Application of Jaya Algorithm for reactive power reserve optimization accounting constraints on voltage stability margin

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Abstract: *Adequate reactive power reserve and voltage stability margin are important issues for secure operation of power system. Adequate reserve and margin is achieved by suitable settings of reactive power control variables. In view of this a novel technique to achieve the above mentioned objectives has been described in this paper. A quadratic performance index which minimizes deviation of reactive power generation from average generation output of the generators. This assures adequate reactive power reserve at various PV-buses on the lower as well as upper bound sides. The fitness function has been minimized using Jaya algorithm subject to desired voltage stability margin and accounting all equality and inequality operating constraints. The developed algorithm has been implemented on two standard test systems. The result obtained has been compared with those obtained using Teaching Learning Based Optimization technique (TLBO), Differential Evolution (DE) and Coordinated Aggregation Particle Swarm Optimization (CAPSO).*

Keywords*- voltage stability margin, reactive power reserve, reactive power control variables, jaya algorithm.*

1. Introduction

Maintaining a desired voltage profile along with adequate voltage stability margin is an important and challenging problem for modern interconnected power network. In current operating state a desired voltage profile is obtained by base point settings of reactive power control variables e.g. PV- base voltages, shunt compensation and OLTC operations. To have desired voltage stability margin one should have

i. adequate reactive power reserve
ii. network capability to transfer the reactive power and
iii. Voltage profile in current loading conditions [1].

For long time proximity indicators have been used for voltage security enhancement. Tiranuchit and Thomas [2] applied minimum singular value of jacobian to maintain desired voltage stability margin (VSM) and voltage profile. Sensitivity analysis has been used by Begovic and Phadke [3] for improving voltage security Chebbo et al [4] developed algorithm for optimum reactive power dispatch employing LP and an optimal impedance solution on voltage stability index. Ajjarapu et al [5] presented an optimal planning strategy for reactive power against voltage instability employing repeated load flow runs up to voltage collapse point. Bansilal et al [6] used least square optimization technique for maintaining desired VSM employing L- index [7]. Arya et al [8] described a method for static voltage stability improvements using a linearized model involving related sensitivities. Arya et al [9] presented a corrective rescheduling methodology for voltage stability margin enhancement using incremental linearized model and adapting a quadratic performance index so as to get closed form relations for obtaining settings of reactive power control variables: Pande et al [10] used functional link network for reactive power management and voltage stability enhancement. Titare et al [11] developed an approach to mitigate probability of voltage collapse accounting parameter uncertainties using improved PSO algorithm.

Taghavi et al [12] used Fuzzy technique to develop a reactive power optimization algorithm for hybrid system. Khazali and Kalantar [13] applied harmony search algorithm for obtaining optimal performance of the system based on reactive power considerations. Genetic algorithm has been employed for voltage stability margin enhancement and reactive power dispatch by Devaraj et al [14]. A preventive strategy for reactive power management along with VSM improvement has been developed by Mousavi et al [15]. Singh et al [16] developed a multi objective VAR management algorithm using modified differential evolution algorithm. Titare et al [17] used voltage dependent reactive power reserves modeling for voltage stability enhancement employing ensemble of mutation and crossover strategies and parameters in differential evolution (EPSDE). Fang et al [18] developed a robust optimal reactive power reserves dispatch under stochastic environment of load injected at buses employing chance constraints relaxation – based method. Bhattacharya and Raj [19] used modal analysis and L-index for optimization of reactive power reserves based on differential evolution technique. Sun et al [20] presented a bi- objective reactive power reserves optimization algorithm to coordinate long and short term voltage stability considerations. Fang et al [21] developed an interval optimal reactive power reserve dispatch considering uncertainties in the load and load direction. Rojas et al [22] presented an excellent review of various metaheuristic techniques used for optimal reactive reserves dispatch.

