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OPTIMIZING THE LOCATION AND CAPACITY OF SOFT OPEN POINTS ON THE DISTRIBUTION POWER NETWORK WITH HIGH RENEWABLE ENERGY PENETRATION

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SUMMARY OF DOCTORAL DISSERTATION

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Chapter 1

OVERVIEW

The distribution power network (DPN) supplies electricity directly to electrical loads via medium- and low-voltage distribution lines, resulting in high grid energy losses [1] and voltage drops at load nodes [2]. Therefore, reducing energy and voltage losses in the DPN is of interest to researchers. To reduce energy losses, the solution is to reduce line current and resistance [3] by installing shunt capacitor bank (SCB) [4], wind turbines (WT) [5], Photovoltaic (PV) [6-7], biomass energy [8], reconfiguration [9], battery energy storage systems (BESS) [10], soft open points (SOPs) [11],… The use of distributed generation (DG) systems based on wind and solar energy is highly effective in reducing power losses and cutting energy supplied from conventional power sources such as hydroelectric, thermal, and nuclear power plants. However, wind and solar energy are variable sources, dependent on natural conditions such as solar radiation and wind speed. Excess electricity from DGs during peak power generation hours and low load demand can lead to inefficient economic and technical problems, such as high power losses, line overload, overvoltage at nodes, and feedback power supply to the grid, affecting the operation and safety of DPN systems.

Thus, previous studies have significantly addressed power and energy losses, varying levels of renewable energy penetration, and voltage improvement in IEEE distribution grids. However, installing SOPs at available locations while neglecting potential locations is a limitation; using a large number of SOPs in the distribution grid is impractical and unfeasible; furthermore, the previously used algorithms have not been very effective. In addition, previous studies have overlooked the real-time data integration of solar radiation and wind speed with SOPs, SCB, and BESS. This thesis will overcome these limitations. The Equilibrium Optimizer (EO) metaheuristic algorithm [42] was used to optimize the power and location of SOPs, WT, PV, and SCB in IEEE 33- and 69-node DPNs and in distribution grids in Vietnam. Actual solar radiation and wind speed data were referenced from documents [43] and [44] to calculate solar and wind power capacity. EO has been successfully applied to optimization problems in electrical engineering, such as optimal power grid reconfiguration and optimal placement of SOPs [45], optimal placement of DGs [46], power grid reconfiguration and optimal placement of DGs [47], and optimal placement of wind power plants in high-voltage power systems [48]. In addition, four other metaheuristic methods were also applied, including: Coot optimization algorithm (COOT) [49], Modified weight inertia factor and modified acceleration coefficients-based particle swarm optimization (CFPSO) [50], Tunicate Swarm Algorithm (TSA) [51], and War Strategy Optimization (WSO) [57].

This thesis examines the minimum total energy generated by conventional power sources over one operating year and the associated costs of purchasing grid electricity. In a typical distribution grid, transformers supply power to loads. These transformers receive power from high-voltage lines, which may be supplied by conventional power plants such as thermal, hydroelectric, or nuclear facilities. Transformers, wind turbines (WT), and photovoltaic (PV) systems collectively meet the active power demand. In contrast, power sources, SCBs, and SOPs address the reactive power demand. SOPs can absorb active power at one node and deliver it to another. Furthermore, SOPs can pump or absorb reactive power at two nodes. Meanwhile, BESSs allow for power storage during periods of low load demand, low electricity selling costs, or when renewable energy sources generate excess power beyond load demand, and for power generation during periods of high load demand, high electricity selling costs, or when renewable energy sources and grid power are insufficient. With varying installation locations, rated capacities, and operating capacities of WT, PV, SCB, BESS, and SOPs, total losses, energy received from transformers, and the cost of purchasing electricity from the grid also differ. Therefore, the research task is to determine the most suitable locations for installing the equipment and the most appropriate rated capacities for the equipment in the design problem. Subsequently, their operating capacities are determined by the operational problem. The first problem is more straightforward than the second, but finding the best solution to the second is very important. The range of rated power in the first problem becomes the search space of operating power in the second problem. In the second problem, an operating year is implemented, and the large number of control variables makes it difficult for previous algorithms. So, a very strong metaheuristic algorithm is very useful for studying two problems. In this study, an enhanced equilibrium optimizer (EEO) is proposed, and the IEEE 69-node and Nha Be 55-node distribution power grids are selected to optimize the placement of SCB, PV, WT, BESS, and SOPs devices in the first stage and operate these devices for one year in the second stage.

Chapter 2

THEORETICAL FOUNDATION

2.1 Introduction to SOPs

The Soft Open Points (SOPs) device is considered a power electronics device. SOPs can compensate for reactive power and control active power flow between feeders. A typical SOPs consists of two voltage source converters (VSC) that connect two feeders, as shown in Figure 2.1.

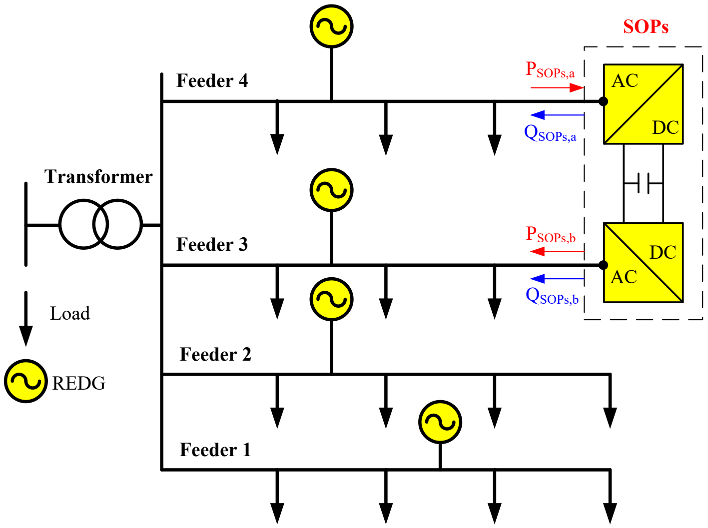


Figure 2.1: Connecting feeder 3 and feeder 4 in the DPN by SOPs

2.2 Constraints of SOPs

$$P_{SOPs,a} = P_{SOPs,b} \quad (2.1)$$

$$\sqrt{Q_{SOPs,a}^2 + P_{SOPs,a}^2} \leq S_{SOPs}^a \quad (2.2)$$

$$\sqrt{Q_{SOPs,b}^2 + P_{SOPs,b}^2} \leq S_{SOPs}^b \quad (2.3)$$

$$0 \leq S_{SOPs}^a,\ S_{SOPs}^b \leq S_{SOP}^{max} \quad (2.4)$$

$$2 \leq L_{SOPs,b},\ L_{SOPs,a} \leq N_n \quad (2.5)$$

$$L_{SOPs,b} \neq L_{SOPs,a} \tag{2.6}$$

2.3 Applied Metaheuristic algorithms

2.7.2 Equilibrium Optimizer (EO)

Details of the EO algorithm have been presented specifically in reference [42]. The operational structure of the EO algorithm includes the following main steps:

- Step 1: initializing the random population

$$E_i = E_i^{low} + Rd \times \left(E_i^{up} - E_i^{low}\right) \text{ với } i = 1,\ldots,N_{PO} \tag{2.10}$$

N_{PO} is population dimension; E_i^{low} is the lowest limit of the solution i, and E_i^{up} is the highest limit of the solution i; E_i is the ith solution; Rd is a random number, chosen from 0 to 1.

- Step 2: updating new candidate solutions

$$E_i^{new} = E_{rf} + (E_i - E_{rf}) \times K + \frac{G}{R \times V} \times (1 - K) \tag{2.11}$$

$$E_{rf} \in [E_{b1}, E_{b2,} E_{b3}, E_{b4}, E_A] \tag{2.12}$$

$$E_A = \frac{E_{b1} + E_{b2} + E_{b3} + E_{b4}}{4} \tag{2.13}$$

2.7.3. Enhanced Equilibrium Optimizer (EEO)

In the section, the proposed EEO is presented. EEO is a modified version of EO based on two proposed modifications implemented on EO. The first modification is to change the determination of the center solution, and the second modification is to improve Equation (2.11) for newly updated candidate solutions. The proposed center solution is obtained by:

$$E_A = (\varepsilon_1 . E_{b1} + \varepsilon_2 . E_{b2} + \varepsilon_3 . E_{b3} + \varepsilon_4 . E_{b4}) \tag{2.14}$$

Where ε_1, ε_2, ε_3, and ε_4 are weighted factors associated with the best, second-best, third-best, and four-best solutions. Normally, the sum of these weighted factors is equal to 1.0. The value selection aims to find a center solution closer to the higher-quality solutions than lower-quality solutions.

