

MINISTRY OF EDUCATION AND TRAINING
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**OPTIMAL BALANCED AND UNBALANCED THREE-PHASE DISTRIBUTION SYSTEMS
WITH DISTRIBUTED GENERATORS**

FIELD: ELECTRICAL ENGINEERING

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SUMMARY OF DOCTORAL DISSERTATION

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CHAPTER 1: INTRODUCTION

1.1 Background

The continuous development of various energy conversion technologies alongside the energy crisis has created many major breakthroughs in integrating distributed generation sources (DGs) into the distribution system to reduce dependence on traditional centralized energy sources such as hydropower plants, thermal power plants, etc. Traditional power plants are often large-scale and far from the consumption, so the transmission and distribution of electricity causes huge power losses as well as negatively affects the quality of electricity. Therefore, the appropriate connection of distributed generation sources, especially renewable energy sources, into the distribution systems is considered an excellent solution to overcome the above existing problems. On the contrary, unplanned connection of these sources can cause many unwanted problems due to changes in the structure of the grid such as overvoltage, increased losses, reduced power quality, and the level of impact depends mainly on the location and sizing DGs. Therefore, it is necessary to determine the solution to connect DGs in the distribution system to maximize benefits and avoid negative impacts on the power grid.

1.2 Objectives and tasks of the research

- Minimize total cost while ensuring all technical criteria
- Ensure the improved power quality including node voltage, branch current and harmonic distortion.
- Demonstrate the impact of distributed generation on balanced and unbalanced three-phase distribution grids.
- Maximize the penetration of renewable distributed generation in the distribution grid.
- Develop a highly efficient algorithm, named Modified Coyote Optimization Algorithm.
- Develop a co-simulation between OpenDSS and MATLAB for solving optimization problems.

1.3 Scope and limitations of the research

- Applied power systems: IEEE 69-node, IEEE 25-node and IEEE 123-node distribution systems.
- Load Data: Load data are referenced from IEEE RTS-96.
- Power output from solar and wind energy: Use Beta and Rayleigh probability distribution functions to simulate solar radiation and wind speed for calculating output power.
- Installation location of grid-connected distributed generation sources: It is assumed that all locations are considered suitable for the installation of generation sources. Solar radiation and wind speed are also considered the same at each location in the system.
- Power conversion equipment efficiency: 100% for photovoltaic modules and wind turbines, and 90% for BESS.
- Harmonics from nonlinear loads and power converter: Harmonic spectrum is selected from previous studies.
- Power quality: Comply with IEEE Std. 1547, IEEE Std. 519, 30/2019/TT-BCT and IEEE Std. 45-2002.

1.4 Research approaches and methods

- Based on previously published domestic and foreign researches on optimization algorithms and related research problems in distribution networks.
- Simulate optimization algorithms and modify algorithms for determining the solution update formulas as well as appropriate control parameters to improve algorithm performance. The co-simulation between two open source software of MATLAB and OpenDSS for addressing the optimization problems.

1.5 Novelties and contributions of the thesis

The novelties of this thesis can be presented as follows:

- Consider the optimal simultaneous connection of solar power sources, wind power, capacitor bank and energy storage system to the distribution system to minimize the total cost. The costs considered include (1) investment cost, (2) O&M cost, (3) electric generation cost from the main grid for load demand and (4) emission cost from conventional power plants.

- Consider the harmonic penetration caused by nonlinear loads and power conversion devices on the grid to comply with IEEE Std. 519 and 30/2019/TT-BCT.
- Propose to improve the COA algorithm to MCOA for application to considering problems. This algorithm has outstanding convergence features, high efficiency and good stability. In addition, the study also proposes to apply the co-simulation between two software: MATLAB and OpenDSS to solve complex optimization problems conveniently.

Based on the obtained results, the contributions of the research in this thesis are as follows:

- Consider the constraints on harmonics and unbalanced voltage deviation: Harmonic distortion has been brought to the allowable limit of IEEE Std. 519. The representative index of unbalanced voltage deviation also complies with IEEE Std. 45-2002.
- Suggest a co-simulation tool: Successfully develop a co-simulation between MATLAB and OpenDSS via COM, which is flexible in solving optimization problems.
- Develop an optimization algorithm: Improve MCOA with good performance and stability.

1.6 Organization of the thesis

This thesis is divided into 6 chapters as follows:

Chapter 1: Introduction.

Chapter 2: Literature review and proposed optimization algorithm..

Chapter 3: Application of optimization algorithm to determine location and capacity for distributed generation sources in the balanced three-phase distribution system.

Chapter 4: Application of optimization algorithm to determine location and capacity for distributed generation sources in unbalanced three-phase distribution system.

Chapter 5: Conclusion and future research directions.

CHAPTER 2: LITERATURE REVIEW & PROPOSED OPTIMIZATION ALGORITHM

2.1 Overview of previous studies

Most of the previous studies have proposed meta-heuristic algorithms due to their superiority over other methods in solving various optimization problems. However, the biggest drawback of these algorithms is that they easily converge to local optima, leading to poor performance. The meta-heuristic algorithms that are commonly used for tackling problems related to the optimal integration of DGs, including: Genetic Algorithm (GA) [1], Particle Swarm Optimization (PSO) [2], Cuckoo Search Algorithm (CSA) [3], Artificial Bee Colony Algorithm (ABC) [4], Ant Colony Optimization (ACO) [5], Biogeographic Based Optimization (BBO) [6], Equilibrium Optimizer (EO) [7], Sunflower Optimization Algorithm (SFO) [8], Coyote Optimization Algorithm (COA) [9], Whale Optimization Algorithm (WOA) [10], Ant Lion Optimization Algorithm (ALOA) [11], Harmony Search Algorithm (HSA) [12], Shuffled Frog Leaping Algorithm (SFLA) [13], Bat Algorithm (BA) [14], Success Rate Group Search Algorithm (SRGSO) [15], Self- Adaptive Lévy Flight Jaya Algorithm (SALFJA) [16], Runner Root Algorithm (RRA) [17], Human Opinion Dynamics Algorithm (HODA) [18], Water Cycle Algorithm (WCA) [19] and Different Cat Swarm Optimization Algorithm (DCSOA) [20]. To solve many complex optimization problems, especially with large number of control variables in large search space, the proposal of new efficient methods is always welcomed. Therefore, in this thesis, a novel efficient algorithm is developed to improve the quality of solutions for various optimization problems.

2.2 Proposal to overcome the shortcomings of previous studies

All the problems that previous studies have not solved, will be implemented in this thesis.

- In previous studies, the main objective is to minimize power losses and improve voltage in the distribution system at a peak load or a few representative load levels. Therefore, the found solution may not be optimal at different load levels.
- The output power of renewable energy sources depends on natural conditions and they vary over time, but considering uncertainties of these sources has not received much attention in the past.
- Unbalanced three-phase distribution systems due to load and line impedance differences have not received much attention in the past.
- Determining the level of harmonic intrusion due to nonlinear loads and power converters of distributed renewable energy sources is equally important, but has not been fully considered in previous studies.
- It would be more beneficial to integrate an energy storage system to store and generate energy reasonably to save operating cost. However, previous studies have not fully evaluated it.
- Reducing total costs will significantly contribute to improving economic efficiency in system operation, but there is still not much research on this issue.

2.3 Modified Coyote Optimization Algorithm

An active algorithm based on the intelligent behavior of coyotes was developed by Dr. Pierezan and Dr. Coelho and is called COA [9]. However, this algorithm still has some shortcomings that need to be overcome to improve the efficiency and stability of the algorithm. Therefore, a modified version called MCOA was introduced. In this algorithm, the initial solutions are randomly distributed within predefined limits:

$$S_{pk,ce} = S^{Min} + rd \cdot (S^{Max} - S^{Min}); pk = 1, 2, \dots, N_{pk}, ce = 1, 2, \dots, N_{ce} \quad (2.1)$$

New solutions in each group are updated according to the first generation solution generation equation as follows:

$$S_{pk,ce}^{New} = S_{pk,ce} + rd_1 \cdot (S_{bestPk,pk} - S_{rd1,pk}) + rd_2 \cdot (S_{bestPop} - S_{rd2,pk}); pk = 1, 2, \dots, N_{pk} \ \& \ ce = 1, 2, \dots, N_{ce} \quad (2.2)$$

In this improved equation, the best solution of the current population is selected to replace the inefficient central solution. In the second new solution generation, each group is assumed to have only one new solution generated by applying equation (2.3) or (2.4) instead of the inactive random solution generation mechanism in the original version.

$$S_{pk}^{New} = S_{bestPop} + rd_3 \cdot (S_{bestPop} - S_{best,r1}) + rd_4 \cdot (S_{bestPop} - S_{best,r2}) \quad (2.3)$$

$$S_{pk}^{New} = S_{bestPop} + rd_3 \cdot (S_{bestPop} - S_{best,r1}) + rd_4 \cdot (S_{bestPop} - S_{best,r2}) + rd_5 \cdot (S_{bestPop} - S_{best,r3}) \quad (2.4)$$

To decide the appropriate time to apply equation in generating the second new solution, the ratio between the number of close solution pairs (N_C) and the number of maximum solution pairs (N_M) is set. The calculated value of this ratio is compared with a predetermined threshold (δ). If the result of N_C/N_M is smaller than δ then Eq. (2.3) is selected and vice versa, Eq. (2.4) is selected. In addition, the solution exchange action is also performed. Two randomly selected solutions from two different random groups in the community will be swapped if the condition of Eq. (2.5) is satisfied [9].

$$\tau < \frac{10^{-2}}{2} \times N_{ce}^2 \quad (2.5)$$

Based on the fitness function's results for all solutions, good solutions are updated according to the following rule:

$$S_{pk,ce} = \begin{cases} S_{pk,ce}^{New} & \text{if } SF_{pk,ce}^{New} < SF_{pk,ce} \\ S_{pk,ce} & \text{else} \end{cases}; pk = 1, 2, \dots, N_{pk}; ce = 1, 2, \dots, N_{ce} \quad (2.6)$$

$$SF_{pk,ce} = \begin{cases} SF_{pk,ce}^{New} & \text{if } SF_{pk,ce}^{New} < SF_{pk,ce} \\ SF_{pk,ce} & \text{else} \end{cases}; pk = 1, 2, \dots, N_{pk}; ce = 1, 2, \dots, N_{ce} \quad (2.7)$$

The flowchart of applying MCOA to solve the optimization problem can be briefly presented as Figure 2.1.

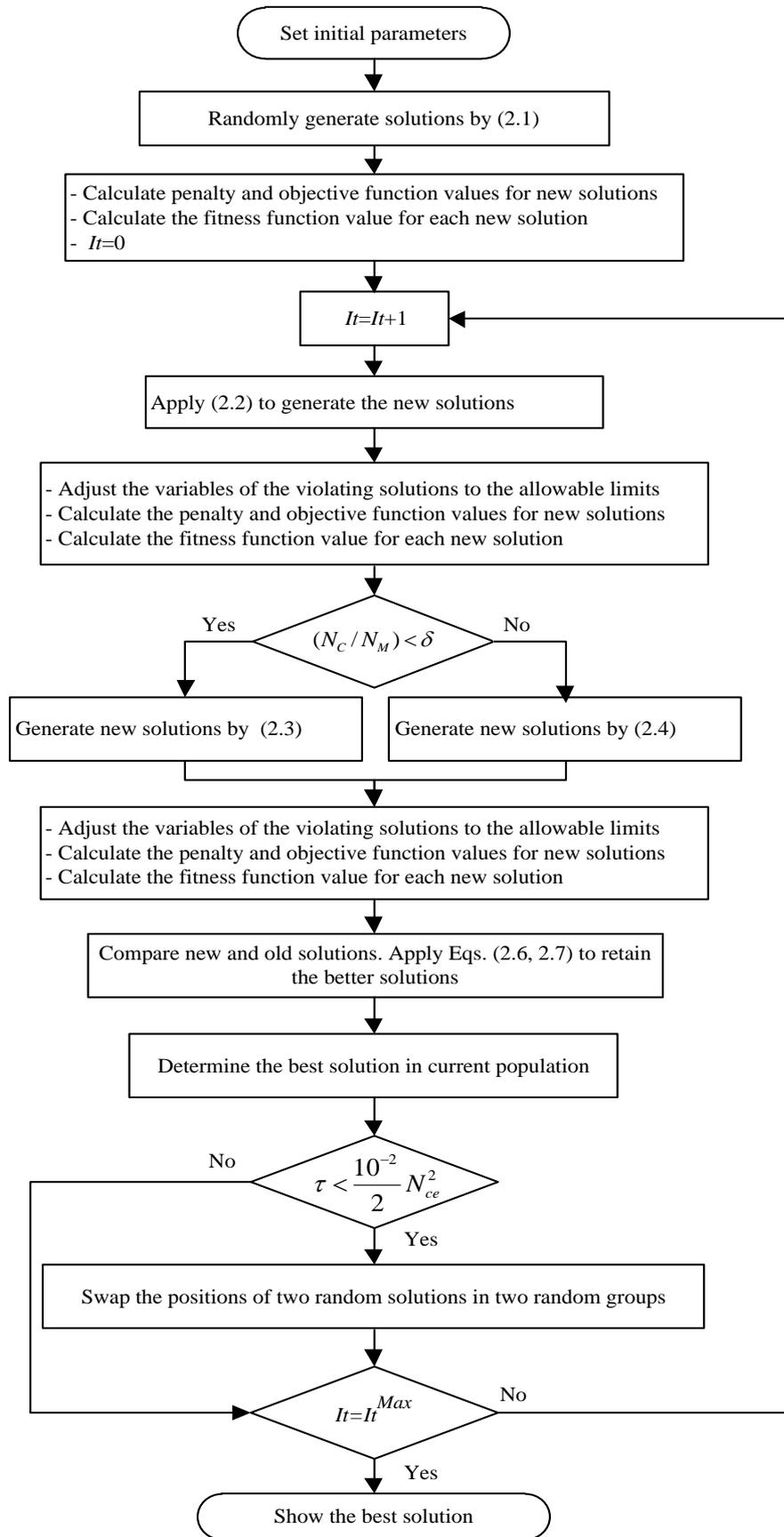


Fig 2.1 Flowchart of MCOA for solving optimization problem.

