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Analysis of Practical Constraints on Multi Objective Optimal Power Flow with IKGMO

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Abstract- In this paper, an improved optimization method is proposed to solve optimal power flow (OPF) problem while satisfying system, practical constraints and to analyze the effect of practical constraints onOPF problem, a novel hybrid algorithm i.e. improved kinetic gas molecules optimization (IKGMO) is presented. To increase the system security in terms of minimizing total power losses (TPL) along with the convex fuel cost (CFC), a multi objective function (MOF) by combining CFC and TPL objectives is formulatedThe proposed methodology is implemented and validated on standard IEEE-30 bus with supporting numerical and graphical results.

Keywords- Ramp-rate limits; POZ limits; Spinning reserve constraints; IKGMO.

I. INTRODUCTION

Economic dispatch (ED) plays vital role in the operation as well as planning of power system. Economic Dispatch means generating the output from generating units with minimum operating cost while satisfying unit and the system constraints. It is one of the imperative problem to be solved in power system for its effective operation. The best solution for economic dispatch problem minimises the generation cost, improves the system reliability.

In conventional ED problem cost function of generator is assumed to be quadratic polynomial and monotonically increasing known as convex cost function. ED with convex cost function was solved by classical methods such as lambda iteration method, Lagrangian multiplier method, gradient method, Quadratic and linear programming. But the actual fuel cost characteristics have non linearities and discontinuities due to ripple effect while opening and closing the steam valve incase of fuel fired generating plants. Such effect is known as valve point effect.To show this effect a sinusoidal function is incorporated in the quadratic cost function known as Non-Convex cost function [1-4]. In emission dispatch problem emission function is considered as an objective function to minimize the amount of emission.

In case of environmental economic dispatch problem emission is minimized in addition to the fuel cost objective function. over the past few years many heuristic search-based methods were applied to solve this problem such particle swarm optimization (PSO), adaptive PSO, chaotic PSO, differential evolution (DE), evolutionary programming (EP), bacterial foraging optimization (BFO), krill herd algorithm (KHA)[5,6], biogeography-based optimization (BBO) algorithm [7],Artificial bee colony algorithm has been developed for solving multi area economic dispatch problem with multiple fuels, valve point loadings, prohibited operating zones [8]. A mixed integer non linearnon linear problem with OPF control variables for simultaneous minimization of fuel cost, emission, and real power loss and voltage deviations under optimized condition using artificial bee colony algorithm [9]. A fuzzy assisted cuckoo search algorithm has been proposed for solving multi objective unit commitment problem [10].A riemannaian sub gradient algorithm has been proposed for optimal scheduling of generating units under equality and inequality constraints [11]. A speicies-based quantum particle swarm optimization method is proposed to solve the problem with smooth and non smooth cost functions while considering network losses, ramp rate,prohibited zones for effective generating management plans[12-16].

In nineteenth century the concept of flexible AC transmission system (FACTS) was first introduced in the power system to enhance its performance such as capacity, flexibility and security of power transmission systems. Various FACTS controllers are introduced in power system to enhance reliability, security, and flexibility of power system. The Unified Power Flow Controller (UPFC) is one of the most versatile FACTS device introduced by Gyugyi. It is the combination of series and shunt controllers capable of controlling real and reactive power flows and bus voltage magnitudes. UPFC is capable of regulating all three variables simultaneously. Phase shifting transformer is a mechanically switched device with injecting and exciting transformers can be able to shift the phase angle of voltage at which it is connected by maintaining the constant voltage magnitude. To effectively control the system performance conventional PST and UPFC are combined together to control both voltage magnitude as well as phase angle. This leads to a hybrid configuration FACTS device named as Optimal Unified Power Flow Controller (OUPFC).

