OPTIMAL POWER FLOW IN THE PRESENCE OF PRACTICAL CONSTRAINTS USING IMPERIALISTIC COMPETITIVE ALGORITHM

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ABSTRACT

The power system operation and control has many non-linearities and computational difficulties. The operation of the power system, more economically and to enhance the security of the system is due to optimal scheduling of the generators, this problem is commonly known as Optimal Power Flow (OPF) problem. This OPF becomes one of the important tools to operate and planning of the power system. OPF is a typical nonlinear programming problem which consists in determining an optimal steady state operation of an electric power system. In this paper, a methodology based on Imperialistic Competition Algorithm (ICA) is presented to solve Economic Dispatch (ED) problem by considering both quadratic and non-convex cost objectives while satisfying equality, in-equality and practical constraints such as ramp-rate limits and prohibited operating zones (POZ). The characteristics of generators have much effect due to the presence of these practical constraints. The effectiveness of the proposed methodology has been successfully implemented on standard IEEE-14 bus test system with supporting numerical results.

KEYWORDS: *Optimal Power Flow, Non-convex fuel cost, Ramp-rate limits, POZ limits, Imperialistic Competitive Algorithm.*

I. INTRODUCTION

Economic Load Dispatch (ELD) problem is one of the fundamental issues in power system operation and is an important task for optimization. The main objective is to allocate generation among various units to meet the load demand by reducing production cost of electrical energy such that the relevant operational constraints are satisfied. The ELD problem can be solved easily by assuming incremental cost curves of the generating units are of monotonically increasing piece-wise linear functions.

The input-output characteristics or cost functions of a generator are approximated using quadratic functions, under the assumption that the incremental cost curves of the units are monotonically increasing. However, real input-output characteristics exhibit higher-order non-linearities and discontinuities due to valve-point loading in fossil fuel fired plants. The valve-point loading effect has been modelled in [1-3] as a recurring rectified sinusoidal function.

The prohibited operating zones in the input-output performance curve for a typical thermal unit can be due to vibration in a shaft bearing caused by a steam valve or can be due to faults in the machines themselves or the associated auxiliary equipment, such as boilers and feed pumps. In practice, the shape of the input-output curve in the neighbourhood of a prohibited zone is difficult to determine by actual performance testing. In actual operation, the best economy is achieved by avoiding operation in these areas [4-7]. The valve-point loading, prohibited operating zones and other constraints turns the decision space into a difficult non-convex optimization problem.

Several conventional methods have been applied for solving ED problems such as gradient search, Newton's method, dynamic programming (DP), hierarchical approach based on the numerical method [8, 9], decomposition method [10] and Maclaurin series based Lagrangian method [11]. In general, the conventional methods are not effective for non-convex ED problems. Recently, many methods based on artificial intelligence have been developed for solving ED problems such as Hopfield neural network (HNN) [12], genetic algorithm (GA) [13-16], evolutionary programming (EP) [17], Taguchi method (TM) [18], biogeography-based optimization (BBO) [19], and particle swarm optimization (PSO) [20-30]. DE algorithm is proposed for solving OPF problem to find the optimal settings of the control variables [31]. For solving OPF problem improved harmony search method is proposed in [32]. In this quadratic cost is analyzed. In [33], evolutionary programming (EP) is proposed to solve security constrained OPF. In [34],Optimal power flow problem is solved by Tabu search algorithm M.A.Abido used particle swarm optimization (PSO) [35] for solving optimal power flow problem with different objectives like minimization of fuel cost, enhancement of voltage profile as well as voltage stability. In [36], Gravitational Search Algorithm (EP) has been applied for solving OPF problem where different objectives are optimized. In [37], BAT Algorithm is presented to solve ED problem.

In [38], enhanced genetic algorithm (EGA) is applied for the solution of OPF problem with both continuous and discrete control variables. In [39], Adaptive biogeography based predator–prey optimization technique used for solving optimal power flow to reduce generation cost, reduction of loss, enhancement of voltage profile as well as voltage stability. In [40], Artificial Bees Colony (ABC) algorithm is used to optimize the powers system by the minimization of fuel cost. The solution of ED with valve point effect by hybrid approach based on sequential combination of GA and active power optimization using Newton's second order in [41].

