Lightning Search Algorithm for Economic Dispatch Solution Considering Practical Constraints and Transmission Loss

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***Abstract*—This paper presents the investigation of the Lightning Search Algorithm (LSA) performances for solving the Economic Dispatch (ED) problem. The main purpose of ED problem is to determine the optimal power output of the committed generators to satisfy the load demand and operational constraints. The LSA employs principles inspired by the natural phenomenon of lightning and the mechanism of step leader propagation. The ED constraints such as valve point effect (VPE), power balance (P_B), ramp rate limits (RRL), prohibited operating zone (PoZ) with and without power losses are considered to solve the ED problem. The proposed LSA has been tested on three different test systems comprised of 6, 13 and 38-generating units to demonstrate the effectiveness of the proposed LSA. The result reveals that the proposed LSA performs well for cost minimization ($/h) compared to existing algorithms.**

Keywords—Lightning Search Algorithm, Power System Dispatch , Ramp Rate Limit, Transmission loss

I. Introduction

The economic dispatch (ED) problem is a pivotal optimization challenge to identify the power output distribution optimally for the generation units at minimal cost while adhering to system constraints. The ED has been performed with conventional and hybrid generation sources incorporating unforeseen loads by different researchers [1]. There are numerous solutions provided by researchers to solve this ED problem that falls into classical, meta-heuristic and hybrid categories. The mathematical methods (MM) among classical category such as Newton Raphson method [2], lambda iteration [3], Lagrangian relaxation (LR) [4], branch and bound algorithm [5], gradient method [6], linear programming (LP) [7], quadratic (QP) programming [8] and interior point [9] are commonly used for ED solution.

However, most of these methods are not feasible to solve the non-linear and non-convex ED problems due to inclusion of practical constraints and transmission loss coefficients [10]. one of the weakness for these MM is that they are sensitive to initial point and convergence to local optima [11]. Therefore, research is progressive to address these complexities by utilizing the new and improved meta-heuristic methods (MTM) in every time span along with hybrid mode. The common adopted MTM such as ant-colony optimization (ACO), evolutionary programming (EP), artificial bee colony (ABC), genetic algorithm (GA), simulated annealing (SA), tabu search (TS) algorithm, differential evolution (DE), particle swarm optimization (PSO) have demonstrated effectiveness in handling ED problem with various cost function formulations [12].

While, MTM have gained traction for solving practical ED problems using different algorithms based on exploitation and exploration scenarios. The Squirrel Search Algorithm (SSA) have been adopted to formulate ED problem based on power balance (P_B), in-equality constraints (I_{EQ}), VPE, multiple fuel option (M_{FO}) and power loss (P_L), constraints for 40, 110, 140 and 160 generation units (G_U) [13]. Equilibrium Optimizer (EO) was adopted to solve the same problem based on P_B, I_{EQ}, R_{RL},VPE, M_{FO}, P_L and PoZ constraints with 13, 15 and 140 G_U [14]. Adaptive Hook- Jeeves (HJA) had been implemented with P_B , I_{EQ} , RRL, VPE, P_L and PoZ constraints based on 3, 6, 13, 15 and 40 G_U [15]. Hybrid Moth-Fame Optimization (MFOHC) was also utilized for this ED problem based on P_B, I_{EQ} and V_{PE} constraints with 5 G_U [16].

Similarly, Multiple Hybrid Lambda Iteration and Simulated Annealing (MHLSA) was also adopted with P_B, I_{EQ}, RRL, VPE, P_L and PoZ constraints based on 3 and 6 G_U [17]. The same study without RRP constraint was tested by using Hunger Games Search (HGS) in [18]. The hybrid harris hawks optimizer (HHO) was utilized with same constraints as MHLSA based on 6, 13, 15, 40 and 140 G_U [19]. Although, hill-climbed Sine–Cosine algorithm (HcSCA) was implemented with P_B , I_{EQ} , RRL, VPE, P_L and PoZ on small

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and large-scale G_U [20]. However, bio-inspired based lightning search algorithm (LSA) which also falls into MTM category is less utilized for the ED problem. The effective analysis of LSA on a small scale G_U as (3 and 6) with and without transmission loss was performed by [21]. Similarly, to enhance the effectiveness of LSA for complicated ED function based on (6 and 13) generation units with inclusion of VPE with transmission loss was demonstrated by [22].

