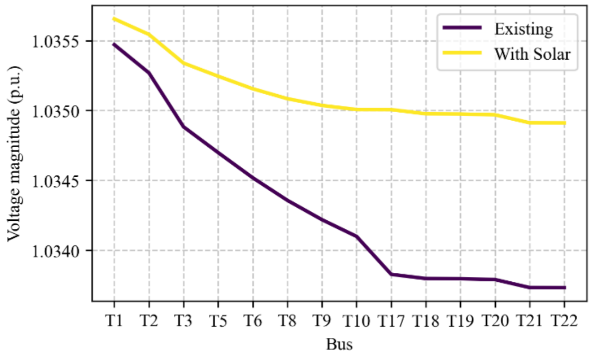

Figure 7. Voltage profile in solar only scenario

Other decreases for the line loading: the PV integration has a positive impact on the line loading since all the line loading decreases after the penetration, as presented in Figure 8. The maximum loading condition in the existing operation is 29.6%, and after penetration, it is 14.4%.

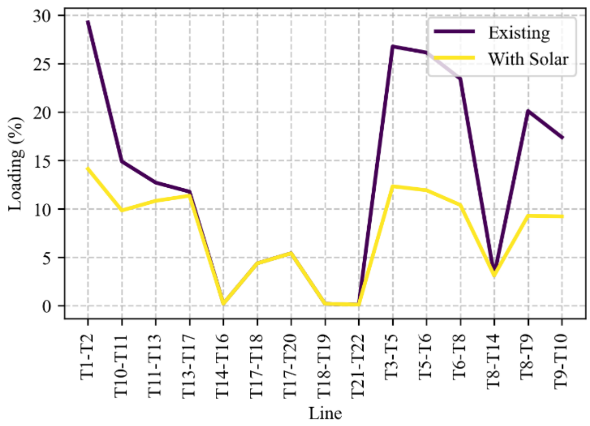

Figure 8. Line loading percentage in solar only scenario

B. Scenario 2: Hydro Only

Hydropower is installed in the Sendangmulyo Village, the nearest location to the Kalibawang waterway directly connected to the bus T20. The optimization is then simulated at 03:00 when the power system load is the lowest. The optimization resulted in an optimum penetration of 2.24 MW. It has been validated using the other size as presented in Figure 9.

Another validation is done under different times of the load profile as presented in Figure 10. At 19:00, when the peak load occurs, the optimal hydro generation size is 3.86 MW. For that reason, the 2.24 MW size is chosen as the size so that no curtailment is needed for 24-hour operation. If the 3.86 MW size is chosen, the operation would be more complicated since the dummy load must be installed in parallel with the customer load. The dummy load is used to anticipate the water flow deviation and load variation. However, this kind of configuration requires more complex operation and more expensive investment costs.

