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Environmental And Economic Optimization For Distribution Power Grids With Soft Open Points, Solar-Based Distributed Generators, And Battery Energy Storage Systems

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Abstract
Distribution electric grids (DEGs) are responsible for supplying electricity to consumers, making them a crucial component of the power system. Researchers have consistently focused on reducing the costs associated with purchasing electricity from DEGs. This study focuses on optimizing the placement and sizing of solar-based distributed generators (SDGs), soft open point (SOP), and battery energy storage systems (BESS) within the Nha Be 55-bus distribution electricity grid in Ho Chi Minh City, Vietnam, to reduce emission cost, fuel cost and the total cost of purchasing electricity from the grid. Equilibrium Optimizer (EO) is used to optimize the location and power output of SDGs, BESS, and SOP devices in two cases: In Case 1, five SDGs and one SOP device are simultaneously placed in the DEG by using the peak load at all buses. Case 2 uses the optimal location of five SDGs and one SOP in Case 1, optimizes the location of BESS, and optimally operates BESS and SOP to minimize the cost of purchasing electricity from the grid. The cost reduction for electricity purchasing is $353.5017, representing 65.53% for Case 1, and $3,897.7532, approximately 45%, for Case 2. The total emission cost can be reduced to 19,272 dollars for a 20-year operating period. Therefore, utilizing SDGs, SOP, and BESS can increase the benefits for the distribution power grid.
Keywords: *Distribution electric grid; Soft open point; Equilibrium Optimizer; solar-based distributed generators; battery energy storage systems.*

I. INTRODUCTION

Distribution electric grids (DEGs) are essential for delivering electricity to consumers, making them a vital part of the power system. Researchers have consistently aimed to lower the costs associated with procuring electricity from DEGs. Several solutions can be implemented. One approach is to install distributed generation (DG) [1] systems to reduce active power requirements in the DEGs. Additionally, placing compensating capacitors [2] can help regulate reactive power. Other strategies include simultaneously optimizing the electric distribution network through reconfiguration and capacitor placement [3], as well as flexibly controlling both active and reactive power using soft open point (SOP) [4, 5]. Using battery energy storage systems (BESS) [6] is also beneficial. This paper focuses on optimizing the sizing and location of solar-based distributed generators (SDGs), SOP, and BESS to achieve both technical and economic advantages for the DEG. The research [7] focuses on optimizing the location and sizing of three DGs and five SOPs on a 33-node DEG to reduce power losses and improve voltage profile. The results indicate that implementing three DGs and five SOPs leads to a 79.5% reduction in power losses compared to a system without these enhancements. The research [8] examines the use of SOPs and reconfiguration in both 33-node and 69-node DEGs. This study tested five scenarios, increasing the number of SOPs from one to five. As the number of SOPs increased, the power losses decreased significantly. Specifically, losses were reduced by 30.94% to 58.65% for the 33-node DEG and from 56.16% to 75.05% for the 69-node DEG. However, the high cost of SOPs makes the use of two, three, four, or five SOPs impractical for the DEG. In reference [9], the authors explore the optimal placement of soft open points (SOPs), shunt capacitor banks (SCBs), and distributed generators (DGs) within the IEEE 69-node distribution electric power grid to minimize power losses over both hourly and annual timeframes. The findings indicate that strategically placing SCBs and DGs, followed by SOPs, is essential for achieving the lowest power losses. While the integration of wind turbines (WTs) and photovoltaic systems (PVs) into the distribution grid can lead to increased power losses during periods of high renewable energy generation, adding SOPs and SCBs can effectively reduce these losses. Ultimately, incorporating both SOPs and SCBs in distribution grids that include renewable energy sources results in a significant reduction in energy losses. In [10], the optimal placement of BESS combined with DGs in DEGs is achieved through a proposed meta-heuristic method known as the Multi-objective Artificial Hummingbird Algorithm (MOAHA). The results obtained using MOAHA have proven to be very effective in enhancing the voltage stability margin and reducing costs in microgrids. The authors in [11] investigated long-term strategies to minimize investments in BESS and reduce electricity costs while considering grid-connected DG from solar energy. They developed a mathematical model to optimize the operational parameters of both BESS and solar energy generated by DG (DGBSE), taking into account the energy output curtailment from DGBSE. The study [12] has applied SOPs in distribution power grids and considered a small power loss, about 1% for each converter at each terminal of SOPs. The study [13] constrained the capacity limit of BESS at the beginning and the end of the operation time. Different values selected would lead to different effectiveness for BESS [14]. The study [15] suggested using the same energy level for BESS at the beginning and end times.

