



## Squirrel Search Optimization for Non-convex Multi-area Economic Dispatch

V. P. Sakthivel<sup>\*a</sup>, P. D. Sathya<sup>b</sup>

<sup>a</sup>Department of Electrical and Electronics Engineering, Government College of Engineering, Dharmapuri, India

<sup>b</sup>Department of Electronics and Communication Engineering, FEAT, Annamalai University, Chidambaram, India

### PAPER INFO

#### Paper history:

Received 04 April 2020

Received in revised form 28 October 2020

Accepted 14 November 2020

#### Keywords:

Metaheuristic Approach

Multi-area Economic Load Dispatch

Multi Fuel Alternatives

Swarm Intelligence

Valve Point Impacts

### ABSTRACT

Multi-area economic load dispatch (MAELD) decides the measure of power that can be fiscally generated in one area and transferred to another area. The goal of MAELD is to determine the most prudent production arrangement that could deliver the nearby power requirement without violating tie-line limits. This study presents a new swarm algorithm called as squirrel search optimization (SSO) to solve the MAELD problems. The impacts of transmission losses, prohibited operating zones, valve point loading and multi-fuel alternatives are additionally contemplated. SSO impersonates the searching conduct of flying squirrels which depends on the dynamic bouncing and skimming procedures. To demonstrate the potency of the suggested approach, it is examined on three different test systems for solving the MAELD problems. Comparative examinations are performed to analyze the adequacy of the suggested SSO approach with exchange market algorithm and different strategies revealed in the literature. The experimental results show that the proposed SSO approach is equipped for acquiring preferred quality solutions over the other existing strategies.

doi: 10.5829/ije.2021.34.01a.14

### NOMENCLATURE

$a_{ij}, b_{ij}, c_{ij}$	Cost coefficients of generator $j$ in area $i$	$nz, ng$	Total number of POZs and generating units respectively
$e_{ij}, f_{ij}$	Cost coefficients of the VPL effect of generator $j$ in area $i$	$P_{Di}$	Power demand in area $i$
$F_{ij}(P_{ij})$	Fuel cost of the generator $j$ in area $i$	$P_{dp}$	predator presence probability
$nf$	Number of fuel alternatives	$P_{ij}$	Real power generation of generator $j$ in area $i$
$M_i$	Number of participated generators in area $i$	$P_{ij,min}, P_{ij,max}$	Minimum and maximum generation $j$ in area $i$
$m$	Index of prohibited zone	$T_{iz}$	Tie line power stream from area $i$ to area $z$

## 1. INTRODUCTION

Multi-area economic load dispatch (MAELD) is a portion of economic load dispatch (ELD) which concentrates on critical issues about energy management of the modern power systems. In reality, MAELD characterizes the amount of power which can be monetarily delivered in one area and transferred to another. The principle objective of MAELD is to determine the most conservative power generation strategy which could stream the nearby power demands with no abusing tie-line limit limitations. As of late, MAELD is considered as a new part of ELD issues which

are profoundly encouraging for utilizing in the power grids.

In recent years, swarm intelligence algorithms have been broadly used to solve the MAELD problem. Jayabarathi et al. [1] proposed a proficient technique for multi-area economic dispatch problems using evolutionary programming (EP) approach. The performance of the various evolutionary algorithms, for example as real-coded genetic algorithm (RCGA), particle swarm optimization (PSO), differential evolution (DE) and covariance matrix adapted evolution strategy (CMAES) on MAELD problems with Karush–Kuhn–Tucker optimality confirmations were examined by Manoharan et al. [2]. The simulation results revealed that

\*Corresponding Author Institutional Email: vp.sakthivel@yahoo.com  
(V. P. Sakthivel)

the CMAES algorithm offers preferred outcomes over different algorithms considered. Sharma et al. [3] investigated and analyzed the performance of different DE strategies enhanced with time-varying mutation to solve the reserve constrained MAELD problem. Somasundaram and Jothi Swaroopan [4] introduced another computationally efficient fuzzified particle swarm optimization algorithm for solving the security-constrained MAELD of an interconnected power system. Basu proposed artificial bee colony (ABC) optimization [5], teaching learning-based optimization (TLBO) [6] and fast convergence evolutionary programming [7] for solving MAELD problem with tie-line constraints, transmission losses, multiple fuels and valve point effects. Nguyen et al. [8] developed hybrid cuckoo search algorithm to solve the MAELD problem. Ghasemi et al. [9] presented hybrid DE-PSO technique for addressing the MAELD, reserve constrained MAELD and reserve constrained multi area ecological/economic dispatch issues. Zhang et al. [10] introduced an improved grasshopper optimization algorithm to take care of the MAELD issue. The suggested approach considered the tie-line constraints including transmission losses, POZ, MFO and VPL impacts, and validated with different meta-heuristics.