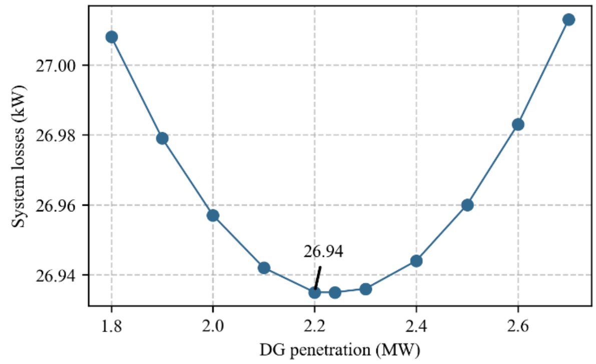

Figure 9. Power system losses under different hydro size in hydro only scenario

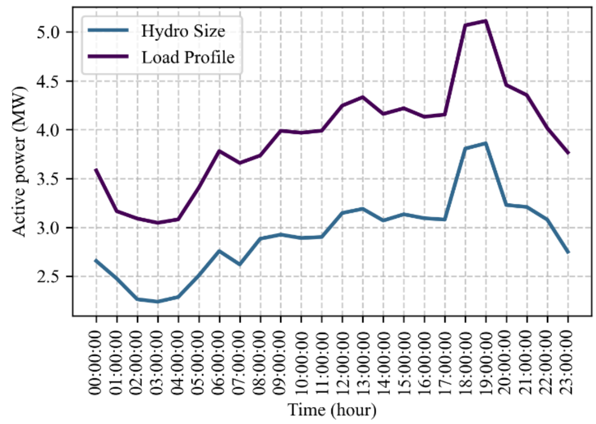

Figure 10. Hydropower optimum sizing in different load

After the hydropower integration, the validation on the voltage profile and line loading is presented in Figure 11 and Figure 12, respectively. Both in the existing and hydro penetration conditions, the voltage profile is still within the permissible range. The active power loss decreases from 28.83 kW to 26.94 kW (6.56% decrease) at 3:00, which satisfies the proposed method. The hydropower penetration also has a positive impact on the line loading condition, with the maximum decrease from 22.46 to 11.33%.

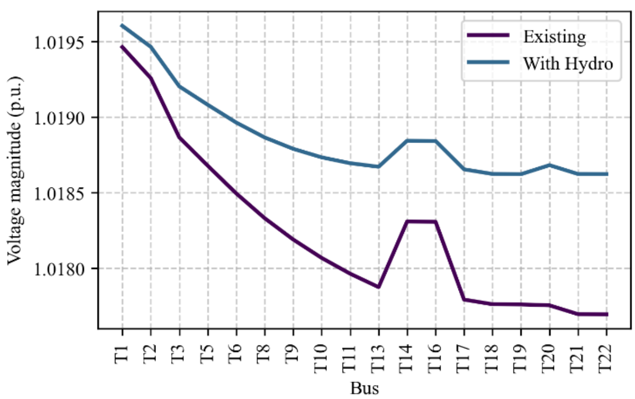

Figure 11. Voltage profile in hydro only scenario

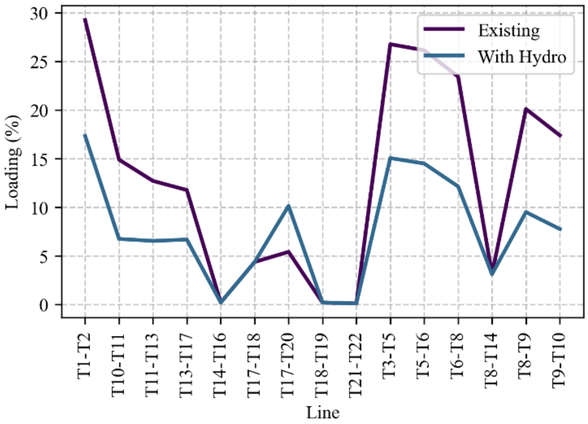

Figure 12. Line loading percentage in hydro only scenario

C. *Scenario 3: Solar-Hydro Optimized*

In this scenario, the PV farm and hydropower will be optimized simultaneously. The option to install hydropower is the same as scenario 2, which is in the Sendangmulyo Village. Simultaneously, the optimized hybrid solar-hydro would choose Bus T20 to install 2.24 MW hydropower and Bus T08 to install 1.53 MWp solar generation as presented in Figure 13.

Compared to scenarios 1 and 2, scenario 3 has a higher penetration level of 3.78 MW compared to 3.14 MW (scenario 1) and 2.24 MW (scenario 2). Combining those two options gives a better trade-off since the objective of the distribution system operator and renewable energy penetration can be optimized.

