Imperialist Competitive Algorithm for Optimal Reactive Power Dispatch Problem: A Comparative Study

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Abstract – In this paper, imperialist competitive algorithm (ICA) is applied to solve the optimal reactive power dispatch (ORPD) problem. The ORPD problem is a key instrument to achieve secure and economic operation of power systems. Due to complex characteristics of ORPD, heuristic optimization has become an effective solver. Based on the IEEE 14- and 30- bus systems, ICA is compared with some basic algorithms. Simulation results show that ICA is a suitable algorithm for ORPD and should deserve more attention.

Keywords: Optimal Reactive Power Dispatch (ORPD), Heuristic Optimization.

INTRODUCTION

The optimal reactive power dispatch (ORPD) plays an important role in optimal operation of electric power systems. The optimal reactive power dispatch problem is a non-linear optimization problem with many uncertainties. The optimal reactive power dispatch is an effective method to improve voltage level, decrease network losses and maintain the power system running under normal conditions. The main objective of the ORPD is to minimize the system real power loss. Generally, the control variables of ORPD consist of transformer tap positions, generator set points (either reactive power injection or voltage), and reactive power compensations [1, 2].

In recent years, some new algorithms based on artificial intelligence have been proposed to solve the reactive power optimization, for examples: fuzzy logic(FL), expert system, artificial neural network (ANN), genetic algorithm (GA)[3], gravitational search algorithm (GSA) [4], differential evolution (DE) [5], tabu search(TS)[6], particle swarm optimization (PSO) [7], ant colony optimization(ACO)[8], evolutionary programming (EP) [9], bacterial foraging optimization (BFO) [10], etc.. These algorithms could treat discrete and non-convex nonlinear problems effectively. The global optimal solution could be gained easier by new algorithms than by conventional ones. So these algorithms have been wildly applied to the reactive power optimization.

In this paper, ICA is applied for solving the ORPD problem. In the process of solving, ORPD problem is formulated as a nonlinear constrained single-objective optimization problem where the real power loss is to be minimized. Simulations have been done using MATLAB program. The proposed algorithm is tested on IEEE 14- and 30- bus systems for evolution of effectiveness of it. Results obtained from ICA are compared with other heuristic methods. Results show that proposed algorithm is more effective and powerful than other algorithms in solution of ORPD problem.

PROBLEM FORMULATION

The objective of the ORPD problem is to minimize the system real power losses by setting generator bus voltages, VAR (volt amp reactive) compensators and transformer taps. Objective function minimized in this paper and constraints are formulated taking from (1, 9) and shown as follows.

1. Minimization of Real Power Loss

The real power loss is a non-linear function of bus voltages, which are functions of control variables. This is mathematically stated as follows:

\[
P_{\text{loss}} = \sum_{k=1}^{nl} g_k \left[ V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j) \right] \quad (1)
\]

Where \(P_{\text{loss}}\) is the total active power losses of the transmission network, \(nl\) is the number of transmission lines, \(g_k\) is the conductance of branch \(k\), \(V_i\) and \(V_j\) are voltage magnitude at buses \(i\) and \(j\) of the \(k\)th, and \(\delta_i\) and \(\delta_j\) are the voltage phase angle at the end buses \(i\) and \(j\).

2. System Constraints
In the reactive power optimization mathematical model, some problem constraints which one is equality and others are inequality had to be met.

2.1. Load Flow Equality Constraints

\[ P_{G_i} - P_{D_i} - \sum_{j=1}^{NB} G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j) = 0 \]  
\[ Q_{G_i} - Q_{D_i} - \sum_{j=1}^{NB} G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j) = 0 \]  

Where \( i=1,...,NG \); \( NB \) is the number of buses, \( P_G \) is the active power generated, \( Q_G \) is the reactive power generated, \( P_D \) is the load active power, \( Q_D \) is the load reactive power, \( G_{ij} \) and \( B_{ij} \) are the transfer conductance and susceptance between bus \( i \) and bus \( j \), respectively.