Therefore, this research has utilized the application of LSA method to validate its performance for handling ED problems from small to medium scale generation units considering the practical constraints and transmission loss for different three test systems. The results demonstrate that LSA exhibits better convergence characteristic and obtained lower cost than other methods. This paper is further structured in following sections. Section II describes the ED problem formulation and constraints. Section III elaborates the formulation of proposed LSA for solving ED problem. Section IV presents the simulation results and comparative analysis of proposed LSA and Section V concludes the effectiveness of the LSA for solving ED problem.

II. Problem Formulation

The main purpose of ED problem is to minimize the total fuel cost (F_C) and represented as the quadratic function of power output as shown as follows [13]:

$$Min\ F_C = \sum_{i=1}^{N_g} F_i(P_i) \tag{1}$$

where, F_C is the total generation cost function, *Ng* is the number of generators, P_i is the generation output of i^{th} generator in (MW). $F_i(P_i)$ is the fuel cost of the i^{th} generator in (\$/h) as follows:

$$F_i(P_i) = a_i + b_i P_i + c_i P_i^2 \tag{2}$$

The VPE is comprised of quadratic and sinusoidal function which makes the ED problem non-convex and non-differentiable as shown in equation 3.

$$F_i(P_i) = (a_i + b_i P_i + c_i P_i^2) + \left|e_i \sin(f_i(P_i^{min} - \quad P_i))\right| \tag{3}$$

where, *a, b, c, e, f* are the coefficients of F_C for the i^{th} generator.

A. Power Balance (P_B) Constraint

The power balance constraint is used to model the system comprehensively so that the total generated power (P_i) matches the total power demand (P_D) with and without power loss (P_L) coefficient. This constraint can be modeled by using equation (4) and the transmission losses were obtained by using kron's loss formula as presented in equation (5).

$$\sum_{i=1}^{N_g} P_i = \quad P_D + P_L \tag{4}$$

$$P_L = \sum_{i=1}^{N_g}\sum_{j=1}^{N_g} P_i B_{ij} P_j \ \sum_{i=1}^{N_g} B_{0i} P_i + B_{00} \tag{5}$$

where "*B*" is consist of $P_L$coefficients based on the i^{th} and j^{th} elements of generation units, B_0 is a vector of same length for i^{th} element as P_i and B_{00} is the constant value for power loss.

B. In-Equality Constraint

The in-equality constraint ensures the secure and reliable operation of the committed generators to maintain their operational minimum and maximum power limits. This constraint is followed by following parameters.

1) Minimum and Maximum Power Limit

This constraint ensures that the output power from each generator should be within their minimum and maximum power limits as shown in equation (6).

$$P_i^{min} \le P_i \le P_i^{max} \tag{6}$$

Where, P_i^{min} is the maximum limit of power and P_i^{max} represent the maximum limit of power for i^{th} generating unit respectively.

2) Ramp Rate Limit (RRL)

This constraint is non-linear in nature and utilized to ensure the safe and reliable operation of power system for ED solution [15]. The RRL constraint represents the limitation of rate at which the power output of generators can be changed and can be modeled by using equation (7).

$$\max\left(P_i^{min}, P_i^0 - DR_i\right) \le P_i \le \min(P_i^{max}, P_i^0 + UR_i) \tag{7}$$

where, P_i^0 represent the active power output in (MW), DR_i and UR_i are the boundary values of RRL constraints for the i^{th} generator respectively. The RRL constraints are practically formulated into the following conditions:

a) *If power generation increases:*

$$P_i - P_i^0 \le UR_i \tag{8}$$

b) *If power generation increases:*

$$P_i^0 - P_i \le DR_i \tag{9}$$

3) Prohibited Operating Zone (PoZ)

This *PoZ* constraint is used to model the generation units within their specific regions based on maximum and minumum power limits to enhance the practical applicability of practical constraints [15]. The PoZ can be formulated as follows:

$$\begin{cases} P_i^{min} \le P_i \le P_{i,1}^{LB} \\ P_{i,k-1}^{UB} \le P_i \le P_{i,k-1}^{LB} \quad k = 2,3 \ldots\ldots N_k \\ P_{i,Nk}^{UB} \le P_i \le P_i^{max} \end{cases} \tag{10}$$

where, $P_{i,k}^{LB}$ and $P_{i,k}^{UB}$ refers the boundary ranges for the i^{th} generator in (MW) respectively and N_k is the no. of prohibited zone.

