Planning and Expansion of the Transmission Network in the Presence of Wind Power Plants

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***Abstract*—The proliferation of renewable energy sources, particularly wind farms, is rapidly gaining momentum owing to their numerous benefits. Consequently, it is imperative to account for the impact of wind farms on transmission expansion planning (TEP), which is a crucial aspect of power system planning. This article presents a multi-objective optimization model that utilizes DC load flow to address the TEP challenge while also incorporating wind farm uncertainties into the model. The present study aims to optimize the expansion and planning of the TEP in the power system by considering investment and maintenance costs as objective functions. To achieve this, a multi-objective approach utilizing the shuffled frog leaping algorithm (SFLA) is proposed and implemented. The proposed objectives are simulated on the RTS-IEEE 24-bus test network. The results obtained from the proposed algorithm are compared with those of the Genetic Algorithm (GA) to assess and validate the proposed approach.**

Keywords*—Wind farms; Transmission Expansion Planning (TEP); multi-objective optimization model; Shuffled Frog Leaping Algorithm (SFLA)

NOMENCLATURE

Abbreviations	
TEP	Transmission expansion planning
SFLA	Shuffled frog leaping algorithm
Parameters and variables	
Cij	The cost of new lines among buses i and j
Nij	The number of new lines among buses i and j
N0ij	The initial lines between buses i and j
lij	The length of new lines between buses i and j
CM, CO	The maintenance and operation costs
S	Intersection matrix for buses
f	Power flow vector
r	Resistance of lines
gij	Vector of the power generation
d	Load demand vector
fij	Power flow between lines in buses i and j
θi	Voltage angle in bus i

I. INTRODUCTION

A. Aims and Related Research

During the past few decades, problems have existed in the electric power generation sector in a traditional system, such as high production costs, environmental effects, high losses and low reliability [1]. Hence, distributed generation systems have been used in such systems, which are installed in the vicinity of consumption centers and have lower power, loss, and cost, as well as more reliability than traditional forms of electric energy generation. Wind energy is one of the energy sources that have received a lot of attention [2]. Investigating the effects of wind energy resources on power networks from various aspects, such as uncertainty and uncontrollability of generation power compared to conventional sources of energy production, has been studied as one of the important challenges in this field [3]. In addition to these cases, the distance from demand centers and the strong dependence of wind turbine production capacity on wind speed should be added as the biggest obstacles to the use of this energy [4]. The objectives of transmission expansion planning (TEP) in the power system are twofold: to plan power systems that ensure a dependable energy supply to customers and to identify optimal locations and methods for investing in new transmission lines that will facilitate reliable energy supply to customers. Additionally, TEP involves the operation of load growth based on demand forecasting [5]. Hence, to implement of reliable energy supply the increase the generation share of wind farms compared to the total generation of electric energy in the traditional systems [6], [7], it is necessary to have a reliable supply of energy in order to maintain customer satisfaction in the power system planning with regard to uncertainties [8], [9].

The research of the power systems considering different areas like power plants, transmission and distribution grids are assessed in this subsection. In research [10], energy optimization with TEP considering power generation of renewable energies such as solar power and wind turbines is proposed. Authors in study [11] installed and sized the solar panels and storage systems in the transmission lines with consideration of the power loss reduction reported. The operation of the generation units in the power plants by using the unit commitment approach is proposed in [12]. In (Moreira et al., 2017), the economic dispatch approach for energy scheduling in the power plants is used. The planning and operation modeling in the power grids with maximizing reliability is studied in [13]. The article in [14] presents an economic approach to power flow analysis, taking into account factors such as fuel costs in power plants and the operation of units during peak demand. Meanwhile, [15] models power flow with a focus on the cost of transmission lines and incorporates the use of Flexible AC Transmission Systems (FACTS) to enhance voltage index. The modeling economic of the microgrids for TEP and power grids for covering the uncertainty of renewable energy is studied in [16].