The constraints in the studies [13-15] are very useful to operate BESS effectively. So, these constraints are reuzitilized in the paper. In addition, the studies [16-17] suggested using fuel and emission functions for the conventional power sources to calculate the effectiveness of using renewable power sources in distribution power grid. In general, previous studies have made significant progress in reducing losses and lowering the cost of electricity from the grid. However, the current use of multiple SOPs in DEG is inefficient. Additionally, only installing SOP and BESS at existing positions while ignoring optimal sites is a major limitation. This paper addresses these issues by employing an Equilibrium Optimizer (EO) [18] to optimize the location and sizing of SDGs, SOP, and BESS in DEG to reduce total fuel cost, emission cost and electricity purchasing costs from the grid. The novelty of the study is as follows:

1. Consider the fuel cost and emission cost for the conventional power sources at the slack node,
2. Test a real distribution power system in Vietnam,
3. Consider new electric component devices, such as SOPs, BESS, and solar panels.

After running EO for simulation cases, the contributions are summarized as follows:

1. Reduce total fuel cost significantly,
2. Reduce electric purchasing costs from other conventional power sources,
3. Reduce emissions for the generating process,
4. Reduce total emission cost significantly.

II. Problem Description

The study focuses on reducing the overall costs of energy purchased from the grid. Additionally, all constraints of base DEG and added electric components, such as SDGs, BESS, and SOP, are expressed as follows:

2.1. The objective function

In this problem, the total cost of electric energy purchased from the grid is minimized. The objective function is given as follows:

$$\text{Reduce } Cost_{grid} = \sum_{hr=1}^{24} (P_{LD,hr} + \Delta P_{loss,hr} + P_{BESS,hr} - P_{SDG,hr}) * EP_{hr} \quad (1)$$

$$P_{LD,hr} = \sum_{k=1}^{N_b} P_{LDk,hr} \quad (kW) \quad (2)$$

$$\Delta P_{loss,hr} = \sum_{ab=1}^{N_{br}} 3.I_{ab,hr}^2 . R_{ab} \quad (kW) \quad (3)$$

$$P_{BESS,hr} = \sum_{i=1}^{N_{BESS}} \left(\frac{P_{BESSi,hr}^{In}}{\eta_{iIn}} - \eta_{iOut} * P_{BESSi,hr}^{Out}\right) \quad (kW) \quad (4)$$

$$P_{SDG,hr} = \sum_{m=1}^{N_{SDG}} P_{SDGm,hr} \quad (kW) \quad (5)$$

where $Cost_{grid}$ is total cost of electric energy purchased from the grid, $P_{LDk,hr}$ is active power load demand at the kth load bus at the hrth hour, $I_{ab,hr}$ is branch current of the abth distribution line at the hrth hour, R_{ab} is branch resistance of the abth distribution line, $P_{BESSi,hr}^{In}$ is charging active power of the ith BESS at the hrth hour, $P_{BESSi,hr}^{Out}$ is discharging active power of the ith BESS at the hrth hour, η_{iIn} and η_{iOut} are charging and discharging efficiencies of the ith BESS, $P_{SDGm,hr}$ is active power output of the mth SDG at the hrth hour, EP_{hr} is electricity price at the hrth hour, N_{br} is the branch number, N_b is the bus number, N_{SDG} is number of SDGs, and N_{BESS} is the BESS number.

In addition, the fuel cost and emission of the conventional power source at slack node are also reduced after placing renewable power sources. So, the total fuel and emission costs are also reduced as follows [16-17]:

$$\text{Reduce Cost}_{Fuel} = \sum_{hr=1}^{24} P_{grid,hr} \cdot (\alpha_f \cdot P^2_{grid,hr} + \beta_f \cdot P_{grid,hr} + \gamma_f)\ (\$) \quad (6)$$

$$\text{Reduce Cost}_{Emission} = \text{Price}_{Emission} \cdot \sum_{hr=1}^{24} (\alpha_e \cdot P^2_{grid,hr} + \beta_e \cdot P_{grid,hr} + \gamma_e)\ (\$) \quad (7)$$

Where, α_f, β_f, and γ_f are the fuel parameters of the conventional power sources [16]; α_e, β_e, and γ_e are the emission parameters of the conventional power sources [17]; $P_{grid,hr}$(in MW) is the power generated by the conventional power source at the hrth hour; and $\text{Price}_{Emission}$ is the price of emission.