In the update method, the proposed EEO sorts the current solution set in the order of decreasing quality. It means the solutions' order is the best, second best, …, and worst solutions. Then, the first half of the population with high-quality solutions and the second half of the population with low-quality solutions are updated based on the two following equations:

$$E_i^{new} = E_{rf} + (E_i - E_{rf}) \times K + \frac{G}{R \times V} \times (1 - K); i = 1, \dots, N'_p \tag{2.15}$$

$$E_i^{new} = E_{b1} + (E_i - E_{rf}) \times K + \frac{G}{R \times V} \times (1 - K);\ i = N'_p + 1, \dots, N_{PO} \tag{2.16}$$

Chapter 3

MINIMUM POWER LOSS AND ENERGY LOSS ON THE DISTRIBUTION POWER NETWORK IN ONE YEAR

3.1 Introduction

Distribution power networks (DPNs) supply electricity to electrical loads and play an important role in the power system. Total power losses in the power system can equal 13% of the total power generated, of which losses in the DPN account for about 70% [65], and high voltage drops during peak load hours. Therefore, reducing power losses and voltage drops in the DPN is always of interest to researchers. To reduce power losses, the solution is to reduce line current and resistance by installing SCB, DG, WT, PV, biomass energy, network reconfiguration, SOPs,…In this chapter, the location and capacity of SCB, WT, PV, and SOPs will be optimized to achieve economic and technical benefits for the DPN.

3.4 Problem formulation

3.4.1 Objective function

The main objectives are to reduce power losses per hour and minimize total energy losses over a day and a year of operation, as outlined below:

$$\text{Reduce: } \Delta P_{loss,h,s} = \sum_{j=1}^{N_{br}} 3.I^2_{brj,h,s}.R_{brj}\ \text{(kW)} \tag{3.1}$$

The minimum energy loss during a 24-hour operating day is considered as follows:

Reduce: $\Delta E_{loss,s}^{day} = \sum_{h=1}^{24} \Delta P_{loss,h,s} * h$ (3.2)

Where: $\Delta E_{loss,s}^{day}$ is the energy loss in one day during the sth month, h = 1÷ 24.

Reduce: $\Delta E_{loss}^{year} = \sum_{s=1}^{N_{ms}} N_{day,s} . \Delta E_{loss,s}^{day}$ (kWh) (3.3)

3.4.2 Constraints

$$P_{cps,h,s} + \sum_{m=1}^{N_{PV}} P_{PVm,h,s} + \sum_{k=1}^{N_{WT}} P_{WTk,h,s} = \sum_{i=1}^{N_n} P_{Li,h,s} + \sum_{j=1}^{N_{br}} 3.I_{brj,h,s}^2 .R_{brj} \quad (3.4)$$

$$Q_{cps,h,s} + \sum_{f=1}^{N_{SOP}} Q_{SOPf,h,s} + \sum_{x=1}^{N_{SCB}} Q_{SCBx,h,s} = \sum_{i=1}^{N_n} Q_{Li,h,s} + \sum_{j=1}^{N_{br}} 3.I_{brj,h,s}^2 .X_{brj} \quad (3.5)$$

3.6 Research results on IEEE 33-node DPN

3.6.2 Optimizing the placement and power of SOPs on the IEEE 33-node DPN

3.6.2.1. Case 1: Optimal sizing and siting of SOPs device in base system (BS)

Bảng 3. 1: Comparison power loss for the DPN 33-node

Case	SOPs devices' optimal power (MVA)	Connected optimal nodes	Power loss (kW)	Loss reduction (%)
BS	-	-	210.9983	0
1	$S_{VSC,6}$=3.00; $S_{VSC,2}$=2.56	6 - 2	75.2201	64.35
2	$S_{VSC,24}$=1.32; $S_{VSC,29}$=1.70	24 - 29	18.8941	91.05

3.6.2.3. Case 3: Optimal operation of SOPs in DPN considering time-varying loads and continuous renewable energy penetration at varying levels over 24 hours