2.4 Conclusion

COA is a powerful meta-heuristic algorithm with good stability, but it still has limitations that directly affect the efficiency of the algorithm. The modifications in the new solution equation in this study have resulted in a new method, called MCOA that has significantly improved the efficiency and stability of the algorithm in solving optimization problems.

CHAPTER 3: APPLICATION OF THE PROPOSED OPTIMIZATION ALGORITHM FOR DETERMINING OPTIMAL LOCATION AND SIZING OF DISTRIBUTED GENERATION SOURCES IN THE BALANCED THREE-PHASE DISTRIBUTION SYSTEM

3.1 Introduction

This chapter presents the application of Modified Coyote Optimization Algorithm (MCOA) for determining the location and capacity of various distributed generation sources (DGs) in the balanced three-phase distribution system. The main purpose of installing DGs is to minimize the total costs in investing and operating the system. Besides, the technical constraints on node voltage, branch current, harmonic index and the penetration level of the generation sources also should to be fully satisfied. The details of the problem formulation are presented as below.

3.2 Problem formulation

3.2.1 Objective function

$$\text{Minimize } TC_{Total} = TC_{WF-PVF-BESS-CB}^{Inv\&OM} + TC_{Grid} (\$) \quad (3.1)$$

3.2.1.1 Total costs for investment and O&M of DGs:

$$TC_{WF-PVF-BESS-CB}^{Inv\&OM} = TC_{PVF} + TC_{WF} + TC_{BESS} + TC_{CB} (\$) \quad (3.2)$$

Where, the component costs can be determined by the below equations:

$$TC_{PF} = \sum_{j=1}^{N_{PF}} (C_{PF}^{Cap} \cdot P_{PF,j}^{Rated}) + 365 \cdot \sum_{y=1}^{20} \sum_{h=1}^{24} \sum_{j=1}^{N_{PF}} (\theta_y \cdot C_{PF}^{O\&M} \cdot P_{PF,j,h,y}) (\$) \quad (3.3)$$

$$TC_{WF} = \sum_{i=1}^{N_{WF}} (C_{WF}^{Cap} \cdot P_{WF,i}^{Rated}) + 365 \cdot \sum_{y=1}^{20} \sum_{h=1}^{24} \sum_{i=1}^{N_{WF}} (\theta_y \cdot C_{WF}^{O\&M} \cdot P_{WF,i,h,y}) (\$) \quad (3.4)$$

$$TC_{BESS} = \sum_{k=1}^{N_{BESS}} (C_{BESS}^{Cap} \cdot E_{BESS,k}^{Rated}) + \sum_{y=1}^{20} \sum_{k=1}^{N_{BESS}} (\theta_y \cdot C_{BESS}^{O\&M} \cdot E_{BESS,k,y}^{Rated}) + \sum_{k=1}^{N_{BESS}} (C_{BESS}^{Aux} \cdot P_{BESS,k}^{Rated}) (\$) \quad (3.5)$$

$$TC_{CB} = \sum_{c=1}^{N_{CB}} (C_{CB}^{Cap} \cdot Q_{CB,c}^{Rated}) + \sum_{c=1}^{N_{CB}} (Loc_{CB,c}) (\$) \quad (3.6)$$

In the Eqs. (3.3 – 3.5),
$$\theta_y = \left(\frac{1}{1+dc} \right)^y \quad (3.7)$$

3.2.1.2 Cost of generating electricity from the main grid:

$$TC_{Grid} = 365 \cdot \sum_{y=1}^{20} \sum_{h=1}^{24} (\theta_y \cdot Pr_{h,y}^{Grid} \cdot P_{Sub,h,y}) (\$) \quad (3.8)$$

3.2.2 Constraints

3.2.2.1 Power balance equations

$$P_{Sub,h,y} + \sum_{j=1}^{N_{PF}} P_{PF,j,h,y} + \sum_{i=1}^{N_{WF}} P_{WF,i,h,y} + \sum_{k=1}^{N_{BESS}} P_{BESS,k,h,y}^{DisCh} = \sum_{b=1}^{N_b} P_{b,h,y} + \sum_{d=1}^{N_d} P_{d,h,y} \quad (3.9)$$

$$P_{Sub,h,y} + \sum_{j=1}^{N_{PF}} P_{PF,j,h,y} + \sum_{i=1}^{N_{WF}} P_{WF,i,h,y} = \sum_{b=1}^{N_b} P_{b,h,y} + \sum_{d=1}^{N_d} P_{d,h,y} + \sum_{k=1}^{N_{BESS}} P_{BESS,k,h,y}^{Ch} \quad (3.10)$$

$$Q_{Sub,h,y} + \sum_{i=1}^{N_{WF}} Q_{WF,i,h,y} + \sum_{j=1}^{N_{PF}} Q_{PF,j,h,y} = \sum_{b=1}^{N_b} Q_{b,h,y} + \sum_{d=1}^{N_d} Q_{d,h,y} \quad (3.11)$$

Where,
$$Q_{PF,j,h,y} = P_{PF,j,h,y} \cdot \beta_{PF,j}; \text{ v\o{i}} \beta_{PF,j} = \tan(\cos^{-1}(PF_{PF,j})) \quad (3.12)$$

and
$$Q_{WF,i,h,y} = P_{WF,i,h,y} \cdot \beta_{WF,i}; \text{ v\o{i}} \beta_{WF,i} = \tan(\cos^{-1}(PF_{WF,i})) \quad (3.13)$$

3.2.2.2 The bus voltage limits

$$V^{Min} \leq V_{s,h,y} \leq V^{Max}, \quad s = 1, 2, \dots, N_b, h = 1, 2, \dots, N_h, y = 1, 2, \dots, N_y \quad (3.14)$$

3.2.2.3 The branch current limits

$$I_{b,h,y} \leq I_{b,h,y}^{Max}; \quad b = 1, 2, \dots, N_b \quad (3.15)$$

3.2.2.4 The harmonic limits

$$THD^{Max} \geq THD_{s,h,y}; \quad s=1, 2, \dots, N_b, h = 1, 2, \dots, N_h, o = 2, \dots, Hr \quad (3.16)$$

$$IHD^{Max} \geq IHD_{s,h,y}^o; \quad s=1, 2, \dots, N_b, h = 1, 2, \dots, N_h, o = 1, 2, \dots, Hr \quad (3.17)$$

Where,

$$THD_{s,h,y}(\%) = \left[\frac{\sqrt{\sum_{o=2}^{Hr} (V_{s,h,y,o})^2}}{V_{s,h,y}^1} \right] \times 100 (\%) \quad (3.18)$$

$$IHD_{s,h,y}^o (\%) = \left[\frac{V_{s,h,y,o}}{V_{s,h,y}^1} \right] \times 100 (\%) \quad (3.19)$$

3.2.2.5 Charging and discharging power limits of BESS

$$P_{BESS}^{Rated} \cdot \varepsilon^{Char} \geq P_{BESS,k,h}^{Ch} \geq 0 \quad (3.20)$$

$$-P_{BESS}^{Rated} \cdot \varepsilon^{DisCh} \leq P_{BESS,k,h}^{DisCh} \leq 0 \quad (3.21)$$

3.2.2.6 Capacity limits of BESS:

$$E_{BESS}^{Min} \leq E_{BESS,h} \leq E_{BESS}^{Max} \quad (3.22)$$

$$E_{BESS,0} = E_{BESS,24} \quad (3.23)$$

3.2.2.7 The penetration limits of WFs, PVFs and CB

$$P_{PF}^{Min} \leq P_{PF,j}^{Rated} \leq P_{PF}^{Max}; j = 1, 2, \dots, N_{PF} \quad (3.24)$$

$$P_{WF}^{Min} \leq P_{WF,i}^{Rated} \leq P_{WF}^{Max}; i = 1, 2, \dots, N_{WF} \quad (3.25)$$

$$Q_{CB}^{Min} \leq Q_{CB,c}^{Rated} \leq Q_{CB}^{Max}; c = 1, 2, \dots, N_{CB} \quad (3.26)$$

3.3 Apply the proposed method to solve the optimization problems

3.3.1 Initialize the initial solution

The initial solutions are generated within predefined limits as Eqs. (3.27 and 3.28). Each newly generated solution needs to be quality-evaluated by the fitness function of (3.29).

$$S^{Min} = [L_i^{Min}, P_i^{Min}, L_j^{Min}, P_j^{Min}, L_{BESS,k}^{Min}, P_{BESS,k,h}^{Min}, L_c^{Min}] \quad (3.27)$$

$$S^{Max} = [L_i^{Max}, P_i^{Max}, L_j^{Max}, P_j^{Max}, L_{BESS,k}^{Max}, P_{BESS,k,h}^{Max}, L_c^{Max}] \quad (3.28)$$

$$SF_{pk,ce} = TC_{Total,pk,ce} + \sigma_V \cdot \sum_{s=1}^{N_s} \Delta V_{s,pk,ce}^2 + \sigma_I \cdot \sum_{b=1}^{N_b} \Delta I_{b,pk,ce}^2 + \sigma_{THD} \cdot \sum_{s=1}^{N_s} \Delta THD_{s,pk,ce}^2 + \sigma_{IHD} \cdot \sum_{s=1}^{N_s} \sum_{o=1}^{Hr} (\Delta IHD_{s,pk,ce}^o)^2 \quad (3.29)$$

Where (3.29),

$$\Delta V_{s,pk,ce} = \begin{cases} V_{s,pk,ce} - V^{Max} & \text{if } V_{s,pk,ce} > V^{Max} \\ V^{Min} - V_{s,pk,ce} & \text{if } V_{s,pk,ce} < V^{Min} \\ 0 & \text{else} \end{cases} \quad (3.30)$$

$$\Delta I_{b,pk,ce} = \begin{cases} I_{b,pk,ce} - I_b^{Max} & \text{if } I_{b,pk,ce} > I_b^{Max} \\ 0 & \text{else} \end{cases} \quad (3.31)$$

$$\Delta THD_{s,pk,ce} = \begin{cases} THD_{s,pk,ce} - THD^{Max} & \text{if } THD_{s,pk,ce} > THD^{Max} \\ 0 & \text{else} \end{cases} \quad (3.32)$$

$$\Delta IHD_{s,pk,ce}^o = \begin{cases} IHD_{s,pk,ce}^o - IHD^{Max} & \text{if } IHD_{s,pk,ce}^o > IHD^{Max} \\ 0 & \text{else} \end{cases} \quad (3.33)$$

3.4 Simulation results

3.4.1 The test system and simulation data

Table 3.1 The involved parameters in calculating total costs

Item	Value
Pr_h^{Grid} at peak, standard and off-peak hours [21]	128,9 \$/MWh, 70,0 \$/MWh & 45,4 \$/MWh
dc [14]	9 %
C_{PF}^{Cap} & $C_{PF}^{O\&M}$ [22]	770000 \$/MW & 10,0 \$/MWh
C_{WF}^{Cap} & $C_{WF}^{O\&M}$ [23]	1882000 \$/MW & 10,0 \$/MWh
C_{CB}^{Cap} & Loc_{CB} [24]	20000 \$/MVA _r & 1000 \$/place
C_{BESS}^{Cap} ; $C_{BESS}^{O\&M}$ & C_{BESS}^{Aux} [25]	200000 \$/MW; 7000 \$/MW _{year} & 380000 \$/MW

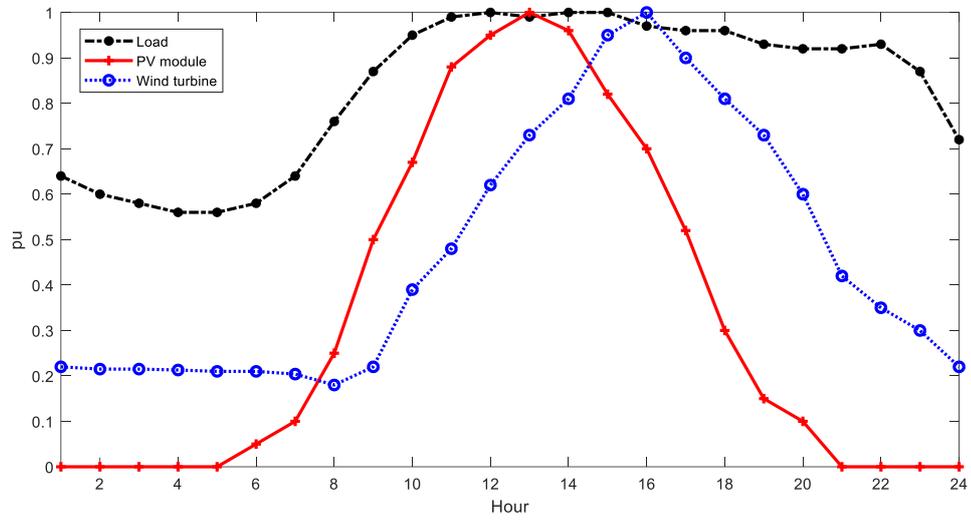
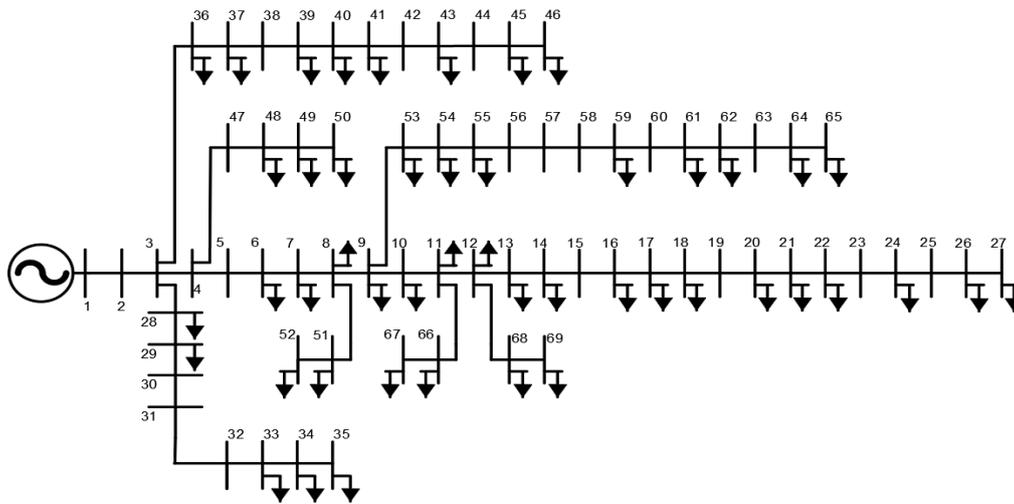


Fig 3.1 The output curves of load, PV modules and wind turbine

The study is implemented integrating 3 PFs and 3 WFs on a 69-node IEEE distribution system. The grid consists of 69 nodes and 48 loads with a total demand of 3,802 MW/ 2,694 MVar. The load and line data are described in the study [27]. Harmonic parameters are described in the study [28].



