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Economic Load Dispatch using Imperialistic Competitive Algorithm: An Effect of Control Variables

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Abstract— The operation of an electric power system is a complex one due to its nonlinear and computational difficulties. One task of operating a power system economically and securely is optimal scheduling, commonly referred to as the Optimal Power Flow (OPF) problem. Optimal power flow has become an essential tool in power system planning and operation. OPF is a typical nonlinear programming problem which consists in determining an optimal steady state operation of an electric power system. In this paper, conventional quadratic and non-convex fuel cost functions optimized while satisfying equality and in-equality constraints. The effect of control variables is identified by considering limited and all control variable cases are analyzed with the supporting numerical results on standard IEEE-14 bus and IEEE-30 bus test systems.

Index Terms—Optimal power flow, Imperialistic competitive algorithm, effect of control variables, Quadratic cost, Non-convex cost.

I. INTRODUCTION

The planning and operation of power systems are becoming increasingly complex. Systems are more interconnected and operating closer to their performance limits [1]. Planning engineers need a better understanding of actual grid operations, as well as the capability to examine the days when there were operational problems [2]. In today's operating environment, conventional planning and operating methods can leave systems exposed to instabilities, which often go undetected until it is too late. Voltage instability is one of the phenomena, which have led to major blackouts [3-5]. Most solutions proposed in the literature to alleviate this problem concentrate on rescheduling the power flow using some kind of economic incentives or economic penalty approaches [6-8]. The dispatch functions include generation scheduling and dispatch with the desired merit order [9]. Optimization methods have been widely used in power system operation, analysis and planning. One of the most significant applications is optimal power flow (OPF). Based on the lagrangian multipliers approach and the principle of incremental fuel cost [10], a number of methods [11-20] have been developed for the economic load dispatch (ELD) problem.

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In the conventional methods, the input-out characteristics of thermal generators are usually approximated by quadratic functions or piece wise quadratic functions. In the case that the input–output curves of the generators are highly non-linear and contemn discontinuities due to the effects of valve points [21], the incremental fuel cost curves of the generators are non monotonic and the conventional methods will have difficulties in determining the global optimum solution for ELD. Wong and Fung [22] applied a simulated–annealing based economic dispatch algorithm and it has been shown that the algorithm is capable of determining the global or near–global optimum solution for ELD. However the speed of that algorithm is slow. Careful study of the former literature reveals that there are some difficulties with the existing optimization methods, to overcome these difficulties, a new algorithm based on imperialistic competition is proposed to optimize quadratic and non-convex fuel cost functions while satisfying equality and in-equality constraints. The feasibility of the proposed method is demonstrated on IEEE 14 bus system and IEEE 30 bus systems. The obtained results using proposed method are compared with existing methods by considering limited and all control variables.

II. PROBLEM FORMULATION

In its general form, the OPF problem can be mathematically represented as

$$\text{Minimize } \ f(x,u)$$

Subjected to $g(x,u)=0$ and $h_{min} \le h(x,u) \le h_{max}$
where

- $f(x,u)$ is the objective function
- x is the vector of dependent variables
- u is the vector of independent or control variables
- $g(x,u)$ represents equality constraints
- $h(x,u)$ represents inequality constraints.

The OPF solution determines a set of optimal variables to achieve a certain goal such as minimum generation cost, power loss etc., subjected to all the equality and inequality constraints. The dependent variables are slack bus active power, load bus voltage magnitudes and its angles, generators reactive powers and line flow limits. The independent variables consist of continuous and discrete variables. The continuous variables are active powers of all generators, except slack bus and generator voltages. The discrete variables are tap settings of regulating transformers and reactive power injections.

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A. Objective Formulation

The primary concern of an ELD problem is the minimization of its objective function. The total cost of power generation that meets the demand and satisfies all other associated constraints, is selected as the objective function. In general, the ELD problem can be formulated mathematically as a constrained optimization problem with an objective function of the form

$$Minimize \quad FC = \sum_{i=1}^{NG} C_i(P_{Gi})$$

Where

FC is the total generation fuel cost,
$C_i(P_{Gi})$ is the fuel cost function of the ith unit,
P_{Gi} is the power generated by the ith unit,
NG is the total number of generating units.

This objective function is modeled in two ways as i) classical quadratic fuel cost function and ii) non-convex fuel cost function.