2.2. Inequality constraints

These constraints include:

- **Generator constraints**: generator voltages and reactive power outputs are restricted by their lower and upper limits as follows:

\[ V_{G_i}^{\text{min}} \leq V_{G_i} \leq V_{G_i}^{\text{max}}, \quad i = 1,...,NG \]  
\[ Q_{G_i}^{\text{min}} \leq Q_{G_i} \leq Q_{G_i}^{\text{max}}, \quad i = 1,...,NG \]  

- **Transformer constraints**: transformer tap settings are bounded as follows:

\[ T_i^{\text{min}} \leq T_i \leq T_i^{\text{max}}, \quad i = 1,...,NT \]  

- **Shunt VAR constraints**: shunt VAR compensations are restricted by their limits as follows:

\[ Q_{vi}^{\text{min}} \leq Q_{vi} \leq Q_{vi}^{\text{max}}, \quad i = 1,...,NC \]  

- **Security constraints**: these include the constraints of voltages at load buses and transmission line loadings as follows:

\[ V_{li}^{\text{min}} \leq V_{li} \leq V_{li}^{\text{max}}, \quad i = 1,...,NL \]  
\[ S_{li} \leq S_{li}^{\text{max}}, \quad i = 1,...,nl \]  

Where \( NG \) is the number of the generator-bus, \( NL \) is the number of bus bars, \( NT \) is the number of the transformer taps, \( NC \) is the member of shunt compensations and \( nl \) is total number of transmission lines.

**Imperialist Competitive Algorithm**

Imperialist competitive algorithm (ICA) [11] is introduced for general searching that is inspired from imperialist competition. Fig.1 shows the flowchart of the ICA. In sum, this algorithm starts with an initial population. Each individual of the population is called a 'country'. Some of the countries in the population with the minimum cost (equal with ‘chromosome’ in GA) are selected to be the imperialist states and the rest form the colonies of these imperialists. Imperialistic competitions among these empires form the basis of the ICA. The imperialist states together with their colonies form some empires. Imperialistic competitions converge to a state in which there exists only one empire and its colonies are in the same position and have the same cost as the imperialist. The power of each country is inversely proportional to its cost.

The objective of optimization is to attain an optimal solution in terms of the variables of the problem. Algorithm-user forms an array of variable values to be optimized. In the ICA terminology, this array is called 'country' (equal with ‘chromosome’ in GA). When solving a \( N_{var} \) dimensional optimization problem, a country is a \( 1 \times N_{var} \) array. This country is defined as follow:

\[ country=[p_1, p_2, p_3,..., p_{N_{var}}] \]  

1. Generating Initial Empires

Fig. 1- Flowchart of the ICA

Fig. 2- Interpretation of country using some of socio-political characteristics

\[ country=[p_1, p_2, p_3,..., p_{N_{var}}] \]  

Where \( p_s \) are considered as the variables that should be optimized.

The candidate solutions of the problem, called country, consist of a combination of some socio-political characteristics such as, welfare, culture, religion and...
mortality. Fig. 2 shows the interpretation of country using some of socio-political characteristics. 

When the problem was optimized, the optimal solution is going to be finding which the one with the minimum cost value is. By evaluating the cost function, \( f \) for variables \( (P_1, P_2, P_3, \ldots, P_{N_{\text{col}}}) \), the cost of a country will be found (Equation (11)):

\[
\text{cost}_i = f(\text{country}) = f(P_1, P_2, P_3, \ldots, P_{N_{\text{col}}}) \quad (11)
\]

To begin the ICA algorithm, initial population of size \( N_{\text{country}} \) is produced. We select \( N_{\text{imp}} \) of the strongest population to form the empires. The remaining \( N_{\text{col}} \) of the population will be the colonies each of which belongs to an empire. We give some of these colonies to each imperialist for dividing the early colonies among the imperialist accordance with their power. To proportionally divide the colonies among imperialists, the normalized cost of an imperialist is defined by:

\[
C_n = \max_i \{c_i\} - c_n \quad (12)
\]

In the above equation, \( c_n \) is the cost of \( n \)th imperialist and \( C_n \) is its normalized cost. When the normalized costs of all imperialists are gathering, the normalized power of each imperialist is evaluate according to the following equation:

\[
P_n = \frac{C_n}{\sum_i C_i} \quad (13)
\]

The initial colonies are divided among empires based on their power. Then, the initial number of colonies of the \( n \)th empire will be:

\[
N_{C_n} = \text{round} \{ P_n N_{\text{col}} \} \quad (14)
\]

Where \( N_{C_n} \) is initial number of empire's colonies and \( N_{\text{col}} \) is the total number of existing colonies countries in the initial countries crowds.

