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Analyzing the effect of power loss allocation to utilities optimally in power systems using constrained load flow

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In present day power system operation and control needs modern methodologies for controlling the power flow in power lines. Usually power electronic based converters are used for diverting/controlling the power flow through power lines which is a costlier solution. The alternative solution to this problem is to impose constraints on the system variables. In this paper, shunt capacitors are connected at loadsfor maintaining the desired magnitude at loads. Also, the losses thus obtained are allocated to respective participants (generators/loads) based on their contributions using tracing based methodology. In this, the proportional sharing principal is used to identify the contribution of participants in the power losses. The effect of imposing constraints on loss allocation to participants is analyzed at OPF (OPF) condition. For solving this, a new methodology based on improved ant lion optimization algorithm is developed. Using this method, the OPF problem wasansweredagainst system limitations. The developed methodologies are tested on standard IEEE-14 bus with supportivenumerary.

Keywords:Power flow tracing; Loss balancing procedure; Constrained load flow;Optimal power flow;Cost allocation.

Notation

NC	Number of shunt capacitors
NL	Number of loads
NG	Number of generators
nl	Number of transmission lines
NT	Number of tap changing transformers
TPL	Total power losses
OPF	Optimal Power Flow
LCF	Loss contribution factor

1. Introduction

The best electrical power flow is issue of power system. The optimum organization process of the practical power system leads to accurate and comfortable operation to the participants. The allocation of transmission price, transmission loss to the participants must do without affecting the other parameters. The participants in the power system are alternators and real power customers. One of the major issues in deregulated power system is the cost of power grid activity. The price control of the power system leads to increase the investment ability of the power grid. For this price flow procedure is done by taking the 'optimization decision making model [1].

In competitive power industrial market, the competition is existing among the participants of power system. This will give optimum and competitive electric pricing mechanism as 'retail' and 'wholesale'. The consumer satisfying component of the power

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system allow bids and submit the same to the 'wholesale' market and also to 'retail' market to rise the profit of authorities [2]. The main objective of power system operation is to increase the customer's satisfaction. 'The constrained nonlinear program' is the paradigm which creates the function with constraints. This function receives the information of power consumption of the customer which is classified into affordable, non-affordable and detachable consumers. The non-affordable consumers are same for all participants. Hence it is required to concentrate on affordable and detachable consumers for objective function [3].

The 'game theory' is one of the optimization algorithms. This algorithm is based on the market status. This is two level optimization approach which optimize generation and customer satisfaction [4]. The 'harmony search' algorithm is the phenomenon which is used for solving the ELD problem. It is self-indulgent process solution [5]. The economics consumption share is the procedure of assigning the load requirement and power generating source available. This problem is modelled as nonlinear dependent simplified issue [6]. The firefly algorithm is the procedure which gives the solution to the nonlinear inequality and nonlinear equality constraints optimization problem is presented in [7].

The optimal region is the major consideration in optimum electrical power flow issue. By using equality and inequality constraints, equivalent optimal region of optimal electrical power flow issue and set of continues stable equal states of a 'quotient gradient system' is derived. This will give optimum solution to allocate the losses in the power system [8]. The 'bio-inspired metaheuristic stud krill herd' procedure handles the best electrical load flow problem of power system. This method gives the optimum solution for the fairly loss allocation among the participants of the power system [9]. The proportional optimum electrical power flow procedures use linearized proportional AC load power flow problem so as to adjust the power flows. The electrical potential angles at the buses are taken as constraints for the objective function. After this, the losses are distributed to the participants to balance the power system [10].

The fractional level linear integral controller is used for solving the problem of optimum electrical power flow. The potential angle of the power system at various bus is not constant and not stable. By taking these two areas into consideration, the stability of the system is improved [11]. So as to combine the quick changes in power system and poor fast optimization calculations a new real time active power and reactive power optimum power flow' problem is solved by mixed integer linear paradigm [12].

After reviewing literature, the findings are that, many conventional methods are available for solving optimization problem. But, these methods fail for solving this problem while satisfying all inequality constraints. Hence, a new revolutionary algorithms based on swarm intelligence techniques have been developed to handle inequality constraints. It is also noticed that, increasing the number of constraints on optimization problem makes the algorithm to fail. Due to this, the recent trend concentrates in developing new hybrid optimization algorithms by taking the advantage of two or more algorithmic operations. In this paper, a new improved hybrid optimization methodology is explained for solving OPF problem by selecting generation fuel cost to be minimized against system limitations.

2. Mathematical formulation of constraints power flow

For any type of power system, maintaining voltage magnitude at load bus is a typical task and needs to alter the active and reactive power flows through transmission lines. This can be accomplished by injecting/absorbing reactive power from the buses for which voltage limits are to be maintained. In this work, the reactive power compensator is used to achieve this objective. The bus with the connection of capacitive compensation is shown in Fig.1.

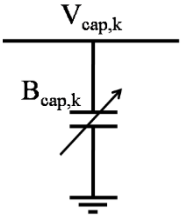


Fig.1 Connection of capacitor at bus-k for compensation

The mathematical expression for the capacitor current injection '$I_{\text{cap,k}}$'with susceptance '$B_{\text{cap,k}}$' and voltage '$V_{\text{cap,k}}$' is

$$I_{\text{cap,k}} = \text{j}B_{\text{cap,k}}V_{\text{cap,k}} \forall \quad k = 1,2,\ldots,\text{NC}$$

Reactive power injected in to the system by the capacitor is expressed as

$$Q_{\text{cap,k}} = -V_{\text{cap,k}}^2 B_{\text{cap}} \quad \forall \quad k = 1,2,\ldots,\text{NC}$$