A new model was proposed to examine impacts of uncertainties associated to component failures, load demand and wind power on the generation scheduling [11]. A dynamic optimization approach for optimal choice of energy carriers in thermal power plants was developed to analyse the substitution of energy carriers in short-term planning of a power plant [12]. A hybrid PSO and genetic operators was used for Pareto based optimization of solar systems [13].

Recently, a new nature-inspired algorithm named red deer algorithm (RDA) which mimicked the behaviour of Scottish red deer was developed [14]. Furthermore, the parameters and operators of RDA were made adaptive to improve the performance of this optimizer [15]. The effectiveness of improved RDA was proved on some benchmarked functions and design optimization of brushless motor. Fathollahi-Fard et al. developed a new single-solution algorithm called social engineering optimizer (SEO) which inspired the social engineering phenomena [16]. An improved SEO was developed to solve a truck scheduling problem in a cross-docking system [17]. A multi-objective SEO was applied to solve the HHC routing and scheduling problem [18] and an integrated water supply and wastewater collection network design problem [19].

From the review of the literature, many studies have neglected MFO, VPL and the intertemporal constraints. The MAELD problem with MFO and VPL effects becomes highly non-convex and challenging. It is vital to apply more effective heuristic approach to overcome the curse of dimension and improve the solution accuracy.

To fill the research gap, a new approach, squirrel search optimization is employed for solving the highly non-convex MAELD problems with several operating constraints. The SSO algorithm proposed by Mohit Jain et al. [20] models the foraging activities of squirrel individuals.

The primary contributions of this paper can be summarized hereunder:

1. This paper models a more realistic formulation of the MAELD problem by considering all actual constraints and nonlinear characteristic of generating units including ramp rate limits, POZ, MFO and VPL impacts.
2. The envisaged research work considers different kinds of MAELD problems.
3. To demonstrate the supremacy of the suggested SSO approach, it has been examined on 2-area, 3-area and 4-area power systems, and compared with the state-of-the-art approaches surfaced in the literature.

## 2. PROBLEM FORMULATION OF MAELD PROBLEM

The goal of MAELD is to endeavor the optimal set of generation values in every zone just as shifting power between various zones so as to minimize the objective function subject to various imperatives.

The quadratic cost function of submitted generation units in all zones can be detailed as follows:

$$F_t = \sum_{i=1}^{n_g} \sum_{j=1}^{M_i} F_{ij}(P_{ij}) \quad (1)$$

$$\sum_{i=1}^{n_g} \sum_{j=1}^{M_i} (a_{ij} + b_{ij}P_{ij} + c_{ij}P_{ij}^2) \quad (2)$$

To display the impact of valve-points, a common amended sinusoid commitment is added to the quadratic function which is defined as:

$$F_t = \sum_{i=1}^{n_g} \sum_{j=1}^{M_i} a_{ij} + b_{ij}P_{ij} + c_{ij}P_{ij}^2 + |e_{ij} \times \sin(f_{ij} \times (P_{ij,min} - P_{ij}))| \quad (3)$$

Since generators are provided with multi-fuel sources, every generator ought to be defined with a few piecewise quadratic capacities superimposed sine terms mirroring the impact of fuel type changes and the generator must distinguish the most conservative fuel to consume. The MAELD problem with VPL and MFO can be modeled as:

$$F_t = \sum_{i=1}^{n_g} \sum_{j=1}^{M_i} a_{ijk} + b_{ijk}P_{ijk} + c_{ijk}P_{ijk}^2 + |e_{ijk} \times \sin(f_{ijk} \times (P_{ijk,min} - P_{ijk}))| \quad (4)$$

where  $k= 1, \dots, nf$

The following equality and inequality constraints are addressed to solve the MAELD problem.

The total power generated from a set of committed units must fulfil the total load demand, tie line power flow and transmission losses, and is given by:

$$\sum_{j=1}^{M_i} P_{ij} = P_{Di} + P_{Li} + \sum_{z,z \neq i} T_{iz} \tag{5}$$

The real output power of thermal units ought to be in their range between minimum and maximum limits:

$$P_{ij,min} \leq P_{ij} \leq P_{ij,max} \tag{6}$$

Because of security basis, power shifted between various lines must not surpass their cutoff points. The power transfer requirement between two unique regions is characterized by

$$-T_{iz,min} \leq T_{iz} \leq T_{iz,max} \tag{7}$$

The POZs are owing to the function of steam valve or vibrations in the shaft bearings. The viable operating sectors of unit is defined by

$$\begin{aligned} P_{ij,min} &\leq P_{ij} \leq P_{ij,1}^L \\ P_{ij,k-1}^U &\leq P_{ij} \leq P_{ij,k}^L \quad k = 2, \dots, nz \\ P_{ij} &\leq P_{ij,max}^U \end{aligned} \tag{8}$$