Power injection model of OUPFC is presented for optimal steady State performance of power system [17-20]. FACTS devices are capable of controlling the power system parameters like voltage, current, power, impedance and phase angle., presence of these devices indeed required for maintain voltage profile, stability of the system, correction of the power factor and loss minimization. Moreover controls the power flow in the network, in such a way to reduce unwanted loop flows in the heavy loaded lines to enhance its loadability. In this paper, the economic constrained non convex economic dispatch problem is formulated. Economic dispatch under emission constrained problem is solved with the proposed algorithm with OUPFC for the effective generation management planning of power plants.

From the careful review of the literature, it is identified that, OUPFC is one of the advanced FACTS controller to control the power system performance. In this paper, a new modeling procedure based on current injections is developed to analyze the effect of this device on power system. The developed current based model (CBM) of OUPFC can be incorporated in conventional Newton-Raphson load flow methodology. From the literature, it is identified that, most of the literature is concentrated in minimizing either the convex fuel cost (CFC) or total power losses (TPL) using optimal power flow (OPF) problem while satisfying system constraints. From this, it is motivated that, it is necessary to minimize both the CFC and TPL objectives simultaneously while satisfying system and practical constraints such as ramp-rate limits, prohibited operating zones, and spinning reserve constraints. For this, a multi objective function (MOF) is formulated by combining CFC and TPL objectives. The OPF problem in the presence of OUPFC is solved while satisfying system, practical constraints and device limits. The proposed methodology is verified and validated on standard IEEE-30 bus and IEEE-57 bus test systems with supporting numerical and graphical results.

II. OPF PROBLEM FORMULATION

In general, the OPF problem with 'J' as an objective can be formulated as

$$Min\ J(x,u) \tag{8}$$

Subjected to

$$g(x,u)=0; \quad h(x,u)\leq 0$$

Where, 'g' and 'h' are the equality and inequality constraints respectively and 'x' is a state vector of dependent variables such as slack bus active power generation ($P_{g,slack}$), load bus voltage magnitudes (V_L) and generator reactive power outputs (Q_G) and apparent power flow in lines (S_l) and 'u' is a control vector of independent variables such as generator active power output (P_G), generator voltages (V_G), transformer tap ratios (T) and reactive power output of VAr sources (Q_{sh}).

The state and control vectors can be mathematically expressed as

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

$$u^T=[P_{G_2},\ldots,P_{G_{NG}},V_{G_1},\ldots,V_{G_{NG}},Q_{sh_1},\ldots,Q_{sh_{NC}},T_1,\ldots,T_{NT}$$

Where, 'NL', 'NG', 'nl', 'NC' and 'NT' are the total number of load buses, generator buses, transmission lines, VAR sources and tap-changing transformers respectively.

A. Constraints

This problem is optimized while satisfying the following equality, in-equality, and practical constraints.

B. Equality Constraints

These constraints are typically power flow equations satisfied in Newton Raphson load flow solution

$$P_{Gi}-P_{Di}-\sum_{j=1}^{N_{bus}}|V_i||V_j||Y_{ij}|\cos(\theta_{ij}+\delta_j-\delta_i)=0$$

$$Q_{Gi}-Q_{Di}-\sum_{j=1}^{N_{bus}}|V_i||V_j||Y_{ij}|\sin(\theta_{ij}+\delta_j-\delta_i)=0$$

Where, P_{Gi},Q_{Gi} are the active and reactive power generations at i^{th}bus, P_{Di},Q_{Di} are the active and reactive power demands at i^{th} bus, N_{bus} is number of buses and $|Y_{ij}|,\theta_{ij}$ are the bus admittance magnitude and its angle between $i^{th}$and j^{th} buses.