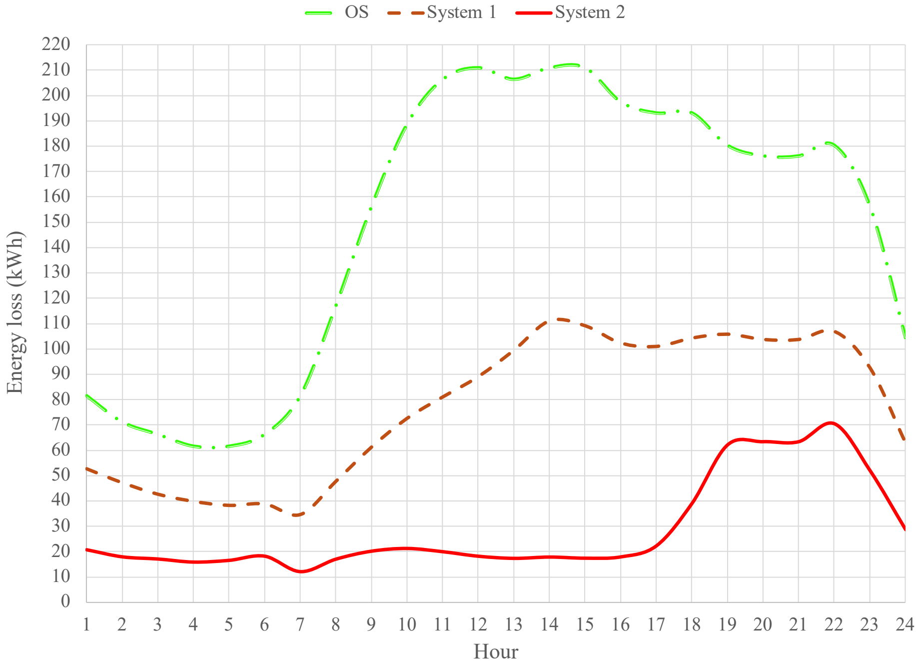


Figure 3.1: Energy loss of systems for 24 hour

3.7 Research results on IEEE 69-node DPN

3.7.1.3 Case 5: Optimal operation of SOPs and SCBs for one year

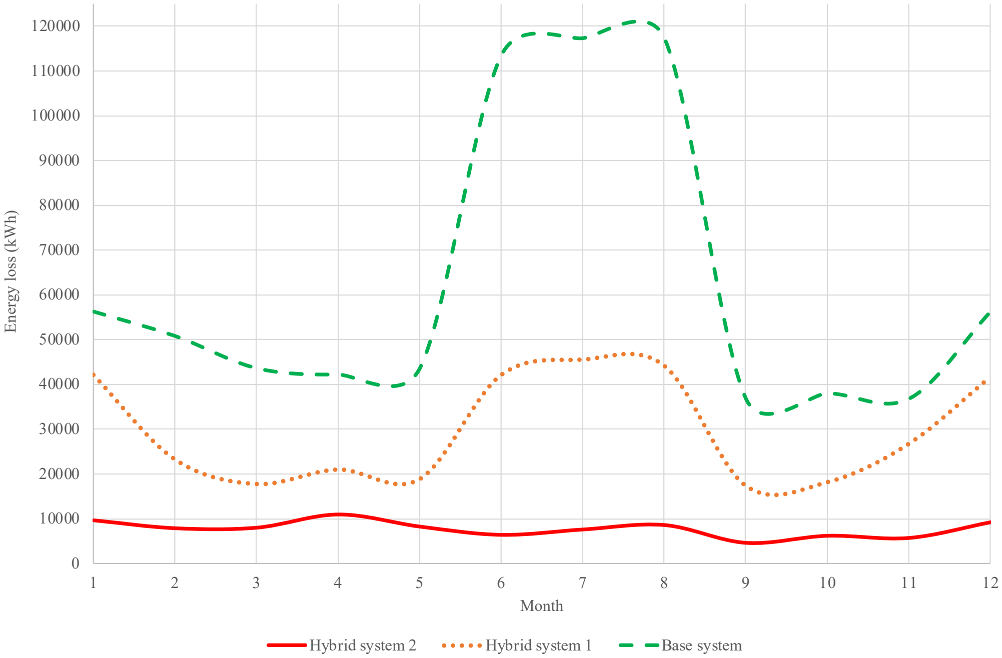


Figure 3.2: Monthly energy loss of systems

3.7.2 Optimizing the placement and power of SOPs on the IEEE 69-node DPN

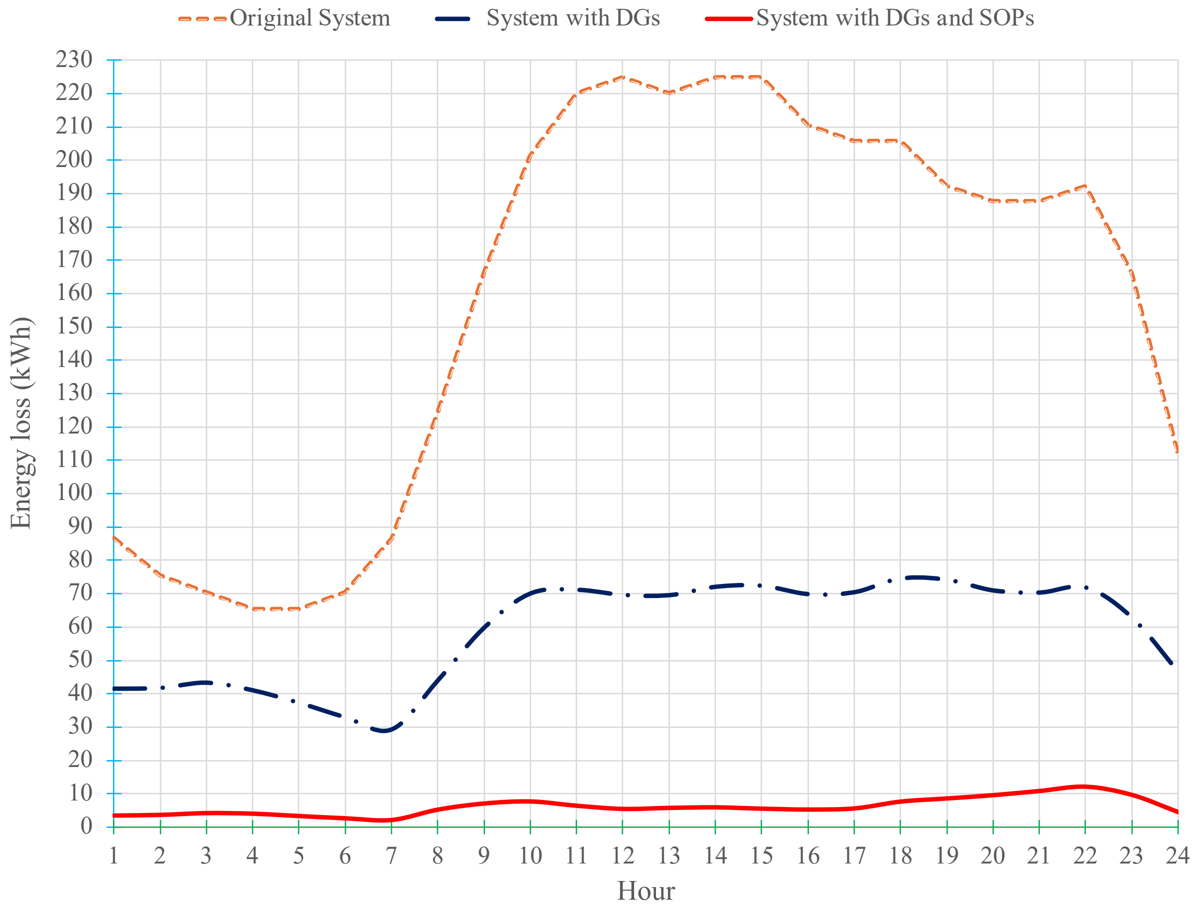
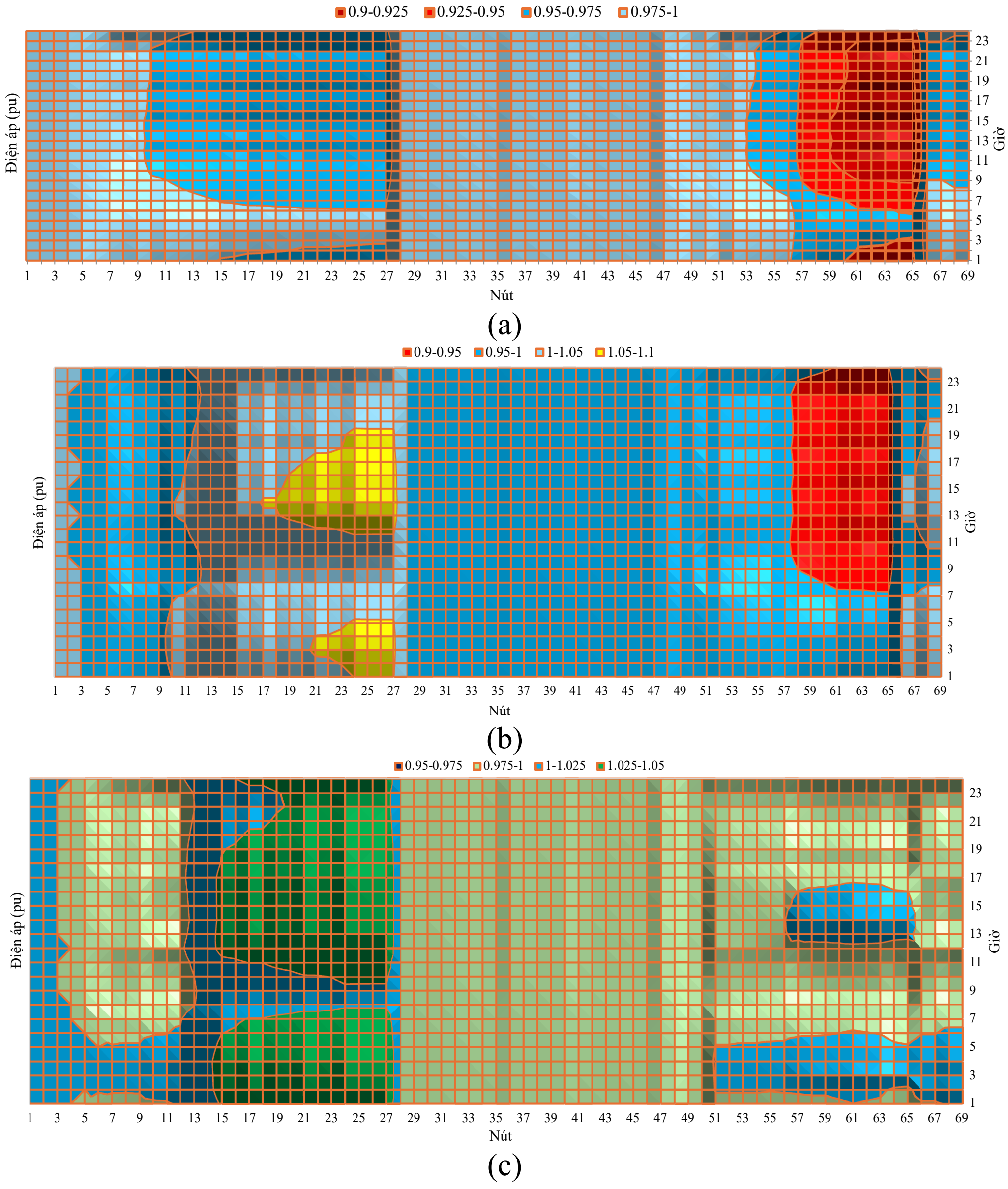


Figure 3.3: Energy loss of various systems for one day

Table 3. 2: Comparison of power loss with different penetration levels of three DGs