### 3. SYNOPSIS OF SSO

The hunt procedure starts when flying squirrels begin scavenging. During fall, the squirrels look for nourishment assets by skimming from one tree to the next. At the same time, they change their area and investigate various regions of trees. As the climatic conditions are sufficiently hot, they can meet their every day vitality needs more rapidly on the eating routine of oak seeds accessible in bounty and thus they devour oak seeds quickly after discovering them. The capacity of hickory nuts will help them in keeping up their vitality prerequisites in amazingly brutal climate and decrease the expensive searching excursions and in this way increment the likelihood of endurance.

Toward the finish of winter season, flying squirrels again become dynamic. This is a monotonous procedure and proceeds till the life expectancy of a flying squirrel and structures the establishment of SSO. The SSO refreshes the places of squirrels as indicated by the ebb and flow season, the sort of squirrels and if chasers show up.

Expecting that the quantity of the populace is N, the upper and lower limits of the pursuit space are  $X_U$  and  $X_L$ . N squirrels are arbitrarily created as follows:

$$X_i = X_L + rand(1, D) \times (X_U - X_L) \tag{9}$$

where,  $X_i$  indicates the  $i$ th squirrel, ( $i = 1 : N$ ); rand is a random number somewhere in the range of 0 and 1; D is the dimension of the problem.

SSO requires that there is just a single squirrel at each tree, accepting the absolute number of the squirrels is N, subsequently, there are N trees in the forests. All the N trees contain one hickory tree and  $N_a$  oak seed trees; the

others are typical trees that have no nourishment. The hickory tree is the best nourishment asset for the squirrels and the oak seed tree comes in just short of the win. The squirrels are separated into three kinds: squirrels situated at hickory trees ( $W_h$ ), squirrels situated at oak seed trees ( $W_a$ ) and squirrels situated at ordinary trees ( $W_n$ ).

The squirrels refresh their situations by skimming to the hickory trees or oak seed trees as follows:

$$X_i^{t+1} = \begin{cases} X_i^t + d_g G_c (X_{ai}^t - X_i^t) & \text{if } r_1 \geq P_{dp} \\ \text{Random location} & \text{otherwise} \end{cases} \tag{10}$$

$$X_i^{t+1} = \begin{cases} X_i^t + d_g G_c (X_h^t - X_i^t) & \text{if } r_2 \geq P_{dp} \\ \text{Random location} & \text{otherwise} \end{cases} \tag{11}$$

where,  $r_1$  and  $r_2$  are random numbers in the range of [0, 1],  $P_{dp}$  is predator presence probability,  $X_h$  is the location of squirrel individual which reached the hickory tree and  $t$  indicates the current iteration.  $G_c$  and  $d_g$  are gliding constant and distance respectively.

Toward the start of every generation, the SSO necessitates that the entire populace is in winter, which implies all the squirrels are refreshed by Equations (10) and (11). The squirrels are refreshed, regardless of whether the season change is decided by the following formulae.

$$S_c^t = \sqrt{\sum_{k=1}^d (X_{ai,k}^t - X_{h,k}^t)^2} \tag{12}$$

$$S_{min} = \frac{10e^{-6}}{(365)^{t/(t_{max}/2.5)}} \tag{13}$$

If  $S_{ic} < S_{min}$ , winter is finished and the season goes to summer, or else, the season is unaltered. When the season goes to summer, all the squirrels who float to  $W_h$  remain at the refreshed area, and all the squirrels who skim to  $W_a$  and do not meet with chasers, move their locations as follows:

$$X_{i_{new}}^{t+1} = X_L + Le'vy(x) \times (X_U - X_L) \tag{14}$$

$Le'vy$  is the arbitrary walk model whose progression complies with the  $Le'vy$  appropriation and can be determined by

$$Le'vy(x) = 0.01 \times \frac{\alpha \times r_a}{|r_b|^\beta} \tag{15}$$

where,  $r_a$  and  $r_b$  are two randomly distributed numbers in [0, 1],  $\alpha$  and  $\beta$  are constants.

### 4. SUCCESSIVE PROGRESSION OF SSO FOR MAELD PROBLEM

In this section, strategy to implement the SSO approach for solving the MAELD problems has been depicted as flow diagram in Figure 1.