2.2. The constraints

2.2.1 Constraints of SOP

The SOP component comprises two voltage source converters connected to two buses within the grid, as illustrated in Figure 1 [9]. The operational characteristics of the SOP component highlight the crucial relationship between active and reactive power at these buses. If the SOP component receives active power from bus x and transfers it to bus y, the active power at bus x will equal the active power at bus y plus any losses incurred by the SOP component. In this work, the power loss of the SOP is neglected because this loss of a VSC is very low, approximately 1% per converter [12]. This relationship can be summarized as follows:

$$P_{SOPx} + P_{SOPy} = 0 \quad (8)$$

In addition, the SOP component can inject reactive power at buses x and y, which are expressed by Q_{SOPx} and Q_{SOPy}, respectively. Unlike the active power at the buses, the reactive powers do not follow the constraint (8). However, the apparent power at the two buses is constrained as follows:

$$\sqrt{P^2_{SOPx} + Q^2_{SOPx}} \leq S^{max}_{SOPx} \quad (9)$$

$$\sqrt{P^2_{SOPy} + Q^2_{SOPy}} \leq S^{max}_{SOPy} \quad (10)$$

When optimizing the placement of SOP components in distribution grids, it must satisfy the constraints mentioned above and another constraint regarding the location as follows:

$$2 \leq L_{SOPx},\ L_{SOPy} \leq N_b \quad (11)$$

$$L_{SOPx} \neq L_{SOPy} \quad (12)$$

where, L_{SOPx} and L_{SOPy} are the locations of the two terminals of SOP connected in the DEG, S^{max}_{SOPx} and S^{max}_{SOPy} are maximum apparent powers of the SOP device at buses x and y.

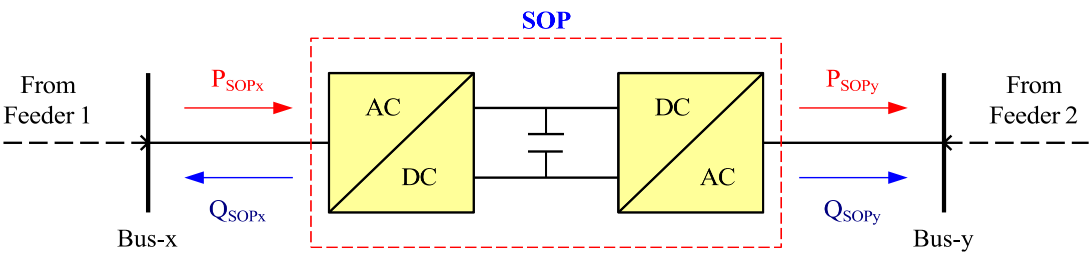

Figure 1. The connection of SOP components in the DEG

2.2.2. The constraints of SDGs

The study optimizes the SDGs within the grids. The added components have two main parameters: power generation and grid location. Therefore, they are constrained by:

$$2 \leq L_{SDGm} \leq N_b \quad (13)$$

$$P^{Low}_{SDGm} \leq P_{SDGm} \leq P^{Up}_{SDGm} \quad (14)$$

where: L_{SDGm} is the location of the mth SDG, P^{Low}_{SDGm} and P^{Up}_{SDGm} are minimum and maximum active power limitations of the mth SDG.

2.2.3. The constraints of electric grids

Line current constraint: Before and after installing additional electric components on a line or node, the line current must always comply with the following rule:

$$I_{ab} \leq I_{ab}^{Up} \quad (15)$$

where, I_{ab} and I_{ab}^{Up} are branch current and upper branch current of the abth distribution line.

Node voltage constraint: All nodes on the grid are constrained by the operating voltage range defined by the lower and upper bounds as follows:

$$V^{Low} \leq V_j \leq V^{Up}; j = 1, \dots, N_b \quad (16)$$

where: V_j is voltage of the jth bus, V^{Low} and V^{Up} are lower and upper voltage limits.

Power equality constraints: The study examines the active power injection of the additional SDGs, so the power equations in the grids are as follows:

$$P_{SDG,hr} + P_{grid,hr} = P_{LD,hr} + \Delta P_{loss,hr} + P_{BESS,hr} \quad (17)$$

$$\sum_{r=1}^{N_{Sop}} Q_{SOPr,hr} + Q_{grid,hr} = \sum_{ab=1}^{N_{br}} 3.X_{ab,hr}.I_{ab,hr}^2 + \sum_{k=1}^{N_b} Q_{LDk,hr} \quad (18)$$

where: $P_{grid,hr}$ and $Q_{grid,hr}$ are active and reactive power from the grid at the hrth hour, X_{ab} is branch reactance of the abth distribution line, $Q_{SOPr,hr}$ is reactive power of the rth SOP at the hrth hour, N_{SOP} is number of SOP.