C. In-equality Constraints

Generator limits

Generator bus voltage limits:

$$V_{G_i}^{min}\leq V_{G_i}\leq V_{G_i}^{max}; \quad \forall\ \ i\in NG$$

Active Power Generation limits:

$$P_{G_i}^{min}\leq P_{G_i}\leq P_{G_i}^{max}; \quad \forall\ \ i\in NG$$

Reactive Power Generation limits:

$$Q_{G_i}^{min}\leq Q_{G_i}\leq Q_{G_i}^{max}; \quad \forall\ \ i\in NG$$

Security limits

Transmission line flow limit:

$$S_{l_i}\leq S_{l_i}^{max}; \qquad i\in nl$$

Load bus voltage magnitude limits:

$$V_i^{min}\leq V_i\leq V_i^{max}; \quad \forall\ \ i\in NL$$

Other limits

Transformers tap setting limits:

$$T_i^{min}\leq T_i\leq T_i^{max}; \quad \forall\ \ i\in NT$$

Capacitor reactive power generation limits:

$$Q_{sh_i}^{min}\leq Q_{sh_i}\leq Q_{sh_i}^{max}; \quad \forall\ \ i\in NC$$

Prohibited operating zones (POZ)

In practice, when adjusting the output of a generator unit, it is important to avoid operating in prohibited zones so that the thermal unit efficiency can be maintained during vibrations in the shaft or other machine faults. This feature can be included in the problem formulation as follows:

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

Where, 'n_i' is the number of prohibited zones and 'k' is the index of prohibited zones in unit-i. $P_{i,k}^L$and$P_{i,k}^U$ are the lower and upper limits, respectively, of the k^{th} prohibited zone in thei^{th} generator.

Ramp-rate limits

The operating limits of the generators are restricted to operate always between two adjacent periods forcibly. The ramp-rate limits can be mathematically expressed as

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

Where, $P_{G_i}^0$ 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.

Spinning reserve constraints (SR)

Spinning reserve is the back-up energy production capacity of the generating unit. It is the additional generating capacity available by increasing the output power of generator connected to a system during contingency or load increase. System reserve constraint can be formulated as follows:

$$\sum_{i=1}^{NG} P_{G_i} \le P^{max} - \mathrm{TRC}$$

Where, P^{max}, TRC are the maximum and total reserve capacities of the system.

The total system reserve (TRC) can be computed from the reserve capacities and contributions of the individual generators. This can be mathematically expressed as

$$\sum_{i=1}^{NG} SR_i \ge \mathrm{TRC}$$

Here, spinning reserve capacity of i^{th} unit can be computed as

$$SR_i = \min\left\{\left(P_{G_i}^{max} - P_{G_i}\right), S_{RC}^i\right\}$$

Where, $P_{G_i}^{max}$ is the maximum generation capacity and S_{RC}^i is the maximum reserve contribution of i^{th} unit respectively.

Hence, these inequalities are incorporated into the objective function using a penalty approach [21]. The augmented function can be formulated as

$$\begin{aligned} J_{aug}(x,u) = J(x,u) + \lambda_p\left(P_{G_1} - P_{G_1}^{limit}\right)^2 + \lambda_q \sum_{i=1}^{NG}\left(Q_{G_i} - Q_{G_i}^{limit}\right)^2 \\ + \lambda_v \sum_{i=1}^{NL}\left(V_i - V_i^{limit}\right)^2 + \lambda_s \sum_{i=1}^{nl}\left(S_{l_i} - S_{l_i}^{max}\right)^2 \end{aligned} \tag{9}$$

Where, $\lambda_p, \lambda_v, \lambda_q,$ and λ_s are the penalty quotients having large positive value. The limit values are defined as

$$x^{lim} = \begin{cases} x, & x^{min} \le x \le x^{max} \\ x^{max}, & x \ge x^{max} \\ x^{min}, & x \le x^{min} \end{cases}$$

Here 'x' is the value of P_{G_1}, Q_{G_i}, and V_i.

III. OBJECTIVES FORMULATION

To increase the reality of the OPF problem, the following objectives are formulated.

