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Symbiotic organisms search algorithm for economic load dispatch problem with valve-point effect

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Abstract. Symbiotic Organisms Search (SOS) is a brand new and effective metaheuristic optimization algorithm. This paper proposes the SOS algorithm to solve the Economic Load Dispatch (ELD) problem with valve-point effect, which is one of the essential optimization problems in modern power systems. The proposed algorithm is tested on five different test cases consisting of 3-machine 6-bus, IEEE 5-machine 14-bus, IEEE 6-machine 30-bus, and 13- and 40-unit test systems both with transmission loss and without transmission loss. These test cases show that SOS is able to converge on the global optima, successfully. Moreover, results obtained from the proposed algorithm are compared through different methods used in solving the ELD problem existing in the literature. According to these results, SOS produces the best values among all methods.

1. Introduction

Economic Load Dispatch (ELD) is one of the most popular and important optimization problems in modern power system operation and aims to minimize the total cost of function scheduling outputs of all generating units to meet the load demand while satisfying some equality and inequality system constraints. ELD becomes a highly non-linear optimization problem when the valve-point effects, multi-fuel effects, etc. are considered. Therefore, solving this non-smooth optimization problem and finding the global optimum become very difficult.

Researchers have made great efforts to solve the ELD problem from past to the present. Classical methods like linear programming [1], interior point [2,3], and dynamic programming [4] were used in early times. In order to overcome some drawbacks of these algorithms, including insecure convergence properties, long execution time, and algorithmic complexity, many meta-heuristic based optimization algorithms were developed and proposed to solve ELD. Simulated Annealing (SA) was implemented [5] in ELD problems and produced nearly optimal solutions in the early 1990s. Then, evolutionary based algorithms were used for solving ELD problem. Genetic Algorithm (GA) [6] and its improved versions [7] were also widely used. Tabu Search (TS) [8], Particle Swarm Optimization (PSO) [9,10], Differential Evolution (DE) [11], Ant Colony Optimization (ACO) [12,13], Bacterial Foraging Optimization (BFO) [14], Artificial Bee Colony algorithm (ABC) [15], Gravitational Search Algorithm (GSA) [16], Biogeography-Based Optimization (BBO) [17], Improved Mutative Scale Chaos Opti-

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mization Algorithm (IMSCOA) [18], Pattern Search method (PS) [19], Seeker Optimization Algorithm (SOA) [20], Taguchi Method (TM) [21], Modified Shuffled Frog Leaping Algorithm (MSFLA) [22], and Firefly Algorithm (FA) [23] are other heuristic search algorithms applied to ELD in course of finding the best optimal solution. Besides hybrid algorithms such as Cultural Self-Organizing Migrating Algorithm (CSOMA) [24], Chaotic Differential Evolution and Quadratic Programming (DEC-SQP) [25], Fuzzy Adaptive Particle Swarm Optimization (FAPSO) [26], hybrid Genetic Algorithm approach based on Differential Evolution (GA-DE) [27], hybrid population-based algorithm (PSOGSA) [28], Genetic Algorithm with Active Power Optimization based on Newton's second order approach (GA-APO) [29], combination of Modified Subgradient and Harmony Search (MSG-HS) [30], hybrid Shuffled Differential Evolution (SDE) algorithm [31,32], Improved Coordinated Aggregation-based Particle Swarm Optimization (ICA-PSO) [33], integrated Particle Swarm Optimization technique with the Sequential Quadratic Programming (PSO-SQP) technique [34], modified hybrid Particle Swarm Optimization and GSA based on fuzzy logic (FP-SOGSA) [35], Real parameter Quantum Evolutionary Algorithm (RQEA) [36], etc. have been developed by authors to solve ELD problem. Even though all of these algorithms produce good solutions and have some advantages, each method has its own drawbacks. As it is declared in [37], SA suffers from slow convergence and its parameter determination is difficult, PSO has a slow fine-tuning ability of solution and it has difficulty in escaping from the local optimum, GA's offspring production capacity is weak and it shows slow convergence near the best optimal solution, and TS is inefficient in describing effective memory structures and strategies adequate for the problem.

Symbiotic Organisms Search algorithm (SOS) is a brand new and effective metaheuristic optimization algorithm developed by Cheng and Prayogo [38] in 2014. It is an improved algorithm for finding the best possible solution to optimization problems with multi-variable functions and simulates symbiotic interaction tactics used by organisms in order to survive in the nature. Because SOS is an algorithm for a newborn, no studies have been applied to different areas. However, Cheng and Prayogo examined it on 26 different benchmark functions and structural design optimization problems in order to show the effectiveness of the algorithm. Then, they compared its performance with other optimization algorithms such as GA, DE, PSO, Bees Algorithm (BA), Mine Blast Algorithm (MBA), and Cuckoo Search (CS). According to results, it was seen that SOS produced better results than others in all cases. Therefore, SOS algorithm is chosen to search the globally optimum solution and investigate the produced results for ELD problem with valve-point effect in this paper. ELD solution, which is performed using SOS, is examined over standard power systems including IEEE 3-machine 6-bus, IEEE 5-machine 14-bus, IEEE 6-machine 30-bus, and 13- and 40-unit test systems both with transmission loss and without transmission loss. The results are compared with those reported in the literature; they show that SOS algorithm produces better solutions than other algorithms to the ELD problem.

The rest of the paper is organized as follows: problem formulation is described in Section 2. SOS algorithm and its application to ELD problem are explained in Section 3. Experimental results are given in Section 4 and, finally, Section 5 presents conclusions.

2. Problem formulation

ELD is the most common and most important nonlinear optimization problem in power system operation and management. The aim of ELD is to meet the load demand while satisfying some equality and inequality system constraints by scheduling the generator outputs. Outputs of generators having multi-valve steam turbines should be increased by opening the valves when an increase occurs in load demand. But, this process creates ripples on heat rate curve of generating units and sinusoidal components on their power outputs. Thus, nonlinear feature of ELD problem increases. Hence, reaching the solution to this problem becomes difficult due to increase in local optimum points in the search space [35]. When the valve-point effect is taken into account, the ELD problem can be described as follows:

$$\min f = \min \sum_{k=1}^{N} F_k\left(P_k\right), \tag{1}$$

$$F_k\left(P_k\right) = a_k + b_k P_k + c_k P_k^2 + \left|d_k \times \sin\left(e_k \times \left(P_k^{\min} - P_k\right)\right)\right|, \tag{2}$$

where $F_k(P_k)$ is total generation cost of unit k; a_k, b_k, and c_k are cost coefficients; d_k and e_k are cost coefficients with valve-point effect of unit k; and P_k is the power output of unit k. The ELD problem described in Eq. (2) is subject to constraints, which are power balance and ramp rate limits. According to the power system constraints, the power generation of total system is equal to the sum of total system load (P_d) and total power loss (P_{ls}). It can be described as follows:

$$\sum_{k=1}^{N} P_k = P_d + P_{ls}, \tag{3}$$

where P_{ls} can be calculated by using B-coefficients as follows:

$$P_{ls} = \sum_{k=1}^{N}\sum_{l=1}^{N} P_k B_{kl} P_l + \sum_{k=1}^{N} B_{0k} P_k + B_{00}, \tag{4}$$

where B_{kl} is the k,l-th elements of loss coefficient square matrix, B_{0k} is the k-th vector of matrix, and B_{00} is the constant of loss coefficient.