In view of the above the objective of the paper is to develop a reactive power reserve optimization algorithm where by the specific objectives is to limit reactive power generation on both side i.e. over excitation as well as under excitation, such that sufficient reactive power reserve is available on either side. It has been proposed to directly evaluate the VSM and it should have at least some threshold. A novel and efficient Jaya algorithm has been used to solve the formulated problem. Results obtained so have been compared with obtained using CAPSO/TLBO/Differential evolution technique

2. Modeling and problem formulation:

For a PV- bus the upper and lower limits of reactive power generation is usually decided by over excitation and under excitation limits. If long lines are present in power network then one may required to absorb the generated reactive power by under exciting the generators [10]. Further it is also possible that some of the generators may require over excitation. In any case it is desired that the current reactive power generation limit must be away from both the limits. This can be better judged by margin from the average reactive generation. Then it is desired that the distance (MVAR) from average MVAR must be minimized either side. In view of this following quadratic performance index is selected as fitness function

$$F = \sum_{p=1}^{NG}\left[\frac{QG_p - QG_p^{avg}}{QG_p^{max} - QG_p^{min}}\right]^2 \qquad (1)$$

Where

QG_p - Reactive power output of p^{th} generator buses.

QG_p^{max} , QG_p^{min} - Upper and lower limit on reactive power output of p^{th} bus.

QG_p^{avg} - Average reactive power output.

QG_p^{avg} is given as follows:

$$QG_p^{avg} = 0.5\left[QG_p^{max} + QG_p^{min}\right] \qquad (2)$$

The term $\left[QG_p^{max} - QG_p^{min}\right]$ in (1) normalizes the expression and provides adequate weightage to respective generator buses.

The objective function is given by (1) is minimized subjects to following constraints

(a) $VSM \geq VSM^{th}$ (3)

This implies that a voltage stability margin (VSM) must be at least required threshold value i.e. VSM^{th}.

Let us assume the current loading is 2 $pu$and 30% VSM in required then this requires maximum loadability point must be at least2.6 puthat is $VSM^{th} = 0.6\ pu$.

This will require repeated load flow solution to ascertain the required VSM for a specific solution of control variables.

(b) Another requirement is that all load bus voltages must be within limit

$$V_i^{min} \leq V_i \leq V_i^{max} \qquad (4)$$

iϵ LVB

LVB - is set of load buses.

V_i^{max} , V_i^{min} - is upper and lower limits on load bus voltages.

(c) Set of decision or control variable consists of PV- bus voltage magnitudes, OLTC setting and shunts compensation. Inequality constraints on control variables are

$$U_K^{min} \leq U_K \leq U_K^{max} \qquad (5)$$

$$K = 1,2, \ldots., \ldots, \ldots., NC$$

U_K - K^{th} Control variable.

U_K^{min} , U_K^{max} - Lower and upper limits on control variable.

NC -Number of total control variables.

The set of control variable is written as

$$\underline{U} = [\underline{VG}, \underline{t}, \underline{QSH}]^T$$

$\underline{VG}$- PV- bus voltage vector.

$\underline{t}$- Vector of OLTC setting.

$\underline{QSH}$- vector of shunts compensation.

(d) The strategy developed here is a sort of preventive control strategy whereby it is ascertained that all constraints mentioned in (b) are satisfied at current operating point as well as at desired VSM operating point. This implies that decision variables must provides all load bus voltages within limits at P_d° and also (1+VSM_{Th}^{d}) P_d°

P_d°- Current total load.

Solution Methodology:

The reactive power optimization problem as formulated in Sec. 2 is solved for optimum setting of control variables using Jaya algorithm and TLBO algorithm and implementation explained in following two sub- sections.

2.1 Computational algorithm using Jaya optimization technique.

Jaya algorithm has been developed by Rao [23] which is extremely simple to implement for the solution of reactive power optimization problem as given by following steps.

Step-1: generate initial population of decision variables (set of reactive power control variables), using random sampling between bounds as follows

$$\underline{U}_i^{\circ}=\left[\underline{V}G_i^{(\circ)},\underline{t}_i^{(\circ)},\underline{QSH}_i^{(\circ)}\right]^T \qquad (6)$$

i= 1, _ _ _ _ M

Each component is obtained as

$$\underline{U}_i^{\Delta}=\underline{U}^{\min}+\quad \mathrm{rand}_i\left[\underline{U}^{\max}-\underline{U}^{\min}\right] \qquad (7)$$

rand_i- is a vector of random digits between [0,1].