Final expressions for active and reactive powers injected can be expressed as

$$P_i = \sum_{\substack{j=1 \\ j\neq k}}^{\text{Nb}} \left(V_i V_j Y_{\text{ij}} \cos(\theta_{\text{ij}} + \delta_j - \delta_i)\right) + \sum_{k=1}^{\text{Ncap}} \left(V_i V_{\text{cap,k}} Y_{\text{ik}} \cos(\theta_{\text{ij}} + \delta_{\text{cap,k}} - \delta_i)\right)$$

$$Q_i = -\sum_{\substack{j=1 \\ j\neq k}}^{\text{Nb}} \left(V_i V_j Y_{\text{ij}} \sin(\theta_{\text{ij}} + \delta_j - \delta_i)\right) - \sum_{k=1}^{\text{Ncap}} \left(V_i V_{\text{cap,k}} Y_{\text{ik}} \sin(\theta_{\text{ij}} + \delta_{\text{cap,k}} - \delta_i)\right)$$

After evaluating power injections, the respective power mismatch equations and Jacobian elements are calculated using procedure given in [12].

3. OPF Problem formulation

Conventionally, OPF problem with 'O_{fun}' as an objective function can be expressed as

$$\text{Min } O_{\text{fun}}(\text{x,u}) \text{Subjected to } g(\text{x,u}) = 0 \ ; \ \text{h(x,u)} \leq 0$$

Where, 'g' represents equality constraints and 'h' represents inequality constraints. 'x' represents a vector of state variables or called as dependent variables or also called as non-self restricted variables. 'u' represents a vector of control variables or called as independent variables or also called as self restricted variables. The details of these vectors can be expressed as

$$x^T = \left[P_{G_1}, V_{L_1}, V_{L_2}, \ldots\ldots, V_{L_{\text{NL}}}, Q_{G_1}, Q_{G_2}, \ldots\ldots, Q_{G_{\text{NG}}}, S_{l_1}, S_{l_2}, \ldots\ldots, S_{l_{\text{nl}}}\right]$$

$$u^T = \left[P_{G_2}, P_{G_3}, \ldots, P_{G_{\text{NG}}}, V_{G_1}, V_{G_2}, \ldots, V_{G_{\text{NG}}}, Q_{\text{sh}_1}, Q_{\text{sh}_2}, \ldots, Q_{\text{sh}_{\text{NC}}}, T_1, T_2, \ldots\ldots, T_{\text{NT}}\right]$$

The control variables are generated through optimization algorithm in such a way that, the state variables are within their operational limits.

3.1 Equality constraints

The power balance equations in a system.

$$\sum_{i=1}^{NG} P_{G_i} - P_D - \sum_{i=1}^{Nbus}\sum_{j=1}^{Nbus} |V_i||V_j||Y_{ij}|\cos(\theta_{ij}+\delta_j-\delta_i) = 0$$
$$\sum_{i=1}^{NG} Q_{G_i} - Q_D + \sum_{i=1}^{Nbus}\sum_{j=1}^{Nbus} |V_i||V_j||Y_{ij}|\sin(\theta_{ij}+\delta_j-\delta_i) = 0$$

3.2 In-equality constraints

These are the constraints imposed on generator control variables, shunt capacitors, tap changing transformers and load buses, etc. These constraints can be mathematically expressed as

Self restricted in-equality constraints

Voltage magnitude limits: $V_{G_i}^{\min} \le V_{G_i} \le V_{G_i}^{\max}$; $\forall$ i ∈ NG

Power generation (active power) limits: $P_{G_i}^{\min} \le P_{G_i} \le P_{G_i}^{\max}$; $\forall$ i ∈ 2,3,…NG

Tap changing transformer limits: $T_i^{\min} \le T_i \le T_i^{\max}$; $\forall$ i ∈ NT

Reactive power (capacitors) limits: $Q_{sh_i}^{\min} \le Q_{sh_i} \le Q_{sh_i}^{\max}$; $\forall$ i ∈ NC

Non self restricted in-equality constraints

Power generation (slack bus) limits: $P_{G_i}^{\min} \le P_{G_i} \le P_{G_i}^{\max}$; $\forall$ i ∈ 1

Power generation (reactive power) limits: $Q_{G_i}^{\min} \le Q_{G_i} \le Q_{G_i}^{\max}$; $\forall$ i ∈ NG

Power flow limit (apparent power) limits: $S_{l_i} \le S_{l_i}^{\max}$; $\forall$ i ∈ nl

Voltage magnitude (load bus) limits: $V_{L_i}^{\min} \le V_{L_i} \le V_{L_i}^{\max}$; $\forall$ i ∈ NL

The self restricted in-equality constraints are fixed within its limits forcibly. Whereas the non self restricted in-equality constraints are handled using penalty approach [13]. The augmented objective function which includes non self restricted in-equality constraints can be expressed as

$$O_{fun}^{Aug}(x,u) = O_{fun}(x,u) + \lambda_p\left(P_{G_1} - P_{G_1}^{limit}\right)^2 + \lambda_q\sum_{i=1}^{NG}\left(Q_{G_i} - Q_{G_i}^{limit}\right)^2$$
$$+\lambda_v\sum_{i=1}^{NL}\left(V_{L_i} - V_{L_i}^{limit}\right)^2 + \lambda_s\sum_{i=1}^{nl}\left(S_{l_i} - S_{l_i}^{max}\right)^2$$