The second constraint is ramp rate limits. According to this, the power output of each generating unit is limited with a minimum value and a maximum one.

$$P_k^{\min} \le P_k \le P_k^{\max}. \tag{5}$$

2.1. Computing for slack generator

According to this calculation method, active power load of first $(N-1)$ generating units is defined when N units generate power subject to the power balance equality given in Eq. (1). In this instance, the power output of Nth unit (i.e., slack generator) can be described as follows [17,35]:

$$P_N = P_d + P_{ls} - \sum_{k=1}^{(N-1)} P_k, \tag{6}$$

where P_{ls} is a function of all outputs of generating units comprising the slack generator and it can be described as follows:

$$P_{ls} = \sum_{k=1}^{N-1}\sum_{l=1}^{N-1} P_k B_{kl} P_l + 2P_N \left(\sum_{k=1}^{N-1} B_{Nk} P_k\right) + B_{NN} P_N^2 + \sum_{k=1}^{N-1} B_{0k} P_k + B_{0N} P_N + B_{00}. \tag{7}$$

Eq. (6) becomes Eq. (8) by expanding and rearranging as follows:

$$B_{NN} P_N^2 + \left(2\sum_{i=1}^{N-1} B_{Ni} P_{Gi} + B_{0N} - 1\right) P_N + \left(P_D + \sum_{i=1}^{N-1}\sum_{j=1}^{N-1} P_{Gi} B_{ij} P_{Gj} + \sum_{i=1}^{N-1} B_{0i} P_{Gi} - \sum_{i=1}^{N-1} P_{Gi} + B_{00}\right) = 0. \tag{8}$$

Eq. (8) can be calculated via standard algebraic methods and, thus, the loading of the dependent generation unit (i.e., Nth) can be found. In order to achieve this, the following simplifications can be used:

$$\alpha P_N^2 + \beta P_N + \delta = 0, \tag{9}$$

$$\alpha = B_{NN},$$

$$\beta = \left(2\sum_{k=1}^{N-1} B_{Nk} P_k + B_{0N} - 1\right),$$

$$\delta = \left(P_d + \sum_{k=1}^{N-1}\sum_{l=1}^{N-1} P_k B_{kl} P_l + \sum_{k=1}^{N-1} B_{0k} P_k - \sum_{k=1}^{N-1} P_k + B_{00}\right). \tag{10}$$

The positive roots of the equation give output of the slack generator to satisfy Eq. (6) and it can be found as follows:

$$P_N = \frac{-\beta \mp \sqrt{\Delta}}{2\alpha}, \tag{11}$$

where $\Delta = \beta^2 - 4\alpha\delta \ge 0$.

3. Symbiotic Organisms Search (SOS) algorithm and application to the ELD problem

The SOS algorithm is a population-based stochastic technique developed by Cheng and Prayogo [38] in 2014. It iteratively uses a population of candidate solutions to the optimization of nonlinear functions at multi-dimensional space in the process of seeking the optimal global solution.

SOS consists in a group of organisms in ecosystem. It simulates the interactive behavior seen among organisms in ecosystem. There is a reliance-based relationship between the organisms, which is known as symbiosis. Symbiosis includes relationships that are mutualistic, parasitic, or commensal and is used to describe a relationship between any two distinct organisms. The symbiotic relationships are performed by applying special operators, namely, *mutualism*, *commensalism*, and *parasitism*. Mutualism represents a symbiotic relationship between two different species in which each individual benefits from the activity of the other. Commensalism is a symbiotic relationship between two different species in which one organism benefits from the other without affecting it. Parasitism is a non-mutual symbiotic relationship between two different species in which one species, the parasite, benefits at the expense of the other, the host. Organisms use symbiotic relationships to adapt to changes in their environment. Thanks to the special operators, fitness and survival advantage of organisms may increase.

In the SOS algorithm, an initial population, called the ecosystem, is firstly created. The ecosystem consists in a group of organisms generated randomly in the search space. Every organism in the ecosystem is a potential solution to the problem and has a certain fitness value, which points out the degree of adaptation to the desired objective. General flowchart of the SOS algorithm is given in Figure 1.

Now, application of SOS algorithm to ELD problem is described below step by step according to the flowchart of the algorithm.

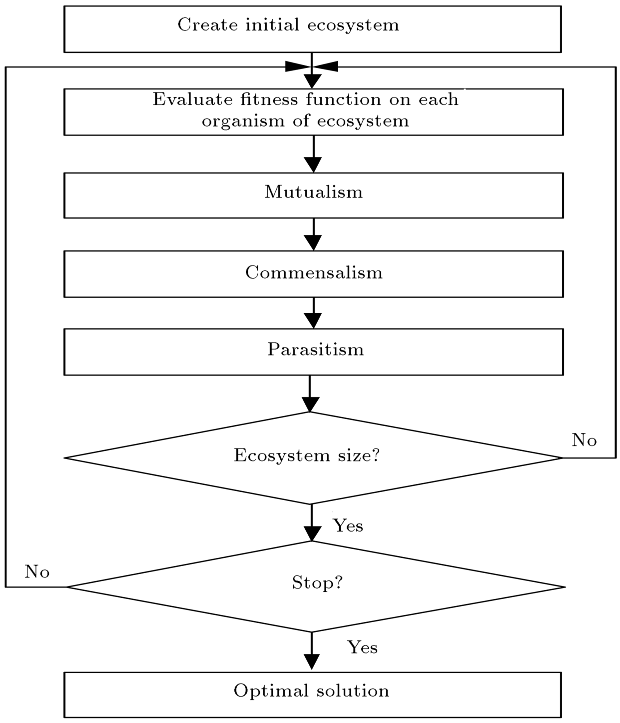

Figure 1. General flowchart of SOS execution.

Step 1. *Create initial ecosystem:* The ecosystem is created in three steps. In the first step, organisms are created. For every organism, a vector (random values for attributes) is generated in the second step. In the last step, ecosystem parameters, number of organisms (eco_size), and maximum iteration (max_iter) are determined. Figure 2 shows the ecosystem and organisms.

Step 2. *Evaluate fitness function of each organism in ecosystem:* Depending on values of attributes ($[a_1, a_2, a_3, ..., a_m]$ is given in Figure 2), the fitness value ($[f_{\text{value}}]$) of each organism is determined by a fitness function. The information on fitness value of an organism is used to search for the fittest organism.

Step 3. *Determine mutualism operator:*

a. An organism is selected randomly from ecosystem, X_j, where $X_j \neq X_i$., through the following codes;
   $/*\ j = i;$
   $while\ i == j$
   $seed = randperm(ecosize);$
   $j = seed(1);$
   $end */$

b. Mutual relationship vector (*Mutual_Vector*) and benefit factors (the value of 1 or 2 is assigned randomly to both BF_1 and BF_2) are determined.

c. $Mutual\_Vector = (X_i + X_j)/2$.

d. Organisms X_i and X_j are modified based on their mutual relationship by using Eqs. (12) and (13):

$$X_{inew} = X_i + rand(0,1) * (X_{best} - Mutual_{Vector} * BF_1), \quad (12)$$

$$X_{jnew} = X_j + rand(0,1) * (X_{best} - Mutual_{Vector} * BF_2). \quad (13)$$

e. Fitness values of X_{inew} and X_{jnew} are calculated. If the modified organisms are fitter than the previous ones, then the modifications are accepted. Otherwise, the modifications are rejected and the previous organisms kept.