1) Quadratic Fuel Cost Function

Generally, the fuel cost of a thermal generating unit is considered as a second order polynomial function (neglecting valve-point effects) and this is called classical quadratic fuel cost function. It is represented as a quadratic equation given by

$$C_i(P_{Gi}) = a_i P_i^2 + b_i P_i + c_i$$

Where a_i, b_i, and c_i are the fuel-cost coefficients of the i^{th} unit.

2) Non-Convex Fuel Cost Function

The generating units with multi-valve steam turbines exhibit a greater variation in the fuel cost functions. Since the valve point results in the ripples, a cost function contains higher order nonlinearity. Therefore, the cost function should be modified to consider the valve point effects. This valve point effect leads to non-smooth, non-convex input-output characteristics. Typically, the valve point results in, as each steam valve starts to open, the ripples like in to take account for the valve–point effects, sinusoidal functions are added to the quadratic cost functions as follows.

$$C_i(P_{Gi}) = a_i P_i^2 + b_i P_i + c_i + \left| e_i \times \sin\left(f_i \times \left(P_i^{\min} - P_i\right)\right)\right|$$

where e_i and f_i are the fuel cost-coefficients of the i^{th} unit reflecting valve-point loading effects. These quadratic or non-convex fuel cost functions are subjected to the following equality and inequality constraints.

B. Constraints

The following are the two types of constraints considered for OPF problem

- Equality constraints
- Inequality constraints

The equality constraints represent the set of nonlinear power flow equations as

$$P_{Gk} - P_{Dm} - \sum_{m=1}^{NB} |V_k||V_m||Y_{km}| \cos(\theta_{km} - \delta_k + \delta_m) = 0$$

$$Q_{Gk} - Q_{Dm} + \sum_{m=1}^{NB} |V_k||V_m||Y_{km}| \sin(\theta_{km} - \delta_k + \delta_m) = 0$$

where,

P_{Gk}, Q_{Gk} are active& reactive power generations at k^{th} bus
P_{Dm}, Q_{Dm} are active & reactive power demands at m^{th} bus
NB is number of buses
$|V_k|$, $|V_m|$ are the voltage magnitudes of k^{th} and m^{th} bus
δ_k , δ_m are the phase angles of voltages at k^{th} and m^{th} bus
$|Y_{km}|$, θ_{km} are the bus admittance magnitude & its angle between k^{th} and m^{th} buses

The following are inequality constraints for OPF problem

Generator bus voltage limits: $V_{G_i}^{\min} \le V_{G_i} \le V_{G_i}^{\max}; \ \forall i \in N_G$

Active Power Generation limits: $P_{G_i}^{\min} \le P_{G_i} \le P_{G_i}^{\max}; \ \forall i \in N_G$

Transformers tap setting limits: $T_i^{\min} \le T_i \le T_i^{\max}; \ i = 1,2,...,n_t$

Capacitor reactive power generation limits:

$$Q_{Sh_i}^{\min} \le Q_{Sh_i} \le Q_{Sh_i}^{\max}; \quad i = 1,2,.....,n_c$$

Transmission line flow limit: $S_{l_i} \le S_{l_i}^{\max}; \quad i = 1,2,....,N_{line}$

Reactive Power Generation limits: $Q_{G_i}^{\min} \le Q_{G_i} \le Q_{G_i}^{\max}; \ \forall i \in N_G$

Load bus voltage magnitude limits:

$$V_i^{\min} \le V_i \le V_i^{\max}; i = 1,2,....,N_{load}$$

where 'n_t', 'n_c' are the total number of taps and the total number of VAr sources, 'N_{load}' is the total number load buses. Finally the above proposed problem is more generalized to solve in-equality constraints can be given as

$$FC_{aug} = FC + R_1\left(P_{g,slack} - P_{g,slack}^{\lim}\right)^2 + R_2 \sum_{i=1}^{N_{Load}} \left(V_i - V_i^{\lim}\right)^2 + R_3 \sum_{i=1}^{NG} \left(Q_{G_i} - Q_{G_i}^{\lim}\right)^2 + R_4 \sum_{i=1}^{N_{line}} \left(S_{l_i} - S_{l_i}^{\max}\right)^2$$