2.2.4. The constraints of BESS

Due to the three operation statues, $P_{BESS,hr}$ in Equation (1) is mathematically determined as follows:

$$P_{BESS,hr} = \begin{cases} -\dfrac{P_{BESS,hr}^{In}}{\eta_{In}} & \text{if } State_{BESS,hr} = 1 \text{ (storage)} \\ \eta_{Out}.P_{BESS,hr}^{Out} & \text{if } State_{BESS,hr} = 0 \text{ (generation)} \\ 0 & \text{No working} \end{cases} \quad (19)$$

Converter power limits: Each BESS utilizes two power converters, including an AC-to-DC converter for energy storage and a DC-to-AC converter for generation. The output power of BESS when working in the DEG at the hrth considered hour $P_{BESS,hr}$ is dependent on the limits of the two power converters. Typically, the operational value of a BESS must be less than or equal to the maximum power, as demonstrated in the following formula:

$$0 \leq |P_{BESS,hr}| \leq P_{BESS}^{max} \quad (20)$$

Battery limit of BESS: At each operating hour, the capacity of the BESS is consistently monitored to ensure it remains within the constraints of its battery capacity [13]:

$$E_{Min}^{request} \leq E_{BESS,hr} \leq E_{BESS}^{max} \quad (21)$$

where $E_{BESS,hr}$ is the remaining energy in BESS at the end of the hrth hour; E_{BESS}^{max} is the maximum capacity of BESS; and $E_{Min}^{request}$ is the requested saving energy in BESS for the case that predicted power is smaller than real power.

The remaining energy of the BESS at the end of each hour is calculated as follows [14]:

$$E_{BESS,hr} = \begin{cases} E_{BESS,hr-1} + \dfrac{P_{BESS,hr}^{in}}{\eta_{in}} & \text{if } State_{BESS,hr} = 1 \text{ (storage status)} \\ E_{BESS,hr-1} - P_{BESS,hr}^{out} & \text{if } State_{BESS,hr} = 0 \text{ (generation status)} \end{cases} \quad (22)$$

Available energy and remaining energy constraint: BESS is designed to be a power source that maintains a certain battery capacity based on the operations of the previous day. To ensure energy security, this capacity must remain the same at both the beginning and the end of the BESS operation over a 24-hour period. This constraint is as follows [15]:

$$E_{BESS,24} = E_{BESS,0} \quad (23)$$

III. Equilibrium Optimizer (Eo) Algorithm

EO is a powerful metaheuristic algorithm. It consists of the main following stages [18]:

1) Randomly producing an initial population,
2) Evaluating the population,

3) Creating newly updated candidate solutions,
4) Checking and correcting the newly obtained solutions,
5) Evaluating these newly obtained solutions,
6) Retaining higher-quality solutions while discarding lower-quality ones.

The only significant difference between EO and other metaheuristic algorithms lies in the stage of generating newly updated candidate solutions. All other stages are similar to those used in other metaheuristic approaches.

In the first stage, a set of solutions M_c (where c=1, …, N_{po}), called population, is randomly produced. In the second stage, new solutions of these current solutions are found based on the following equation.

$$M_c^{new} = M_{top5} + \delta.(M_c - M_{top5}) + \frac{(1-\delta).\rho}{G_{RP}.V} \quad (24)$$

where: N_{po} is population size, M_c and M_c^{new} are the cth existing and new solutions in the current and newly updated population; M_{top5} is one out of the five high-quality candidate solutions; δ is the scaling factor; ρ is the enhanced factor for balancing the exploitation and exploration phases. G_{RP} and V are the return proportion factor and the given volume. G_{RP} is a random number in the range [0, 1], and V is selected to be 1. The M_{top5}, δ and ρ are obtained as follows:

$$M_{top5} \in [M_{best}, M_{2best}, M_{3best}, M_{4best}, M_{center}] \quad (25)$$

$$\delta = 2.\mathrm{sign}(rdn_{0-1} - 0.5).[e^{-G_{Iter}} - 1] \quad (26)$$

$$\rho = \delta.rdn_{spec}(M_{top5} - G_{Iter}.M_c) \quad (27)$$

In these equations, M_{best} is the most effective solution of the current solution set. M_{2best}, M_{3best}, M_{4best} are the second, third and fourth most effective solutions. M_{center} is the center solution of the top four best solutions; G_{Iter} is the function of the current iteration and maximum iteration number; and rdn_{spec} is a special random number within 0 and 0.5. The three parameters are obtained by:

$$M_{center} = 0.25.(M_{best} + M_{2best} + M_{3best} + M_{4best}) \quad (28)$$

$$G_{Iter} = \left(1 - \frac{Iter_{cur}}{Iter_{max}}\right)^{\frac{Iter_{cur}}{Iter_{max}}} \quad (29)$$

$$rdn_{spec} = \begin{cases} 0, & \text{if } rdn_{0-1} \le 0.5 \\ rdn_{0-0.5}, & \text{else} \end{cases} \quad (30)$$

where: $Iter_{cur}$, $Iter_{max}$ are the current and maximum iterations. rdn_{0-1}, $rdn_{0-0.5}$ are randomly produced number belonging to the range [0, 1] and the range [0, 0.5].

