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1	Huu Tinh Tran, Ngoc Dieu Vo, and Huy Anh Quyen	2017	A Pseudo-Gradient Particle Swarm Optimization Approach Applied to Transmission Expansion Planning	The 12th GMSARN International Conference 2017	E-76
2	Dieu Ngoc Vo, Tri Phuoc Nguyen, Tinh Huu Tran, and Hai Minh Nguyen	2017	A Hybrid Particle Swarm Optimization and Differential Evolution for Security-Constrained Optimal Power Flow	The 12th GMSARN International Conference 2017	E-75
3	Quy Truong Xuan, Dieu Vo Ngoc, and Huu Tinh Tran	2017	Pseudo-Gradient Integrated in Particle Swarm Optimization for Solving Security Constrained Optimal Power Flow Problem	The 12th GMSARN International Conference 2017	E-82
4	Trần Hữu Tính[1*], Trần Nhựt Hiếu[2], Võ Minh Thiện[3]	2019	Đánh giá độ tin cậy hệ thống điện có xét đến cường độ cắt cưỡng bức	Tạp chí Khoa học công nghệ Đại học Thái Nguyên	ISSN: 1859-2171 195(02): 89 - 94
5	Trần Hữu Tính[1*], Võ Ngọc Điều[2], Quyền Huy Ánh[1]	2020	Tổng quan quy hoạch mở rộng lưới điện truyền tải	Tạp chí Khoa học công nghệ Đại học Thái Nguyên	ISSN: 1859-2171 225(06): 223 - 228
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9	Huutinh Tran, Ngocdieu Vo, Huyanh Quyen	2022	A Search Method for Power Transmission System Planning Problem in Ben Tre Province, Viet Nam	In International Conference on Advanced Engineering Theory and Applications. Singapore: Springer Nature Singapore. (Scopus – Q4)	ISSN 1876-1100 (333-344)
10	Huutinh Tran, Ngocdieu Vo, Huyanh Quyen	2023	A Cuckoo Search Algorithm for Transmission Expansion Planning	Proceedings of 2023 International Conference on System Science and Engineering	pp. 55-60, doi: 10.1109/ICSSE58758.2023.10227232

PSEUDO GRADIENT PARTICLE SWARM OPTIMIZATION APPROACH APPLIED TO TRANSMISSION EXPANSION PLANING

Tran Huu Tinh, Vo Ngoc Dieu, and Quyen Huy Anh

Abstract— *Today, electricity is an indispensable part of energy in living and productive society. Power system has the basic function that provides electricity to meet the requirements of quantity, quality, reliability and economy for consumers. Transmission expansion planning (TEP) is a mathematic complex optimization. The task of extending grid is to increase the capacity of transmission system to meet the increasing demands of load, satisfying economic and technical constraints. This study applied Pseudo-gradient Particle Swarm Optimization (PGPSO) method to solve the TEP problem with a pseudo-gradient coefficient and velocity enhancement that increase the capacity convergence. This proposed method is proven on the IEEE 30-nodes and the obtained results are compared other methods.*

Keywords— **Pseudo-gradient Particle Swarm Optimization, Transmission expansion planning, A pseudo-gradient coefficient.**

1. INTRODUCTION

Power system plays an important role in the continuous supply of electricity. Power system is divided into three parts: generation system, transmission system and distribution system. Power system planning that is developed in the future is a very important task. Along with the developable life, the demand for electricity is increasing, and the requirements for transmission expansion planning is increasingly difficult. The growing transimission requires the optimial algorithm that defines the efficient grid structure.

Transmission expansion planning problens are based on mathematical model of mathematical algorithms, and optimal solutions based on prior constraints. The problem consists of variables, objective functions, and constraints. The objective functions soluted to the optiminal TEP problem such as investment cost and operating cost. The constraints included building conditions, upper and lower bound of the variables, power source, etc. The mathematical models of grid expansion are constraints of line overload and balancing power.

To solve the problem of grid planning, we solve the problems of linear planning, dynamic planning, branch and bound algorithm, and geometric methods. However, there were some limitations in calculations when they applied in practice. Solving methods are variable interactions. However, the variable numbers are very large and the constraints were very complex, the optimization tools will solve difficulty for large mathematic optimizations..

2. MODIFIED PARTICLE SWARM OPTIMIZATION ALGORITHMS

2.1. Particle Swarm Optimization algorithm

Particle Swarm Optimization (PSO) is one of the algorithms that builds on the herd intelligence to solute optimization problems in the search space. PSO is a form of evolutionary algorithms that known previously such as genetic algorithms (GA). However, PSO is different from GA that it uses more interpersonal interaction to explore search space than GA. PSO is the modeling result of flying birds to search food that categorizes the herd intelligence algorithm. PSO was introduced in 1995 at an IEEE conference by James Kennedy and Rusell C. Eberhart.

In the PSO algorithm, the each individual orbits in the search space are calibrated by varying individual velocities, through their flight experience and the flight experience of other individuals in the search space. To search vector position and velocity vectors of an i particle in a multidimensional space are:

$$\mathrm{X_i} = (\mathrm{x_{11}}; \mathrm{x_{12}}; \dots; \mathrm{x_n}) \quad (1)$$

$$\mathrm{V_i} = (\mathrm{v_{11}}; \mathrm{v_{12}}; \dots; \mathrm{v_n}) \quad (2)$$

By setting the definitive function, we will find the optimal value at time t as Gbest = (p_{11}; p_{12}; ...; p_n). Then, the new velocity and the new individual are calculated by the following expressions:

$$\mathrm{v_{id}^{k+1}} = \mathrm{v_{id}^{k}} + \mathrm{c_1.rand_1}\left(\mathrm{pbest_{id}^{k}} - \mathrm{x}_{\mathrm{id}}^{k}\right) + \mathrm{c_2.rand_2}(\mathrm{gbest_{id}^{k}} - \mathrm{x_{id}^{k}}) \quad (3)$$

$$\mathrm{X_{id}^{k+1}} = \mathrm{X_{id}^{k}} + \mathrm{X_{id}^{k+1}} \quad (4)$$

Where: c_1; c_2 accelerated constants

Rand$_1$ and rand$_2$ are random number generators in [0; 1] (these two functions are congruent to each other).

The first equation (3) represents previous velocity, in order to create momentum for the individual to continue wandering in the search space. The second component, considered a cognitive component, represents the artificial individuals. This component will direct its best position. The third component is considered a social component, which represents the colaborative effect of the individual in the finding process of a global optimal solution, and the social component will entice the individual towards of a global optimal value.

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Initial individuals are created with a random location, then the random velocities are assigned to each individual. The suitable individuals are estimated through the objective function. At each moment, the velocity individual is calculated through and the estimate position is updated formula (4). After each of period time, if the locative individuals found more optimal than the previous location individuals, the individual location is stored in memory. Generally, the maximum velocity (V_{max}) for each module velocity vectors of individuals is defined to control the individual ranges in the search space for self-defined users.

2.2. Particle Swarm Optimization - Time Varrying Inertial Weight

Shi and Eberhart introduced the inertia concept in addition to the standard PSO version to balance local and global results in the search process. The calculating expression for this idea is shown below:

$$\mathrm{v}_{\mathrm{id}}^{\mathrm{k}+1} = \mathrm{C}\{\omega \mathrm{v}_{\mathrm{id}}^{\mathrm{k}} + \mathrm{c}_1.\mathrm{rand}_1\left(\mathrm{pbest}_{\mathrm{id}}^{\mathrm{k}} - \mathrm{x}_{\mathrm{id}}^{k}\right) + \mathrm{c}_2.\mathrm{rand}_2\left(\mathrm{gbest}_{\mathrm{id}}^{\mathrm{k}} - \mathrm{x}_{\mathrm{id}}^{\mathrm{k}}\right) \qquad (5)$$

Where ω is given by the formula:

$$\omega = (\omega_1 - \omega_2).\frac{(MAXITER - iter)}{MAXITER} + \omega_2 \qquad (6)$$

With ω_1 and ω_2 as the initial and end value of the inertial weight "iter" is the current loop and "MAXITER" is the maximum value of the loop that is accepted. This method is called Particle Swarm Optimization - Time Varrying Inertial Weight **(**PSO-TVIW). The results show that PSO-TVIW is ineffective for "tracking dynamic systems". Instead, dynamic applications are in the nature, they have proposed some random inertia for the tracking dynamic system.

$$\omega = 0{,}5 + \mathrm{rand}(.)/2 \qquad (7)$$

This method is called PSO-RANDIW

Both methods have developed PSO towards TVIW. Although PSOTVIW could give good results, it compared to other evolutionary algorithms and obtained good results.

2.3. *Particle Swarm Optimization - Time Varying Acceleration Coefficients*

Suganthan tested a linear reduction method for acceleration coefficients all time but the results showed that the acceleration coefficients gived by (3), (4) give better value. However, his research showed that the acceleration coefficients were not alway necessarily equal to (3), (4).

A technology enhances convergence for the PSO algorithm is introduced as time varying acceleration coefficients (TVAC). This objective improvement is to enhance a global search solution in the initial stages of the processive optimization and to encourage convergent individuals and global optimal values in the final stages of the processive search.

The expressive algorithm is as follows:

$$\mathrm{v}_{\mathrm{id}}^{\mathrm{k}+1} = \mathrm{C}\{\omega \mathrm{v}_{\mathrm{id}}^{\mathrm{k}} + \mathrm{c}_1.\mathrm{rand}_1\left(\mathrm{pbest}_{\mathrm{id}}^{\mathrm{k}} - \mathrm{x}_{\mathrm{id}}^{k}\right) + \mathrm{c}_2.\mathrm{rand}_2\left(\mathrm{gbest}_{\mathrm{id}}^{\mathrm{k}} - \mathrm{x}_{\mathrm{id}}^{\mathrm{k}}\right)\} \qquad (8)$$

Where:

$$\boldsymbol{c_1 = \left(c_{1f} - c_{1i}\right).\frac{iter}{MAXITER} + c_{1i}} \qquad (9)$$

$$\boldsymbol{c_2 = \left(c_{2f} - c_{2i}\right).\frac{iter}{MAXITER} + c_{2i}} \qquad 10)$$

In the above equation c_{1f} and c_{1i} are set to 0.5; c_{2f} and c_{2i} are set to 2.5. Thus, in this algorithm, c_1 usually has had a value between 2.5 and 0.5, and c_2 usually has had a value between 0.5 and 2.5.

2.4. Pseudo-gradient Particle Swarm Optimization

This algorithm was developed by Dr. Vo Ngoc Dieu and Peter Schegner that based on the PSO algorithm.

PGPSO is also a PSO form, and a pseudo-gradient enhances the aspect ratio to help accelerate the processive convergence. The purpose of the pseudo-gradient directs to move to a better point element that it can obtian quickly reach convergence.

In the PSO with coefficients (Clerc & Kennedy 2002), the velocity elements is determined as follows:

$$\mathrm{v}_{\mathrm{id}}^{(\mathrm{k}+1)} = \mathrm{C}\{\mathrm{v}_{\mathrm{id}}^{\mathrm{k}} + \mathrm{c}_1.\mathrm{rand}_1(\mathrm{pbest}_{\mathrm{id}}^{(\mathrm{k})} - \mathrm{x}_{\mathrm{id}}^{(\mathrm{k})} + \mathrm{c}_2.\mathrm{rand}_2(\mathrm{gbest}_{\mathrm{id}}^{(\mathrm{k})} - \mathrm{x}_{\mathrm{id}}^{(\mathrm{k})})\} \quad (11)$$

$$\text{Where: } \mathrm{C} = \frac{2}{\left|2-\varphi-\sqrt{\varphi^2-4\varphi}\right|}, \quad \varphi = \mathrm{c}_1 + \mathrm{c}_2, \quad \varphi > 4 \ (12)$$

In this case, the coefficient φ affects the convergence system and must be greater than 4. However, if the value φ increases, the coefficient c will decrease that generates variance and lead to the slow answer. The special value of φ is usually 4.1, $c_1 = c_2 = 2.05$.

When a pseudo-gradient made in PSO, two points were considered respectively x_k and x_l in the search space pseudo-gradient at the positive element at k and k + 1 in x(k) and x(k + 1). Therefore, the new positive element is rewritten:

$$\mathbf{x}_{\mathbf{id}}^{(\mathbf{k+1})} = \begin{cases} \mathbf{x}_{\mathbf{id}}^{(\mathbf{k})} + \boldsymbol{\delta}\left(\mathbf{x}_{\mathbf{id}}^{(\mathbf{k+1})}\right) \times \left|\mathbf{v}_{\mathbf{id}}^{(\mathbf{k+1})}\right| & \textbf{if } \mathbf{g_p}\left(\mathbf{x}_{\mathbf{1}}^{\mathbf{k+1}}\right) \neq \mathbf{0} \\ \mathbf{x}_{\mathbf{id}}^{(\mathbf{k})} + \mathbf{v}_{\mathbf{id}}^{(\mathbf{k+1})} & \textbf{contrary} \end{cases} (13)$$

In the above program, if the pseudo-gradient is nonzero, the element will move the correct point and the speed movement to the optimal point that will accelerate in the search space, and the positive element will be updated. Not only the proposed PGPSO method is also based on the PSO method but also the virtue pseudo gradient helps the moving elements to the correct point that have been warned, their velocity is enhanced by the pseudo-gradient so they can move quickly. To convergence point, PGPSO is better in solving optimization problem than conventional PSO method.

3. PSEUDO GRADIENT PARTICLE SWARM OPTIMIZATION ALGORITHM SOLVES TRANSMISSION EXPANSION PLANING PROBLEM

3.1. Transmission Expansion Planning Problem

Not only the TEP problem was built new lines, but also it had existing lines or upgraded the transmission capacity of existing lines, such as it increased the voltage level. Each option j is characterized by the investment cost ICj. Then, if a particular j is chosen for a particular year p, there would be a binary variability K^{P}_{ij} set at level 1, and the investment cost in year 0, interest rate ir matched risk invest. Using these factors, we estimated the operating costs of OC_{pi} and returned to the initial stage using the ir interest rate. Targeted functions with constraints related to the physical characteristics of the generation and transmission system, investment cost, service quality and reliability. With the objective function:

$$\min CostX_i^k = \sum_{p=0}^{np+1}\left[\sum_{j=1}^{npr} IC_j K_{ij}^p + OC_{pi}\right]/(1+ir)^p \qquad (14)$$

Operating costs would dealt with linear functions for each stage. In each period, there was a combination of existing electricity and forecast future. In this formula c_k, P_{gk} and P_{lk} were generating power cost, generating power and the linking loads at node k, G was the penalty when it stopped Power Not Supplied (PNS), a_{bk} is the sensitivity of active power in the branch b that was related to the rate

S of the node k, and was the upper and lower limits of the generation power at node k . P_b^{min} and P_b^{max} was the upper and lower limits of the transmission power at the branch.

$$\min f = \sum c_k . Pg_k + G \sum PNS_k \quad (15)$$

Inequality and constrainable equality:

$$P_G = P_D + P_L \quad (16)$$

$$\sum Pg_k + \sum PNS_k = \sum Pl_k \quad (17)$$

$$Pg_k^{min} \leq Pg_k \leq Pg_k^{max} \quad (18)$$

$$PNS_k \leq Pl_k \quad (19)$$

$$P_b^{min} \leq \sum a_{bk} . (Pg_k + PNS_k - Pl_k) \leq P_b^{max} \quad (20)$$

$$P_{gi} - P_{di} = V_i \sum_{j=1}^{N_b} V_j [G_{ij} \cos(\delta_i - \delta_j) - B_{ij} \sin(\delta_i - \delta_j)]; \ i = 1, \dots, N_b \quad (21)$$

$$Q_{gi} - Q_{di} = V_i \sum_{j=1}^{N_b} V_j [G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j)]; \ i = 1, \dots, N_b \quad (22)$$

Where: P_{gi}, Q_{gi} is the active power and resistance power of the i generator.

P_{di}, Q_{di} is the active power and the feedback resistance power at the i node.

V_i, δ_i is the magnitude and voltage angle at the i node.

G_{ij}, B_{ij} is the conductor and charge between i and j node.

N_b ís the number of system nodes.

This Direct Current - Optimal Power Flow model is developed further transmission losses according to the following scheme:

Algorithm

i) Choice of problem parameters;

ii) Calculate the phase voltage;

iii) Estimate the power losses per m-n branch (23). In this expression, g_{mn} is the conductance branch mn and θ_{mn} the phase difference of the phase;

$$\text{Loss}_{mn} = 2.g_{mn}.(1- \cos \theta_{mn}) \quad (23)$$

iv) a half of the addition power loss was to the m-n branches in the initial load between node n and m. Recalculate (14) to (22) and voltage;

v) In the end, the difference voltage in all nodes would be smaller than the specified level ε, unless it returned to *iii).*

The convergence of this processive iteration was achieved in less than 5 iterations and eventually we get the cost, power loss and value for the Power Not Supplied.

3.2. Pseudo-gradient Particle Swarm Optimization Algorithm Applies To Solve Transmission Expansion Planning Problem

In the PSO algorithm, the variables control each of positive element that are defined as follows:

$$V_d = [V_{gld}, \dots, V_{gld}, T_{ld}, \dots, T_{Nld}, Q_{cld}, \dots, Q_{cNd}]^T \quad (24)$$

d = 1,…,NP

For each upper and lower limit of velocity is determined on the upper and lower limit of its position:

$$v_{d,max} = R.(x_{d,max} - x_{d,min}) \quad (25)$$

$$V_{dmin} = -V_{dmax} \quad (26)$$

Where: R is the limiting coefficient for the velocity element which is usually chosen in [0,1; 0,25].

Both positions and velocities are not initialized to their limits that they determined:

$$x_d^0 = x_{d,min} + rand_3 . (x_{d,max} - x_{d,min}) \quad (27)$$

$$v_d^0 = v_{d,min} + rand_4 . (v_{d,max} - v_{d,min}) \quad (28)$$

Where : $rand_3$ and $rand_4$ are random values in [0,1]. During the iterations, after they are recalculated in each iteration, the positive velocity of the elements always adjustes within their limits as follows:

$$v_d^{new} = \min\{v_{d,max}, \max(v_{d,min}, v_d)\} \quad (29)$$

$$x_d^{new} = \min\{x_{d,max}, \max(x_{d,min}, x_d)\} \quad (30)$$

Minimun appropriate functions are based on the objective function, variable dependents are included reactive generation power, and load node voltage and line power are defined as follows:

$$\min F = min\, CostX_i^k = \sum_{p=0}^{np+1} \frac{\left[\sum_{j=1}^{npr} IC_j K_{ij}^p + OC_{pi}\right]}{(1+ir)^p} + \sum_{y=1}^{5} a_y \quad (31)$$

$$\min f = \sum c_k . Pg_k + G \sum PNS_k \quad (32)$$

Where: α_y is penalty that it is stopped the power supply

After determining the parameters of the grid to use for the PSO algorithm and selecting random initial values that can accelerate convergence. The first values are determined randomly. Then the TEP problem uses PGPSO as follows.

The optimal reactive power dispatch algorithm uses PGPSO:

Step 1: Parameters choose for PGPSO including total number NP elements, number maximum repetitions, c_1, c_2, maximum velocity coefficient R, penalty coefficient.

Step 2: the initial random value of the NP elements choose for the control variables within their limits, including the initial position x_{id} represents the state variables and vid velocity (27), (28) . In d = 1, ..., NP.

Step 3: In each element, the calculable value of the dependent variable bases on the power calculation using Matpower toolbox 4.1 and estimates the appropriate function Fpbest by equation (31), (32). The best value decides for the whole of the function Fgbest = min (Fpbest).

Step 4: Initialize Xpbest1 = X_i^0 at the forward X_i and Xgbest to the best accordant element between all the Xgbest_1 elements.

Step 5: The initial pseudo-gradient associates with the elements to the zero position. Initial times k = 1.

Step 6: The new velocity recalculates and updates each of positive element using equation (11), (13). Note the velocity and position of the set elements should be within the upper and lower limits by Equation (29), (30).

Step 7: The power distribution problem solves by the Matpower toolbox that bases on the new positive value of each accordant element.

Step 8: The appropriate function F recalculates for each element with the new abtainable position using the objective function F (31), (32). The F value compares with the previous iteration to achieve the most suitable function and to store in Fpbestd at the current iteration.

Step 9: Each element chooses the $pbest_{id}^k$ corresponding $F_{pbestid}^k$ position and defines the most appropriate global $F_{pbestid}^k$ and fit $gbest_i^k$ position.

Step 10: The pseudo-gradient recalculates for each element that base on the two accordant points of X_i^k and X_i^{k-1}.

Step 11: If k < k_{max} initializes k = k + 1 back to Step 6, otherwise stops.

The TEP problem ends when between the difference posterior value of the iteration k + 1 and the k_{th} order is less than the allowable $|F_{k+1} - F_k| \leq \varepsilon$.

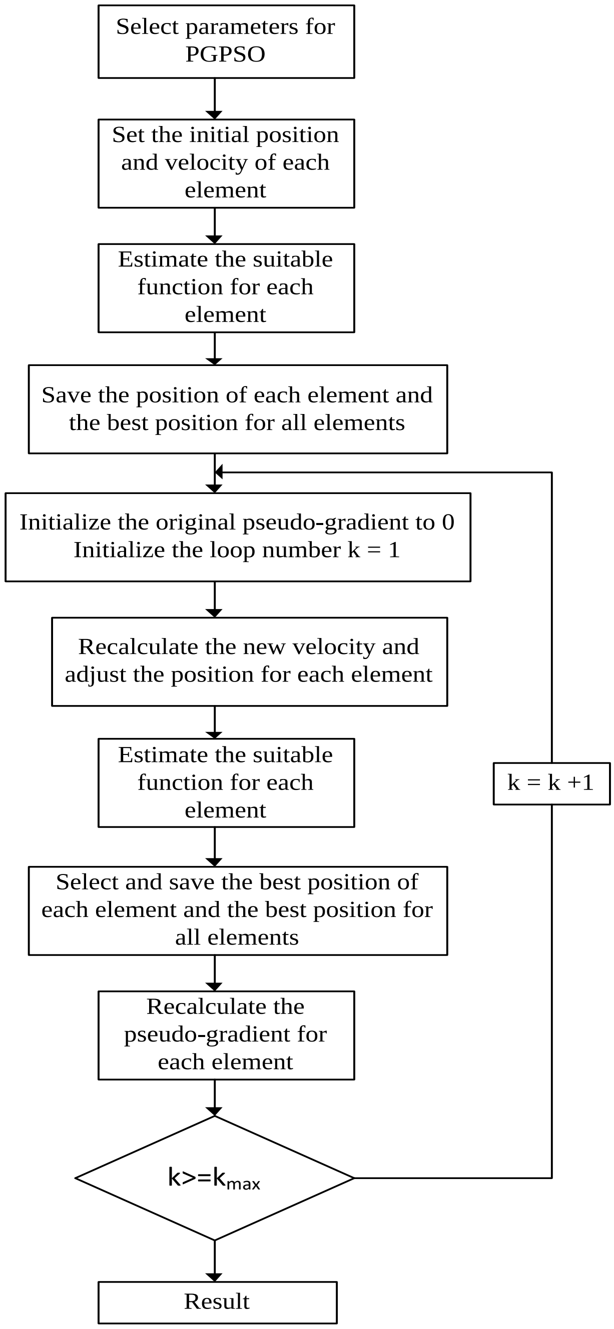

Figure 1. Diagram algorithm of PGPSO algorithm for TEP problem.

4. NUMERCAL RESULTS

4.1. Input parameters

This study uses IEEE power system 30-nodes that validate and compare the objective functions with force conditions to compare some other artificial intelligence methods. In this way, the fast convergence and efficiency of PGPSO can be seen. The results of the PSO-TVIW, the PSO-TVAC, the PSO methods are compared with the PGPSO method to show the optimal PGPSO method.

Table 1: Basic parameters of the PGPSO method

Method	**PGPSO**	**PSO**	**PSO – TVAC**	**PSO - TVIW**
w_{max}	-	-	-	0.9
w_{min}	-	-	-	0.4
c_1, c_2	2.05	2.05	-	2
c_{1i}, c_{2f}	-	-	2.5	-
c_{1f}, c_{2i}	-	-	0.2	-
R	0.15	0.15	0.15	0.15

The IEEE power system 30-nodes is shown in Figure 2. consists of 6 generation nodes, 24 load nodes and 41 branches. The generations are connected to 1, 2, 13, 22, 23, 27 nodes. The number elements of the PGPSO method in this case is 60.

Table 2. Parameter branches of the IEEE 30 node network

Line	**From bus**	**To bus**	**Line impedance (p.u.)**		**Half line charging susceptance (p.u.)**	**MVA rating**
			Resistance	**Reactance**		
1	1	2	0.02	0.06	0.03	130
2	1	3	0.05	0.2	0.02	130
3	2	4	0.06	0.18	0.02	65
4	2	5	0.05	0.02	0	130
5	2	6	0.06	0.18	0.02	65
6	3	4	0.01	0.04	0	130
7	4	6	0.01	0.04	0	90
8	4	12	0	0.23	0	65
9	5	7	0.03	0.08	0	130
10	6	7	0.03	0.08	0	130
11	6	8	0.01	0.09	0	32
12	6	9	0	0.21	0	65
13	6	10	0	0.56	0	32
14	6	28	0.07	0.06	0.01	32
15	8	28	0.06	0.2	0.02	32
16	9	11	0	0.21	0	65
17	9	10	0	0.11	0	65
18	10	20	0.09	0.21	0	32
19	10	17	0.03	0.09	0	32
20	10	21	0.03	0.08	0	32
21	10	22	0.07	0.15	0	32
22	12	13	0	0.14	0	65
23	12	14	0.12	0.26	0	32
24	12	15	0.07	0.13	0	32
25	12	16	0.01	0.12	0	32
26	14	15	0.22	0.12	0	16
27	15	18	0.11	0.22	0	16
28	15	23	0.1	0.21	0	16
29	16	17	0.08	0.19	0	16
30	18	19	0.06	0.13	0	16
31	19	20	0.03	0.07	0	32
32	21	22	0.01	0.22	0	32
33	22	24	0.11	0.18	0	16
34	23	24	0.13	0.27	0	16
35	24	25	0.19	0.33	0	16
36	25	26	0.25	0.38	0	16
37	25	27	0.11	0.22	0	16
38	27	29	0.22	0.4	0	16
39	27	30	0.32	0.6	0	16
40	28	27	0	0.4	0	65
41	29	30	0.24	0.45	0	16

Table 3. The power and generation cost of generators

Generator number	**p_{min} (MW)**	**p_{max} (MW)**	**a_i ($/(MWhr)^2)**	**b_i ($/MWhr)**	**c_i ($/hr)**
G_1	0	80	0.00375	2	0
G_2	0	80	0.0175	1.75	0
G_3	0	50	0.0625	1	0
G_4	0	55	0.00834	3.25	0
G_5	0	30	0.025	3	0
G_6	0	40	0.025	3	0

Table 4. Parameter nodes of IEEE 30-node network

Bus	Bus voltage		Generation		Load		Reactive power limits	
	Mag. (p.u.)	Phase angle (degree)	Real power (MW)	Reac. power (MVar)	Real power (MW)	Reac. power (MVar)	Q_{min} (MVar)	Q_{max} (MVar)
1	1	0	0	0	24.963	-4.638	-20	150
2	1	0	21.7	12.7	60.97	27.677	-20	60
3	1	0	2.4	1.2	0	0	0	0
4	1	0	7.6	1.6	0	0	0	0
5	1	0	0	0	0	0	0	0
6	1	0	0	0	0	0	0	0
7	1	0	22.8	10.9	0	0	0	0
8	1	0	30	30	0	0	0	0
9	1	0	0	0	0	0	0	0
10	1	0	5.919	2	0	0	0	0
11	1	0	0	0	0	0	0	0
12	1	0	11.2	7.5	0	0	0	0
13	1	0	0	0	37	13.949	-15	44.7
14	1	0	6.2	1.6	0	0	0	0
15	1	0	8.2	2.5	0	0	0	0
16	1	0	3.5	1.8	0	0	0	0
17	1	0	9	5.8	0	0	0	0
18	1	0	3.2	0.9	0	0	0	0
19	1	0	9.5	3.4	0	0	0	0
20	1	0	2.2	0.7	0	0	0	0
21	1	0	19.669	11.2	0	0	0	0
22	1	0	0	0	31.59	40.34	-15	62.5
23	1	0	3.2	1.6	22.2	8.13	-10	40
24	1	0	15	6.7	0	0	0	0
25	1	0	1	0	0	0	0	0
26	1	0	3.5	2.3	0	0	0	0
27	1	0	0	0	28.91	10.97	-15	48.7
28	1	0	0	0	0	0	0	0
29	1	0	3.659	0.9	0	0	0	0
30	1	0	12	1.9	0	0	0	0

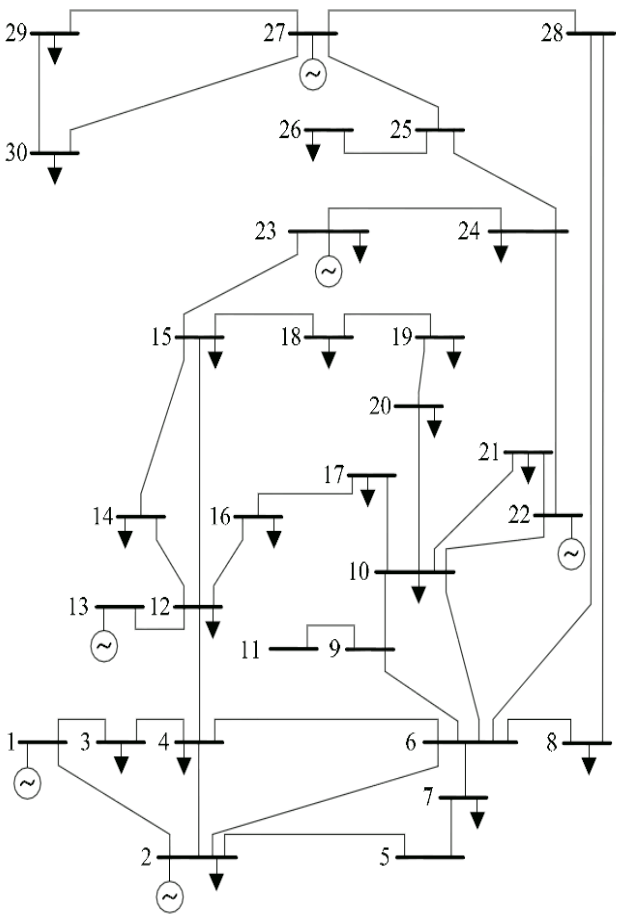

Figure 2. IEEE power system 30-nodes

4.2. Simulation Results

Matlab simulation results extend IEEE 30-nodes by the PGPSO method with number 60 elements, and the number iterations are 20. The calculating time is 35.75 seconds.

Table 5. Simulation results of IEEE 30 nodes through simulation

	Before adding a new line	After adding a new line
Optimal solution	-	49 (2-7) ; 52 (2-10)
Power loss	2443,8031 kW	1899,8603 kW
Decrease rate %		22,258%

If we build two lines in 2-7, 2-10 branches and power distributions of generation according to table 6 , we will obtain the lowest power loss value and all the constraints of the problem will satisfy.

Table 6. Distributable power generator and generation cost. With a, b, c coefficient costs are given in Table 3.

Node	Before adding a new line			After adding a new line		
	Power generation		Generation cost	Power generation		Generation cost
	P (MW)	Q (Mvar)		P (MW)	Q (Mvar)	
1	25.97	-1	54.46915338	25.43	-4.18	53.28506838
2	60.97	32	171.7509658	60.97	-18.7	171.7509658
3	0	0	0	0	0	0

4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
11	0	0	0	0	0	0
12	0	0	0	0	0	0
13	37	11.35	122.5625	37	8.38	122.5625
14	0	0	0	0	0	0
15	0	0	0	0	0	0
16	0	0	0	0	0	0
17	0	0	0	0	0	0
18	0	0	0	0	0	0
19	0	0	0	0	0	0
20	0	0	0	0	0	0
21	0	0	0	0	0	0
22	21.59	39.57	74.05500835	21.59	6.16	74.05500835
23	19.2	7.95	58.5216	19.2	5.77	58.5216
24	0	0	0	0	0	0
25	0	0	0	0	0	0
26	0	0	0	0	0	0
27	26.91	10.54	82.54037025	26.91	8.98	82.54037025
28	0	0	0	0	0	0
29	0	0	0	0	0	0
30	0	0	0	0	0	0
Total	191.64	100.41	563.8995977	191.1	6.41	562.7155127

The PGPSO results for IEEE 30 nodes are compared with other PSO methods that are configured the computer with the same 30 loops

Table 7. The PGPSO results for IEEE 30 nodes.