B. Contributions

This paper presents a multi-objective optimization model for TEP in the power system, taking into account the operation of wind farms. The objective functions based on investment and maintenance costs are modeled for implementing TEP in the power systems. The shuffled frog leaping algorithm (SFLA) is proposed for solving the optimization approach. The expansion of the wind farms in the TEP is modeled based uncertainty approach. The DC power flow is considered for TEP with wind farm operations. Hence, the contributions of this paper can be summarized as follows:

1) *Proposing* multi-objective modeling for TEP in the power system considering wind farm participation.

2) *Implementing* TEP by investment and maintenance costs.

3) *Utilizing* shuffled frog leaping algorithm (SFLA) for solving problems.

4) *Modeling* wind farm based on uncertainty approach.

II. TEP FORMULATION

The inability to accurately predict the load due to the uncertainty of power generation, such as wind energy, leads to the introduction of new technologies in electrical energy generation. Hence, wind farms, due to the randomness of the generation power in their generation, cannot be ignored. Therefore, the modeling of these uncertainties in the planning of power systems will lead to the creation of stronger planning that can meet different conditions [17]. It should be noted that the uncertainties of the network structure make the decision-making process difficult. In traditional planning, the main goal is to minimize investment costs [18]. However, in modern planning, several different goals are optimized simultaneously, and traditional methods are not able to provide acceptable solutions [19].

A. Wind power modeling

The amount of power produced by wind farms is contingent upon the speed of the wind. As a result, the power output of a wind turbine differs significantly from that of a conventional energy generation unit [20]. Hence, modeling wind power is formulated by the "power-speed" curve in Fig. 1 and other parameters of the turbine. Also, modeling wind turbines is formulated by Eq. (1) [20].

$$P_{WT}(v) = \begin{cases} 0 & if \quad v \le V_{cin} \\ P_{N,WT} \times \left(\dfrac{v - V_{cin}}{V_r - V_{cin}} \right) & if \quad V_{cin} \le v \le V_r \\ P_{N,WT} & if \quad V_r \le v \le V_{co} \\ 0 & if \quad V_{co} \le v \end{cases} \tag{1}$$

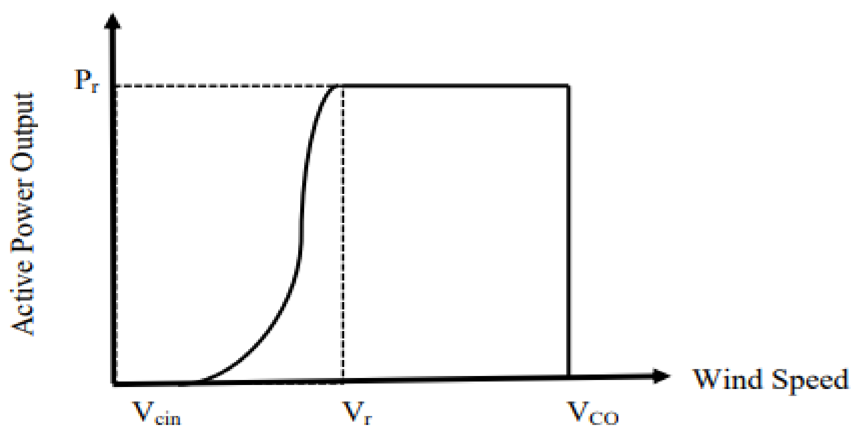


Fig. 1. Wind turbine "power-speed" characteristic.