In this paper, the economic load dispatch problem is solved while satisfying equality, inequality and practical constraints such as ramp-rate and prohibited operating zones. The effect of practical constraints is analyzed on standard IEEE-14 bus system using proposed ICA algorithm. The detailed control parameters for quadratic and non-convex cost objectives are presented and variation of bus voltage magnitudes and transmission line apparent power flows are analyzed.

The later paper is organized as follows; the second section describes the problem formulation, in this the generation fuel cost objectives such as quadratic as well as non-convex fuel cost functions are formulated. The system and practical constraints are described in detailed. The detailed work flow of the proposed ICA algorithm is described in section-3. Section-4 gives the detailed results obtained for the proposed methodology.

II. PROBLEM FORMULATION

In ED problem the fuel cost can be represented as

$$Minimize\ FC = \sum_{i=1}^{NG} C_i(P_{Gi}) \qquad \$/h \tag{1}$$

where, $C_i(P_{Gi}) = a_i P_i^2 + b_i P_i + c_i$ without valve point loading effect and $C_i(P_{Gi}) = a_i P_i^2 + b_i P_i + c_i + \left| e_i \times \sin\left(f_i \times \left(P_i^{\min} - P_i\right)\right)\right|$ with valve point loading effect. Where, a_i, b_i, and c_i are the fuel-cost coefficients of the i^{th} unit, e_i and f_i are the fuel cost-coefficients of the i^{th} unit reflecting valve-point loading effects. 'FC' is the total generation cost, '$C_i(P_{Gi})$' is the fuel cost function of the i^{th} unit, 'P_{Gi}' is the power generated by the i^{th} unit. The minimization of generation cost is subjected to the following equality, inequality and practical constraints.

2.1. Equality constraints

These constraints are usually load flow equations described as

$$P_{Gk} - P_{Dm} - \sum_{m=1}^{NB} |V_k||V_m||Y_{km}| \cos(\theta_{km} - \delta_k + \delta_m) = 0 \tag{2}$$

$$Q_{Gk} - Q_{Dm} + \sum_{m=1}^{NB} |V_k||V_m||Y_{km}| \sin(\theta_{km} - \delta_k + \delta_m) = 0 \tag{3}$$

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

2.2. In-equality constraints

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

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

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

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: $Q_{G_i}^{\min} \le Q_{G_i} \le Q_{G_i}^{\max}; \quad \forall i \in N_G$

Load bus voltage magnitude limits: $V_i^{\min} \le V_i \le V_i^{\max} \quad i = 1,2,....,N_{load}$

2.3. Ramp-rate limits

The constraints of the ramp-rate limits, the operating limits of the generators are restricted to operate always between two adjacent periods forcibly. The ramp-rate constraints are

$$\max\left(P_{G_i}^{\min}, P_i^0 - DR_i\right) \le P_{G_i} \le \min\left(P_{G_i}^{\max}, P_i^0 + UR_i\right) \tag{4}$$

where, P_i^0 is i^{th} unit power generation at previous hour. DR_i and UR_i are the respective down and up ramp-rate limits of i^{th} unit.

2.4. Prohibited Operating Zone (POZ) limits

To improve the efficiency of the thermal power plant generators are avoid to operate in the prohibited operating zones. This can be represented as

$$P_i = \begin{cases} P_i^{\min} \le P_i \le P_{i,1}^L \\ P_{i,k-1}^U \le P_i \le P_{i,k}^L \ ; \ k = 2,3,...,n_i \\ P_{i,n_i}^U \le P_i \le P_i^{\max} \end{cases} \tag{5}$$

where n_i is the number of POZ's and k-index of POZ of unit-i. $P_{i,k}^L$ and $P_{i,k}^U$ are the respective lower and upper limit of k^{th} POZ of i^{th} generator.