Step-2: using load flow analysis ascertain that these M- set of control variables are feasible i.e. they satisfy constraints (a),(b),(c) and(d) as given in Sec.2

Step-3: set generation count$k = 1$

Step-4: modify all the sets of control vectors using following relations

$$\underline{U}_i^{(k)}=\underline{U}_i^{(k-1)}+\underline{\mathrm{rand}}_{1,i}\left[U_{best}^{(k-1)}-\left|U_i^k\right|\right]$$
$$-\underline{\mathrm{rand}}_{2,i}\left[U_{worst}^{(k-1)}-\left|U_i^k\right|\right] \qquad (8)$$

If any component$U_{i-j}^{(k)}$crosses the limits, it is set to its limiting values

Step-5: perform load flow analysis with modified set of control variables and if $U_i^{(k)}$is better than$U_i^{(k-1)}$in terms of fitness function and all constraints are (a)-(d) are satisfied, then $U_i^{(k)}$is a member of new population, otherwise$U_i^{(k-1)}$is retained in the new population.

Step-6: repeat step-5 for all i= 1, _ _ _ M. Then new modified sets of control variables are obtained.

Step-7: increase generation count$k = k + 1$.

Step-8: If $k \geq k_{max}$ stop.

Where, k_{max} - Maximumnumber of iterations specified, say 500.

Step-9: perform repeated load flow analysis for the new modified set of population of control variables and obtain$U_{best}^{(k)}$ and $U_{worst}^{(k)}$ $U_{best}^{(k)}$ and $U_{worst}^{(k)}$ are best and worst sets on which gives the best and worst value of fitness function. Repeat from step-4.

The process modification is terminated either a fixed number of generations have been executed or there is no significant change in the fitness function for that specified iteration.

2.2 Computational algorithm using TLBO optimization technique [24]

Step-1: initialize the optimization parameters for reactive power rescheduling.

Population size (M_n)

Number of design variables (D_n)

Step-2: **initialize the population:** generate random population according to the population size and the number of design variables. For TLBO, population size indicates the number of learners and the design variables indicate the reactive power control variables. Generated population is normally distributed in the range $\underline{U}_{ij}<U_{ij}<\overline{U}_{ij}$, $j=1,2,\ldots,NC$.

$$population = \begin{bmatrix} U_{1,1}, U_{1,2}, \ldots\ldots\ldots\ldots, U_{1,D} \\ U_{2,1}, U_{2,2}, \ldots\ldots\ldots\ldots, U_{2,D} \\ \vdots \ldots\ldots \vdots \ldots\ldots\ldots\ldots\ldots \vdots \\ U_{Mn,1}, U_{Mn,2}, \ldots\ldots\ldots, U_{g\,Mn,D} \end{bmatrix} \quad (9)$$

Step-3: calculate fitness function using eq. (1) for the feasible vectors and rank the population according to their respective minimum value of fitness function.

Step-4: set generation count $k = 1$.

Step-5: **teacher phase;** Calculate the mean of the population column wise, which will give the mean of the particular reactive power control variables as:

$$M_{,D} = [m_1, m_2, \ldots\ldots\ldots, m_D] \quad (10)$$

Step-6: based on the value of objective function, identify the best solution vector, which will act as a new mean ($M_{new,D}$).

$$U_{teacher} = U_{f(U)=\min}$$
$$M_{new,D} = U_{teacher,D} \quad (11)$$

Step-7: **e**valuate difference between the existing and the new mean:

$$Difference\_Mean,_D = r(M_{new,D} - T_F M_{,D}) \quad (12)$$

where, r - is the random number [0, 1].

T_F – Teaching learning factor [1, 2]

Step-8: update the Teacher’s knowledge with the help of teacher’s knowledge.

$$U_{new,D} = U_{old,D} + Difference\_Mean,_D \quad (13)$$

Step-9: **learner phase;** Learners increase their knowledge/value by two means; one through input from teacher and other through interaction between themselves. Select two different learners U_i and U_j such that $i \neq j$, are to be within specified limit of reactive power control variables.