Method	PGPSO	PSO	PSO – TVAC	PSO - TVIW
New construction line	2-7; 2-10	2-7; 2-10	2-7; 2-10	2-7; 2-10
A number of minimum loops deposit convergence results	6	7	6	7
Calculating times (s)	52,28	52,46	54,16	51,47

The PGPSO results obtain power system that the objective function chooses new construction lines for optimizing power losses, and improving voltage are given in Table 5, 6, Fig 2. Calculating power distribution and power loss results on the branches. The results are compared to the conventional PSO-TVIW, PSOTVAC, PSO methods of convergence rate and calculating time reprogrammed on the same computer. When 4 algorithms are running on the same computer, the PGPSO results convergence with the best calculating time. From objective results bring about comparatively accurate results, after about 10 loops, these methods converge with precision (inaccuracy $\leq 10^{-5}$) and calculated a little time.

5. CONSLUSION

PGPSO method solves transmission expansion planning. Algorithm has been successful in optimal points with fast convergence speed. This study applies to solve only IEEE 30 nodes, but the method presented is not constrained by number nodes or more complex problems. Therefore, the algorithm can be applied in power system with a larger number of nodes. In the future, PGPSO method will be applied to formulate the multi-objective transmission expansion planning with optimal investment, optimal operating costs and loss optimal power loss that create reactive TEP problems.

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APPENDIX

Table: Power distribution and power loss on branch of IEEE - 30 nodes

Branch	From bus	To bus	From Bus Injection		To Bus Injection		Loss	
			P (MW)	Q (Mvar)	P (MW)	Q (Mvar)	P (MW)	Q (Mvar)
1	1	2	14.13	-6.14	-14.09	3.27	0.044	0.13
2	1	3	11.3	1.96	-11.23	-3.68	0.068	0.26
3	2	4	9.73	3.25	-9.66	-5.03	0.068	0.19
4	3	4	8.83	2.48	-8.82	-2.44	0.009	0.03
5	2	6	7.29	1.42	-7.26	-3.28	0.029	0.12

6	2	6	12.71	4.48	-12.59	-6.1	0.115	0.34
7	4	6	15.66	6.82	-15.63	-6.7	0.03	0.12
8	5	7	7.26	3.47	-7.22	-4.36	0.035	0.08
9	6	7	0.29	-1.18	-0.29	0.21	0	0
10	6	8	24.6	24.81	-24.47	-24.31	0.126	0.51
11	6	9	3.16	-6.23	-3.16	6.34	0	0.11
12	6	10	1.8	-3.56	-1.8	3.65	0	0.09
13	9	11	0	0	0	0	0	0
14	9	10	3.16	-6.34	-3.16	6.39	0	0.06
15	4	12	-4.78	-0.95	4.78	1.01	0	0.06
16	12	13	-37	-6.37	37	8.38	0	2.01
17	12	14	5.1	1.03	-5.06	-0.96	0.033	0.07
18	12	15	8.27	-0.64	-8.22	0.74	0.049	0.09
19	12	16	7.66	-2.53	-7.6	2.66	0.06	0.13
20	14	15	-1.14	-0.64	1.14	0.64	0.004	0
21	16	17	4.1	-4.46	-4.07	4.53	0.03	0.07
22	15	18	8.15	-1.05	-8.08	1.2	0.077	0.15
23	18	19	4.88	-2.1	-4.86	2.14	0.018	0.04
24	19	20	-4.64	-5.54	4.66	5.58	0.016	0.04
25	10	20	6.94	6.46	-6.86	-6.28	0.08	0.19
26	10	17	4.97	10.44	-4.93	-10.33	0.04	0.11
27	10	21	-1.5	8.54	1.52	-8.49	0.022	0.05
28	10	22	-3.14	3.52	3.15	-3.49	0.015	0.03
29	21	22	-19.02	-2.71	19.06	2.79	0.037	0.07
30	15	23	-9.28	-2.84	9.38	3.03	0.097	0.19
31	22	24	-0.62	6.86	0.668	-6.77	0.057	0.09
32	23	24	6.62	1.14	-6.57	-1.02	0.059	0.12
33	24	25	-2.81	1.13	2.83	-1.1	0.018	0.03
34	25	26	3.55	2.37	-3.5	-2.3	0.046	0.07
35	25	27	-6.38	-1.27	6.42	1.36	0.047	0.09
36	28	27	-7.19	-3.98	7.19	4.23	0	0.28
37	27	29	6.17	1.68	-6.08	-1.51	0.01	0.17
38	27	30	7.12	1.67	-6.95	-1.35	0.171	0.32
39	29	30	3.68	0.61	-3.65	-0.55	0.035	0.07
40	8	28	-5.53	-5.69	5.57	3.9	0.034	0.11
41	6	28	-1.62	-1.05	1.62	0.08	0.001	0
42	2	7	15.43	5.2	-15.29	-6.75	0.138	0.41
43	2	10	8.21	-49.01	-8.11	-41	0.1	0.26

Pseudo-Gradient Integrated in Particle Swarm Optimization for Solving Security Constrained Optimal Power Flow Problem

Quy Truong Xuan, Dieu Vo Ngoc, and Huu Tinh Tran

Abstract**—** *This paper presents a proposed method of PSO using navigated pseudo-gradient and constriction coefficients to approach the optimum of SCOPF problem, which minimize the operating cost while satisfying the security constraints of system at normal condition and single line outage. The proposed method was tested on IEEE system 6, 39 and 118 bus to evaluate how it deal with the fitness function by the severity index related to power flow limitation and generator priority index that provide prior data of generation to operate and secure.*

Keywords**— Constriction coefficients, Pseudo-gradient, Security constrained Optimal Power Flow (SCOPF), Generator Priority Index (GI)**

1. INTRODUCTION

Optimal Power Flow (OPF) is one of the most concerned problems in power system planning or operating, determines optimum operating state of the system considering the constraints of the other control variables such as voltage levels, power and reactive power flow limit. The full model of OPF is complex economically, electrically and computationally, contains both linear and nonlinear parts. The optimized function normally is economic that requires multiple nonlinear of pricing. For electrical satisfactions the power flow is considered under AC which generates additional nonlinearities. Computationally, the optimization has nonconvexities: continuous functions and binary variables, causing the problem is more difficult. One of the first sufficient surveys about OPF was presented by H. H. Happ and K. A. Wigrau [1], like bibliography of economic-security scenario in power system. At that time, the OPF was researched under classical Lagrangian techniques that were reported in Carpentair survery [2].

The other conventional methods were used to solve this problem is Linear Programming (LP) [3], Newton-Raphson (NR) [4], Quadratic Programming (QP) [5], Non Linear Programming (NLP) [6] and Interior Point (IP) [7] with their improvement. However, due to the expansion in dimension of OPF because of more detail of generations, which were regarding more real situation such as Valve Point loading effect [8], thermal unit [9], the added elements on power grid like FACTS [10] or energy storage [11], the generators priority (related to unit commitment problem) [12] or simply, because of the surveyed system. The conventional methods, which were easily trapped in local optima or failed dealing with discrete or binary variables, were occupied by meta-heuristic methods based on the simulation of worldview acting and trend. Genetic Algorithm (GA) [13], Differential Evolution (DE) [14] Particle Swarm Optimization (PSO) [15], Ant Colony Optimization (ACO) [16] are some famous methods which have been enhanced in various ways in the other research. A comprehensive survey for computational intelligence method could be found in [16].

Security constrained Optimal Power Flow (SCOPF) is expanded from OPF by adding faulted scenarios to based OPF problem to evaluate the endurance of power system while optimizing the objective function. By adding security constraints and full evaluation for all scenarios, SCOPF is more complex than OPF. A review of some SCOPF research was introduced in [17]. The recent SCOPF works are inspired by the above listed meta-heuristic methods: PSO with reconstructions in [18] or PSO with Hybrid (HPSO) in [19], DE in [20], which solve the full single islanding outage, not only consider some of prior cases. The proposed research in this paper is an improvement of PSO (IPSO) causing rapidly converged. The results were tested on some popular IEEEE systems for comparison. Due to the dimension of SCOPF problem, decomposition of size is also presented.

2. OPF AND SCOPF FORMULATION

2.1 Formulation

Both OPF and SCOPF is built based on mathematics concepts

$$\begin{cases} F(x,u)\,\text{min} \\ g(x,u)=0 \\ h(x,u)\le 0 \end{cases} \tag{1}$$

x is the vector of controlled variables: the voltage and phase of load, reactive power of the generators and real power of slack bus.

$$x=(\mathrm{P}_{G1},\theta_2,\ldots,\theta_N,V_{L1},\ldots,V_{LNL},Q_{g1},\ldots,Q_{gng})^T \tag{2}$$

u is the vector of controlling variables: voltage of generators, tap-setting of transformers and the reactive

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power at compensator.

$$u = (V_{g1}...V_{gng}, T_1...T_{NT}, Q_{c1}...Q_{cNc})^T \tag{3}$$

$F(x,u)$ called the objective function whose output is the minimum value we want. $g(x,u)$ and $h(x,u)$ is called equality and inequality constraints respectively.

In OPF formulation, the objective function normally is the fuel cost which is formulated as follows:

$$F(x,u) = \sum_{n=1}^{NG} FC_n(P_n) \tag{4}$$

where $FC^n(P^n)$ is the fuel cost function of generator n^{th}. NG is the total of generators in power system. In recent research, the fuel cost function is modeled by a quadratic function:

$$FC_n(P_n) = a_n + b_n P_n + c_n P_n^2 \tag{5}$$

where a_i, b_i, c_i is the fuel cost coefficients.

$g(x,u)$ is the equality constraints, it follows the power conservation law:

$$P_G = P_D + P_L \tag{6}$$

This equation can be spread:

$$\begin{cases} P_{gi} - P_{di} - v_i \sum v_j (g_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) = 0 \\ Q_{gi} - Q_{di} - v_i \sum v_j (g_{ij} \sin\theta_{ij} + B_{ij} \cos\theta_{ij}) = 0 \end{cases} \tag{7}$$

with g_{ij} and B_{ij} is the transfer conductance and susceptance between bus i and bus j.

P_{di}, Q_{di} is the real and reactive power outputs of generating at bus i and P_{gi}, Q_{gi} is the real and reactive power outputs of generating unit i.

These equality constraints is checked by running Power Flow by Newton-Raphson method in Matlab.

$h(x,u)$ is the inequality constraints, it is the running limitations of variables.

a) The power limitations:

$$\begin{cases} P_{gslack}^{\min} \le P_{gslack} \le P_{gslack}^{\max} \\ Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} \end{cases} \tag{8}$$

b) The voltage limitations:

$$V_i^{\min} \le V_i \le V_i^{\max} \tag{9}$$

c) Transformers tap-settings constraints:

$$T_i^{\min} \le T_i \le T_i^{\max} \tag{10}$$

d) The compensator capacitor limitations:

$$Q_c^{\min} \le Q_c \le Q_c^{\max} \tag{11}$$

e) The power flow limitations:

$$S_i \le S_i^{\max} \tag{12}$$

with S_i is the maximum power flow between bus i and bus j.

$$S_i = \max\{|S_{ij}|, |S_{ji}|\} \tag{13}$$

To check the inequality constraint, we use the Static Square method. The objective function F not only have the output value but also adding the penalty function $k\sum(f(x_i))^2$ with:

$$f(x) = \begin{cases} 0 & x_{\min} \le x_i \le x_{\max} \\ (x_i - x_{\max})^2 & x_i > x_{\max} \\ (x_{\min} - x_i)^2 & x_i < x_{\min} \end{cases} \tag{14}$$

So with the penalty function, the objective function will be rewritten as:

$$F_p = F + k\sum_{i=1}^{NG} f(Q_{gi}) + k\sum_{i=1}^{NPQ} f(V_i) + k\sum_{i=1}^{NI} f(S_i) \tag{15}$$

For SCOPF formulation, $g(x,u)$ and $h(x,u)$ will be added the equality constraints for each n-1 contingency (NL is the total of contingencies), respectively.

$$g(x,u) = \begin{cases} g(x,u) & OPF \\ g_l(x,u) & l = 1:NL \end{cases} \tag{16}$$

$$h(x,u) = \begin{cases} h(x,u) & OPF \\ h_l(x,u) & l = 1:NL \end{cases} \tag{17}$$

2.2 Decomposed SCOPF (DSCOPF)

From (16) and (17), the SCOPF problem could be formulated by:

$$\begin{cases} F(x_0, u_0) \\ g_l(x_l, u_0) = 0 \quad l = 1,2,3 \ldots NL \\ h_l(x_l, u_0) \le 0 \end{cases} \tag{18}$$

So, assuming that the computation time of OPF is T, which is normally proportional to the square of number of constraints N: $T = N^2$ (if assuming the proportional coefficient is 1).

By adding NL constraints to the problem, each constraint has also N constraints, the total constraints would be: $N + NL \times N = (NL+1)N$, $T = (NL+1)^2N^2$. It could be observed that if we do fully contingencies (for example, 177 single line outage contingencies with IEEE – 118 bus system), we would spend around 261 hours (around 11 days) if assuming spending 30s for OPF problem.

DSCOPF was first applied by Li et al in [21] to reduce the size and computed time of SCOPF. The flow chart of this algorithm is shown in the figure [1].

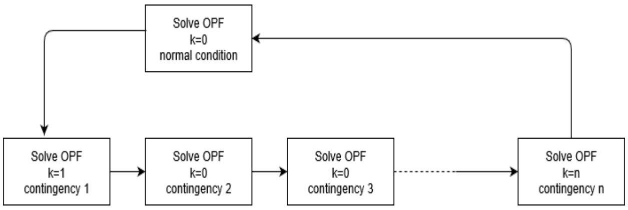

Fig. 1 DSCOPF Flow Chart.

DSCOPF was first applied by Li et al in [21] to reduce

the size and computed time of SCOPF. The formulation is divided into master (OPF) (19) and contingencies (20).

$$\begin{cases} F(x_0, u_0) \\ g_0(x_0, u_0) = 0 \\ h_0(x_0, u_0) \le 0 \end{cases} \tag{19}$$

$$\begin{cases} \varepsilon_k \\ g_k(x_k{}^0, u_0 + \varepsilon_k) = 0 \\ h_k(x_k{}^0, u_0 + \varepsilon_k) \le 0 \end{cases} \tag{20}$$

The flow chart of this algorithm is shown in the figure [1]. The problem is first solved in OPF (master solution). If any contingencies need additional constraints that requires re-dispatch, the k=n contingencies will be re-generated and solved by Bender cut [22]. From recent research, it needs only about 2-3 cycles to re-dispatch. Assuming n is the total cycles in a SCOPF running, the computation time will be reduced to n(NL+1). For the problem with IEEE-118 bus, the time will be reduced to 4 hours.

2.3 Evaluation index

To evaluate the relative severity of a contingency to line overload, the severity index (SI) is used for ranking contingency [23]:

$$SI = \sum_{i=1}^{NL} \left(\frac{S_{L,i}}{S_{L,i}^{\max}} \right)^2 \tag{21}$$

In some cases, the results do not perform the effect of a line to the faulted line. For example, if the line i-th is outage, 9 lines is overload with only 5% per line, the SI will be approximately 10. It is bigger than a line overload at 3 times. However, most of line could be overload from 10-15% so the first case is acceptable but it's not for the second case because of security. If we could add the limit of overload to the maximum capacity of each line, it could be exactly performed.

In addition, due to the different in fuel cost coefficients of each generator, the optimal power flow should have the priority in which, the generator with low cost coefficients should be operated at high and vice versa. For example, with the test case 3 in Results, the cost of 1st generator is 75.14 $ at minimum capacity (10 MW), which is over a half of generator at bus 26th at maximum capacity (133.47 $ at 414 MW). Intuitively, we would like to run the second choice instead of first choice. The generator priority index is presented to evaluate the trend of generators dispatch:

$$GI_i = \frac{|P_i - P_{i\min}|}{|P_{i\max} - P_{i\min}|} \tag{22}$$

$\mathrm{GI_i}$ is in [0,1]. If $\mathrm{GI_i}$ is nearly 0, the $\mathrm{i^{th}}$ generators is not prior to operate and vice versa. A good results will be prior with the generators that have low coefficients.

3. PSO FOR SOLVING PROBLEM

PSO is one of the most applied meta-heuristic algorithm based on the searching of particles in a tremendous space. A particle upgrade to its own best by itself (pbest) or by looking to the nearby particle (gbest). The velocity and position for each particle at each iteration is:

$$v_{\mathrm{id}}^{(k+1)} = wv_{\mathrm{id}}^{(k)} + c_1 \times rand_1 \times (pbest_{\mathrm{id}}^{(k)} - x_{\mathrm{id}}^{(k)}) + c_2 \times rand_2 \times (pbest_{\mathrm{d}}^{(k)} - x_{\mathrm{id}}^{(k)}) \tag{23}$$

$$x_{\mathrm{id}}^{(k+1)} = x_{\mathrm{id}}^{(k)} + v_{\mathrm{id}}^{(k+1)} \tag{24}$$

Various enhanced PSO was applied in OPF or similar problem. The basis of most of enhancement is to create "trend" or "signal" to direct the fitness function to the optimal point faster. In [24], the sign function was used to evaluate the derivatives of the nonconvex function. With the mathematics extrema survey, derivatives is used for defining trend of function at the nearby range. If the derivatives is 0, the function is in local optima, which define a "bad region" of solution. We need to follow to another navigation. In [25], an acceleration is added to boost the converged process of OPF problem. This was proved usefully with the velocity of fitness function, but could be trap in local optima. The idea for research on this paper is a combination of two ways of approaching: direction and acceleration. Like riding a bike, to be in destination rapidly, we need a good one with high accelerator but same priority is the right direction. The proposed method is built with the factor below.

Velocity of function:

$$v_{\mathrm{id}}^{(k+1)} = C \times \begin{bmatrix} \omega v_{\mathrm{id}}^{(k)} + c_1 \times rand_1 \times (pbest_{\mathrm{id}}^{(k)} - x_{\mathrm{id}}^{(k)}) \\ +c_2 \times rand_2 \times (pbest_{\mathrm{d}}^{(k)} - x_{\mathrm{id}}^{(k)}) \end{bmatrix} \tag{25}$$

where: $C = \dfrac{2}{\left|2 - \varphi - \sqrt{\varphi^2 - 4\varphi}\right|}$ in which $\varphi = c_1 + c_2, \varphi > 4$ (26)

and C is the constriction factor, which can be found in [26]. With the constriction factor, the fitness function is not only boosted by accelerator as [25] but also narrow the searching space. It look like a planet is constricting to a black hole, increasing the density of potential solution.

Updated position of particle:

$$\mathrm{x_{id}^{(k+1)}} = \begin{cases} \mathrm{x_{id}^{(k)}} + \delta(\mathrm{x_{id}^{(k+1)}}) \times |\mathrm{v_{id}^{(k+1)}}|, \textit{ which } \mathrm{g_p}(\mathrm{x_{id}^{(k+1)}}) \neq 0 \\ \mathrm{x_{id}^{(k)}} + \mathrm{v_{id}^{(k)}} \end{cases} \tag{27}$$

The fitness function will be added penalty functions of all security constraints:

$$\begin{aligned} FT &= F(x,u) + K_p(P_{gi} - P_{gi}^{\lim})^2 \\ &+ K_q \sum_{i=1}^{N_g} (Q_{gi} - Q_{gi}^{\lim})^2 + K_v \sum_{i=1}^{N_d} (V_{li} - V_{li}^{\lim})^2 \\ &+ K_s \sum_{l=1}^{N_l} (S_l - S_{l,\max})^2 + K_{q-sc} \sum_{R=1}^{N_o} \sum_{i=1}^{N_g} (Q_{gi} - Q_{gi}^{\lim R})^2 \\ &+ K_{v-sc} \sum_{R=1}^{N_o} \sum_{i=1}^{N_d} (V_{li} - V_{li}^{\lim R})^2 + K_{s-sc} \sum_{R=1}^{N_o} \sum_{l=1}^{N_l} (S_l - S_{l,\max\mathrm{R}})^2 \end{aligned} \tag{28}$$

The procedure to solve a SCOPF problem via IPSO follows the steps below:

Step 1: Generate IPSO parameters (population, iteration, accelerator, constriction factor…)

Step 2: Input initial position and velocity including security constraints

Step 3: Calculate fitness function and select the minimum value

Step 4: Record the best value of each particle and global best

Step 5: Input initial pseudo-gradient = 0 at k=1

Step 6: Calculate the new velocity and update each particle new position

Step 7: Re-calculate power flow

Step 8: Calculate the new fitness function for each particle, compare with the previous iteration

Step 9: Define new best local and global value

Step 10: Calculate the new pseudo-gradient for the last 2 positions

Step 11: If out of iteration, stop, else return to the step 6.

The flow chart of IPSO-SCOPF is shown in the figure 2.

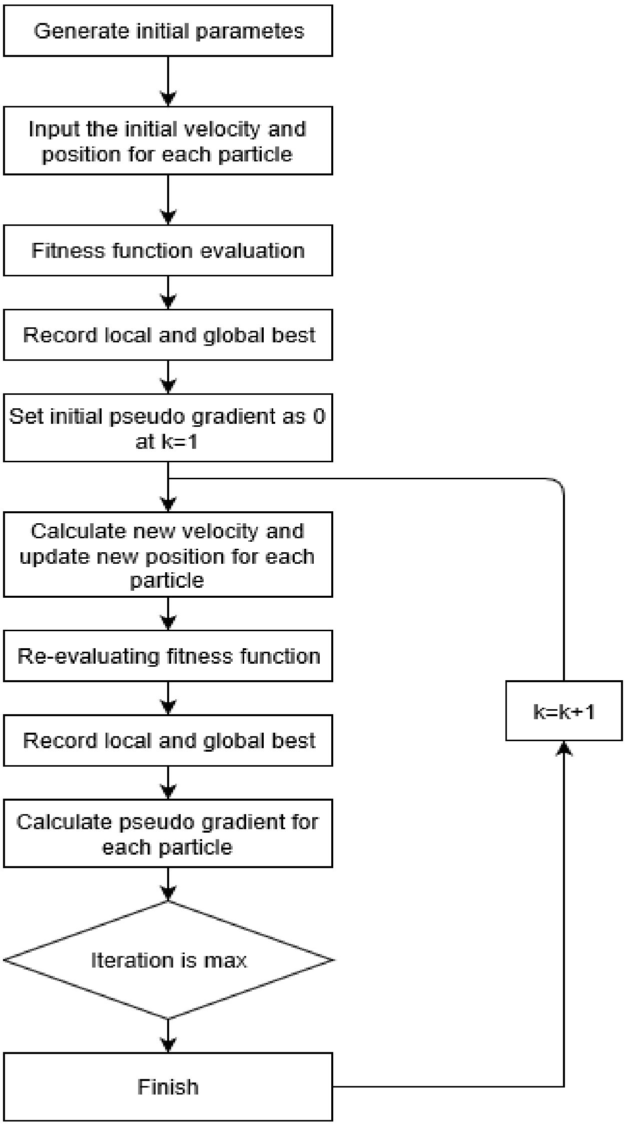

Figure 2 Flow chart of solving SCOPF by IPSO.

4. RESULTS

The proposed IPSO is experimented for IEEE 6 bus, "New England System" 39 bus and IEEE 118 bus by MATLAB 2012, comparing with the recent results.

4.1 *Test case 1*: IEEE 6 bus [27]

The network diagram is shown in figure 3. This system has 3 generators and 11 transmission lines and the data could be found in [30]. The case will be run out in the Optimal Power Flow (or base case) and the single landing outline case in which, line 2-3 is faulted.

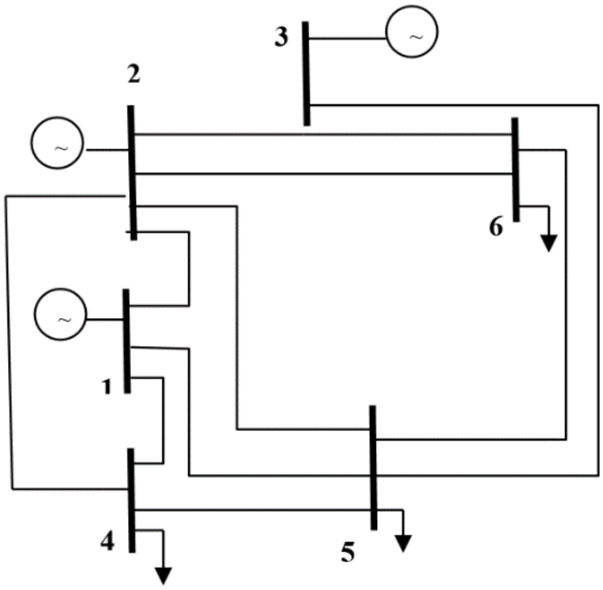

Fig. 3. Network diagram of IEEE 6-bus test system.

Due to the small size of the system, IPSO would be in the local optimum if selecting high population. From the test, NP = 3 and the iteration is 200. The fitness function is recorded in the figure 4.

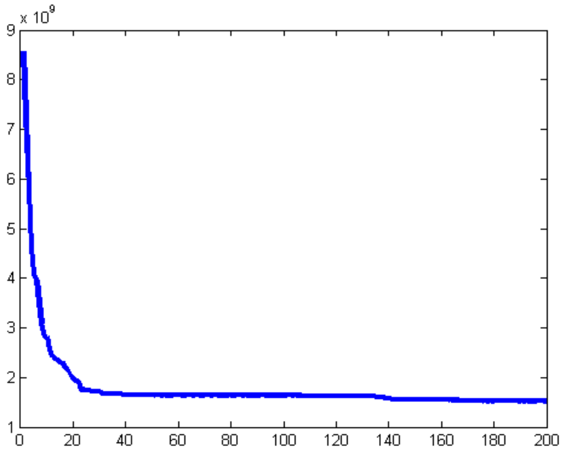

Fig. 4 Fitness function for OPF test case 1.

The fitness function is fast laid in the optimum in the around 20 iterations. Although some noise, it is no need to increase the iteration.

A difference with [27] is that, M. R. Babu and D. Harini use only the DC Power Flow for the base case. Consequently, the operating cost is only compared by the value, not focusing on the limit of line power flow The table 1 shows the related value to the OPF results.

For demonstration SCOPF, a single line 2-3 outage would be considered here. Results of operating cost, Generator data (compare with the AC Power Flow case in [27] could be found in the Table 2.

Table 1 Results of IPSO in test case 1 OPF

Parameters	LP	IPSO
Operating cost ($/h)	3169.6	3149.3
P_{G1}	100.26	99.84
P_{G2}	61.61	61.55
P_{G3}	54.99	56.65

Table 2 Results of IPSO in test case 1 SCOPF

Parameters	LP [27]	IPSO
Operating cost ($/h)	3171.9	3149.3
P_{G1}	100	103.70
P_{G2}	56.79	51.13
P_{G3}	60.07	63.23

Observing from results, due to different in solving way (DC Power Flow versus AC Power Flow), the results in IPSO is better in operating cost. However, IPSO cause the overload on line 1-4, 1-5, 2-4, 2-5, 2-6, 3-5 and 3-6. The severity index is 9.2533, higher than 2.0774 of LP [27]. It would be recognized that the fitness function could not adapt to the constraints because of the population of IPSO. If it's high, the results would be in local optimum (checked with 50 species and the results is same for 500 trial run). When it's low (as the number is 3 in the experiment), the initial is not enough to trend the results. Initial value would affect a lot to the results because the 6-bus system is small and less variables to search.

4.2 *Test case 2*: "New England System" 39 bus [28]

The network diagram could be found in figure [5]. It has 10 generators and 46 transmission lines and the data of system could be found in [28] (only a mistake with a and c coefficients to each other). The results would be compared with SCOPF case 2 in [28] (double outage lines: 6-11 and 12-13).

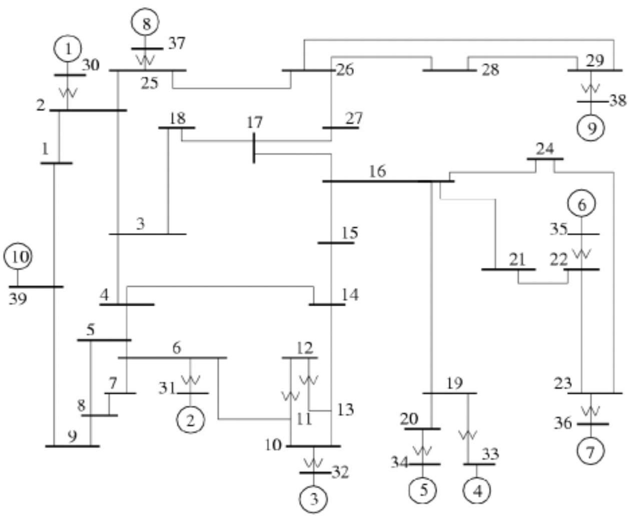

Fig. 5. Network diagram New England System 39 bus

In this test case, the selected population is 30 and running in 1000 iterations. Fitness function is performed in figure [6] by the logarit of axis X due to the large number of iteration. The optimal operating cost and power loss is shown in the table 3.

Table 3. Operating cost and power loss of test case 2

Parameters	IP [28]	IPSO
Operating cost ($/h)	42147.06	42097.43
Power loss (MW)	47.64	35.19

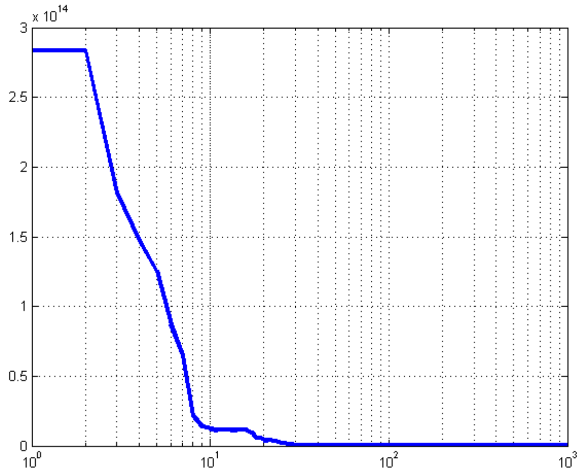

Fig. 6. Fitness function of IPSO in test case 2.

As can see from the figure [6], the fitness function converged fast (at 38th iteration) with a short range of noise. The operating cost is significantly better than IP method with the power loss is less and no violations in power flow, voltage or reactive power at generators. This shows the advance of IPSO for dealing with IEEE 39 bus with enough population for searching.

The value of controlling variable is shown in Table 4.

Table 4 Value of control variables in test case 2

Variables	IP	IPSO	Variables	IP	IPSO
P_{G30}	716.68	558.92	V_{G30}	1.032	1.000
P_{G31}	646	606.07	V_{G31}	1.006	0.950
P_{G32}	564.31	602.37	V_{G32}	0.969	1.014
P_{G33}	639.50	594.10	V_{G33}	1.002	1.019
P_{G34}	508	508.00	V_{G34}	1.008	1.050
P_{G35}	644.66	598.20	V_{G35}	1.005	1.047
P_{G36}	580	580.00	V_{G36}	1.05	1.043
P_{G37}	564	564.00	V_{G37}	1.03	1.021
P_{G38}	674.68	577.76	V_{G38}	1.02	0.990
P_{G39}	764.04	1100.00	V_{G39}	1.047	1.012

Because of the same coefficients for all generators, we do not discuss about generator priority index.

4.3 Test case 3: IEEE 118 bus [29]

Network diagram of IEEE 118 bus is shown in figure 7. It has 54 generators, 186 branches with 130 controlling variables (53 power of generators (except slack bus), 54 voltage of generators, 8 tap generators, 1 phase shifter and 14 compensators). Due to the severing in line data, there is some difference in generator cost in recent research. IPSO is used in OPF and full SCOPF for evaluating.

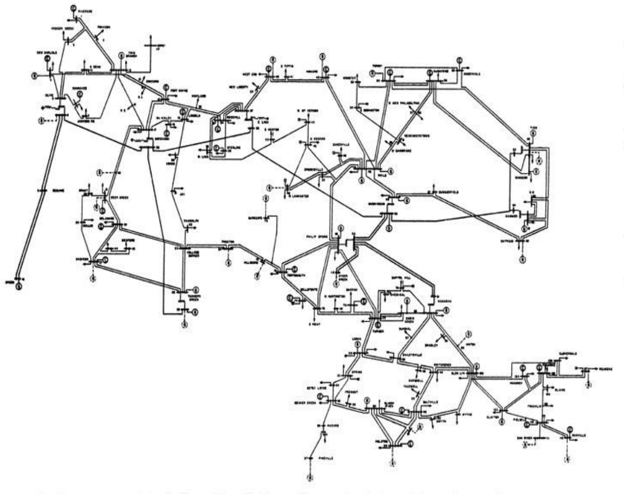

Fig. 7. Network diagram of IEEE 118 bus.

4.4 IEEE 118 bus Optimal Power Flow (Data reference: [31])

The selected population is 50 and iteration is 5000 (same iteration with [31]). The results of operating cost of IPSO and the other method as shown in table 6 with the fitness function performed in figure 8.