B. Objective functions formulation

The objective functions, such as investment and maintenance costs, are minimized to TEP in this section. The modeling of the objectives is as follows:

1) *Cost of investment:* The modeling investment considering constraints for this objective is as follows:

$$\min f_{IC} = \sum_{i,j=1}^{n} C_{ij} \times l_{ij} \times N_{ij} \tag{2}$$

Subject to:

$$Sf + g = d \tag{3}$$

$$f_{ij} - r(N_{ij}^{0} + N_{ij})(\theta_i - \theta_j) = 0 \qquad \forall i, j, n \tag{4}$$

$$\left| f_{ij} \right| \le (N_{ij}^{0} + N_{ij}) f_{ij}^{\max} \qquad \forall i, j, n \tag{5}$$

$$0 \le N_{ij} \le N_{ij}^{\max} \qquad \forall i, j, n \tag{6}$$

$$0 \le g_{ij} \le g_{ij}^{\max} \qquad \forall i, j, n \tag{7}$$

Where constraints in Eq. (3) and Eq. (4) are power flow balance and power flow in branches *i* and *j*, respectively, the constraints in Eq. (5) and Eq. (6) limit the power flow and limit of the number lines *i* and *j*, respectively. Constraint in Eq. (7) is active power generation by units in buses *i* and *j*.

2) *Maintenance and operation costs:* The second objective is to minimize the maintenance and operation costs of the TEP:

$$\min f_2 = \sum_{i,j=1}^{n} C_M N_{ij} + C_O N_{ij} \quad (8)$$

In objective function in Eq. (8) first and second terms are maintenance and operation costs, respectively.

III. Optimization Method

This study uses SFLA as an optimization method to solve the objective functions. SFLA is modeled based on the population of frog groups or memeplexes to find food. This method addresses the creation of frog populations as part of local and global strategies and objective functional changes based on the replacement of existing frogs. SFLA can be done by following these steps [21], [22]:

1) Population generation: Randomly generates a population "p", considering each frog's position and search space.

2) Creation of the memeplexes: The frogs must be evenly distributed in the memeplexes, taking into account their fitness function, where the population of frogs as m memeplexes with n frogs is p = [m × n].

3) Update frog location: Frogs in memeplexes are updated based on their best and worst locations from local search. Then the worst frog (Ωw) is updated with the best frog (Ωb) in each memeplex and the whole memeplex with the best frog (Ωgb):

$$\Omega_w^{new} = \Omega_w + rand \times (\Omega_b - \Omega_w) \quad (9)$$

$$\Omega_w^{new} = \Omega_w + rand \times (\Omega_{gb} - \Omega_w) \quad (10)$$

Here, 0 ≤rand ≤1 is a random number. With (9), the worst frog Ω_w can be upgraded by placing the best frog Ω_b. In this step, if Ω_w^{new} is better than Ωw, Ωw is replaced by Ω_w^{new}; otherwise, Ωw can be replaced with Eq. (10) by the best frog in the Ω_{gb} memeplex. To find the optimal solution of SFLA, this process is performed for all iterations and memeplexes. The process of the SFLA is presented by Algorithm 1.

Algorithm 1: Process of the SFLA.

Algorithm 1 pseudocode of the SFLA
1. Start
2. Create population of *P* frogs, randomly;
3. Calculate fitness function of the *i* frog;
4. Sort the frogs based on their fitness;
5. Distribution of the frogs by *m* memeplexe and *n* frog (*P* = *m*×*n*);
In each memeplex;
Determine X_B and X_W;
Improve the X_W position using Eqs. (11) and (12);
Repeat for number of iterations;
Stopping critical satisfied? Yes End Else=go to step 2

taSince objectives are optimized in this study simultaneously. The frontier solutions will be obtained. The energy operator must determine the optimal solution for objectives in the frontier solutions as a decision maker. Hence, the max-min fuzzy method is proposed for a determined optimal solution as follows [23], [24]:

$$\Gamma\left(f_z(\vartheta)\right) = \begin{cases} 0 & otherwise \\ \dfrac{f_z^{\max} - f_z(\vartheta)}{f_z^{\max} - f_z^{\min}} & f_z^{\min} \le f_z(\vartheta) \le f_z^{\max} \\ 1 & f_z^{\min} \ge f_z(\vartheta) \end{cases} \quad (11)$$

$$\max\left\{\min \Gamma\left(f_z(\vartheta)\right)\right\} \quad (12)$$

Here, *Γ (f_z (ϑ))* and *f_z(ϑ)* are membership functions or solutions in *zth* objective and value of objective at ϑth frontier solutions, respectively. Also, to determine the optimal solution in frontier solutions maximum and minimum procedure is presented in Eq. (11). In Eq. (12), a high rate of minimum solution is introduced as the optimal solution.