Where, λp, λq, λv and λs are the coefficients related to slack bus active power generation, PV bus reactive power generation, load bus voltage and transmission line power flow limits. In the above equation, the limit values can be expressed as

for slack bus active power generation $P_{G_1}^{lim} = \begin{cases} P_{G_1}; \text{if} P_{G_1}^{min} \le P_{G_1} \le P_{G_1}^{max} \\ P_{G_1}^{max}; \text{if} P_{G_1} \ge P_{G_1}^{max} \\ P_{G_1}^{min}; \text{if} P_{G_1} \le P_{G_1}^{min} \end{cases}$

for PV bus reactive power generation $Q_G^{lim} = \begin{cases} Q_G; \text{if} Q_G^{min} \le Q_G \le Q_G^{max} \\ Q_G^{max}; \text{if} Q_G \ge Q_G^{max} \\ Q_G^{min}; \text{if} Q_G \le Q_G^{min} \end{cases}$

for load bus voltage magnitude $V_L^{lim} = \begin{cases} V_L; \text{if} V_L^{min} \le V_L \le V_L^{max} \\ V_L^{max}; \text{if} V_L \ge V_L^{max} \\ V_L^{min}; \text{if} V_L \le V_L^{min} \end{cases}$

for transmission line power flow $S_l^{lim} = \begin{cases} S_l; \text{if} S_l \le S_l^{max} \\ S_l^{max}; \text{if} S_l \ge S_l^{max} \end{cases}$

3.3 Total cost function

Total cost objective formulated using costs related to TPL and shunt capacitors cost. The equation used to this cost function is given as

$$O_{\text{COST}}(\text{x,u}) = \sum_{i=1}^{\text{NG}} \text{FC}_i\left(P_{G_i}\right) + \text{COST}_{\text{TOTAL}}\$/\text{hr} \quad (1)$$

Here, the total cost of ith generating unit fuel can be expressed as

$$\text{FC}_i\left(P_{G_i}\right) = a_i P_{G_i}^3 + b_i P_{G_i}^2 + c_i P_{G_i} + d_i \$/\text{hr}$$

Similarly, the total cost can be given as

$$\text{COST}_{\text{TOTAL}} = \text{COST}_{\text{TPL}} + \text{COST}_{\text{CAPACITOR}}\$/\text{hr} \quad (2)$$

3.3.1 TPL cost

The mathematical expression used to calculate TPL in a given system is given as

$$\text{TPL} = \sum_{i=1}^{\text{nl}} \left(g_i \left[|V_i|^2 + \left|V_j\right|^2 - 2|V_i|\left|V_j\right| \cos\left(\delta_i - \delta_j\right) \right] \right) \text{MW}$$

After this, the cost of total power losses with 'λ_{TPL}' cost factor with a value 5 \$/MWhr clearing price can be calculated as [14]

$$\text{COST}_{\text{TPL}} = \sum_{i=1}^{\text{nl}} \left(\frac{|\text{Pflow}_i| \times \lambda_{\text{TPL}}}{f_{\text{mn}}^i} \right) \$/\text{hr}$$

Here, '$P_{\text{flow,i}}$' is the active power flow in ith line and 'f_{mn}^i' is a factor of ith line connected between buses m and n, which can be calculated using

$$f_{\text{mn}}^i = \frac{\delta_m - \delta_n}{X(i)}$$

Here, X(i) is the reactance of ith line.

3.3.2 Capacitor's reactive power compensation cost

The expression used to calculate cost of capacitor's reactive power compensation is considered with the ratio of costs related to investment and operational is 0.03652 \$/MVArhfrom [15, 16] and is given as

$$\text{COST}_{\text{CAPACITOR}} = \frac{\text{Investment cost}}{\text{Operating cost}} \times \text{Capacitor}(s) \text{ reactive power value} \quad \$/\text{hr}$$

The modified equation is given as

$$\text{COST}_{\text{CAPACITOR}} = 0.03652 \times Q_{\text{sh}}$$

4. TPLsharingprocedure

In order to share losses to generating units, the economic load dispatch (ELD) problem is solved at first. Then after, the active power generated from generating units is evaluated using procedure given in [17], the expression given below is used to calculate power generated from unit-i.

$$P_{G_i} = \left| \frac{-b_i + \sqrt{b_i^2 - 3\text{a}_i(c_i - \lambda)}}{3\text{a}_i} \right| \quad (3)$$

Upon simplification,

$$P_{\text{Gi}} = \frac{-b_i}{3\text{a}_i} + \sqrt{\left(\frac{b_i}{3\text{a}_i}\right)^2 - \frac{(c_i - \lambda)}{(3\text{a}_i)}}$$

$$P_{\text{Gi}} = \frac{-b_i}{3\text{a}_i} + \frac{b_i}{3\text{a}_i}\sqrt{1 - \frac{(c_i - \lambda)}{(3\text{a}_i)}\left(\frac{3\text{a}_i}{b_i}\right)^2}$$

$$P_{\text{Gi}} = \frac{-b_i}{3\text{a}_i} + \frac{b_i}{3\text{a}_i}\left(1 - \frac{(c_i - \lambda)}{(3\text{a}_i)}\left(\frac{3\text{a}_i}{b_i}\right)^2\right)^{\frac{1}{2}} \quad (4)$$

Binomial series expansion is considered for simplification,

$$P_{\text{Gi}} = \frac{\lambda - c_i}{2\text{b}_i} \quad (5)$$

Upon simplification, the value of 'λ' can be given as

$$\lambda = \frac{\frac{\sum_{j=1}^{NG} P_{Gj}+\sum_{j=1}^{NG}\frac{b_j}{3a_j}}{\sum_{j=1}^{NG}\frac{1}{3a_j}}-\sum_{j=1}^{NG} b_j+\sum_{j=1}^{NG}\frac{3a_j c_j}{2b_j}}{\sum_{j=1}^{NG} 3a_j} \quad (6)$$

Using above equations, the final equation obtained to calculate new value for generation from unit-i can be given as

$$P_{Ginew} = \frac{\frac{\frac{\sum_{j=1}^{NG} P_{Gj}+\sum_{j=1}^{NG}\frac{b_j}{3a_j}}{\sum_{j=1}^{NG}\frac{1}{3a_j}}-\sum_{j=1}^{NG} b_j+\sum_{j=1}^{NG}\frac{3a_j c_j}{2b_j}}{\sum_{j=1}^{NG} 3a_j}-c_i}{2b_i} \quad (7)$$