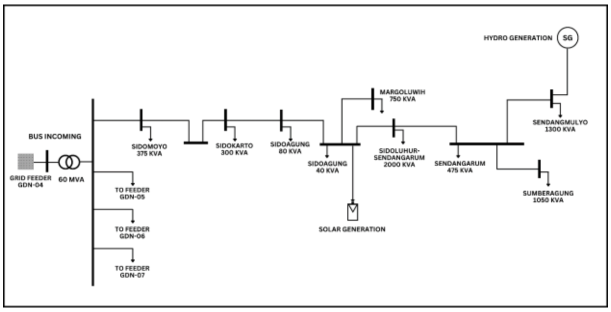

Figure 13. Location of PV farm and hydropower in optimized solar-hydro scenario

For validation purposes, Figure 14 shows the voltage profile in the existing condition, scenario 1, and scenario 3, which are all still within permissible voltage regulation. Scenario 3 also produces fewer losses than the existing and scenario one, with the system losses at 11:00 being 46.3, 49.93, and 46.51 kW for scenarios 3, 1, and the existing, respectively. There is a 7.27% decrement on power system loss. The line loading condition also had a positive impact, as presented in Figure 15.

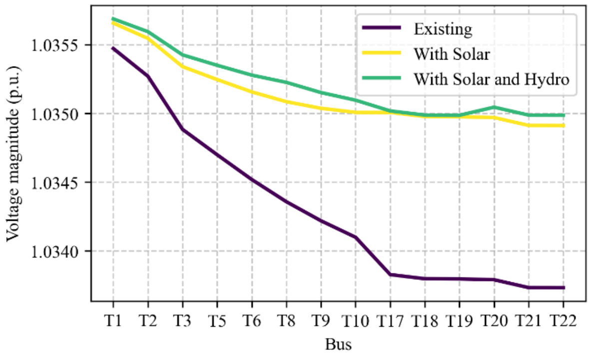

Figure 14 Voltage profile in optimized solar-hydro scenario

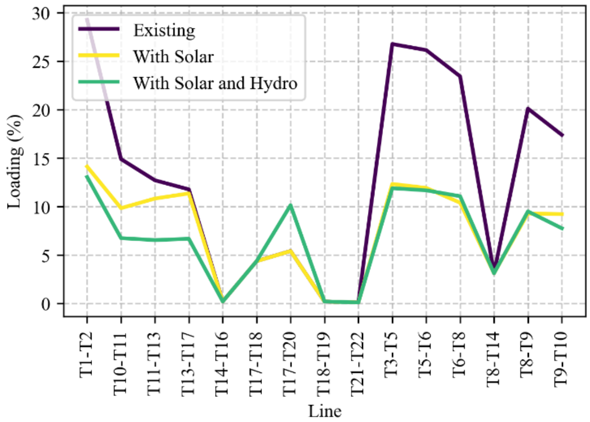

Figure 15. Line loading percentage in optimized solar-hydro scenario

In the proposed method, HC is determined by the sensitivity of the operation limit of the distribution system. The characteristics of hydropower and solar power are different depending on the optimum generation capability and system load period. The most solar power energy would be generated in the daytime around 11:00, while for hydropower, it depends on the water flow. In this optimization process, optimal PV farms would try to produce as much as possible in the daytime while hydropower produces power evenly during the 24 hours. Not all scenarios have reverse power to upstream violation. However, if DG penetrations occur in scenarios 1, 2, and 3, the power factor in the distribution substation would drop below 0.85, which may make the upstream level suffer from reactive power management.

IV. CONCLUSION

Distribution systems usually directly manage the power system from the upstream level. Installing the DG, which is not owned by the utility, may disturb the operation. For that reason, the integration scheme for the distribution system utility has the answer in how much the optimum size and number of DG can be installed on its system using the proposed method by minimizing the power system losses. The proposed method works in the real case of the GDN-04/feeder 4 20 kV Godean Distribution System, which has abundant resources of solar and hydropower. From the simulation result, it shows that installing DG in some buses and different resources may increase the penetration level, which is 3.14, 2.24, and 3.78 MW, simultaneously for scenarios 1, 2, and 3. Furthermore, scenario 3 also results in a higher decrement of 7.27% compared to 6.85% (scenario 1) and 6.56% (scenario 2). The proposed method also confirms that the operational constraints, such as voltage and line loading, are not violated. It also has been confirmed in the simulation result for all scenarios. Further research may discuss reactive power management for the upstream level if DG integration becomes popular in common power systems.

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