Step-10: update the learners’ knowledge by utilizing the knowledge of other learner according to eq. (30).

$$U_{new,i} = \begin{cases} U_{old,i} + r_i.(U_i - U_j), if [f(U_i) < f(U_j)] \\ U_{old,i} + r_i.(U_j - U_i), if [f(U_j) < f(U_i)] \end{cases} \quad (14)$$

Step-11: run continuation power flow program incorporating updated $U_{new,i}$. If updated $U_{new,i}$ maximize objective function go to next step. Otherwise go to step-8.

Step-12: increase generation count $k = k + 1$. If $k \le k_{\max}$ repeat from step-4. Otherwise stop.

3. Results & Discussions:

In this paper, Jaya an algorithm has been applied to obtain optimum reactive power reserve using reactive power control variables such as PV- bus voltages, OLTC and shunt compensations on IEEE 14-bus and 30-bus standard test systems. The proposed algorithm is implemented using the MATLAB R2008a software and run on a PC with Intel (R) Core(TM) i3-3120M CPU @ 2.50 GHz 2.00 GB RAM. Developed algorithms have been implemented for maximization of reactive power reserve at generator buses.

IEEE 14-Bus System

The 14-bus [17] system consists of 3 generators, 11 load buses &20 transmission lines. This system has 7 reactive power control variables; which are 3 generators (bus no. 1st, 2nd& 3th), and 2 OLTC line number 4th& 10th and 2 shunt compensations are connected at buses 4th and 12th, The limits of generators bus voltages, OLTCs and shunt compensations limits have been assumed as 0.95pu to 1.15pu, and 0.90 to 1.10, and 0.00 to 0.055 [17] respectively. Reactive power limits (minimum and maximum) of generating bus no. 1st lying between −0.5000puto 3.000pu, bus no. 2nd& 3rdlying between −0.5000pu to 1.1000pu[17] respectively. The desired range of load bus voltage is 0.95pu to 1.05pu. The total base case active and reactive power demand on the system are 3.4517pu&1.2632pu, and fitness function (F) =

0.3381. Table-1 shows reactive power control variables (PV-bus voltages, shunt compensations and OLTCs) and all load bus voltages under base case condition. Threshold value of voltage stability margin selected as$\mathrm{VSM}^{\mathrm{th}} = 1.1027$ pu.Initially, 100 populations of each control variable have been generated randomly using excel software according distribution characteristic of control variable. Maximum numbers of iteration is taken as 700 and terminated after 392 iterations. Table-2 shows the comparison of each algorithm to find the best optimal control variable settings with and without optimization using Jaya, TLBO, DE and CAPSO [25, 26] techniques.Table-3 shows the comparison of reactive reserves at different generator bus (bus nos. 1st, 2nd & 3rd)using Jaya, TLBO, DE and CAPSO techniques.Table-4shows the comparison of Jaya with TLBO, DE and CAPSO techniques based on arithmetic mean value, standard deviation, best value, worst value, frequency of convergence, standard error, length of confidence interval and confidence interval of fitness function [27]. Fig. 1 shows a plot for comparison of the convergence of fitness function with respect to number of iteration for Jaya, TLBO, DE and CAPSO techniques. Static voltage stability limit of the system is obtained using Jaya, TLBO, DE and CAPSO techniques are 5.3533pu, 5.2677pu,5.2164pu and 5.1308pu respectively. Voltage stability margin obtained at the end of optimization processes namely; Jaya, TLBO, DE and CAPSO techniques are 45.64%, 43.31%, 41.91% and 39.58% respectively. It is observed that Jaya gives much better global optimal results than TLBO, DE and CAPSO techniques.