Upon simplification, the final expression for active power generation

$$P_{Ginew} = \left[\frac{P_{Gi\,sch}}{2b_i\left(\sum_{j=1}^{NG}3a_j\right)\left(\sum_{j=1}^{NG}\frac{1}{3a_j}\right)}+\frac{\sum_{j=1}^{NG}\frac{b_j}{3a_j}}{2b_i\left(\sum_{j=1}^{NG}3a_j\right)\left(\sum_{j=1}^{NG}\frac{1}{3a_j}\right)}-\frac{\sum_{j=1}^{NG}b_j}{2b_i\sum_{j=1}^{NG}3a_j}+\frac{\sum_{j=1}^{NG}\frac{3a_j c_j}{2b_j}}{2b_i\sum_{j=1}^{NG}3a_j}-\frac{c_i}{2b_i}\right]+\left(LCF_i \times P_L\right) \quad (8)$$

Here, the equation for LCF can be given as $LCF_i = \frac{1}{2b_i\left(\sum_{j=1}^{NG} 3a_j\right)\left(\sum_{j=1}^{NG}\frac{1}{3a_j}\right)}$

5. Improved Antlion Optimization Algorithm (IALO)

This algorithm is in spired from the hunting behavior of antlions [18]. Every optimization algorithm starts with the random generation of control variables within the respective minimum and maximum boundaries for a given 'N' number of populations. In this problem, the control problems are self restricted inequality constraints explained in section 3.2. The step by step methdology to be followed is respresented in the following flowchart shown in Fig.222.

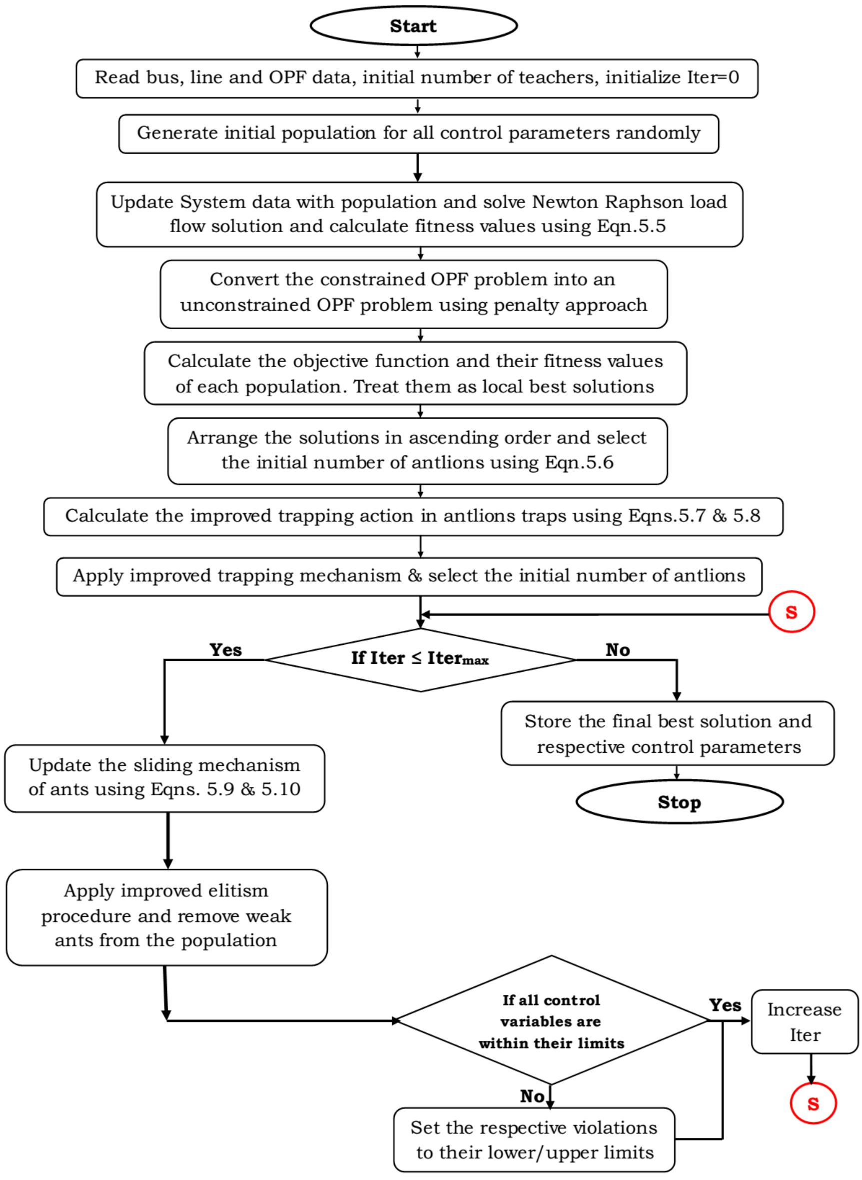


Fig.2 Flowchart of the improved antlion optimization algorithm

7. Results and Analysis

To analyze the effect of OPF on loss and loss cost allocation methodologies, the developed methodology is tested on IEEE-14 bus test system [23]. The entire analysis is performed for the following Modules.

Module-1: Analyzing the effect of combining loss cost with the generation cost in conventional load flow.

To identify the effect of selecting loss cost in addition to generation fuel cost in Module-1, OPF problem is solved separately for the three costs.

i. Generation fuel cost $\left(\sum_{i=1}^{NG} FC_i\left(P_{G_i}\right)\right)$
ii. Sum of power loss cost and compensators cost $(COST_{TPL} + COST_{CAPACITOR})$
iii. Total cost objective $(O_{COST}(x,u))$

Module-2: Analyzing the effect of combining loss cost with the generation cost in constrained load flow.