Table 5 Results of fuel cost in test case 3 - OPF

Method	**Operating cost ($/h)**
GA [31]	8278.9
EPGA [32]	6902.0
EPGA II [32]	6347.2
HPSO [19]	5691.4
IPSO	4682.8
GSA [29]	4131.8
RDEA [33]	3780.9
IBF [34]	3776.3
EGSA [29]	3776.2
Bi-level [29]	3774.6

The fitness function is converged at 457th iteration (better than GA which is converged at 2033). The result is higher than SAs method but significantly better than GAs method. Due to the difference in coefficient of different generators, the results of GI index is shown with comparing the data by GA and EPGA II in Figure 9.

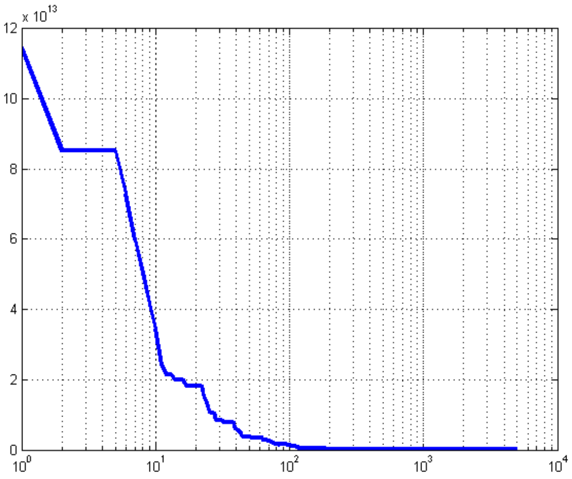

Fig. 8. Fitness function of IPSO in test case 3 – OPF.

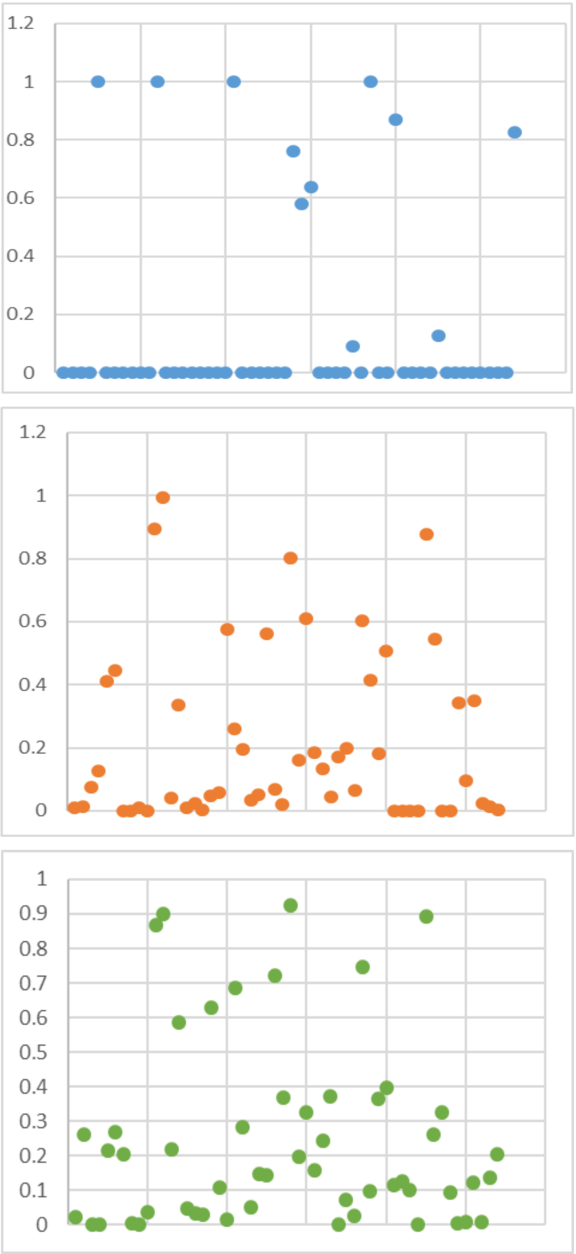

Fig. 9. GI index performance for OPF solution of a) IPSO; b) EPGA II; c) GA respectively

Regarding that, most of generators in IPSO has reached the priority selection is 0 or approximately 0. Vice versa, few of generators had run full or nearly full of capacity (Generators: 10th, 26th, 49th, 80th). In [31] and [32], GA is chaotic, in which, no generators reach the peak and a few of generators reach the minimum value of power. EPGA is better but the most popular value is around 0.1. Because GA generates off-spring, it has no direction to approach and only try to decrease fitness function over the time. PSO with Pseudo gradient lead the fitness function to a way and keep the way of results.

Particularly, 34/35 Type 1 Generators in IPSO has the priority is less than 0.1, only the final generators (116th) has run with the capacity is 84.4. The reason for concerning these 35 generators is IEEE 118 bus model history. From [35], IEEE 118 bus used to have 19 generators and 35 generators is added recently. In MATPOWER [36], the operating value of 35 generators is initially set at 0 with the high coefficients at operating cost. It would be an idea for doing this OPF for IEEE 118 bus regarding unit commitment.

4.5 IEEE 118 bus SCOPF (Data reference: [29])

IEEE 118 bus has 186 branches, but due to the security, only 177 single lines could be outage except {8-9, 9-10, 71-73, 85-86, 86-87, 110-111, 110-112, 68-116, 12-117}. Although using DSCOPF, the number of calculation for checking constraints and running power flow still be large. Consequently, we choose the number of population is same with OPF but the iteration is drop to 1000. The value of operating cost and fitness function performance is shown in table 7 and figure 10 respectively.

The results of SCOPF is nearly equal to IBF, which is upgrade of BF, higher than EGSA and Bi-level but the difference is too much. The fitness function of SCOPF for IEEE 118 bus using IPSO is converged at around iteration 300th. It is said "nearly" feasible because the power flow violations only occur at single line outage: 3rd, 4th and 81th with the severity index is 1.0253, 1.3681, and 1.0204 respectively. Because of saving memory and time to run the simulation, the data of power flow for each single line outage case is not recorded, but, due to the formula of severity index and knowing that, the severity index of an assuming line is caused by 176 other line, this severity index is too small and can be passed out (if the index is less than 2, only one line is violated at each case with the over ratio is 17% for the maximum severity index case).

Table 6. Results of SCOPF 118 bus test system in test case 3

Method	**Operating cost ($/h)**
BF [34]	6376.1 – infeasible
IPSO	5680.7 – infeasible (nearly)
IBF [34]	5571.5 – feasible
EGSA [29]	5438.4 – feasible
Bi-level [29]	4893.6 – feasible

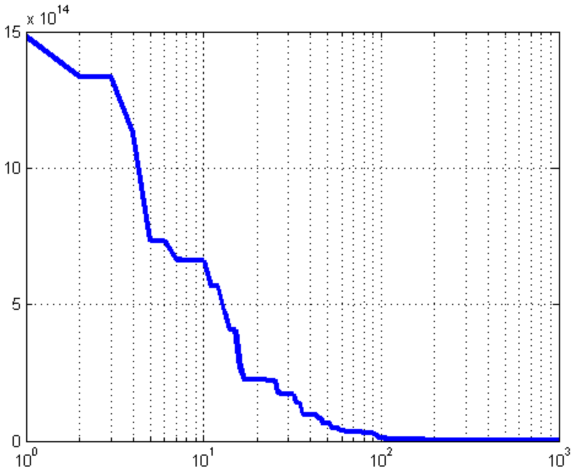

Fig. 10 Fitness function performed by IPSO for SCOPF with test case 3

The priority selection of this case is shown in figure 11. Observing that, the trend of SCOPF is not too different to OPF case. There are 6 generators run full or nearly full (26th, 49th, 65th, 76th, 100th and 116th). 10th and 80th generator, which run full in OPF case, only run about half of capacity in SCOPF because of security constraints. Alternatively, 76th and 100th generators, which is run a few in OPF, has run full of capacity. But, the trend is still unchanged. 33/35 Type 1 generators (except two a.m generators) has reached or nearly minimum of capacity.

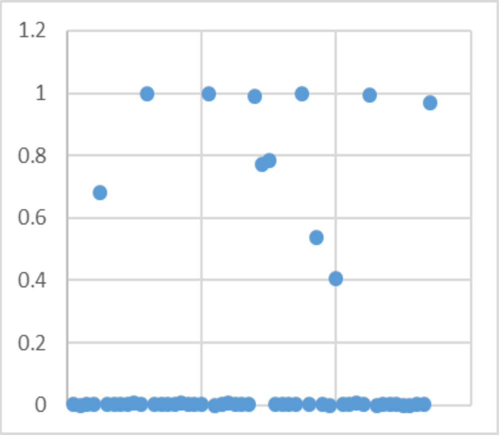

Fig. 11. GI index performance IPSO for SCOPF in test case. 3.

5. CONCLUSION

This paper has introduced a new method of PSO (IPSO) based on the current PSO method to solve the full SCOPF with high dimension. This has the good characteristics of the origin with rapid convergence and do not be in local optima. When comparing with other recent results, it spends more iterations and one-way method instead hybrid one. Regarding to generator priority or severity index, it provides basis for expand OPF or SCOPF problem, regarding to selected security or unit commitment. For upgrading method, PSO should be mixed with the other approach like generating offspring: GA, DE or adding more detailed researching parameters like BBO, Tabu search, to reduce the iteration if the system is bigger but maintain the rapid movement and right direction that IPSO had.

ACKNOWLEDGMENT

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A Hybrid Particle Swarm Optimization and Differential Evolution for Security-Constrained Optimal Power Flow

Dieu Ngoc Vo, Tri Phuoc Nguyen, Tinh Huu Tran, and Hai Minh Nguyen

Abstract— *The security-constrained optimal power flow (SCOPF) has a significant role in the power system operation. However, the SCOPF is a large-scale and complex problem and thus it is a real challenge for solution methods. This paper proposes a hybrid particle swarm optimization and differential evolution (HPSO-DE) method for solving the SCOPF problem. The proposed HPSO-DE is a new developed method to employ the advantages of the PSO and DE methods. The proposed method has been tested on the IEEE 30-bus system for the normal and outage cases with different objective functions of quadratic and valve loading effects. The obtained results from the proposed method have been verified via comparing to those from PSO, DE, and other methods in the literature. The result comparisons have indicated that proposed HPSO-DE method is very effective for dealing with the large-scale and complex SCOPF problem.*

Keywords— **Differential evolution, hybrid particle swarm optimization and differential evolution, security-constrained optimal power flow.**

1. INTRODUCTION

The general problem of the optimal power flow (OPF) was first introduced by Carpentier in 1962 [1]. The OPF is to find the optimum settings of control variables such as generator active power outputs and voltages, shunt capacitors/reactors, and transformer tap changing settings in order to minimize total generation cost while satisfying the generator and system constraints [2]. OPF is a complex and large-dimension optimization problem because there are many adjustable variables. In addition, the problems of OPF have a nonlinear characteristic due to the nonlinear objective function and constraints. With the challenges of OPF problem brought, over the last half-century many researchers have contributed a lot in terms of effort and time to figure out approaches solve this problem. These methods can be classified into three groups including conventional, intelligent and hybrid approaches.

Several conventional methods have been implemented for solving the OPF problem such as Newton-based techniques [3], linear programming [4], non-linear programming [5], quadratic programming [6], and interior point methods [7]. In general, these methods are effective in solving the simple OPF problems with some theoretical assumptions such as convex, continuous, and differential objective functions [8]. However, the OPF problem is an optimization problem with non-convex, non-continuous, and non-differentiable objective functions. Consequently, conventional methods may be difficult to cope with such problems. Therefore, the determination of a global optimal solution is not possible with conventional methods.

As a result, artificial intelligence-based methods have emerged as one of the alternative options for solving the OPF problem with obtained promising results. The main solution methods include genetic algorithm (GA) [9], evolutionary programming (EP) [10], artificial neural network (ANN) [11], bacteria foraging algorithm (BFA) [12], tabu search (TS) [13], and simulated annealing (SA) [14]. In addition to the single methods, hybrid methods have been also widely implemented for solving the OPF problem such as a hybrid shuffle frog leaping algorithm and simulated annealing (SFLA-SA) method [15] as well as a hybrid modified imperialist competitive algorithm and teaching learning algorithm (MICA-TLA) [16].

In addition, the OPF can also include constraints that represent operation of the system after contingency outages. These security constraints allow the OPF to dispatch the system in a defensive manner. That is, the OPF now forces the system to be operated so that if a contingency happened, the resulting voltages and flows would still be within limit. This special type of OPF which is called a security-constrained OPF (SCOPF) is a vital research area for industrials to enhance the reliability of practical power systems. Recently, a series of articles have been proposed for solving this problem. In [17], the authors have presented a self-organizing hierarchical particle swarm optimization with time-varying acceleration coeffcients (SOHPSO-TVAC) for dealing with the SCOPF problem. Xu et al [18] have introduced a contingency partitioning approach for preventive-corrective security-constrained optimal power flow computation. A modified bacteria foraging algorithm

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(MBFA) has been proposed in [19] to determine the optimal operating conditions with the aim of minimizing the cost of wind-thermal generation system and reducing the active power loss while maintaining a voltage secure operation. In [20], the authors have proposed a fuzzy harmony search algorithm (FHSA) to find out the optimal solution for OPF problem for power system security enhancement. In [21], the SCOPF problem has been solved using adaptive flower pollination algorithm (APFPA). The results reported were promising and encouraging for further research in this direction.

In this paper, a hybrid particle swarm optimization and differential evolution (HPSO-DE) [22] is proposed for solving the SCOPF problem with non-smooth cost functions such as quadratic cost function and fuel cost with valve point effects. The proposed approach combines differential information obtained by DE with the memory information extracted by PSO to create the promising solution. The proposed method is tested on IEEE 30-bus system and their results are compared with conventional PSO, conventional DE and other methods available in the literature.

2. PROBLEM FORMULATION

The SCOPF problem is a very large-scale and nonlinear optimization problem with many complex constraints. The objective of the SCOPF problem is to minimize the total cost of thermal units for both normal and outage cases satisfying different constraints. In this research, various constraints are considered such as the power balance at buses, real and reactive power limits at generation buses, voltage limits at generation and load buses, reactive power limits of switchable capacitor banks, transformer tap setting limits, and transmission limits of transmission lines.

The general mathematical model of the SCOPF problem is formulated as follows:

$$\text{Min } F(X, U) \tag{1}$$

subject to the equality and inequality constraints of the normal case:

$$g(X, U) = 0 \tag{2}$$

$$h(X, U) \le 0 \tag{3}$$

and the equality and inequality constraints of the outage case:

$$g(X^S, U^S) = 0 \tag{4}$$

$$h(X^S, U^S) \le 0 \tag{5}$$

where F is the fuel cost function of thermal units, X is the vector of control variables, U is the vector of state variables, $g(.)$ is the set of equality constraints, $h(.)$ is the set of the inequality constraints, and S is the set of outage lines.

The detailed model of the problem is formulated as follows.

$$\text{Min } F = \sum_{i=1}^{N_g} F_i(P_{gi}) \tag{6}$$

where $F_i(P_{gi})$ is the fuel cost function of thermal unit i represented whether by a quadratic function:

$$F_i(P_{gi}) = a_i + b_i P_{gi} + c_i P_{gi}^2 \tag{7}$$

or by a sinusoidal function added to the quadratic function representing valve point loading effects:

$$F_i(P_{gi}) = a_i + b_i P_{gi} + c_i P_{gi}^2 + | e_i \times \sin(f_i \times (P_{gi,\min} - P_{gi})) | \tag{8}$$

in which, P_{gi} is the power output of thermal unit i, $P_{gi,min}$ is the minimum power output of thermal unit i, and a_i, b_i, c_i, e_i and f_i are fuel cost coefficients.

The equality and inequality constraints for the normal and outage cases as follows.

- *Power balance constraints*: The real and reactive power should be balanced at each bus in the system.

$$P_{gi} - P_{di} = |V_i| \sum_{j=1}^{N_b} |Y_{ij}| |V_j| \cos(\delta_i - \delta_j - \theta_{ij}), \; i = 1, 2, \dots, N_b \tag{9}$$

$$Q_{gi} - Q_{di} = |V_i| \sum_{j=1}^{N_b} |Y_{ij}| |V_j| \sin(\delta_i - \delta_j - \theta_{ij}), \; i = 1, 2, \dots, N_b \tag{10}$$

where Q_{gi} is the reactive power output of thermal unit i, P_{di} and Q_{di} are the active and reactive power demands at bus i, respectively, N_b is the number of buses in the system, $|V_i|\angle\delta_i$ and $|V_j|\angle\delta_j$ are the voltage at buses i and j, respectively, and $|Y_{ij}|\angle\theta_{ij}$ is an element in Y_{bus} matrix related to buses i and j.

- *Power generation limits*: The active and reactive power outputs of thermal units are limited between their upper and lower boundaries.

$$P_{gi,\min} \le P_{gi} \le P_{gi,\max}, \; i = 1, 2, \dots, N_g \tag{11}$$

$$Q_{gi,\min} \le Q_{gi} \le Q_{gi,\max}, , \; i = 1, 2, \dots, N_g \tag{12}$$

where $P_{gi,max}$ is the maximum active power output of thermal unit i, $Q_{gi,min}$ and $Q_{gi,max}$ are the minimum and maximum reactive power outputs of thermal unit i, and N_g is the number of generators.

- *Bus voltage limits*: The voltage at both generation and load buses should be within their upper and lower limits.

$$V_{gi,\min} \le V_{gi} \le V_{gi,\max}, \; i = 1, 2, \dots, N_g \tag{13}$$

$$V_{li,\min} \le V_{li} \le V_{li,\max}, , \; i = 1, 2, \dots, N_d \tag{14}$$

where V_{gi} is the voltage at generation bus i, V_{li} is the voltage at load bus i, $V_{gi,max}$ and $V_{gi,min}$ are the maximum and minimum voltages at generation bus i, respectively, $V_{li,max}$ and $V_{li,min}$ are the maximum and minimum voltages at load bus i, respectively, and N_d is the number of load buses.

- *Switchable capacitor capacity limits*: The capacity of switchable capacitor banks should be in their upper and lower limits.

$$Q_{ci,\min} \le Q_{ci} \le Q_{ci,\max},\ i = 1, 2, ..., N_c \tag{15}$$

where Q_{ci} is the capacity of switchable capacitor bank at bus i, $Q_{ci,max}$ and $Q_{ci,min}$ are the maximum and minimum capacity of switchable capacitor banks, and N_c is the number of buses with switchable capacitor bank.

- *Transformer tap setting limits*: The tap changer of transformers should be limited in their lower and upper boundaries.

$$T_{k,\min} \le T_k \le T_{k,\max},\ k = 1, 2, ..., N_t \tag{16}$$

where T_k is the value of the tap changer of transformer k, $T_{k,min}$ and $T_{k,max}$ are the minimum and maximum values of tap changer of transformer i, respectively, and N_t is the number of transformers with tap changer.

- *Transmission line limits*: The power flow in transmission lines is limited by their capacity.

$$S_l \le S_{l,\max},\ l = 1, 2, ..., N_l \tag{17}$$

where S_l is the power flow in line l, $S_{l,max}$ is maximum capacity of transmission line l, and N_l is the number of transmission lines.

In this problem, the vector of control variables is represented as follows:

$$\begin{aligned} X = [&P_{g2}, P_{g3}, ..., P_{gN_g}, V_{g1}, V_{g2}, ..., V_{gN_g}, \\ &Q_{c1}, Q_{c2}, ..., Q_{N_c}, T_1, T_2, ..., T_{N_t}] \end{aligned} \tag{18}$$

in which, P_{g1} is selected as the slack bus of the system.

The vector of state variables is represented by:

$$U = [Q_{g1}, Q_{g2}, ..., Q_{gN_g}, V_{l1}, V_{l2}, ..., V_{lN_l}, S_{l1}, S_{l2}, ..., S_{N_l}] \tag{19}$$

3. IMPLEMENTATION OF HPSO-DE FOR SOLVING THE PROBLEM

3.1 Particle Swarm Optimization Method

The particle swarm optimization (PSO) method was developed in 1995 [23] for simulating the social behavior and a swarm representing the movement organization of a bird flock or a fish school. The general advantages of PSO are simple and easy for implementation. In the PSO algorithm, a population (swarm) includes particles (individuals) typically represented by two parameters of position and velocity, where a particle moves from a position to another with a certain velocity. However, to guarantee the intake of swarm, the position and velocity of each particle should not exceed their limits.

Suppose that a population with N_p particles and each particle d (d = 1, 2, ..., N_p) has a position X_{id} and velocity V_{id} where i = 1, 2, ..., N is the dimension of the particle's position. The velocity and position of each particle are calculated and updated as follows:

$$\begin{aligned} V_{id}^{(n)} = \omega V_{id}^{(n-1)} &+ c_1 * rand_3 * (Pbest_d - X_{id}^{(n-1)}) \\ &+ c_2 * rand_4 * (Gbest - X_{id}^{(n-1)}) \end{aligned} \tag{10}$$

$$X_{id}^{(n)} = X_{id}^{(n-1)} + V_{id}^{(n-1)} \tag{11}$$

where ω the inertia weight parameter, n is the current number of iterations, c_1 is the individual cognitive factor, c_2 is the social cognitive factor, $Pbest_d$ is the best position of individual d up to iteration n-1, and $Gbest$ is the best position among positions of particles.

To enhance the convergence and stability of PSO, a constriction factor has been introduced in 1999 by Clerc and Kennedy [24]. For the PSO with constriction factor, the velocity of particles is calculated by:

$$V_{id}^{(n)} = \chi \begin{pmatrix} \omega V_{id}^{(n-1)} + c_1 * rand_3 * (Pbest_d - X_{id}^{(n-1)}) \\ + c_2 * rand_4 * (Gbest - X_{id}^{(n-1)} \end{pmatrix} \tag{12}$$

where the constriction factor χ is determined by:

$$\chi = \frac{2}{\left|2 - \varphi - \sqrt{\varphi^2 - 4\varphi}\right|},\ \varphi = c_1 + c_2,\ \varphi > 4 \tag{13}$$

On the other hand, the position updating for particles can be enhanced by using a concept of pseudo-gradient [25]. The pseudo-gradient is effective for determining the best search direction in the search space of non-differentiable problems. The pseudo-gradient at a point $g_p(x)$ for the minimization a function $f(x)$ is determined as follows [26]. Suppose that a point x_k in the search space moves to another x_l, there are possibilities for the this movement:

i) If $f(x_k) \ge f(x_l)$: It indicates that the direction is right and the particle should continue to move on this way. Therefore, the pseudo-gradient at point l is nonzero, e.g. $g_p(x_l) \neq 0$.

ii) If $f(x_k) \ge f(x_l)$: It indicates that the direction is not right and the particle should not continue to move on this way. Consequently, the pseudo-gradient at point l is zero, e.g. $g_p(x_l) = 0$.

The new position of particles is updated using the pseudo-gradient as follows:

$$X_{id}^{(n)} = \begin{cases} X_{id}^{(n-1)} + g_p(X_{id}^{(n)}) * |V_{id}^{(n)}| & \text{if } g_p(X_{id}^{(n)}) \neq 0 \\ X_{id}^{(n-1)} + V_{id}^{(n)} & \text{otherwise} \end{cases} \tag{14}$$

Therefore, the PSO method in this paper is the pseudo-gradient based PSO with constriction factor is used in the proposed hybrid method.

3.2 Differential Evolution Method

The DE is a simple population based method developed by Storn and Price in 1995 [27] for solving optimization problems. In the DE method, there are three stages for generating a new population including mutation, crossover, and selection.

- *Mutation stage*: In this stage, a base individual is added by a difference of other individuals to create a new one so that the search space can be explored. In this research, the DE/rand/1 mutation scheme is used as follows:

$$X_{id}^{'(n)} = X_{r1d}^{(n)} + F*(X_{r2d}^{(n)} - X_{r3d}^{(n)}) \tag{15}$$

where *r1*, *r2*, and *r3* are differently random numbers in the range [1,N_p], $X_{id}^{'(n)}$ is the new individual created by other random individuals, and *F* is the mutation in the range [0,1].

- *Crossover stage*: When the mutation stage is completed, this stage, which is also referred as the recombination stage, is activated to increase the diversity of the perturbed individuals. This stage is to mix the successful individuals from the previous generation with the newly created individuals. A trial individual is created as:

$$X_{id}^{''(n)} = \begin{cases} X_{id}^{'(n)} & \text{if } rand_5 \le CR \text{ or } d = D_{rand} \\ X_{id}^{(n)} & otherwise \end{cases} \tag{16}$$

where $rand_5$ is a random number in [0,1], D_{rand} is a random number in the range [1,N_p], and CR is the crossover rate in the range [0,1].

- *Selection stage*: This stage is to decide that an individual is whether selected for the next generation or not by comparing the best individuals from the previous generation with the new created ones in the current generation. The better individuals will be selected for the next generation.

3.3. The Hybrid PSO and DE Method

Although both PSO and DE are efficient methods for dealing with optimization problems, they suffer difficulties when dealing with large-scale and complex problems. The PSO method can quickly obtain the optimal solution for a problem but the quality of the obtained solution is not good for the complex problems. In the contrary, the DE can easily find a high quality solution of a problem but it may not find the feasible solution the complex problems. In this research, a hybrid PSO and DE is proposed to utilize the advantages of the both methods for dealing with complex problem such as the security-constrained optimal power flow problem.

The main stages of the hybrid method are for solving an optimization problem as follows:

- *Initialization*: A population with *Np* individuals is randomly initialized in their limits like many other meta-heuristic search methods.
- *Creation of the first new generation*: In this stage, a new generation is created based on the initialized one via the mechanism of the PSO and the new generated population will be evaluated to select the best ones for the next generation.
- *Creation of the second new generation*: A new generation is created in this stage using the mechanism of the DE method and the newly created population is also evaluated to select the best individuals for the next iteration.

3.4. Implementation of the Hybrid PSO and DE Method

The overall procedure of the proposed HPSO-DE applied for solving the SCOPF problem includes the steps as follows:

Step 1: Select the control parameters such as the population size N_p, maximum number of iterations N_{max}, cognitive coefficients c_1 and c_2, mutation fact *F*, and crossover ratio *CR*.

Step 2: Initialize a population

A population with N_p individuals where each individual contains the vector of control variables is represented by

$$X_{id} = [P_{g2d}, P_{g3d}, ..., P_{gN_gd}, V_{g1d}, V_{g2d}, ..., V_{gN_gd}, Q_{c1d}, Q_{c2d}, ..., Q_{N_cd}, T_{1d}, T_{2d}, ..., T_{N_td}]$$

, in which $i = 1, 2, ..., N$ with $N = 2*N_g + N_c + N_d - 1$ and $d = 1, 2, ..., N_p$.

Each individual in the population is initialized by:

$$X_{id}^{(0)} = X_{id}^{\min} + rand_1 * (X_{id}^{\max} - X_{id}^{\min}) \tag{17}$$

On the other hand, the velocity of each individual in the population is also initialized as:

$$V_{id}^{(0)} = V_{id}^{\min} + rand_2 * (V_{id}^{\max} - V_{id}^{\min}) \tag{18}$$

where X_{id}^{max} and X_{id}^{min} are the upper and lower limits of individual *d*, respectively, V_{id}^{max} and V_{id}^{min} are the upper and lower velocity limits of individual *d*, respectively, and $rand_1$ and $rand_2$ are the random numbers in the range [0,1].

The maximum and minimum velocities of individuals are calculated by:

$$V_{id}^{\max} = R * (X_{id}^{\max} - X_{id}^{\min}) \tag{19}$$

$$V_{id}^{\min} = -V_{id}^{\max} \tag{20}$$

where *R* is the scale factor for the velocity.

Step 3: Evaluation of the initialized population:

Solve the power flow problem for the initialized population and the obtained result is used to evaluate the quality of the initialized population via calculating the fitness function including the outage case:

$$
\begin{aligned}
FT_d^{(0)} &= \sum_{i=1}^{N_g} F_i(P_{gi}) + K_{p0} * (P_{g1} - P_{g1}^{\lim})^2 \\
&+ K_{q0} * \sum_{i=1}^{N_g} (Q_{gi} - Q_{gi}^{\lim})^2 + K_{v0} * \sum_{i=1}^{N_d} (V_{li} - V_{li}^{\lim})^2 \\
&+ K_{s0} * \sum_{l=1}^{N_l} (S_l - S_{l,\max})^2 \\
&+ \sum_{s=1}^{N_o} \left(\begin{aligned} & K_p * (P_{g1} - P_{g1}^{\lim,s}) + K_q * \sum_{i=1}^{N_g} (Q_{gi} - Q_{gi}^{\lim,s})^2 \\ & + K_v * \sum_{i=1}^{N_d} (V_{li} - V_{li}^{\lim,s})^2 + K_s * \sum_{l=1}^{N_l} (S_l - S_{l,\max,s})^2 \end{aligned} \right)
\end{aligned}
\tag{21}
$$

where K_{p0}, K_{q0}, K_{v0}, and K_{s0} are the penalty factors for real power at the slack bus, reactive power at generation buses, voltage at load buses, and power flow in transmission lines the normal case, respectively, K_p, K_q, K_v, and K_s are the penalty factors for the outage case, $P_{g1}^{\lim}$ is the real power limit of the slack generator, $Q_{gi}^{\lim}$ is the reactive power limit at generation buses, $V_{li}^{\lim}$ is the voltage limit at load buses, $P_{g1}^{\lim,s}$ is the real power limit of the slack generator corresponding to the outage line s, $Q_{gi}^{\lim,s}$ is the reactive power limit at generation buses corresponding to the outage line s, $V_{li}^{\lim,s}$ is the voltage limit at load buses corresponding to the outage line s, and N_o is the number of outage lines.

The limits of the state variables including real power at the slack bus, reactive power at generation buses, and voltage at load buses for both normal and outage cases are determined as follows:

$$
X^{\lim} = \begin{cases} X_{\max} & \text{if } X > X_{\max} \\ X_{\min} & \text{if } X < X_{\max} \\ X & \text{otherwise} \end{cases}
\tag{22}
$$

where X represents P_{g1}, Q_{gi}, and V_{li}.

Set the initialized population to the best position of each particle $Pbest_d$ with the corresponding best fitness function FT_d^{best} and the best position among particles in the population is set to *Gbest*.

Set the iteration counter $n = 1$.

Step 4: Calculate a new population:

In this step, the new population is created using the mechanism of PSO. The new velocity of individuals is calculated by using (12). If the new obtained velocity violates its limits, a repairing action is performed as follows:

$$
V_{id}^{(n)} = \begin{cases} V_{id}^{\max} & \text{if } V_{id}^{(n)} > V_{id}^{\max} \\ V_{id}^{\min} & \text{if } V_{id}^{(n)} < V_{id}^{\min} \end{cases}
\tag{23}
$$

The new generation of the population is updated by using (14). If the new position violates its limits, a repairing is carried out:

$$
X_{id}^{(n)} = \begin{cases} X_{id}^{\max} & \text{if } X_{id}^{(n)} > X_{id}^{\max} \\ X_{id}^{\min} & \text{if } X_{id}^{(n)} < X_{id}^{\min} \end{cases}
\tag{24}
$$

Step 5: Evaluation of the first generated population:

Solve the power flow problem for the first new population $X_{id}^{(n)}$ and the obtained result is used to calculate the fitness function $FT_d^{(n)}$ in (21).

Step 6: Mutation:

The second new population $X_{id}^{'(n)}$ in this step is calculated, based on the population $X_{id}^{(n)}$ created from the PSO mechanism, using the mutation process of DE by using (15).

The new position $X_{id}^{'(n)}$ is prepared using (24) if its limits are violated.

Step 7: Crossover:

The crossover process gives new individuals of the population determined by (16).

Step 8: Evaluation of the second generated population:

Solve the power flow problem for the second new population and the obtained result is used to calculate the fitness function $FT''^{(n)}_d$ in (21).

Step 9: Selection:

The selection of the new population based on the first and second new generated populations is described by:

$$
X_{id}^{new(n)} = \begin{cases} X_{id}^{''(n)} & \text{if } FT_d^{''(n)} \le FT_d^{(n)} \\ X_{id}^{(n)} & otherwise \end{cases}
\tag{25}
$$

Update the new fitness function value $FT_d^{new(d)}$ corresponding to $X_{id}^{new(n)}$.

Step 10: Update the best population:

The best position of each particle is updated using the new population and the best stored values given by:

$$
Pbest_d = \begin{cases} X_{id}^{new(n)} & \text{if } FT_d^{new(n)} \le FT_d^{best} \\ Pbest_d & otherwise \end{cases}
\tag{26}
$$

Update the corresponding best fitness function FT_d^{best}. The best position among $Pbest_d$ is set to *Gbest*.

Step 11: Check the sopping criteria:

If $n < N_{max}$, $n = n + 1$ and return to Step 4, Otherwise, stop.