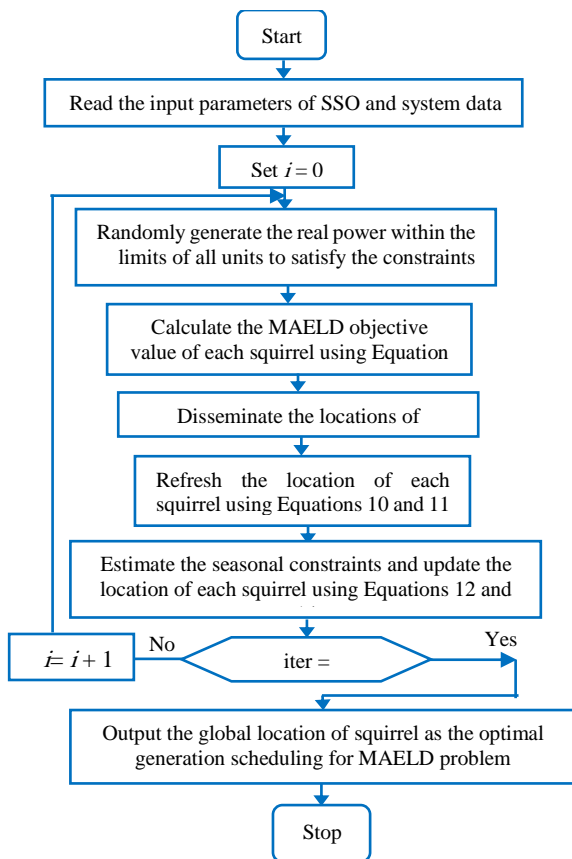


Figure 1. Flow chart of SSO approach applied in MAELD problems

5. NUMERICAL RESULTS

To assess the efficaciousness of the envisaged SSO approach in solving the MAELD, computational simulations are applied on three diverse test systems such as two-area system with 6 generating units, three-area system with 10-units and four-area system with 40 units. Furthermore, to check the adequacy of the envisaged SSO approach, the EMA approach is utilized for solving the MAELD and compared with those of recently published state-of-the-art approaches. The SSO and EMA approaches are executed using MATLAB 7.1 on an Intel core i3 processor with 4 GB RAM, and is executed for 50 free runs for all the test systems. The accompanying three case studies are contemplated.

Case study 1. MAELD with transmission line losses and POZ impacts

Case study 2. MAELD with transmission losses, VPL and MFO

Case study 3. MAELD with VPL impacts

5.1. Parameter Tuning Taguchi method is used to tune the parameters of the suggested SSO algorithm. The parameters such as number of iterations, population

size,  $P_{dp}$  and  $G_c$  are chosen as independent design variables. Each variable has three set values (level values) as given in Table 1. Then,  $L_9$  orthogonal array is used to determine the optimal SSO parameters. Table 2 presents the tuned SSO parameters. The parameters are tuned at Run # 4 (a, b, c, d: 2, 1, 2, 3) for Case study 1, and Run # 5 (a, b, c, d: 2, 2, 3, 1) for Case studies 2 and 3 in the Taguchi array.

5.2. Case Study 1 This case study considers a two-area test system having six generating units. The total power load is 1263 MW. The power balance, generating unit limits, tie line limitations, transmission losses and POZ are considered. In Ref. [5], the data of cost coefficients, emission coefficients and POZ are given. The power demand shared by area 1 and area 2 are 60 and 40 % of absolute load demand separately. The power stream from area 1 to area 2 is limited to 100 MW.

The generation plan and the fuel cost procured by the proposed SSO approach are tabulated in Table 3. Besides, the area 1 imports power from area 2. Figure 2 shows a comparison between the fuel costs procured by the SSO and EMA approaches, and other techniques surfaced in the literature.

In Figure 2, it is obvious that the SSO approach has obtained the minimum generation cost than the fuel costs procured by the other aforementioned approaches.

5.3. Case Study 2 In this case, 3 areas, 10-unit test system with transmission losses, VPL and MFO is taken into consideration. Area 1, area 2 and area 3 comprise 4, 3 and 3 generating units respectively which are displayed in Figure 4. The power demand of this system is 2700 MW. The power demand shared by area 1, area 2 and area 3 are 50 %, 25% and 25 % of total load

TABLE 1. Calibration of SSO

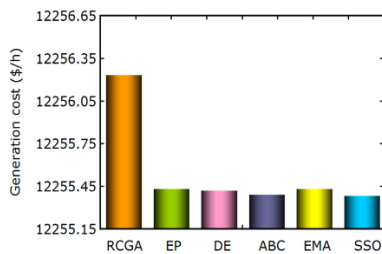
Parameters	Level 1	Level 2	Level 3
a: Number of iterations	100	200	500
b: Population size	10	20	40
c: $P_{dp}$	0.05	0.1	0.15
d: $G_c$	1.8	1.9	2

TABLE 2. Tuned parameters of SSO

Parameters	Case study 1	Case study 2	Case study 3
Number of iterations	200	200	200
Population size	10	20	20
$P_{dp}$	0.1	0.15	0.15
$G_c$	2	1.8	1.8