Step 4. *Determine commensalism operator:*

a. An organism is selected randomly from ecosystem, X_j, where $X_j \neq X_i$.

b. Organism X_j is used to modify organism X_i by using Eq. (14):

$$X_{inew} = X_i + rand(-1,1) * (X_{best} - X_j). \quad (14)$$

c. Fitness value of X_{inew} is calculated. If the

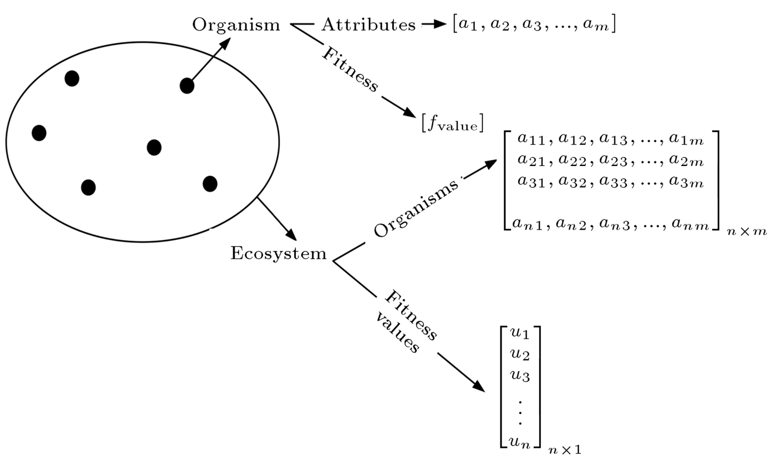

Figure 2. Representation of ecosystem and organisms.

```
1: create initial ecosystem
2: for (num_iter; max_iter_num;num_iter+1)
        for (eco_size; max_eco_size;eco_size+1)
            (i) calculate the fitness value of organisms and determine X_best (best
                organism) in ecosystem
            (ii) Apply symbiosis operators:
                f(mutualism)
                f(commensalism)
                f(parasitism)
        if (termination criteria is achieved)
                save X_best as optimum solution
                else go to step 2
3: finalize the searching process and save the vector of the most suitable organism
   in the ecosystem
```

Figure 3. The pseudocode of SOS algorithm to search the optimum solution.

modified organism is fitter than the previous one, then the new organism is accepted to replace X_i. Otherwise, the modification is rejected and the previous organism kept (X_i).

Step 5. *Determine parasitism operator:*

a. An organism is selected randomly from ecosystem, X_j, where $X_j \neq X_i$.

b. A parasite vector (*Parasite_Vector*) is created from organism X_i.

c. Fitness value of X_i is calculated. If the fitness value of *Parasite_Vector* is fitter than X_j, then organism X_j is replaced with *Parasite_Vector*. Otherwise, replacement operation is performed, X_j kept, and *Parasite_Vector* deleted.

Step 6. *Determine ecosystem size:* It is the number of organisms in ecosystem. Each organism is a potential solution to the problem at hand. The population size in genetic algorithm and the number of bees in a colony in artificial bee colony algorithm are also known.

Step 7. *Stop:* Termination criteria are determined to stop the optimization process. If one of the termination criteria is reached, then the X_{best} is saved as optimum solution; otherwise, we return to Step 2 and start the next iteration.

The pseudocode developed for SOS algorithm is given in Figure 3.

3.1. Implementation of SOS algorithm for ELD problem

This section introduces the step-wise procedure for implementing SOS algorithm to solve non-convex ELD problem with valve-point effects while satisfying both equality and inequality constraints. The process and computational producer of the SOS algorithm are laid out as follows:

- *Representation of the ecosystem:* The aim in ELD problems is to determine the most suitable generator output power. Because generator output values form this in optimization variables, they are used to represent molecules in an organism. Thus, an organism is represented in the form of the following matrix:

$$X = [M_1, M_2, M_3, ..., M_n]\,, \tag{15}$$

where M is the molecule and n is the total number of generators. Each organism is a possible solution to the non-convex ELD problem with valve-point effects. Finally, the ecosystem is created by the combination of all organisms. An ecosystem is represented as follows:

$$E = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ \vdots \\ X_m \end{bmatrix}. \tag{16}$$

m is the number of organisms.

- *Problem parameters identification:* The number of generator units, maximum and minimum capacities of each generator, power demand, B-coefficients matrix for calculation of transmission losses, and fuel cost function coefficients are specified. Also, the SOS parameters, like number of organisms and maximum iteration number, are determined.

- *Ecosystem initialization:* For initialization, the initial molecule is defined by generating a uniform random number between lower and upper limits for the related generator power output as follows:

$$M_i = P_i^{\min} + rand(0,1) * (P_i^{\max} - P_i^{\min}). \tag{17}$$

The ecosystem is obtained by applying this operation to all molecules making up each organism.

- *Calculation and evaluation of fitness function for each organism of ecosystem:* FC represents the fuel cost of all generators in the test system for the power demand. Calculated fuel costs for an ecosystem are represented as follows:

$$FC_{eco} = \begin{bmatrix} FC_1 \\ FC_2 \\ FC_3 \\ \vdots \\ FC_m \end{bmatrix}. \tag{18}$$

Here, FC_1 shows the fitness value of the first organism of ecosystem. The organism with the minimum fuel cost value in the ecosystem is chosen as the best organism (X is signified with best).

- *Mutualism, commensalism, and parasitism phases:* New organisms are obtained through operations as indicated in SOS algorithm. The organisms obtained here represent a better solution to the non-convex ELD problem with valve-point effects.
- If the termination criteria are not reached, the next iteration is started.
- The end.

4. Experimental results

The SOS algorithm has been used for solving the ELD problem with valve-point effect. Five different test systems are used to show effectiveness of the proposed method. They are IEEE 3-machine 6-bus, IEEE 5-machine 14-bus, IEEE 6-machine 30-bus, and 13- and 40-unit test systems both with transmission loss and without transmission loss. The setting parameters of the proposed heuristic technique are given in Appendix Table A.1 in the Appendix. The program is written in MATLAB and run on a 2.63 GHz Pentium IV personal computer with 512MB RAM. Descriptions of the test systems are given as follows:

- **Test Case 1:** IEEE 3-machine 6-bus test system is considered in this case. The generators data are obtained from [29] and presented Tables A.2 and A.3 in the Appendix. The load demand of all units with 210 MW should be satisfied. The proposed method is run 40 times and the obtained results are illustrated in Table 1 by comparison with other methods reported before. Minimum, average, and maximum results of the proposed method and comparison with the results obtained from the other methods in the literature are shown in Table 2.