Case	**Penetration levels of DG (%)**	**0**	**25**	**50**	**85**	**100**
With DGs	Power loss (kW)	225	145.9294	96.2662	69.7663	72.1456
	Loss reduction (%)	0	35.14	57.22	68.99	67.94
With DGs and SOPs	Power loss (kW)	23.2	17.252	13.122	5.334	6.787
	Loss reduction (%)	89.69	88.18	86.37	92.35	90.59

	Optimal location/power of SOPs (MVA)	2-61/ S_2=2.34; S_{61}=2.24	2-61/ S_2=1.94; S_{61}=1.83	2-61/ S_2=1.62; S_{61}=1.50	17-61/ S_{17}=0.36; S_{61}=1.24	12-61/ S_{12}=0.6; S_{61}=1.23



(a)

(b)

(c)

Figure 3.4: The voltage profile of the systems: (a) without DGs and SOPs; (b) with DGs; (c) with DGs and SOPs

3.8 Conclusions

The contributions of Chapter 3 are summarized as follows:

- - Found EO and WSO, these are the most efficient algorithms achieving lower power losses than previous algorithms, including: PSO [40], TM [54], MOTA [54], BA [55], HSA [56], LSPSO [15], MPSO [13], CSA [13], AO [13], and DSSA [13].
- For basic DPNs without renewable energy involvement, optimizing the location and capacity of SOPs reduces power losses by up to 64.35% for the IEEE 33-node DPN and 89.69% for the IEEE 69-node DPN, raising the voltage at all nodes to nearly 1.0 pu.
- For DPNs with high renewable energy penetration, SOPs participate in flexible power flow control at two connection points, contributing to a significant reduction in power losses. The penetration of renewable energy, combined with optimal SOPs distribution, has helped reduce power losses by up to 91.05% compared to the base system on an IEEE 33-node DPN and by 96.98% on an IEEE 69-node DPN.
- When renewable energy is continuously introduced throughout the day with varying levels of penetration that change over 24 hours, the use of SOPs is a viable solution. Results from a 33-node IEEE DPN showed that optimal 24-hour SOPs operation reduced energy consumption by 2870.7237 kWh (approximately 80.7%) compared to the base system and by 1161.3453 kWh (approximately 62.85%) compared to a system with only renewable energy and no SOPs. Results from a 69-node IEEE DPN showed that the system with DG and SOPs achieved a significant reduction of 3638.6229 kWh (approximately 96.1%) compared to the base system and an impressive reduction of 1257.2779 kWh (approximately 89.49%) compared to a system with only DG.
- Case 5 results on the IEEE 69-node DPN demonstrate the effectiveness of a combined solution that optimizes the operation of SCBs and SOPs when renewable energy penetration varies hourly and monthly, and load varies seasonally. Optimizing the operation of SCBs and SOPs over a year can reduce energy consumption by 660,193.772 kWh compared to the base system without renewable energy, and by 266,264.637 kWh compared to the system with renewable energy penetration. This reduction in energy loss can be quantified in monetary terms at an electricity price of $60/MWh. As a result, over a year, savings of $39,612 can be achieved compared to the baseline system and $15,976 compared to the system with renewable energy penetration.

Chapter 4

APPLYING EEO TO MINIMIZE THE ONE-YEAR ENERGY FOR THE DISTRIBUTION POWER NETWORK

4.4 Problem formulation

4.4.1 Objective function

$$\text{Reduce: } E_{grid} = \sum_{m=1}^{N_m}\sum_{d=1}^{N_{dm}}\sum_{h=1}^{T_h}\left(P_{Load,h,d} + \Delta P_{loss,h,d} - P_{WT,h,d} - P_{PV,h,d}\right) * h \quad \text{(kWh)} \tag{4.1}$$

$$P_{Load,h,d} = \sum_{p=1}^{N_b} P_{Loadp,h,d} \quad \text{(kW)} \tag{4.2}$$

$$\Delta P_{loss,h,d} = \sum_{ij=1}^{N_{ij}} 3.I_{ij,h,d}^{2}.R_{ij} \quad \text{(kW)} \tag{4.3}$$

$$P_{WT,h,d} = \sum_{k=1}^{N_{WT}} P_{WTk,h,d} \quad \text{(kW)} \tag{4.4}$$

$$P_{PV,h,d} = \sum_{n=1}^{N_{PV}} P_{PVn,h,d} \quad \text{(kW)} \tag{4.5}$$

4.4.2 Constraints

Power balance constraints: This chapter considers the installation of WT, PV, SOPs, and SCB in a distribution grid. SOPs and SCBs can supply reactive power, while WT and PV can supply active power. Therefore, the balance of active and reactive power is written as follows:

$$\sum_{n=1}^{N_{PV}} P_{PVn,h,d} + \sum_{k=1}^{N_{WT}} P_{WTk,h,d} + P_{Grid,h,d} = \Delta P_{loss,h,d} + P_{Load,h,d} \tag{4.6}$$

$$\sum_{f=1}^{N_{SOP}} Q_{SOPf,h,d} + \sum_{q=1}^{N_{SCB}} Q_{SCBq,h,d} + Q_{Grid,h,d} = \sum_{ij=1}^{N_{ij}} 3.X_{ij}.I_{ij,h,d}^{2} + \sum_{p=1}^{N_b} Q_{Loadp,h,d} \tag{4.7}$$