Hinh 3.2 IEEE 69- bus distribution system

3.4.2 Simulation results analysis

The results of Table 3.2 show that the MCOA method can find the optimal solution which has better stability than other methods. Besides, the best solution in 40 test runs reported in Table 4.3 brings more economic benefits. Specifically, it can save up to \$4.662 million (equivalent to 22.42%) as compared in Table 3.4.

Table 3.2 Comparison table of the fitness function values and average running time of applied methods

Method	SMA	COA	MCOA
The worst value	16,723 million \$	16,562 million \$	16,501 million \$
The mean value	16,521 million \$	16,314 million \$	16,271 million \$
The best value	16,356 million \$	16,148 million \$	16,130 million \$
The average running time	4211 seconds	4282 seconds	4267 seconds

Table 3.3 The best solution of used methods in IEEE 69- bus system

Method	PFs	WFs	BESS	CB
SMA	Bus: 09 – 9432 modules Bus: 54 – 3651 modules Bus: 69 – 14170 modules	Bus: 17 – 04 turbines Bus: 65 – 10 turbines Bus: 63 – 08 turbines	Bus: 46 – 1,092 MW/ 3,228 MWh	Bus: 61 – 1,29 MVar

COA	Bus: 63 – 2162 modules Bus: 49 – 15386 modules Bus: 53 – 8670 modules	Bus: 65 – 10 turbines Bus: 61 – 08 turbines Bus: 21 – 05 turbines	Bus: 28 – 0,793 MW/ 2,681 MWh	Bus: 59 – 1,11 MVar
MCOA	Bus: 32 – 5952 modules Bus: 05 – 2000 modules Bus: 61 – 18814 modules	Bus: 15 – 07 turbines Bus: 57 – 09 turbines Bus: 62 – 07 turbines	Bus: 05 – 1,088 MW/ 2,495 MWh	Bus: 61 – 1,18 MVar

Bảng 3.4 Associated components in total costs over 20-year project life cycle

Method	Base case	SMA	COA	MCOA
TC_{PF} , million \$	-	2,115	2,030	2,075
TC_{WF} , million \$	-	4,961	5,187	5,187
TC_{BESS} , million \$	-	1,267	1,009	1,030
TC_{CB} , thousand \$	-	26,800	26,800	26,800
$TC_{WF-PVF-BESS-CB}^{Inv\&OM}$, million \$	-	8,370	8,253	8,319
TC_{Grid} , million \$	20,792	7,986	7,895	7,811
Tổng chi phí (TC_{Total} , million \$)	20,792	16,356	16,148	16,130
Saving (million \$)	-	4,436	4,644	4,662
Saving ratio (%)	-	21,335	22,336	22,422

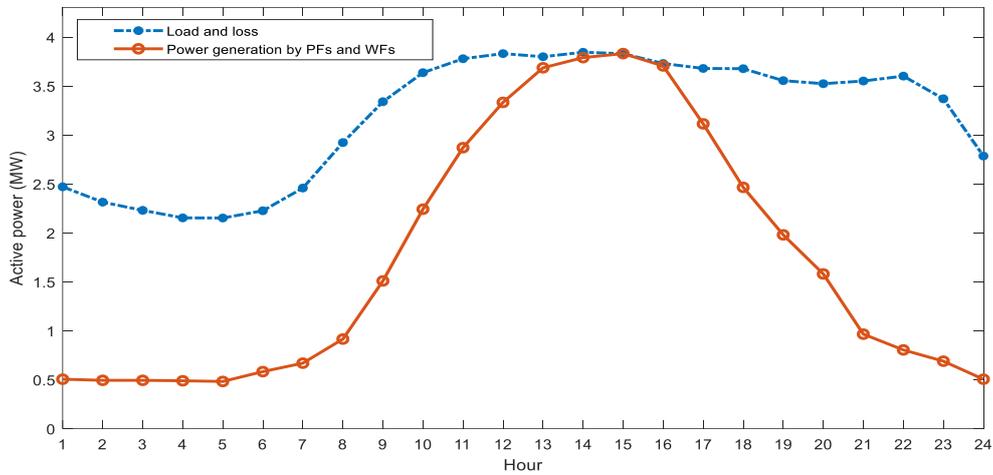


Fig 3.3 Power consumption and generation from renewable energies

By applying the global optimal solution of MCOA, the total penetration by renewable energy sources is up to 54.55% compared to the total consumption demand of the system as shown in Figure 3.3. Figures 3.4 and 3.5 show the hourly generation and storage capacity of BESS. In general, BESS tends to charge power at off-peak hours and generate power at peak hours to save the cost in grid operation. In addition, to keep the power factor not less than 0.9, the capacitor also generates reactive power to the grid at each time as shown in Figure 3.6.

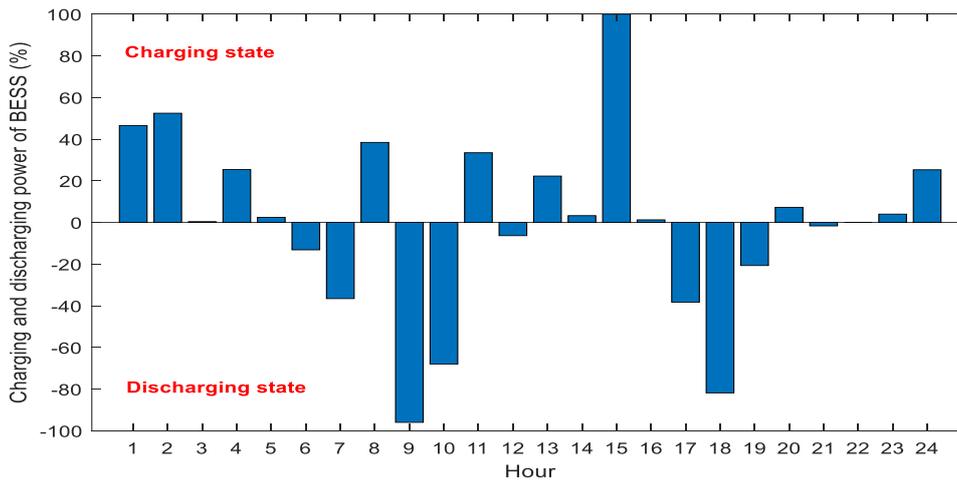


Fig 3.4 Charging and discharging stages of BESS.

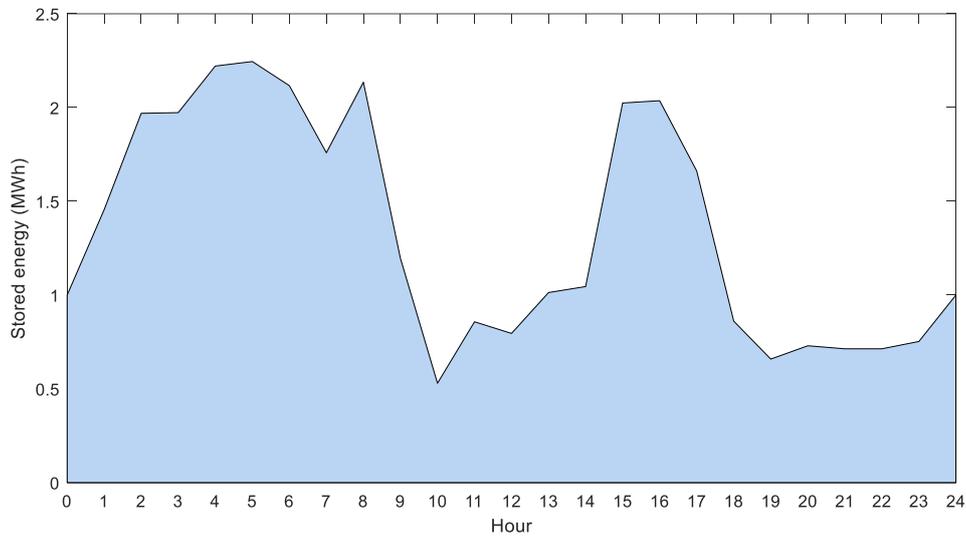


Fig 3.5 Stored energy of BESS.

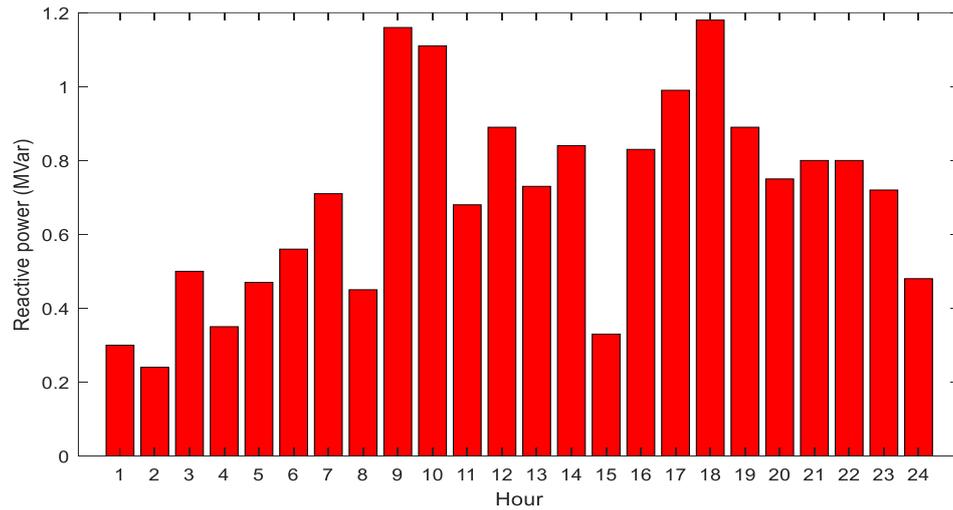


Fig 3.6 Reactive power's generation of capacitor.

Moreover, after integrating distributed sources, the total power loss is also strongly reduced up to 78.692% compared to the original system as shown in Figure 3.7. The voltage is also significantly improved from the region [0.911 1.00] (pu) to [0.950 1.032] (pu) like shown in Figures 3.8 and 3.9. In addition, the harmonic values THD and IHD are also mitigated with the maximum values from 5.265% and 3.403% to 4.499% and 2.908% after integration, respectively. Thus, the harmonic indices also satisfy the IEEE Std. 519.