The convergence curve of the total fuel cost obtained from SOS algorithm for Test Case 1 is shown in Figure 4. According to Figure 4, the SOS algorithm reaches the optimal solution in about 25 iterations. This result shows that the SOS algorithm

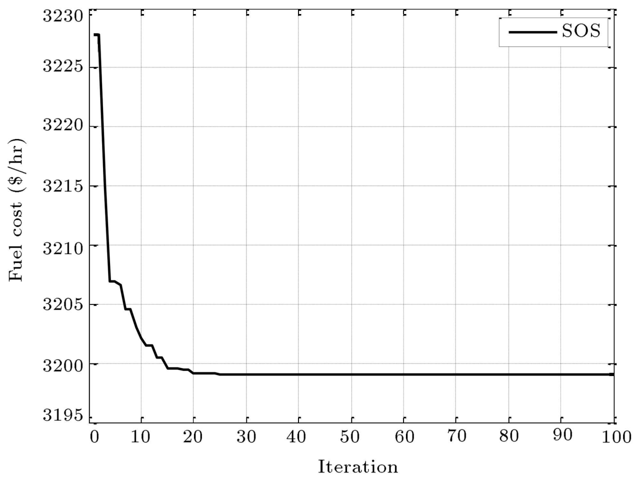

Figure 4. Convergence of total fuel cost obtained from SOS for Test Case 1.

Table 1. Comparison of the results obtained from SOS for Test Case 1.

Units	Methods			
	GA [29]	**GA-APO [29]**	**NSOA [29]**	**SOS**
P_1	53.2604	61.6467	50	50
P_2	88.9645	95.1632	86.0356	76.0015
P_3	74.7693	60.5402	79.7438	90.8627
Total power output (MW)	216.9942	217.3501	215.7794	**216.8642**
Total fuel cost ($/hr)	3252.4576	3341.771	3206.0022	**3199.0113**
P_{loss} (MW)	6.9939	7.346085	5.7794	**6.8641**
Simulations times of the SOS algorithm (s)				**8.2587**

Table 2. The results obtained from the SOS for Test Case 1.

Method	Min.	Average	Max.
GA [29]	3252.46	–	3463.37
GA-APO [29]	3341.77	–	3294.81
NSOA [29]	3205.99	–	3206.00
SOS	**3199.0113**	**3199.0113**	**3199.0113**

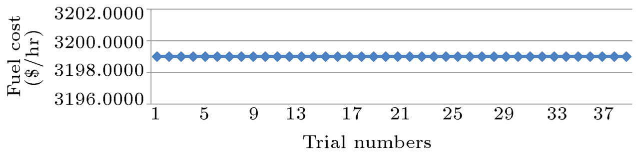

Figure 5. The total fuel cost values obtained from the SOS algorithm for 40 trials (Test Case 1).

converges on the solution quickly. As can be seen in Table 1, optimal solution of SOS for this test case is less than the best solution reported in [29] by 6.99 $/hr. Besides, minimum, average, and maximum results of SOS algorithm have the same value for 40 runs. This result shows that SOS algorithm produces very accurate and fast results in all trials for small power systems. The total fuel cost values obtained from the proposed approach for the solutions performed 40 times for Test Case 1 are shown in Figure 5.

Test Case 2: IEEE 5-machine 14-bus test system is considered in this case. The total load demand is 259 MW. The generators data are obtained from [29] and presented in Tables A.2 and A.3. The proposed algorithm is run 40 times and the results obtained from it are presented in Table 3 by comparison with other methods reported before in the literature. According to the results in Table 3, the proposed algorithm produces the minimum fuel cost with 834.1302 $/hr and it is obviously seen that this result is the best among all in the literature. The convergence curve of total fuel cost obtained from SOS for this case is illustrated in Figure 6. The SOS algorithm reaches the optimal solution in about 55 iterations as seen in Figure 6. The minimum, average, and maximum results of the SOS method and results obtained from the other heuristic techniques previously reported in the literature for this test system are given in Table 4. The total fuel cost values obtained from the proposed SOS algorithm

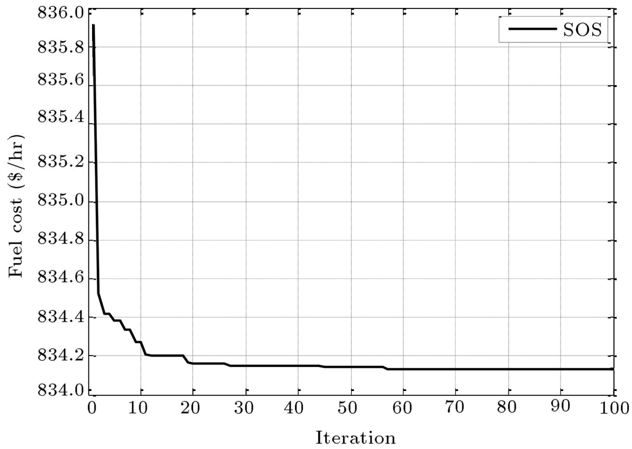

Figure 6. Convergence of total fuel cost obtained from SOS for Test Case 2.

Table 4. The results obtained from the proposed approach for Test Case 2.

Method	Min.	Average	Max.
GA [29]	926.5530	–	1012.44
GA-APO [29]	926.5530	–	960.55
NSOA [29]	905.5437	–	906.63
PSO [30]	836.4568	834.969	837.716
MSG-HS [30]	834.363	834.673	836.119
FPSOGSA [35]	834.1308	834.1312	834.1337
SOS	**834.1302**	**834.1310**	**834.1331**

in the solutions done 40 times for Test Case 2 are shown in Figure 7. From Figure 7, it is obvious that the total fuel cost values have been changed by 0.0029 unit.

- **Test Case 3:** IEEE 6-machine 30-bus test system is considered in this case. The total load demand is 283.4 MW for this case. The generators data are obtained from [29,35] and presented in Tables A.2 and A.3. Results are obtained from the proposed

Table 3. Comparison of the results obtained from SOS for Test Case 2.

Units	Methods						
	GA [29]	GA-APO [29]	NSOA [29]	PSO [30]	MSG-HS [30]	FPSOGSA [35]	SOS
P_1	172.7647	172.7647	181.1287	197.4696	199.6923	199.5997	199.5997
P_2	26.6212	26.6212	46.7567	20.0000	20.0000	20.0000	20.0000
P_3	24.8322	24.8322	19.1526	21.3421	20.8157	20.9133	20.9913
P_4	23.4152	23.4152	10.1879	11.6762	15.5504	15.4893	15.4673
P_5	19.1885	19.1885	10.7719	17.7744	12.5069	12.5527	12.4960
Total power output (MW)	266.8217	266.8217	267.9977	268.2623	268.5653	268.555	**268.5543**
Total fuel cost ($/hr)	926.5530	926.5530	905.5437	836.4568	834.363	834.1308	**834.1302**
P_{loss} (MW)	7.8250	7.8250	8.9977	9.2623	9.5654	9.555	**9.5543**
Simulations times of the SOS algorithm (s)							**14.7816**

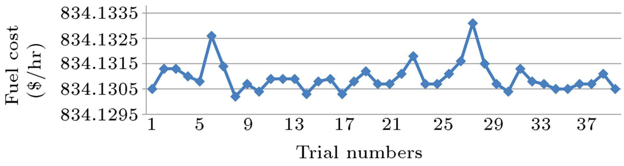

Figure 7. The total fuel cost values obtained from the SOS algorithm for 40 trials (Test Case 2).