4.6 Research results of Chapter 4

4.6.2 Research results on IEEE 69-node DPN

4.6.2.2 Results obtained in Case 1

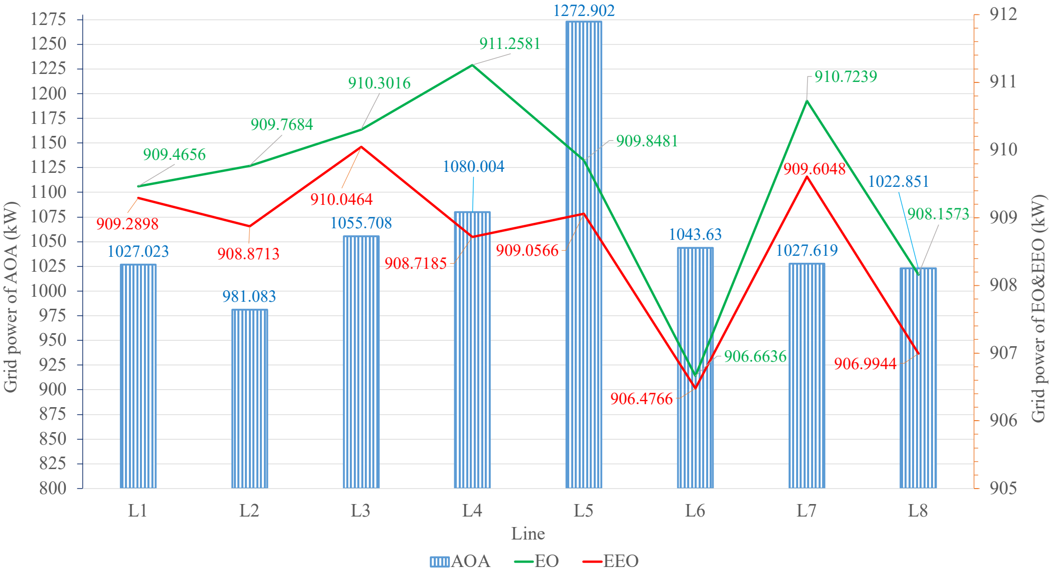


Figure 4.1: The grid power for different locations of one added SOPs in Case 1

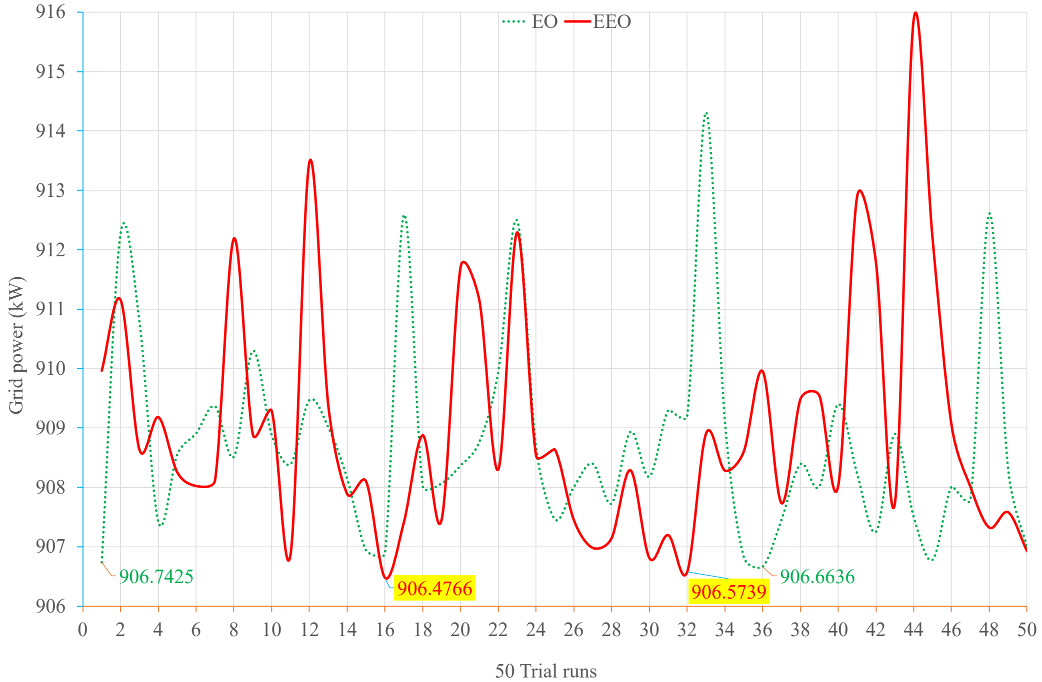
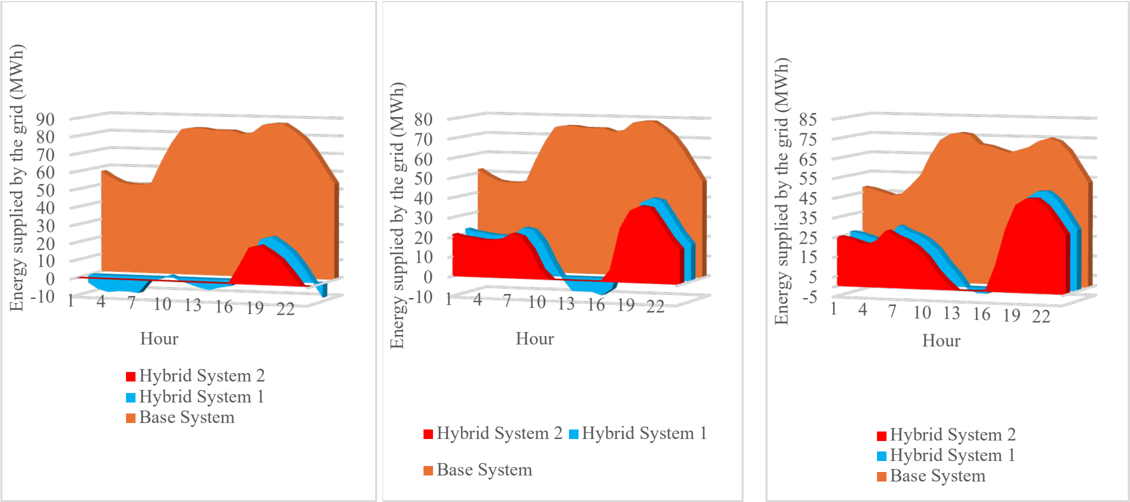


Figure 4.2: Comaprison of fifty solutions obtained by EO and EEO when placing SOP at L6

Table 4. 1: Optimal site and rated power of the added components for Case 1 obtained by three algorithms

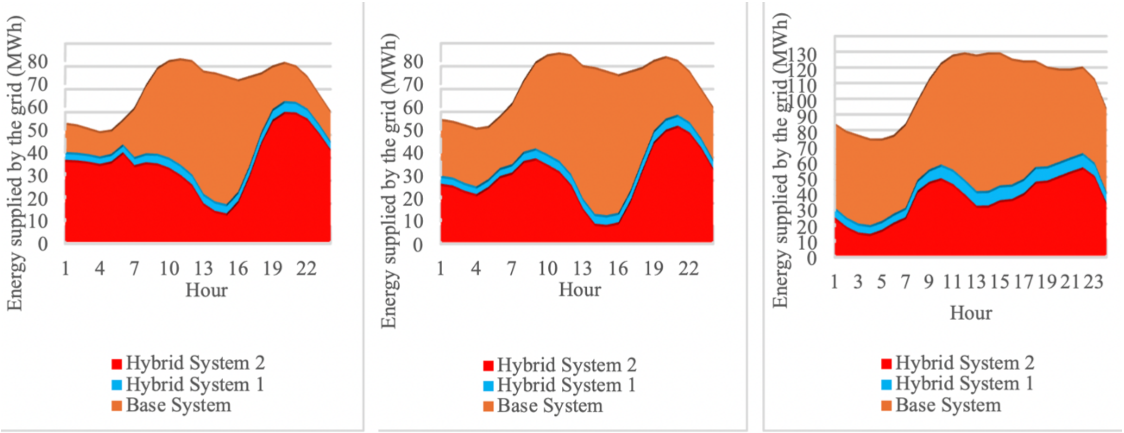
Method	DG (WT; PV1; PV2)		SCB (SCB1; SCB2)		SOPs	
	Node	Size (kW)	Node	Size (kVAr)	Line	Size (MVA)
AOA	58; 2; 9	2000; 500; 400	57; 25	734,254; 1032,217	L2	$S_{VSC,13}$=1,203 $S_{VSC,21}$=1,465
EO	3; 11; 18	2000; 500; 400	17; 67	277,63; 220,804	L6	$S_{VSC,2}$=2,081 $S_{VSC,61}$=2,06
EEO	2; 11; 17	2000; 500; 400	11; 18	339,606; 257,526	L6	$S_{VSC,2}$=1,723 $S_{VSC,61}$=2,056

4.6.2.5 Results obtained in Case 4



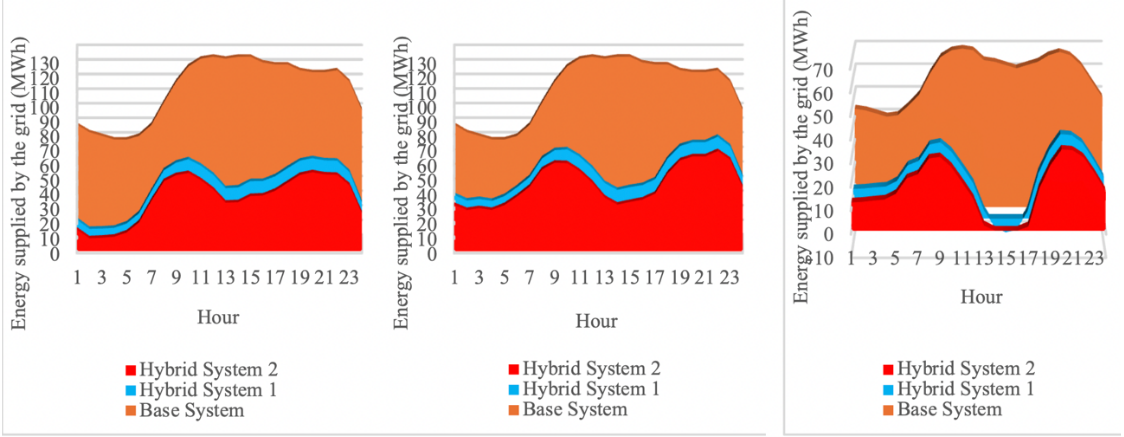
(a) (b) (c)