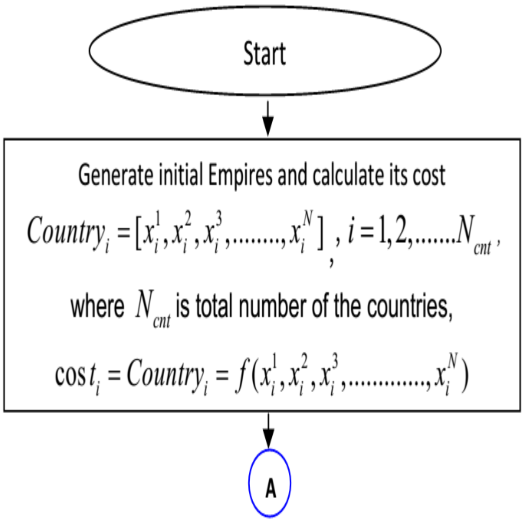
where, R_1, R_2, R_3 and R_4 are the penalty quotients having large positive value. The limit values are defined as

$$x^{\lim} = \begin{cases} x^{\max}, & x > x^{\max} \\ x^{\min}, & x < x^{\min} \end{cases}$$

Here 'x' is the value of $P_{g,slack}$, V_i and Q_{G_i}

III. SOLUTION METHODOLOGY

In this paper, the methodology based on Imperialistic Competition is proposed and the corresponding step by step procedure is represented as a flow chart in Fig.1 [23].



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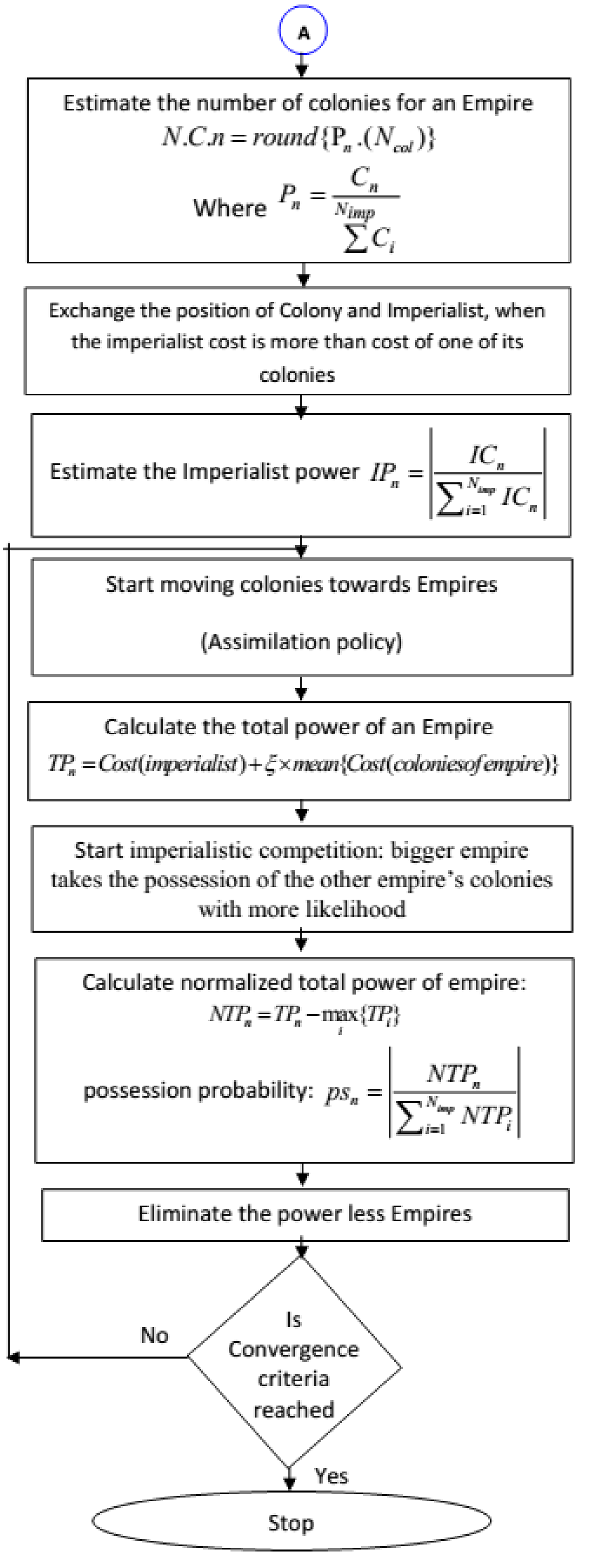

Fig. 1 Flow Chart of the Proposed Methodology

IV. RESULTS AND ANALYSIS

In order to demonstrate the effectiveness and robustness of the proposed method, two examples namely IEEE 14 bus system and IEEE 30 bus system have been considered. The existing and proposed methodologies are implemented on a personal computer with Intel Pentium Core2Duo 2GHz processor and 2 GB RAM. The input parameters of existing method and the proposed method for the three examples are given in Table.1.