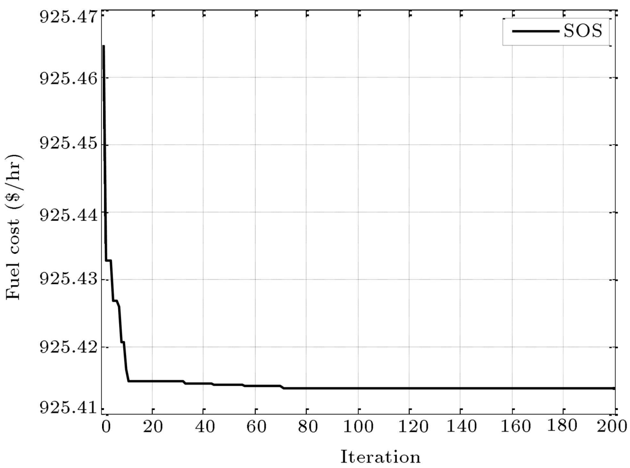

Figure 8. Convergence of total fuel cost obtained from SOS for Test Case 3.

algorithm for 40 runs and given in Table 5 by comparison with other techniques reported before in the literature. The SOS algorithm has the same value for total fuel cost of 925.4137 $/hr and it is less than others reported before. Moreover, the proposed algorithm meets the total load demand exactly, but FPSOGSA misses with a little difference. Thus, SOS is a good alternative method to solve such a power system. The convergence curve of total fuel cost for this case is presented in Figure 8. The proposed algorithm converges on the global optima after about 70 iterations as seen in Figure 8. The minimum, average, and maximum results of the SOS method and results obtained from the other stochastic methods in the literature for this test system are given in Table 6. The total fuel cost values obtained from the proposed SOS algorithm for the solutions done 40 times for Test Case 3 are shown in Figure 9. From Figure 9, it is clear that the total fuel cost values are changed by 0.0060 unit.

Table 6. The results obtained from the proposed approach for Test Case 3.

Method	Min	Average	Max
GA[29]	996.0369	–	1117.13
GA-APO [29]	1101.491	–	996.04
NSOA [29]	984.9365	–	992.48
PSO [30]	925.7581	926.388	928.427
MSG-HS [30]	925.6406	926.851	928.599
FPSOGSA [35]	925.4137	925.4175	925.4213
SOS	925.4137	925.4143	925.4197

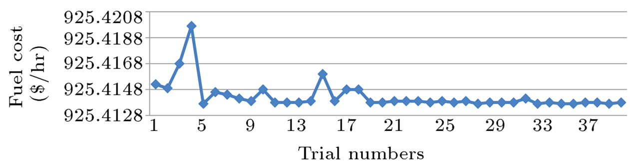

Figure 9. The total fuel cost values obtained from the SOS method for 40 trials (Test Case 3).

- **Test Case 4:** IEEE 13-machine test system is considered in this case. Three different load demands, namely, 1800 MW and 2520 MW with transmission loss and 2520 MW constrained, are considered. In the constrained case, power outputs of the 11th and 12th generators are fixed at 75 MW and 60 MW. Generators data and B-coefficient are

Table 5. Comparison of the results obtained from SOS for Test Case 3.

Units	Methods						
	GA [29]	GA-APO [29]	NSOA [29]	PSO [30]	MSG-HP [30]	FPSOGSA [35]	SOS
P_1	150.724	133.9816	182.478	197.8648	199.6331	199.5997	199.5997
P_2	60.8707	37.2158	48.3525	50.3374	20.0000	20.0000	20.0000
P_3	30.8965	37.7677	19.8553	15.0000	23.7624	23.9896	23.9768
P_4	14.2138	28.3492	17.1370	10.0000	18.3934	18.8493	18.8679
P_5	19.4888	18.7929	13.6677	10.0000	17.1018	18.2153	18.2212
P_6	15.9154	38.0525	12.3487	12.0000	15.6922	13.8506	13.8402
Total power output (MW)	292.1096	294.1600	293.8395	295.2022	294.5829	294.5045	**294.5058**
Total fuel cost ($/hr)	996.0369	1101.491	984.9365	925.7581	925.6406	925.4137	**925.4137**
P_{loss} (MW)	8.7060	10.7563	10.4395	11.8022	11.1830	11.1044	**11.1058**
Simulations times of the SOS algorithm (s)							**21.5872**

obtained from [35] and presented in Tables A.4 and A.5 in the Appendix. Results obtained from SOS algorithm for these cases are given in Table 7 by comparing other methods reported before. The SOS has the lowest total fuel costs by 18134.2805 $/hr and 24515.2275 $/hr for 1800 MW and 2520 MW load demands, respectively. The convergence curves for these cases are shown in Figures 10 and 11. It is seen from these figures that for both load demands, the SOS algorithm converges on the global optima after about 20 iterations. The total fuel cost values obtained from the proposed SOS algorithm in the solutions done 40 times for Test Case 4 are shown in Figures 12 and 13. From Figures 12 and 13, it is apparent that the total fuel cost values are changed by 0.1924 and 0.1857 unit, respectively.

Results obtained from SOS algorithm for 2520 MW constrained case are presented in Table 8. According to this table, SOS produces the best result together with FPSOGSA among all methods and has the lowest fuel cost with 24252.9363 $/hr. The convergence curve of fuel cost for this case is also shown in Figure 14.

- **Test Case 5:** IEEE 40-machine test system without loss is considered in this case. Total load demand is 10500 MW. Generators data are taken from [35, 39] and can be observed in the mentioned studies. Results obtained from the proposed algorithm are given in Table 9 and compared with other results ob-

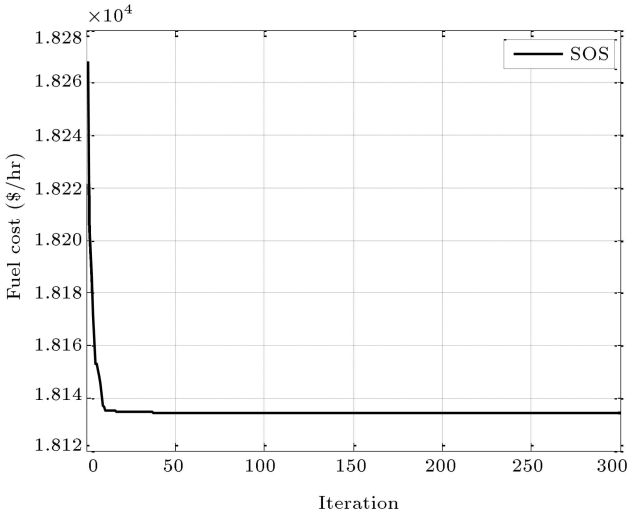

Figure 10. Convergence of total fuel cost obtained from SOS for 1800 MW load demand.

Table 7. Comparison of the results obtained from SOS for 1800 MW and 2520 MW load demands.