Table-1. ***Load flow solution for 14-bus test system under stressed condition.***

Total load$(S_d) = 3.6758$ pu, Static voltage stability limit $= 4.6858$ pu

S. No	Control variables	Control variables Magnitude (pu)	Load bus voltages	Load bus voltage Magnitude (pu)
1	V_1	1.0812	V_4	0.8248
2	V_2	1.0485	V_5	0.8618
3	V_3	1.0739	V_6	0.9522
4	B_{SH4}	0.0015	V_7	0.8618
5	B_{SH12}	0.0057	V_8	0.9696
6	TAP_4	1.0657	V_9	0.8291
7	TAP_{10}	1.0673	V_{10}	0.8126
			V_{11}	0.8114
			V_{12}	0.7970
			V_{13}	0.7917
			V_{14}	0.7897

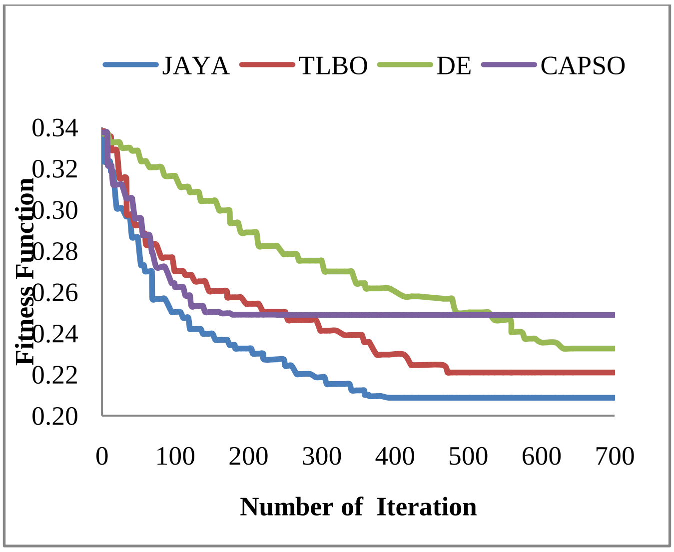

Fig. 1. ***Plot of convergence of fitness function with respect to number of iteration using Jaya, TLBO, DE and CAPSO techniques for IEEE 14-bus system.***

IEEE 30-Bus System

The 30-bus [28] system consists of 6 generators, 24 load buses & 41 transmission lines. This system has 12 reactive power control variables; which are 6 generators (bus no. 1st, 2nd, 5th, 8th, 11th& 13th), and 4 OLTC (line number 11th, 12th, 15th& 36th) and 2 shunt compensations are connected at buses 10th and 24th, The limits of generators bus voltages and OLTCs have been assumed as 0.95pu to 1.15pu, and 0.90 to 1.10 respectively. Shunt compensations limit (lower and upper) of bus no. 10th, 0.00pu to 0.19pu and bus no. 24th, 0.00pu to 0.04pu [28] respectively. Reactive power limits (minimum and maximum) of generating bus no. 1st lying between -0.2000pu to 1.5000pu, bus no. 2nd lying between -0.2000pu to 0.6000pu, bus no. 5th lying between -0.1500pu to 0.6250pu, bus no. 8th lying between -0.1500pu to 0.5000pu, bus no. 11th lying between -0.1500pu to 0.4000pu, bus no. 13th lying between -0.1500pu to 0.4500pu [28]. The desired range of load bus voltage is 0.95pu to 1.05pu. The total base case active and reactive power demand on the system are 4.2626pu & 1.9222 pu, and fitness function $(F) = 2.2925$. Table-5 shows reactive power control variables (PV-bus voltages, shunt compensations and OLTCs) and all load bus voltages under base case condition. Threshold value of voltage stability margin selected as $\mathrm{VSM}^{\mathrm{th}} = 1.4028$ pu.Initially, 50 populations of each control variable have been generated randomly using excel software according distribution characteristic of control variable. Maximum numbers of generation is taken as 700 and terminated after 548 generations that are no improvement in fitness function. Table-6 shows the comparison of each algorithm to find the best optimal control variable settings with and without optimization using Jaya, TLBO, DE and CAPSO techniques. . Table-7shows the comparison of reactive reserves at different generator bus (bus nos. 1st, 2nd, 5th, 8th, 11th& 13th)using Jaya, TLBO, DE and CAPSO techniques.Table-8shows the comparison of Jaya with TLBO, DE and CAPSO techniques based on arithmetic mean value, standard deviation, best value, worst value, frequency of convergence, standard error, length of confidence interval and confidence interval of objective function [27].Fig. 2 shows a plot for comparison of the convergence of fitness function with respect to number of iteration for Jaya, TLBO, DE and CAPSO techniques. Static voltage stability limit of the system is obtained using Jaya, TLBO, DE and CAPSO techniques are 7.4195pu, 7.1893pu,7.0185pu and 6.8948pu respectively. Voltage stability margin obtained at the end of optimization processes namely; Jaya, TLBO, DE and CAPSO techniques are 58.67%, 53.75%, 50.09% and 47.45% respectively. It is observed that Jaya gives much better global optimal results than TLBO, DE and CAPSO techniques.