Table 1. Input Parameters for Test Examples

S. No	Optimization method	Parameters	Quantity
1	Existing DE Method [24]	Population size	50
		Mutation constant (F)	0.9
		Crossover constant (CR)	0.5
		Number of iterations	100
2	Proposed ICA method	Number of initial countries	1000
		Number of initial imperialists	8
		Number of decades	200
		Revolution rate	0.05
		Assimilation coefficient	0.2
		Zeta (ζ)	0.02
		Damp ratio	0.99
		Uniting threshold limit	0.02

4.1 Example-1

An IEEE 14 bus system is considered as first example. In this system, bus 1 is slack bus, while buses 2, 3, 6 and 8 are generator buses and other buses are load buses. The solution for optimal power flow problem has been obtained using existing differential evolution method [24] and proposed ICA methods. Table.2 summarizes the OPF results obtained for quadratic and non-convex fuel cost functions using existing method and proposed methods for 100 iterations with limited control variables i.e. only active powers generated by the generators. From Table.2, it can be observed that the OPF solution obtained using proposed method is close to the existing method. But, the total real power generation, the real power loss and cost is less in proposed ICA method than existing DE method. Further, the computing time for quadratic cost using existing method is 30.2891 seconds whereas for proposed method it is 19.9928 seconds, which is 10.2963 seconds less in comparison with existing DE.

Table 2. Comparison of OPF Solution for IEEE 14 Bus System with Limited Control Variables

S. No	Parameter		Quadratic		Non-convex	
			DE	ICA	DE	ICA
1	Real power generation (MW)	P_{G1}	93.4803	93.5299	98.9078	98.9062
		P_{G2}	75.5496	74.766	88.2472	87.8954
		P_{G3}	27.862	28.0449	27.486	27.4812
		P_{G6}	45.8694	46.2277	34.0855	33.9323
		P_{G8}	20.8569	21.0298	15.437	15.9302
2	Total generation (MW)		263.6182	263.5983	264.1635	264.1453
3	Total power loss (MW)		4.6183	4.5994	5.1634	5.1453
4	Fuel cost ($/h)		**768.2769**	**767.9396**	**935.1092**	**934.8642**
5	Computing time (Sec)		30.2891	19.9928	35.1872	20.2816

For both of the cost functions with ICA method, the iterative process begins with minimum cost and the change in cost from initial to final is less which indicates convergence rate is fast for proposed method than existing method as shown in the Figs.2 and 3. This is because of best strings selected during the assimilation process in the proposed method and evolutionary operations are performed on these best strings.

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Further, the number of evolutionary operation is less for proposed method than DE which leads reduction in the computing time.

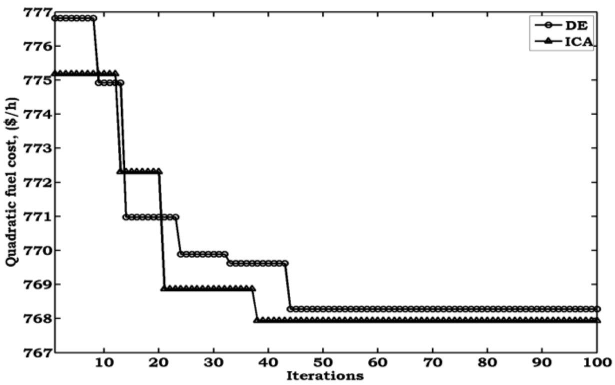

Fig. 2 Quadratic Cost vs Iterations of IEEE 14 Bus System with Limited Control Variables