	Output power (MW)						
	P_D = 1800 MW			**P_D = 2520 MW**			
Unit	**SDE [31]**	**FPSOGSA [35]**	**SOS**	**SDE [31]**	**ICA-PSO [33]**	**FPSOGSA [35]**	**SOS**
P_1	448.80	448.7990	448.7990	628.32	628.32	628.3185	628.3184
P_2	297.93	297.9312	296.8851	299.20	299.19	299.1993	299.199
P_3	223.30	223.3374	224.3995	299.20	294.51	299.1993	299.1992
P_4	109.85	109.8666	109.8666	159.73	159.73	159.7331	159.7331
P_5	109.85	109.8666	109.8665	159.73	159.73	159.7331	159.7329
P_6	159.71	159.7331	159.7331	159.73	159.73	159.7331	159.7331
P_7	109.86	109.8666	109.8665	159.73	159.73	159.7331	159.7331
P_8	60.00	60.0000	60.0000	159.73	159.73	159.7331	159.733
P_9	109.82	109.8666	109.8665	159.73	159.73	159.7331	159.7331
P_{10}	40.00	40.0000	40.0000	77.40	114.80	76.9368	77.3988
P_{11}	40.00	40.0000	40.0000	113.12	116.45	114.2795	113.4981
P_{12}	55.00	55.0000	55.0000	92.40	55.00	92.2438	92.3998
P_{13}	55.00	55.0000	55.0000	92.40	92.40	92.2007	92.3997
Total power output (MW)	1819.13	1819.2671	1819.2828	2560.43	2559.05	2560.7765	**2560.8113**
P_{loss} (MW)	19.13	19.2669	19.2829	40.43	39.05	40.7765	**40.8112**
Total fuel cost ($/hr)	18134.49	18134.39457	18134.2805	24514.88	24540.06	24515.35543	**24515.2275**
Average fuel cost ($/hr)	18138.56	18136.96721	18134.2977	24516.31	24561.46	24516.68231	**24515.2626**
Simulation times of the SOS algorithm (s)			**45.7831**	Simulation times of the SOS algorithm (s)			**45.6429**

Table 8. Comparison of the results obtained from SOS for 2520 MW constrained load demand.

Unit	EP-SQP [34]	PSO-SQP [34]	ICA-PSO [33]	RQEA [36]	SDE [32]	FPSOGSA [35]	SOS
P_1	628.3136	628.3205	628.32	628.3170	628.31853071796	628.3185	628.3185
P_2	299.1715	299.0524	299.20	299.1991	299.1990034188	299.1993	299.1993
P_3	299.0474	298.9681	291.90	299.1990	299.19930034189	299.1993	299.1993
P_4	159.6399	159.4680	159.73	159.7334	159.73310011396	159.7331	159.7331
P_5	159.6560	159.1429	159.73	159.7331	159.73310011396	159.7331	159.7331
P_6	158.4831	159.2724	159.73	159.7330	159.73310011396	159.7331	159.7331
P_7	159.6749	159.5371	159.73	159.7324	159.73310011396	159.7331	159.7331
P_8	159.7265	158.8522	159.73	159.7329	159.73310011396	159.7331	159.7331
P_9	159.6653	159.7845	159.73	159.7331	159.73310011396	159.7331	159.7331
P_{10}	114.0334	110.9618	114.80	107.4875	107.48435537177	107.4843	107.4844
P_{11}	75.0000	75.0000	75.00	75.0000	75.00000000000	75.0000	75.0000
P_{12}	60.0000	60.0000	60.00	60.0000	60.00000000000	60.0000	60.0000
P_{13}	87.5884	91.6401	92.40	92.3994	92.39991254274	92.3999	92.3999
Total power output (MW)	2520.0000	2520.0000	2520.00	2519.9999	2520.000000000	2520.0000	**2520.0000**
Total fuel cost ($/hr)	24266.440	24261.050	24261.69	24252.950	24252.936305152	24252.9362294	**24252.9363**
Simulation times of the SOS algorithm (s)							**62.6591**

Table 9. Results obtained from SOS for Test Case 5.

Unit	SOS	Unit	SOS	Unit	SOS	Unit	SOS
P_1	110.7998	P11	94.0000	P21	523.2794	P31	190.0000
P_2	110.7998	P12	94.0000	P22	523.2794	P32	190.0000
P_3	97.3999	P13	214.7598	P23	523.2794	P33	190.0000
P_4	179.7331	P14	394.2794	P24	523.2794	P34	164.7998
P_5	87.7999	P15	394.2794	P25	523.2794	P35	194.3978
P_6	140.0000	P16	394.2794	P26	523.2794	P36	200.0000
P_7	259.5997	P17	489.2794	P27	10.0000	P37	110.0000
P_8	284.5997	P18	489.2794	P28	10.0000	P38	110.0000
P_9	284.5997	P19	511.2794	P29	10.0000	P39	110.0000
P_{10}	130.0000	P20	511.2794	P30	87.7999	P40	511.2794
Total power output (MW)							**10500.000**
Total fuel cost ($/hr)							**121412.5355**
Simulation times of the SOS algorithm (s)							**105.8743**

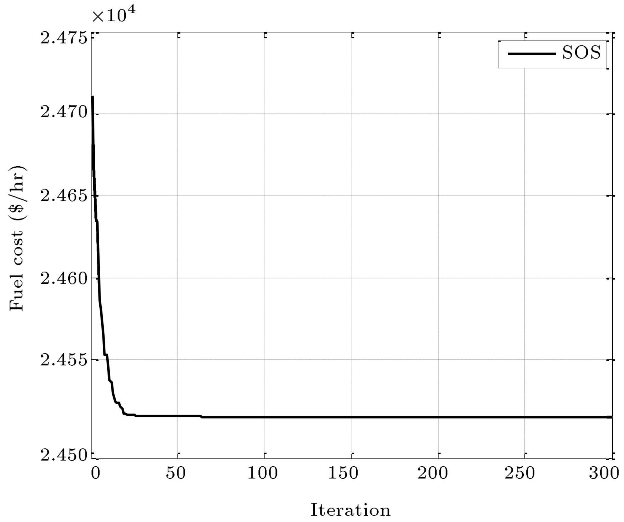

Figure 11. Convergence of total fuel cost obtained from SOS for 2520 MW load demand.

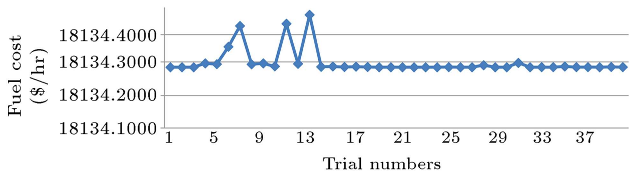

Figure 12. The total fuel cost values obtained from the SOS method for 40 trials (for 1800 MW).

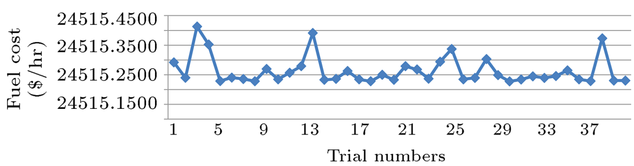

Figure 13. The total fuel cost values obtained from the SOS method for 40 trials (for 2520 MW).