2. Absorption Policy Modeling

As mentioned earlier, imperialist states made their colonies to move toward themselves along different socio-political axis such as welfare, culture and religion. In fact this central government tries to close colony country to its self by applying attraction policy, in different political and social dimensions, with considering showing manner of country in solving optimization problem. This movement is shown in Fig. 3 in which a colony moves toward the imperialist by units. While moving toward the imperialist, if a colony reaches a better point than an imperialist, they will be replaced by each other. After that, the algorithm continues with imperialist country in new location and this time it is the new imperialist country in which begins to applying assimilation policy for its colonies.

3. Position Displacement of Colony and Imperialist

While moving toward the imperialist, a colony will move to the Best point. However, the power of the colonies of an empire has an effect, albeit negligible, on the sum power of that empire. In this case the sum cost of an empire calculates as follow:

\[
T\, C_n = \text{Cost (imperialist)}_n + \xi \text{mean}\{\text{Cost (colonies of empire)}_n\} \quad (17)
\]

Where \( T\, C_n \) is the total cost of the \( n \)th empire and \( \xi \) is a positive number that is usually between zero and one and near to zero. A low value for \( \xi \) causes the total power of the empire to be determined by just the imperialist and increasing it will increase to the role of the colonies in determining the total power of an empire. The value of 0.15 for \( \xi \) has shown good results in most of the implementations.
5. Imperialistic Competitions

There has always been a competition among the empires to take control and possess each other’s colonies. The imperialistic competition is modeled by just picking some (usually one) of the weakest colonies of the weakest empire and making a competition among all empires to possess these (this) colonies. Based on their total power, in this competition, each of the empires will have a likelihood of taking possession of the mentioned colonies. These weakest colonies will not definitely be possessed by the most powerful empires, but these empires will be more likely to possess them.

For modeling the competition between the empires for possessing these colonies, first of all, the weakest empire is chosen and then the possession probability of each empire is estimated. The possession probability $P_p$ is proportionate to the total power of the empire. The normalized total cost of an empire is simply obtained by:


(18)

Where $T . C . _n$ is total cost of $n$th empire and $N . T . C . _n$ is normalized cost of that $n$th empire. Having the normalized total cost, the possession probability of each empire is defined by:

$$ P_p = \left[ \frac{N . T . C . _n}{\sum_{i=1}^{N \max} N . T . C . _i} \right] $$

(19)

We divide the mentioned colonies accidentally between the empires, but with related probability to ownership probability of each empire. In order to divide the given colonies among the empires, vector $P$ is formed as follows:

$$ P = [P_{p1}, P_{p2}, P_{p3}, ..., P_{pN_{max}}] $$

(20)

After that, the vector $R$ should be defined with the same size of vector $P$. The arrays of this vector are accidental number with the same distribution in [0, 1].

$$ R = [r_1, r_2, r_3, ..., r_{N_{max}}] $$

(21)

Then, vector $D$ is constructed by subtracting $R$ from $P$.

$$ D = P - R = [D_1, D_2, D_3, ..., D_{N_{max}}] $$

(22)

$$ = [p_{p1} - r_1, p_{p2} - r_2, p_{p3} - r_3, ..., p_{pN_{max}} - r_{N_{max}}] $$

We give the mentioned colonies to the empires with having vector $D$ so that related index in vector $D$ is bigger than others.

The imperialistic competition will gradually result in an increase in the power of great empires and a decrease in the power of weaker ones. The weak empires will slowly lose their power and getting weakened by the time.

**Simulation Results**

In order to verify the proposed approach, ICA is applied to IEEE 14-bus and IEEE 30-bus power systems. The topology and data of these two systems can be found in [12, 13]. In all case studies, as decision variables, generator voltages, transformers tap settings, and reactive power compensators are chosen. In this paper, these variables are considered to be continuous [14].