Figure 4.3: Hourly grid power of systems: a) Janurary, b) February, c) March



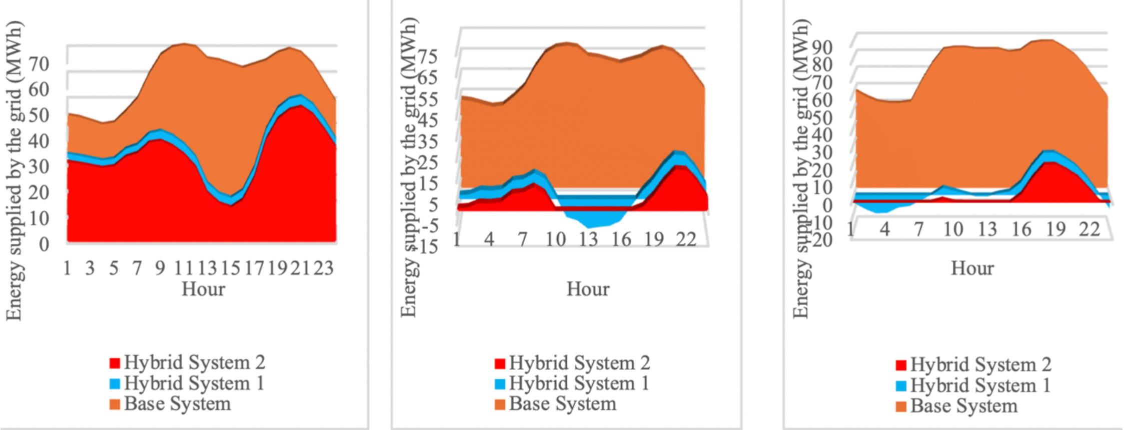
(a) (b) (c)

Figure 4.4: Hourly grid power of systems: a) April, b) May, c) Jun



(a) (b) (c)

Figure 4.5: Hourly grid power of systems: a) July, b) August, c) September



(a) (b) (c)

Figure 4.6: Hourly grid power of systems: a) October, b) November, c) December

The total energy supplied by the grid for each month is presented in Figure 4.7. Hybrid System 2 used the smallest energy from the grid among the three systems, and its energy is less than that of Hybrid System 1 and the base system by 569.605 MWh and 14,178.175 MWh, respectively. The less energy is about 7.7% and 67.5% of Hybrid System 1 and the Base system.

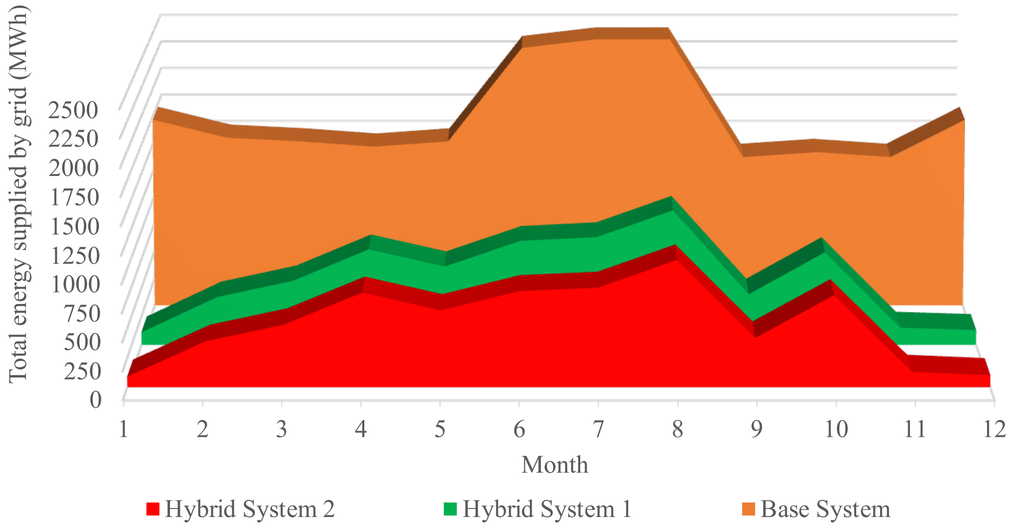


Figure 4.7: Total grid power for each month

4.6.3 Study scenarios in the Nha Be 55-node DPN

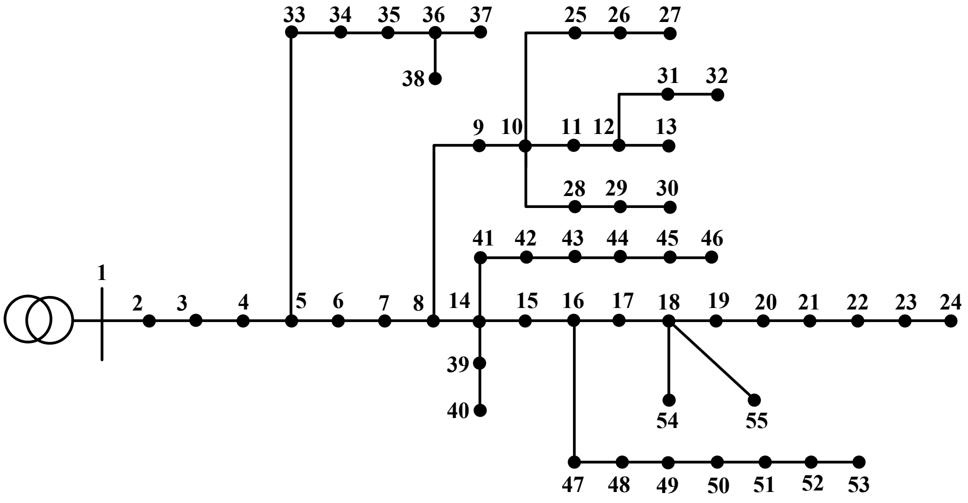


Figure 4.8: The Nha Be 55-node DPN in Ho Chi Minh City

4.6.3.1 Results of Scenario 1

Table 4.2: The optimal site and sizing of the added components for Scenario 1 and grid power

Component	Node	Size	Grid power of Base system (kW)	Grid power of Scenario 1 (kW)	Grid power reduction (kW) / (%)
PV1, PV2 (kW)	22; 44	1000; 1000	7706.803	5666.643	(2040.160) / (26.47)
SCB1; SCB2 (kVAr)	22; 8	1000; 973.195			
SOPs (MVA)	2-20	$S_{VSC,2}$=3; $S_{VSC,20}$=3;			

4.6.3.2 Results of Scenario 2

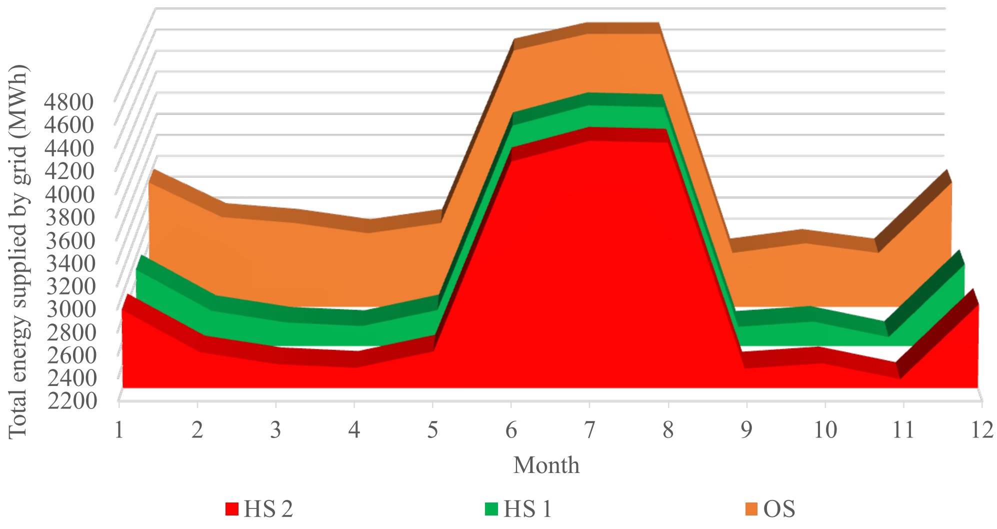


Figure 4.9: Total grid power for each month in the Nha Be 55-node DPN

4.7 Conclusions

The study proposed an EEO algorithm to minimize the total one-year energy supplied by the grid by optimally determining the capacity and operating values of one SOP device, one WT, two PVs, and two SCBs in the IEEE 69-node DPN and Nha Be 55-node DPN in Vietnam. The proposed EEO was compared to other algorithms, such as EO, AOA, EEFA, and POA, executed in the study and previous studies by using the IEEE 33-node DPN for two cases and the IEEE 69-node DPN for two cases. In the IEEE

33-node DPN, Case 1 considered a 1.0 power factor for three added PVs, and Case 2 considered a range between 0 and 1.0 for the power factor. In the IEEE 69-node, Case 1 optimized all added components simultaneously, and Case 2 optimized one WT, two PVs, and two SCBs simultaneously in the first stage and then one SOPs device in the second stage. For each case, the location of one WT, two PVs, and two SCBs was optimized, but that of one SOPs device was, in turn, set to one of eight predetermined lines (L1, L2, …, L8). On the contrary, the capacity of all added components was optimized. So, there were eight circumstances for each case, and each circumstance involved fifty trials. The results are summarized as follows:

- In the IEEE 33-node, the proposed EEO could find the same power loss with several algorithms, with 72.788 kW for Case 1 and 11.741 kW for Case 2; meanwhile, other remaining algorithms found a higher power loss, from 72.79 kW to 83.72 kW for Case 1 and from 53.127 kW to 11.76 kW for Case 2. So, the proposed EEO is more suitable than many other algorithms for the IEEE 33-node DPN under one single hour, including three applied algorithms: EO, EEFA, and POA.