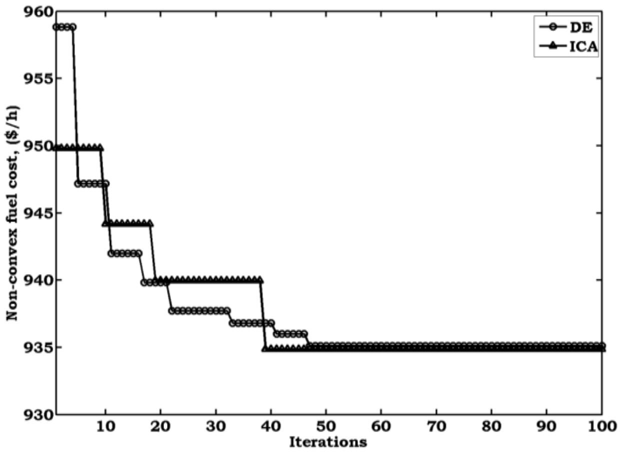

Fig. 3 Non-Convex Cost vs Iterations of IEEE 14 Bus System with Limited Control Variables

The similar observations are identified when all control variables are considered. The corresponding results for quadratic and non-convex cost functions using existing and proposed methods are given in Table.3.

Table 3. Comparison of OPF Solution for IEEE 14 Bus System with all Control Variables

S. No	Parameter		Quadratic		Non-convex	
			DE	ICA	DE	ICA
1	Real power generation (MW)	P_{G1}	172.9107	171.984	216.3024	218.1539
		P_{G2}	46.0332	47.957	25.2428	23.5231
		P_{G3}	20.8342	20.7051	18.0594	16.9747
		P_{G6}	16.4991	16.0129	5	5.9796
		P_{G8}	10.8111	10.2569	5	5
2	Generator voltages (p.u.)	V_{G1}	1.1	1.1	1.1	1.1
		V_{G2}	0.9508	0.9	0.9678	0.9
		V_{G3}	0.9989	0.9958	1.0157	0.9504
		V_{G6}	0.9543	0.9794	1.039	0.9776
		V_{G8}	1.042	1.0306	0.9327	0.99
3	Transformer tap setting (p.u.)	T_{4-7}	0.9962	1.0617	0.9864	1.0606
		T_{4-9}	0.9318	0.9748	1.0194	0.988
		T_{5-6}	0.9	1.013	0.9615	0.9997
4	Shunt compensator (MVA)	Q_{C9}	20.9486	16.2258	29.956	13.565
5	Total generation (MW)		267.0883	266.9159	269.6046	269.6313
6	Total power loss (MW)		8.0882	7.9157	10.6046	10.6312
7	Fuel cost ($/h)		**714.7914**	**714.1395**	**823.0769**	**822.783**
8	Computing time (Sec)		42.1892	23.1728	50.8001	31.1192

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The corresponding convergence patterns are shown in Figs. 4 and 5. From these figures, it is observed that the proposed method starts the iterative process with good initial value and reaches final best value in less iterations when compared to existing DE method.

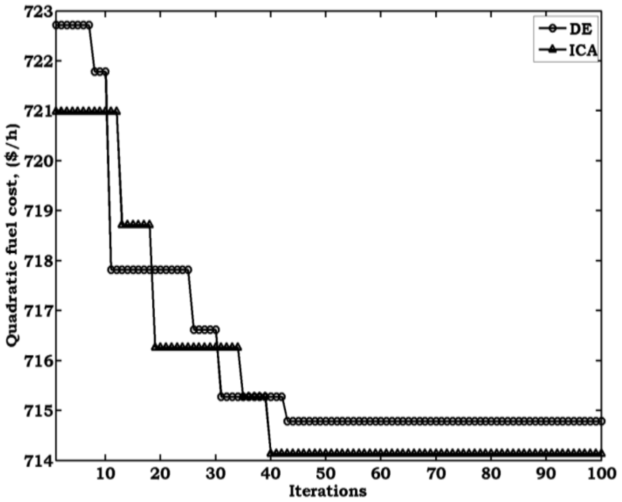

Fig. 4 Quadratic Cost vs Iterations of IEEE 14 Bus System with all Control Variables

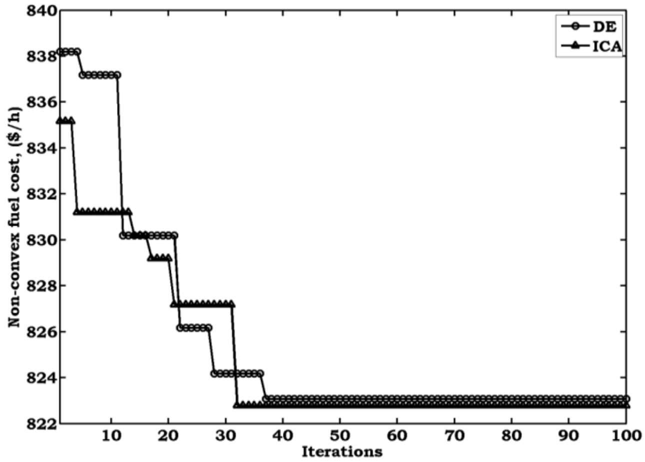

Fig. 5 Non-Convex Cost vs Iterations of IEEE 14 Bus System with all Control Variables