4. NUMERICAL RESULTS

The proposed HPSO-DE has been tested on the IEEE

30-bus system for the two cases where the fuel cost with quadratic function and valve point loading effects are considered for the normal and outage cases. In the outage case, two subcases are considered with 5 and 9 outage lines. The test system has 30 buses, four transformers, 41 transmission lines, and two switchable capacitor banks. For the outage cases, the 5-outage lines include 1, 2, 3, 5, and 7 and the 9-outage lines consist of 1, 2, 4, 5, 7, 33, 35, 37, and 38.

The data of the test system is from [28] with the fuel cost coefficients for quadratic function from [28]. The fuel cost coefficients for valve point loading effects and the transmission line limits are given in Appendix. The lower voltage limit of all buses in the system is set to 0.95 while the upper limit for the slack, generation, and load buses is set to 1.05, 1.10, and 1.05, respectively. The lower and upper limits for tap changer of transformers are set to 0.90 and 1.10, respectively. The lower limit of switchable capacitor banks is set to zero while their upper limit is set to the fixed value in the original data. The lower and upper limits of reactive power at generation buses are selected as in [29]. The power problem in this research is solved by Newton-Raphson method using Matpower [29].

For implementation of the proposed method, the control parameters of the proposed HPSO-DE for the test system are selected based on experiments as follows. The number of population is set to 10, all penalty factors to 10^6, all cognitive factors of PSO to 2.05, the scale factor for velocity of individuals to 0.15, the mutation factor to 0.7, and the crossover rate to 0.5. For the number of iterations, the different number of iterations is used for different test cases. The number is set to 150 for the normal case with quadratic fuel cost function, 200 for the normal case with valve point loading effects, 250 for the cases with 5 and 9 outage lines with quadratic fuel cost function, and 300 for the cases with 5 and 9 outage lines with valve loading effects. The proposed HPSO-DE method is coded in Matlab and each case is performed 50 independent runs to obtain the best solution. Moreover, the PSO and DE methods have also implemented to solve the same cases with HPSO-DE for result comparison. The parameters of PSO and DE are selected similar to the ones in the HPSO-DE method.

4.1 Normal case

For the normal, the proposed HPSO-DE is implemented for solving the OPF problem for the two cases with the objective of quadratic function and valve point loading effects.

4.1.1 Objective with quadratic function

In this case, the only HPSO-DE method is applied to solve the OPF problem with quadratic fuel cost function. The obtained results by the proposed method including best cost, average cost, worst cost, standard deviation, and computational time are given in Table 1. As observed from the table, the average cost closes to the best cost and the standard deviation is rather small. Therefore, the solution quality obtained the proposed method in this case is high.

The obtained result from the proposed HPSO-DE has been compared to that from other methods such as tabu search (TS) [30], evolutionary programming (EP) [31], parallel EP [32], parallel self-adaptive differential evolution with augmented Lagrange multiplier (pSADE_ALM) [33], and PSO methods [34-35]. The total cost obtained by the proposed method is better than that from many other methods except for PSO-TVIW and SOHPSO-TVAC in [6]. The total cost from the proposed method is slightly higher than that from PSO-TVIW and SOHPSO-TVAC due to the voltage limit at the slack bus. The upper voltage limit at the slack bus has an impact on the objective function. For example, the total cost obtained by HPSO-DE in this case is $ 802.2484 with the upper voltage limit at the slack bus set to 1.05 pu while the total cost from the methods from [35] is obtained at the upper voltage limit of the slack of 1.06 pu. The higher upper voltage limit at the slack bus is used, the lower total of thermal units is obtained. In general, the proposed HPSO-DE is effective to find the optimal solution for the OPF problem in the normal case. The optimal solution obtained by the HPSO-DE method fir this case is given in Appendix.

Table 1. Obtained result obtained by HPSO-DE in the normal case with the objective of quadratic fuel cost function

Best cost ($)	802.2484
Average cost ($)	805.8013
Worst cost ($)	840.1040
Standard deviation	8.7117
Avg. CPU time (s)	8.719

Table 2. Result comparison for the normal case with the objective of quadratic fuel cost function

Methods	Best total fuel cost ($)	CPU time (s)
TS [30]	802.29	NA
EP [31]	802.62	NA
Parallel EP$^{\alpha}$ [32]	802.51	5.02
SADE_ALM [33]	802.404	15.934
pSADE_ALM [33]	802.405	17.295
Conventional PSO [34]	802.586	28.208
PSO-TVAC [34]	802.67	11.255
PG-PSO [34]	802.252	11.416
BPSO [35]	803.13	35.15
PSO-TVIW [35]	802.11	33.756
PSO-TVAC [35]	803.56	35.82

SOHPSO-TVAC [35]	802.03	29.43
HPSO-DE	**802.248**	**9.298**

4.1.2 Objective with valve point loading effects

In this case, the valve loading effects are considered in the objective of the problem. However, the DE method cannot find the feasible solution with the selected parameters as the HPSO-DE. Therefore, to obtain a feasible solution for the problem in this case, the population for DE is set to 70. The obtained solutions including the best cost, average cost, the worst cost, standard deviation, and computational time from PSO, DE, and the proposed method are given in Table 3. Among the three methods, the proposed method can obtain the best total cost and the DE provides the worst total cost. For the computational time, the PSO method is faster than the other methods while the DE method takes longer time than the others due to using a large population. The convergence characteristic of HPSO-DE, PSO, and DE methods for this case are shown in Figure 1. As shown in the figure, the proposed method can reach better solution than both PSO and DE after 200 iterations. The optimal solutions obtained by these methods are given in Appendix.

Table 3. Obtained result for the normal case considering objective with valve point loading effects

Method	PSO	ED	HPSO-DE
Best cost ($)	930.3223	970.7400	917.7518
Average cost ($)	974.6577	999.3013	958.5162
Worst cost ($)	1042.9890	1038.7125	1099.4167
Standard deviation	29.1070	14.4135	23.1749
Avg. CPU time (s)	7.750	39.779	11.517

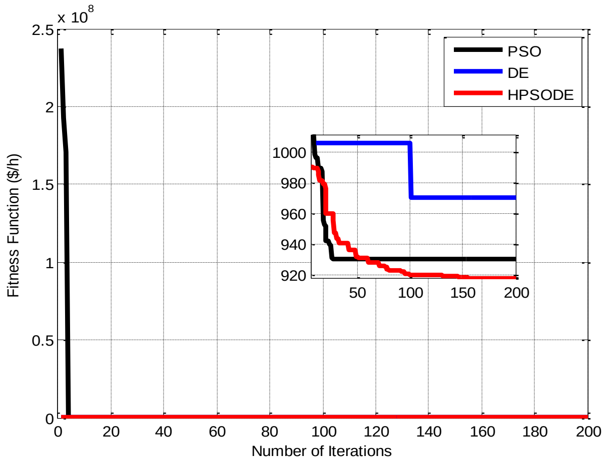

Fig. 1. Convergence characteristics of PSO, DE and HPSO-DE for the normal case with valve point loading effects.

4.2 Outage case

For the outage case, two scenarios are considered including 5 and 9 outage lines in the system for both cases with the objective with quadratic function and valve point loading effects.

4.2.1 Objective with quadratic function

- *The case with 5-outage lines*

The obtained results including the best cost, average cost, the worst cost, standard deviation, and computational time from the HPSO-DE, PSO, and DE methods in this case are given in Table 4. As observed from the table, the HPSO-DE can obtained better cost than the other methods in terms of the best cost, average cost, the worst cost, and standard deviation while the PSO method is faster than the others. The convergence characteristic of these methods for this case is given in Figure 2. As observed, the proposed HPSO-DE and PSO method can reach an approximate solution while the DE method need more iterations but the obtained solution is not good enough compared to HPSO-DE and PSO methods. The optimal solutions obtained by these methods for this case are also given in Appendix.

The best cost from the HPSO-DE, PSO, and DE methods have been compared to those from PSO and DE based methods from the literature as in Table 5. As seen from this table, the proposed method can obtain better total cost than other methods do. The result comparison has verified that the proposed HPSO-DE is effective for dealing with the problem in this case with 5-outage lines.

Table 4. Obtained result for the case of 5-outage lines with the objective of quadratic fuel cost function

Method	PSO	ED	HPSO-DE
Best cost ($)	826.1400	833.6628	825.3571
Average cost ($)	840.5281	877.0613	834.9393
Worst cost ($)	904.3178	936.0727	870.7170
Standard deviation	19.5032	24.1500	14.5300
Avg. CPU time (s)	70.675	469.641	99.638

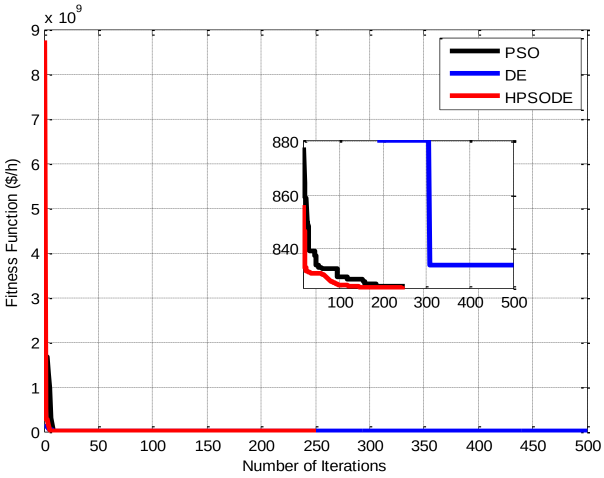

Fig. 2. Convergence characteristics of PSO, DE and HPSO-

DE for the case of 5-outage lines with the objective of quadratic fuel cost function.

Table 5. Result comparison for the case of 5-outage lines with the objective of quadratic fuel cost function

Methods	Best total fuel cost ($)	CPU time (S)
SADE_ALM [33]	826.979	46.896
pSADE_ALM [33]	826.242	119.812
Conventional PSO [34]	827.186	175.245
PSO-TVAC [34]	828.012	130.59
PSO	**826.1400**	**70.675**
DE	**833.6628**	**469.641**
HPSO-DE	**825.3571**	**99.638**

- *The case with 9-outage lines*

For this case, the HPSO-DE and PSO methods can obtain the optimal solution while the DE method cannot find feasible solution due to violating constraints. The obtained solutions including the best cost, average cost, the worst cost, standard deviation, and the computational time from the HPSO-DE and PSO are given in Table 6. The results obtained from the proposed HPSO-DE are all better than those from the PSO method except the computational time, especially the best cost from the proposed method is much better than that from the PSO method. The convergence characteristic of these methods is shown in Figure 3. In this figure, the HPSO-DE method reaches stable after 250 iterations while the PSO can be further improved and DE cannot reach the feasible solution. The optimal solutions by the HPSO-DE, PSO, and DE methods are given in Appendix.

Table 6. Obtained result for the case of 9-outage lines with the objective of quadratic fuel cost function

Method	PSO	HPSO-DE
Best cost ($)	834.3601	825.4352
Average cost ($)	873.4729	849.5369
Worst cost ($)	937.0004	920.6872
Standard deviation	24.9403	26.2689
Avg. CPU time (S)	97.566	144.327

Table 7. Result comparison for the case of 9-outage lines with the objective of quadratic fuel cost function

Methods	Best total fuel cost	CPU time (S)
SADE_ALM [33]	834.547	82.932
pSADE_ALM [33]	826.978	157.401
Conventional PSO [34]	833.504	637.528
PSO-TVAC [34]	837.728	417.145
PG-PSO [34]	825.993	179.574
PSO	**834.3601**	**97.566**
HPSO-DE	**825.4352**	**144.327**

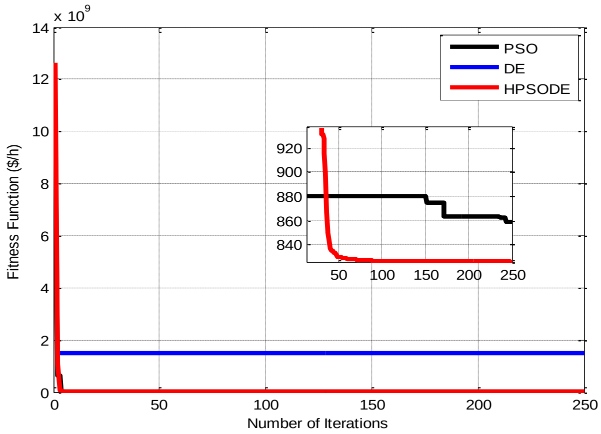

Fig. 3. Convergence characteristics of PSO, DE and HPSO-DE for the case of 9-outage lines with the objective of quadratic fuel cost function

The best cost from the HPSO-DE and PSO methods has been compared to that from other methods such as DE and PSO based methods as given in Table 7. As shown in the table, the total cost from the proposed method is better than the other methods. The result comparison has indicated that the proposed method is very effective for dealing with the problem for the most severity case.

4.2.2 Objective with valve point loading effects

For the case that the objective with valve pint loading effects, the two scenarios with 5 and 9-outage lines are also considered.

- *The case with 5-outage lines*

For dealing with the case of 5-outage lines, the DE needs 500 iterations to find the optimal solution. The results including the best cost, average cost, the worst cost, standard deviation, and computational time obtained by the HPSO-DE, PSO, and DE are given in Table 8. As observed from the table, the proposed HPSO-DE method can obtain better results than other methods for all the best cost, average cost, the worst cost, and standard deviation. For the CPU time, the PSO method is faster than the other methods. The obtained results have indicated that the proposed HPSO-DE can be a very effective method for dealing the complex problem in this case. The convergence characteristic of HPSO-DE, PSO, and DE is given in Figure 4 and the optimal solution obtained by these methods is given in Appendix.

Table 8. Best result of SCOPF in case of 5-outage lines considering objective with valve point loading effects

Method	PSO	ED	HPSO-DE
Best cost ($)	1036.3883	1047.5443	1035.9443
Average cost ($)	1051.0038	1090.9916	1040.5190
Worst cost ($)	1145.2705	1185.9028	1081.6711
Standard deviation	22.6513	31.1450	7.3536
Avg. CPU time (s)	64.796	565.113	117.571

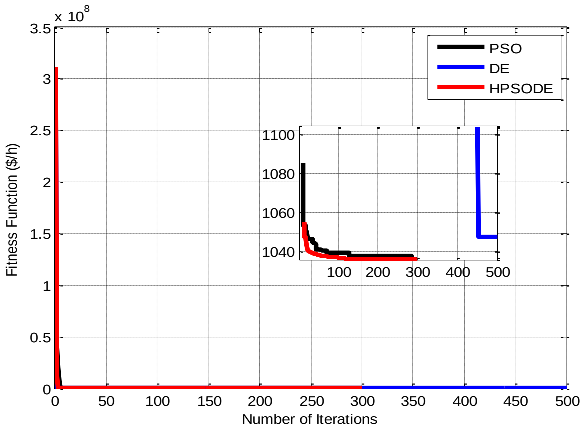

Fig. 4. Convergence characteristics of PSO, DE, and HPSO-DE for the case of 5-outage lines with the objective of valve point loading effects.

- *The case with 9-outage lines*

For dealing with this case, the number of individuals and maximum number of iterations for the DE method are set to 70 and 1500, respectively. However, DE cannot obtain any feasible solution. Therefore, the DE method cannot properly deal with a very complex problem in this case. The results obtained by HPSO-DE and PSO in this case are given in Table 9. For this case, the best cost and average cost from the proposed HPSO-DE are better than those from the PSO method while the worst cost and standard deviation from the PSO method are better than those from the proposed method. The he PSO method is faster than the HPSO-DE in this case. The convergence characteristic of PSO, DE, and HPSO-DE are given in Figure 5 and the optimal solutions by HPSO-DE and PSO methods are given in Appendix.

Table 9. Obtained result for the case of 9-outage lines considering objective with valve point loading effects

Method	PSO	HPSO-DE
Best cost ($)	1041.9920	1036.8080
Average cost ($)	1072.2306	1061.3965
Worst cost ($)	1172.6504	1173.9480
Standard deviation	23.6435	34.8727
Avg. CPU time (s)	117.247	175.688

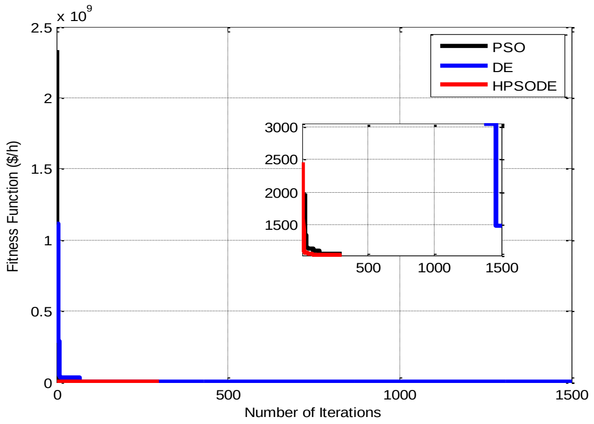

Fig. 5. Convergence characteristics of PSO, DE, and HPSO-DE for the case of 9-outage lines with the objective of valve point loading effects.

5. CONCLUSION

In the paper, the proposed HPSO-DE method has been effectively implemented for solving the SCOPF problem. The SCOPF problem is really a challenge for optimization methods due to its complexity and large-scale. The proposed HPSO-DE has effectively exploited the advantages of both PSO and DE methods for dealing with the SCOPF for different scenarios. The effectiveness of the proposed method has been verified on the IEEE 30-bus system with quadratic and valve point effects objective considering 5-outage and 9-outage lines. The obtained results by the proposed method have been compared to those from other methods and both PSO and DE methods. The result comparisons have indicated that the proposed method can effectively deal with the problem for different cases. Therefore, the proposed HPSO-DE method can be an alternative method for dealing with the complex and large-scale SCOPF problem.

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APPENDIX

Table A1. Fuel cost with valve point effects of the IEEE 30-bus system

Unit	a_i (\$/h)	b_i (\$/MWh)	c_i (\$/MW^{2}h)	e_i (\$/h)	f_i (1/MW)
1	150	2.00	0.00160	50	0.063
2	25	2.50	0.01000	40	0.098
3	0	1.00	0.06250	0	0
4	0	3.25	0.00834	0	0
5	0	3.00	0.02500	0	0
8	0	3.00	0.02500	0	0

Table A2. Transmission limits of the IEEE 30-bus system

Line number	1	2	3	4	5	6	7	8	9
S_{lmax} (MVA)	130	130	65	130	130	65	90	130	130
Line number	10	11	12	13	14	15	16	17	18
S_{lmax} (MVA)	32	65	32	65	65	65	65	32	32
Line number	19	20	21	22	23	24	25	26	27
S_{lmax} (MVA)	32	16	16	16	16	32	32	32	32
Line number	29	30	31	32	33	34	35	36	37
S_{lmax} (MVA)	32	32	16	16	16	16	16	16	65
Line number	38	39	40	41	42				
S_{lmax} (MVA)	16	16	16	32	32				

Table A3. Optimal solutions by PSO, DE and HPSO-DE for the objective with quadratic fuel cost function

Optimal solution	Normal case	5-outage lines			9-outage lines		
	HPSO-DE	PSO	DE	HPSO-DE	PSO	DE*	HPSO-DE
P_{G1} (MW)	176.2417	123.2310	122.0641	123.3957	116.9869	133.1681	123.3180
P_{G2} (MW)	48.8183	64.6073	48.6945	64.1584	62.0662	66.2429	63.0275
P_{G5} (MW)	21.5263	25.1179	29.6548	25.9006	22.4018	23.3168	25.0899

P_{G8} (MW)	22.1117	35.0000	35.0000	35.0000	35.0000	16.2312	35.0000
P_{G11} (MW)	12.1442	21.1329	26.4425	21.3319	23.8303	26.1852	23.3210
P_{G13} (MW)	12.0000	20.8805	27.5348	19.9969	29.3561	26.5965	19.9988
V_{G1} (pu)	1.0500	1.0500	1.0500	1.0500	1.0500	1.0214	1.0500
V_{G2} (pu)	1.0374	1.0306	1.0364	1.0348	1.0314	1.0138	1.0354
V_{G5} (pu)	1.0102	0.9966	0.9946	1.0112	1.0034	1.0197	1.0081
V_{G8} (pu)	1.0175	1.0101	1.0183	1.0210	1.0112	1.0048	1.0179
V_{G11} (pu)	1.1000	1.0981	1.0644	1.0999	1.0684	1.0726	1.1000
V_{G13} (pu)	1.0852	1.0417	1.0840	1.0741	1.0775	0.9500	1.0794
T_{11} (pu)	1.0131	1.0598	0.9696	1.0625	0.9800	0.9721	1.0324
T_{12} (pu)	0.9193	0.9022	1.0084	0.9077	0.9000	1.1000	0.9277
T_{15} (pu)	0.9988	1.0047	0.9797	0.9796	0.9859	0.9055	1.0026
T_{36} (pu)	0.9414	0.9517	0.9837	0.9653	0.9438	0.9634	0.9575

* The result is infeasible due to violating constraints.

Table A4. **Optimal solutions by PSO, DE and HPSO-DE methods for the objective with objective of valve point loading effects**

Optimal solution	Normal case			5-outage lines			9-outage lines		
	PSO	DE	HPSO-DE	PSO	DE	HPSO-DE	PSO	DE*	HPSO-DE
P_{G1} (MW)	198.8043	191.9567	199.0761	99.9253	100.0975	99.8674	98.9462	91.2403	99.9352
P_{G2} (MW)	51.4459	20.0000	49.0582	80.0000	78.6888	80.0000	80.0000	80.0000	80.0000
P_{G5} (MW)	15.0000	37.1975	15.0000	27.0034	27.4269	25.7563	29.3441	42.6574	26.8497
P_{G8} (MW)	10.0000	14.6233	10.0000	34.9769	35.0000	35.0000	35.0000	23.0529	35.0000
P_{G11} (MW)	10.0000	10.0000	10.0000	24.1627	30.0000	25.2155	21.0345	30.0000	22.3602
P_{G13} (MW)	12.0000	20.0575	12.0000	22.9804	18.9334	23.1453	24.7469	21.8148	24.9929
V_{G1} (pu)	1.0500	1.0204	1.0500	1.0500	1.0500	1.0500	1.0500	1.0500	1.0500
V_{G2} (pu)	1.0290	0.9993	1.0301	1.0391	1.0369	1.0423	1.0363	1.0361	1.0406
V_{G5} (pu)	0.9500	0.9605	1.0030	1.0183	0.9665	1.0171	0.9912	1.0244	1.0143
V_{G8} (pu)	0.9594	0.9500	1.0045	1.0256	0.9936	1.0290	1.0166	1.0017	1.0075
V_{G11} (pu)	1.0023	1.1000	1.0575	1.0999	0.9698	1.0589	1.1000	1.0825	1.1000
V_{G13} (pu)	1.0781	1.0591	1.0614	1.0561	1.0866	1.0842	1.0942	1.0340	1.0521
T_{11} (pu)	1.0557	0.9000	0.9857	1.0367	1.0833	0.9773	1.0055	0.9711	1.0160
T_{12} (pu)	0.9920	1.0770	0.9812	0.9276	0.9682	0.9574	0.9819	1.1000	0.9000
T_{15} (pu)	0.9000	0.9000	1.0589	0.9853	0.9882	1.0141	1.0149	0.9037	0.9549
T_{36} (pu)	0.9000	0.9000	0.9520	0.9538	0.9356	0.9527	0.9527	0.9345	0.9490

* The result is infeasible due to violating constraints.

ĐÁNH GIÁ ĐỘ TIN CẬY HỆ THỐNG ĐIỆN CÓ XÉT ĐẾN CƯỜNG ĐỘ CẮT CƯỠNG BỨC

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TÓM TẮT

Một trong những yếu tố quan trọng trong quản lý và vận hành hệ thống điện là đánh giá độ tin cậy của hệ thống nguồn, hệ thống nguồn kết hợp với hệ thống truyền tải, hệ thống truyền tải. Nhiệm vụ chính của việc đánh giá độ tin cậy hệ thống điện là ước tính khả năng sản xuất, vận chuyển và cung cấp điện năng của hệ thống. Nghiên cứu này sử dụng phương pháp *Nodal Effective Load Model* có xét đến cường độ cưỡng bức FOR (*force outage rate*) của tổ máy phát, máy biến áp và đường dây truyền tải để đánh giá các chỉ số độ tin cậy của hệ thống điện. Công cụ sử dụng là phần mềm TRANREL.FOR để đánh giá độ tin cậy theo các tham số xác suất ngẫu nhiên và được chứng minh trên hệ thống điện cao áp thực tế với tổng số nút 24.

Từ khoá: *chỉ số độ tin cậy, cường độ cắt cưỡng bức, xác suất ngẫu nhiên, hệ số không sẵn sàng, chỉ tiêu thiếu nguồn*

Ngày nhận bài: 22/01/2019; Ngày hoàn thiện: 21/02/2019; Ngày duyệt đăng: 28/02/2019

RELIABILITY EVALUATION OF POWER SYSTEM CONSIDERING FORCE OUTAGE RATE

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ABSTRACT

In the management and operation of power systems, reliability evaluations of generation system, combined generation and transmission system, as well as transmission system are extremely essential. The fundamental objective of reliability evaluation is to estimate the power supply and transfer capacities of power systems. In this study, the Nodal Effective Load Model method is used for assessing the overall system reliability indices with the consideration of the force outage rate (FOR) of the generators, transformers, and transmission lines. Moreover, the software TRANREL.FOR is ultilised as a simulation tool for the probabilistic reliability assessment and it is tested on a practical 24-bus power system.

Key words: *reliability indices, force outage rate, probabilistic, unavailability, loss of load expectation*

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ĐẶT VẤN ĐỀ

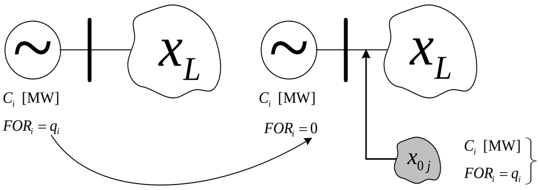
Hệ thống điện (HTĐ) là một hệ thống bao gồm nhà máy điện, đường dây truyền tải, máy biến áp, đường dây phân phối và các phần tử khác. Nhiệm vụ cơ bản của HTĐ là sản xuất và cung cấp điện năng tới nơi tiêu thụ một cách liên tục và chất lượng với giá thành thấp nhất. Nhiệm vụ cơ bản của hệ thống truyền tải là vận chuyển điện năng từ nơi sản xuất đến nơi tiêu thụ với độ tin cậy cao nhất.

Khi chuyển từ mô hình hoạt động điện độc quyền sang thị trường điện cạnh tranh thì đánh giá độ tin cậy, ổn định của hệ thống điện và nâng cao chất lượng điện năng là một trong những nhiệm vụ chính. Chỉ số độ tin cậy (LOLP, LOLE, EENS, v.v…) là chững chỉ số rất quan trọng đối với nhà quản lý và vận hành, được thể hiện [1]-[3]. Hiện tại có rất nhiều phương pháp và giải thuật để làm công cụ đánh giá độ tin cậy của hệ thống điện như *Monte carlo simulation, phương pháp xác suất ngẫu nhiên, v.v...*với nhiều phần mềm MECORE (*Monte carlo Evaluation of Composite system Reliability*) do University of Saskatchewan (Canada) phát triển; TRELSS (*Transmission Reliability Evaluation Large Scale System*), CREAM (*Composite Reliability Assessment by Monte-Carlo*) và PRA (*Probabilistic Reliability Assessment*) do EPRI (*Electric Power Reserch Institute*) and Southern Company Services của Mỹ phát triển và quản lý; METRIS do tập đoàn EDF của Pháp phát triển và quản lý [3]. Nghiên cứu này sử dụng phương pháp *Nodal Effective Load Model* có xét đến cường độ cưỡng bức (*FOR*) của tổ máy phát, máy biến áp và đường dây truyền tải để đánh giá các chỉ số độ tin cậy của hệ thống điện.

ĐÁNH GIÁ ĐỘ TIN CẬY THEO XÁC SUẤT NGẪU NHIÊN

Đánh giá độ tin cậy theo cấp độ I

Cấp độ I của hệ thống điện là chỉ chú ý đến hệ thống nguồn điện. Do đó, chỉ số độ tin cậy của hệ thống điện cấp độ I chính là của hệ thống nguồn điện. Có nhiều phương pháp để đánh giá độ tin cậy ở cấp độ I. Hệ thống thực cấp độ I như trình bày ở Hình 1(a) có thể được mô phỏng thành hệ thống tương đương như trình bày ở Hình 2(b). Điều này tương đương với việc tăng thêm công suất C_i (MW) vào phụ tải với cùng tỉ lệ cưỡng bức theo công thức (1).



(a) Hệ thống thực (b) Hệ thống tương đương

Hình 1. *Hệ thống điện thực tế và mô phỏng tương đương ở cấp độ I*

$$x_e = x_L + \sum_{i=1}^{NG} x_{oi} \tag{1}$$

Trong đó,

x_e: biến ngẫu nhiên của phụ tải cộng thêm vào

x_L: biến ngẫu nhiên của phụ tải đã có

x_{oi}: biến ngẫu nhiên của xác suất phụ tải là nguyên nhân bởi *FOR* tổ máy thứ *i* (biến ngẫu nhiên là giá trị bất kỳ một tổ máy nào bị hỏng)

NG: tổng số tổ máy có trong hệ thống điện

Đường cong phụ tải tương đương của HLI có thể được tính toán theo công thức (2) như sau:

$$\begin{aligned} {}_{HLI}\Phi_i(x_e) &= {}_{HLI}\Phi_{i-1}(x_e) \otimes {}_{HLI}\, f_{oi}(x_{oi}) \\ &= \int {}_{HLI}\Phi_{i-1}(x_e - x_{oi})\, {}_{HLI}\, f_{oi}(x_{oi})dx \end{aligned} \tag{2}$$

Trong đó,

⊗ toán tử tích phân toàn bộ đường cong phụ tải nối dài

${}_{HLI}\Phi_0(x_e - x_{0i}) = {}_{HLI}\Phi(x_L)$

${}_{HLI}\, f_{0i}(x_{oi})$ là hàm phân phối xác suất của cường độ cắt cưỡng bức của máy phát thứ *i*

LP là đại lượng phụ tải cực đại [MW]

Chỉ số độ tin cậy cấp độ I là LOLE$_{\text{HLI}}$ (Loss of load expectation) và EENS$_{\text{HLI}}$ (Expected energy not served) được tính như sau:

$$LOLE_{HLI} = {}_{HLI}\Phi(x)\big|_{x=IC} \quad \text{[hours/year]} \quad (3)$$

$$EENS_{HLI} = \int_{IC}^{IC+Lp} {}_{HLI}\Phi(x)dx \quad \text{[MWh/year]} \quad (4)$$

Trong đó,

IC là tổng công suất của các tổ máy phát [MW]

Đánh giá độ tin cậy cấp độ II

Cấp độ II tức là đánh giá cùng lúc hệ thống nguồn và hệ thống truyền tải. Các chỉ số độ tin cậy hệ thống điện mức độ II là chỉ tiêu thiếu nguồn LOLE (loss of load expectation), thời gian cắt tải EDLC (Expected duration of load curtailments), chỉ tiêu thiếu nguồn EENS (Expected energy not supplied), chỉ số SI (Severity Index), chỉ số năng lượng độ tin cậy EIR (Energy Index of Reliability). Có nhiều máy phát, đường dây truyền tải được cố định trong phân tích phân bố công suất, phân tích sự ngẫu nhiên, điều độ máy phát, phân tích quá tải trên đường dây truyền tải,… Hình 2 trình bày hệ thống tương đương ở HLII. CG_1, CT_1, q_1, tương ứng là công suất nguồn phát, công suất đường dây truyền tải, hệ số không sẵn sàng, *NT* là số đường dây truyền tải, *k* là chỉ số tải tại các nhánh và *j* các trạng thái của hệ thống [3].