Finally the above proposed problem is more generalized to solve in-equality constraints can be given as

$$FC_{aug} = FC + R_1\left(P_{g,slack} - P_{g,slack}^{\lim}\right)^2 + R_2 \sum_{i=1}^{N_{Load}} \left(V_i - V_i^{\lim}\right)^2 + R_3 \sum_{i=1}^{N_G} \left(Q_{G_i} - Q_{G_i}^{\lim}\right)^2 + R_4 \sum_{i=1}^{N_{line}} \left(S_{l_i} - S_{l_i}^{\max}\right)^2 \tag{6}$$

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, Q_{Gi}.

III. IMPERIALISTIC COMPETITIVE ALGORITHM

Imperialistic competitive algorithm [42] is inspired by the imperialistic competition in geo-political interactions between countries. Initially, countries for the considered control variables are generated. Out of which, some of them are best countries (lowest cost) treated as “imperialist” and the remaining are treated as “colonies”. All colonies are moved towards their imperialists based on their powers. Here the power of each country is inversely proportional to its cost value. Finally, the “empires” are formulated by combining imperialists with the corresponding colonies.

After this, the assimilation policy is applied to move the empires towards their imperialist. Then power of each empire is calculated as the sum of the power of the imperialist and percentage of mean of power of its colonies. Then, all these empires participate in imperialistic competition and finally, the empire which has least power is eliminated from the system. The colonies will move towards their relevant imperialist and cause all the countries to converge to a state with single empire in the process. The important steps in this algorithm are briefly discussed below:

1. Generating initial empires

Initially population is generated for all control variables as countries (Ncountry). For N-dimensional problem, the position of ith country is defined as follows:

$$Country_i = \lfloor P_{G_1},..P_{G_{NG}}, V_{G_1},..V_{G_{NG}}, T_1,..T_{nt}, Q_{sh_1},....Q_{sh_{nc}} \rfloor$$

The control variables corresponds to each population are updated in bus and line data then perform load flow and finally calculate the cost (Ci) of each country. Initialize the total number of imperialists (Nimp) and there by calculate the number of colonies (Ncol=Ncountry-Nimp). To divide the colonies among imperialists proportionally, the normalized cost of all imperialists is calculated and based on this normalized powers are calculated [ref]. From this the number of colonies for nth empire is evaluated. As the imperialists force to move the colonies towards them by applying attraction policy.

2. Moving colonies towards their imperialists

If a colony has best cost value than that of the imperialist, then exchange these colony and imperialist to continue this process in new location.

3. Calculation total power of an empire

The total power of an empire is the sum of the power of the imperialist and powers of the colonies.

4. Imperialistic competition

All these empires try to take the possession of colonies of other empires and try to control them. In this process, the power of the powerful empire increases where as the weak empire decreases. This competition is modeled by choosing some of the weakest colonies of the weakest empires and competition among all empires to possess these colonies. Then, total power of each empire is calculated.

5. Eliminating powerless empires

The powerless empires will collapse in the imperialistic competition. Different criteria can be defined for collapse mechanism. In this paper, an empire is assumed collapsed when it loses all of its colonies. Weak empires gradually decline in imperialistic competition and strong empires take the possession of their colonies. There are different conditions for declining an empire.

6. Stopping criteria

After some imperialistic competitions, all the empires except the most powerful one will collapse and all of the countries under their possession become colonies of this empire. All the colonies have the same positions and the same costs and there is no difference between the colonies and their imperialist. In such a case, the algorithm stops.

IV. RESULTS AND ANALYSIS

A standard test system with 5 units [43] is used to demonstrate the effectiveness of proposed approach. In this example, the first three units have prohibited operating zones as well as ramp rate limits. The system load is 259 MW. The data of unit characteristics, ramp rate limits, and prohibited operating zones of generating units is given in Appendix.