**TABLE 3.** Best dispatch solution acquired by the envisaged SSO approach for case study 1

Unit	Power generation (MW)
P1,1	500
P1,2	200
P1,3	149.9909
P2,1	204.3295
P2,2	154.6983
P2,3	67.5957
T21	82.7642
PL1	9.4267
PL2	4.1891
Generation cost (\$/h)	12255.3789

**Figure 2.** Comparison of generation costs procured by various approaches for Case study 1**TABLE 4.** Best dispatch solution acquired by the envisaged SSO approach for case study 2

Unit	Fuel types	Power generation (MW)
P <sub>1,1</sub>	2	225.7694
P <sub>1,2</sub>	1	211.5842
P <sub>1,3</sub>	2	491.3265
P <sub>1,4</sub>	3	238.5371
P <sub>2,1</sub>	1	252.6869
P <sub>2,2</sub>	3	235.7538
P <sub>2,3</sub>	1	264.7952
P <sub>3,1</sub>	3	236.4286
P <sub>3,2</sub>	1	330.8961
P <sub>3,3</sub>	1	247.9518
T <sub>21</sub>		17.2813
T <sub>31</sub>		9.8161
T <sub>32</sub>		8.6328
Generation cost (\$/h)		654.4665

demand respectively. The power stream from one area to another area is restricted to 100 MW. Table 4 presents the simulation results acquired by the proposed SSO approach. It can be seen that the optimal generation cost acquired by the SSO approach is 654.4665 \$/h which is

the least among the compared approaches. The Area 1 imports power from areas 2 and 3, and area 3 exports power to area 2. The comparison between the results of SSO approach with those of EMA, RCGA, EP, DE and ABC approaches are illustrated in Figure 3. The results show that the proposed strategy obtains the best generation scheduling in comparison with different strategies.

#### 5. 4. Case Study 3

A four-area with forty units' system is utilized in this case study. All the units have VPL impacts, and thus the cost functions are non-arched. The cost coefficients of this system are accessible in Ref. [5]. The system has a total load equivalent to 10500 MW. The schematic diagram of this four area test system is shown in Figure 6. Each area consists of 10 generation units. The distribution of power demand for area 1, area 2, area 3 and area 4 are 15, 40, 30 and 15 % of total load demand respectively.

The power flow from area 1 to area 3, area 2 to area 3 and area 2 to area 4 are restricted to 200 MW. The tie-line limits for area 1 to area 4, area 2 to area 4 and area 3 to area 4 is 100 MW. The optimal generation dispatch acquired by the envisaged approach is given in Table 5. The area 2 imports power from areas 1, 3 and 4; the area 1 imports power from areas 3 and 4, and area 4 exports power to area 3. In this case study, the effectiveness of the SSO approach has been compared with that of the EMA, RCGA, EP, DE and ABC approaches.

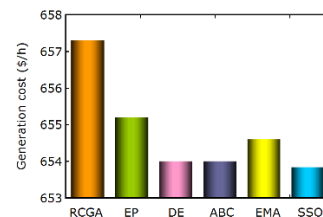
Figure 4 outlines the results of this examination. Once more, the SSO gave prevalent results than the previously mentioned approaches.

#### 5. 5. Sensitivity Analysis

The sensitivity analysis is performed for the number of food sources ( $N_{fs}$ ), and the results are tabulated in Table 6. It is seen from the investigation that the expansion in number of food sources brings about upgraded precision and stability of the approach. The expanded level of  $N_{fs}$  prompts more focuses in search space around which search is engaged. Consequently, new solutions are discovered and better investigation of search space is accomplished.