Mô hình tải cấp độ HLII có thể xác định từ tổng hợp tải ban đầu và xác suất tải gây ra bởi sự không sẵn sàng của máy phát và đường dây truyền tải và ký hiệu như SFEG ở mỗi điểm tải như hình 2c. Mô hình tải hữu ích ngẫu nhiên và có thể tính như công thức (5):

$$ {}_k x_e = {}_k x_L + \sum_{j=1}^{NS} {}_k x_{osij} \quad (5)$$

Trong đó,

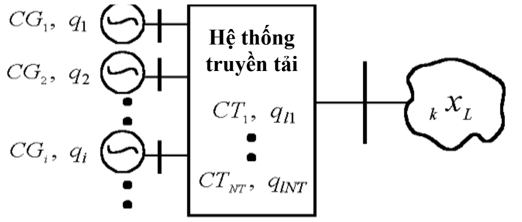
${}_k x_e$ biến ngẫu nhiên tải hữu ích trong hệ thống điện hợp nhất ở điểm tải thứ k

${}_k x_L$ biến ngẫu nhiên của tải ban đầu ở điểm tải thứ k

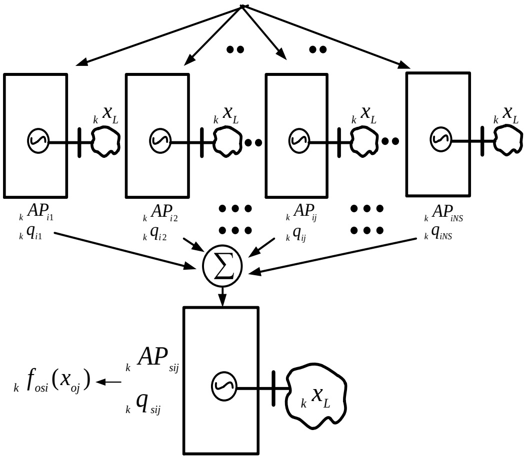
${}_k x_{osij}$ biến ngẫu nhiên của xác suất tải gây ra bởi SFEG ở điểm tải thứ *k*

J số trạng thái của hệ thống

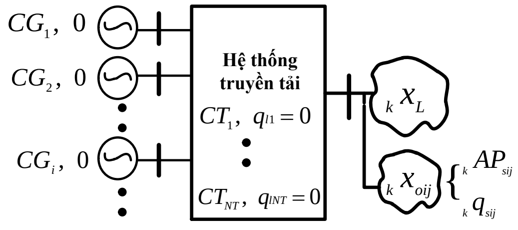
NS tổng số trạng thái của hệ thống



(a) Hệ thống thực tế



(b) Tổng hợp giả thiết tương đương máy phát SFEG (Synthesized Fictitious Equivalent Generator)



(c) Hệ thống tương đương

Hình 2. *Hệ thống thực, hệ thống tương đương HLII*

Sau tải các máy phát 1^{th} đến i^{th} hàm phân bố xác suất ${}_k\Phi_i$ của CMELDC (Composite power system Equivalent Load Duration Curve) ở điểm tải thứ *k* có thể biểu diễn tính toán theo công thức (6):

$$ {}_k\Phi_i(x_e) = {}_k\Phi_o(x_e) \otimes {}_k f_{osi}(x_{osi}) = \int {}_k\Phi_o(x_e - x_{osi})\, {}_k f_{osi}(x_{osi})dx_{osi} \quad (6)$$

Trong đó,

${}_k\Phi_o$ biến đổi LDC ở điểm tải thứ *k*

$_k f_{osi}$ công suất hỏng móc của SFEG hoạt động bởi nhiều máy phát 1^{th} đến i^{th} ở điểm tải.

Đánh giá độ tin cậy của hệ thống truyền tải

Đánh giá độ tin cậy xác suất ngẫu nhiên của hệ thống truyền tải là hiệu số giữa chỉ số độ tin cậy của hệ thống điện cấp độ II với chỉ số độ tin cậy của hệ thống điện cấp độ I được thể hiện công thức sau:

$$LOLE_{TS} = LOLE_{HLII} - LOLE_{HLI} \quad (7)$$

$$EENS_{TS} = EENS_{HLII} - EENS_{HLI} \quad (8)$$

ĐỐI TƯỢNG NGHIÊN CỨU

Thông số đầu vào đánh giá độ tin cậy lưới

Bảng 1. *Thông số nguồn của hệ thống điện cao áp ĐBSCL*

TT	Nút thanh cái	Số tổ máy	Công suất tổ máy [MW]	FOR
1	2	1	330	0,08
2	8	4	37,5	0,02
3	8	1	33	0,02
4	10	4	253	0,05
5	10	2	265	0,05

Bảng 2. *Thông số đường dây hệ thống điện cao áp ĐBSCL*

TT	Bus	Bus	Số mạch	Công suất đường dây [MW]	FOR
1	1	2	2	335	0,0035
2	1	6	1	335	0,0035
3	1	7	1	335	0,0035
4	2	5	1	335	0,0035
5	2	8	1	335	0,0035
6	2	10	2	335	0,0035
7	2	13	1	335	0,0035
8	3	4	2	367	0,0035
9	3	5	2	367	0,0035
10	3	9	1	335	0,0035
11	5	9	1	335	0,0035
12	5	7	1	335	0,0035
13	8	9	1	335	0,0035
14	9	10	3	511	0,0035
15	10	11	1	335	0,0035
16	10	12	1	335	0,0035
17	10	13	1	335	0,0035
18	12	13	1	335	0,0035

Nghiên cứu này sẽ áp dụng lý thuyết cho lưới điện có mức điện áp từ 110kV đến 220kV của hệ thống điện Đồng Bằng Sông Cửu Long (ĐBSCL) thuộc cấp quản lý của truyền tải điện Miền Tây. Hằng số không sẵn sàn (FOR) của các phần tử là thông số đầu vào rất quan trọng để tính toán các chỉ số độ tin cậy của hệ thống điện. Nghiên cứu này sử dụng hằng số FOR cho từng nhóm phần tử trên các bài báo khoa học trên tạp chí IEEE [3]-[5] để làm cơ sở tính toán độ tin cậy của hệ thống điện như trình bày tại Bảng 1,2,3,4, 5.

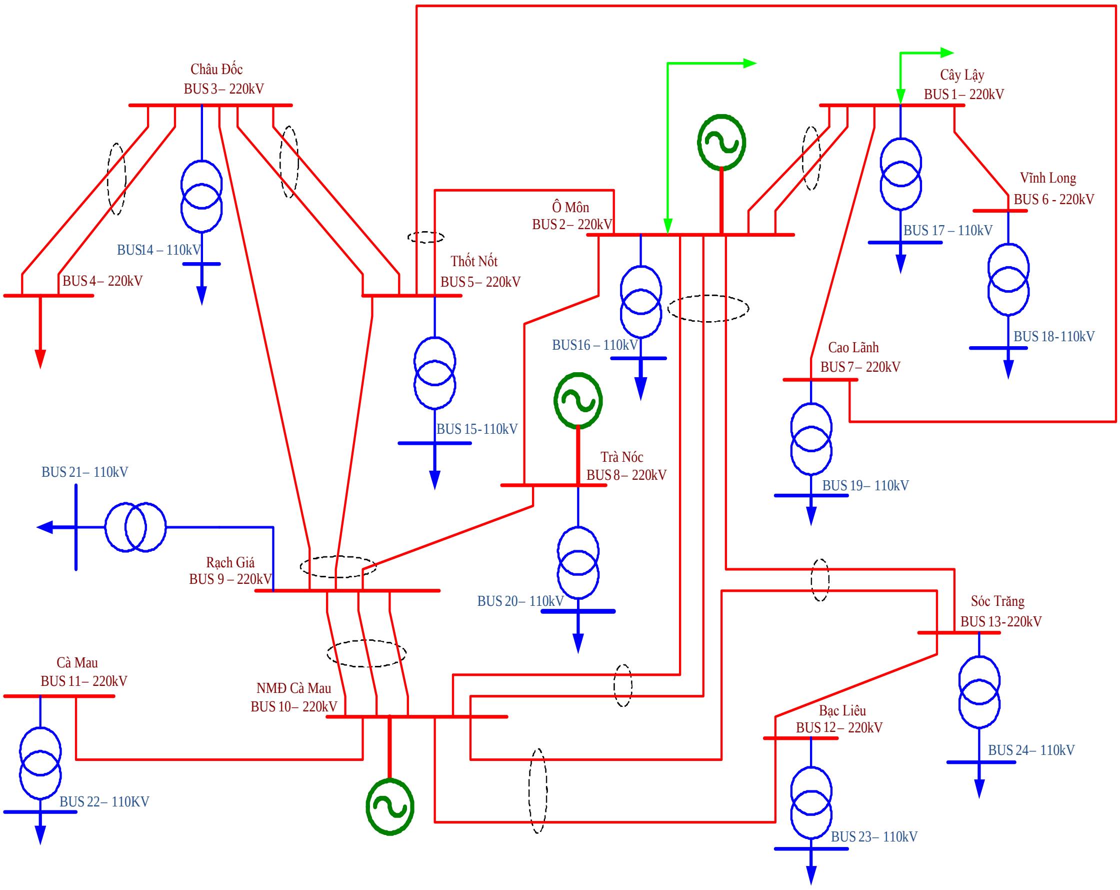
Bảng 3. *Thông số phụ tải ngày hệ thống điện cao áp hiện tại*

TT	Nút phụ tải	Công suất phụ tải [MW]	TT	Nút phụ tải	Công suất phụ tải [MW]
1	1	330	8	18	75
2	2	135	9	19	60
3	4	120	10	20	130
4	14	75	11	21	180
5	15	45	12	22	75
6	16	90	13	23	45
7	17	120	14	24	60

Bảng 4. *Thông số trạm biến áp 220kV/110kV của hệ thống điện cao áp ĐBSCL*

TT	Tên trạm biến áp	Công suất [MW]	FOR
1	Bus 1 - 17	2x125	0,0015
2	Bus 2 - 16	2x125	0,0015
3	Bus 5 - 15	2x125	0,0015
4	Bus 3 - 14	2x250	0,0015
5	Bus 6 - 18	2x125	0,0015
6	Bus 7 - 19	1x125	0,0015
7	Bus 8 - 20	2x125	0,0015
8	Bus 9 - 21	1x250+1x125	0,0015
9	Bus 11 - 22	1x250	0,0015
10	Bus 12 - 23	1x125	0,0015

Từ các thông số trên sơ đồ hình 3 sẽ trình bày hệ thống điện cao áp từ cấp điện áp 110kV đến 220kV.



Hình 3. *Sơ đồ hệ thống điện cao áp theo cấp quản lý của truyền tải điện Miền Tây*

Kết quả đánh giá độ tin cậy

Công cụ sử dụng để đánh giá này là phần mềm TRANREL.FOR. Theo kinh nghiệm đánh giá của các chuyên gia đánh giá độ tin cậy hệ thống điện thì chỉ số EIR phải đạt 0,9999. Kết quả đánh giá chỉ số độ tin của toàn hệ thống theo bảng 5 và đánh giá được chỉ số độ tin cậy các Bus phụ tải tại bảng 6.

Bảng 5. *Chỉ số độ tin cậy của toàn hệ thống*

LOLE$_{Sys}$ [Hrs/Day]	EENS$_{Sys}$ [MWh/Day]	ELC$_{Sys}$ [MW/Cur.Day]	EIR$_{Sys}$
2,02468	2232,32	1147,5	0,99872331

Bảng 6. *Chỉ số độ tin cậy các Bus phụ tải*

Bus	LOLE$_{Bus}$ [Hrs/Day]	EENS$_{Bus}$ [MWh/Day]	SI$_{Bus}$ [phút/năm]	ELC$_{Bus}$ [MW/Cur.Day]	EIR$_{Bus}$
1	2,02468	501,109	33.255,37	247,5	0,99939162
2	2,02468	222,715	36.129,31	110	0,99881028
4	2,02468	170,833	31.176,84	84,375	0,99853538
14	2,02468	101,234	29.560,18	50	0,99830599
15	2,02468	75,9256	36.950,34	37,5	0,997489233
16	2,02468	136,666	33.255,37	67,5	0,998418218
17	2,02468	189,814	34.640,98	93,75	0,99875646
18	2,02468	94,9069	27.712,7	46,875	0,99815643
19	2,02468	86,049	31.407,89	42,5	0,997903289
20	2,02468	187,283	34.640,98	92,5	0,997903289
21	2,02468	189,814	23.093,99	150	0,99875646
22	2,02468	96,172	28.082,15	47,5	0,998194962
23	2,02468	70,864	34.487,03	35	0,997266053

Từ chỉ số độ tin cậy tại các nút của hệ thống điện cao áp ĐBSCL theo cấp quản lý của truyền tải điện Miền Tây cho ta thấy tại tất cả các nút này chỉ số EIR là không đạt chuẩn theo các nhà nghiên cứu về độ tin cậy trên thế giới. Cho nên hệ thống cần phải nâng cấp hay mở rộng thêm đường dây truyền tải.

KẾT LUẬN

Nghiên cứu này tập trung đánh giá và phân tích các chỉ số độ tin cậy của hệ thống điện cao áp thuộc quyền quản lý của truyền tải điện Miền Tây - - Vùng Đồng Bằng Sông Cửu Long. Áp dụng phương pháp đánh giá độ tin cậy xác suất ngẫu nhiên có xét đến cường độ cưỡng bức (*FOR*) đã đánh giá được chỉ số độ tin cậy của toàn hệ thống, tại nguồn phát, hệ thống truyền tải và tại các nút của hệ thống điện. Điều này thể hiện kết quả rất khả quan về hệ thống nguồn phát của hệ thống điện là rất tốt không cần phải cải tạo hay phát triển thêm, chỉ có hệ thống truyền tải là cần phải quy hoạch hay mở rộng thêm để đảm bảo cung cấp đủ điện năng cho khu vực.

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TỔNG QUAN QUY HOẠCH MỞ RỘNG LƯỚI ĐIỆN TRUYỀN TẢI

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TÓM TẮT

Mục tiêu chính của quy hoạch mở rộng lưới điện truyền tải (LĐTT) là xác định được nơi nào cần quy hoạch và mở rộng, công suất cần phải mở rộng, xác định được tổng chi phí quy hoạch, độ tin cậy của hệ thống phải được cải thiện,... Bài toán quy hoạch mở rộng LĐTT là vấn đề quy mô lớn, phức tạp và tổ hợp số nguyên của các vấn đề phi tuyến tính hỗn hợp. Giải pháp chính xác cho vấn đề quy hoạch mở rộng LĐTT là rất quan trọng trong hệ thống điện (HTĐ). Do đó, các phương pháp tối ưu hóa đã được áp dụng đem lại nhiều hiệu quả thiết thực. Nghiên cứu này sẽ tổng quan các vấn đề quy hoạch mở rộng LĐTT từ nhiều khía cạnh khác nhau như phương pháp giải, độ tin cậy, tính không chắc chắn và an toàn, thị trường điện và từ mô hình hóa nhằm giúp các nhà nghiên cứu khác có được thuật toán khả thi về mặt học thuật và thương mại. Bài báo này mục đích chủ yếu là trình bày tổng quan các tài liệu về phương pháp quy hoạch mở rộng LĐTT.

Từ khoá: *Quy hoạch mở rộng lưới điện truyền tải; phương pháp tối ưu hóa; thị trường điện; độ tin cậy; không chắc chắn và an toàn.*

Ngày nhận bài: 02/7/2019; Ngày hoàn thiện: 12/5/2020; Ngày đăng: 20/5/2020

OVERVIEW OF TRANSMISSION EXPANSION PLANNING

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ABSTRACT

The objective main of transmission expansion planning (TEP) decided the local to be planed and expanded, the expanded power, investment cost, the reliability index to be improved. The TEP problem is a large-scale, complex and a mixed integer non-linear problem. A good solution of TEP is very important in power system. Therefore, the optimization methods applied to bring practical effects. This study presents the overview of TEP problem from different aspects such as, solving methods, reliability, uncertainty and security, electricity market, and from the modeling prospective in order to facilitate the other researcher's works in this hot area to get a feasible algorithm academically and commercially. This paper aims essentially at presenting the literature overview of the TEP procedure.

Key words: *Transmission expansion planning; optimition methods; electricity market; reliability; uncertainty and security.*

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1. Đặt vấn đề

Ngày nay nhu cầu năng lượng đang là vấn đề thời sự cho sự phát triển của nền kinh tế và sự gia tăng dân số toàn cầu, trong đó năng lượng điện đóng vai trò then chốt. Từ đó, hệ thống điện (HTĐ) cũng được liên tục mở rộng cả về nguồn phát và đường dây truyền tải. Kinh nghiệm vận hành HTĐ cho thấy tại một thời điểm trên hệ thống điện có những đường dây bị quá tải trong khi các đường dây khác non tải và ngược lại. Việc sử dụng hiệu quả và tối ưu các nguồn cung cấp là một vấn đề mà các nhà nghiên cứu rất quan tâm. Vì vậy, bài toán được đặt ra tối ưu hóa trong quy hoạch mở rộng LĐTT nhằm đáp ứng nhu cầu phát triển phụ tải là vấn đề rất quan trọng trong HTĐ.

Thông thường công tác quy hoạch mở rộng lưới điện truyền tải (LĐTT) theo ngay sau quy hoạch hệ thống nguồn điện. Nhiệm vụ của quy hoạch mở rộng LĐTT là xác định tối ưu hoá vị trí, mở rộng công suất truyền tải và vận chuyển điện năng từ nơi sản xuất đến nơi tiêu thụ với độ tin cậy cao trong HTĐ. Trong những năm gần đây, các nghiên cứu trong lĩnh vực tổng hợp các mô hình quy hoạch mở rộng LĐTT có nhiều thử thách khi mở rộng. Nhiều bài báo và các báo cáo mô hình mới được đăng trên nhiều tài liệu nhằm cải thiện tính sẵn có của máy tính, giải thuật tối ưu mới và mức độ không chắc chắn lớn trong thị trường điện cạnh tranh. Các nhà quy hoạch mở rộng LĐTT đã thử nhiều phương pháp để giải quyết vấn đề mở rộng. Các nhà quy hoạch đã sử dụng mô hình mở rộng tự động để xác định quy hoạch mở rộng LĐTT tối ưu bằng cách tối thiểu hóa hàm mục tiêu toán học với nhiều ràng buộc. Bài báo này sẽ khảo sát các quy hoạch mở rộng LĐTT [1] được xét ở nhiều khía cạnh khác nhau.

2. Khảo sát các vấn đề quy hoạch mở rộng LĐTT

2.1. Mô hình toán trong quy hoạch mở rộng LĐTT

Vấn đề quy hoạch mở rộng LĐTT không chỉ sử dụng mô hình nguồn điện xoay chiều mà còn áp dụng ở mô hình nguồn điện một chiều. Thực tế các nhà quy hoạch quan tâm đến mô hình nguồn điện xoay chiều dựa vào các giả thuyết như: giúp cho nhà quy hoạch tiếp tục nghiên cứu vấn đề ổn định điện áp sau khi giải quyết vấn đề quy hoạch mở rộng LĐTT, để giải quyết vấn đề quy hoạch mở rộng LĐTT có thể sử dụng phép toán phi tuyến tính [2] như điều khiển linh hoạt hệ thống truyền tải điện xoay chiều, mô hình tuyến tính được sử dụng trong quy hoạch được tăng cường hơn và cho phép giải quyết vấn đề quy hoạch mở rộng LĐTT song song vấn đề phân bố công suất phản kháng.

2.2. Các phương pháp giải bài toán trong quy hoạch mở rộng LĐTT

Mục tiêu chính quy hoạch mở rộng LĐTT là đạt được tối thiểu tổng chi phí đầu tư nhưng phải đáp ứng nhu cầu phát triển phụ tải và độ tin cậy khi vận hành. Hiện nay, quy hoạch mở rộng LĐTT được xây dựng thành bài toán đa mục tiêu. Một số thuật toán đã được đề xuất để giải quyết các vấn đề liên quan đến quy hoạch mở rộng LĐTT và được phân thành ba loại như: phương pháp toán học tối ưu, phương pháp Heuristic, phương pháp Metaheuristic [1].

- Phương pháp toán học tối ưu [3] và phương pháp heuristic [4], [5] gồm: lập trình phi tuyến tính, lập trình tuyến tính, phân tích Bender, phương pháp cận biên và nhánh, lý thuyết trò chơi, giải thuật tìm kiếm dựa vào chỉ số độ nhạy, phân tích thứ bậc, lập trình động, lập trình số nguyên hỗn hợp.
- Phương pháp Metaheuristic [6]-[9] gồm: đàn kiến, hệ thống miễn dịch nhân tạo, kết nối mạng nơron nhân tạo, giải thuật con ong và Chaos, tiến hóa đặc biệt, hệ thống chuyên gia, giải thuật bước nhảy con ếch, Fuzzy, giải thuật di truyền, giải thuật di truyền mã hóa thập phân, giải thuật lai di truyền với Fuzzy, giải thuật di truyền không phân loại, tìm kiếm ngẫu nhiên Greedy, tìm kiếm hòa điệu, PSO, giải thuật tìm kiếm Grid, tìm kiếm tabu, mô phỏng tuyến tính, liệt kê ẩn 0-1, tìm kiếm scatter [6]-[9].

2.2.1. Phương pháp toán học tối ưu

Phương pháp toán học tối ưu đã được áp dụng nhiều để giải quyết bài toán quy hoạch mở rộng LĐTT. Phương pháp này có ưu nhược điểm như sau:

a. Ưu điểm phương pháp

- Giải pháp tối ưu đạt được độ chính xác và thời gian giải quyết ngắn.

- Nhiều phương pháp đạt được sự hội tụ phù hợp.

b. Nhược điểm phương pháp

- Mô hình hóa HTĐ cân bằng vào mô hình lập trình tối ưu rất phức tạp.

- Tổ hợp lại các ràng buộc mới gặp nhiều khó khăn, điều này đòi hỏi phải sắp xếp lại toàn bộ mô hình.

- Chỉ có một số ít phương pháp có thể tiến hành và thực hiện nghiên cứu động như sự ổn định.

2.2.2. Phương pháp heuristic

Tương tự như phương pháp toán học tối ưu thì phương pháp heuristic được sử dụng nhiều trong thời gian gần đây. Phương pháp này có ưu nhược điểm như sau:

a. Ưu điểm phương pháp

- Các phương pháp này dễ sử dụng và không phức tạp.

- Không cần phải chuyển đổi HTĐ thành mô hình lập trình tối ưu.

- Các nghiên cứu động có thể thực hiện bằng các phương pháp này.

b. Nhược điểm phương pháp

- Giải pháp tối ưu có thể được kết hợp sự xấp xỉ và thời gian mô phỏng sẽ nhiều hơn.

- Có thể rơi vào cực tiểu vị trí thay vì cực tiểu toàn bộ.

- Các phương pháp heuristic có một vấn đề đó là, chúng không đủ mạnh, đặc biệt là từ phía toán học và kết quả của chúng không thể hiệu quả đối với các mạng phức tạp.

2.2.3. Phương pháp Metaheuristic

Phương pháp Metaheuristic kết hợp các đặc điểm nổi bật của hai phương pháp trên. Khi áp dụng phương pháp Metaheuristic luôn đạt được giải pháp tốt cho HTĐ lớn với thời gian tính toán ngắn. Nhưng trong phương pháp này có ưu nhược điểm như sau:

a. Ưu điểm phương pháp

- Phương pháp này đơn giản và dễ sử dụng.

- Không cần phải chuyển đổi HTĐ thành mô hình lập trình tối ưu.

- Sử dụng cho nghiên cứu tĩnh và động. Công cụ của phương pháp này thì nghiên cứu dễ dàng và linh hoạt được thực hiện.

b. Nhược điểm phương pháp

- Để đạt được giải pháp tối ưu cần nhiều thời gian.

- Có thể rơi vào cực tiểu từng vị trí thay vì cực tiểu toàn bộ.

- Đã cải thiện được khả năng hội tụ nhưng còn thấp hơn so với phương pháp toán học tối ưu.

2.3. Quy hoạch mở rộng LĐTT ràng buộc an toàn

Quy hoạch mở rộng LĐTT là vấn đề hết sức quan trọng không những cần phải có chi phí đầu tư lớn mà còn kết hợp với vấn đề an toàn. Có rất nhiều sự nghiên cứu quy hoạch mở rộng LĐTT có ràng buộc an toàn [10]. Các ràng buộc khác nhau về an toàn trong quy hoạch mở rộng LĐTT được quan tâm như sau: biên độ ổn định điện áp, đặc tính điện áp an toàn và chỉ số an toàn (N-1), dòng điện đường dây và giới hạn nguồn phát.

2.4. Quy hoạch mở rộng LĐTT được kết hợp với đường dây tắc nghẽn

Ở thị trường điện cạnh tranh thì LĐTT tắc nghẽn là vấn đề quan trọng điều này cần thiết để hợp nhất trong vận hành HTĐ và quy hoạch mở rộng hệ thống kết nối. Quy hoạch mở rộng LĐTT được kết hợp với đường dây tắc nghẽn [11] được vận dụng ở nhiều mục tiêu khác nhau như: xét đến chi phí vận hành do tắc nghẽn, xét đến giá trị vận chuyển, xét đến khả năng truyền tải dư thừa, xét đến khả năng tải đường dây, xét đến quản lý tắc nghẽn trong nghiên cứu quy hoạch mở rộng LĐTT thực và được giảm nhẹ tắc nghẽn trong quy hoạch mở rộng LĐTT.

2.5. Quy hoạch mở rộng LĐTT trong thị trường điện cạnh tranh

Phương pháp truyền thống quy hoạch mở rộng LĐTT không còn khả thi trong việc tái cấu trúc lại hệ thống điện. Tối ưu hóa LĐTT đòi hỏi cần phải có công cụ và phương pháp mới để giải quyết vấn đề này. Thị trường điện (TTĐ) đòi hỏi đường dây truyền tải mới phải đạt tối thiểu chi phí đầu tư và vận hành hệ thống phải đạt được sự hài lòng. Tuy nhiên, trong TTĐ cạnh tranh mục tiêu chính của quy hoạch mở rộng LĐTT là cung cấp điện không phân biệt khách hàng và các nhà đầu tư cạnh tranh nhau về độ tin cậy hệ thống cung cấp. Vấn đề quy hoạch mở rộng LĐTT trong môi trường cạnh tranh [12], [13] được xem xét theo nhiều quan điểm khác nhau như xem xét giá trị nút, chi phí cắt giảm tải, chi phí tắc nghẽn truyền tải, lợi nhuận xã hội và rủi ro thấp nhất. Ngoài ra, sự ảnh hưởng của quy hoạch mở rộng LĐTT trong môi trường cạnh tranh đã được dự báo đến khu vực nguồn phát điện cạnh tranh.

2.6. Độ tin cậy trong quy hoạch mở rộng LĐTT

Để quy hoạch HTĐ phù hợp được đánh giá ở hai giai đoạn: giai đoạn vĩ mô và giai đoạn vi mô. Nghiên cứu quy hoạch trong giai đoạn vĩ mô phải được xuất phát từ quan điểm chính sách chiến lược, nhưng đối với nghiên cứu quy hoạch trong giai đoạn vi mô chỉ cần xét đến lợi ích nguồn năng lượng. Phân tích thích hợp, chắc chắn và độ tin cậy thì liên quan đến giai đoạn vĩ mô và phân tích kỹ thuật về lỗi và ổn định thì liên quan đến giai đoạn vi mô. Thông thường quy hoạch mở rộng LĐTT thì cần phải thực hiện phân tích độ tin cậy và thích hợp trước khi phân tích lỗi và ổn định. Quy hoạch HTĐ nói chung cũng như quy hoạch mở rộng LĐTT nói riêng cần phải phân tích độ an toàn [14], [15] hoặc tin cậy [16], [17]. Do đó, quy hoạch mở rộng LĐTT dài hạn cần phải đánh giá độ tin cậy sau khi quy hoạch.

2.7. Sự không chắc chắn trong quy hoạch mở rộng LĐTT

Theo điều kiện không chắc chắn của HTĐ thì quy hoạch mở rộng LĐTT trong được phân thành hai phương pháp là phương pháp xác định và phương pháp không xác định. Trong phương pháp xác định thì quy hoạch mở rộng LĐTT trong được xét ở điều kiện xấu nhất và không tính đến xác suất xuất hiện [18]. Đối với phương pháp không xác định thì quy hoạch mở rộng LĐTT sẽ xét đến các trường hợp các khả năng xảy ra trong tương lai. Ngoài ra, phương pháp không xác định còn xét đến kinh nghiệm vận hành HTĐ và dự đoán điều kiện không chắc chắn có thể xảy ra trong tương lai.

2.8. Quy hoạch mở rộng LĐTT được kết hợp với quy hoạch công suất phản kháng

Trong HTĐ thực thì công suất phản kháng (CSPK) của tải được cung cấp thông qua nguồn phát. Trong trường hợp này CSPK được vận chuyển thông qua đường dây truyền tải, sự vận chuyển như thế có thể làm giảm khả năng truyền tải và điều này có thể dẫn đến xây dựng thêm nhiều đường dây mới. Tuy nhiên, để cải thiện vấn đề trên bằng cách cung cấp nguồn CSPK gần trung tâm phụ tải có thể cung cấp nhu cầu CSPK làm cho công suất đường dây truyền tải tăng lên và giảm tổn thất công suất. Vì vậy, quy hoạch mở rộng LĐTT cần kết hợp với quy hoạch CSPK; Trường hợp không có sự kết hợp này thì quy hoạch mở rộng LĐTT sẽ dẫn đến xây dựng thêm nhiều đường dây mới [18].

2.9. Quy hoạch mở rộng LĐTT từ thiết bị điều khiển linh hoạt xoay chiều (FACTS)

Trong quy hoạch mở rộng LĐTT thì sự mở rộng mạng điện luôn gặp theo cách bổ sung các đường dây mới vào mạng điện để tăng công suất lưới điện truyền tải. Mặt khác, có thể sử dụng thiết bị điều khiển linh hoạt LĐTT xoay chiều [19], [20] để tăng thêm công suất cho hệ thống đang vận hành.

3. Các nhược điểm và kiến nghị

Các vấn đề ở trên đều giải quyết được bài toán quy hoạch mở rộng LĐTT nhưng vẫn chưa tìm ra được tối ưu để giải quyết tất cả các vấn đề trong quy hoạch mở rộng LĐTT. Một số nhược điểm đã được nêu trong các phương pháp trên khi quy hoạch mở rộng LĐTT. Nói chung, các phương pháp đã được đề xuất áp dụng trong quy hoạch mở rộng LĐTT có một số nhược điểm như sau:

- Các nhà nghiên cứu ít quan tâm đến vấn đề quy hoạch CSPK khi giải quyết vấn đề quy hoạch mở rộng LĐTT, mặc dù điều đó rất quan trọng.
- Điều kiện không chắc chắn khi thay đổi kích thước nguồn phát ít được quan tâm đến. Vấn đề này nên được xét một cách linh hoạt ở bất kỳ tình huống nào khi quy hoạch mở rộng LĐTT.
- Các phương pháp quy hoạch mở rộng LĐTT được mô phỏng trong mô hình HTĐ một chiều chiếm phần đa số. Tuy nhiên, đã có một số mô hình HTĐ xoay chiều được xét đến.
- Các ràng buộc về chuẩn độ tin cậy và chuẩn an toàn đã được xét đến trong các phương pháp Metaheuristic.
- Các nghiên cứu trước đây thì vấn đề quy hoạch mở rộng LĐTT chỉ xem xét nghiên cứu quy hoạch ngắn hạn và vấn đề quy hoạch dài hạn đã được quan tâm đến nhưng chưa nhiều. Trong LĐTT điện nếu được quan tâm nhiều thì quy hoạch dài hạn tốt sẽ tiết kiệm được thời gian và tối thiểu chi phí đầu tư.
- Thiết bị điều khiển linh hoạt hệ thống điện xoay chiều (FACTS) trong quy hoạch mở rộng LĐTT không được xem xét phù hợp.
- Quy hoạch mở rộng LĐTT kết hợp với quy hoạch nguồn phát điện cần được quan tâm đến các ràng buộc.

4. Kết luận

Quy hoạch mở rộng LĐTT đã được tổng quan lại ở nhiều khía cạnh khác nhau trong bài báo này. Cụ thể là các bài báo được công bố gần đây được đánh giá từ nhiều quan điểm khác nhau. Các dẫn chứng trong bài báo cho thấy rằng vấn đề quy hoạch mở rộng LĐTT được yêu cầu đáp ứng sự phát triển phụ tải trong tương lai. Bên cạnh đó, các nghiên cứu vấn đề quy hoạch mở rộng LĐTT được quy hoạch tốt hơn và linh hoạt được xét ở nhiều khía cạnh khác: mô hình toán, phương pháp giải, độ tin cậy, TTĐ cạnh tranh, sự không chắc chắn, ràng buộc an toàn, đường dây tắc nghẽn, và công suất phản kháng. Nghiên cứu vấn đề quy hoạch mở rộng LĐTT trong bài báo này mở ra cánh cửa cho các công việc tiếp theo trong lĩnh vực này.

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QUY HOẠCH HỆ THỐNG ĐIỆN CÓ XÉT ĐẾN TỐI ƯU HÓA ĐỘ DỰ TRỮ

Power system expansion planning in consideration of optimal reserve

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TÓM TẮT

Nhiệm vụ chính của quy hoạch mở rộng hệ thống truyền tải là xác định vị trí tối ưu, công suất và thứ tự ưu tiên sẽ đầu tư của từng đường dây, đảm bảo yêu cầu dự báo phụ tải dài hạn với tổng chi phí đầu tư thấp nhất. Nghiên cứu này sẽ áp dụng phương pháp cận biên và nhánh để giải bài toán quy hoạch lưới điện; Phương pháp không chỉ giúp kiểm tra được độ ổn định cũng như tính tối ưu độ dự trữ nút của hệ thống sau khi quy hoạch, mà còn xác định tập hợp tối ưu các tuyến dây cần được mở rộng, đề xuất thứ tự ưu tiên đầu tư từng tuyến nhằm tăng tính kinh tế. Phương pháp đề xuất được chứng minh trên hệ thống truyền tải cao áp thực tế với tổng số nút 24; Tỷ lệ độ dự trữ của hệ thống điện đến 20% ứng với mỗi mức tăng 5% thì chi phí đầu tư cũng tăng dần và hệ thống truyền tải đã đáp ứng nhu cầu phụ tải.