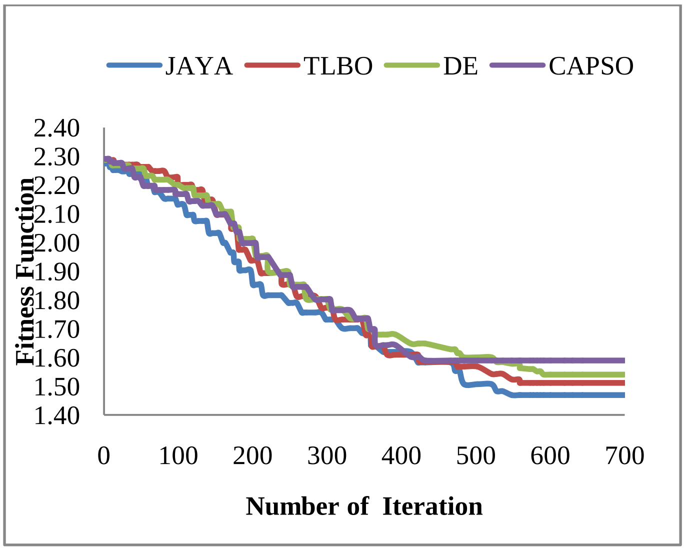

Fig. 2. Plot of convergence of fitness function with respect to number of iteration using Jaya, TLBO, DE and CAPSO techniques for IEEE 30-bus system.

4. Conclusion

A methodology has been presented for the management of reactive power reserves in order to maintain voltage profile as well as voltage stability margin by using Jaya algorithm. These objectives are achieved by the rescheduling of the reactive control variables such as; PV-bus magnitude, OLTC and static VAR compensations. Jaya optimization algorithm is based on the concept that the result obtained for a given problem should avoid the worst result and travel towards the best result. This algorithm requires only the common control parameters and does not require any algorithm-specific control parameters. This optimization algorithm is an efficient optimization method for large scale non-linear optimization problems for finding the global optimal solutions. Performance of the developed algorithm has been compared based on mean value, median value, mean deviation, variance, standard deviation, best value, worst value, frequency of convergence, standard error, length of confidence interval, confidence interval, class interval & proportionate frequencies of fitness function, with TLBO, DE and CAPSO techniques. It is observed that Jaya algorithm performs much better result than TLBO, DE and CAPSO techniques for IEEE 14-bus and 30-bus system.

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Table-2. Reactive power control variables using Jaya, TLBO, DE and CAPSO algorithms for IEEE 14-bus system $(S_{dt}) = \mathbf{3.6758}pu$.

Sr. No.	**Reactive Control Variables**	**Base Case**	**JAYA**	**TLBO**	**DE**	**CAPSO**
1	**Tap$_4$**	1.0657	0.9317	0.9320	0.9326	0.9284
2	**Tap$_{10}$**	1.0673	0.9266	0.9254	0.9258	0.9217
3	**Qc$_4$**	0.0015	0.0508	0.0370	0.0447	0.0409
4	**Qc$_{12}$**	0.0057	0.0473	0.0483	0.0357	0.0318
5	**V$_1$**	1.0812	1.0788	1.0798	1.0797	1.0776
6	**V$_2$**	1.0485	1.0428	1.0445	1.0457	1.0447
7	**V$_3$**	1.0739	1.0693	1.0704	1.0716	1.0693

Table-3. Reactive power reserve at generator buses and fitness function using Jaya, TLBO, DE and CAPSO techniques for IEEE14-bus system $(S_{dt}) = \mathbf{3.6758}pu$.