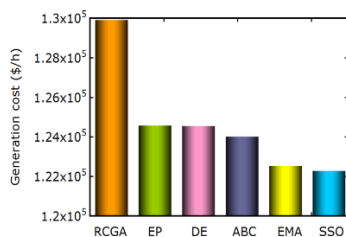
#### 5. 6. Managerial Insights

The application of SSO to the MAELD problem demonstrates new managerial

**Figure 3.** Comparison of generation costs procured by various approaches for Case study 2

**TABLE 5.** Best dispatch solution acquired by the envisaged SSO approach for case study 3

Unit	Power generation (MW)	Unit	Power generation (MW)
P <sub>1,1</sub>	110.8909	P <sub>3,1</sub>	523.8627
P <sub>1,2</sub>	110.5472	P <sub>3,2</sub>	523.558
P <sub>1,3</sub>	97.9593	P <sub>3,3</sub>	523.7572
P <sub>1,4</sub>	178.5386	P <sub>3,4</sub>	523.7537
P <sub>1,5</sub>	88.2575	P <sub>3,5</sub>	523.3404
P <sub>1,6</sub>	140	P <sub>3,6</sub>	523.5308
P <sub>1,7</sub>	258.8407	P <sub>3,7</sub>	10
P <sub>1,8</sub>	284.2543	P <sub>3,8</sub>	10
P <sub>1,9</sub>	284.5497	P <sub>3,9</sub>	10
P <sub>1,10</sub>	130	P <sub>3,10</sub>	86.4694
P <sub>2,1</sub>	164.7045	P <sub>4,1</sub>	190
P <sub>2,2</sub>	168.9706	P <sub>4,2</sub>	153.5285
P <sub>2,3</sub>	141.9572	P <sub>4,3</sub>	189.7943
P <sub>2,4</sub>	393.5854	P <sub>4,4</sub>	164.1622
P <sub>2,5</sub>	393.8418	P <sub>4,5</sub>	164.6892
P <sub>2,6</sub>	470.9157	P <sub>4,6</sub>	164.3112
P <sub>2,7</sub>	489.7922	P <sub>4,7</sub>	87.6541
P <sub>2,8</sub>	489.9491	P <sub>4,8</sub>	87.2630
P <sub>2,9</sub>	510.9340	P <sub>4,9</sub>	108.1656
P <sub>2,10</sub>	510.7577	P <sub>4,10</sub>	512.9133
T <sub>12</sub>	195.1514	T <sub>41</sub>	60.5383
T <sub>31</sub>	35.7749	T <sub>42</sub>	90.9470
T <sub>32</sub>	178.4934	T <sub>43</sub>	95.9961
Generation cost (\$/h)			122268.82



**Figure 4.** Comparison of generation costs procured by various approaches for Case study 3

insights. This method provides a better performance in comparison with other heuristic approaches. Examining the results obtained by the SSO and other approaches, the following points can be noticed.

Tables 1-3 provide that the minimum fuel costs accomplished by SSO approach. The fuel cost obtained are 12255.3789 \$/h, 654.4665 \$/h, and 122268.8214

**TABLE 6.** Sensitivity analysis with different the number of food sources

Number of food sources ( $N_f$ ), (%)	Fuel cost (\$/h)		
	Case study 1	Case study 2	Case study 3
20	12256.1364	655.2347	122292.6732
40	12255.3789	654.8431	122284.3763
60	12255.3789	654.4665	122268.8214
80	12255.3789	654.4665	122268.8214

\$/h for case studies 1, 2, and 3 respectively. Those fuel costs are less when compared with the revealed results in recent literature as shown in Figures 2-4. This fact demonstrates that the SSO algorithm is capable to obtain solutions of a better quality and more stable than the other algorithms.

The quality of the solutions is evaluated based on a sequence of runs. In this paper, 50 independent runs are performed for EMA and SSO approaches. For this sequence, the values of the best, average, worst and standard deviation of the generation costs are recorded. The statistical values obtained from the EMA and SSO approaches are tabulated in Table 7.

The low value of the standard deviation indicates that the SSO algorithm have the ability to reach stable solutions, when more runs are performed (50 runs). Furthermore, the SSO has a better one than the EMA strategy.

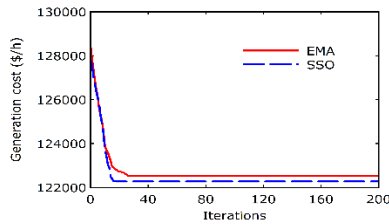
The convergence comparison of SSO and EMA approaches is shown in Figure 5. It can be observed that the SSO approach takes lesser number of cycles to unite into the global optimal solution. Figure 6 shows the average CPU time adopted by the SSO, EMA and other strategies for the case study 3. It is significant that time prerequisite is less and better than other referenced techniques. Consequently, it tends to be noted that the SSO technique is computationally productive when compared with the recently referenced strategies.

Finally, Wilcoxon rank-sum test is performed for all the case studies. the A p-value beneath 0.05 accomplished utilizing this test is estimated as plentiful proof over the null hypothesis. Figure 7 shows the p-values acquired by SSO versus EMA using Wilcoxon

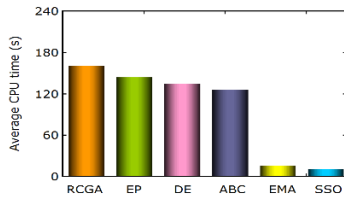
**TABLE 7.** Comparison of results between EMA and SSO

Fuel cost	Case study 2		Case study 3	
	EMA	SSO	EMA	SSO
Best cost	654.6	654.46	122525.75	122268.82
Average cost	656.86	655.53	122854.83	122352.95
Worst cost	657.99	656.96	123148.32	122653.37
Standard deviation	0.954	0.74	35.78	20.36

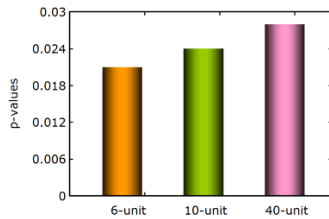




**Figure 5.** Convergence comparison of SSO and EMA approaches



**Figure 6.** Comparison of average CPU time adopted by various approaches for Case study 3



**Figure 7.** Comparison of Wilcoxon test results for all the Case studies

rank-sum tests. It is apparent from the figure that the p-value for each study is lower than the ideal estimation of 0.05. Consequently, the SSO approach produces statistically significant results.