In this analysis, the ramp rate limits and prohibited operating zones (POZ) of units are taken into account for practical application to optimize quadratic and non-convex fuel cost functions. Each of the cost function is analyzed for the following four cases:

Case-A: without ramp-rate and without POZ
Case-B: with ramp and without POZ
Case-C: without ramp and with POZ
Case-D: with ramp and with POZ

For this system, total 14 control variables which includes, 5 active power generations, 5 generation voltage magnitudes, 3 tap settings of tap-changing transformers, 1 reactive compensator are considered for all cases. The proposed ICA method is used to optimize the quadratic as well as non-convex cost functions subjected to satisfy equality and in-equality constraints. The input parameters for the proposed ICA algorithm are given in Table.1.

Table.1. Parameters for test examples

Parameters	Quantity
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. Quadratic cost

In this, the results of optimized values for all control variables for minimization of quadratic cost objective using proposed ICA method by considering effect of practical constraints for the above four cases is presented. The summary of test results for four cases is given in Table.2. The convergence characteristics of the proposed algorithm for all the cases are shown in Fig.1.

From Table.2, it is observed that the generation fuel cost is increased from 714.1395 $/h in case-A to 715.6184 $/h in case-D. The practical constraints followed by the units are given in Table.3. From this table, it is observed that, all units are following practical constraints.

From Fig.1, it is observed that, the initial starting cost value is increased as the number of constraints is increasing. Similarly, the number of iterations taken for convergence is increased from case-A to case-D.

Table.2. OPF results of quadratic cost for four cases

S.No	Parameter		Case-A	Case-B	Case-C	Case-D
1	Real power generation (MW)	PG1	171.984	173.4223	172.1329	168.7799
		PG2	47.957	47.3096	46.9893	50.3254
		PG3	20.7051	21.0555	21.2613	21.1789
		PG6	16.0129	16.2356	16.8266	18.1432
		PG8	10.2569	8.9861	9.7375	8.6787
2	Generator voltages (p.u.)	VG1	1.1	1.1	1.1	1.0886
		VG2	0.9	0.9498	0.9296	1.0565
		VG3	0.9958	1.0348	0.9634	0.9419
		VG6	0.9794	1.0549	1.0482	1.0505
		VG8	1.0306	1.0546	1.0397	1.015
3	Transformer tap setting (p.u.)	T4-7	1.0617	1.0375	1.0321	1.0508
		T4-9	0.9748	1.0143	0.9841	0.9362
		T5-6	1.013	1.0284	1.0243	1.0188
4	Shunt compensator (MVAr)	QC9	16.2258	25.4556	22.3882	19.4419
5	Total generation (MW)		266.9159	267.0091	266.9476	267.1061
6	Total power loss (MW)		7.9159	8.0091	7.9476	8.1061
7	Quadratic cost ($/h)		714.1395	714.2923	714.3932	715.6184

Table.3. Ramp rates and POZ limits followed by the generators of quadratic cost for four cases

Gen. No	Case-A	Case-B	Case-C	Case-D
1	-	Up	2	Up, 2
2	-	Up	2	Up, 2
3	-	Down	1	Down, 1
6	-	-	-	-
8	-	-	-	-

1-Below POZ lower limit 2-Above POZ upper limit
3-Equal to POZ lower limit 4-Equal to POZ upper limit
UP-following up-ramp rate Down-following down-ramp rate

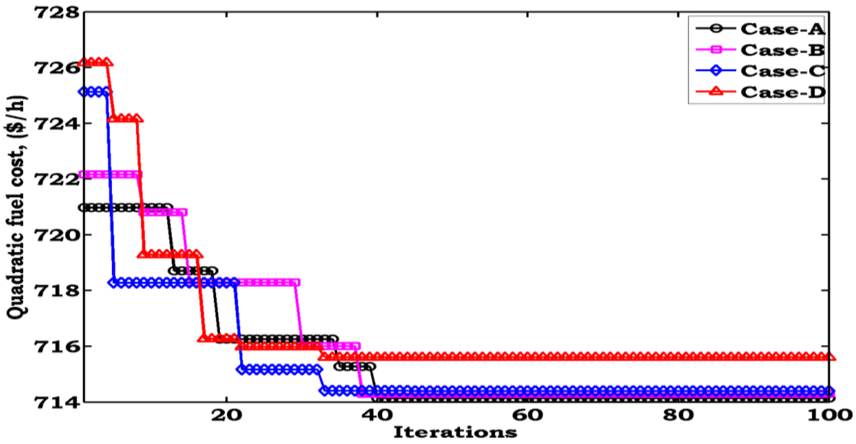

Fig.1. Convergence characteristics of quadratic cost for four cases

4.2. Non-convex cost

In this, the results of optimized values for all control variables for minimization of non-convex cost objective using proposed ICA method by considering effect of practical constraints for the above four cases is presented. The summary of test results for four cases is given in Table.4. The convergence characteristics of the proposed algorithm for all the cases are shown in Fig.2.