A. Convex fuel cost (CFC)

Economic operation of a generator is characterized by its fuel cost curve. The value of fuel cost varies depending on the amount of generation. For this, the conventional convex fuel cost function can be expressed as

$$\mathrm{CFC} = \sum_{i=1}^{NG}\left(a_i P_{G_i}^2 + b_i P_{G_i} + c_i\right) \quad ; \quad \$/h \tag{10}$$

Where, a_i, b_i, c_i are the fuel cost coefficients of i^{th} unit which represents investment, operating and opportunity cost functions. The variation of CFC of 2nd generator in IEEE-30 bus system is shown in Fig.4. The respective fuel cost coefficients are tabulated in Table.A1.

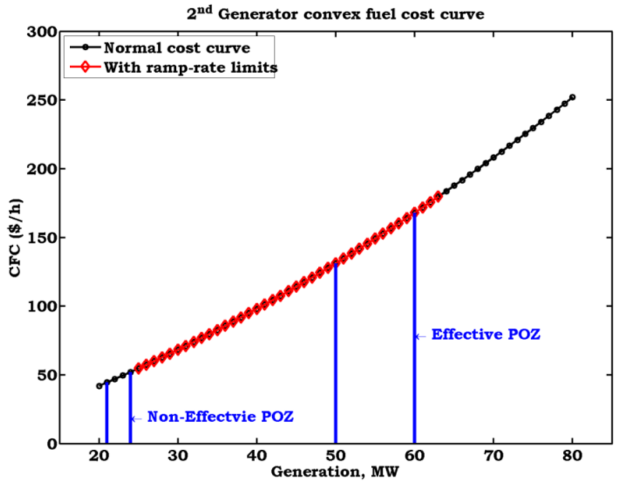

Fig.4: Variation of CFC of 2nd generator in IEEE-30 bus system

B. Total power losses (TPL)

In power system, the active power loss should be minimized to enhance power delivery performance and can be calculated using

$$TPL = \sum_{i=1}^{nl} g_i\left[V_i^2 + V_j^2 - 2V_iV_j\cos\left(\delta_i - \delta_j\right)\right] \quad ; \quad MW \tag{11}$$

Where, 'g_i' is the conductance of i^{th}line which connects buses 'i' and 'j'.V_i, V_j and $\delta_i, \delta_j$are voltage magnitude and angles at i^{th} and j^{th}buses.

C. Multi objective function (MOF)

To minimize the emissions from the generating plants, the generation from the thermal units must be restricted. The modified fuel cost function includes emission restrictions can be expressed as

$$\text{MOF} = \text{CFC+TPL} = \sum_{i=1}^{NG} \left(a_i P_{G_i}^2 + b_i P_{G_i} + c_i \right) + \frac{CFC}{P_d} \times TPL \quad (12)$$

Where, 'P_d' is the total active power demand on a given system.

IV. PROPOSED IKGMO ALGORITHM

Sara Moein, RajasvaranLogeswaran [22] introduced KGMO based on the properties of gas molecules. In this algorithm gas molecules are considered as agents are tried to move in a container until they reaches the position where the temperature and kinetic energy are minimum. Gas molecules move in a container based on volume of the container, mass, velocity, Kinetic energy acquired by the gas molecules. In KGMO, each gas molecule updates their position in a multi dimensional search space. Each gas molecule moves towards the optimum point based on the updated velocity.

A. Overview of the existing KGMO

In general, for a given optimization problem and for a given number of population (K), the control variablesand their velocities are generated between their minimum and maximum limits using the following expression

$$X_i = X_i^{min} + rand(0,1) \times (X_i^{max} - X_i^{min}) \quad ; \quad i = 1, 2, \ldots, n$$

$$v_i = v_i^{min} + rand(0,1) \times (v_i^{max} - v_i^{min}) \quad ; \quad i = 1, 2, \ldots, n$$