## 6. CONCLUSION

In this paper, a new swarm insight approach, squirrel search optimization (SSO) approach is effectively bestowed to solve the MAELD problem. To assess the potency of the suggested approach, a benchmarking analysis is directed between the SSO, EMA and different heuristic approaches surfaced in the literature. Three sorts of non-smooth MAELD issues; MAELD with transmission losses and POZ (2-area with 6-unit system), MAELD with VPL impacts (4-area with 40-unit system), and MAELD with VPL and MFA impacts (3-area with 10-unit system) are addressed. The main conclusions of the paper are itemized hereunder:

- In SSO, the predator presence behaviour and a seasonal monitoring condition are incorporated to update the position of squirrel in a better way, which enhances the exploration and exploitation search

abilities of the algorithm significantly. The global search ability of the algorithm is further enhanced by Levy distribution. Accordingly, the convergence behaviour and the global optimization capability of the suggested SSO approach are better than those of the other heuristic approaches in solving different MAELD problems.

- Simulation results prove that the suggested SSO approach is of prominent dominance in both solution quality and computational efficiency.

As a scope of further research, the SSO algorithm can be applied for solving more complex large-scale static and dynamic ELD problems, large-scale multi-area economic environmental dispatch, and unit commitment problems.

## 7. REFERENCES

1. Jayabarathi, T., Sadasivam, G., and Ramachandran, V., "Evolutionary programming based multi-area economic dispatch with tie line constraints", *Electric Machines & Power Systems*, Vol. 28, No. 12, (2000), 1165-1176. doi: 10.1080/073135600449044.
2. Manoharan, P.S., Kannan, P.S., Baskar, S., and Iruthayarajan, M., "Evolutionary algorithm solution and KKT based optimality verification to multi-area economic dispatch", *International Journal of Electrical Power & Energy Systems*, Vol. 31, No. 7-8, (2009), 365-73. doi: 10.1016/j.ijepes.2009.03.010.
3. Sharma, M., Manjaree, P., and Laxmi, S., "Reserve constrained multi-area economic dispatch employing differential evolution with timevarying mutation", *International Journal of Electrical Power & Energy Systems*, Vol. 33, No. 3, (2011), 753-66. doi: 10.1016/j.ijepes.2010.12.033.
4. Somasundaram P., and Jothi Swaroopan, N.M., "Fuzzified Particle Swarm Optimization Algorithm for Multi-area Security Constrained Economic Dispatch", *Electric Power Components and Systems*, Vol. 39, No. 10, (2011), 979-990. doi: 10.1080/15325008.2011.552094.
5. Basu, M., "Artificial bee colony optimization for multi-area economic dispatch," *International Journal of Electrical Power & Energy Systems*, Vol. 49, (2013), 181-187. doi:10.1016/j.ijepes.2013.01.004.
6. Basu, M., "Teaching-learning-based optimization algorithm for multi-area economic dispatch", *Energy*, Vol. 68, (2014), 21-28. doi: 10.1016/j.energy.2014.02.064.
7. Basu, M., "Fast Convergence Evolutionary Programming for Multi-area Economic Dispatch", *Electric Power Components and Systems*, Vol. 45, No. 15, (2017), 1629-1637. doi: 10.1080/15325008.2017.1376234.
8. Nguyen, K.P., Dinh, N.D., and Fujita, G., "Multi-area economic dispatch using hybrid cuckoo search algorithm", In: 50<sup>th</sup> International Universities Power Engineering Conference (UPEC), Stoke on Trent, UK; (2015), 1-6. doi: 10.1109/UPEC.2015.7339777.
9. Ghasemi, M., Aghaei, J., Akbari, E., Ghavidel, S., and Li, L., "A differential evolution particle swarm optimizer for various types of multi-area economic dispatch problems," *Energy*, Vol. 107, (2016), 182-195. doi: 10.1016/j.energy.2016.04.002.
10. Zhang, P., Ma, W., and Dong, Y., "Multi-area economic dispatching using improved grasshopper optimization algorithm", *Evolving Systems*, (2019). doi: 10.1007/s12530-019-09320-6.