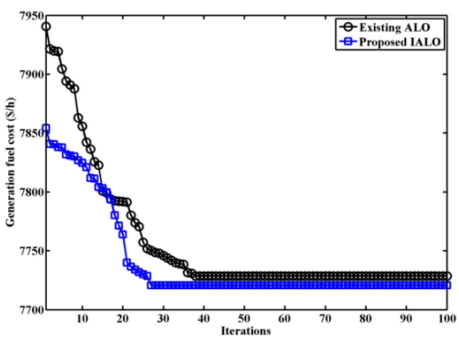
Module-3: Allocating power losses to generators using balancing procedure.

In Module-1, the OPF results for the three different cost objectives are tabulated in Table.1. From this table, it is observed that, the cost objective value is decreased with proposed IALO method when compared to existing ALO method. It is also noticed that, while minimizing generation cost objective, the cost pertaining to total power losses is increased and vice-versa. Hence, the total cost objective function is formulated and is minimized while satisfying system equality and inequality constraints. The results obtained with total cost objective are compromised results with both generation cost and loss cost objectives. It is observed that, the time taken for convergence is decreased with proposed IALO when compared with ALO irrespective of the cost objective. The convergence characteristics of three cost objectives are shown in Fig.4. From these figures, it is identified that, due to the effectiveness of the proposed method, the iterative process starts with good initial value and converges to final best value in less number of iterations when compared to existing method.

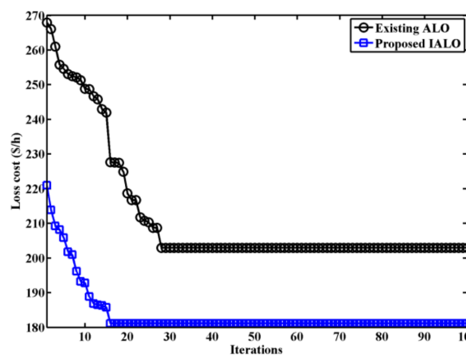
Table.1 OPF results for three cost objectives with conventional load flow using existing and proposed methods of IEEE-14 bus system

Parameters		**Cost objective related to ($/hr)**					
		Generation		**Losses**		**Total cost**	
		Existing ALO	**Proposed IALO**	**Existing ALO**	**Proposed IALO**	**Existing ALO**	**Proposed IALO**
Active power generations (MW)	PG1	35.2766	36.51058	10.71735	29.67454	33.57665	18.0453
	PG2	92.03853	87.97381	130.7939	96.23036	117.3704	106.896
	PG3	60	60	60	60	46.59449	60
	PG6	49.08658	50	42.77829	49.46524	39.78489	50
	PG8	25.00054	26.723	17.35166	26.29561	25.1086	26.32913
Generator voltage magnitudes, (p.u.)	VG1	1.096046	1.1	1.1	0.998875	1.002215	1.1
	VG2	0.956629	0.97664	0.991703	0.921178	0.924751	0.9
	VG3	0.989146	0.939744	0.9	0.9668	0.968049	0.967198
	VG6	1.010136	1.1	1.091719	0.987745	0.965168	1.040072
	VG8	1.022868	1.1	1.082621	0.997982	0.969008	1.054437
Tap changing transformer settings, (p.u.)	TAP 4-7	1.086569	0.992494	1.019094	0.995313	1.044813	1.038584
	TAP 4-9	1.0704	1.010329	1.017971	0.956667	1.030385	1.050459
	TAP,5-6	1.054269	0.967281	0.973671	0.983193	0.994583	1.030088
Reactive power of shunt capacitor,	QC9	30	30	30	30	29.05232	30

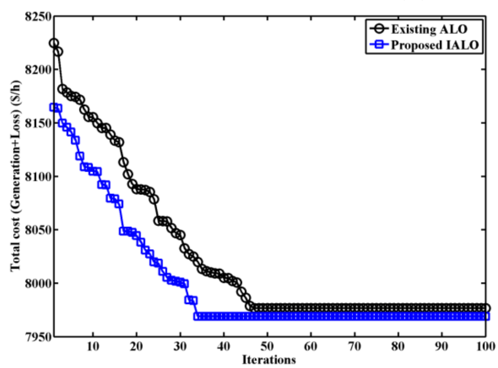
(MVAr)						
Total active power generation, MW	261.4023	261.2074	261.6412	261.6657	262.4351	261.2705
Total generation fuel cost, $/hr	7728.557	7720.724	7816.409	7737.807	7785.342	7755.937
Total active power losses, MW	2.40225	2.20738	2.64119	2.665738	3.435059	2.270468
Total power loss cost, $/hr	221.8569	230.7002	202.8787	181.0995	191.3279	212.9241
Voltage deviation (Vdev), p.u	0.58689	0.559884	0.670301	0.542116	0.711618	0.498182
Time, Sec	35.1789	31.0021	28.8273	26.1762	49.2881	43.9283



(a) Generation fuel cost



(b) Total loss cost



(c) Total cost (Generation cost + Loss cost)

Fig.4 Convergence characteristics with existing and proposed methods using conventional load flow of IEEE-14 bus system

Further, the OPF result of generation cost objective with the proposed IALO method is validated with the existing methods given in Table.2. From this table, it is identified that, the generation fuel cost objective value is decreased with proposed method when compared to existing methods listed in the literature.