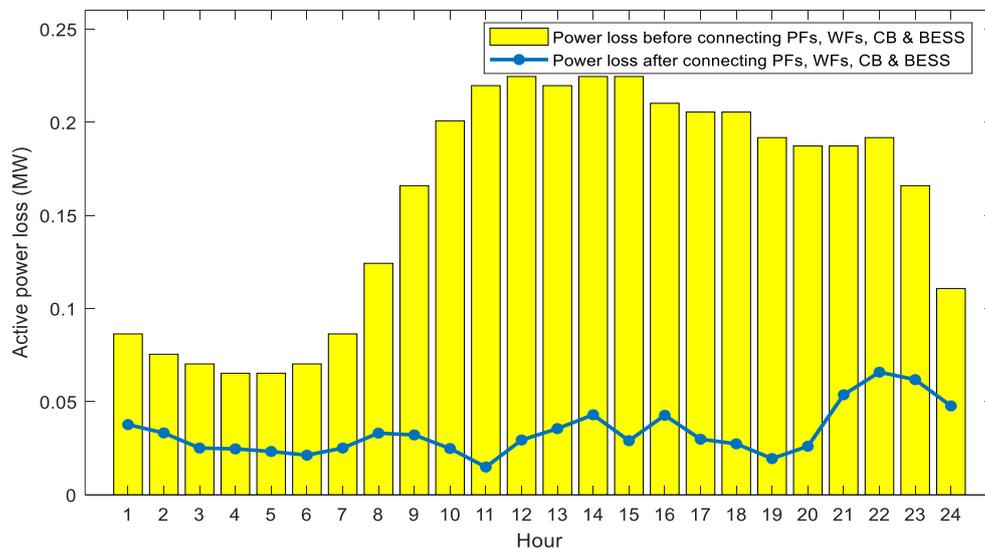


Fig 3.7 Power loss before and after connecting DGs

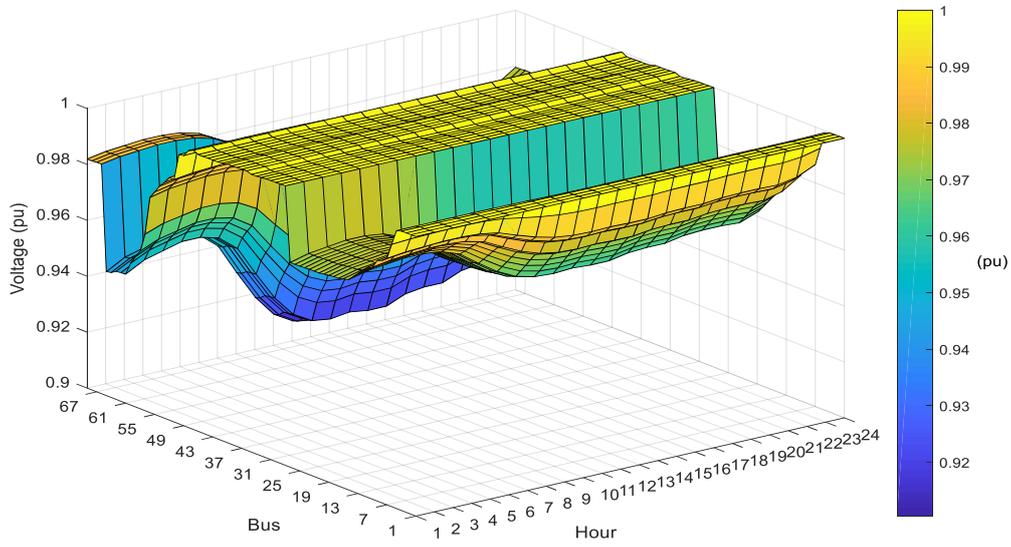


Fig 3.8 Voltage profile before connecting DGs

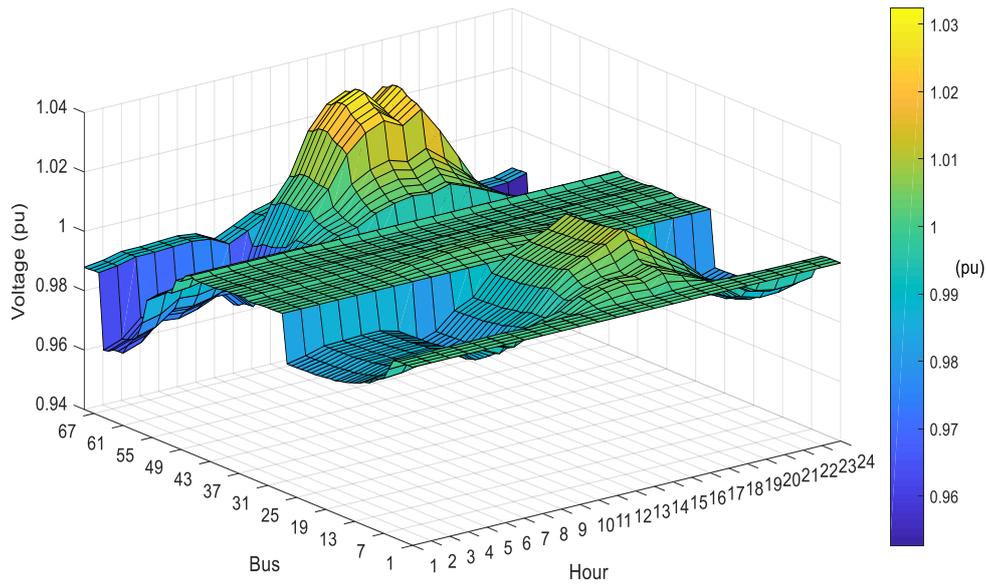


Fig 3.9 Voltage profile after connecting DGs

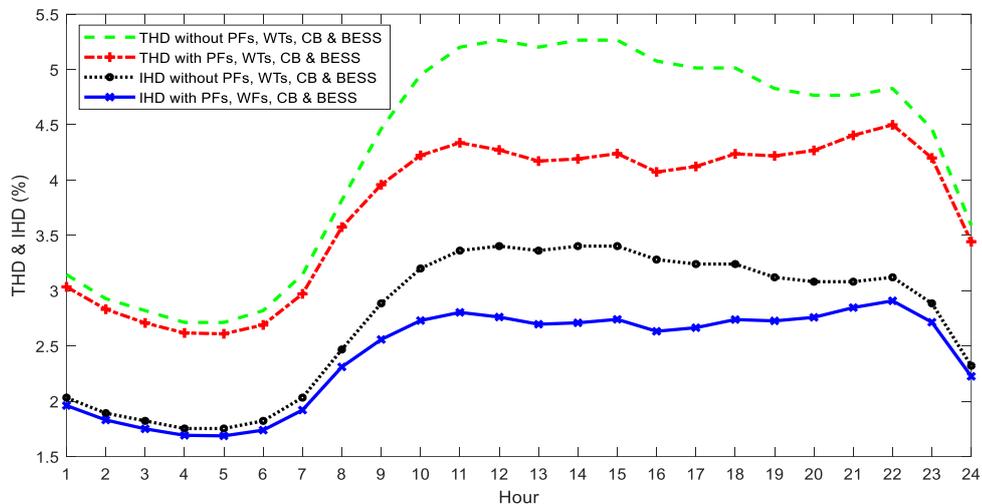


Fig 3.10 The maximum values of THD and IHD before and after connecting DGs

3.5 Conclusion

- This study has successfully determined the location and capacity of PFs, WFs, CBs and BESS in IEEE 69 Bus system with high penetration of many nonlinear loads.
- The main objective of the study is to minimize the total investment and O&M costs for PFs, WFs, CBs and BESSs as well as the cost of purchasing energy from the main grid for loads and losses on distribution branches.

The study not only achieves economic benefits but also satisfies the requirements of technical constraints such as bus voltage, branch current, harmonic distortion and penetration of generation sources.

- This study has introduced a new algorithm called MCOA to solve the problem of optimizing the connection of distributed sources. The results show that MCOA is better than other compared methods with the same objectives and constraints.

CHAPTER 4: APPLICATION OF THE PROPOSED OPTIMIZATION ALGORITHM FOR DETERMINING OPTIMAL LOCATION AND SIZING OF DISTRIBUTED GENERATION SOURCES IN THE UNBALANCED THREE-PHASE DISTRIBUTION SYSTEM

4.1 Introduction

In real world, three-phase distribution systems are difficult to achieve balance due to the asymmetry between the loads in each phase of the system. Therefore, the consideration of unbalanced three-phase distribution systems is complicated. This chapter applies the proposed algorithm (MCOA) to determine the optimal location and capacity of distributed generation sources in unbalanced three-phase distribution networks to minimize the total cost of investment and O&M of the system. In this chapter, the study applies the proposed algorithm to solve two problems on two different types of unbalanced systems. In addition, the study also proposes to apply the co-simulation between MATLAB and OpenDSS to address the optimization problems quickly and conveniently.

4.2 The first problem formulation

4.2.1 Objective function

$$\text{Minimize } TC_{Total} = TC_{Inv} + TC_{OM} + TC_{Grid} + TC_{Emis} \text{ (\$)} \quad (4.1)$$

The components of the objective function can be defined as below:

$$TC_{Inv} = C_{PF}^{Cap} \cdot P_{PF}^{Rated} + C_{WF}^{Cap} \cdot P_{WF}^{Rated} \text{ (\$)} \quad (4.2)$$

$$TC_{OM} = 30,4167 \cdot \sum_{y=1}^{20} \sum_{h=1}^{288} \theta_y \cdot (C_{PF}^{O\&M} \cdot P_{PF,h,y} + C_{WF}^{O\&M} \cdot P_{WF,h,y}) \text{ (\$)} \quad (4.3)$$

$$TC_{Grid} = 30,4167 \cdot \sum_{y=1}^{20} \sum_{h=1}^{288} \theta_y \cdot (Pr_{h,y}^{Grid} \cdot P_{Sub,h,y}) \text{ (\$)} \quad (4.4)$$

$$TC_{Emis} = 30,4167 \cdot \sum_{y=1}^{20} \sum_{h=1}^{288} \theta_y \cdot (Pr_{Emis} \cdot G_{Emis} \cdot P_{Sub,h,y}) \text{ (\$)} \quad (4.5)$$

4.2.2 Constraints

4.2.2.1 Power balance equations

$$P_{Sub,h,y} + \sum_{i=1}^{N_{WF}} P_{WF,i,h,y} + \sum_{j=1}^{N_{PF}} P_{PF,j,h,y} = \sum_{d=1}^{N_d} P_{d,h,y} + \sum_{b=1}^{N_b} P_{b,h,y} \quad (4.6)$$

$$Q_{Sub,h,y} + \sum_{i=1}^{N_{WF}} Q_{WF,i,h,y} + \sum_{j=1}^{N_{PF}} Q_{PF,j,h,y} = \sum_{d=1}^{N_d} Q_{d,h,y} + \sum_{b=1}^{N_b} Q_{b,h,y} \quad (4.7)$$

4.2.2.2 Branch current limits

$$I_b^{Max} \geq I_b^p; \quad b = 1,2 \dots, N_b \text{ \& } p = 1,2 \dots, N_p \quad (4.8)$$

4.2.2.3 Bus voltage limits

$$V^{Min} \leq |V_s^p| \leq V^{Max}, \quad s = 1,2 \dots, N_s \text{ \& } p = 1,2 \dots, N_p \quad (4.9)$$

4.2.2.4 Unbalanced phase voltage limits

$$UV_{dev,s}(\%) \leq UVD_{Std}^{Max}(\%) \quad (4.10)$$

Where

$$UV_{dev,s}(\%) = 100 \cdot \frac{V_{dif,s}^{Max}}{V_{un,s}^{Mean}}, \quad s = 1,2 \dots, N_s \quad (4.11)$$

Calculation for $V_{un,s}^{Mean}$ and $V_{dif,s}^{Max}$ can shown as:

$$V_{un,s}^{Mean} = \frac{V_s^1 + V_s^2 + V_s^3}{3}, \quad s = 1, \dots, N_s \quad (4.12)$$

Where, V_s^1 , V_s^2 and V_s^3 are the voltages from phase A, phase B and phase C of the s^{th} bus.

$$V_{un,s}^{\Delta A} = |V_{un,s}^{Mean} - V_s^1|, s = 1, \dots, N_s \quad (4.13)$$

$$V_{un,s}^{\Delta B} = |V_{un,s}^{Mean} - V_s^2|, s = 1, \dots, N_s \quad (4.14)$$

$$V_{un,s}^{\Delta C} = |V_{un,s}^{Mean} - V_s^3|, s = 1, \dots, N_s \quad (4.15)$$

$$V_{dif,s}^{Max} = \max [V_{un,s}^{\Delta A}, V_{un,s}^{\Delta B}, V_{un,s}^{\Delta C}], s = 1, \dots, N_s \quad (4.16)$$

4.2.2.5 Harmonic distortion limits

$$THD^{Max}(\%) \geq THD_{s,h,y}(\%) \quad (4.17)$$

$$IHD^{Max}(\%) \geq IHD_{s,h,y}^o(\%) \quad (4.18)$$

4.2.2.6 Power loss reduction constraints

$$\sum_{b=1}^{N_b} P_{b,h,y}^{Bef} > \sum_{b=1}^{N_b} P_{b,h,y}^{Aft} \quad (4.19)$$

$$\sum_{b=1}^{N_b} Q_{b,h,y}^{Bef} > \sum_{b=1}^{N_b} Q_{b,h,y}^{Aft} \quad (4.20)$$

4.2.2.7 Constraints of generation of grid-connected units

$$P_{PF}^{Min} \leq P_{PF}^{Rated} \leq P_{PF}^{Max} \quad (4.21)$$

$$P_{WF}^{Min} \leq P_{WF}^{Rated} \leq P_{WF}^{Max} \quad (4.22)$$

$$P_{PF,h,y} + P_{WF,h,y} \leq \sum_{d=1}^{N_d} P_{d,h,y} + \sum_{b=1}^{N_b} P_{b,h,y}^{Aft} \quad (4.23)$$

4.2.3 Using proposed methods for solving the optimization problem

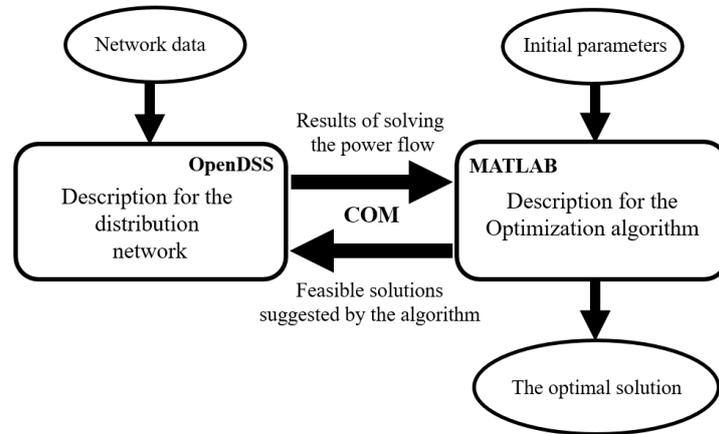


Fig 4.1 Co-simulation between OpenDSS and MATLAB through COM

4.2.4 Simulation results

4.2.4.1 IEEE 25-bus distribution system

In this study, IEEE 25-bus distribution system, which represents a three-phase unbalanced system, is selected for simulation. The system operates at 4.16 kV with the total load demand of 3.3466 MW/ 2.5267 MVar. The system consists of 25 buses, 24 branches and 22 loads. The detailed data are described in the study [29].