For the two test cases, the performance of ICA is compared with the following algorithms.

1. PSO [7];
2. GA [3];
3. Invasive weed optimization (IWO) [15];
4. Shuffled frog leaping algorithm (SFLA) [16];

All programs were implemented in MATLAB R2010a. Because the most time-consuming parts in these methods are the repeated power flow calculations and the number of such calculations is fixed, the computational time of all algorithms is not significantly different. The comparison in this paper will be based on quality of the final results.

### 1. IEEE 14-Bus System

The IEEE 14-bus system consists of five generators, 20 lines where 3 of which are equipped with ULTC (under-load tap changer) transformers. The one line diagram of IEEE 14-bus system is shown in Fig. 4. The lower and upper limits of voltage magnitude at all buses are 0.95 and 1.10 p.u., respectively, while the transformer tap settings are varied between 0.9 and 1.1 p.u. Shunt reactive power compensator is connected to bus 9. The susceptances of capacitor banks are within the interval [0, 0.3] p.u.. In the IEEE 14-bus system, totally 9 control variables are taken for optimal reactive power dispatch. The line parameters and the loads are taken from [12] and the initial transmission line loss is 13.393 MW for the IEEE 14-bus system. The network loads are given as follows: $P_D = 259$ MW and $Q_D = 73.5$ MVAR.

The values of parameters and limits of generators for system case1 are given in Table 1. Five algorithms of PSO, GA, IWO, SFLA and ICA for solving objective reactive power optimization problem are shown in Fig. 5. From the optimal value of the convergence curve, ICA algorithm is fast at the beginning of generations decline, showing that the algorithm optimizing the effectiveness and superiority of the system; In the iteration 10 ,it have been able to very close to the optimal solution, but PSO algorithm to 50 iterations to achieve the optimal solution. GA, IWO and SFLA should be about 80, 180 and 100 iterations to achieve the optimal solution, respectively. So, ICA is better than PSO, GA, IWO and SFLA. The algorithm proposed in this paper has better convergence and accuracy. Table 2 shows the optimized algorithms the optimal value of the control variables.
TABLE 1
Generator Data of IEEE 14-Bus System

<table>
<thead>
<tr>
<th>Bus</th>
<th>( P_c ) (MW)</th>
<th>( Q_{p, \text{max}} ) (MVAr)</th>
<th>( Q_{p, \text{min}} ) (MVAr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>232.4</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>50</td>
<td>-40</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>24</td>
<td>-6</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>24</td>
<td>-6</td>
</tr>
</tbody>
</table>

Fig. 4 - Single line diagram of IEEE 14-bus test system [12]

Table 3 shows the statistical comparison of results obtained by PSO, GA, IWO, SFLA and ICA algorithms as regards to the objective function of minimizing real power loss only, the ICA algorithm is better than GA, IWO and SFLA, even as the average and maximum values of ICA algorithm are better of PSO algorithm. Fig. 6 shows the voltage magnitudes of all the bus bars as calculated from the ORPD solution by the different methods. It can be seen that all the bus voltages obtained by the proposed method are within the limits.

**TABLE 3**
Comparison of Best, Worst and Average Values for Different Algorithms for IEEE 14-Bus System

<table>
<thead>
<tr>
<th>Algorithms</th>
<th>PSO</th>
<th>GA</th>
<th>IWO</th>
<th>SFLA</th>
<th>ICA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>12.3787</td>
<td>13.0356</td>
<td>12.3791</td>
<td>12.6082</td>
<td>12.3431</td>
</tr>
</tbody>
</table>

**2. IEEE 30-Bus System**

The network consists of 6 generators; 41 lines; 4 transformers and 2 capacitor banks. The one line diagram of IEEE 30-bus system is shown in Fig. 7. In the transformer tests, tap settings are considered within the interval \([0.9, 1.1]\). The susceptances of capacitor banks are within the interval \([0, 0.3]\) \(p.u\.), and they are connected to buses 10 and 24. Voltages are considered within the range of \([0.95, 1.1]\). In this case, the decision space has 12 dimensions, namely, the 6 generator voltages, 4 transformer taps, and 2 capacitor banks.