IV. SIMULATION RESULTS

1.1. Studied system and simulation cases

In this section, EO is employed to optimize the location and power output of SDGs, BESS, and SOP devices in a Nha Be 55-bus DEG, Ho Chi Minh City, Vietnam. The Nha Be 55-bus DEG is plotted in Figure 2. The DEG's nominal voltage is 23 kV, and the total load demands are 7654.626 kW and 2292.1 kVAr. The load power at each bus in the 55-bus DEG is illustrated in Figure 3. The fuel cost parameters in Eq. (6) are respectively, 0, 20, 0.25 [16], and the emission parameters in Eq. (7) are, repectively, 0.002, 0.4, 50, 0 and 0. $Price_{Emission}$ is selected to be $0.05/kg.

EO is run 50 times for Case 1 and 10 times for Case 2. The population size and iteration number are set to 50 and 500 for Case 1 and 100 and 1000 for Case 2. In Case 1, five SDGs and one SOP device are simultaneously placed in the Nha Be 55-bus DEG by using the peak load at all buses. Case 2 uses the optimal location of five SDGs and one SOP in case 1, optimizes the location of BESS, and optimally operates BESS and SOP to minimize the cost of purchasing electricity from the grid. In case 2, five SDGs have capacities ranging from 0 kW to 1,000 kW, depending on the actual solar radiation in Nha Be District, Ho Chi Minh City, Vietnam. The maximum power limit of SOP is 3 MVA. The results obtained for Case 1 and Case 2 are as follows:

Case 1: Optimize the simultaneous placement of one SOP device and five SDGs.

Case 2: Based on the results of Case 1 to optimize the placement of BESS and operate BESS and SOP to minimize total electricity purchasing cost by the grid over 24 hours.

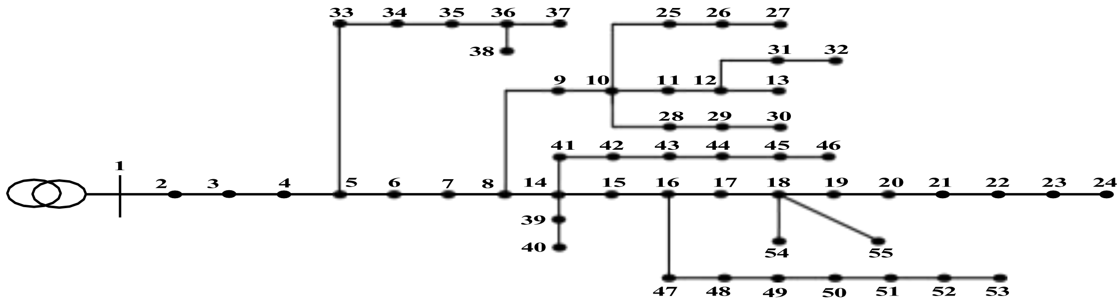

Figure 2. The Nha Be 55-bus DEG in Ho Chi Minh City, Vietnam

Figure 3. The load demands at the Nha Be 55-bus DEG

1.2. Resutls obtained for Case 1

To simulate Case 1, five SDGs and one SOP are limited to a range of 0 to 1000 kW and from 0 to 3 MVA. The price of electricity is 0.07 $/kWh. The results obtained by the proposed EO are reported in Table 1 and Table 2. Five SDGs are placed on buses 8, 18, 22, 43, and 35. Two buses to connect the SOP device are 2 and 20. The optimal capacity of the five added SDGs is 1000 kW. An apparent power of 2.3 MVA is selected for bus 2, while bus 20 is assigned an apparent power of 3.0 MVA. The electricity purchasing cost is $539.4891 for the base system and $185.9874 for the modified system with the added components. The electricity purchasing cost reduction is $353.5017, corresponding to 65.53%. Table 3 indicates that the total fuel cost is $1189.88 for the Base system and $141.85 for Case 1; meanwhile, the total emission cost is $2.66 and $2.55 for the Base system and Case 1. Clearly, the total fuel cost is reduced significantly, and the emission cost is reduced slightly for one hour. However, if the operation of renewable power sources is 20 years, the total emission cost can be reduced to $(2.66-2.55)\times 8760 \times 20$=19,272 dollars.