From Table.4, it is observed that the generation fuel cost is increased from 822.783 $/h in case-A to 824.7462 $/h in case-D. The practical constraints followed by the units are given in Table.5. From this table, it is observed that, all units are following practical constraints. From Fig.2, it is observed that, the initial starting cost value is increased as the number of constraints is increasing. Similarly, the number of iterations taken for convergence is increased from case-A to case-D.

Table.4. OPF results of non-convex cost for four cases

S.No	Parameter		Case-A	Case-B	Case-C	Case-D
1	Real power generation (MW)	PG1	218.1539	218.0334	216.3309	213.2493
		PG2	23.5231	21.4406	26.0655	23.2421
		PG3	16.9747	20	17.3533	20
		PG6	5.9796	5	5	7.7983
		PG8	5	5	5	5
2	Generator voltages (p.u.)	VG1	1.1	1.1	1.1	1.0883
		VG2	0.9	0.9768	0.9045	1.0599
		VG3	0.9504	1.065	0.9612	1.007
		VG6	0.9776	1.0432	0.9871	0.9836
		VG8	0.99	1.0363	0.921	1.0507
3	Transformer tap setting (p.u.)	T4-7	1.0606	1.09	1.0137	1.1
		T4-9	0.988	1.0085	1.0766	0.9579
		T5-6	0.9997	1.0343	0.9794	1.0773

4	Shunt compensator (MVAr)	QC9	13.565	21.1242	29.9645	9.3157
5	Total generation (MW)		269.6313	269.474	269.7497	269.2897
6	Total power loss (MW)		10.6313	10.474	10.7497	10.2897
7	Non-convex cost ($/h)		822.783	823.0278	823.3653	824.7462

Table.5. Ramp rates and POZ limits followed by the generators of non-convex cost for four cases

Gen. No	Case-A	Case-B	Case-C	Case-D
1	-	Up	2	Up, 2
2	-	Down	1	Down, 1
3	-	Down	1	Down, 1
6	-	-	-	-
8	-	-	-	-

1-Below POZ lower limit 2-Above POZ upper limit
3-Equal to POZ lower limit 4-Equal to POZ upper limit
UP-following up-ramp rate Down-following down-ramp rate

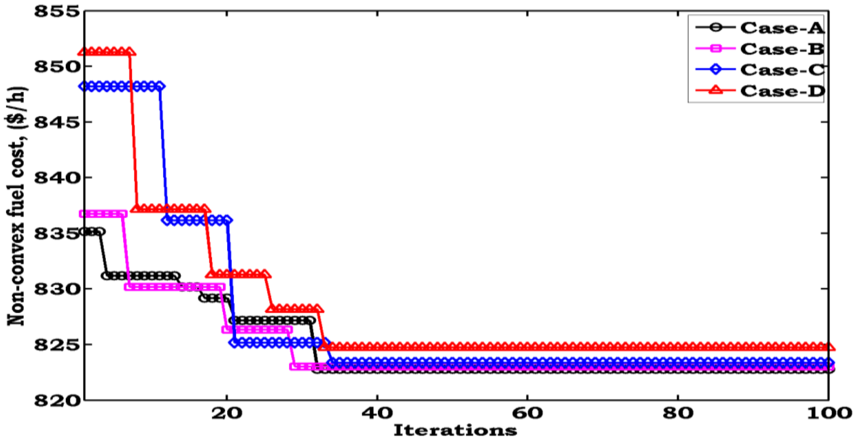

Fig.2. Convergence characteristics of non-convex cost for four cases

The variation of voltage magnitude at system buses and the apparent power flow through the transmission lines are shown in Figs 3 and 4.