IV. Numerical Simulation

In this section, TEP studies have been carried out using the proposed algorithm in the MATLAB software environment in a system with a 4 GHz CPU and 6 GB RAM using DC load flow. The RTS-IEEE 24-bus test network is used for implementing TEP considering wind farm installation. In Fig. 2, the RTS-IEEE 24-bus test network with wind farms is shown. The wind speed based on average value is shown in Fig. 3. As should be mentioned, the TEP time study is considered for ten years. The average wind speed is considered in the simulation, and data from the wind farm is presented in Table I. The two wind farms have the same data. Also, load demand data is listed in Table II. Information on the generator units and test network are extracted from study [25]–[27].

TABLE I. Wind Farm Data

Parameters	Value
PN, WT	10 MW
Vr	10 m/s
Vcin	3 m/s
Vco	16 m/s
NWT	35

TABLE II. Load Demand Data

Bus	Demand (MW)	Bus	Demand (MW)
1	323	10	586
2	292	13	796
3	541	14	583
4	223	15	950
5	212	16	302

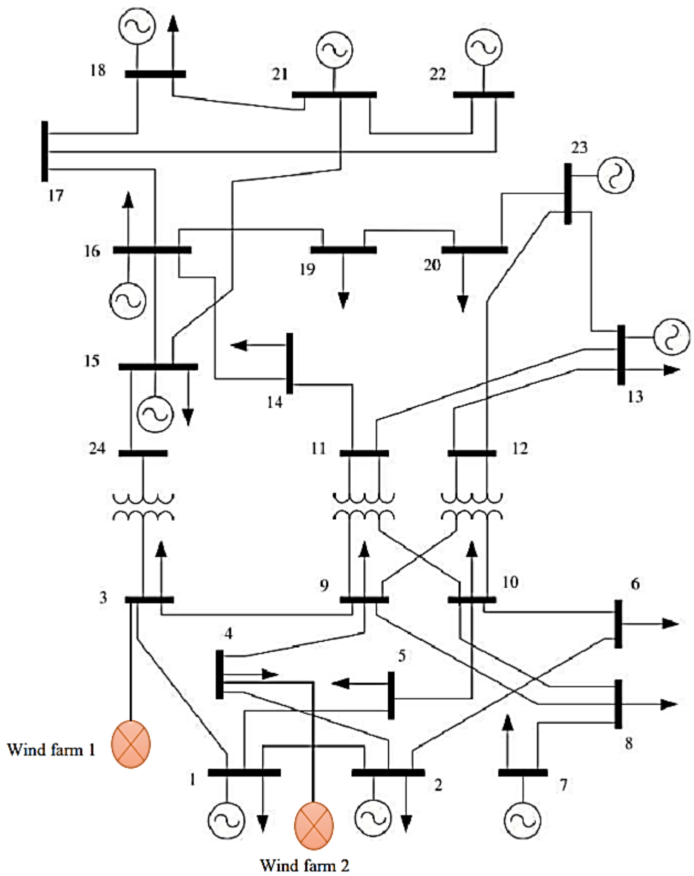


Fig. 2. RTS-IEEE 24-bus test network with wind farms.