- For Case 1 of the IEEE 33-node DPN, the proposed EEO could find the best power loss of 72.7882 kW with the settings (60 and 50) and (50 and 75) for the population and iteration number; meanwhile, the original reached the same power loss with the setting (80 and 50) and (50 and 100) for the population and iteration number. So, the proposed EEO is faster than the original EO by 20 for the population and 25 for the iteration number for Case 1. Similarly, the proposed EEO is faster than the original EO by 50 for the iteration number and 50 for the population when reaching the best power loss for Case 2 of the IEEE 33-node DPN.

- When running the proposed EEO and other algorithms for Case 1 of the IEEE 69-node DPN under one single hour, the proposed EEO could find the grid power of 906.4766 kW, but that grid power was from 906.6636 kW to 981.083 kW for others. Similarly, the proposed EEO could find the grid power of 907.9939 kW, but others found the grid power of 908.4779 kW and 979.9003 kW for Case 2. So, the proposed EEO is more effective than others for the IEEE 69-node DPN under one single hour.

- When running the proposed EEO for the IEEE 69-node DPN for one operation year to optimize the operation of WT, PVs, SCBs, and SOPs, the total one-year grid energy was smaller by 14,178.175 MWh (about 67.5%) than the base system and 569.605 MWh (about 7.7%) than the hybrid system with WT and PVs.
- As running the proposed EEO to optimize the placement and operation of two 2 PVs, 1 SOPs, and 2 SCBs in Nha Be 55-node DPN, the total energy supplied by the grid for one year is 35,642.775 MWh. Meanwhile, the total one-year grid energy was 40,964.218 MWh for the Base system and 35,727.183 MWh for a hybrid system with two PVs. The solution of the proposed EEO could reduce the grid energy by 84.407 MWh and 5,321.443 MWh, equaling 13% and 0.24% of the total grid energy of the Base system and the Hybrid system without the SOPs device.

Chapter 5

MINIMIZATION OF ELECTRICITY PURCHASING COST FROM THE DISTRIBUTION POWER NETWORK OVER ONE YEAR

5.4. Problem formulation

5.4.1 Objective function

Minimize the total cost of purchasing electricity from the distribution grid over one year:

Minimize:

$$TCPMĐ = \sum_{i=1}^{N_{my}} \sum_{d=1}^{N_d} \sum_{h=1}^{T_h} (P_{LD,h,i} + \Delta P_{loss,h,i} + P_{BESS,h,i} - P_{PV,h,i}) * Giá\ điện_{h,i} \tag{5.1}$$

$$P_{LD,h,i} = \sum_{m=1}^{N_n} P_{LDm,h,i} \ \text{(kW)} \tag{5.2}$$

$$\Delta P_{loss,h,i} = \sum_{n=1}^{N_{bn}} 3.I_{n,h,i}^2.R_n \ \text{(kW)} \tag{5.3}$$

$$P_{BESS,h,i} = \sum_{k=1}^{N_{BESS}} \left(\frac{P_{BESSk,h,i}^{In}}{\eta_{kIn}} - \eta_{kOut} * P_{BESSk,h,i}^{Out}\right) \ \text{(kW)} \tag{5.4}$$

$$P_{PV,h,i} = \sum_{l=1}^{N_{SG}} P_{PVl,h,i} \ \text{(kW)} \tag{5.5}$$

5.5 Research results

5.5.1 Research results on Hoang Dieu 26-node DPN

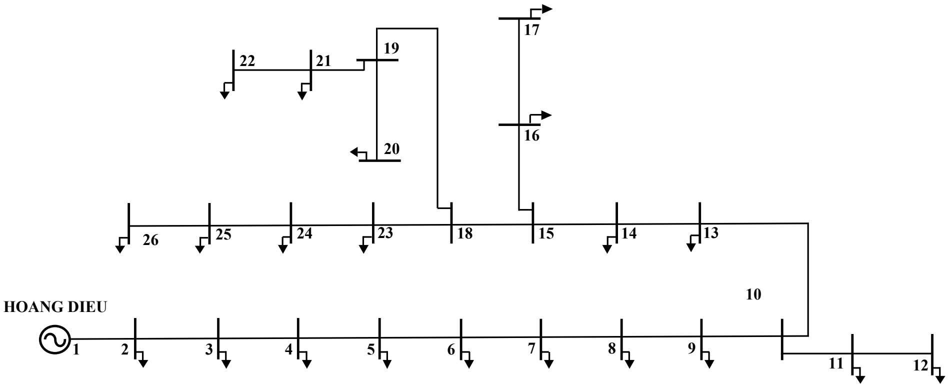


Figure 5.1: The Hoang Dieu 26-node DPN in Ho Chi Minh City

5.5.1.1. Resutls obtained for Case 1

Table 5.1: Total cost of the base system and case 1

Base system's cost ($)	Case 1's cost ($)	Reduction of cost in $ / %
277.2198	60.9786	216.2412 / 78

5.5.1.2. Resutls obtained for Case 2

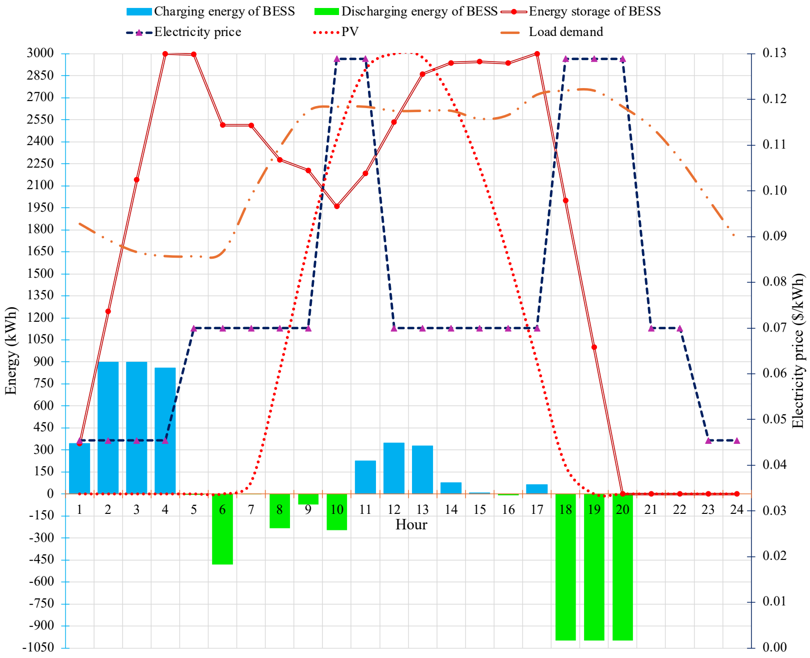


Figure 5.2: The energy charging and discharging of the BAESS at node 2 over a 24-hour period

The optimal operation of the SOPs devices and BESS over one day, HS2 has reduced $2,062.5543 (approximately 46.63%) compared to the BS, and decreased $292.2087 (approximately 11.01%) compared to HS1.