From Fig.3, it is observed that, less voltage magnitude is obtained in case-D at bus-14 and high voltage magnitude obtained in case-A at bus-8. From Fig.4, it is observed that, the major variation in power flows occur in lines 8, 9 and 14.

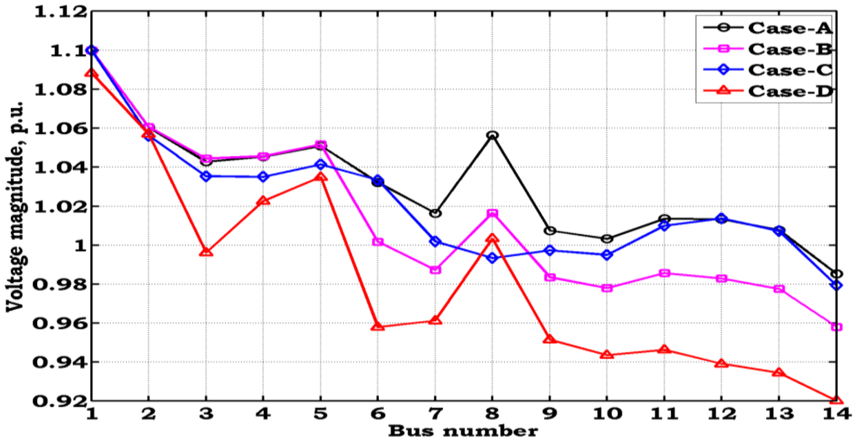

Fig.3. Variation of bus voltage magnitudes of non-convex cost for four cases

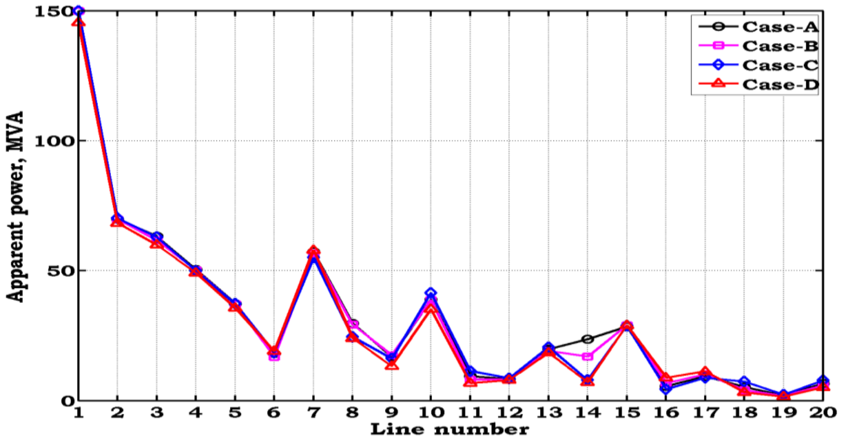

Fig.4. Variation of line apparent power flows of non-convex cost for four cases

V. CONCLUSIONS

In this paper, the ICA method has been successfully employed to solve the ELD problem while satisfying practical constraints such as ramp-rate limits and prohibited operating zones. Due to this, the quadratic and non-convex cost values have been increased. The flexibility of the proposed method in handling more number of constraints has been validated. The proposed method has been tested on standard IEEE-14 bus test system and results have been analyzed by taking voltage and apparent power flow variations.

VI. FUTURE WORK

The effect of these practical constraints may be considered while optimizing other power system objective such as emission, transmission losses, etc. In future this work can be extended with FACTs controllers. The effect of these practical constraints may be analyzed in the presence of series, shunt and combined series-shunt controllers.

APPENDIX

Table. A. Generator practical constraints data of IEEE-14 bus system

S.No	Gen. No	UR (MW)	DR (MW)	P_{i0} (MW)	POZ (MW)
1	1	30	60	70	[20-25] [60-72]
2	2	16	20	30	[30-35]
3	3	5	50	70	[25-31] [50-57]

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