Từ khoá: *đánh giá độ tin cậy, hệ thống điện, hệ thống truyền tải, thuật toán cận biên và nhánh, tỷ lệ độ dự trữ*

ABSTRACT

The transmission system expansion planning problem aims to determine the optimal location, power, and the investment priority order of each line, ensuring long-term load prediction requirements with the objective of minimization of total investment cost. The proposed method is known as an effective tool in assessing reliability as well as in estimating optimal reserve of the planned transmission system. Moreover, the method helps to determine the optimal set of lines that need to be extended as well as to propose the investment priority order of each line in order to gain economic benefits. The effectiveness of the method is tested on a practical 24-bus system; The optimal reserve of the power system is to 20% for each 5% increase, the investment cost also increases and the transmission system meets the load demand.

Keywords: *reliability evaluation, power system, transmission system, branch and bound method, optimal reserve*

1. Giới thiệu

Nhiệm vụ cấp bách của hệ thống điện là đáp ứng yêu cầu phụ tải tăng với tốc độ nhanh, yêu cầu kỹ thuật cao và lợi ích kinh tế. Hệ thống điện cần được mở rộng và củng cố nhằm tăng khả năng đáp ứng yêu cầu phụ tải với độ tin cậy, chất lượng cao với giá thành thấp nhất [1]. Điều này sẽ rất khó có thể đạt được một giải pháp quy hoạch tối ưu toàn hệ thống điện bao gồm nhà máy điện, máy biến áp, đường dây truyền tải, phân phối và các thành phần khác một cách đồng

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thời. Bởi vì, hệ thống điện là một hệ thống lớn nên thời gian tính toán sẽ rất lớn. Chính vì thế các vấn đề quy hoạch hệ thống điện đã được chia ra làm nhiều lĩnh vực như quy hoạch hệ thống nguồn điện, hệ thống truyền tải và hệ thống phân phối [2].

Trong nhiều thập kỷ qua, quy hoạch và phát triển hệ thống nguồn điện đã được quan tâm và phát triển mạnh mẽ cả về phương pháp, giải thuật cũng như đầu tư. Trong khi đó quy hoạch và mở rộng hệ thống truyền tải chưa được quan tâm đúng mức. Quy hoạch và mở rộng hệ thống truyền tải là một nhiệm vụ rất quan trọng trong ngành điện, thường được thực hiện sau khi quy hoạch nguồn điện [3]. Các thiết kế tối ưu của quy hoạch mở rộng hệ thống truyền tải là một phần quan trọng của nhiệm vụ quy hoạch tổng thể của hệ thống điện trong thị trường điện cạnh tranh [1-5]. Nghiên cứu áp dụng phương pháp cận biên và nhánh để quy hoạch hệ thống truyền tải có xét đến điều kiện ràng buộc tối ưu hóa độ dự trữ cho hệ thống điện thực 24 nút. Điều này sẽ giải quyết vấn đề phát triển hệ thống truyền tải điện hiện nay và trong tương lai.

2. Nghiên cứu quy hoạch hệ thống truyền tải có xét tối ưu hóa độ dự trữ

2.1. Hàm mục tiêu

Thông thường quy hoạch hệ thống truyền tải là làm tối thiểu tổng chi phí đầu tư cùng với việc đầu tư mới đường dây hoặc máy biến áp được mô tả như:

$$\text{minimize } C^T = \sum_{(x,y)\in\rho}\left[\sum_{i=1}^{m(x,y)} C_{(x,y)}^{(i)} U_{(x,y)}^{(i)}\right] \quad (1)$$

Trong đó:

C_T là tổng chi phí xây dựng phần tử mới;

ρ là tổng số nhánh (đường dây, máy biến áp);

m(x,y) là số phần tử đưa vào giữa *x* và *y*;

$C_{(x,y)}^{(i)}$ là tổng chi phí lắp đặt phần tử mới từ 1 đến *i* giữa *x* và *y* [VNĐx10^9];

$$C_{(x,y)}^{(i)} = \sum_{j=1}^{i} \Delta C_{(x,y)}^{(j)} \quad (2)$$

Với $\Delta C_{(x,y)}^{(j)}$ là chi phí lắp đặt phần tử thứ *j* nối từ *x* và *y;*

$U_{(x,y)}^{(i)}$ là biến nhị phân thay đổi theo đường dây (*1* nếu từ *1* đến thứ *i* được lắp đặt, *0* cho các trường hợp khác):

$$U_{(x,y)}^{(i)} = \begin{cases} 1, \ khi \ P_{(x,y)} = P_{(x,y)}^{(0)} + P_{(x,y)}^{(i)} \\ 0, \ khi \ P_{(x,y)} \neq P_{(x,y)}^{(0)} + P_{(x,y)}^{(i)} \end{cases} \quad (3)$$

$$P_{(x,y)}^{(i)} = \sum_{j=1}^{i} \Delta P_{(x,y)}^{(j)} \quad (4)$$

Với $P_{(x,y)}^{(i)}$ là tổng công suất các nhánh mới giữa *x* và *y;*

$\Delta P_{(x,y)}^{(j)}$ là Với công suất 1 phần tử mới giữa *x* và *y;*

$P_{(x,y)}^{(0)}$ là công suất có sẵn nối giữa *x* và *y*.

2.2. Các điều kiện ràng buộc

Hệ thống điện không thiếu công suất cung cấp có nghĩa là tổng công suất của các nhánh thì lớn hơn hoặc bằng tổng công suất các tải [5]. Cũng tương tự như công suất nút thắt cổ chai (hoặc là dòng cực đại của hệ thống). Vì thế điều kiện không thiếu công suất cung cấp được mô tả công thức (5) như sau:

$$P_c(S,T) \geq L_p \qquad (s \in S, t \in T) \quad (5)$$

Trong đó: $P_c(S,T)$ là công suất mặt cắt tối thiểu; *S* và *T* là nút nguồn chứa *s* và nút tải chứa *t* tương ứng khi tất cả các nút bị chia ra bởi mặt cắt tối thiểu.

Điều kiện (5) có thể được mô tả bởi (6) với *k* là số mặt cắt (*k = 1,2,....,n*), *n* là số lượng mặt cắt.

$$\sum_{(x,y)\in(S_k,T_k)}\left[P^{(0)}_{(x,y)}+\sum_{i=1}^{m(x,y)}P^{(i)}_{(x,y)}U^{(i)}_{(x,y)}\right]\geq L_p(1+BRR/100) \quad (6)$$

Trong đó:

L_p là tổng tải yêu cầu;

$P^{(i)}_{(x,y)}$ là tổng công suất các nhánh mới giữa *x* và *y*;

$P^{(0)}_{(x,y)}$ là công suất đường dây hoặc máy biến áp giữa *x* và *y;*

k là số thứ tự mặt cắt (*k =1, 2, ..., n*);

m(x,y) là tổng số nhánh mới giữa nút *x* và nút *y;*

BRR (*Bus Reserve Rate*) là độ dự trữ tại nút phụ tải ($\frac{\sum AP-L}{L}$);

AP (*Arrival Power*) là công suất cực đại khi đến tải thanh cái.

2.3. Giới thiệu hệ thống điện truyền tải

Nghiên cứu này áp dụng cho lưới điện có mức điện áp từ 110kV đến 220kV, trên cơ sở kế hoạch xây dựng, vận hành hệ thống điện cùng với phát triển hệ thống nguồn và đã sử dụng kết quả dự báo nhu cầu phụ tải dài hạn.

Bảng 1. Dự báo nhu cầu phụ tải

Nút phụ tải	**Công suất cực đại (MW)**	**Nút phụ tải**	**Công suất cực đại (MW)**
1	119	14	85
2	600	15	65
3	200	16	48
4	200	17	33
5	183	18	31
6	48	19	31
9	275	20	24
10	215	21	36
11	64	22	25
12	126	23	25
13	80	24	49

2.4. Các thông số đầu vào lưới điện

Thông số đầu vào của hệ thống để tính toán quy hoạch cho lưới điện như trình bày tại Bảng 2. Trong đó : GN (*Generators*), TRF (*Transformers*), TRL (*Transmission Lines*) và LD (*Loads*) là đại diện cho các máy phát điện, máy biến áp, đường dây truyền tải và phụ tải tương ứng ; SB (*Start Buses*) và EB (*End Buses*) là các nút nguồn và thiết bị đầu cuối tương ứng ; T^0_{i-j} và C^0_{i-j} là chi phí đầu tư và công suất tương ứng của các ứng viên sẽ đầu tư ; T^k_{i-j} và C^k_{i-j}, k = 1 - 4 là số đường dây sẽ đầu tư song song với đường dây hiện hữu, với i và j là số nút đầu và nút cuối.

2.5. Kết quả quy hoạch

Công cụ giải bài toán quy hoạch này là phần mềm CMEXPP.FOR. Kết quả cho thấy, khi tăng độ dự trữ nút thanh cái từ 0 đến 20% thì hệ thống điện càng tin cậy, điều này sẽ tăng đầu tư nhiều đường dây, do đó chi phí đầu tư cũng tăng theo Bảng 3. Chính vì, nếu yêu cầu độ dự trữ nút thanh cái tăng thì chi phí đầu tư thực hiện quy hoạch mở rộng lưới điện sẽ tăng theo như trình bày tại Hình 1.

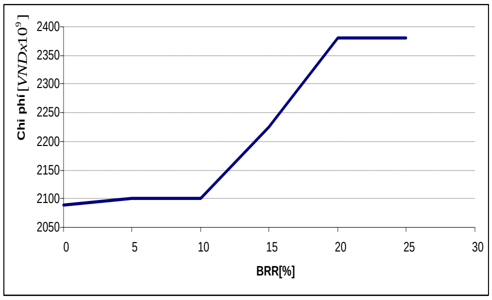
Bảng 2. Thông số đầu vào của quy hoạch lưới điện

$T^k_{i\text{-}j}$: (MW) and C(*): (VNĐx10^9)

L	SB	EB	ID	$T^0_{i\text{-}j}$	$T^1_{i\text{-}j}$	$T^2_{i\text{-}j}$	$T^3_{i\text{-}j}$	$T^4_{i\text{-}j}$	$C^0_{i\text{-}j}$	$C^1_{i\text{-}j}$	$C^2_{i\text{-}j}$	$C^3_{i\text{-}j}$	$C^4_{i\text{-}j}$
1	0	1	GEN	800	0	0	0	0	0	0	0	0	0
2	0	2	GEN	1200	0	0	0	0	0	0	0	0	0
3	0	3	GEN	800	0	0	0	0	0	0	0	0	0
…	…	…	…	…	…	…	…	…	…	…	…	…	…
6	1	6	TRF	250	250	250	250	0	0	10	10	10	0
7	2	7	TRF	500	250	250	250	0	0	10	10	10	0
8	3	8	TRF	125	250	250	250	0	0	10	10	10	0
…	…	…	…	…	…	…	…	…	…	…	…	…	…
11	3	4	TRL	285	285	285	285	0	0	641	641	641	0
12	6	16	TRL	80	80	80	80	0	0	83	83	83	0
13	6	17	TRL	93	93	93	93	0	0	20	20	20	0
…	…	…	…	…	…	…	…	…	…	…	…	…	…
32	1	25	LOD	119	0	0	0	0	0	0	0	0	0
33	2	25	LOD	600	0	0	0	0	0	0	0	0	0
34	3	25	LOD	200	0	0	0	0	0	0	0	0	0
…	…	…	…	…	…	…	…	…	…	…	…	…	…
51	22	25	LOD	25	0	0	0	0	0	0	0	0	0
52	23	25	LOD	25	0	0	0	0	0	0	0	0	0
53	24	25	LOD	49	0	0	0	0	0	0	0	0	0

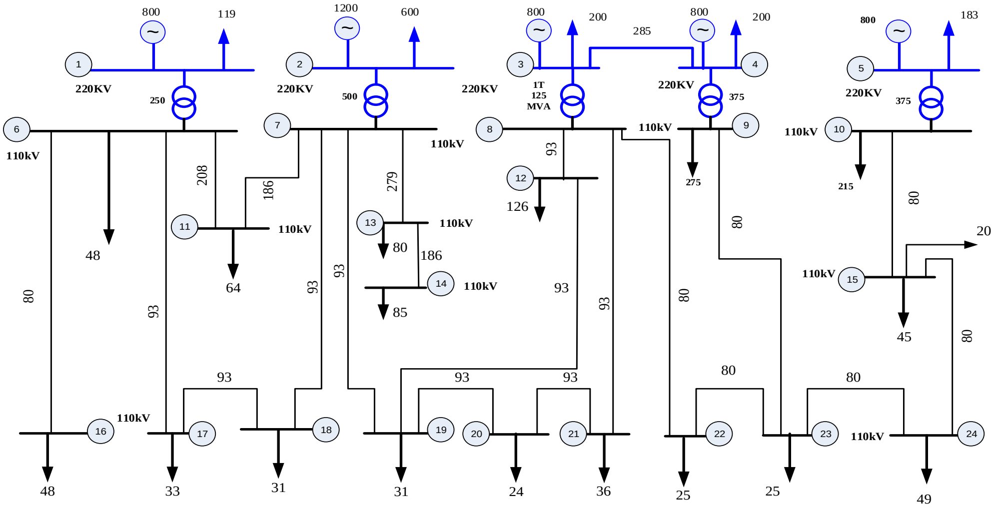
Bảng 3. Kết quả quy hoạch và mở rộng lưới điện theo độ dự trữ

TH	BRR [%]	ĐẦU TƯ THÊM	Chi phí [VNĐx10^9]
1	0	T_{3-8}^{1}, T_{3-8}^{2}, T_{3-4}^{1}, T_{7-19}^{1}, T_{7-19}^{2}, T_{8-12}^{1}, T_{20-21}^{1}, T_{19-20}^{1}, T_{8-21}^{1}, T_{12-19}^{1}, T_{10-15}^{1}	2089
2	5	T_{3-8}^{1}, T_{3-8}^{2}, T_{3-8}^{3}, T_{3-4}^{1}, T_{7-19}^{1}, T_{7-19}^{2}, T_{8-12}^{1}, T_{20-21}^{1}, T_{19-20}^{1}, T_{8-21}^{1}, T_{12-19}^{1}, T_{10-15}^{1}	2099
3	10	T_{3-8}^{1}, T_{3-8}^{2}, T_{3-8}^{3}, T_{3-4}^{1}, T_{7-19}^{1}, T_{7-19}^{2}, T_{8-12}^{1}, T_{20-21}^{1}, T_{19-20}^{1}, T_{8-21}^{1}, T_{12-19}^{1}, T_{10-15}^{1}	2099
4	15	T_{3-8}^{1}, T_{3-8}^{2}, T_{3-8}^{3}, T_{3-4}^{1}, T_{7-19}^{1}, T_{7-19}^{2}, T_{8-12}^{1}, T_{8-12}^{2}, T_{12-19}^{1}, T_{12-19}^{2}, T_{10-15}^{1}	2225
5	20	T_{3-8}^{1}, T_{3-8}^{2}, T_{3-8}^{3}, T_{3-4}^{1}, T_{7-19}^{1}, T_{7-19}^{2}, T_{7-19}^{3}, T_{8-12}^{1}, T_{8-12}^{2}, T_{12-19}^{1}, T_{12-19}^{2}, T_{10-15}^{1}	2381
6	25	T_{3-8}^{1}, T_{3-8}^{2}, T_{3-8}^{3}, T_{3-4}^{1}, T_{7-19}^{1}, T_{7-19}^{2}, T_{7-19}^{3}, T_{8-12}^{1}, T_{8-12}^{2}, T_{12-19}^{1}, T_{12-19}^{2}, T_{10-15}^{1}	2381



Hình 1. Đường cong tổng chi phí đầu tư theo yêu cầu độ dự trữ BRR[%]

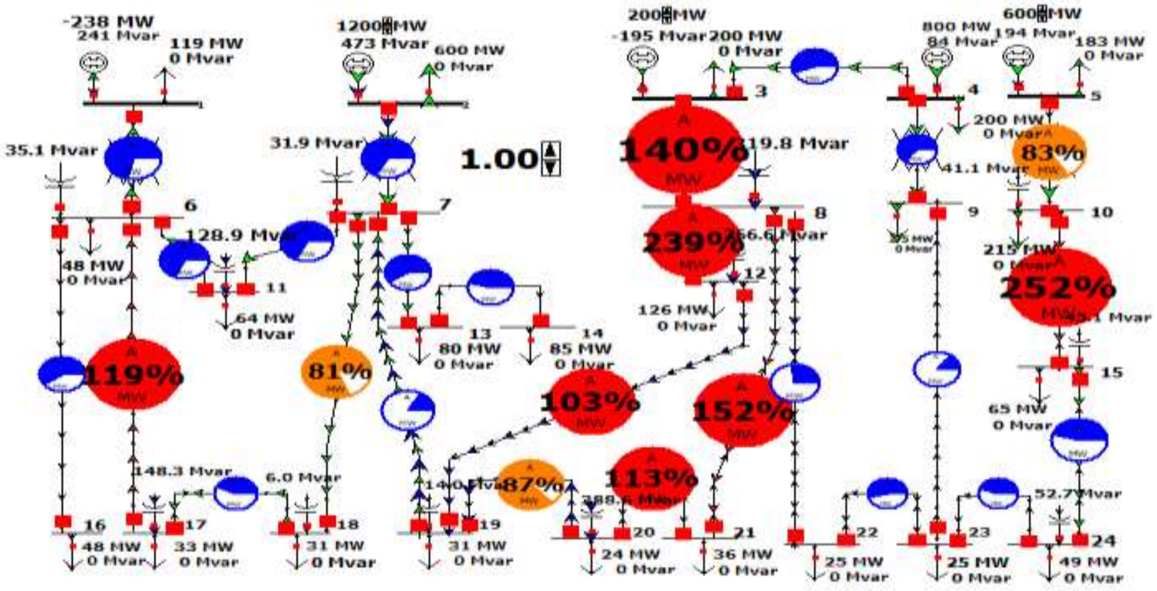
Sơ đồ đơn tuyến hệ thống truyền tải sẽ được mở rộng nhằm đáp ứng yêu cầu phụ tải tăng như trình bày tại Hình 2.



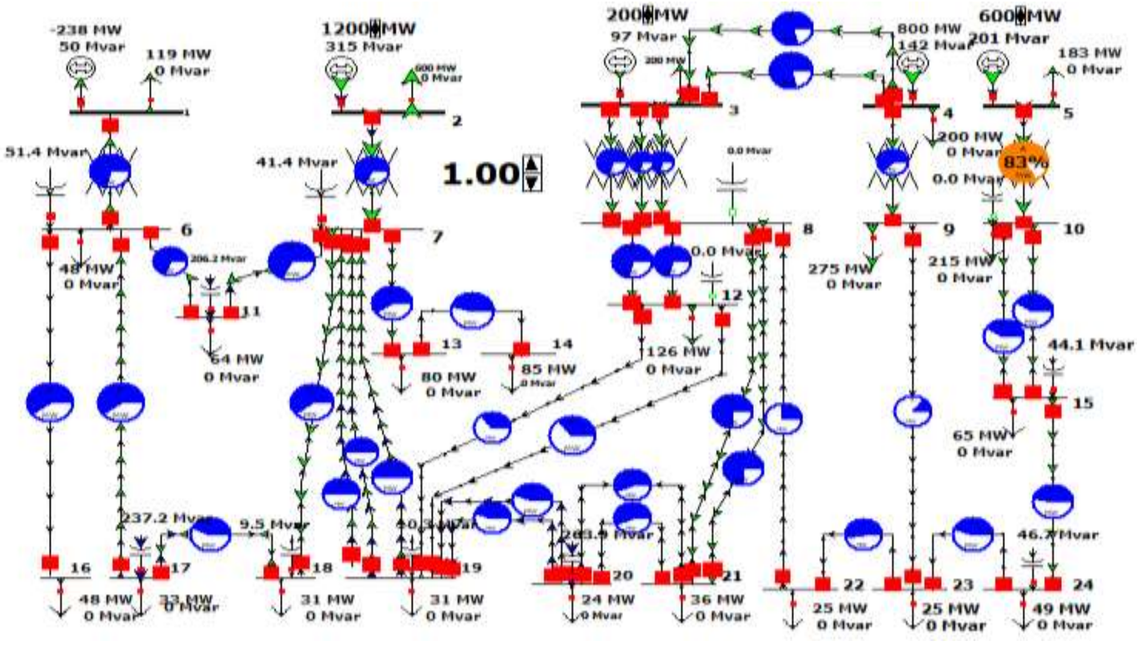
Hình 2. Sơ đồ đơn tuyến hệ thống truyền tải (BRR=5%)

2.6. Kiểm tra phân bố công suất bằng phần mềm PowerWord

Kiểm tra độ ổn định và khả năng tải của đường dây và máy biến áp sau khi quy hoạch sử dụng phần mền PowerWord. Hình 3 thể hiện hệ thống truyền tải trước quy hoạch, chỉ ra đường dây và trạm biến áp mang quá tải trên 90% thì hệ thống truyền tải có 7 trường hợp bị quá tải. Sau khi quy hoạch lại theo kết quả trình bày tại Bảng 3 thì hệ thống truyền tải đã ổn định không có trường hợp nào bị quá tải vượt 90%. Điều này được thể hiện ở Hình 4, hệ thống truyền tải đã được đầu tư mở rộng theo yêu cầu của độ dự trữ BRR = 5%.



Hình 3. Hệ thống trước khi kiểm tra quy hoạch



Hình 4. Hệ thống sau khi kiểm tra quy hoạch với độ dự trữ BRR=5%

3. Kết luận

Việc áp dụng phương pháp cộng biên và nhánh đã giải bài toán quy hoạch tối ưu xác định được tập tối ưu các đường dây sẽ đầu tư sao cho chi phí thấp nhất, vị trí theo độ dự trữ. Nghiên cứu không chỉ áp dụng thành công phương pháp tối ưu độ dự trữ trong quy hoạch hệ thống truyền tải mà còn sử dụng công cụ phần mềm PowerWorld để kiểm tra hệ thống sau khi quy hoạch. Giải thuật đã chứng minh tính khả thi trên quy hoạch dài hạn lưới điện cao áp.

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Transmission System Expansion Planning in Consideration of Reliability Criteria and Optimal Reserve

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Abstract. Life will not exist if it has no energy. Electricity has been a vital part human civilization in both recent time and future. All of the industrial devices and appliances cannot operate without electricity. Therefore, planning and expanding power systems is an extremely important task for operators and managers. In this research, the branch and bound method has been applied to deal with the network planning problems. The proposed method is known as an effective tool in assessing reliability as well as in estimating optimal reserve of the planned transmission system. The effectiveness of this approach will be illustrated in this case study by using the 35-node high-voltage and ultra high-voltage transmission system.

Keywords: Branch and bound · Optimal integer function · Transmission system · Reliability criteria · Optimal reserve

1 Introduction

The fundamental objective of transmission expansion planning is not only to determine the placements but also to specify the sizes of addition plans of new facilities to meet the forecasted demand (in 10–15 years) of minimum cost, satisfying prescribed budget and reliability criteria at the same time. A research on transmission expansion planning is a hot task of the Vietnam power system now.

This research proposed a practical approach to obtain optimum transmission expansion planning at minimum cost but still keep reliability level, which is deterministic reliability criterion (load buses reserve rate BRR). Especially, this research is also to determine the construction priority of new transmission lines and to consider operation mode of new power system.

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2 Optimal Transmission System Expansion Planning

2.1 Objective Function

The static transmission system expansion problem can be stated as follows. Given the generation and load patterns in a target in the future, find a set of transmission line additions to minimize the total investment cost, subject to load constraints, reliability constraints, reserve constraints and right of way constraints [2].

$$minimize \quad C^T = \sum_{(x,y)\in B} \left[\sum_{i=1}^{m(x,y)} C^i_{(x,y)} U^i_{(x,y)} \right] \tag{1}$$

where, C^T: the total construction cost of new equipment.

B: a set of all branches.

$m(x,y)$: the number of new branches between nodes x and y.

$C^i_{(x,y)}$: total construction cost of new branches between node x and y *[M$]*.

$$C^i_{(x,y)} = \sum_{j=1}^{i} \Delta C^i_{(x,y)} \tag{2}$$

$\Delta C^i_{(x,y)}$: construction cost of new *#i* parallel element of branches.

$U^i_{(x,y)}$: decision variable associated with the line.

$$U^{(i)}_{(x,y)} = \left[\begin{array}{l} 1 \; P_{(x,y)} = P^{(0)}_{(x,y)} + P^{(i)}_{(x,y)} \\ 0 \; P_{(x,y)} \neq P^{(0)}_{(x,y)} + P^{(i)}_{(x,y)} \end{array} \right. \tag{3}$$

$$P^i_{(x,y)} = \sum_{j=1}^{i} \Delta P^j_{(x,y)}$$

where, $P^i_{(x,y)}$: capacity of transmission line or generator between node x and y.

$\Delta P^i_{(x,y)}$: capacity of new *#i* parallel element of branches.

$P^0_{(x,y)}$: capacity of branches between node x and y.

2.2 Constraint Conditions

No power supply shortage requires that the total capacity of the branches involved in the minimum cut-set should be greater or equal to the total load of the system [5]. This is also referred to as the bottleneck capacity [4].

$$P_c(X, \overline{X}) \geq L \qquad (s \in X, t \in \overline{X}) \tag{4}$$

The demand constraint can be formulated by Eq. (5)

$$\sum_{(\mathrm{x,y})\in(\mathrm{x_k}, \overline{\mathrm{x}}_\mathrm{k})} \left[\mathrm{P}^{(0)}_{(\mathrm{x,y})} + \sum_{\mathrm{i}=1}^{\mathrm{m(x,y)}} \mathrm{P}^{(\mathrm{i})}_{(\mathrm{x,y})} \mathrm{U}^{\mathrm{i}}_{(\mathrm{x,y})} \right] \geq \mathrm{L(1 + BRR/100)} \tag{5}$$

where, L: total demand.

$P(x,y)$: capacity of transmission line or generator between node x and y.

$\Delta C^{(j)}_{(x,y)}$: construction cost of new #*j* parallel element of branches.

$\Delta P^{(j)}_{(x,y)}$: capacity of new #*j* parallel element of branches.

k: cut-set subscript number (=*1, 2, k, n*)

BRR: load bus reserve rate $\left(=\frac{\sum AP-L}{L}\right)$.

AP: maximum arrival power at load bus.

The second condition requires the reliability standard of management [3] which outlines in the formula:

$$LOLE_{SYS}(P^{(i)}_{(x,y)}, \Phi) \leq {}_{R}LOLE \tag{6}$$

where, ${}_{R}LOLE$: the required transmission reliability criterion for the new system.

$LOLE_{SYS}$: the transmission system reliability criterion case.

LOLE: loss of load expectation.

2.3 Flow Chart

See Fig. 1.

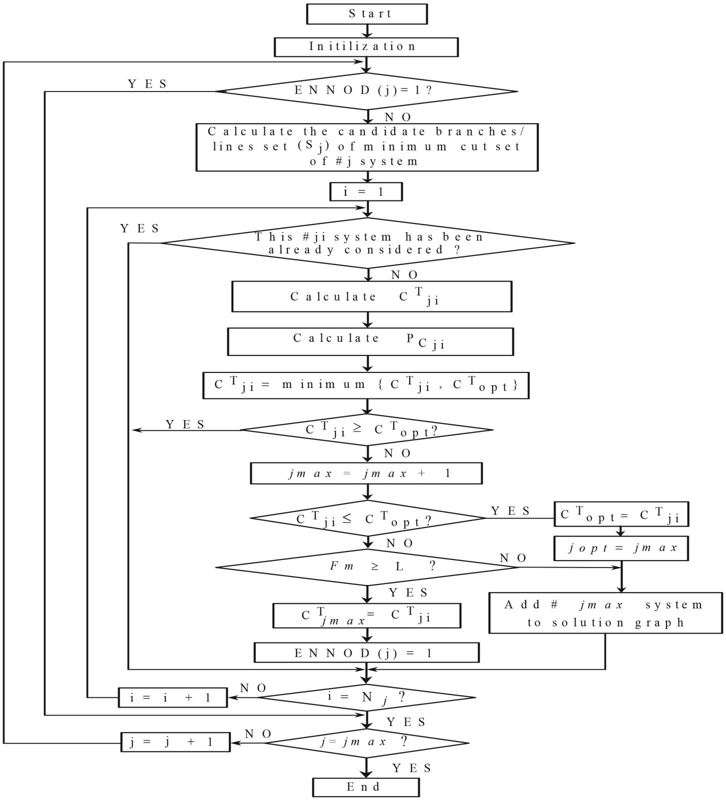

Fig. 1. Flow chart

3 Case Studies

3.1 Introduction of Power Systems

This study applied to a higher voltage of power system on the construction and operation system with the developmental source system (Table 1).

Table 1. Forecast of supply power systems

Load bus number	P_{max} (MW)	Load bus number	P_{max} (MW)	Load bus number	P_{max} (MW)	Load bus number	P_{max} (MW)
1	580	10	350	18	120	32	343
2	125	11	343	20	240	33	300
3	6000	12	450	27	200	34	200
4	350	14	407	28	800		
7	475	16	350	30	200		

3.2 Input Parameters

SB and EB are the start and end buses, respectively. $\Delta P_{(x,y)}^{(0)}[MW]$ and $\Delta C_{(x,y)}^{(0)}[M\$]$ are the capacity and cost of constructing the original transmission lines or generators. $\Delta P_{(x,y)}^{(i)}$ $[MW]$ and $\Delta C_{(x,y)}^{(i)}[M\$]$, *for* $k = 1–4$ are respectively, the capacity and cost of the candidate lines. Where subscripts *i* and *j* are numbers of starting and end buses (Table 2).

Table 2. Capacity and cost data

NL	SB	EB	$\Delta P_{(x,y)}^{(0)}$ [MW]	$\Delta P_{(x,y)}^{(1)}$ [MW]	$\Delta P_{(x,y)}^{(2)}$ [MW]	$\Delta P_{(x,y)}^{(3)}$ [MW]	$\Delta P_{(x,y)}^{(4)}$ [MW]	$\Delta C_{(x,y)}^{(0)}$ [M$]	$\Delta C_{(x,y)}^{(1)}$ [M$]	$\Delta C_{(x,y)}^{(2)}$ [M$]	$\Delta C_{(x,y)}^{(3)}$ [M$]	$\Delta C_{(x,y)}^{(4)}$ [M$]
1	0	1	183	0	0	0	0	0	0	0	0	0
2	0	2	2800	0	0	0	0	0	0	0	0	0
3	0	8	1518	0	0	0	0	0	0	0	0	0
…	…	…	…	…	…	…	…	…	…	…	…	…
69	32	36	343	0	0	0	0	0	0	0	0	0
70	11	36	343	0	0	0	0	0	0	0	0	0
71	29	36	2390	0	0	0	0	0	0	0	0	0

3.3 Transmission Expansion Planning Results

CMEXPP.FOR software solved this planning problem. The reliability standard of this study investigated the reliability standard (N-2TL) which the power system accepted two damaged lines (Table 3).

Table 3. Optimal transmission expansion planning

Case	${}_{R}$LOLE [hrs/yr]	Construction of new lines	Cost [M$]
(N-2TL)	5,000	$T^{1}{}_{32-14}$, $T^{1}{}_{9-10}$	20
	4,600	$T^{1}{}_{32-14}$, $T^{1}{}_{9-10}$, $T^{1}{}_{11-12}$	30
	4,500	$T^{1}{}_{32-14}$, $T^{1}{}_{9-10}$, $T^{1}{}_{11-12}$, $T^{1}{}_{6-7}$	37

The reserve substations of the planning system had broken 2 elements (N-2TL) considering the reliability index of power system is shown in Table 4.