Where, 'n' is the total number of control variables, X_i^{min}, X_i^{max} and v_i^{min}, v_i^{max} are the minimum and maximum limits of the control variables and velocities respectively. For an electrical problem, the control vector is generated for a given population can be represented as

$$X = \begin{bmatrix} P_{G_1}^1, \ldots P_{G_{NG}}^1, V_{G_1}^1, \ldots V_{G_{NG}}^1, T_1^1, \ldots T_{NT}^1, Q_{sh_1}^1, \ldots Q_{sh_{NC}}^1 \\ P_{G_1}^2, \ldots P_{G_{NG}}^2, V_{G_1}^2, \ldots V_{G_{NG}}^2, T_1^2, \ldots T_{NT}^2, Q_{sh_1}^2, \ldots Q_{sh_{NC}}^2 \\ \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \\ \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \\ P_{G_1}^K, \ldots P_{G_{NG}}^K, V_{G_1}^K, \ldots V_{G_{NG}}^K, T_1^K, \ldots T_{NT}^K, Q_{sh_1}^K, \ldots Q_{sh_{NC}}^K \end{bmatrix}$$

For each of the population the fitness function is calculated using

$$fit_i = \frac{1}{1+J_i} \quad \forall \quad i = 1, 2, \ldots, K$$

After evaluating fitness and objective function values (p_{best}), identify the global best function value (g_{best}). Using these local and global best values, the updated velocity in $(t+1)^{th}$iteration fori^{th}control parameters in k^{th} population can be calculated as

$$v_i^k(t+1) = T_i^k(t) \times w(t) \times v_i^k(t) + C_1 \times rand_1 \times \left(g_{best}^k - X_i^k(t)\right) + C_2 \times rand_2 \times \left(p_{best}^k - X_i^k(t)\right) \quad (8)$$

Here,

$T_i(t) = T_i^{max} - \frac{T_i^{max} - T_i^{min}}{t^{max}} \times t$is the temperature, and this value linearly varies from 0.95 to 0.1.

$w(t) = w_{max} - \frac{w_{max} - w_{min}}{t^{max}} \times t$is the inertia weight, and this value linearly varies from 0.9 to 0.4.

$v_i(t), X_i(t)$are the velocity and positions of the i^{th} control parameter in t^{th} iteration respectively.

$C_1, C_2,$ and $rand_1, rand_2$are the acceleration coefficients and random numbers generated between 0 and 1.

The new position of the control variables can be calculated as

$$X_i^k(t+1) = X_i^k(t) + v_i^k(t+1) + a_i^k(t+2) \quad ; \quad a \ \exists \ t > 1 \quad (13)$$

Where, $a_i^k(t+2) = \sqrt{\left(\frac{2\left(S_i^k(t+1) - S_i^k(t)\right)}{m} \right)}$,

here, $S_i^k(t+1) = \frac{3}{2} K b T_i^k(t+1)$

Where, 'b' is the Boltzmann constant, 'm' is the random number between 0 and 1 and this value is fixed throughout the iterative process.

B. Improved Kinetic Gas Molecules Optimization (IKGMO)

The performance of existing KGMO algorithm is improved by calculating acceleration coefficients and inertia weight dynamically rather than a constant value. Due to this, the searching capability of the particles in each iteration is improved.

Calculation of acceleration coefficients:

These coefficients improve the search efficiency of the particles with increased velocity in searching the global best solution and with decreased velocity in searching the local best solution. The dynamically acceleration coefficients can be calculated as

$$C_1 = C_2 = 1 + \frac{1}{\left(1 + \exp^{(-\lambda \times f(gbest))}\right)} \quad (14)$$

Here, $\lambda = \frac{1}{(f(gbest))^{new}}$

Calculation of dynamic inertia weight:

The weight factor is introduced to regulate the impact of previous velocity on the present velocity. In each iteration, this factor is calculated as

$$w'(t) = w_{max} - \frac{w_{max} - w_{min}}{t^{max}} \times t$$
$$D(t) = \mu \times D(t-1) \times (1 - D(t-1)) \tag{15}$$
$$w(t) = w'(t) * D(t)$$

Here, 'μ' is a control parameter taken between 0 and 4. 'D' is a chaotic parameter changes as per the iteration number.