III. Lightning Search Algorithm for Solving Ed Problem

The lightning search algorithm (LSA) is a nature-inspired metaheuristic algorithm used for solving complex optimization problems. This was inspired by the step leader (SL) propagation mechanism of lightning discharges [22]. LSA depends on SLs, which are fast-moving particles that explore the search space and use three types of projectiles (PJ) to create and update the SL population. These types are transition projectiles, space projectiles and lead projectile. [23]-[24]. The LSA iterates by repeatedly firing these three types of projectiles and continues until a termination criterion is met, such as a maximum number of iterations or a desired

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level of convergence. Fig. 1 presents a flowchart of proposed LSA for solving ED problems.

1) Transition projectiles (T-PJ)

Transition projectiles play an important role in LSA by creating a diverse population of SLs. This diversity helps to improve the exploration capabilities of the algorithm and allows it to find better solutions to complex optimization problems. The mathematical formulation of T-PJ is shown below [22].

$$F(y^T) = \begin{cases} \dfrac{1}{x-l} & for\ l \leq y^T \leq x \\ 0 & for\ y^T < l\ or\ y^T > k \end{cases} \quad (11)$$

where 'l' and 'x' refer the limitation of the search space, y^T represents the tip energy (E_{Sli}) of SL as (S_{Li}). The population of $NS_L = [S_{L1}, S_{L2}, S_{L3}, \ldots, S_{LN}]$ a set of PJ as $PT = [P_{T1}, P_{T2}, P_{T3}, \ldots, P_{TN}]$ are required.

2) Space projectiles (S-PJ)

These projectiles are fired from random locations within the existing population of SLs and attempt to become the leader. The mathematical equation is formulated as follows [22]:

$$F(y^S) = \begin{cases} \frac{1}{\mu} e^{y^S/\mu} & y^S \geq 0 \\ 0 & otherwiswe \end{cases} \quad (12)$$

where μ is referred as the shaping parameter to locate the lead projectile. However, y^S denotes a random variable.

1) Lead projectiles (L-PJ)

This type of PJ can be updated same as S-PJ using a random number modeling from a normal distribution function as described follows [22].

$$F(y^L) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(y^L-\mu)^2}{2\sigma^2}} \quad (13)$$

The positioning of L-PJ (PL) to get optimal solution can be modeled with aid of normal random number function as *normrand* which is mathematically represented as follows:

$$P^L_{new} = P^L + normrand\ (\mu_L, \sigma_L) \quad (14)$$

where, σ represent the scaling parameter used for exploitation purpose.

IV. Test System And Results

The benchmarking of the three different test systems for solving the ED problem with different constraints as shown in Table I. The optimization parameters including the number of population (N_{pop}), maximum iterations (I_{Tmax}) and number of runs (N_R) for different test systems have been chosen to verify the effectiveness of proposed LSA. The simulation has been performed by using MATLAB version 2023b platform on core i7, quad processor 3.60 GHz and 4 GB Ram.

TABLE I. Optimization Parameters and Constraints for Each Test Systems.