Table 1. The optimal location and size of the additional components for Case 1

Component	Bus	Capacity
SDG1; SDG2; SDG3; SDG4; SDG5 (kW)	8; 18; 22; 43; 35	1000; 1000; 1000; 1000; 1000
SOP (MVA)	2-20	$S_{SOP,2}$=2.3; $S_{SOP,20}$=3.0;

Table 2. The electricity purchasing cost of the Base system and Case 1

Electricity purchasing cost of Base system ($)	Electricity purchasing cost of Case 1 ($)	Electricity purchasing cost reduction in $ & in %
539.4891	185.9874	$353.5017/65.53%

Table 3. The fuel cost and emission cost of the Base system and Case 1

Result	Base System	Case 1
Fuel cost ($/h)	1189.88	141.85
Emission ($/h)	2.66	2.55

1.3. Resutls obtained for Case 2

This section simulates two systems to analyze the electricity purchasing costs from the grid. The total cost of purchasing electricity from the grid is calculated for both systems: the original system (OS), which does not include any additional electric components, and the Hybrid System (HS), which incorporates five

SDGs, an SOP device, and one BESS.

Figure 4 illustrates the power variation of five SDGs over 24 hours. In Case 1, the optimal placement of the SOP is at nodes 2 and 20. Figure 5 displays the optimal power output of the SOP for each hour. Additionally, Figure 6 depicts the fluctuations in load demand power, the total power for the five SDGs, and the OS and HS power outputs throughout the day. Figure 7 shows the energy charging and discharging of the BESS at node 33 over 24 hours, along with the corresponding electricity prices. Figure 8 displays the Nha Be 55-bus DEG in Ho Chi Minh City, Vietnam, which includes additional electric components. Finally, Figure 9 presents the total cost of purchasing electricity from the grid for one day.