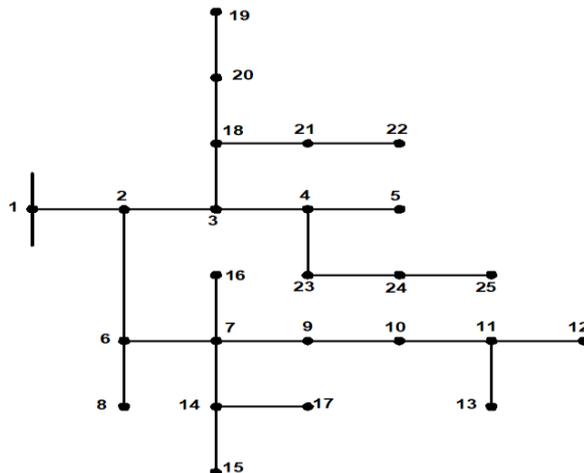


Fig 4.2 IEEE 25- bus unbalanced distribution system

4.2.4.2 Simulation data

The study determines the optimal integrated solution for solar and wind power generation sources in Can Gio district, Ho Chi Minh City. Data for three years (2019-2021) is collected and 288 data points are used to represent 12 months in a year (24 hours in a day represents a month). The study considers the harmonic generation from nonlinear loads and power converters with harmonic spectrum as indicated in Table 4.1. The parameters for the cost function are shown in Table 3.1.

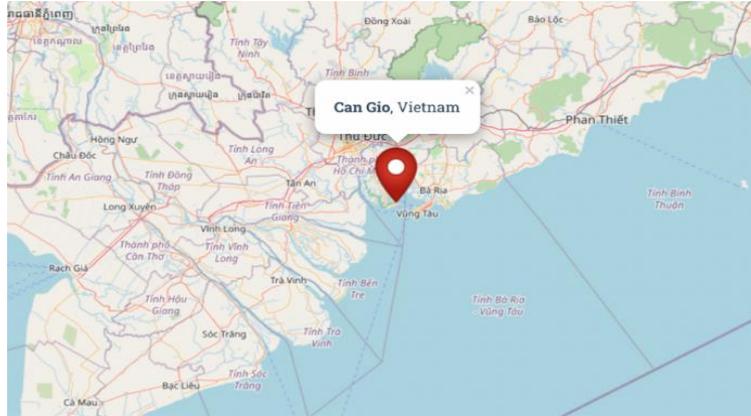


Fig 4.3 The survey area in Can Gio, Vietnam

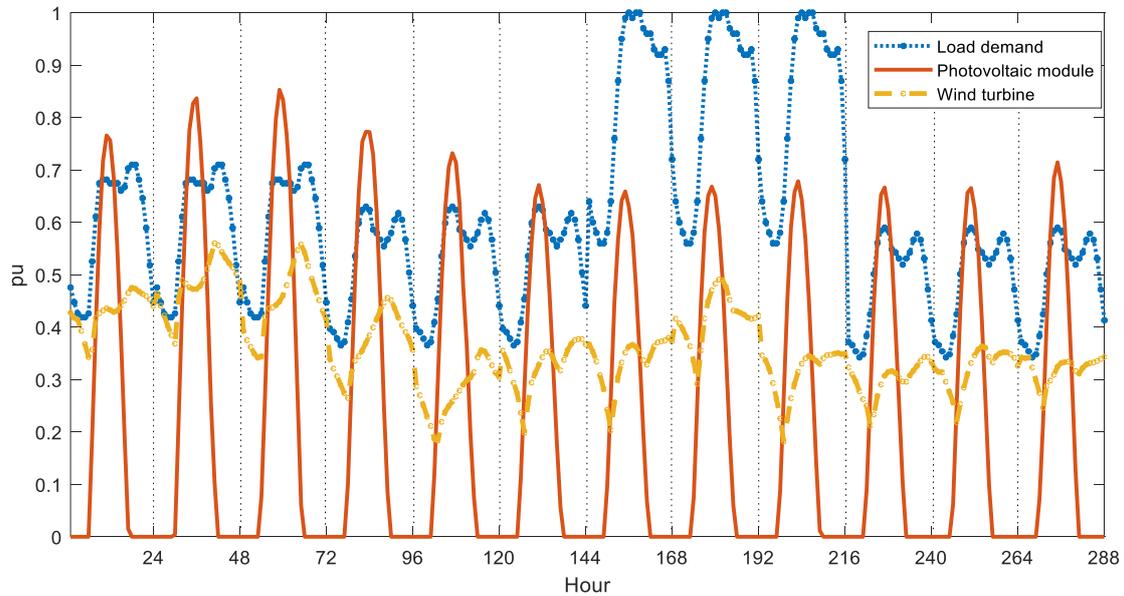


Fig 4.4 The output curves of load, PV modules and wind turbine

Table 4.1 Harmonic spectrum from nonlinear loads and inverters of renewable energies [30].

Harmonic order		1	5	7	11	13	17	19	23	25	29	31
Non-linear load	Amplitude (%) of type 1 at Bus 13 and Bus 23	100	20,0	14,3	9,1	7,7	5,9	5,3	4,3	4,0	3,4	3,2
	Amplitude (%) of type 2 at Bus 08 and Bus 19	100	19,1	13,1	7,2	5,6	3,3	2,4	1,2	0,8	0,2	0,2
Inverters	Amplitude (%) of inverters of DGs	100	4,0	4,0	2,0	2,0	1,5	1,5	0,6	0,6	0,6	0,6

4.2.4.3 Simulation results analysis

In this study, MCOA is the best and most stable method compared to other methods as compared in Figure 4.5. The solution from MCOA can save the total cost up to 10.69% compared to the original system and besides, MCOA also brings more economic benefits than COA, CSA and IPSO as proven in Table 4.2.

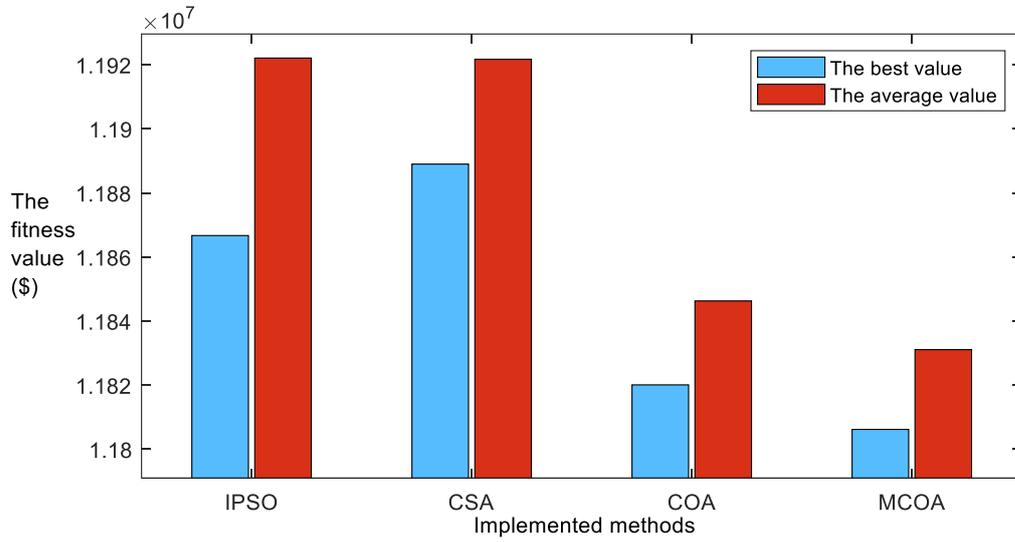


Fig 4.5 The best and the average values in trial runs from implemented methods

Table 4.2 The best solution in trial runs of implemented methods

Method	Optimal solution	TC_{Inv} (million \$)	TC_{OM} (million \$)	TC_{Grid} (million \$)	TC_{Emis} (million \$)	$TC_{TotalCosts}$ (million \$)
	PFs & WFs					
Base	-	-	-	12,7520	0,4683	13,2203
IPSO	Bus 05 – 21440 modules Bus 09 – 18 turbines	4,6258	0,8002	6,2105	0,2302	11,8667
CSA	Bus 03 – 19933 modules Bus 09 – 20 turbines	4,9151	0,8384	5,9170	0,2185	11,8890
COA	Bus 07 – 22916 modules Bus 10 – 16 turbines	4,3346	0,7617	6,4827	0,2412	11,8201
MCOA	Bus 15 – 23317 modules Bus 10 – 16 turbines	4,3577	0,7669	6,4418	0,2397	11,8062

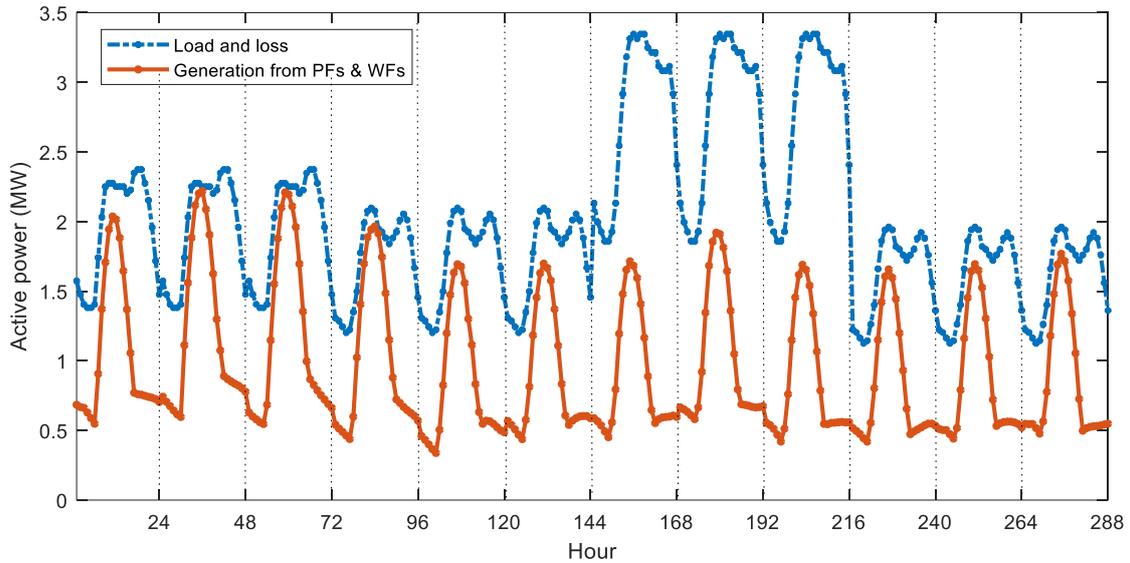


Fig 4.6 Total load demand and total power generation by DGs

By applying the solution from MCOA, the total generation capacity accounts for 47.42% of the total grid demand as presented in Figure 4.6. Besides, the power loss is also significantly reduced up to 56.23% compared to the original system as shown in Figure 4.7. Moreover, the phase voltage is also improved from the region [0.93 1.00] (pu) to [0.950 1.023] (pu) like Figure 4.8. The average voltage is also improved from [0.93 1.00] (pu) as shown in Figure 4.9 to [0.952 1.022] (pu) as shown in Figure 4.10 with the initial bus constraint is satisfied.

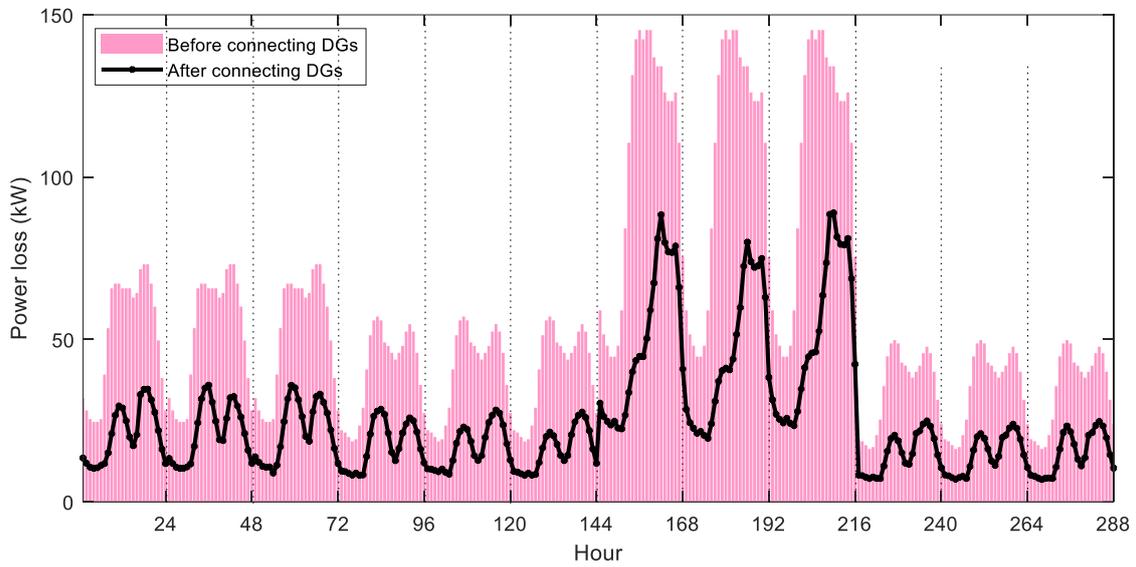


Fig 4.7 Power loss before and after connecting DGs

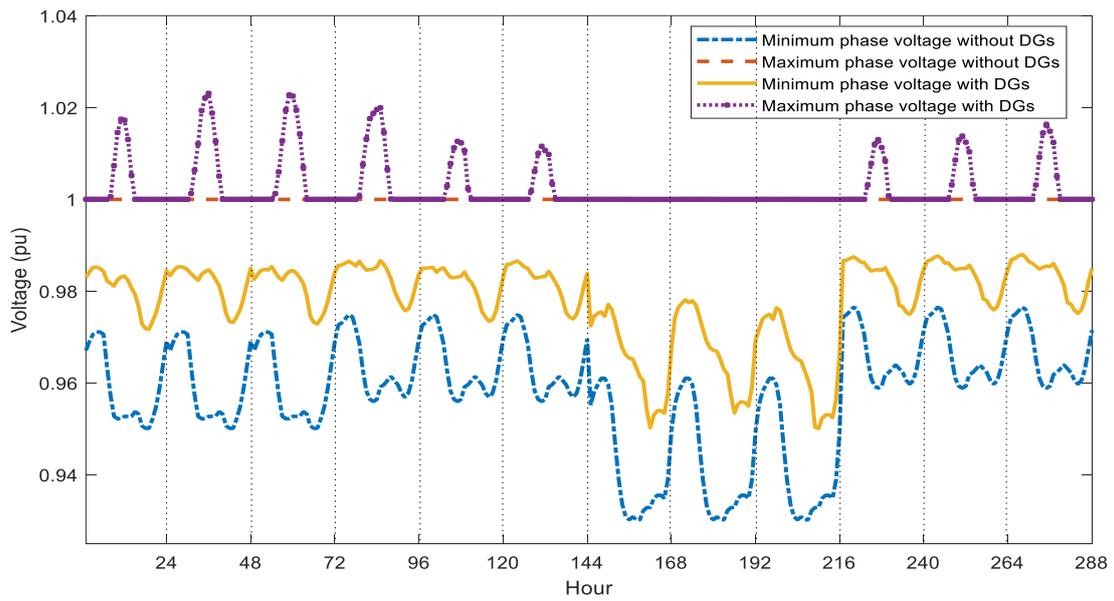


Fig 4.8 Minimum and maximum phase voltage before and after connecting DGs.