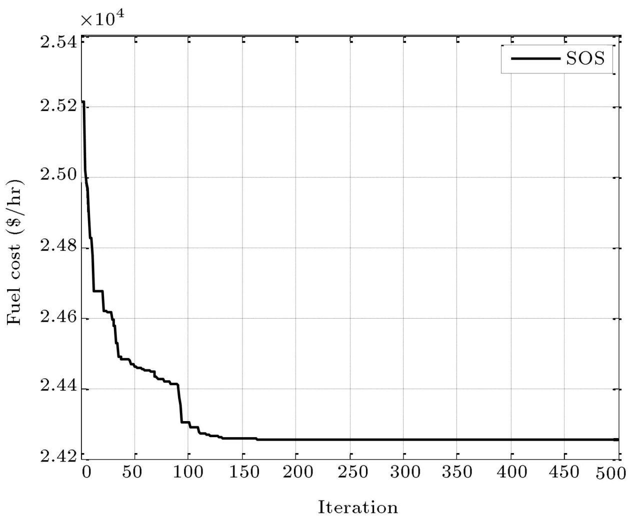

Figure 14. Convergence of total fuel cost obtained from SOS for 2520 MW constrained load demand.

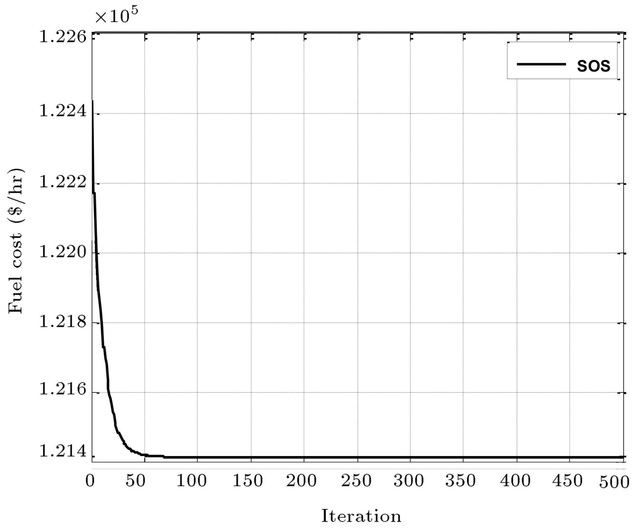

Figure 15. Convergence of total fuel cost obtained from SOS for Test Case 5.

tained from different methods in the literature, provided in Table 10. It can be seen in Table 10 that the proposed algorithm has the lowest fuel cost function with 121412.5355 $/hr among all methods, which is the best value produced up to now. The convergence curve of the total fuel cost obtained from SOS is shown in Figure 15. The optimal solution is found after about 50 iterations as seen in Figure 15.

5. Conclusion

This paper has employed SOS algorithm for the ELD problem with valve-point effect, which is one of the important optimization problems in power systems. The proposed algorithm was examined on 3-machine 6-bus, IEEE 5-machine 14-bus, IEEE 6-machine 30-bus, and 13- and 40-unit test systems both with transmission loss and without transmission loss. Obtained results showed that SOS algorithm solved the ELD problem successfully and effectively. From this comparative study, it could be concluded that the proposed algorithm could be effectively used to solve different types of ELD problems. In order to prove feasibility of the proposed method, results obtained from SOS were compared with other methods existing in the literature. According to the comparisons, the proposed algorithm reduced the total fuel cost values for 5-machine 14-bus system with 210 MW load demand by 6.99 $/hr, for 5-machine 14-bus system with 259 MW load demand by 0.99 $/hr (the results of SOS for 6-machine 30-bus system are same as the result of FPSOGSA), for 13-machine system with 1800 MW load demand by 2.669 $/hr, for 13-machine system with 2520 MW load demand by 1.419 $/hr, and for 40-machine system with 10500 MW load demand by 0.00661 $/hr. It could be clearly seen from the results that SOS produced better

Table 10. Comparison of results for Test Case 5.

Method	Minimum cost ($/hr)	Average cost ($/hr)	Maximum Cost ($/hr)
HGPSO [40]	124797.13	126855.70	NA
SPSO [40]	124350.40	126074.40	NA
PSO [34]	123930.45	124154.49	NA
CEP [39]	123488.29	124793.48	126902.89
HGAPSO [40]	122780.00	124575.70	NA
FEP [39]	122679.71	124119.37	127245.59
MFEP [39]	122647.57	123489.74	124356.47
IFEP [39]	122624.35	123382.00	125740.63
TM [21]	122477.78	123078.21	124693.81
EP-SQP [34]	122323.97	122379.63	NA
MPSO [10]	122252.26	NA	NA
ESO [41]	122122.16	122524.07	123143.07
HPSOM [40]	122112.40	124350.87	NA
PSO-SQP [34]	122094.67	122245.25	NA
GA_MU [42]	122000.2837	NA	NA
Improved GA [43]	121915.93	122811.41	123334.00
HPSOWM [40]	121915.30	122844.40	NA
IGAMU [42]	121819.25	NA	NA
HDE [44]	121813.26	122705.66	NA
PSO [45]	121735.4736	122513.9175	123467.4086
APSO(1) [45]	121704.7391	122221.3697	122995.0976
ST-HDE [44]	121698.51	122304.30	NA
NPSO-LRS [46]	121664.43	122209.31	122981.59
APSO(2) [45]	121663.5222	122153.6730	122912.3958
MTS [47]	121532.10	121798.51	122022.15
SOH_PSO [48]	121501.14	121853.57	122446.30
CPSO-SQP [49]	121458.54	122028.16	NA
GA_PS_SQP [50]	121458.14	122039.00	NA
BBO [17]	121426.9530	121508.0325	121688.6634
PSO_MSAF [51]	121423.23	NA	NA
DE/BBO [52]	121420.8948	121420.8952	121420.8963
FAPSO-NM [26]	121418.30	121418.8030	121419.80
HGA [53]	121418.27	121784.04	NA
FA [23]	121415.05	121416.57	121424.56
MDE [54]	121414.79	121418.44	121466.04
IPSO-TVAC [55]	121412.5450	121419.30	121423.80
FPSOGSA [35]	121412.542110	121413.561938	121414.983790
SOS	**121412.5355**	**121413.2597**	**121413.9281**

results than other well-known meta-heuristic methods for both small and big test systems. Moreover, the proposed approach has some merits such as simple concept, easy implementation, and better effectiveness than previous methods.

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Appendix

Tables A.1.to A.5 are described as data of the test cases.

Table A.1. Setting parameters of the SOS algorithm for the ELD problem.

Test system	Number of organisms (eco_size)	max_iter
6-bus 3-machine system	50	100
IEEE 14-bus 5-machine system	50	100
IEEE 30-bus 6-machine system	50	200
13-unit test system (for 1800 MW and 2520 MW)	80	300
13-unit test system (for 2520 MW constrained)	100	500
40-unit test system	100	500

Table A.2. Cost coefficients of the generating units [29,34].