Table.2 Validation of OPF results for generation cost objective of IEEE-14 bus system

Methods		Total generation fuel cost, $/hr	Time, Sec
Existing	GA [24]	18611.07	-
	PPSO [24]	18610.40	-
	ALO	7728.557	35.1789
Proposed IALO		7720.724	31.0021

Further, in Module-2, the OPF results with conventional and constrained load flow methods for the three different cost objectives are tabulated in Table.3. From this table, it is observed that, with constrained load flow, the value of cost objectives related generations, losses and total costs is increased when compared to conventional load flow method. Similarly, the time taken for convergence is also increased with constrained load flow when compared to conventional load flow method. It is also observed that, the total generation and there by the total power losses are increased with constrained load flow method. The convergence characteristics with proposed IALO method using conventional and constrained load flows methods are shown in Fig.5. From this figure, it is observed that, due to imposition of voltage constraint with constrained load flow, the iterative process starts with highest initial value and reaches final best value in more number of iterations when compared to conventional load flow method.

The variation of generations with three cost objectives using conventional and constrained load flows is shown in Fig.6. From this figure, it is noticed that, there is a significant variation of generations connected at buses 1 and 2 so as to minimize the respective cost objectives.

Table.3 OPF results for three cost objectives with conventional and constrained load flow methods of IEEE-14 bus system

Parameters		**OPF results with cost objective related to ($/hr)**					
		Conventional results			**Constrained results**		
		Generation	**Losses**	**Total cost**	**Generation**	**Losses**	**Total cost**
Active power generations (MW)	PG1	36.51058	29.67454	18.0453	21.51601	12.9161	49.29146
	PG2	87.97381	96.23036	106.896	107.0802	117.2719	113.5223
	PG3	60	60	60	60	58.0344	49.47036
	PG6	50	49.46524	50	50	49.70681	36.5905
	PG8	26.723	26.29561	26.32913	23.14529	23.80739	13.75687
Generator voltage magnitudes, (p.u.)	VG1	1.1	0.998875	1.1	1.079982	1.088378	1.086362
	VG2	0.97664	0.921178	0.9	0.9	0.932507	0.924385
	VG3	0.939744	0.9668	0.967198	0.948917	0.995988	0.974697
	VG6	1.1	0.987745	1.040072	0.992585	0.993127	0.996091
	VG8	1.1	0.997982	1.054437	1.037065	1.031871	1.034422
Tap changing transformer settings, (p.u.)	TAP,4-7	0.992494	0.995313	1.038584	1.032817	1.053598	1.043845
	TAP,4-9	1.010329	0.956667	1.050459	1.001049	0.998067	1.015606
	TAP,5-6	0.967281	0.983193	1.030088	1.095757	1.1	1.082125
Reactive power of shunt capacitor, (MVAr)	QC9	30	30	30	30	30	30
Total active power generation, MW		261.2074	261.6657	261.2705	261.7415	261.7366	262.6315
Total generation fuel cost, $/hr		7720.724	7737.807	7755.937	7759.377	7782.068	7779.104
Total active power losses, MW		2.20738	2.665738	2.270468	2.741492	2.736637	3.631509
Total power loss cost, $/hr		230.7002	181.0995	212.9241	230.3082	192.6807	193.8231
Voltage deviation (Vdev), p.u		0.559884	0.542116	0.498182	0.602343	0.577016	0.955624
Time, Sec		31.0021	26.1762	43.9283	39.0012	28.3478	53.2911

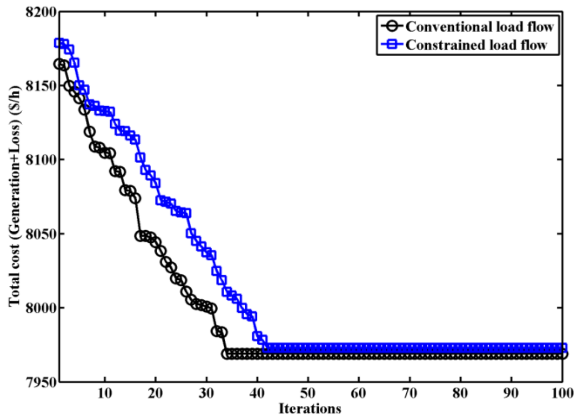


Fig.5 Convergence characteristics of OPF with IALO using conventional and constrained load flows of IEEE-14 bus system

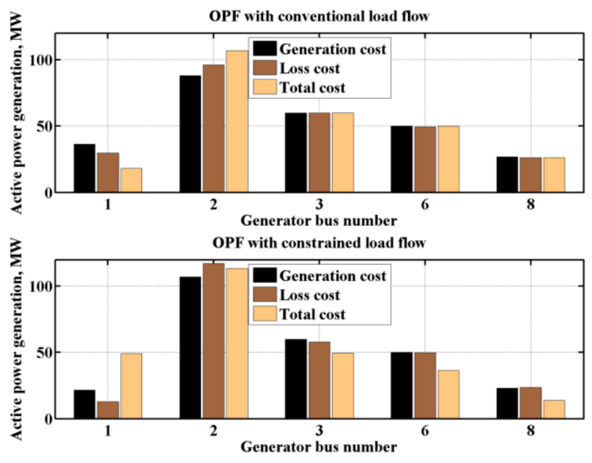


Fig.6 Variation of generations with three OPF cost objectives using conventional and constrained load flows of IEEE-14 bus system

In this Module, the comparative results with load flow and OPF problems are tabulated in Table.4. From this table, it is observed that, with OPF, the total generation and there by the total power losses is decreased when compared to load flow. It is also observed that, with OPF, the value of generation fuel cost objective is increased due to imposition of inequality constraints when compared to load flow. Variation of generations in load flow and OPF methods with conventional and constrained load flows is shown in Fig.7. From this figure, it is observed that, due to satisfy inequality constraints in OPF, the generator connected at bus-1 is decreasing its generation and whereas the generators connected at buses 2 and 3 are increasing its generation when compared to load flow.