After evaluating the dynamic acceleration coefficients and inertia weight, a new modification is implemented to update the position of the gas molecules. In early iterations, the gas molecules are far away from the optimum solution in a search space with large radius. Due to this, the particles require more number of iterations to reach global best solution since then also the particles may not be able to reach global solution. Hence, the particles need the solution search space with small radius. For this, the dynamically varying search radius can be calculated as

$$\delta_i = \delta_i^{max} - \exp^{\left(\log\left(\frac{\delta_i^{min}}{\delta_i^{max}}\right) \times \frac{t}{t^{max}}\right)} \tag{16}$$

Here, $\delta_i^{max} = \frac{X_i^{max} - X_i^{min}}{2}, \delta_i^{min} = 10^{-5}$.

The new position of the gas molecules is calculated as

$$X_{i_{new}}^k(t+1) = X_i^k(t+1) + (\delta_i \times rand(0,1))$$

This new position improves the effectiveness of the particles in searching the global best rather than local best.

V. RESULTS AND ANALYSIS

To show the effectiveness of the proposed methodology, two test systems namely IEEE-30 bus [23-25] and IEEE-57 bus [26]test systems are considered. At first, for each of the systems, to show the effect of considered practical constraints such as POZ, ramp-rate limits and spinning reserve constraints on OPF problem, the CFC, TPL and MOF objectivesare solved for the following two cases:

Case-1: Without practical constraints
Case-2: With all practical constraints

Results obtained using the proposed methodology is validated with the existing literature.

A. Test system-1

For IEEE-30 bus system, a total of eighteen control parameters to be optimized, which includes, active power generations, and voltage magnitudes at six generators, four tap changing transformers and two shunt compensators.

The formulated OPF problem in section-2 is solved with the objectives formulated in section-3 while satisfying system equality and in-equality constraints. The OPF results for the considered two cases are tabulated in Table.1. From this table, it is identified that, minimization of one objective increases the value of other objectives. For example, minimization of CFC increases the value of TPL and MOF and vice-versa. It is also identified that, the proposed IKGMO yields better results in less time when compared to existing method. It is also identified that, the execution time is increased to solve the OPF problem with all constraints when compared to without constraints. From this table, it is cleared that, the generators which has least cost characteristics increases its generation when minimizing CFC, whereas, when minimizing TPL, the generators nearer to load are increasing generation and which works independent of the cost characteristics. To support the implementations and effectiveness of the proposed IKGMO, the variation of dynamic acceleration coefficients, inertia weight and convergence characteristics for CFC minimization are shown in Figs. 5 to 7.

From Fig.5, in the proposed IKGMO, the initial value of the acceleration coefficients is less than 2 and after few iterations this value is equal to 2. Due to this, the particles velocity and directions are adjusted towards global best in the starting stage of the iterative process. Similarly, in iterative process, some population requires high inertia weight and some other require less inertia weight to reach the global best solution. From Fig.6, the dynamic inertial weight favors the local best solutions to reach the global best solution. In the same way, the convergence characteristics for the CFC minimization are shown in Fig.7. From this figure, it is observed that, the proposed IKGMO algorithm starts the iterative process with good initial value and reaches final best value in less number of iterations when compared to existing KGMO method.