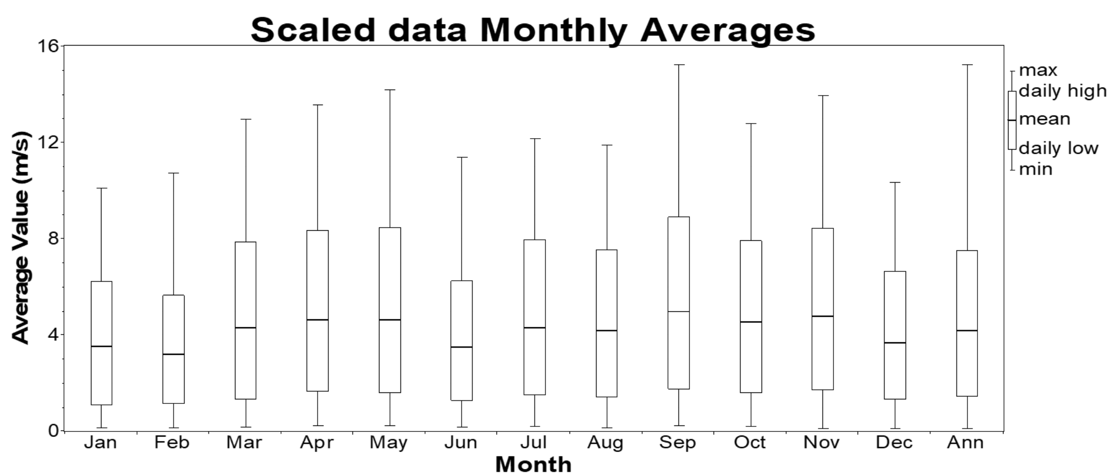


Fig. 3. Wind speed in test network.

A. Results Analyse

To examine the impact of various conditions on the outcomes of resolving the TEP issue utilizing the suggested algorithm, the ensuing scenarios were analyzed and executed on the 24-bus RTS-IEEE test system. The scenarios are as follows:

Scenario A) Implementing TEP without wind farms.

Scenario B) Implementing TEP with wind farms.

Also, in this study, the proposed optimization approach is compared with the Genetic Algorithm (GA) for verification and confirmation of the SFLA. In Fig. 4 and 5, frontier solutions of the objective functions for scenarios A and B by comparing SFLA with GA are shown, respectively. The obtained optimal solution by fuzzy method for the first and second objectives by SFLA in scenario A are equal to

\$11996.3 and \$768.6, respectively. The optimal solution generated by GA yields a first objective amount of \$12453.3 and a second objective amount of \$796.4. These results of the SFLA represented more convergence of the optimization for TEP in scenario A than GA. The value of the optimal solutions in scenario A, by the fuzzy method for SFLA and GA, is equal to 0.46 and 0.43, respectively.

On the other side, with implementing TEP with wind farms, the results of the objective functions in Fig. 5 are more optimizer than scenario. In scenario B, the SFLA algorithm has yielded optimal solutions of \$11153.4 and \$750.6 for the first and second objective functions, respectively. It's visible with the installation of the wind farms; expansion of the transmission lines for supply load demand is optimized than scenario A. Furthermore, the utilization of GA in scenario B results in a decrease in the values of both the first and second objective functions. These reductions of the objective functions in scenario B are due to more generation capacities, dropping power flow in lines, and increasing line capacities in meeting load demand.

Fig. 6 and Fig. 7 depict TEP implementation in scenarios A and B using SFLA and GA in the RTS-IEEE 24-bus test network. The orange lines represent optimal TEP solutions to meet load demand while considering economic power generation from the units. The implementation of the TEP by SFLA in both scenarios leads to reduce investment costs and maintenance and operation costs in comparison with GA.