Table 4. Reserve substations of the planning system

From	To	Reserve rate (%)			From	To	Reserve rate (%)		
		${}_{R}$LOLE = 4,500 [hrs/yr]	${}_{R}$LOLE = 4,600 [hrs/yr]	${}_{R}$LOLE = 5,000 [hrs/yr]			${}_{R}$LOLE = 4,500 [hrs/yr]	${}_{R}$LOLE = 4,600 [hrs/yr]	${}_{R}$LOLE = 5,000 [hrs/yr]
1	5	100.00	100.00	100.00	21	35	100.00	100.00	100.00
3	31	41.67	41.67	47.22	22	34	100.00	100.00	100.00
6	7	5.00	0.00	0.00	23	33	100.00	100.00	100.00
9	10	6.67	6.67	6.67	24	27	100.00	100.00	100.00
11	12	10.00	10.00	0.00	25	30	88.89	88.89	88.89
13	32	60.11	60.11	60.11	26	28	55.56	55.56	55.56
15	16	0.00	0.00	0.00	29	2	100.00	100.00	100.00
17	18	4.00	4.00	4.00	31	4	53.33	53.33	53.33
19	20	4.00	4.00	4.00	32	14	0.00	0.00	0.00

4 Conclusion

This study applies a methodology for deciding the optimal reliability criterion for transmission system expansion planning. A deterministic reliability index, BRR is used in this study. A strong point of this method is the use of very little input data which solves transmission system planning in considering of reliability criteria and optimal reserve. In addition, this method can apply for larger power system.

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OPTIMAL TRANSMISSION EXPANSION PLANNING USING CROW SEARCH ALGORITHM

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Abstract. This paper proposes an application of Crow Search Algorithm (CSA) to solve the static transmission expansion planning (STEP) problem in power systems based on the DC power flow model. The main objective of the problem is to minimize the investment cost of transmission lines in addition to the existing network in order to supply the forecasted load as an economical manner subject to many system constraints including the power balance, the generation capacity requirements, line capacity connections and thermal limits. To validate the study, the transmission system is analyzed to appraise the feasibility of the CSA. The compared results have shown that the proposed CSA method has outperformed the other methods in terms of convergence characteristic and computational efficiency. Therefore, the proposed CSA can be a favorable method for dealing the optimal transmission expansion planning problem in power systems.

1. Introduction

The transmission expansion planning (TEP) is not only to determine the placements but also to specify the sizes of addition plans of new facilities (transformers, transmission lines and other network equipments) to meet the forecasted demand (in 10 – 15 years) of minimum cost, satisfying prescribed budget and reliability criteria at the same time [1]. Models of TEP can be categorized as static or dynamic according to the treatment of the study period[2]. Static planning involves single horizontal planning and answers the questions of *what* type of and *where* new equipment should be installed in a way that minimizes the installation and operational costs.

This study introduces the application of CSA to the DC power flow-based model for solving the static TEP. The results obtained by CSA are compared to those obtained by conventional approaches i.e. Genetic Algorithm (GA) [3] and Tabu Search (TS) [4] methods in term of solution quality, convergence characteristic and computational efficiency.

2. Methodology

2.1. Problem formulation

2.1.1. Objective Function of TEP

The objective function of TEP is to minimize the investment cost of transmission lines subjected to constraints[6]. In this study, the classical DC power flow model is used for static TEP, which can be calculated as:

$$minimize\ C_T = \sum_{i,j \epsilon \Omega} c_{ij} n_{ij} \qquad (1)$$

Where C_T is the total investment cost of transmission lines.

c_{ij} is the cost of a circuit to be added to the right-of-way *i-j*.

n_{ij} is the number of circuits added to the right-of-way *i-j*.

Ω is the set of all rights-of-way *i-j*.

2.1.2. Constraints

a. Equality constraints.

- *Power Balance*

This constraint represents the conservation of power in each node[7].

$$SP_i + P_g - P_d = 0 \tag{2}$$

Based on the above assumptions, the DC load flow can be obtained by the following equation.

$$P_i = \sum_{j=1}^{N}\left(B_{ij}\left(\theta_i - \theta_j\right)\right); i = 1,2,3,\dots N \tag{3}$$

where S is the branch-node incidence transposed matrix.

P_i is the real power flow injection at bus i .

P_g is generation injection of nodes (generation in bus k).

P_d is the load demand vector in all networks nodes.

B_{ij} is the susceptance matrix of the existing and added lines in the network.

N is the total number of buses in the system.

- *Kirchoff's voltage law (KVL)*

This law is the conservation of energy in the equivalent DC network Subject to constraints that are nonlinear.

$$P_{ij} - b_{ij}\left(n_{ij}^{0} + n_{ij}\right)\left(\theta_i - \theta_j\right) = 0 \tag{4}$$

where P_{ij} is the power flow in branch i - j.

b_{ij} is the susceptance in the right-of-way i - j.

n^{0}_{ij} is the number of circuits in the original base system.

θ_i, θ_j is the phase angle of the terminal bus i and j .

b. Inequality constraints

- *Transmission capacity limit or power flow limit.*

These constraints can represent the maximum power of the transmission line that can be carried based on thermal and dynamic stability considerations[9].

$$\left|P_{ij}\right| \leq \left(n_{ij}^{0} + n_{ij}\right).P_{ij}^{max} \tag{5}$$

Where P_{ij}^{max} is the maximum branch power flow in the right-of-way i-j

- *Power generating limit*

These constraints give the maximum and minimum generating capacities, outside of which it is not feasible to generate power due to technical or economic reasons.

$$P_g^{min} \leq P_g \leq P_g^{max} \tag{6}$$

where P_g^{min} is the minimum active power output generated at bus k .

P_g^{max} is the maximum active power output generated at bus k .

- *Right-of-way limit*

The constraint defines the line location and the maximum number of lines that can be installed in a specified location. It is represented as follow:

$$0 \leq n_{ij} \leq n_{ij}^{max} \tag{7}$$

Where n_{ij}^{max} is the maximum number of circuits that can be added in the right-of-way i-j.

2.2. Crow Search Algorithm

Crows (crow family or corvids) are considered the most intelligent birds[8]. They contain the largest brain relative to their body size. Based on a brain-to-body ratio, their brain is slightly lower than a human brain. Evidences of the cleverness of crows are plentiful. They have demonstrated self-awareness in mirror tests and have tool-making ability. Crows can remember faces and warn each other when an unfriendly one approaches. Moreover, they can use tools, communicate in sophisticated ways and recall their food's hiding place up to several months later.

Crows have been known to watch other birds, observe where the other birds hide their food, and steal it once the owner leaves. If a crow has committed thievery, it will take extra precautions such as moving hiding places to avoid being a future victim. In fact, they use their own experience of having been a thief to predict the behavior of a pilferer, and can determine the safest course to protect their caches from being pilfered.

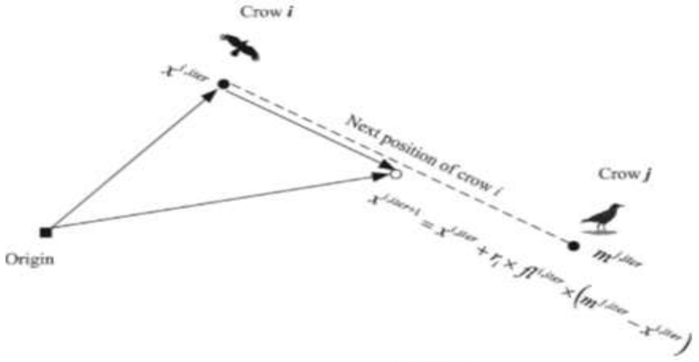
It is assumed that there is a *d*-dimensional environment including a number of crows. The number of crows (flock size) is *N* and the position of crow *i* at time (iteration) iter in the search space is specified by a vector $x^{i,iter}$ $(i = 1,2,3, \ldots ,N; \;\; iter= 1, 2, \ldots , iter_{max})$ where $x^{i,iter} =[x_1^{i,iter} , x_2^{i,iter} , \ldots , x_d^{i,iter}]$ and $iter_{max}$ is the maximum number of iterations. Each crow has a memory in which the position of its hiding place is memorized. At iteration *iter*, the position of hiding place of crow *i* is shown by $m^{i,iter}$. This is the best position that crow *i* has obtained so far. Indeed, in memory of each crow the position of its best experience has been memorized. Crows move in the environment and search for better food sources (hiding places). Assume that at iteration *iter*, crow *j* wants to visit its hiding place, $m^{j,iter}$. At this iteration, crow *i* decides to follow crow *j* to approach to the hiding place of crow *j*. In this case, two states may happen:

State 1: Crow *j* does not know that crow *i* is following it. As a result, crow *i* will approach to the hiding place of crow *j*. In this case, the new position of crow *i* is obtained as follows:

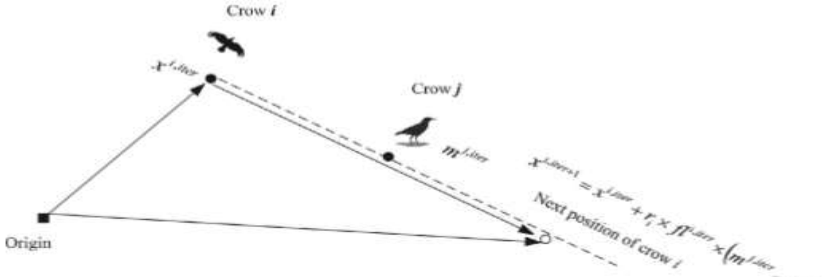
$$x^{i,iter+1} = x_1^{i,iter} + r_i \, fl^{i,iter} (m^{i,iter} - x^{i,iter}) \tag{7}$$

where r_i is a random number with uniform distribution between *0* and *1* and $fl^{i,iter}$ denotes the flight length of crow *i* at iteration *iter*.

Fig. 1 shows the schematic of this state and the effect of *fl* on the search capability.



(a) *fl* < 1



(b) *fl* > *1*

Fig. 1. Flowchart of state 1 in CSA (a) fl < 1 and (b) fl > 1. Crow I can go to every position on the dash line.

State 2: Crow *j* knows that crow *i* is following it. As a result, in order to protect its cache from being pilfered, crow *j* will fool crow *i* by going to another position of the search space. Totally, states *1* and *2* can be expressed as follows:

$$x^{i,iter+1} = \begin{cases} x_1^{i,iter} + r_i \, fl^{i,iter} (m^{i,iter} - x^{i,iter}) & r_j \geq AP^{j,iter} \\ a \; random \; position & otherwise \end{cases} \tag{8}$$

where r_j is a random number with uniform distribution between *0* and *1* and $AP^{j,iter}$ denotes the awareness probability of crow *j* at iteration *iter*.

2.3. CSA implementation for TEP

The step-wise procedure for the implementation of CSA is given in this section.

Step 1: Initialize problem and adjustable parameters The optimization problem, decision variables and constraints are defined. Then, the adjustable parameters of CSA (flock size (N), maximum number of iterations ($iter_{max}$), flight length (*fl*) and awareness probability (*AP*)) are valued.

Step 2: Initialize position and memory of crows *N* crows are randomly positioned in a d-dimensional search space as the members of the flock. Each crow denotes a feasible solution of the problem and *x* is the number branch of decision variables.

$$Crows = \begin{bmatrix} x_1^1 & x_2^1 & \dots & x_d^1 \\ x_1^2 & x_2^2 & \cdots & x_d^2 \\ \dots & \dots & \cdots & \dots \\ x_1^N & x_2^N & \dots & x_d^N \end{bmatrix}$$

The memory of each crow is initialized. Since at the initial iteration, the crows have no experiences, it is assumed that they have hidden their foods at their initial positions.

$$Memory = \begin{bmatrix} m_1^1 & m_2^1 & \dots & m_d^1 \\ m_1^2 & m_2^2 & \cdots & m_d^2 \\ \dots & \dots & \cdots & \dots \\ m_1^N & m_2^N & \dots & m_d^N \end{bmatrix}$$

Step 3: Evaluate fitness (objective) function For each crow, the quality of its position is computed by inserting the decision variable values into the objective function.

Step 4: Generate new position Crows generate new position in the search space as follows: suppose crow *i* wants to generate a new position. For this aim, this crow randomly selects one of the flock crows (for example crow *j*) and follows it to discover the position of the foods hidden by this crow (m_j). The new position branch of crow *i* is obtained by Eq. (8). This process is repeated for all the crows.

Step 5: Check the feasibility of new position branches

The feasibility of the new position branch of each crow is checked. If the new position of a crow is feasible, the crow updates its position. Otherwise, the crow stays in the current position branch and does not move to the generated new position.

Step 6: Evaluate fitness function of new position branches. The fitness function value for the new position of each crow is computed.

Step 7: Update memory The crows update their memory as follows:

$$m^{i,iter+1} = \begin{cases} x^{i,iter+1} & f\left(x^{i,iter+1}\right) \text{ is better than } f(m^{i,iter}) \\ m^{i,iter} & \text{otherwise} \end{cases}$$

where *f(.)* denotes the objective function value. It is seen that if the fitness function value of the new position of a crow is better than the fitness function value of the memorized position, the crow updates its memory by the new position branch.

Step 8: Check termination criterion *Steps 4–7* are repeated until itermax is reached. When the termination criterion is met, the best position of the memory in terms of the objective function value is reported as the solution of the optimization problem.

3. Results and Discussion

The TEP-CSA method was tested on the well-known Garver's 6-bus test system shown in Fig. 2. The Garver system has 6 buses and 15 candidate branches [5]. The total demand is 760 MW and the relevant data are given in Tables 1 and 2. The maximum possible number of added lines (right-ofway limit) per branch equals four.

The result of the optimal planning solution for Garver's system is $n_{24} = 4$, $n_{35} = 1$, and $n_{46} = 2$ as shown in Fig. 3. The simulation was made for comparison to the GA and TS methods. All methods were performed for 10 trials, under the same evaluation function and individual definition, in order to compare their solution quality, convergence characteristic, and computational efficiency.

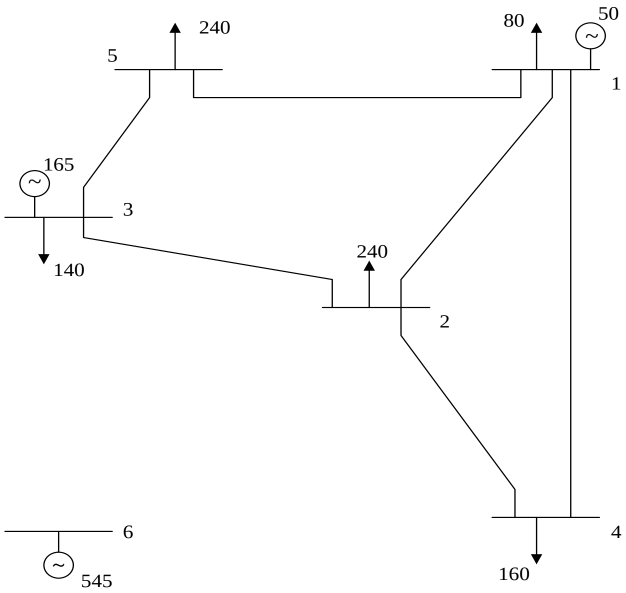


Figure 2. Initial configuration of Garver's 6-bus network

Table 1. Generation and load data for Garver's 6-bus system.

Bus	**Generation (MW)**		**Demand (MW)**
	Max.	**Level**	
1	150	50	80
2	-	-	240
3	360	165	40
4	-	-	160
5	-	-	240
6	600	545	-

Table 2. Branch data for Garver's 6-bus system

From-To(Ω)	n_{ij}**0**	**r (p.u)**	**x (p.u)**	P_{ij}**max**	**Cost (x 10^3 $)**
1-2	1	0.10	0.40	100	40
1-3	0	0.09	0.38	100	38
1-4	1	0.15	0.60	80	60
1-5	1	0.05	0.20	100	20
1-6	0	0.17	0.68	70	68
2-3	1	0.05	0.20	100	20
2-4	1	0.10	0.40	100	40
2-5	0	0.08	0.31	100	31
2-6	0	0.01875	0.30	100	30
3-4	0	0.15	0.59	82	59
3-5	1	0.25	0.20	100	20
3-6	0	0.12	0.48	100	48
4-5	0	0.16	0.63	75	63
4-6	0	0.0375	0.30	100	30
5-6	0	0.15	0.61	78	61

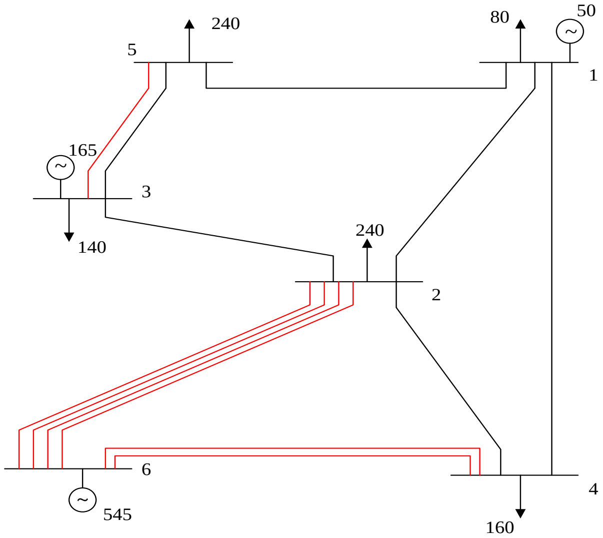


Figure 3. Optimal plan of Garver's 6-bus system.

Table 3. Results of Garver's 6-bus Test System.

Method	n_{ij}	**Investment cost (10^3\$)**			**Standard Deviation**	**Used Time (s)**
		Worst	**Average**	**Best**		
GA	7	368	227	200	41.27	46.686
TS	7	244	218	200	26.56	36.983
CSA	7	200	200	200	0	15.72

4. Conclusion

This proposed study is a novel approach for adopting and CSA to solve a TEP problem that works corporately with the DC power flow model. The proposed method with Garver's 6-bus test system which gives a good performance in comparison to the conventional GA and TS methods in terms of less calculation time, better quality of solution and more stable-convergence characteristic. In the future, the CSA method will apply a large power system.

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A Search Method for Power Transmission System Planning Problem in Ben Tre Province, Vietnam

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Abstract Energy is one of the essential factors for the existence and development of society and is also an issue that attracts the attention of all countries at all times. It is impossible to imagine a day when energy no longer exists in human activities, especially in this day and age. In the era when science and technology are developing more and more, people have gradually restored nature and mastered their lives. Power system planning and expansion are one of the most important tasks for power system managers and operators. This study proposes the application of a transmission system expansion method that not only meets the requirements of long-term load prediction but also satisfies the reliability standard of the transmission system with the objective function of minimizing total investment cost. The algorithm is built on the integer optimization function and uses the optimal solution according to the bound and branch method.

Keywords Grid expansion · Bound and branch method · Integer optimization

1 Introduction

The electricity industry is one of the key industries attracting investors due to the economic growth rate and the increasing demand for electricity. The electricity demand has continuously increased over the years. The State has continuously mentioned, considered, and organized research on this issue. However now, many

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problems still need to be studied further, and the power system still needs to be expanded and developed. Development planning policies must forecast the demand and ability to meet the energy demand based on the country's energy potential to formulating optimal development strategies for the system, from the power source development planning to the transmission and distribution of electricity.

This paper proposes an approach to transmission system expansion planning. The branch and bound algorithm, include the network flow theory. A maximum flow-minimum cut set theorem is proposed to obtain the optimal solution with the highest satisfaction level of the decision maker. Solve the problem of planning the transmission expansion planning [1–5]. The effectiveness of the proposed approach algorithm is demonstrated by testing it on a 16-bus test system in Ben Tre. The following are the assumption used:

- A network flow method considering active power is used.
- The network flow method is sufficient for the long-term planning problem.
- The problem is limited to a static expansion-planning problem.

2 Transmission Expansion Planning

2.1 Objective Function

The objective function of transmission expansion planning is to reduce the investment costs of transmission lines that are physically and economically constrained [1–4]. This study applies the bound and branch algorithms to solve the grid expansion and planning problem [5]. The study gives beneficial results to managers before making investment decisions. The objective function of the problem is to minimize the total investment cost presented by as follows:

$$minimize \quad C^T = \sum_{(x,y)\in B} \left[\sum_{i=1}^{m(x,y)} C^i_{(x,y)} U^i_{(x,y)} \right] \tag{1}$$

where

C^T: is the total cost of installing new transmission lines.

ρ: is the total number of branches (transmission lines).

m(x,y): is the number of new branches connected to the node between x and y.

$C^{(i)}_{(x,y)}$: is the total cost of installing a new branch connected to the node between x and y [M$].

$U^{(i)}_{(x,y)}$: is a variable that varies with the line (*1* if from *1* to *i-th* is constructed, *0* for otherwise).

2.2 Inequality Constraints

Initially controlling the resistance after expanding the grid, the system must ensure the power supply required by the long-term load prediction [6] as shown in the following equation:

$$\sum_{(x,y)\in(S_k T_k)} \left[P_{(x,y)}^{(0)} + \sum_{i=1}^{m(x,y)} P_{(x,y)}^{(i)} U_{(x,y)}^{(i)} \right] \geq L_p \tag{2}$$

where

$P_{(x,y)}^{(0)}$: is the total capacity of new branches between *x* and *y*.

$P_{(x,y)}^{(i)}$: is the available capacity connecting *x* and *y*.

The second condition is to satisfy the requirements of the desired manager's reliability standard as presented by [3]:

$$LOLE_{SYS}\left(P_{(x,y)}^{(i)}\right) \leq {}_{R}LOLE \tag{3}$$

where

$_{R}LOLE$: is the criterion of the desired system reliability index.

$LOLE_{SYS}$: is the system reliability index after planning.

LOLE: is the expected number of days or hours in a survey period when the maximum load exceeds the available capacity.

When measuring the number of days without sources during the survey period, the indicator of lack of resources (*LOLE*) is determined according to the following equation:

$$LOLE = \sum_{i=1}^{n} K_i P_i (C_i - L_i) \tag{4}$$

where

C_i: is the available capacity on day *i*.

L_i: is the load peak predicted day *i*.

$P_i(C_i\text{-}L_i)$: is the probability of lack of power.

K_i: is the number of days with the probability of missing the source P_i.

2.3 The Proposed Branch and Bound-Based Method

$$\left.\begin{array}{l} Maximize \quad \lambda \\ Sub.to \quad \lambda \leq \mu_C\left\{P_{(x,y)}\right\} \\ \qquad\quad \lambda \leq \mu_R\left\{P_{(x,y)}\right\} \\ \qquad\quad \lambda \geq 0 \end{array}\right\} \tag{5}$$

where,

λ: represents the satisfaction level of the decision maker.

$\mu_C\left\{P_{(x,y)}\right\}$: membership function of the set for construction cost.

$\mu_R\left\{P_{(x,y)}\right\}$: membership function of the set for supply reserve rate.

The branch and the bound algorithm have merits in the case of a complex optimization problem with many constraints [11]. A fuzzy branch and bound algorithm which includes the network flow theory and the maximum flow-minimum cut set theorem is proposed to obtain the optimal solution with highest satisfaction level considering membership functions that reflect uncertainties and ambiguities associated with construction cost and delivery power marginal rate.

3 Case Studies

3.1 Overview of the Planned Power Grid

This study will apply the theory to the 110 kV power grid of the power transmission system in Ben Tre province. This study uses the results of long-term load demand prediction (Table 1).

Table 1 Power supply system

Number	Supply name	P_{max} (MW)
1	Wind power plant Binh Dai	330
2	Wind power plant 5 Thanh Hai	110
3	Wind power plant V1-3 Ben Tre	30
4	Power station 220kV Ben Tre	80
5	Power station 220kV Mo Cay	240

3.2 Input Parameters

Input data to calculate the planning for the power grid is shown in Table 2. SB and EB are the beginning and end nodes of the element (line, transformer, generating source, respectively). $\Delta P_{(x,y)}{}^{(0)}$ and $\Delta C_{(x,y)}{}^{(0)}$ are the power and invested cost of the existing element, respectively. $\Delta P_{(x,y)}{}^{(i)}$ and $\Delta C_{(x,y)}{}^{(i)}$are the maximum power and investment cost of the ith candidate element connecting the x and y nodes, respectively ($i = 1, 2, 3, 4$). In this program, the number of candidate elements to join between 2 nodes x and y is $m(x,y) = 4$.

4 Results

4.1 Calculation Results

The tool to solve this planning problem is the software CMEXPP.FOR. The reliability standard in this study was investigated with the reliability standard case N-2TL (the power system, after planning, accepts both redundant lines) [7]. The obtained results also show that the transmission line can still meet the load demand, and the planner can reduce the cost of expanding the transmission line, as shown in Table 3.

The system reliability index statistics for short-term, medium-term, and long-term planning are shown in the table below [8, 9] (Tables 4 and 5).

Consider that the system's reliability index is 2003 [hrs/yr]. Sources at buses and $T_{6\text{-}3}$ transmission lines have a reserve ratio of less than 40%, which means that further expansion plans are needed in the future, as shown in Fig. 1. TF2-10 substations., TF3-12, TF4-11, TF5-14, TF6-13, TF7-15, and TF8-16 have very low reserve ratios, less than or equal to 10%. This means managers and operators need to quickly conduct expansion investments to meet the corresponding future load demand.

Single line diagram of 110 kV power transmission system after planning in 2042, with additional elements to meet increased load demand in Fig. 2.

Table 2 Input parameters of power grid planning

NL	SB	EB	Name	$\Delta P^{(0)}_{(x,y)}$ [MW]	$\Delta P^{(1)}_{(x,y)}$ [MW]	$\Delta P^{(2)}_{(x,y)}$ [MW]
1	0	7	S BDI	330	0	0
2	0	8	S BAT	30	0	0
3	0	4	S BTH	110	0	0
4	0	2	S MCY	240	0	0
5	0	6	S BTE	80	0	0
4	1	9	T CLH	23	36	36
5	2	10	T MCY	72	36	36
6	3	12	T GLG	72	36	36
7	4	11	T BTH	36	36	36
8	5	14	T GTM	36	36	36
9	6	13	T BTE	113	36	36
10	7	15	T BĐI	93	36	36
11	8	16	T BAT	72	57	36
12	2	1	MCY-CLH	116	58	58
13	2	4	MCY-BTH	116	58	58
14	6	2	MCY-BTE	98	49	49
15	6	3	BTE-GLG	116	58	58
16	6	5	BTE-GTM	98	49	49
17	5	7	GTM-BĐI	98	49	49

(continued)

Table 2 (continued)

NL	SB	EB	Name	$\Delta P^{(0)}_{(x,y)}$ [MW]	$\Delta P^{(1)}_{(x,y)}$ [MW]	$\Delta P^{(2)}_{(x,y)}$ [MW]	$\Delta P^{(3)}_{(x,y)}$ [MW]	$\Delta P^{(4)}_{(x,y)}$ [MW]	$\Delta C^{(0)}_{(x,y)}$ [M$]	$\Delta C^{(1)}_{(x,y)}$ [M$]	$\Delta C^{(2)}_{(x,y)}$ [M$]	$\Delta C^{(3)}_{(x,y)}$ [M$]	$\Delta C^{(4)}_{(x,y)}$ [M$]
18	5	8	GTM-BAT	98	49	49	0	0	0	0	0	0	0
19	9	17	CLH-LOD	31	0	0	0	0	0	0	0	0	0
20	10	17	MCY-LOD	98	0	0	0	0	0	0	0	0	0
21	11	17	BTH-LOD	49	0	0	0	0	0	0	0	0	0
22	12	17	GLG-LOD	98	0	0	0	0	0	0	0	0	0
23	13	17	BTE-LOD	154	0	0	36	0	0	1	1	1	0
24	14	17	GTM-LOD	49	0	0	36	0	0	1	1	1	0
25	15	17	BDI-LOD	127	0	0	36	0	0	1	1	1	0
26	16	17	BAT-LOD	98	0	0	36	0	0	1	1	1	0
							36	0	0	1	1	1	0
							36	0	0	1	1	1	0

(continued)

Table 2 (continued)

$\Delta P^{(3)}_{(x,y)}$ [MW]	$\Delta P^{(4)}_{(x,y)}$ [MW]	$\Delta C^{(0)}_{(x,y)}$ [M\$]	$\Delta C^{(1)}_{(x,y)}$ [M\$]	$\Delta C^{(2)}_{(x,y)}$ [M\$]	$\Delta C^{(3)}_{(x,y)}$ [M\$]	$\Delta C^{(4)}_{(x,y)}$ [M\$]
36	0	0	1	1	1	0
36	0	0	1	1	1	0
$\Delta P^{(3)}_{(x,y)}$ [MW]	$\Delta P^{(4)}_{(x,y)}$ [MW]	$\Delta C^{(0)}_{(x,y)}$ [M\$]	$\Delta C^{(1)}_{(x,y)}$ [M\$]	$\Delta C^{(2)}_{(x,y)}$ [M\$]	$\Delta C^{(3)}_{(x,y)}$ [M\$]	$\Delta C^{(4)}_{(x,y)}$ [M\$]
58	58	0	4	2	4	2
58	58	0	5	3	5	3
49	49	0	2	2	2	2
58	58	0	3	1	2	1
49	49	0	3	2	3	2
49	49	0	3	2	3	2
49	49	0	3	2	3	2
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0

Table 3 Calculation results of two cases of N-2TL

Case	Years	$_{R}$LOLE [hrs/yr]	Construction of new lines	Cost [M$]
N-2TL	2024	2003	T^1_{1-9}	1
	2032	2003	T^1_{1-9}, T^1_{2-10}, T^1_{3-12} T^1_{4-11}, T^1_{5-14}, T^1_{6-13}, T^1_{7-15}, T^1_{8-16}, T^1_{6-2}	10
	2042	2003	T^1_{1-9}, T^1_{2-10}, T^1_{3-12} T^1_{4-11}, T^1_{5-14}, T^1_{6-13}, T^1_{7-15}, T^1_{8-16}, T^1_{6-2}	10

Table 4 System reliability criteria

Case	Year	R_{LOLE} [hrs/yr]	EENS [MWh/yr]	ELC [MW/Cur.yr]	$LOLE_{SYS}$ [hrs/yr]	EIR [pu]
N-2TL	2024	2003	0	0	0	1
	2032	2003	0	0	0	1
	2042	2003	0	0	0	1

EENS: Expected energy not served*; ELC*: Expected load curtailment*; EIR*: Energy Index of Reliability

4.2 Power Distribution After Expanding the Transmission Line

The stability and load capacity of lines and transformers after planning were checked using PowerWord software [10]. Figure 3 shows lines and substations carrying overloads above 100%. Figure 4 shows the planned grid after 20 years according to the reliability index $_{R}$LOLE = 2003 [hrs/yr].