Test System No.	Optimization Parameters			Constraints					
	N_{pop}	I_{Tmax}	N_R	P_B	P_L	I_EQ	RRL	PoZ	VPE
1 [25]	100	500	50	Y	Y	Y	Y	Y	-
2 [28]	50	1000	50	Y	Y	Y	-	-	Y
3 [19]	200	1000	50	Y	-	Y	-	-	-

- Not utilized: Y- utilized

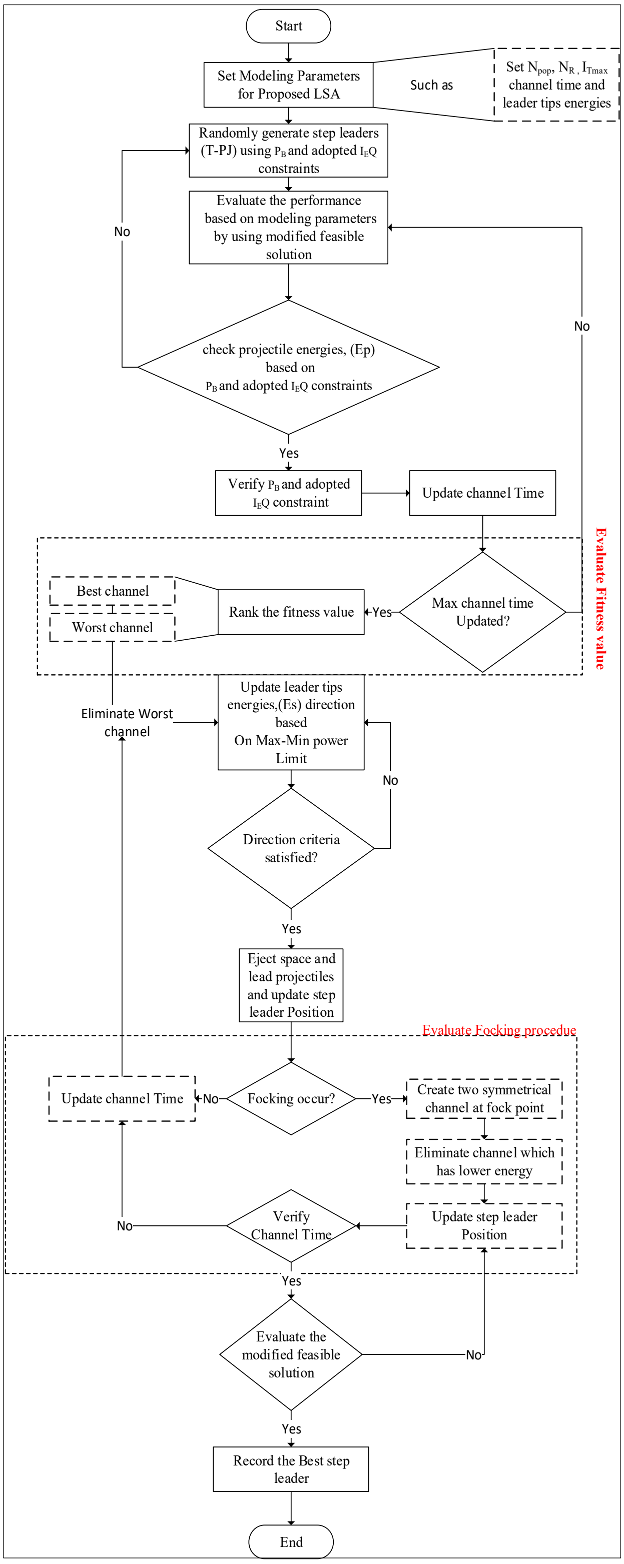

Fig. 1 Flowchart of LSA for proposed ED problem

A. Test System-1:

The test system consist of 6 generators considering the P_B, P_L, maximum and minimum power limit, RRL and PoZ as in equations (2), (4), (5), (6), (7) and (10) respectively [25].

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The P_D for this test system is 1263 MW. The LSA explore the best solution and converges within range of 297 to 330th iterations as presented in Fig. 2. The simulation results are compared with the evolutionary particle swarm optimization (EPSO) [25], modified particle swarm optimization with time varying acceleration coefficients (MPSO-TVAC) [26] and IPSO [26] as shown in Table II. The output (P_{GEN}) represent the sum of total power generated by each unit while, F_C ($/h) present the final cost of the applied test system using LSA.

However, the comparative analysis for 50 trails based on cost values and standard deviation (SD) in ($/h) is shown in Table III. The result reflects that LSA is better than GA [25], PSO [25] and its variants as EPSO [25], NPSO [25], NPSO with local random search strategy (LRS) [25], MPSO-TVAC [26], IPSO [26] and bee-colony optimization (BCO) [27] algorithms in percentile value as 5.89%, 0.07%, 0.03%, 0.07%, 0.07%, 0.01%, 2.33% and 0.09% respectively.