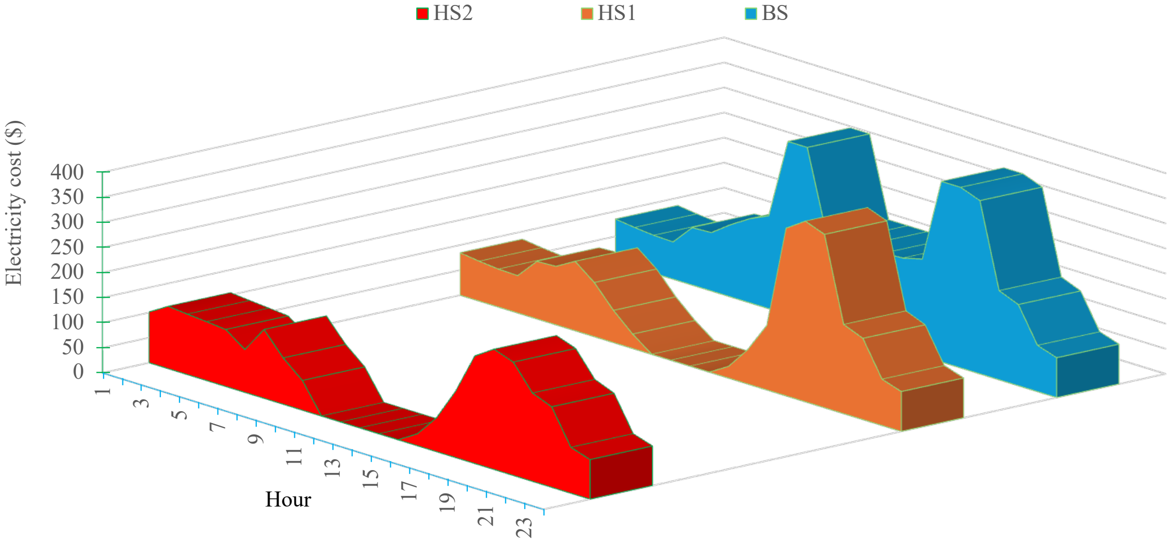


Figure 5.3: The cost of buying electricity from the grid for three different systems

5.5.2 Research results on Nha Be 55-node DPN

5.5.2.1 Results of Scenario 1

Table 5.2: Optimal location and capacity of PV, SCB, and SOPs in Scenario 1

Device	Node	Capacity	Original system's cost ($)	Scenario 1's cost ($)	Reduction of cost in ($) / (%)
PV1; PV2; PV3; PV4; PV5 (kW)	55; 35; 20; 8; 43	1000; 1000; 1000; 1000; 1000	539.4891	185.9772	(353.5119) / (65.53)
SCB1; SCB2 (kVar)	5; 47	526.564; 679.952			
SOPs (MVA)	2-22	$S_{VSC,2}$=2.28; $S_{VSC,22}$=2.49;			

5.5.2.2 Results of Scenario 2

HS2 had the lowest electricity purchase cost among the three simulated systems, saving $1,194,990.954 (36.73%) compared to Original system (OS); HS2 saved $98,854.905 (4.58%) compared to HS1.

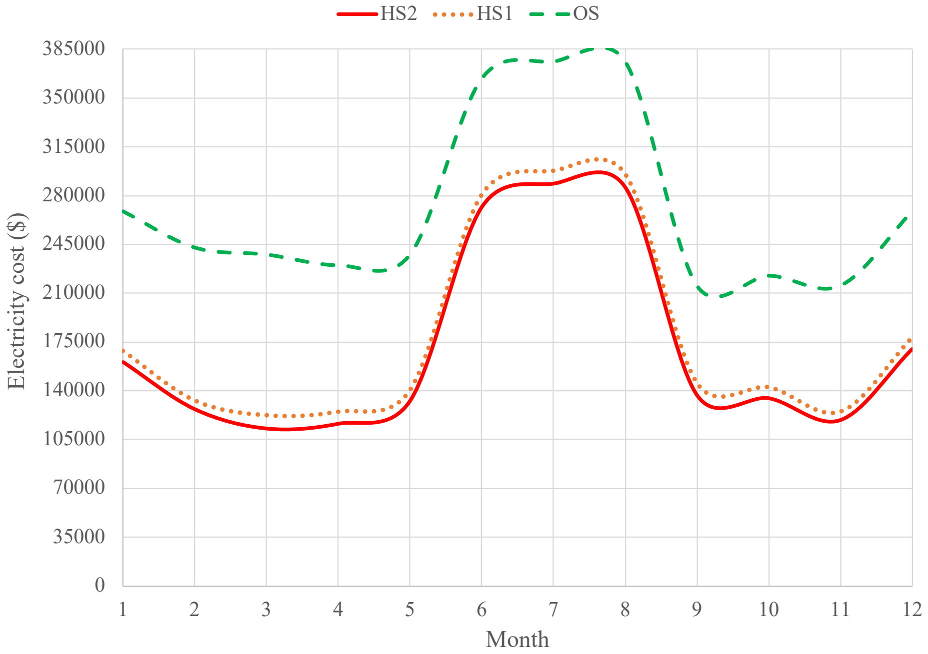


Figure 5.4: The cost of purchasing electricity from three different systems in the Nha Be distribution grid

5.6 Conclusions

Chapter 5 optimized the location and capacity of SOPs, PVs, SCBs, and BESSs on the Hoang Dieu 26-node and Nha Be 55-node distribution grids to minimize the cost of purchasing electricity from the distribution grid. For the Hoang Dieu distribution grid, the WSO method was used to determine the optimal location and capacity of PVs, BESSs, and SOPs. In Case 1, three PVs and one SOP were optimized simultaneously with the rated load at all nodes. In Case 2, using the optimal locations of three PVs and one SOPs determined in Case 1, the BESS installation location was optimized, and the BESS and SOPs were operated for 24 hours to minimize the cost of grid electricity. For the Nha Be grid, EEO was applied to optimize the location and capacity of PVs, SOPs, SCBs, and BESSs. In Scenario 1, five PVs, two SCBs, and one SOPs are optimized simultaneously using the rated load at all nodes. Scenario 2 uses the results from Scenario 1 and optimizes the operation of the BESS, 2 SCBs, and 1 SOPs to minimize the cost of purchasing electricity from the grid during one operating year. The results are presented as follows:

- Case 1 in the Hoang Dieu grid: Simultaneous optimization of 3 PVs and SOPs reduced total grid electricity purchase costs by 78% per hour of operation compared to the basic system without 3 PVs and SOPs.

- Using the results from Case 1, and optimizing SOPs and BESS for one day in Case 2, HS2 reduced costs by \$2062.5543 (approximately 46.63%) compared to BS, and by \$292.2087 (approximately 11.01%) compared to HS1.

- By optimizing the location and installation capacity of 5 PVs, 2 SCBs, and 1 SOPs in scenario 1 in the Nha Be distribution grid, the cost of purchasing electricity from the grid decreased by \$353.5119 (equivalent to 65.53%).

- Using the results from Scenario 1, combined with optimal operation of SOPs, BESS, and SCB, HS2 saves \$1,194,990.954 (36.73%) compared to OS and \$98,854.905 (4.58%) compared to HS1.

Chapter 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

This thesis successfully applied new, efficient algorithms such as EO, WSO, and the improved EEO algorithm to optimize the location and capacity of SOPs, WT, PV, SCB, and BESS on IEEE 33-node, IEEE 69-node, Hoang Dieu 26-node, and Nha Be 55-node distribution grids, contributing to reducing power losses, energy losses, power consumption, and electricity purchase costs from distribution grids.

6.2 Limitations of the thesis

This thesis still has limitations, including the failure to consider power losses in the two converters of SOPs and the actual distance between the two nodes where SOPs are installed. It also does not consider the investment and maintenance costs of SOPs, DG, SCB, and BESS. In the future, improved EEO will be applied to address additional constraints, and the results will provide a comprehensive view of the installation and operation of DG, SCB, BESS, and SOPs in distribution grids.

6.3 Future work

- Further improvements to the EEO algorithm are needed to enhance stability and performance for future multi-objective engineering problems.

- Consider incorporating the actual distance between two SOPs connection nodes and the losses across the two SOPs converters into the research problem.

- The study applies SOPs to other objectives related to improving power quality; minimizing the total investment, operation, and maintenance costs of SOPs, DGs, SCBs, and BESSs; reducing emissions to protect the environment; and identifying, mitigating, and restoring power grid failures.

- The study extends the application of SOPs to the transmission grid, accounting for electricity prices in the future electricity market.

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