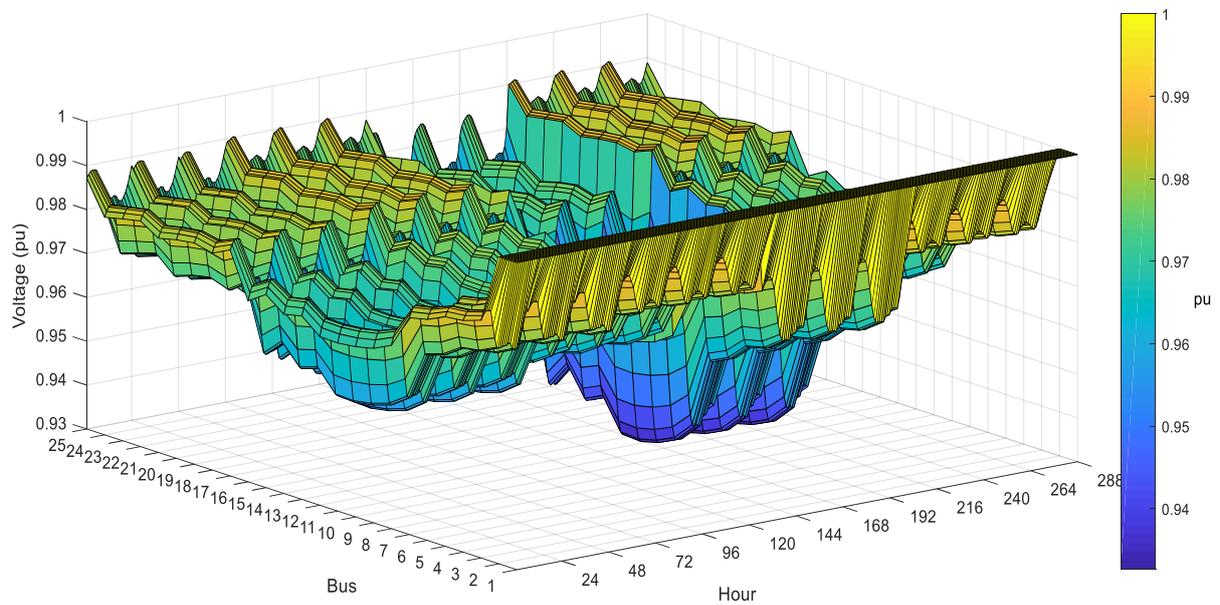


Fig 4.9 Average phase voltage before connecting DGs

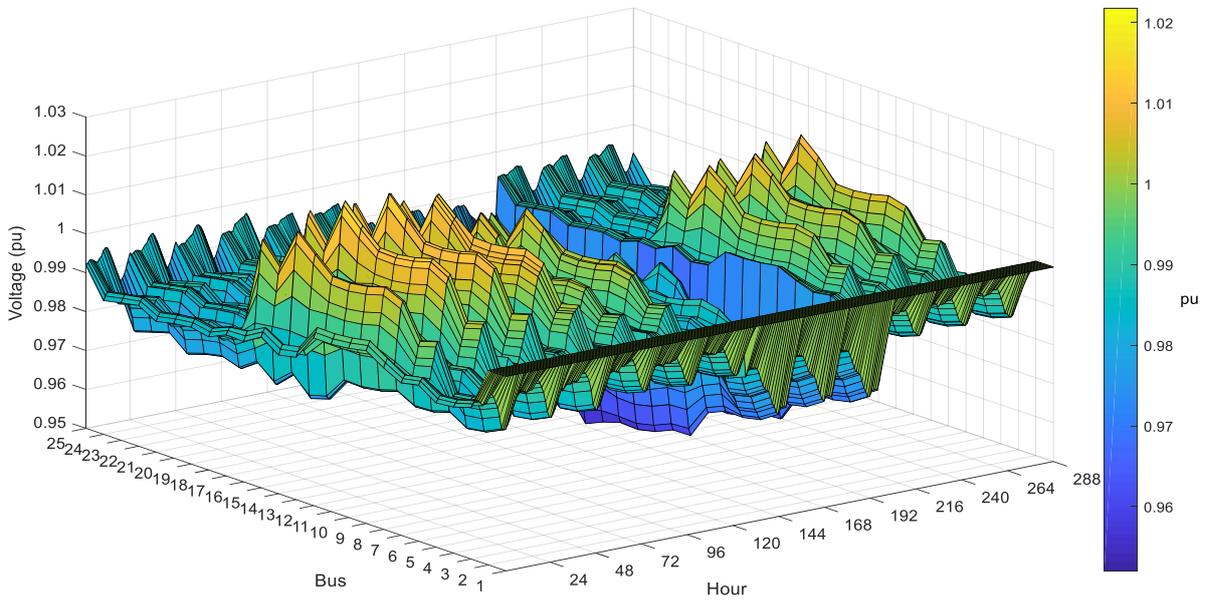


Fig 4.10 Average phase voltage after connecting DGs

As mentioned, this study considers the voltage deviation between phases in the same bus in an unbalanced distribution system. As shown in Figure 4.11, the unbalanced voltage deviation index is also improved by reducing from 0.523% for the original system to 0.454% for the system with integrated distributed generation sources and meeting IEEE Std. 45-2002. Not only that, as plotted in Figure 4.12, the harmonic related index, THD also satisfies IEEE Std. 519 and 30/2019/TT-BTC with the maximum THD's value of 2.24% after integration.

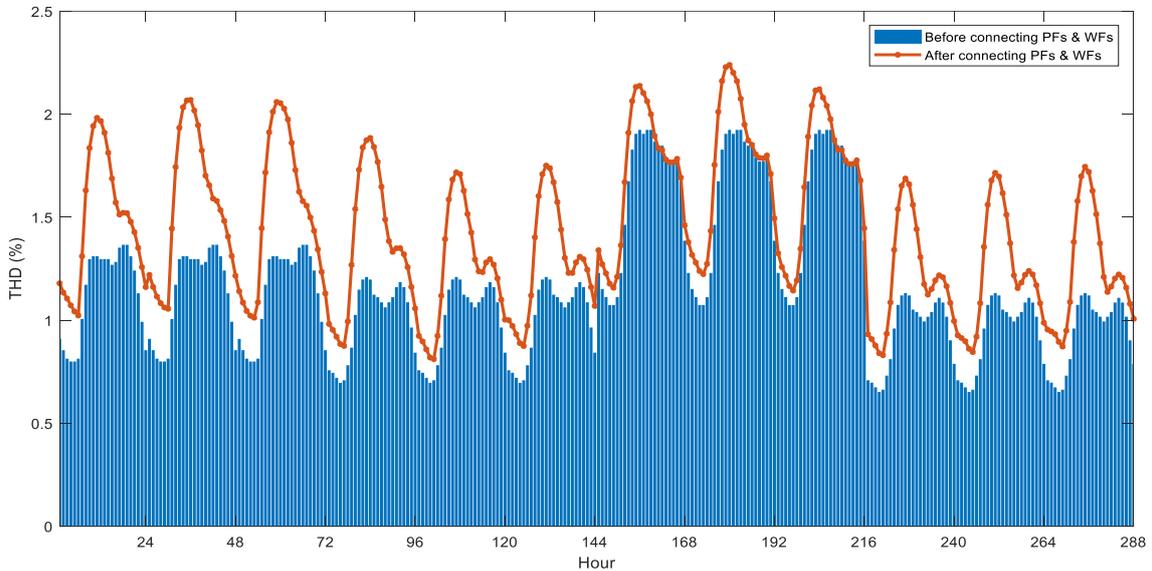


Fig 4.11 Maximum THD values before and after connecting DGs

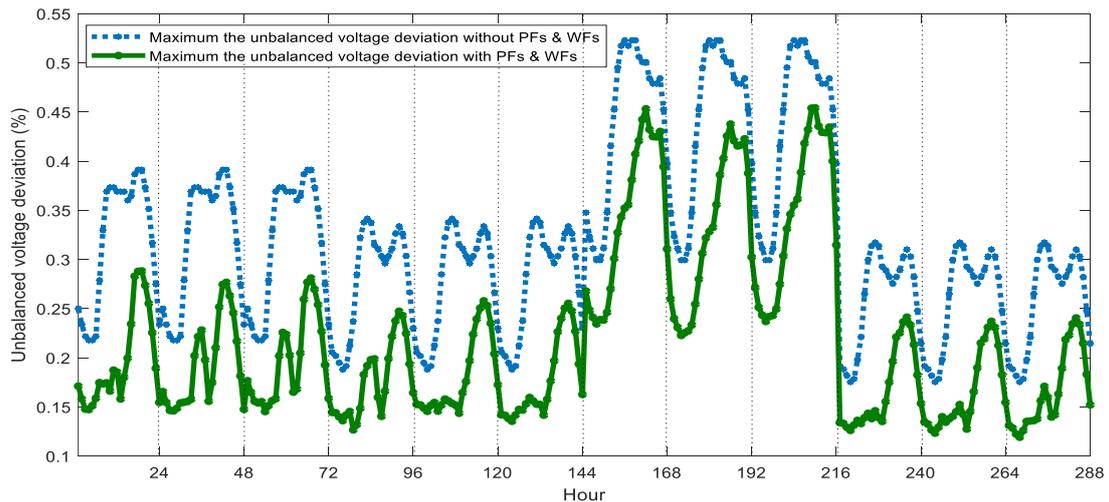


Fig 4.12 Maximum the unbalanced voltage deviation before and after connecting DGs

4.2.4.4 Conclusion

- The study has successfully applied MCOA to determine the optimal solution for location and capacity of distributed power sources such as wind turbines and solar powers in the IEEE 25-bus unbalanced distribution grid with the penetration of diverse harmonic sources.
- The main objective of this work is to minimize the total cost including (1) investment cost, (2) O&M cost for PFs and WFs, (3) cost of purchasing energy from the main grid for load demand and power loss, and (4) cost of emissions from conventional plants. The study not only achieves economic benefits compared to the original system but also satisfies the technical constraints.
- The research has also successfully developed a co-simulation between OpenDSS and MATLAB in solving various optimization problems in distribution systems conveniently and quickly.