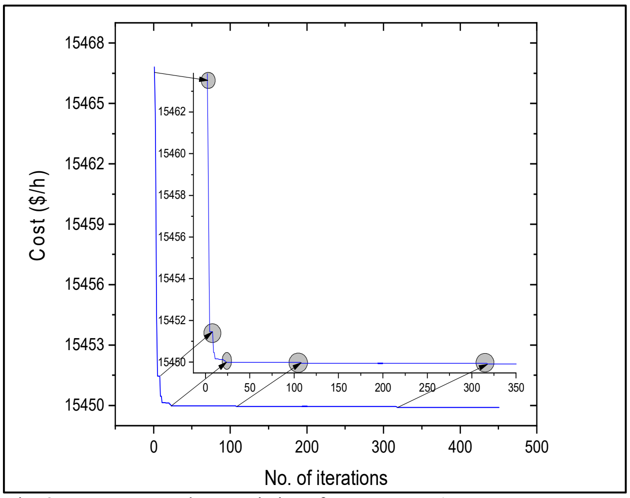

Fig. 2 Convergence characteristics of Test system-1

TABLE II. BEST SIMULATION RESULT OF TEST SYSTEM -1

Unit Output (MW)	Algorithms			
	LSA	***EPSO[25]***	***MPSO-TVAC [26]***	***IPSO [26]***
P_1	447.876	447.470	448.170	449.802
P_2	173.085	172.650	173.291	171.042
P_3	263.565	265.000	263.145	250.865
P_4	139.076	137.870	138.714	150.000
P_5	164.507	165.180	165.960	159.347
P_6	87.846	87.810	86.691	94.633
P_{GEN}	1275.948	1275.980	1275.970	1275.690
P_L	12.948	12.980	12.970	12.690
F_C ($/h)	**15449.899**	15449.940	15449.920	15453.500

TABLE III. 50 TRAILS RESULT COMPARISON OF TEST SYSTEM -1

Method	Cost ($/h)			SD ($/h)
	Minimum	***Maximum***	***Average***	
LSA	**15449.899**	15449.900	15450.000	1.115
GA [25]	15459.000	15524.000	15469.000	-
PSO [25]	15450.000	155455.000	15454.000	-
NPSO [25]	15450.000	15454.000	15452.000	-
NPSO-LRS [25]	15450.000	15452.000	15450.500	-
MPSO-TVAC [26]	15449.920	15451.570	15450.170	0.37
BCO [27]	15450.031	15451.951	15451.130	-

- Not reported in the reference

B. Test System-2

The test system consist of 13 generators and modeled with VPE, P_B, P_L and constraints of maximum and minimum power limit by using equations (3), (4), (5) and (6) respectively to investigate the LSA for solving the non-convex optimization problem [28]. The P_D for this test system is 2520 MW. The LSA can obtain the best solution within the 350 to 375th iterations as shown in the Fig. 3. The results obtained by LSA is compared with the results produced by the oppositional invasive weed optimization (OIWO) [28], and shuffled differential evolution (SDE) [28] as shown in Table IV.

The comparative analysis for 50 trails to evaluate cost values and standard deviation (SD) in ($/h) is drafted in Table V. The obtained result of LSA reveals that it performs better than OIWO [28], SDE [28], improved coordinated aggregation based PSO (ICA-PSO) [28], biogeography based optimization (BBO) [28], disruption based symbiotic organism search DSOS [29] and differential evolution based a hybrid mutation strategy algorithm (L-HMDE) [30] with improved percentile result as 0.04%, 0.06%, 10.32%, 0.19%, 0.06% and 0.06% respectively.