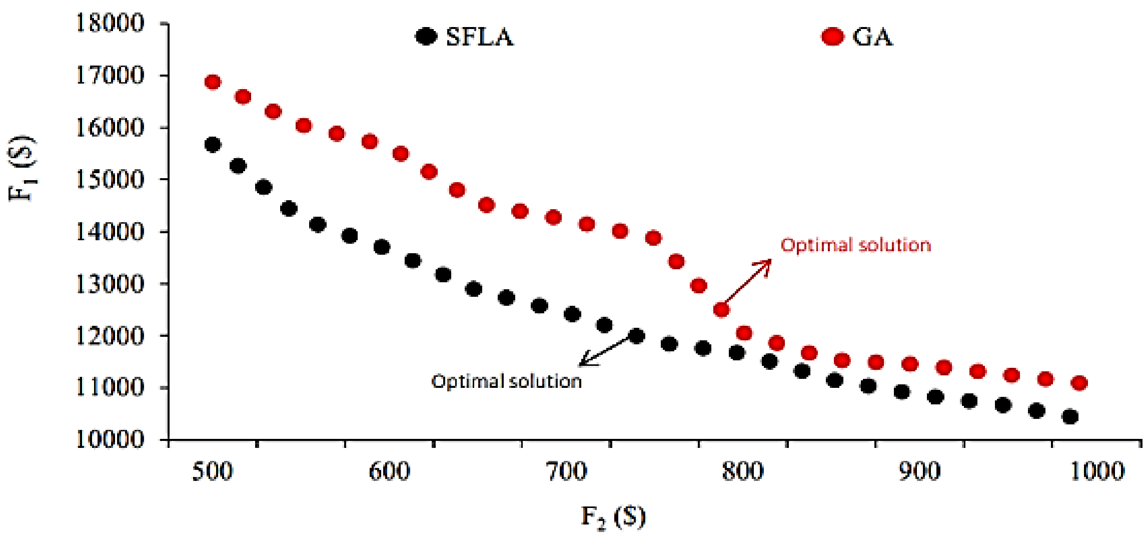


Fig. 4. Objectives in scenario A.