Table.4 Comparative results of load flow and OPF problems for cost objective of IEEE-14 bus system

Parameters	Conventional results with				Constrained results with			
	Load flow		OPF		Load flow		OPF	
	Gen (MW)	Cost ($/hr)	Gen (MW)	Cost ($/hr)	Gen (MW)	Cost ($/hr)	Gen (MW)	Cost ($/hr)

Active power generations (MW)	PG 1	85.56861	1351.419	18.0453	875.2808	86.18531	1355.809	49.29146	1094.493
	PG 2	27.7663	1720.573	106.896	2360.167	27.7663	1720.573	113.5223	2421.043
	PG 3	39.68745	1565.959	60	1710.656	39.68745	1565.959	49.47036	1635.572
	PG 6	81.88998	1325.246	50	1099.486	81.88998	1325.246	36.5905	1005.156
	PG 8	27.7663	1720.573	26.32913	1710.347	27.7663	1720.573	13.75687	1622.84
Total active power generation, MW		262.6786	-	261.2705		263.2953	-	262.6315	
Total generation fuel cost, $/hr		-	7683.771	-	7755.937	-	7688.161	-	7779.104
Total active power losses, MW		3.678633	-	2.270468	-	4.295339	-	3.631509	-
Qsh, MVAr		19	-	30	-	19	-	30	-

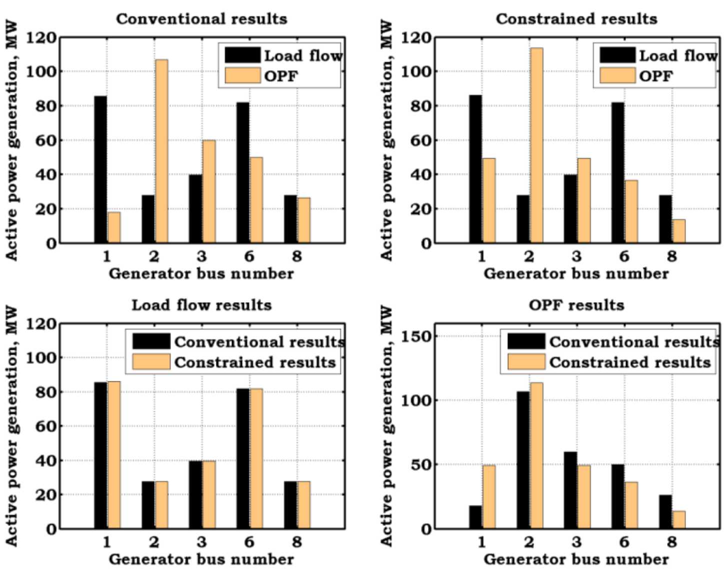


Fig.7 Variation of generators generations with load flow and OPF in conventional and constrained results of IEEE-14 bus system

Voltage magnitudes obtained with load flow and OPF problems are tabulated in Table.5. From this table, it is identified that, due to imposition of voltage magnitude constraints in OPF, the voltage magnitudes at buses are maintained nearly at 1.0 p.u when compared to load flow. Variation of voltage magnitudes in load flow and OPF problems with conventional and constrained load flows is shown in Figs.8 and 9.

Table.5 Voltage magnitudes obtained with OPF after balancing power losses to generators of IEEE-14 bus system

Bus No	**Voltage magnitude, p.u.**			
	Conventional results		**Constrained results**	
	Load flow	**OPF**	**Load flow**	**OPF**

01	1.06	1.06	1.06	1.06
02	1.045	1.036134	1.045	1.038157
03	1.01	0.996096	1.01	0.997351
04	1.030888	1.003212	1.028158	1.009085
05	1.034219	1.008711	1.032466	1.013694
06	1.07	1.020976	1.07	1.040944
07	1.062872	1.004365	1.054123	1.033864
08	1.09	0.992626	1.09	1.073014
09	1.05145	1.001604	1.034118	1.011231
10	1.046331	0.9968	1.024923	1.001217
11	1.05349	1.00464	1.023448	0.997167
12	1.055238	1.005267	1.051422	1.020354
13	1.048846	0.999293	1.041674	1.010093
14	1.031776	0.98145	1	0.959647

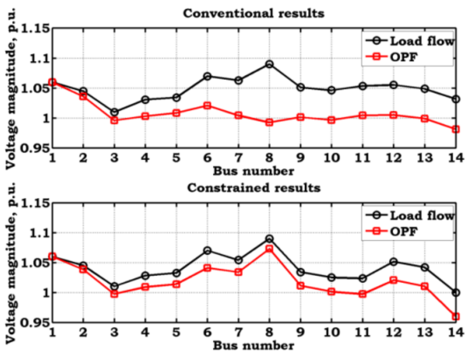


Fig.8 Variation of voltage magnitudes with OPF in conventional and constrained results of IEEE-14 bus system

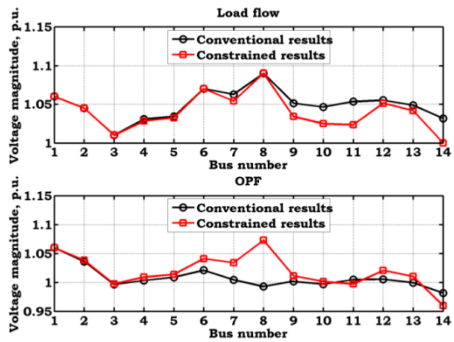


Fig.9 Variation of voltage magnitudes in load flow and OPF results of IEEE-14 bus system

Similarly, power flows obtained with load flow and OPF problems are tabulated in Table.6. From this table, it is identified that, due to imposition of line flow thermal constraints in OPF, the power flow in lines are maintained below the rated MVA limit when compared to load flow.