11. Valinejad, J., Oladi, Z., Barforoushi, T., and Parvania, M., "Stochastic unit commitment in the presence of demand response program under uncertainties", *International Journal of Engineering, Transactions B: Applications*, Vol. 30, No. 8, (2017), 1134-1143. doi: 10.5829/ije.2017.30.08b.04.
12. Razzaghi, T., and Kianfar, F., "The optimal energy carriers' substitutes in thermal power plants: A fuzzy linear programming model", *International Journal of Engineering, Transactions C: Aspects*, Vol. 25, No. 1, (2012), 55-66. doi: 10.5829/idosi.ije.2012.25.01c.07.
13. Bagheri, A., Sadafi, M., and Safikhani, H., "Multi-objective optimization of solar thermal energy storage using hybrid of particle swarm optimization, multiple crossover and mutation operator", *International Journal of Engineering, Transactions B: Applications*, Vol. 24, No. 3, (2011), 367-376. doi: 10.5829/idosi.ije.2011.24.04b.07.
14. Fathollahi-Fard, A.M., Hajiaghahi-Keshteli, M., and Tavakkoli-Moghaddam, R., "Red deer algorithm (RDA): a new nature-inspired meta-heuristic," *Soft Computing*, Vol. 24, (2020), 14637-14665. doi: 10.1007/s00500-020-04812-z.
15. Fathollahi-Fard, A.M., Azari, M.N., and Hajiaghahi-Keshteli, M., "An improved red deer algorithm to address a direct current brushless motor design problem," *Scientia Iranica*, (2019). doi: 10.24200/SCI.2019.51909.2419.
16. Fathollahi-Fard, A.M., Hajiaghahi-Keshteli, M., and Tavakkoli-Moghaddam, R., "The social engineering optimizer (SEO)," *Engineering Applications of Artificial Intelligence*, Vol. 72, (2018), 267-293. doi:10.1016/j.engappai.2018.04.009.
17. Fathollahi-Fard, A.M., Ranjbar-Bourani, M., Cheikhrouhou, N., and Hajiaghahi-Keshteli, M., "Novel modifications of social engineering optimizer to solve a truck scheduling problem in a cross-docking system," *Computers & Industrial Engineering*, Vol. 137, (2019), 106103. doi: 10.1016/j.cie.2019.106103.
18. Fathollahi-Fard, A.M., Ahmadi, A., Goodarzian, F., and Cheikhrouhou, N., "A bi-objective home healthcare routing and scheduling problem considering patients' satisfaction in a fuzzy environment," *Applied Soft Computing Journal*, Vol. 93, (2020), 106385. doi:10.1016/j.asoc.2020.106385.
19. Fathollahi-Fard, A.M., Ahmadi, A., and Mirzapour Al-e-Hashem, S.M.J., "Sustainable closed-loop supply chain network for an integrated water supply and wastewater collection system under uncertainty," *Journal of Environmental Management*, Vol. 275, (2020), 111277. doi:10.1016/j.jenvman.2020.111277.
20. Jain, M., Singh, V., and Rani, A., "A novel nature-inspired algorithm for optimization: Squirrel search algorithm", *Swarm and Evolutionary Computation*, Vol.44, No. 2, (2019), 148-175. doi: 10.1016/j.swevo.2018.02.013.

---

### Persian Abstract

---

#### چکیده

اعزام بار اقتصادی چند ناحیه ای (MAELD) اندازه گیری توانی را تعیین می کند که می تواند در یک منطقه به صورت مالی تولید شود و به منطقه دیگری منتقل شود. هدف MAELD تعیین مختاطانه ترین ترتیب تولید است که می تواند نیاز برق تقریباً را نقض کند و محدودیت های خط اتصال را نقض کند. این مطالعه یک الگوریتم ازدحام جدید به نام بهینه سازی جستجوی سنجاب (SSO) برای حل مشکلات MAELD ارائه می دهد. تأثیرات تلفات انتقال، مناطق عملیاتی ممنوع، بارگذاری نقطه سوپاپ و گزینه های چندگانه سوز علاوه بر این نیز مورد بررسی قرار می گیرد. SSO جعل هویت سنجاب های پرند را انجام می دهد که بستگی به روشهای پرش و پرش پوستی دارد. برای نشان دادن قدرت روش پیشنهادی، آن را در سه سیستم آزمون مختلف برای حل مشکلات MAELD بررسی شده است. معاینات مقایسه ای برای تجزیه و تحلیل کفایت روش SSO پیشنهادی با الگوریتم بازار ارز و استراتژی های مختلف نشان داده شده در ادبیات انجام می شود. نتایج تجربی نشان می دهد که روش SSO پیشنهادی برای دستیابی به راه حل های با کیفیت ترجیحی نسبت به سایر استراتژی های موجود مجهز است.

---