4.3 The second problem formulation

4.3.1 Objective function

$$\text{Minimize } TC_{Total} = TC_{WF-PF-BESS}^{Inv\&OM} + TC_{Grid}(\$) \quad (4.24)$$

4.3.1.1 Invest,emt and O&M costs of PFs, WFs and BESS

$$TC_{WF-PF-BESS}^{Inv\&OM} = TC_{WF} + TC_{PF} + TC_{BESS}(\$) \quad (4.25)$$

$$\text{Where (4.25), } TC_{WF} = \sum_{i=1}^{N_{WF}} (C_{WF}^{Cap} \cdot P_{WF,i}^{Rated}) + 91,25 \sum_{y=1}^{20} \sum_{h=1}^{96} \sum_{i=1}^{N_{WF}} (\theta_y \cdot C_{WF}^{O\&M} \cdot P_{WF,i,h,y}) (\$) \quad (4.26)$$

$$TC_{PF} = \sum_{j=1}^{N_{PF}} (C_{PF}^{Cap} \cdot P_{PF,j}^{Rated}) + 91,25 \sum_{y=1}^{20} \sum_{h=1}^{96} \sum_{j=1}^{N_{PF}} (\theta_y \cdot C_{PF}^{O\&M} \cdot P_{PF,j,h,y}) (\$) \quad (4.27)$$

$$TC_{BESS} = \sum_{k=1}^{N_{BESS}} (C_{BESS}^{Cap} \cdot E_{BESS,k}^{Rated}) + \sum_{k=1}^{N_{BESS}} (C_{BESS}^{Aux} \cdot P_{BESS,k}^{Rated}) + \sum_{y=1}^{20} \sum_{k=1}^{N_{BESS}} (\theta_y \cdot C_{BESS}^{O\&M} \cdot E_{BESS,k,y}^{Rated}) (\$) \quad (4.28)$$

4.3.1.2 Electric generation cost from the main grid

$$TC_{Grid} = 91,25 \sum_{y=1}^{20} \sum_{h=1}^{96} (\theta_y \cdot Pr_{h,y}^{Grid} \cdot P_{Sub,h,y}) (\$) \quad (4.29)$$

4.3.2 Constraints

4.3.2.1 Power balance equations

$$P_{Sub,h,y} + \sum_{i=1}^{N_{WF}} P_{WF,i,h,y} + \sum_{j=1}^{N_{PF}} P_{PF,j,h,y} = \sum_{b=1}^{N_b} P_{b,h,y}^{Aft} + \sum_{d=1}^{N_d} P_{d,h,y} + \sum_{k=1}^{N_{BESS}} P_{BESS,k,h,y}^{Ch} \quad (4.30)$$

$$P_{Sub,h,y} + \sum_{i=1}^{N_{WF}} P_{WF,i,h,y} + \sum_{j=1}^{N_{PVF}} P_{PVF,j,h,y} + \sum_{k=1}^{N_{BESS}} P_{BESS,k,h,y}^{DisCh} = \sum_{b=1}^{N_b} P_{b,h,y}^{Aft} + \sum_{d=1}^{N_d} P_{d,h,y} \quad (4.31)$$

$$Q_{Sub,h,y} + \sum_{i=1}^{N_{WF}} Q_{WF,i,h,y} + \sum_{j=1}^{N_{PF}} Q_{PF,j,h,y} = \sum_{b=1}^{N_b} Q_{b,h,y}^{Aft} + \sum_{d=1}^{N_d} Q_{d,h,y} \quad (4.32)$$

4.3.2.2 Branch current limits

$$I_b^{Max} \geq I_{b,p}; b = 1,2, \dots, N_b \& p = 1,2, \dots, N_p \quad (4.33)$$

4.3.2.3 Bus voltage limits

$$V^{Max} \geq V_{s,h,y}^p \geq V^{Min}, s = 1,2, \dots, N_b \& p = 1,2, \dots, N_p \quad (4.34)$$

4.3.2.4 Charging and discharging power limits of BESS

$$0 \leq P_{BESS,k,h}^{Ch} \leq \varepsilon^{Ch} \cdot P_{BESS}^{Rated}; h = 1,2, \dots, 96 \& k=1,2, \dots, N_{BESS} \quad (4.35)$$

$$0 \geq P_{BESS,k,h}^{DisCh} \geq -P_{BESS}^{Rated} \cdot \varepsilon^{DisCh}; h = 1,2, \dots, 96 \& k=1,2, \dots, N_{BESS} \quad (4.36)$$

4.3.2.5 Harmonic limits

$$THD^{Max} \geq THD_{s,h,y}; s=1,2, \dots, N_b \quad (4.37)$$

$$IHD^{Max} \geq IHD_{s,h,y}^{Hr}; s=1,2, \dots, N_b \quad (4.38)$$

4.3.2.6 Penetration limits of PFs, WFs and BESS

$$P_{WF}^{Max} \geq P_{WF,i}^{Rated} \geq P_{WF}^{Min}; i = 1,2, \dots, N_{WF} \quad (4.39)$$

$$P_{PF}^{Max} \geq P_{PF,j}^{Rated} \geq P_{PF}^{Max}; j = 1,2, \dots, N_{PF} \quad (4.40)$$

$$E_{BESS}^{Min} \leq E_{BESS,h} \leq E_{BESS}^{Max}, h = 1,2, \dots, 96 \quad (4.41)$$

4.3.3 Simulation results

4.3.3.1 IEEE 123-bus unbalanced distribution system

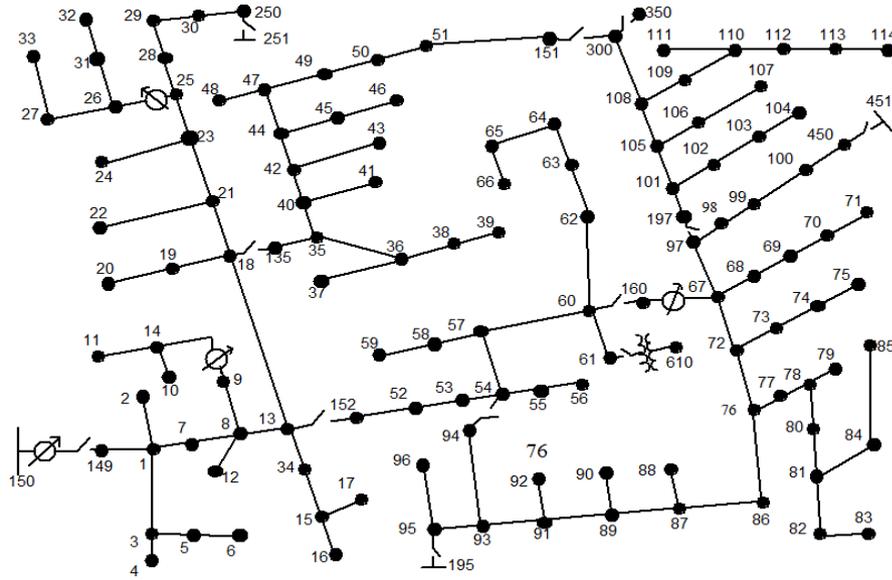


Fig 4.13 IEEE 123-bus unbalanced distribution system

This study determines the optimal location and sizing of WFs, PFs and BESS for integration into a complex IEEE 123 Bus distribution system. This is a three-phase unbalanced system operating at 4.16 kV with multiple grid-connected devices such as capacitors, switches and voltage regulators. Detailed data are described in [31]. Information related to the calculation of the total cost function is given in Table 3.1 and the harmonic spectrum for harmonic sources is given in Table 4.1. In which, the nonlinear loads of type 1 at buses 32, 41, 70 and 95, and the nonlinear loads of type 2 at buses 12, 55, 84 and 111 are assumed.

4.3.3.2 Used data for simulation

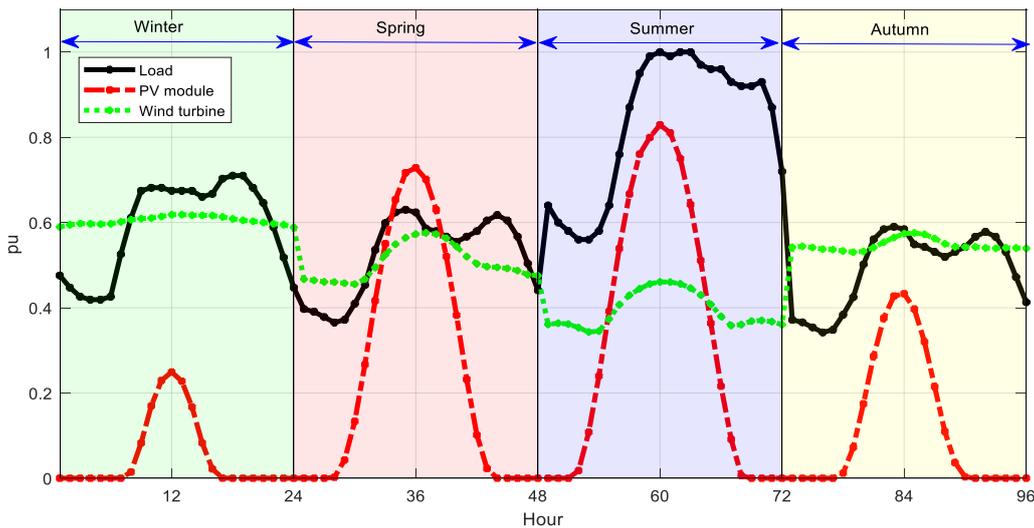


Fig 4.14 The output curves of load, PV modules and wind turbine

4.3.3.3 Simulation results analysis

The best solutions from the implemented methods are clearly presented in Table 4.3. As compared in Table 4.4, the solution from the proposed MCOA method can save up to \$1.9216 million (equivalent to 14.33%) compared to the original system. Not only that, MCOA also outperforms other methods in the same objective under the constraints.

Table 4.3 The best solution from used methods in IEEE 123-bus unbalanced distribution system

Method	WFs	PFs	BESS
SSA	Bus: 95 – 07 turbines – 3 phases Bus: 21 – 13 turbines – 3 phases	Bus: 55 – 3010 modules – 3 phases Bus: 59 – 8873 modules – 1 phase	Bus: 108 0,222 MW/ 1,889 MWh – 3 phases

COA	Bus: 15 – 15 turbines – 1 phase Bus: 34 – 07 turbines – 1 phase	Bus: 300 – 8901 modules – 3 phases Bus: 94 – 6586 modules – 1 phase	Bus: 300 0,444 MW/ 1,445 MWh – 3 phases
MCOA	Bus: 19 – 12 turbines – 1 phase Bus: 300 – 10 turbines – 3 phases	Bus: 53 – 3018 modules – 3 phases Bus: 15 – 9747 modules – 1 phase	Bus: 15 0,232 MW/ 1,513 MWh – 1 phase

Table 4.4 Comparison of involved costs over 20 year project life cycle

Item	Base system	SSA	COA	MCOA
TC_{WF} (million \$)	-	4,5365	4,9975	5,0339
TC_{PF} (million \$)	-	0,8195	1,0681	0,8803
TC_{BESS} (million \$)	-	0,5829	0,5500	0,4874
$TC_{WF-PF-BESS}^{Inv\&OM}$ (million \$)	-	5,9389	6,6156	6,4016
TC_{Grid} (million \$)	13,4079	5,7789	4,9024	5,0847
TC_{Total} (million \$)	13,4079	11,7178	11,5180	11,4863
Saving (million \$)	-	1,6901	1,8899	1,9216
Saving ratio (%)	-	12,61	14,10	14,33

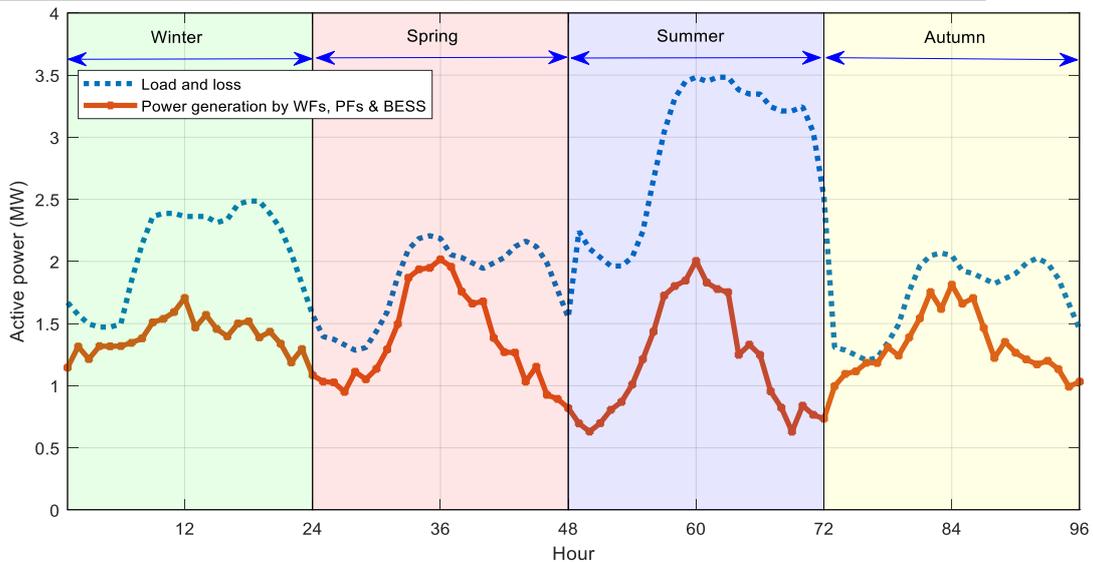


Fig 4.15 Power generation of WFs, PFs and BESS from optimal solution of MCOA.

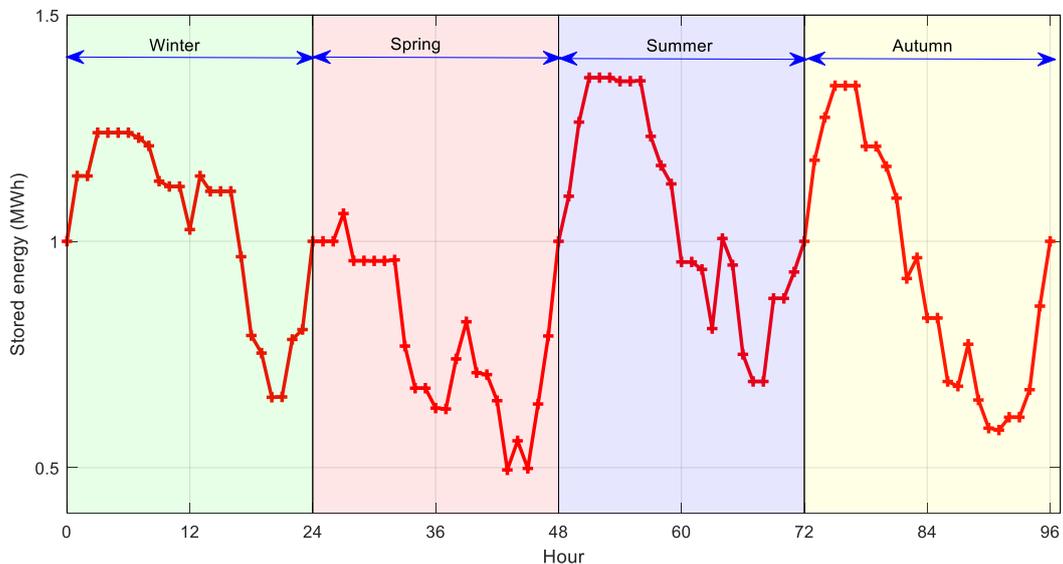


Fig 4.16 Stored energy of BESS.