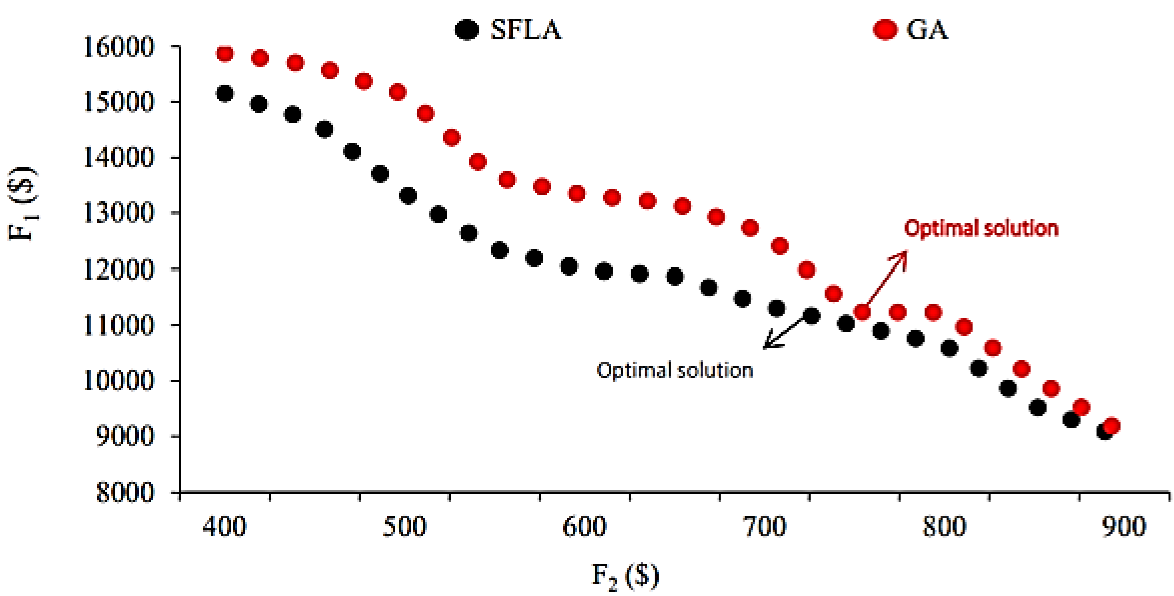
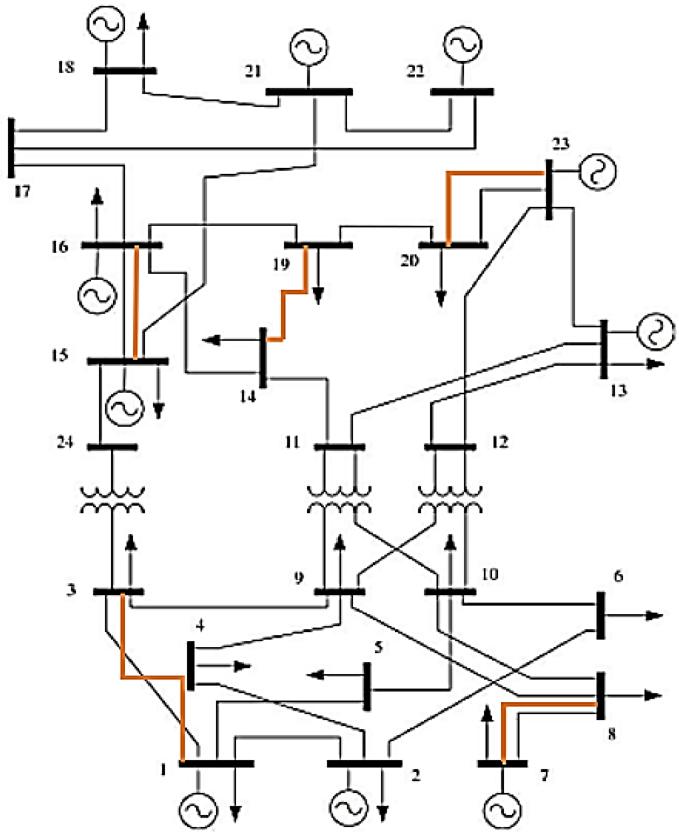
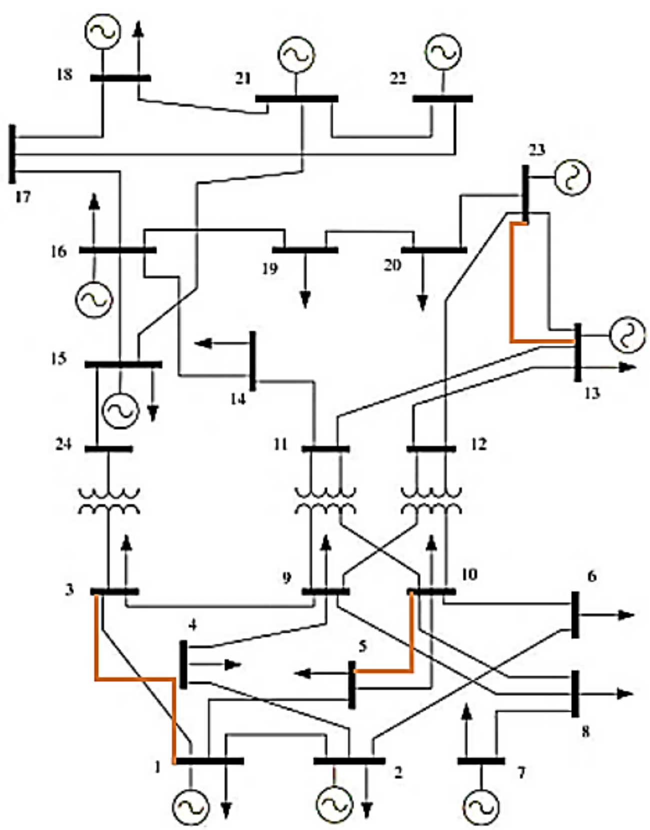


Fig. 5. Objectives in scenario B.



(a)



(b)

Fig. 6. TEP in scenario A. a) GA and b) SFLA.