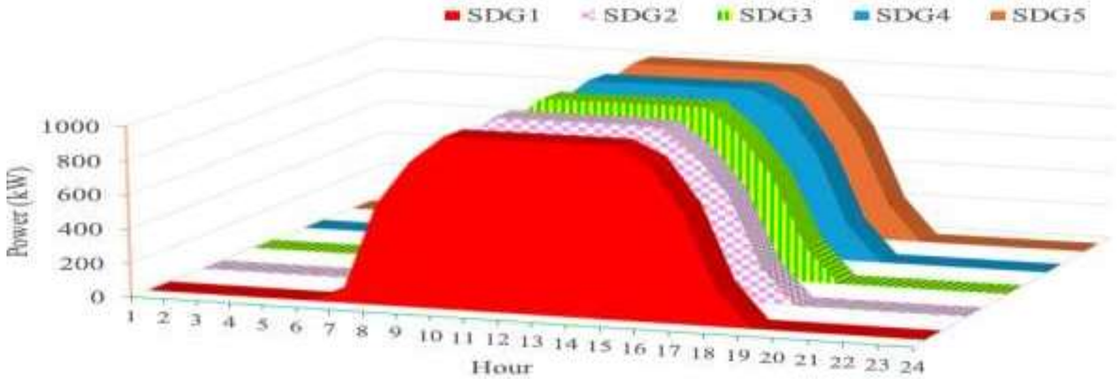

Figure 4. Power variation of five SDGs over 24 hours

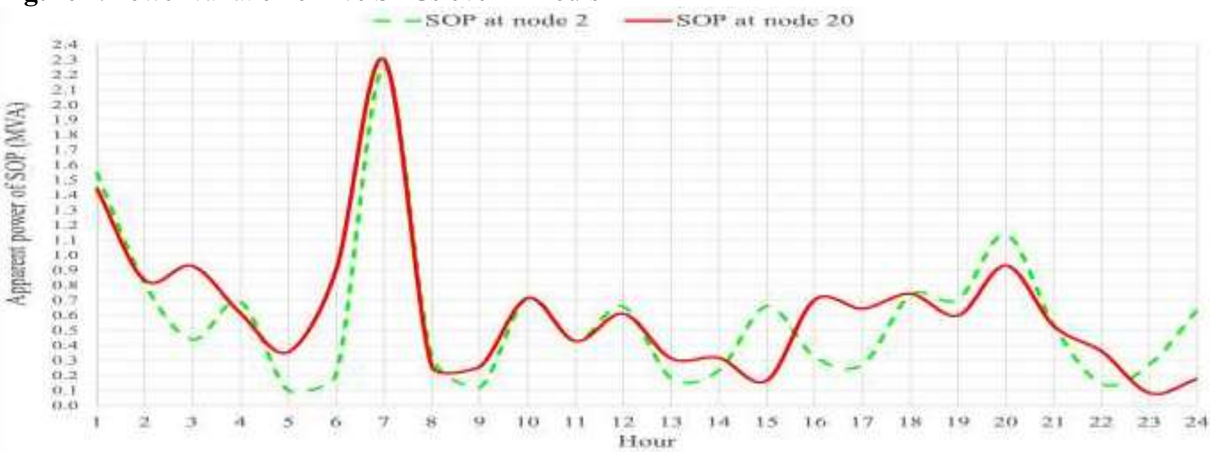

Figure 5. The optimal power output of the SOP for each hour

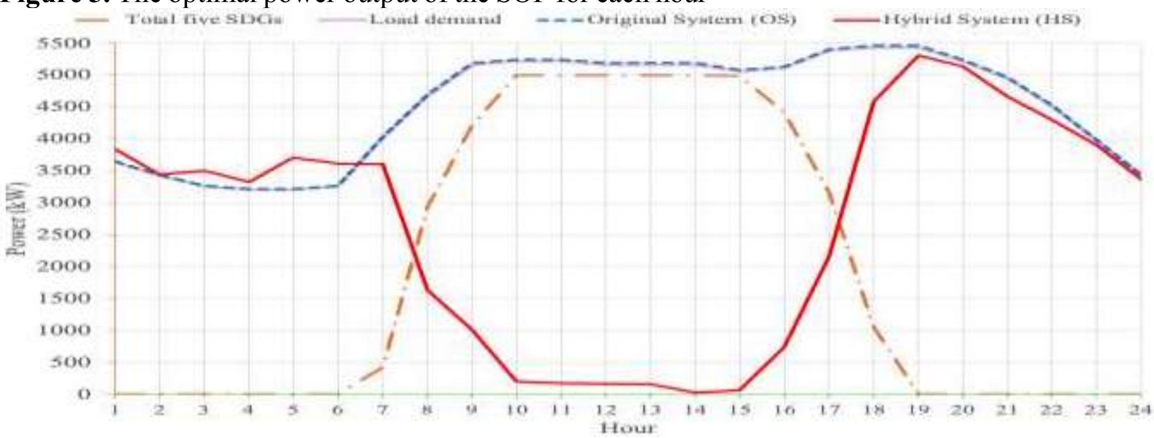

Figure 6. The fluctuations in load demand power, the total power for the five SDGs, and the power outputs of the OS and HS throughout the day

Figure 7. The energy charging and discharging of the BESS at node 33 over 24 hours, along with the corresponding electricity prices

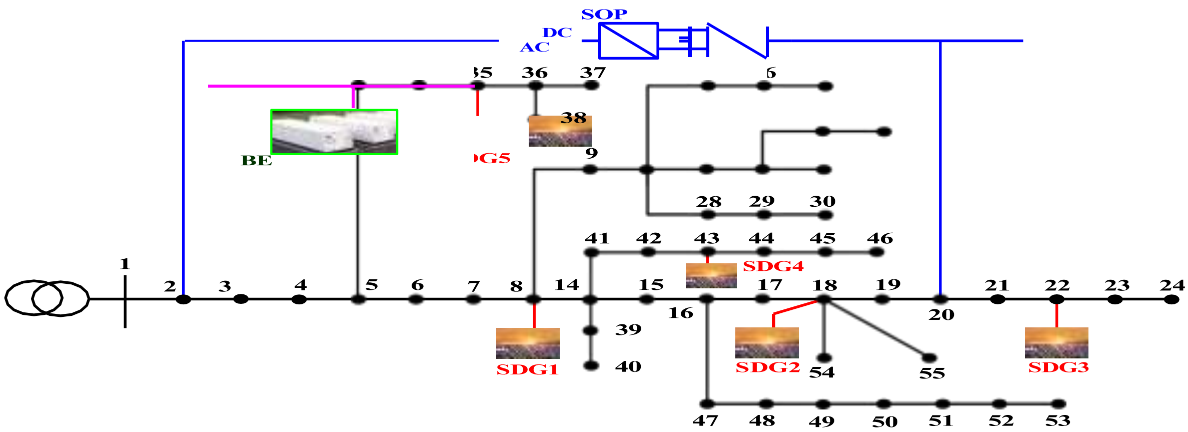

Figure 8. The Nha Be 55-bus DEG in Ho Chi Minh City, Vietnam, includes additional electric components

In an OS, the minor electricity purchasing cost is $145.9883 at 4 o'clock, and the highest cost of purchasing electricity is equal to $703.9256 at 18 o'clock, and 19 o'clock; the total cost of buying electricity for 24 hours is equal to $8662.7823. In the HS, the lowest electricity purchasing cost is equal to $1.6429 at 14 o'clock, the maximum cost of purchasing electricity is equal to $684.3114 at 19 o'clock, and the total cost of buying electricity is equal to $4765.0291 for one day. So, with optimal operation of the SOP devices and BESS over one day, HS has reduced $3,897.7532 (about 45%) compared to the OS.