	Test system	Bus	a	b	c	d	e	$P^{\min}$	$P^{\max}$
1	6-bus 3-machine system	1	213.1	11.669	0.00533	130	0.0635	50	200
		2	200.0	10.333	0.00889	90	0.0598	37.5	150
		3	240.0	10.833	0.00741	100	0.0685	45	180
2	IEEE 14-bus 5-machine system	1	150.0	2.00	0.0016	50.0	0.0630	50	200
		2	25.0	2.50	0.0100	40.0	0.0980	20	80
		3	0.0	1.00	0.0625	0.0	0.0	15	50
		6	0.0	3.25	0.00834	0.0	0.0	10	35
		8	0.0	3.00	0.025	0.0	0.0	10	30
3	IEEE 30-bus 6-machine system	1	150.0	2.00	0.0016	50.0	0.0630	50	200
		2	25.0	2.50	0.0100	40.0	0.0980	20	80
		5	0.0	1.00	0.0625	0.0	0.0	15	50
		8	0.0	3.25	0.00834	0.0	0.0	10	35
		11	0.0	3.00	0.025	0.0	0.0	10	30
		13	0.0	3.00	0.025	0.0	0.0	12	40

Table A.3. B-coefficients for test systems [29,34].

	Test system	B-Coefficients
1	6-bus 3-machine system	$[B]=\begin{bmatrix}0.0552 & 0.0062 & -0.0046\\ 0.0062 & 0.0253 & 0.0064\\ -0.0046 & 0.0064 & 0.0286\end{bmatrix}$ $[B_0]=\begin{bmatrix}0.0046 & 0.0035 & 0.0019\end{bmatrix}$ $B_{00}=0.00055711$
2	IEEE 14-bus 5-machine system	$[B]=\begin{bmatrix}0.0212 & 0.0085 & -0.0009 & 0.0021 & 0.0007\\ 0.0085 & 0.0206 & -0.0041 & 0.0037 & 0.0001\\ -0.0009 & -0.0041 & 0.0395 & -0.0207 & -0.0251\\ 0.0021 & 0.0037 & -0.0207 & 0.0613 & -0.0071\\ 0.0007 & 0.0001 & -0.0251 & -0.0071 & 0.0406\end{bmatrix}$ $[B_0]=\begin{bmatrix}-0.0002 & 0.0030 & -0.0017 & 0.0101 & -0.0038\end{bmatrix}$ $B_{00}=0.00085357$
3	IEEE 30-bus 6-machine system	$[B]=\begin{bmatrix}0.0224 & 0.0103 & 0.0016 & -0.0053 & 0.0009 & -0.0013\\ 0.0103 & 0.0158 & 0.0010 & -0.0074 & 0.0007 & 0.0024\\ 0.0016 & 0.0010 & 0.0474 & -0.0687 & -0.0060 & -0.0350\\ -0.0053 & -0.0074 & -0.0687 & 0.3464 & 0.0105 & 0.0534\\ 0.0009 & 0.0007 & -0.0060 & 0.0105 & 0.0119 & 0.0007\\ -0.0013 & 0.0024 & -0.0350 & 0.0534 & 0.0007 & 0.2353\end{bmatrix}$ $[B_0]=\begin{bmatrix}-0.0005 & 0.0016 & -0.0029 & 0.0060 & 0.0014 & 0.0015\end{bmatrix}$ $B_{00}=0.0011$

Table A.4. Generators data of Test Case 4 [35].

Test system	Units	a	b	c	d	e	$P^{\min}$	$P^{\max}$
4	1	550	8.10	0.00028	300	0.035	0	680
	2	309	8.10	0.00056	200	0.042	0	360
	3	307	8.10	0.00056	200	0.042	0	360
	4	240	7.74	0.00324	150	0.063	60	180
	5	240	7.74	0.00324	150	0.063	60	180
	6	240	7.74	0.00324	150	0.063	60	180
	7	240	7.74	0.00324	150	0.063	60	180
	8	240	7.74	0.00324	150	0.063	60	180
	9	240	7.74	0.00324	150	0.063	60	180
	10	126	8.60	0.00284	100	0.084	40	120
	11	126	8.60	0.00284	100	0.084	40	120
	12	126	8.60	0.00284	100	0.084	55	120
	13	126	8.60	0.00284	100	0.084	55	120

Table A.5. B-coefficients for 13-unit test system [31,35].

***B*-Coefficients**

$$[B] = \begin{bmatrix} 0.0014 & 0.0012 & 0.0007 & -0.0001 & -0.0003 & -0.0001 & -0.0001 & -0.0001 & -0.0003 & -0.0005 & -0.0003 & -0.0002 & 0.0004 \\ 0.0012 & 0.0015 & 0.0013 & 0 & -0.0005 & -0.0002 & 0 & 0.0001 & -0.0002 & -0.0004 & -0.0004 & 0 & 0.0004 \\ 0.0007 & 0.0013 & 0.0076 & -0.0001 & -0.0013 & -0.0009 & -0.0001 & 0 & -0.0008 & -0.0012 & -0.0017 & 0 & -0.0026 \\ -0.0001 & 0 & -0.0001 & 0.0034 & -0.0007 & -0.0004 & 0.0011 & 0.005 & 0.0029 & 0.0032 & -0.0011 & 0 & 0.0001 \\ -0.0003 & -0.0005 & -0.0013 & -0.0007 & 0.009 & 0.0014 & -0.0003 & -0.0012 & -0.001 & -0.0013 & 0.0007 & -0.0002 & -0.0002 \\ -0.0001 & -0.0002 & -0.0009 & -0.0004 & 0.0014 & 0.0016 & 0 & -0.0006 & -0.0005 & -0.0008 & 0.0011 & -0.0001 & -0.0002 \\ -0.0001 & 0 & -0.0001 & 0.0011 & -0.0003 & 0 & 0.0015 & 0.0017 & 0.0015 & 0.0009 & -0.0005 & 0.0007 & 0 \\ -0.0001 & 0.0001 & 0 & 0.005 & -0.0012 & -0.0006 & 0.0017 & 0.0168 & 0.0082 & 0.0079 & -0.0023 & -0.0036 & 0.0001 \\ -0.0003 & -0.0002 & -0.0008 & 0.0029 & -0.001 & -0.0005 & 0.0015 & 0.0082 & 0.0129 & 0.0116 & -0.0021 & -0.0025 & 0.0007 \\ -0.0005 & -0.0004 & -0.0012 & 0.0032 & -0.0013 & -0.0008 & 0.0009 & 0.0079 & 0.0116 & 0.02 & -0.0027 & -0.0034 & 0.0009 \\ -0.0003 & -0.0004 & -0.0017 & -0.0011 & 0.0007 & 0.0011 & -0.0005 & -0.0023 & -0.0021 & -0.0027 & 0.014 & 0.0001 & 0.0004 \\ -0.0002 & 0 & 0 & 0 & -0.0002 & -0.0001 & 0.0007 & -0.0036 & -0.0025 & -0.0034 & 0.0001 & 0.0054 & -0.0001 \\ 0.0004 & 0.0004 & -0.0026 & 0.0001 & -0.0002 & -0.0002 & 0 & 0.0001 & 0.0007 & 0.0009 & 0.0004 & -0.0001 & 0.0103 \end{bmatrix}$$

$$[\mathbf{B_0}] = \begin{bmatrix} \mathbf{-0.0001} & \mathbf{-0.0002} & \mathbf{0.0028} & \mathbf{-0.0001} & \mathbf{0.0001} & \mathbf{-0.0003} \\ & \mathbf{-0.0002} & \mathbf{-0.0002} & \mathbf{0.0006} & \mathbf{0.0039} & \mathbf{0.0017} & \mathbf{0} & \mathbf{-0.0032} \end{bmatrix}$$

$B_{00} = 0.0055$

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