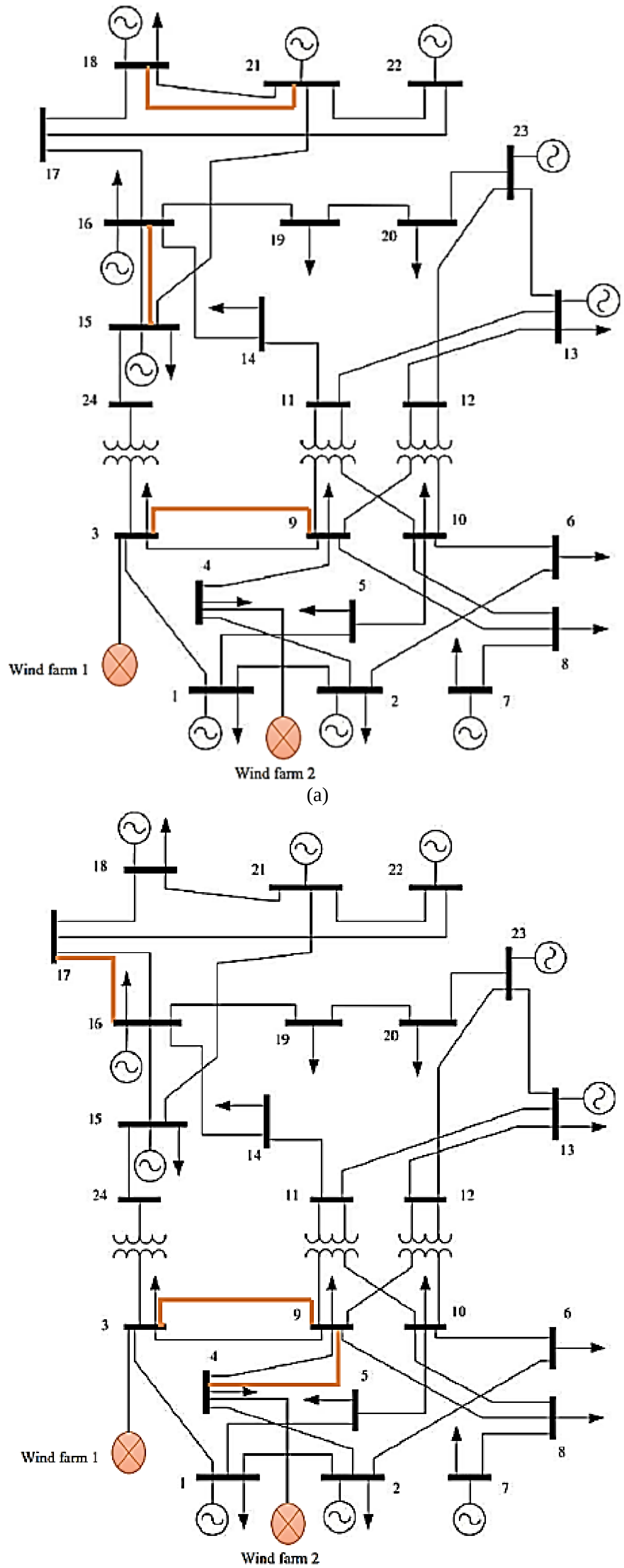


Fig. 7. TEP in scenario B. a) GA and b) SFLA.

V. Conclusion

As a result of the escalating load growth and the integration of renewable resources into the power system, TEP has become an unavoidable issue. This article addresses the TEP problem as a multi-objective optimization problem, taking into account the presence of wind farms. Specifically, the study investigates the effectiveness of the SFLA on the modified RTS-IEEE 24-bus network. The proposed method aims to minimize investment and maintenance costs. Comparative analysis between SFLA and GA demonstrates the superiority of the former in achieving the desired objectives.

In comparison to other models, a significant advantage of this particular model lies in its investment and maintenance costs, which align with the fundamental objectives of TEP. Consequently, it is imperative to incorporate the cost of investment and maintenance as a component of fixed costs, given their crucial role in the planning process of power systems. Furthermore, the inclusion of wind farms in TEP-related matters will progressively enhance the performance of power networks in accordance with the load demand rate.

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