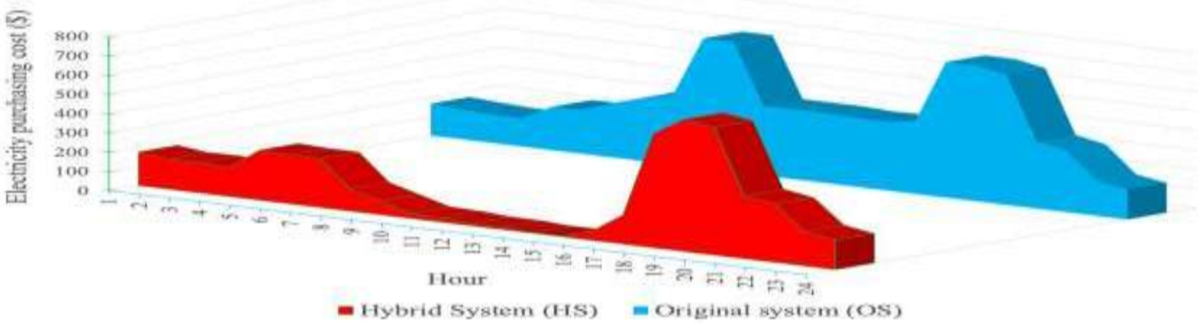

Figure 9. Total cost of purchasing electricity from the grid for one day

1.4. Discussion on voltage profile improvement

Figure 10 displays the voltage profile of the base system, which does not include any additional electrical components, alongside the system in Case 1 that incorporates five SDGs and one SOP. In the base system, the voltage profile between bus 22 and bus 24 is lower by 0.9889 per unit (pu). However, by optimally positioning and sizing the five SDGs and the single SOP, and integrating them into the DEG, the voltage profiles for all buses reached approximately 1.0 pu. These findings highlight the significant contributions of the SDGs and SOPs within the 55-bus DEG.

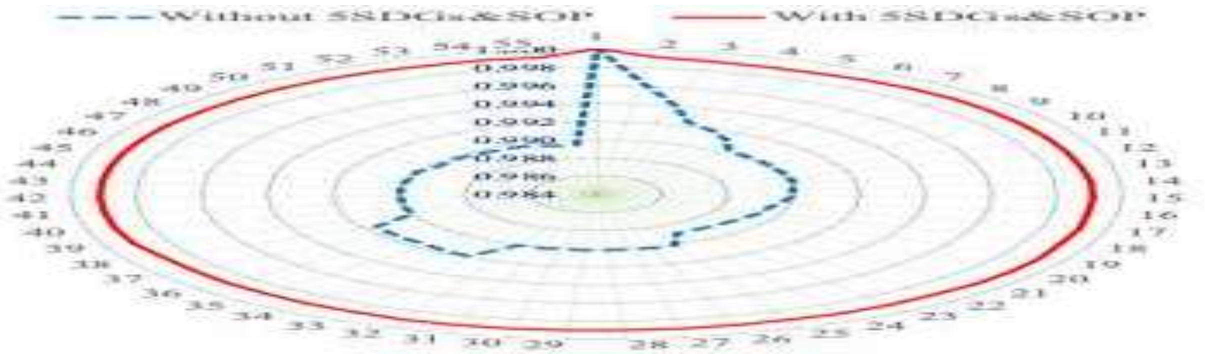

Figure 10. Voltage profile of the Nha Be 55-bus DEG in Ho Chi Minh City, Vietnam

V. CONCLUSION

The paper utilized the EO method to optimize the sizing and placement of SDGs, BESS, and SOP devices within a 55-bus DEG in Nha Be, Ho Chi Minh City, Vietnam. The aim was to reduce the total cost of purchasing electricity from the grid over one hour and over 24 hours. Two research studies were conducted. Five SDGs and one SOP device are simultaneously placed in the DEG by using the peak load at all buses for Case 1. Case 2 uses the optimal location of five SDGs and one SOP in Case 1, optimizes the location of BESS, and optimally operates BESS and SOP to minimize the cost of purchasing electricity from the grid. In Case 1, the cost of purchasing electricity for the base system is $539.4891, while for the modified system with additional components, it is $185.9874. This results in a cost reduction of $353.5017, which corresponds to 65.53%. Furthermore, with the optimal operation of the SOPs device and the BESS over one day, HS has achieved a reduction of $3,897.7532, approximately 45% compared to the OS. These results emphasize the significant role of SOP, BESS, and SDGs integrated into the power system.The research made significant contributions to the power system by reducing the overall cost of purchasing electricity from the grid. However, it did not consider the investment and operational costs associated with installing SDGs, SOP, and BESS. Future studies will address these limitations to provide more substantial benefits for the power system.

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