Table.6 Power flows obtained with OPF after balancing power losses to generators of IEEE-14 bus system

Line No	Power flow, MVA				MVA Limit
	Conventional results		Constrained results		
	Load flow	OPF	Load flow	OPF	
01	58.86035	39.99843	58.8137	35.369	150
02	23.75018	24.86626	23.95568	32.01929	85
03	34.97252	32.47181	34.78535	40.74617	85
04	20.31584	31.71575	20.35061	39.87376	85
05	10.02681	24.68357	10.3918	31.43853	85
06	19.2086	5.759455	18.38614	8.242197	85
07	43.8671	30.59421	42.71899	36.43101	150
08	6.650658	10.75119	5.536416	12.66635	30
09	3.562349	9.262137	5.712273	11.58283	32
10	25.65331	26.46907	24.21849	25.54518	45
11	19.29802	13.11217	25.33717	21.09559	14

12	9.41871	8.780948	10.10396	9.743732	32
13	24.486	21.67897	26.57311	24.95387	22
14	31.92323	27.38311	34.72648	26.7003	32
15	25.41541	28.81145	29.64147	34.20549	29
16	10.78	5.759801	15.26214	11.84503	32
17	6.975795	7.61065	12.31609	17.48794	18
18	15.57537	9.171989	17.46827	10.47438	12
19	3.047364	2.34193	3.645822	3.51447	12
20	13.07425	9.130183	14.78863	13.65302	12

In Module-3, OPF results before and after balancing total power losses are tabulated in Table.7. From this table, it is identified that, in conventional load flow, the total generation and its fuel cost and thereby the total power losses are increase dafter balancing total power losses. It is also observed that, the generations are modified after balancing power losses accordingly as their contributions. But, in OPF results with constrained load flow problem, the total generation, its cost and power losses are increased when compared to OPF results with conventional load flow problem even after balancing total power losses. From the results, it is also identified that, with constrained load flow, the generators connected at buses 1 and 2 are increasing its generation and where as generators connected at buses 3, 6 and 8 are decreasing its generation. Variation of generators generation before and after balancing losses in OPF with conventional and constrained load flows is shown in Fig.10.

Table.7 OPF results with cost objectives before and after balancing power losses of IEEE-14 bus system

Parameters		**Conventional results**				**Constrained results**			
		Before balancing		**After balancing**		**Before balancing**		**After balancing**	
		Gen (MW)	**Cost ($/hr)**	**Gen (MW)**	**Cost ($/hr)**	**Gen (MW)**	**Cost ($/hr)**	**Gen (MW)**	**Cost ($/hr)**
Active power generations (MW)	PG1	18.0453	875.2808	17.20226	869.3928	49.29146	1094.493	47.9273	1084.882
	PG2	106.896	2360.167	106.9564	2360.716	113.5223	2421.043	113.6189	2421.94
	PG3	60	1710.656	60.85177	1716.737	49.47036	1635.572	50.83272	1645.277
	PG6	50	1099.486	50.64895	1104.06	36.5905	1005.156	37.62846	1012.445
	PG8	26.32913	1710.347	26.38953	1710.776	13.75687	1622.84	13.85348	1623.5
Total active power generation, MW		261.2705	-	262.0489	-	262.6315	-	263.8609	-
Total generation fuel cost, $/hr		-	7755.937	-	7761.682	-	7779.104	-	7788.044
Total active power losses, MW		2.270468	-	3.048949	-	3.631509	-	4.8609	-
Total power loss cost, $/hr		-	212.9241	-	184.2794	-	193.8231	-	644.7657
Qsh, MVAr		30	-	30	-	30	-	30	-
Voltage deviation (Vdev), p.u		0.498182	-	0.56738	-	0.955624	-	0.998293	-

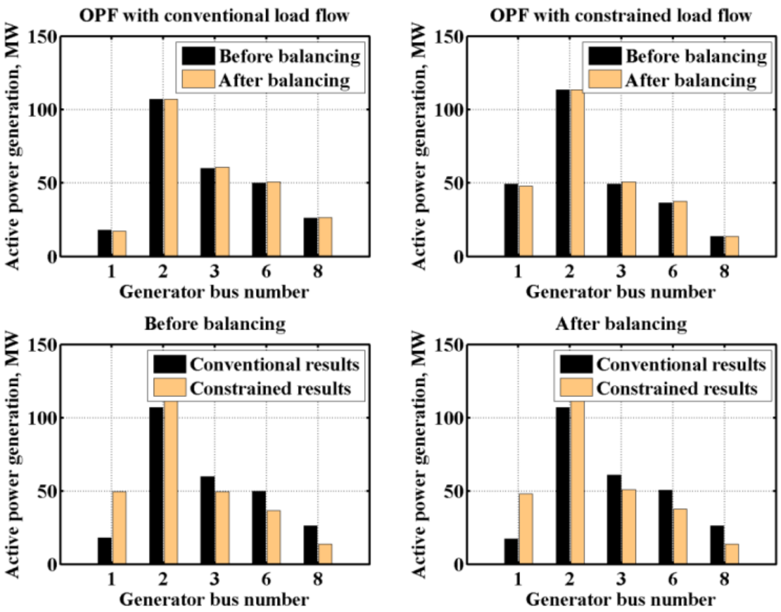


Fig.10 Variation of generators generation before and after balancing losses in OPF with conventional and constrained load flows of IEEE-14 bus system

9. Conclusions

In this paper, a new hybrid optimization algorithm namely improved ant-lion optimization algorithm has been developed. With this, the OPF problem has been solved by taking generation fuel cost as an objective while satisfying system equality and inequality constraints. From the results, it has been observed that, the proposed method has proven its effectiveness in solving OPF with constrained load flow problem along with system constraints. It has been also identified that, the developed method starts the iterative process with good initial value and reaches final best value in less number of iterations when compared to existing method. The losses thus obtained have been allocated to generators accordingly based on their contributions. The comparative results have been analyzed by comparing with load flow results.

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