In order to validate the proposed approach, it is tested with two test systems having non-linear characteristics.

**2.1. System Case 1**

The system loads and power losses are given as follows:

\[ P_D = 283.4 \text{MW}, \quad Q_D = 126.2 \text{MVAr}, \quad P_{l, \text{loss}} = 17.577 \text{MW}. \]

The values of parameters and limits of generators for system case 1 are given in Table 4. Also, Fig. 8 shows the performances of GA, PSO, IWO, SFLA and ICA during reactive power optimization.

![Fig. 5 - Convergence characteristics of IEEE 14-bus system](image-url)
Table 5 gives the optimum has been obtained after iterating about 10 generations by ICA, whereas 40 generations by standard PSO algorithm, 180 generations by IWO, 95 generations by GA and 100 generations by SFLA. Table 5 gives the optimal settings of decision variables in p.u. for the reactive control of IEEE 30-bus system as proposed by competitors and the ICA.

As shown in Fig. 8, by using the ICA algorithm, the iterations for convergence can be reduced greatly. The optimum has been obtained after iterating about 10 generations by ICA, whereas 40 generations by standard PSO algorithm, 180 generations by IWO, 95 generations by GA and 100 generations by SFLA. Table 5 gives the optimal settings of decision variables in p.u. for the reactive control of IEEE 30-bus system as proposed by competitors and the ICA.

Table 6 shows that comparison of best, worst and average values for different methods. Due to probabilistic characteristic of heuristic algorithms, results reported here correspond to average from 30 trials. From Table 6 we can see: the best value, worst value and average value found by the ICA algorithm are apparently better than those obtained by GA, IWO and SFLA. Hence, the conclusion can be drawn that ICA algorithm is better than, or comparable to, all the other listed algorithms in terms of global and local search. As shown in the table, the average value, the best solution and the worst solution obtained by the proposed algorithm is much better than those of obtained by the others. Also the algorithm converges to global solution in 19 times while the PSO, GA, IWO and SFLA reach to the best solution in 15, 5, 12, and 8 times, respectively. We can conclude that the ICA algorithm is robust.

After the ORPD result given by each method, power flow is calculated to determine bus voltages as shown in

![Single line diagram of IEEE 30-bus system](image1)

![Convergence characteristics for IEEE 30-bus system for case 1](image2)

![Comparison of Best, Worst and Average Values for Different Algorithms](image3)
Fig. 9. It is shown that all bus voltages can be maintained within the limits. These voltage profiles confirm the merits of ORPD in achieving reduced power losses.

2.2. System Case 2
The system loads and power losses are given as follows: \( P_L = 283.4 \text{MW}, Q_L = 126.2 \text{MVAR}, P_{loss} = 3.829 \text{MW} \).

The values of parameters and limits of generators for system case 2 are given in Table 7. The convergence of active power losses averaged from 30 independent trials of different algorithms is shown in Fig. 10. In terms of the convergence characteristic, ICA is the very good. The optimum control parameter settings of proposed approach are given in Table 8. The best power loss obtained from proposed approach is 3.1775 MW. Statistical results are shown in Table 9. In this test case, minimum, average and maximum of power losses from ICA are the lowest among all methods. Only minimum amount of PSO algorithm is equal with ICA.

Fig. 11 shows the voltage profiles at load buses resulting from all methods. Again, all optimization algorithms can maintain all bus voltages within the limits.

![Voltage profiles of IEEE 30-bus system for case 2](image)

### CONCLUSIONS
The optimal reactive power dispatch is a global optimization problem of a non-continuous nonlinear function arising from large-scale industrial power systems. ICA algorithm for optimal reactive power dispatch problem is presented by this study in the first time. According to the simulation results, it is seen that this method is very effective and quite efficient for solving ORPD. From the simulation results, it has been seen that ICA algorithm converges to the global optimum. The optimization strategy is general and can be used to other power system optimization problems as well. The simulation results indicate the effectiveness and robustness of the proposed algorithm to solve optimal reactive power dispatch problem in test systems.

### REFERENCES