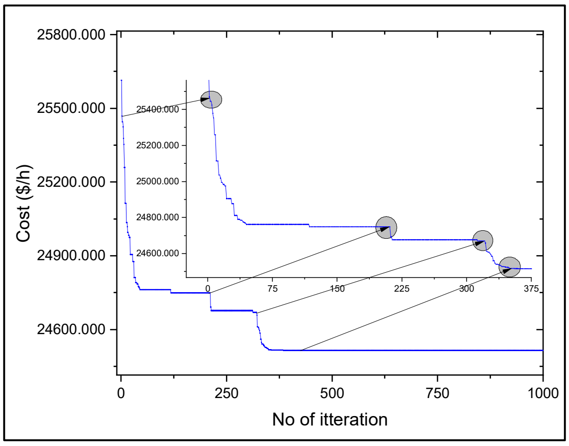

Fig. 3 Convergence Characteristics of Test System-2

TABLE IV. BEST SIMULATION RESULT OF TEST SYSTEM -2

Unit Output (MW)	Algorithms		
	LSA	***OIWO [28]***	***SDE [28]***
P_1	628.133	628.318	628.320
P_2	299.027	299.198	299.200
P_3	299.981	299.199	299.200
P_4	159.674	159.733	159.730
P_5	159.345	159.733	159.730
P_6	160.555	159.733	159.730
P_7	159.520	159.733	159.730
P_8	160.215	159.733	159.730
P_9	159.853	159.733	159.730
P_{10}	113.564	77.395	77.400
P_{11}	78.007	113.107	113.120
P_{12}	93.893	92.359	92.400
P_{13}	91.806	92.391	92.400
P_{GEN}	2563.579	2560.368	2560.440
P_L	43.579	40.368	40.440
F_C ($/h)	**24514.739**	24514.830	24514.880

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TABLE V. 50 TRAILS STATICAL RESULT COMPARISON OF TEST SYSTEM -2

Method	Cost ($/h)			SD ($/h)
	Minimum	*Maximum*	*Average*	
LSA	**24514.739**	24709.309	24564.761	49.892
OIWO[28]	24514.830	24514.830	24514.830	-
SDE [28]	24514.880	-	24516.310	-
ICA-PSO [28]	24540.060	24,589.450	24561.460	-
BBO[28]	24515.210	24,516.090	24515.320	-
DSOS [29]	24514.880	-	-	-
L-HMDE [30]	24514.880	24514.880	24514.880	-

- Not reported in the reference

C. Test System-3

This test system consists of 38 units with P_D of 6000 MW [19]. In this test system the formulation was performed by equations (2), (4) without loss and (6) respectively to investigate the LSA on medium scale power system. The LSA has obtained the best solution within the range of 800 to 850th iteration as illustrated in the Fig. 4. The simulation results obtained by LSA is compared with the results of PSO [25], NPSO [25], Particle Swarm optimization with time varying acceleration coefficients (PSO-TVAC) [25], and EPSO [25] as drafted in Table VI. Moreover, the comparative analysis for 50 trails of LSA with algorithms such as; PSO [25], NPSO [25], PSO-TVAC [25], EPSO [25], IPSO [26] and MPSO-TVAC [26], is tabulated in Table VII. It clearly shows that the LSA can produce lower cost as 4.44%, 1.05%, 0.87%, 0.15%, 4.07% and 0.01% respectively with above stated algorithms.