Table.1 Consolidated OPF results for IEEE-30 bus system

Control variables	CFC ($/h)			TPL (MW)			MOF ($/h)		
	Case-1		Case-2	Case-1		Case-2	Case-1		Case-2
	KGMO	IKGMO		KGMO	IKGMO		KGMO	IKGMO	
PG1, MW	177.78	176.9982	162.1736	51.64135	51.38489	116.3811	165.613	166.0397	149.2671
PG2, MW	48.51606	48.81979	63	80	80	60	49.45416	49.04015	62.98663
PG5, MW	21.07861	21.28896	21.1105	49.95667	49.98561	42.65678	22.09823	22.77916	21.54085
PG8, MW	21.44266	20.66817	18.52956	34.92914	34.97926	24.03812	26.95626	27.5922	30
PG11, MW	11.32253	12.29891	13.01787	30	30	22.51782	14.29061	13.57965	13
PG13, MW	12.10204	12.04176	14	39.85263	39.98723	24	13.07449	12.38556	14.00759
VG1, p.u.	1.1	1.1	1.1	1.099524	1.099867	1.025632	1.099897	1.1	1.1
VG2, p.u.	1.088227	1.08716	1.016108	1.09722	1.098231	1.025922	1.063148	1.031191	1.091678
VG5, p.u.	1.064861	1.05949	1.0656	1.082393	1.080639	1.005611	1.060425	1.064062	1.065672
VG8, p.u.	1.073782	1.070269	1.084604	1.088076	1.088633	0.996913	1.069154	1.071483	1.075341
VG11, p.u.	0.950784	1.055592	1.075338	1.1	1.087332	1.034548	1.011475	1.099856	1.074894
VG13, p.u.	1.087731	1.1	1.099976	1.1	1.1	0.986655	1.099971	1.099804	1.069116
Tap 6-9, p.u.	1.012617	1.01904	0.999343	0.970215	0.986562	1.021151	1.029343	1.025716	1.030254
Tap 6-10, p.u.	0.990613	0.969349	0.961985	1.014711	1.06459	0.971899	0.947536	0.993701	0.969927
Tap 4-12, p.u.	1.026455	1.007708	0.993057	1.013577	0.981599	0.914471	1.03769	1.012984	1.033954
Tap 28-27, p.u.	1.01408	0.974031	0.973433	0.983832	0.979049	1.022053	0.98262	0.976586	0.989432
Qc 10, p.u.	21.90756	28.94979	18.6408	5.052801	30	14.43742	23.13282	23.95778	5.158646
Qc 24, p.u.	15.77924	13.36823	12.13039	13.94663	12.87413	17.94073	13.20319	12.28952	15.62943
Total generation, MW	292.2419	292.11579	291.8315	286.3798	286.337	289.5939	291.4868	291.4164	290.8022
MOF, $/h	824.63703	823.98475	828.8669	976.8419	977.163	876.2503	824.0476	823.6014	828.5315
Cost, $/h	799.6874	799.3996	804.9194	966.6778	967.1402	857.509	801.1859	800.9454	807.4418
TPL, MW	8.841863	8.715832	8.431545	2.979783	2.936995	6.193859	8.086755	8.016447	7.40218
Time (sec)	35.1928	29.4857	45.2938	38.19238	25.2938	41.2938	52.3918	43.12839	60.10923