Thanks to the optimal solution from MCOA, the total generation capacity of the grid-connected distributed generation sources is 126,335 MW, while the total load demand and power loss is 204,319 MW. Therefore, the main grid will

compensate for the power shortage of 77,984 MW as plotted in Figure 4.15. In this study, the charging/discharging strategy of the BESS to the grid is also shown in Figures 4.16 and 4.17. In general, the BESS tends to generate at peak hours and charge at off-peak hours to save electricity purchase costs. The total power loss is also reduced sharply by 40.79% as shown in Figure 4.18 and the voltage is also enhanced from [0.9265 1.0125] (pu) to [0.950 1.0227] (pu) as shown in Figure 4.19. Additionally, the THD value also satisfies the IEEE Std. 519 with the maximum value of up to 2.987% as presented in Figure 4.20.

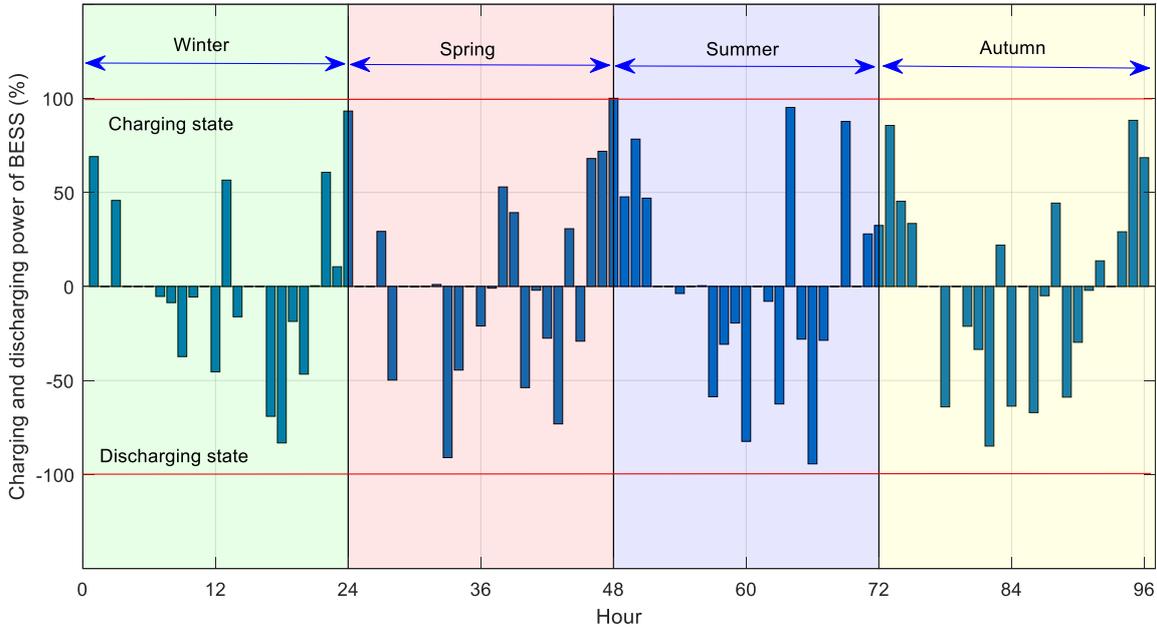


Fig 4.17 Charging and discharging stages of BESS.

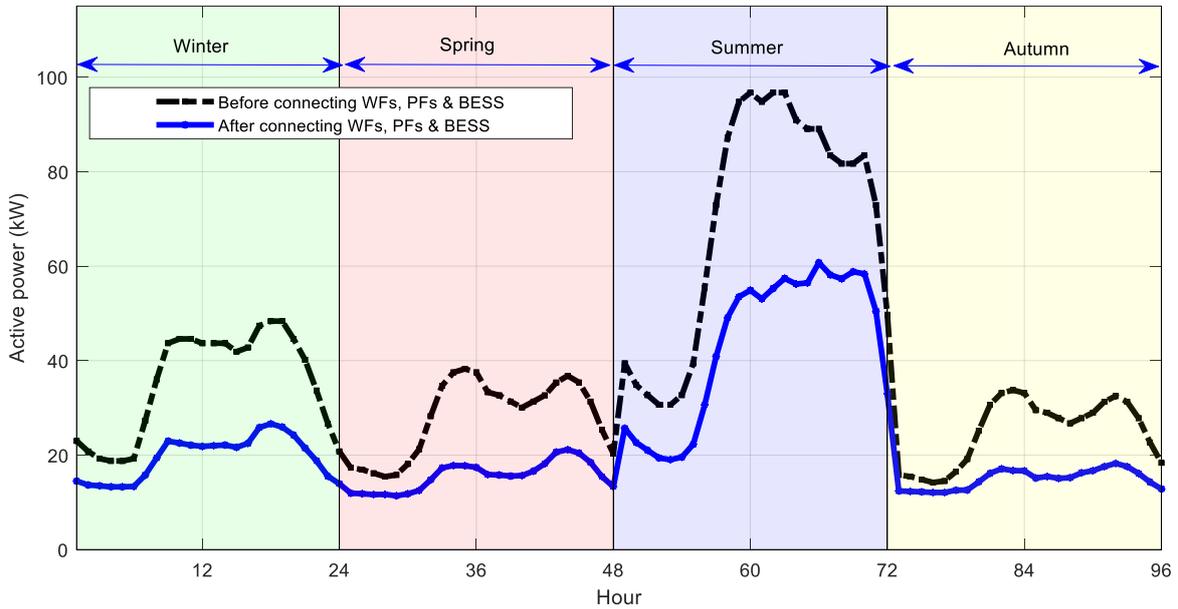


Fig 4.18 Power loss before and after connecting PFs, WFs and BESS.

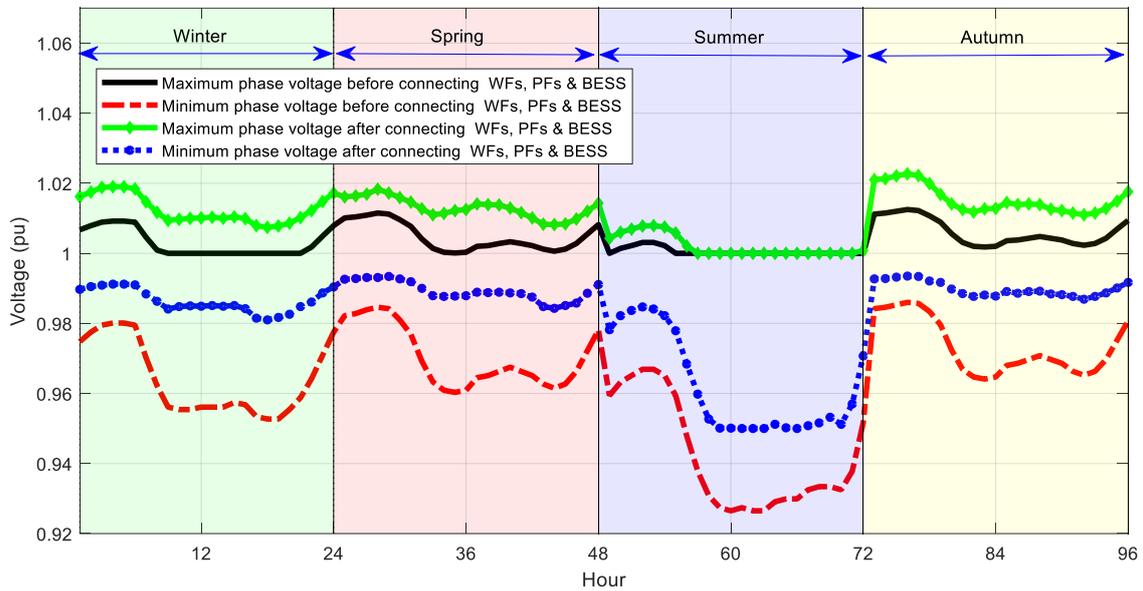


Fig 4.19 Maximum and minimum phase voltage before and after connecting PFs, WFs and BESS

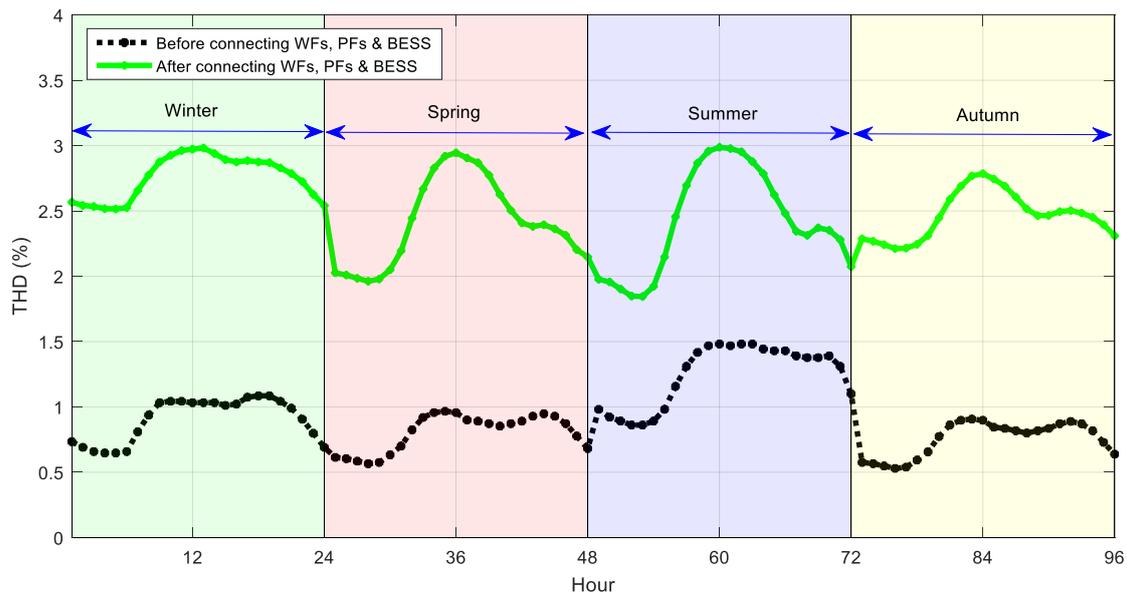


Fig 4.20 Maximum THD's value at each hour before and after connecting PFs, WFs and BESS.

4.3.4 Conclusion

- This study has successfully applied the co-simulation between OpenDSS and MATLAB with MCOA algorithm for determining the optimal installation of WFs, PFs and BESS as well as the charging/discharging strategy of BESS in a three-phase unbalanced IEEE 123 Bus system with multiple nonlinear loads penetration.
- The main objective is to minimize the total cost including investment cost, O&M cost and the cost of purchasing energy from the grid for load demand and losses on distribution branches. The results indicated that the total system cost can be significantly reduced through the integration of suitable generation sources.

CHAPTER 5: CONCLUSION AND FUTURE RESEARCH DIRECTIONS

5.1 The main contributions of the thesis

- This thesis has addressed various optimization problems related to the connection of distributed generation sources such as WF, PF, CB and BESS. The objective of the study is to minimize the total investment cost, O&M cost as well as reduce the generation cost from the main grid and the emission cost from conventional power plants while still meeting the technical constraints.
- This study not only considers the harmonic generation from nonlinear loads but also considers the harmonics from power conversion devices of PFs, WFs and BESSs to satisfy the IEEE Std. 519 and 30/2019/TT-BCT.

- A powerful algorithm with high stability called Modified Coyote Optimization Algorithm is also developed and proposed for solving various optimization problems.
- An open source software called OpenDSS is suggested for fast power flow calculation. Furthermore, the co-simulation between two software including OpenDSS and MATLAB is also successfully developed to solve the optimization problem flexibly and conveniently.

5.2 The limits of the thesis

- Limits of input data: The study uses the equivalent model of three distribution grids of IEEE 69-bus, IEEE 25-bus and IEEE 123-bus with data for simulating solar radiation and wind speed collected from the actual area in the last three years. In addition, this study only considers the change of load at each hour and the load data is referenced from IEEE RTS-96. Therefore, these data may not be close to the actual situation at specific times in the considered area. Not only that, this study also considers the integration of renewable energy sources through power converter with 100% efficiency as assumed. However, with current technology, the efficiency only reaches over 99.5% through the integration of additional power optimization technology and the highest efficiency is 99.75% thanks to the application of high efficiency energy conversion system (HEECS) technology [32]. Therefore, the assumed efficiency in this study is not consistent with the existing technology. Besides, the investment and O&M costs for PFs, WFs, CBs and BESSs are common values that are referenced from other studies in the world, so the current cost may be different from the results in this study.
- Limits of the proposed method: The MCOA method is applied to solve three optimization problems related to the integration of distributed generation sources in different distribution systems. However, MCOA may not be effective for complex problems with the large number of variables and the large search areas. Therefore, this is considered a limitation of the proposed method.

5.3 The future works

- Consideration of integrating the voltage controller for voltage regulation in the system when the voltage at the buses drops or increases beyond the allowable limit should be implemented to maximize economic and technical benefits.
- Input data on solar radiation and wind speed will also be grouped by specific areas to improve the accuracy of calculating the output power of photovoltaic modules and wind turbines
- Actual distribution systems coupled with actual data and potential installation locations for generating sources also need to be pre-determined through surveys to ensure that the proposed solution for the integrated system development project satisfies the geographical location conditions that are feasible for implementation in practice.
- Furthermore, the proposed MCOA also needs to be further improved to enhance its performance and stability in solving complex optimization problems with large search spaces. All of the above work will be carried out in the upcoming work.

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LIST OF PUBLISHED PAPERS

1. **T. D. Pham**, T. T. Nguyen, L. C. Kien, “Minimization of total costs for distribution systems with battery energy storage systems and renewable energy sources,” *Scientific Reports*, vol. 15, no. 1, pp. 1-24, 2025. (**SCIE, Q1, IF=3.9**).
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