Table 5 Reserve ratio

NL	SB	EB	Name	Reserve ratio (%)		
				Year 2024	Year 2032	Year 2042
1	0	7	S BDI	42.12	41.21	33.33
2	0	8	S BAT	0	0	0
3	0	4	S BTH	53.64	24.55	13.64
4	0	2	S MCY	27.5	11.67	6.67
5	0	6	S BTE	10	0	0
4	1	9	T CLH	59.32	54.24	49.15
5	2	10	T MCY	0	23.15	12.04
6	3	12	T GLG	0	23.15	25.93
7	4	11	T BTH	0	41.67	34.72
8	5	14	T GTM	0	41.67	54.17
9	6	13	T BTE	0	12.08	1.34
10	7	15	T BĐI	0	16.28	5.43
11	8	16	T BAT	0	23.15	12.04
12	2	1	MCY-CLH	79.31	76.72	74.14
13	2	4	MCY-BTH	87.07	64.66	58.62
14	6	2	MCY-BTE	5.1	2.72	0
15	6	3	BTE-GLG	37.93	28.45	31.03
16	6	5	BTE-GTM	79.59	90.82	100
17	5	7	GTM-BĐI	57.14	45.92	33.67
18	5	8	GTM-BAT	0	12.24	0
19	9	17	CLH-LOD	0	0	0
20	10	17	MCY-LOD	−2.7	0	0
21	11	17	BTH-LOD	−2.7	0	0
22	12	17	GLG-LOD	−2.7	0	−15.78
23	13	17	BTE-LOD	−0.88	0	−1.34
24	14	17	GTM-LOD	−2.7	0	−29.79
25	15	17	BDI-LOD	−3.12	0	0
26	16	17	BAT-LOD	−2.7	0	0

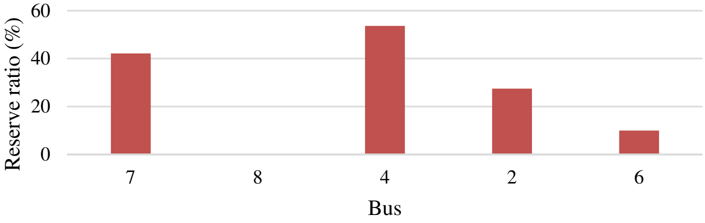

Fig. 1 Power reserve ratio in the post-planning system when $_{R}LOLE = 2003$ [hrs/yr]

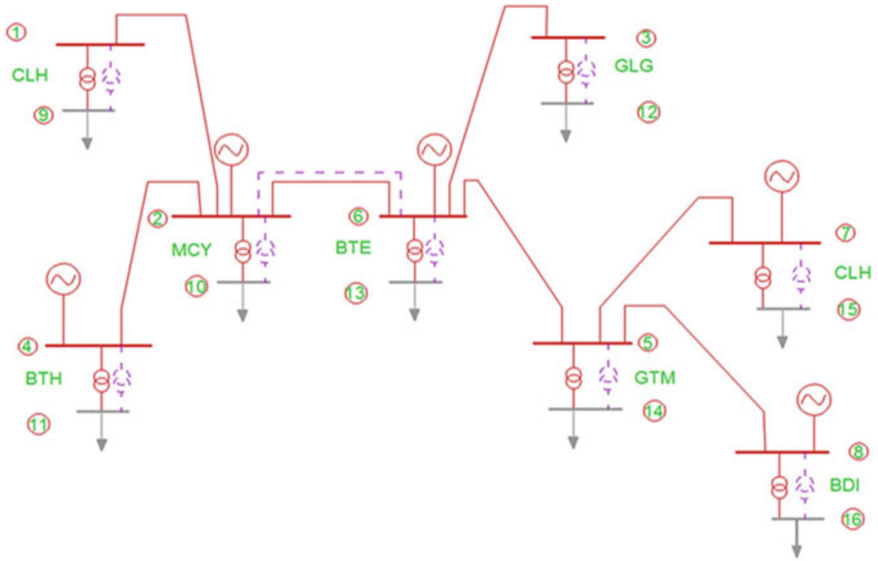

Fig. 2 Single line diagram of 110 kkV transmission system

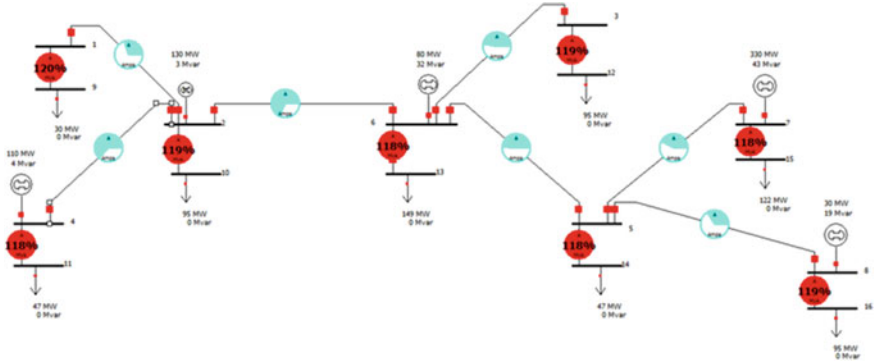

Fig. 3 Power grid in 2042

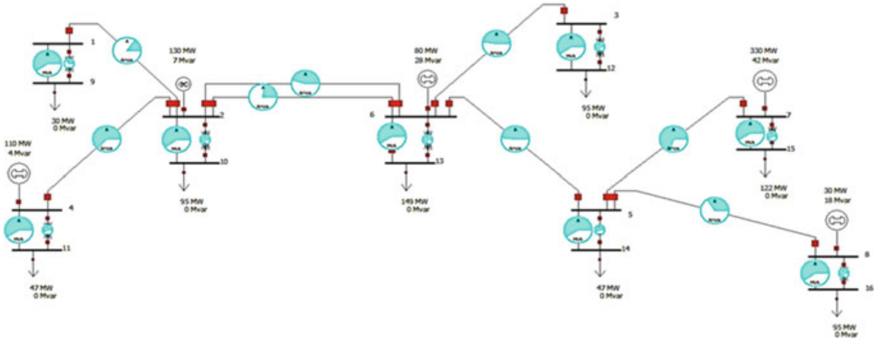

Fig. 4 Planned power grid in 2042

5 Conclusion

This study uses the bound and branch method and integer optimization to make the calculation easier. The results compared with the traditional calculation, this method is optimal, the input data is less, and the reliability coefficient of the transmission system can be adjusted by changing the $_{R}$LOLE index. This method can also calculate for larger transmission expansion planning.

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A Cuckoo Search Algorithm for Transmission Expansion Planning

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***Abstract*— Today, energy is a topical issue for the developing economy and the growing population, and electrical energy plays a key role. The power system is both continuously expanding generations and developing transmission lines. The efficient problem and the optimal generation is an issue in which researchers are very interested. Therefore, the problem is the optimization in the grid expansion planning for development load, which is a very important issue in the power system. To solve the transmission expansion planning, there are many algorithms that have been applied to efficiency but need a lot of input data, a little computing time, etc. In the proposed methodology, a DC power flow subproblem is solved for each network resulting from adding a potential solution developed by the cuckoo search algorithm to the base network. The cuckoo search algorithm will apply to the transmission expansion planning problem that proves 46 bus system with many constraints, and it brings the optimization solution to meet the load demand in the future. The new solutions achieve a remarkable reduction in the total investment cost.**

Keywords — *Cuckoo search algorithm, transmission expansion planning, power system, optimization solution, DC power flow*.

I. INTRODUCTION

The problems of the transmission expansion planning answer the questions "Where to plan and expand?", "What is the capacity to expand?", "What is the total cost for the planning?" , "How is the reliability of the electrical system improved after conducting the planning?", etc. In the past three decades, there have been many the algorithms and methods to prove effectively the planning solution problem. The power system as well as the transmission grid such as: Ant Colony Optimization, Genetic Algorithm, Particle Swarm Optimization, Tabu Search, A Zero-One Implicit, A Decomposition Approach, A Cooperative Expert System, A Kernel-Oriented Algorithm, Chaos, Fuzzy, Harmony, Harmony Search, Scatter Search, ... Artificial intelligent methods applied a short time and found optimal solutions to the whole exactly [1]. The methods of the expansion planning based on the method of the modeling problem of mathematical form and used mathematical algorithms to find the optimal solution based on previous constraints [2]. To solve the problem of the planning grid, we solve the problems of linear planning, non-linear planning, dynamic planning ... However, there are also some limitations in calculation when they applied in reality. The methods solve the problem with interacting variables. However, the number of variables is very large and very complex constraints, so the optimal tools will be difficult to solve for great optimal problems [3].

This article studied solving the transmission expansion planning problem, selecting the advantageous methods to solve the transmission expansion planning problem with the constraints in the plan in a short time and the experience finds the best. In addition, this study will explore the method of an artificial intelligence algorithm based on the search for animals in the wild to solve the DC transmission expansion planning problem with a combination of balanced and unbalanced constraints.

II. MODEL THE OPTIMAL TRANSMISSION EXPANSION PLANNING PROBLEM

There are many mathematical models used by many different sources for the TEP model problem, such as transportation models, DC models, AC models, hybrids and separation models. These models differ in complexity and accuracy. The DC model is the most common model used with the TEP model because it is less complicated and easier to solve without much time. At the same time, the DC model has a relatively higher accuracy than other models. According to the DC model, the TEP problem can be presented.

A. Objective function

The objective function of the expansion planning grid is the minimum total investment cost to meet economic and operating constraints. The classic DC model is used for TEP [4] as follows:

$$TC = \sum_{i,j\in\Omega} \beta \times cl_{ij} \times n_{ij} \tag{1}$$

$$cl_{ij} = \left(clf_{ij} + clv_{ij}\right) \times l \tag{2}$$

Where: *TC* total investment cost.

Ω is the set of all rights-of-way *i-j*.

cl_{ij} investment cost of adding a new circuit between buses *i* and *j*.

n_{ij} number of added circuits between buses *i* and *j*.

clf_{ij} and clv_{ij} fixed and variable construction costs of each line in the corresponding *i-j* network.

l length of each line.

β the coefficient to convert the cost to represent this value is called the rate of appreciation.

B. Constraints

1) Node current balance constraint

The linear equilibrium constraint represents the conservation of energy at the nodes and achieves [5].

$$\begin{cases} P_1 = \sum\limits_{\substack{j=1 \\ j\neq 1}}^{NB} P_{1j} + d_1 \\ P_2 = \sum\limits_{\substack{j=1 \\ j\neq 2}}^{NB} P_{2j} + d_2 \\ \cdots\cdots\cdots \\ P_{NB} = \sum\limits_{\substack{j=1 \\ j\neq NB}}^{NB} P_{NBj} + d_{NB} \end{cases} \tag{3}$$

$$\Rightarrow P_i = \sum_{j=1}^{NB} P_{ij} + d_i \quad (i = 1, 2, \ldots, NB), \; (\forall i, j \in \Omega) \tag{4}$$

$$P_i = \sum_{y=1}^{Nu_i + Nc_i} P_{yi} \tag{5}$$

Where: *NB* the total number of buses

P_i and d_i generation *i* and demand *i*.

Nu_i number of units available on the bus *i*.

Nc_i number of building units on the bus *i*.

In addition, P_{ij} is the power distribution of each branch *i-j*, which is calculate as follows:

$$P_{ij} = \gamma_{ij} \times \left(n_{ij}^0 + n_{ij}\right) \times \left(\theta_i - \theta_j\right) \tag{6}$$

$$\gamma_{ij} = b_{ij} \times l \tag{7}$$

Where: γ_{ij} set of all right-of-ways *i-j*

b_{ij} susceptance of the circuit between buses i and j

n_{ij}^0 number of circuits between buses i and j in the base network.

In addition, θ_i and θ_j are the bus are the voltage phase angle of buses *i* and *j* respectively. By replacing (6) and (7) in (4):

$$\sum_{y=1}^{Nu_i + Nc_i} P_{yi} = d_i + \sum_{j=1}^{NB} \gamma_{ij} \times (n_{ij}^0 + n_{ij}) \times \left(\theta_i - \theta_j\right) \tag{8}$$

For the simple, the left hand side corresponds to *g*, the first and second right hand side corresponds to *d* and *Sf*.

$$g = d + Sf \tag{9}$$

Where: P_{yi} power generated by unit *y* on bus *i*.

g and *d* generation vector and demand vector.

S branch-node incidence matrix.

F active power matrix in each corridor.

1) Power distribution limit on the transmission line

The non-rule constraints apply the transmission expansion planning to limit the power distribution for each path.

$$\left|P_{ij}\right| \le Nl_{ij} \times P_{ij}^{max} \quad \left(\forall i, j \in \Omega\right) \tag{10}$$

$$Nl_{ij} = n_{ij}^0 + n_{ij} \tag{11}$$

Replace P_{ij} and Nl_{ij} from (6) and (11) in (10) as:

$$\left|\gamma_{ij} \times \left(n_{ij}^0 + n_{ij}\right) \times \left(\theta_i - \theta_j\right)\right| \le \left(n_{ij}^0 + n_{ij}\right) \times P_{ij}^{max} \tag{12}$$

$$\Rightarrow \left(n_{ij}^0 + n_{ij}\right) \times \left|\left(\theta_i - \theta_j\right)\right| \times \left|\gamma_{ij}\right| \le \left(n_{ij}^0 + n_{ij}\right) \times P_{ij}^{max} \tag{13}$$

By shortening $(n_{ij}^0 + n_{ij})$ from two sides of (13) as:

$$\left|\left(\theta_i - \theta_j\right)\right| \times \left|\gamma_{ij}\right| \le P_{ij}^{max} \tag{14}$$

In the above formula, Nl_{ij} the number of the total number of circuits (new and existing) *i-j* and P_{ij}^{max} the power distributes maximum of the network *i-j*.

2) Priority constraints

It is clear that in order to exactly the transmission expansion planning, the location and exact capacity of the new circuits should be considered in the transmission expansion planning. In terms of mathematics, the maximum number of circuits can be tied to each network. Equation (15) shows the number of newly built circuits in each network limited by n_{ij}^{max} :

$$0 \le n_{ij} \le n_{ij}^{max} \tag{15}$$

Where: n_{ij}^{max} is the maximum number of circuits that can be added in the right-of-way *i-j*.

3) Limit the angle of phase voltage

In the DC current model, the magnitude of the rod voltage is ignored and only considers the phase angle of the rod voltage. This parameter is considered in the transmission expansion planning and the phase angle is calculated. It is smaller or the phase angle value is defined in advance.

$$\left|\theta_i\right| \le \left|\theta_i^{max}\right| \tag{16}$$

Where: θ_i^{max} the maximum phase angle value of the bus *i*.

Indeed, the constraint in the formula (10-14) shows the conservation of energy in each bus if the DC electricity network is equivalent. This constraint models the bus of Kirchhoff (KCL) in which binding in the formula (6) is an expression of Ohm's law for the equivalent DC network. In addition, the law of Kirchhoff voltage (KVL) is completely taken into account. There are nonlinear constraints, including constraints in the formula (14) showing the transmission power limit on the transmission line and the variable pressure. The constraint in the formula (15) represents the limits of newly built circuits in the *i-j* network and the formula (16) refers to the limit of the voltage phase angle of the bus. The transmission expansion planning problem as built above is an integer nonlinear problem (INLP).

II. ALGORITHM SEARCHING CUCKOO SEARCH

Cuckoo search is a new meta-heuristic algorithm inspired from the nature for solving optimisation problems developed by Yang and Deb in 2009 [6]. The basic idea of this algorithm is based on the obligate brood parasitic behaviour of some cuckoo species in combination with the Lévy flight behaviour of some birds and fruit flies.

A. The mathematical model of the Cuckoo search

There are three idealised rules for the new CSA described as follows [6].

(1) An egg represents a solution and is stored in a nest. An artifcial cuckoo can lay only one egg at a time.

(2) The cuckoo bird searches for the most suitable nest to lay the eggs in (solution) to maximize its eggs' survival rate. An elitist selection strategy is applied, so that only high-quality eggs (best solutions near the optimal value) which are more similar to the host bird's eggs have the opportunity to develop (next generation) and become mature cuckoos.

(3) The number of host nests (population) is fxed. The host bird can discover the alien egg (worse solutions away from the optimal value) with a probability of $Pa \in [0, 1]$, and these eggs are thrown away or the nest is abandoned and a completely new nest is built in a new location. Otherwise, the egg matures and lives to the next generation. New eggs (solutions) laid by a cuckoo choose the nest by Levy flights around the ´ current best solutions.From the above point of view, in CS calculation, the total multiplication,, of *n* eggs (individuals) are developed from the initial points ($k = 0$) to the total number of repeated information ($k = 2$) . Each egg is described in a dimension vector, in which each afternoon is opposite to a decisive variable of the optimal problem is solved. The quality of each egg (appropriate solution) is evaluated using the target function, the final result describes the appropriate value of. The three different operators determine the evolution process of CS: (a) Lévy Flight, (b) Replace some nests by building new solutions, and (c) the best selection strategy.

a) Lévy Flight (A)

One of the most powerful features of cuckoo search is the use of Levy flights to generate new candidate solutions (eggs). Under this approach, a new candidate solution, e_i^{k+1} $(i \in [1, \ldots, N])$, is produced by perturbing the current *i* with a change of position c_i. In order to obtain c_i a random step s_i, is generated by a symmetric Lévy distribution. For producing s_i, Mantegna's algorithm is employed as follows:

$$s_i = \frac{u}{|v|^{1/\beta'}} \tag{17}$$

Where: u $(\{u_1,\ldots, u_n\})$ and k $(\{v_1,\ldots, v_n\})$ are *n*-dimensional vectors and $\beta = 3/2$. Each element of *u* and *v* is calculated by considering the following normal distributions:

$$u \sim N\left(0,\sigma_u^2\right), \quad v \sim N\left(0,\sigma_v^2\right),$$

$$\sigma_u = \left(\frac{\Gamma(1+\beta).\sin\left(\pi.\frac{\beta}{2}\right)}{\Gamma(\left(\frac{1+\beta}{2}\right).\beta.2^{(\beta-1)/2}}\right)^{1/\beta}, \sigma_v = 1 \tag{18}$$

Where: $\Gamma(\cdot)$represents the gamma distribution. Once s_i has been calculated, the required change of position c_i is computed.

$$c_i = 0.01 s_i \otimes \left(e_i^k - e^{best}\right) \tag{19}$$

Where: ⊕ denotes entrywise multiplications

whereas e^{best} is the best solution (egg) seen so far in terms of its ftness value. Finally, the new candidate solution, e_i^{k+1}, is calculated by using.

$$e_i^{k+1} = e_i^k + c_i \tag{20}$$

b) Replacement of Some Nests by Constructing New Solutions (B)

Under this operation, a set of individuals (eggs) are probabilistically selected and replaced with a new value. Each individual, e_i^k $(i \in [1,\ldots, N])$, can be selected with a probability of $p_a \in [0, 1]$. In order to implement this operation, a uniform random number, r_1, is generated within the range *[0, 1]*. If r_1 is less than p_a, the dividual e_i^k is selected and modifed according to (20). Otherwise, e_i^k remains without change. The operation can be resumed by the following model:

$$e_i^{k+1} = \begin{cases} e_i^k + rand \bullet \left(e_{d1}^k - e_{d2}^k\right), with\ probability\ \ p_a \\ e_i^k\ \ with\ probability\ \left(1 - p_a\right) \end{cases} \tag{21}$$

where *rand* is a random number normally distributed, d_1 and d_2 are random integers from *1* to *N*.

c) Elitist Selection Strategy (C)

After producing e_i^{k+1} either by operator A or by operator B, it must be compared with its past value e_i^{k+1}. If the fitness value of e_i^{k+1} is better than e_i^k, then e_i^{k+1} is accepted as the final function. Otherwise, e_i^k is retained. This procedure can be resumed by the following satement:

$$e_i^{k+1} = \begin{cases} e_i^{k+1}, & if\ f\left(e_i^{k+1}\right) < f\left(e_i^k\right), \\ e_i^k & otherwise \end{cases} \tag{22}$$

This elitist selection strategy denotes that only high-quality eggs (best solutions near the optimal value) which are more similar to the host bird's eggs have the opportunity to develop (next generation) and become mature cuckoos.

B. The cuckoo search algorithm applies TEP

In the proposed CS method, each host representing a solution and gathering the groups used to find the best solution for the same problem as many other Meta-Heristic search methods [7-8]. The main steps for the proposed CS are described as follows:

Initialisation: A population of N_p host nests is represented by $X = [X_1, X_2, \ldots, X_{Np}]^T$, where each nest $X_d = [X_{d1}, X_{d2}, \ldots, X_{ds-1}]^T$ $(d = 1\ \ldots, N_p)$ represents power output of units except the slack unit is initialised by:

$$X_{di} = Lb_i + rand_1 * \left(Ub_i - Lb_i\right) \tag{23}$$

Where : Lb_i and Ub_i maximun and minimun number of added branch, $rand_1$ is a uniformly distributed random number in [*0, 1*]. This original solution is further tested for TEP violations. If violations are found, update the strategy to the viable area. Based on the initial nest population, the reduced objective function corresponding to each nest for the problem under consideration is calculated.

$$F = \sum_{i,j=1}^{N} n_{ij} c_{ij} \qquad (24)$$

The limits on the number of added branches are calculated

$$Lb_i \le n_{ij} \le Ub_i \qquad (25)$$

The initial population of the host nests is set to best value of each nest X_{bestd} $(d = 1, \ldots, Nd)$ and the nest corresponding to the best fitness function in (24) is set to the best nest G_{best} among all nests in the population.

Generation of new solution via Lévy flights: The new solution is calculated based on the previous best nests via Lévy flights. In the proposed method, the optimal path for the Lévy flights is calculated by Mantegna's algorithm [8]. The new solution by each nest is calculated.

$$X_d^{new} = Xbest_d + \alpha * rand * X_d^{new} \qquad (26)$$

Where $\alpha > 0$ the updated step size; $rand_2$ is a normally distributed stochastic number; and the increased value ΔX_d^{new} is determined.

$$X_d^{new} = v * \frac{\sigma_x(\beta)}{\sigma_y(\beta)} * \left(Xbest_d - Gbest\right) \qquad (27)$$

$$v = \frac{rand_x}{\left|rand_y\right|^{1/\beta}} \qquad (28)$$

Where $rand_x$ and $rand_y$ are two normally distributed stochastic variables with standard deviation $\sigma_x(\beta)$ and $\sigma_y(\beta)$ given by:

$$\sigma_x(\beta) = \left[\frac{\Gamma(1+\beta) * \sin\left(\frac{\pi\beta}{2}\right)}{\Gamma\left(\frac{1+\beta}{2}\right) * \beta * 2^{\left(\frac{\beta-1}{2}\right)}} \right]^{1/\beta} \qquad (29)$$

$$\sigma_y(\beta) = 1 \qquad (30)$$

Where β is the distribution factor ($0,3 \le \beta \le 1,99$) and $\Gamma(.)$is the gamma distribution function.

For the newly obtained solution, its lower and upper limits should be satisfied according to the unit's limits

$$X_{di}^{new} = \begin{cases} Ub_i \text{ if } X_{di}^{new} \ge Ub_i \\ 0 \text{ if } X_{di}^{new} < Lb_i \end{cases} \qquad (31)$$

In addition, the newly adapted solution needs further testing for TEP violations [8-9]. The objective function (24) will be re-evaluated for the new solution to determine the newly best value of each nest X_{bestd} and the best nest of all nests G_{best} by comparing the stored fitness values and the newly calculated ones.

Alien egg discovery and randomisation: The action of discovery of an alien egg in a nest of a host bird with the probability of p_a also creates a new solution for the problem similar to the Lévy flights. The new solution because of this action is calculated as follows:

$$X_d^{dis} = X_{bestd} + K * \Delta X_d^{dis} \qquad (32)$$

Where K is the updated coefficient determined based on the probability of a host bird to discover an alien egg in its nest.

$$K = \begin{cases} 1 & if \;\; rand_3 < p_a \\ 0 & otherwise \end{cases} \qquad (33)$$

and the increased value ΔX_d^{dis} is determined by:

$$\Delta X_d^{dis} = rand_4 * [rand_{p1}(Xbest_d) - rand_{p2}\left(Xbest_d\right)] \qquad (34)$$

Where $rand_3$ and $rand_4$ are the distributed random numbers in $[0, 1]$ and $rand_{p1}(X_{bestd})$ and $rand_{p2}(X_{bestd})$ are the random perturbation for positions of nests in X_{bestd} .

Similar to the solution obtained via Lévy flights, this new solution is also redefined as in (31) if the upper or lower limit is violated and Section A. if any prohibited zones are violated. The newly best value for each nest X_{bestd} and the best value of all nests G_{best} are also determined based on comparing the calculated fitness function in (24) from this new solution.

Stopping criteria: The proposed algorithm is terminated when the predefined maximum number of iterations is reached.

The flowchart of the proposed CSA method for solving the TEP problem is given in Figure 1.

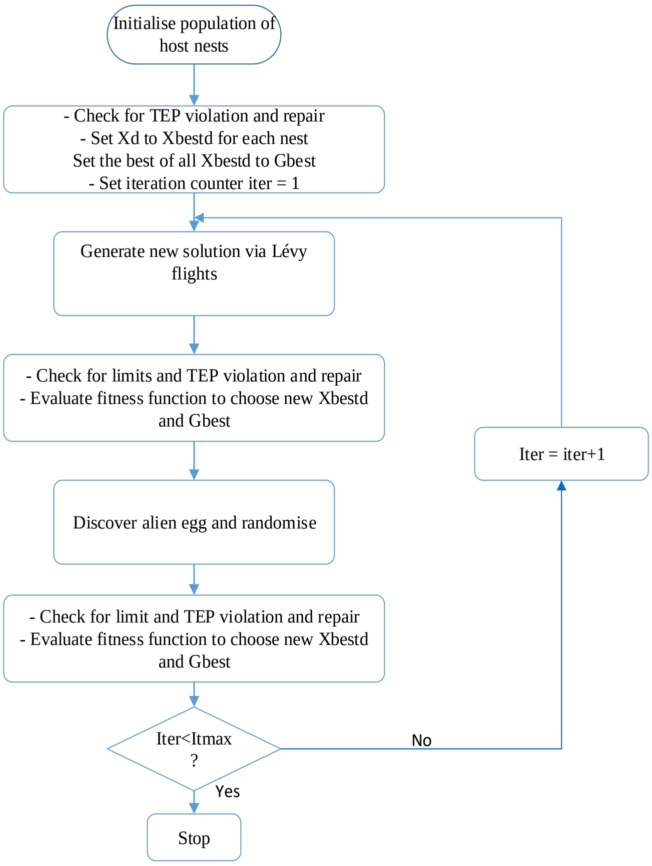

Figure 1. The flowchart algorithm applies the search algorithm CS – TEP.

III. RESULTS OF SOLVING THE PROPLEM OF PLANNING EXPANSION OF DC TRANSMISSION GRID

A. Parameters of South Brazil 46 buses

The southern Brazilian electricity system includes 46 buses, 79 associated branches and the total load demand is 6,880MW [10]. Appendix of Table 1. showing the number of links between nodes, n^0_{ij} the number of links the original status is set *0* is without a link, the value *1* is a bonding branch, corresponding to the linked values of the buss Initially, the resistance *x (p.u)*, the maximum power of the Link Link Line *i* to *j* is P_{ij}^{max} *(MW)*, the expected investment cost when building buss *i* and *j* is expected to multiply $10^3\$$. The maximum number of lines that can be added to the buss is *6*. The 46 buses electric network diagram is shown in Figure 2., with the instant lines that shows connected, lines Slash is expected to add to the connection.

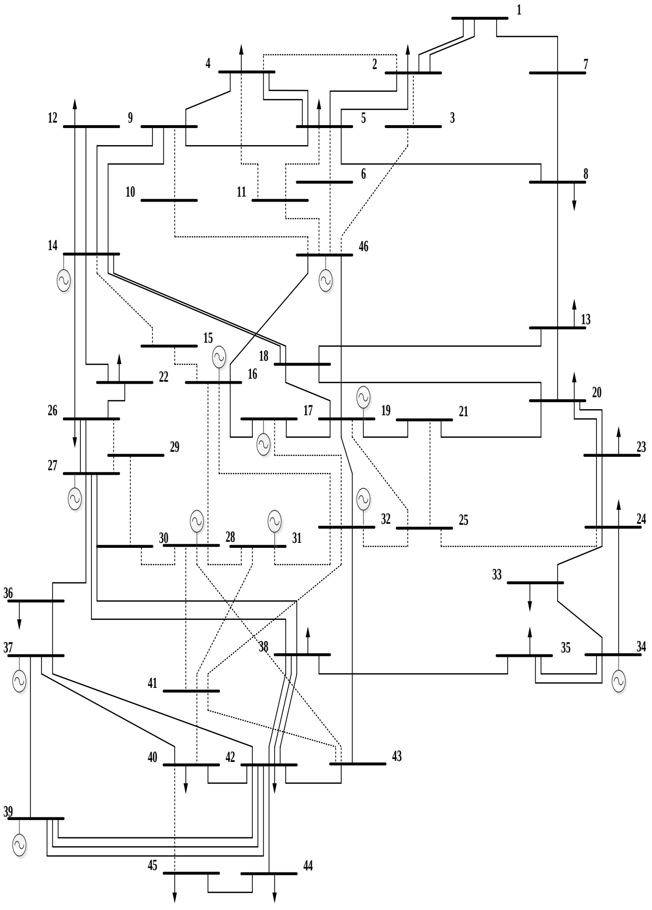

Figure 2. South Brazil's power system 46 buses

B. Steps to apply the Cuckoo search algorithm to TEP and the results of the southern Brazilian electricity system 46 buses

In the control parameters for the CS search algorithm to get the optimal solution for the Brazilian power network 46 buses, there are four main parameters that must be determined in advance as the number of NP teams, the maximum number of branches repeated. Link *N*, distribution coefficient *β* and probability of foreign eggs detected in the nest is *PA*. Among these parameters, the number of groups *79* is fixed. Because CS method is a powerful search method, it only needs a small number of teams to handle different systems. In the testing, the number of host nests is *79* for all test systems. On the other hand, the maximum number of repetitions for CS can also be easily fixed depending on the level of complexity and scale of the issues considered. The maximum number of repetitions for CS is in the range of *5,000* for the system. Choose the value of *β* fixed at *1.5* for all test systems in this article. The value of the probability of detecting foreign eggs can be selected in [*0, 1*]. However, different values of *PA* can lead to different optimal solutions for the systems. This study selected the optimal probability, its value varies from *0.7* to *0.9* with the step size of *0.1* for the planning problems to expand the transmission grid. The optimal solution of the 46 buses South Brazil's power system planned *21* linked lines was added with a total investment cost of ***175,970,000$.***

Table 1. Results of the 46 buses Brazilian grid expansion system

To	**From**	**Number lines**	**Cost (x10^3\$)**	**Cost investment (x10^3\$)**
2	5	1	2,581	2,581
5	11	5	6,167	30,835
11	46	2	8,178	16,356
12	14	1	5,106	5,106
17	19	1	8,715	8,715
20	21	2	8,178	16,356
23	24	1	5,308	5,308
24	25	1	8,178	8,178
25	32	1	37,109	37,109
26	27	1	5,662	5,662
29	30	2	8,178	16,356
31	32	1	7,052	7,052
42	43	2	8,178	8,178
Total cost investment($)			**175,970,000**	

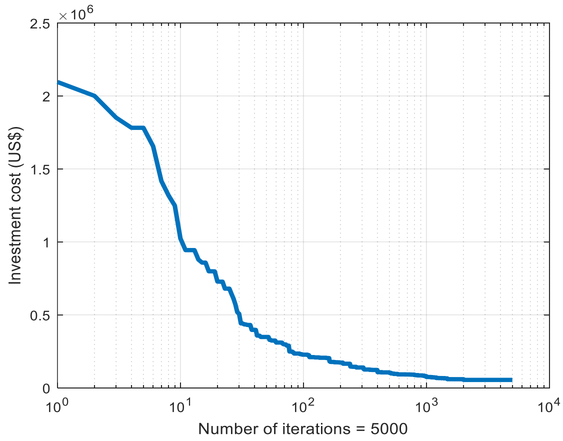

Figure 3. Compared to the number of loops

The diagram of the electricity system after the 46 buses Brazilian power network planning is shown in Figure 4.

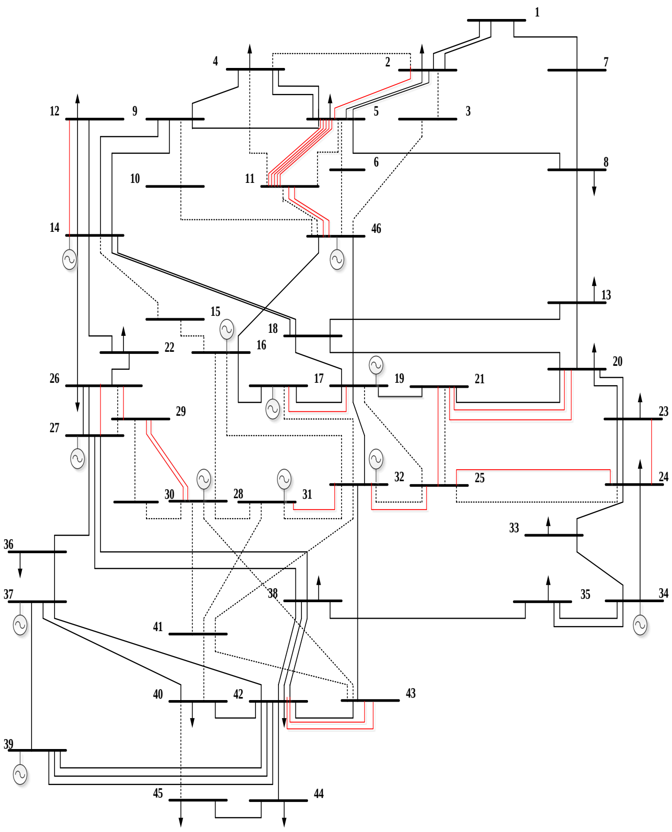

Figure 4. Brazilian power system 46 buses after planning.

The statistical results of the CS search algorithm are applied to solve the TEP problem on investment costs, the standard deviation shown in Table 2. In addition, the results of the method are also compared to the BF-DEA methods, the investment costs shown in Table 3.

Table 2. Optimal results of the 46 buses Brazilian electricity network investment

No	**Results planning**	**CS method**
		Cost investment($)
1	Best	175,970,000
2	Average	175,970,000
3	Mean	175,970,000
4	Standard deviation	0

Table 3. Compare the results of the methods tested with the power network Brazilian 46 buss

No	**Methods**	**Number evaluate function**	**Optimal cost investment ($)**
1	HS	$2.40\mathrm{x}10^{5}$	337,809,000
2	BF-DEA	$2.98\mathrm{x}10^{5}$	361,863,000
3	GA	$2.67\mathrm{x}10^{6}$	432,350,000
4	**CS**	$\mathbf{5.40\mathrm{x}10^{4}}$	**175,970,000**

The results show that the proposed CS search algorithm can achieve the best results, so the 46 buses Brazilian system investment cost is the smallest compared to the announced results.

IV. CONCLUSION

The CS search algorithm applies to the planning problem expansion of the transmission grid proved on the South Brazilian electricity network 46 buses; The results have been collected with investment expenses, standard deviations with optimal value, and CS search algorithms are also compared with many artificial intelligence algorithms, BF-DEA, stations with total low investment costs, The number of target function assessments is lower. The strong point of the CS method applied is that there are few sources of input data, many binding conditions, finding locations to invest in expanding and solving the planning problem of the transmission system with a complex electrical system; In the coming time, it will be applied to the large actual electrical system.

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