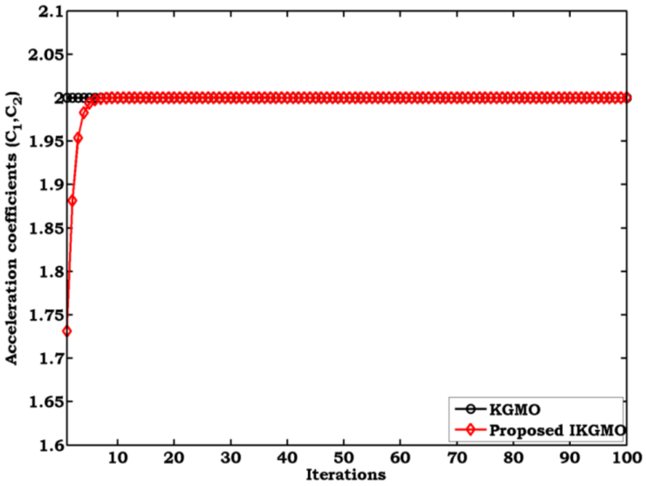

Fig.5: Variation of acceleration coefficients in the proposed IKGMO algorithm

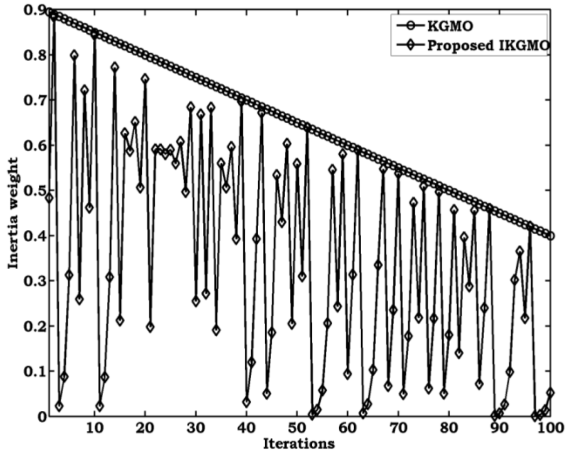

Fig.6 Variation of dynamic inertia weight in the proposed IKGMO algorithm

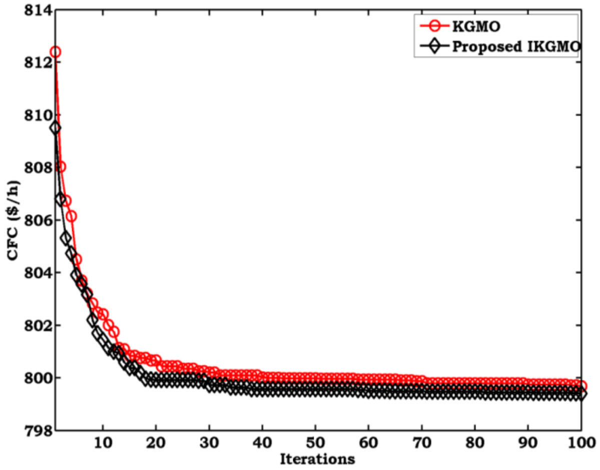

Fig.7: Convergence characteristics of CFC minimization for IEEE-30 bus system

To validate the proposed IKGMO algorithm, the OPF results obtained for CFC and TPL objectives are compared with the existing literature and are tabulated in Table.2. From this table, it is clear that, the results obtained using the proposed method are best when compared to the existing methods.

Table.2 Validation of OPF results for IEEE-30 bus system

		CFC ($/h)	**TPL (MW)**
Existing methods	PSO [27]	802.190	3.6294
	GSO [28]	802.092	-
	GSOICLW [28]	802.025	-
	UDTPSO [29]	799.5376	-
	HCSA [30]	802.0347	3.2080
	KGMO	799.6874	2.97978
Proposed IKGMO		799.3996	2.93699

VI. CONCLUSION

The OPF problem with CFC and TPL as objectives has been solved while satisfying system equality, in-equality and practical constraints. From this, it is identified that, there is an effect of practical constraints on OPF problem. A new multi objective function has been formulated to minimize CFC and TPL objective simultaneously. The OPF problem has been solved using the proposed IKGMO algorithm while satisfying system and practical constraints. From this, analysis, it has been identified that, the proposed algorithm yields better results when compared to the existing methods. The proposed methodology has been tested on standard IEEE-30 bus test systems with supporting numerical and graphical results and with supporting validations.

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Appendix

Table.A1 Generator fuel cost characteristics for IEEE-30 bus system

S. No	Gen No	Convex cost			PGmin (MW)	PGmax (MW)	Ramp-rate limits			POZ (MW)
		a ($/MW^{2}h)	b ($/MWh)	c ($/h)			UR (MW)	DR (MW)	Pi0 (MW)	
1	1	0.00375	2	0	50	250	60	80	150	110-120
2	2	0.0175	1.75	0	20	80	28	10	35	50-60
3	5	0.0625	1	0	15	50	10	20	39	30-36
4	8	0.00834	3.25	0	10	35	10	5	20	25-30
5	11	0.025	3	0	10	30	10	5	18	25-28
6	13	0.025	3	0	12	40	15	6	20	24-30