4.2 Example-2

An IEEE 30 bus system [25, 26] has been considered to find the solution for optimal power flow problem. In this system, bus 1 is slack bus, while buses 2, 5, 8, 11 and 13 are generator buses and other buses are load buses. The solution for optimal power flow problem has been obtained using existing differential evolution method and proposed method. The optimal solution obtained using existing DE method and proposed method with limited control variables is given in Table.4. The similar observations as that of example-1 can be observed for this system.

Table 4. Comparison of OPF Solution for IEEE 30 Bus System with Limited Control Variables

S. No	Parameter		Quadratic		Non-convex	
			DE	ICA	DE	ICA
1	Real power generation (MW)	P_{G1}	176.516	176.8802	192.7069	192.4606
		P_{G2}	48.8865	48.7998	48.3343	46.7787
		P_{G5}	21.4259	21.6319	19.854	20.8135
		P_{G8}	22.1588	21.4775	11.4093	12.0502
		P_{G11}	11.9501	12.1691	10	10.0888
		P_{G13}	12	12	12	12
2	Total generation (MW)		292.9373	292.9585	294.3045	294.1918
3	Total power loss (MW)		9.5372	9.5584	10.9045	10.7918
4	Fuel cost ($/h)		**802.4977**	**802.4961**	**919.1385**	**919.1051**
5	Computing time (Sec)		32.8562	23.1748	38.4689	24.46881

The optimal solution obtained using existing DE method and proposed method with all control variables is given in Table.5.

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Table 5. Comparison of OPF Solution for IEEE 30 Bus System with all Control Variables

S. No	Parameter		Quadratic		Non-convex	
			DE	ICA	DE	ICA
1	Real power generation (MW)	P_{G1}	176.1839	175.8526	193.5204	194.0038
		P_{G2}	47.2198	49.1042	45.2507	43.7583
		P_{G5}	21.4303	21.1186	19.917	21.8325
		P_{G8}	23.0694	22.1447	13.6546	12.7241
		P_{G11}	12.6678	12.7814	10.0941	10
		P_{G13}	12.4055	12	12	12
2	Generator voltages (p.u.)	V_{G1}	1.05	1.05	1.05	1.05
		V_{G2}	1.0346	1.0357	1.0298	1.0296
		V_{G5}	1.005	1.0098	0.9933	1.004
		V_{G8}	1.0179	1.0171	1.0133	1.0186
		V_{G11}	0.976	1.0204	0.9978	1.017
		V_{G13}	1.0059	1.0461	1.0175	1.05
3	Transformer tap setting (p.u.)	T_{6-9}	1.0922	0.9832	1.0709	1.0959
		T_{6-10}	0.9922	1.0329	0.9474	0.9861
		T_{4-12}	1.0593	0.9702	0.9914	1.0024
		T_{28-27}	1.0227	0.9904	1.004	0.993
4	Shunt compensators (MVAr)	Q_{C10}	18.1354	16.0279	25.9421	26.5731
		Q_{C24}	13.1862	18.2836	16.5185	15.1947
5	Total generation (MW)		292.9767	293.0015	294.4368	294.3187
6	Total power loss (MW)		9.5766	9.6015	11.0369	10.9187
7	Fuel cost ($/h)		**803.0521**	**802.8811**	**919.0704**	**918.6617**
8	Computing time (Sec)		43.46737	26.46292	53.0882	35.3112

V. CONCLUSION

In this paper, the proposed imperialistic competitive algorithm has been presented to optimize conventional quadratic and non-convex fuel cost functions. The effectiveness of the proposed method has demonstrated through IEEE 14 bus system and IEEE 30 bus systems. The results obtained for test systems using proposed method are compared with existing methods. The observations reveal that the results obtained using proposed method is close to the existing method. Also, it is clear that the iterative process begins with best population and convergence rate is fast for proposed method. Hence, the computation time has been less for proposed method in comparison with existing method. It was also observed that, the objective function value has been further minimized when all control variables are considered instead of limited control variables.

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