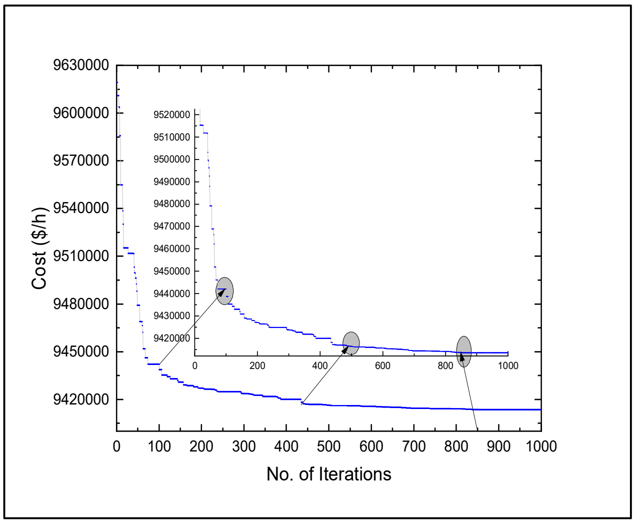

Fig. 4. Convergence characteristics of Test system-3

TABLE VI. POWER OUTPUT AND COSTS OF TEST SYSTEM -3

Unit Output (MW)	Algorithms			
	LSA	*NPSO [25]*	*PSO-TVAC [25]*	*EPSO [25]*
P_1	440.966	550.000	443.659	388.2933
P_2	298.868	512.263	342.956	388.2933
P_3	423.181	485.733	433.117	500.000
P_4	451.155	391.083	500.000	500.000
P_5	402.858	443.846	410.000	500.000
P_6	384.977	358.398	482.864	500.000
P_7	403.337	415.729	409.483	391.276
P_8	455.039	320.816	446.079	391.276
P_9	117.892	115.347	119.566	114.000
P_{10}	146.031	204.422	137.274	114.000
P_{11}	192.293	114.000	138.933	114.000
P_{12}	116.830	249.197	155.401	114.000
P_{13}	110.010	118.886	121.719	110.000
P_{14}	105.134	102.802	90.924	90.000
P_{15}	82.044	89.039	97.941	82.000
P_{16}	121.153	120.000	128.106	120.00
P_{17}	161.373	156.562	189.108	154.960
P_{18}	65.026	84.265	65.000	65.000
P_{19}	82.364	65.041	65.000	65.000
P_{20}	250.838	151.104	267.422	272.000
P_{21}	271.222	226.344	221.383	272.000
P_{22}	254.763	209.298	130.804	260.000
P_{23}	141.477	85.719	124.269	117.899
P_{24}	11.641	10.000	11.535	10.000
P_{25}	116.664	60.000	77.103	60.000
P_{26}	82.642	90.489	55.018	55.000
P_{27}	37.543	39.670	75.000	35.000
P_{28}	22.534	20.000	21.682	20.000
P_{29}	20.967	20.995	29.829	20.000
P_{30}	20.422	22.810	20.326	20.000
P_{31}	20.000	20.000	20.000	20.000
P_{32}	37.990	20.416	21.84	20.000
P_{33}	41.346	25.000	25.620	25.000
P_{34}	27.049	21.319	24.261	18.000
P_{35}	8.362	9.122	9.667	8.000
P_{36}	28.795	25.184	25.000	25.000
P_{37}	24.041	20.000	31.642	20.000
P_{38}	21.172	25.104	29.935	20.000
P_{GEN}	6000.000	6000.003	6000.005	6000.000
F_C ($/h)	**9413621.617**	9516448.312	9500448.307	9431139.150

- Not reported in the reference

TABLE VII. 50 TRAILS STATICAL RESULT COMPARISON OF TEST SYSTEM -3

Method	Cost ($/h)		
	Minimum	*Maximum*	*Average*
LSA	**9416951.721**	9826564.945	9436769.767
PSO [25]	9854846.460	10769579.950	10316687.360
NPSO [25]	9516448.312	-	-
PSO-TVAC [25]	9500448.307	-	-
EPSO [25]	9431139.150	9470838.180	9448492.980
IPSO [26]	9817444.504	-	-
MPSO-TVAC [26]	9417430.000	-	-

- Not reported in the reference

V. CONCLUSION

This paper investigated the performance of LSA for solving ED problem with different constrains including the VPE, RRL, PoZ and transmission loss. LSA was tested on three test system from small to medium scale with 6, 13 and 38 generation units. The result obtained for these test systems is compared with the referenced methods to validate the effectiveness of proposed LSA to obtain the optimal cost ($/h) which illustrate that in test system-1; LSA possess 5.89% better result in contrast to GA. While in the test system-2; LSA is proven 10.32% better with ICA-PSO. Similarly, in test system-3; LSA is 4.44% improved than PSO. The simulation results reveal that the proposed LSA is effective to solve considered ED problems while satisfying power balance and

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inequality constraints. Moreover, the results also authenticate that the LSA possess better exploitation characteristic with practical scalability to handle the ED problem efficiently. Therefore, the proposed LSA can be utilized to solve any power system optimization problem including multi-objective solution for the future research. The performance of LSA can be improved by combining with other algorithm to form outstanding hybrid method.

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