Sr. No.	Methodology	Reactive Power Reserve (pu)			Total Reactive Power Reserve (pu)	Fitness Function
		Qgk(res)1	Qgk(res)2	Qgk(res)3		
1	**JAYA**	**2.6991**	**0.8181**	**0.014**	**3.5312**	**0.2088**
2	TLBO	2.7114	0.7916	0.0152	3.5183	0.221
3	DE	2.737	0.7646	0.012	3.5136	0.2326
4	CAPSO	2.7628	0.707	0.0319	3.5016	0.2489
5	Base Case	2.5295	0.6628	0.0398	3.2321	0.3381

Table -4. ***Comparison of Jaya with TLBO, DE and CAPSO techniques based on statistical interence for IEEE14-bus system.***

Optimization methods	**Arithmetic mean value of the objective function**	**Median value of the objective function**	**Mean deviation of objective function**	**Variance of objective function**	**Standard deviation of objective function**	**Best value of objective function**	**Worst value of objective function**	**Frequency of convergence**	**Confidence level**	**Determined value for the Engg. Application**	**Standard error of the mean objective function**	**Confidence interval of the objective function**	**Length of confidence interval of the objective function**
	$(\overline{F})$	(m)	(d)	(s)	(σ)	(F_{best})	(F_{worst})		(γ)	(c)	(ε)	(μ)	(L)
JAYA	**0.2132**	**0.2115**	**2.00E-05**	**2.47E-05**	**0.0049**	**0.2088**	**0.2273**	**13**	**0.95**	**2.0452**	**0.0023**	**0.2109≤ μ ≤ 0.2155**	**0.0094**
TLBO	0.2275	0.2255	4.00E-05	5.05E-05	0.0071	0.2210	0.2480	11	0.95	2.0452	0.0032	0.2243≤ μ ≤0.2307	0.0131
DE	0.2430	0.2421	1.50E-05	8.03E-05	0.0089	0.2326	0.2662	10	0.95	2.0452	0.0041	0.2389≤ μ ≤0.2471	0.0167
CAPSO	0.2669	0.2653	1.50E-05	1.77E-04	0.0133	0.2489	0.2951	10	0.95	2.0452	0.0061	0.2608≤ μ ≤0.2730	0.0249

Table-5 ***Load flow solution for 30-bus test system under stressed condition.***

Total load $(S_d) = 4.6759\ pu$***, Static voltage stability limit*** $= 6.2231\ pu$

S. No	**Control variables**	**Control variables magnitude(pu)**	**Load bus voltages**	**Load bus voltage magnitude(pu)**
1	V_1	1.0842	V_3	1.0231
2	V_2	1.0476	V_4	1.0105
3	V_5	1.0112	V_6	1.0052
4	V_8	1.0262	V_7	0.9902
5	V_{11}	1.0845	V_9	0.9400
6	V_{13}	1.0928	V_{10}	0.8948
7	B_{SH10}	0.0106	V_{12}	0.9516
8	B_{SH24}	0.0040	V_{14}	0.9135
9	TAP_{11}	1.0686	V_{15}	0.8996
10	TAP_{12}	1.0693	V_{16}	0.9110
11	TAP_{15}	1.0563	V_{17}	0.8873
12	TAP_{36}	0.9215	V_{18}	0.8686
			V_{19}	0.8578
			V_{20}	0.8651
			V_{21}	0.8674
			V_{22}	0.8693
			V_{23}	0.8703
			V_{24}	0.8511
			V_{25}	0.8593
			V_{26}	0.8379
			V_{27}	0.8749
			V_{28}	0.9981
			V_{29}	0.8311
			V_{30}	0.8084

Table-6. Reactive power control variables using Jaya, TLBO, DE and CAPSO algorithms for IEEE 30-bus system $(S_{dt}) = 4.6759pu$.

Sr. No.	Control Variables	Base Case	JAYA	TLBO	DE	CAPSO
1	Tap_{11}	1.0686	0.9247	0.9232	0.9232	0.9253
2	Tap_{12}	1.0693	1.0263	1.0238	1.0238	1.0275
3	Tap_{15}	1.0563	0.9314	0.9327	0.9349	0.9266
4	Tap_{36}	0.9215	1.0759	1.0839	1.0692	1.0791
5	Qc_{10}	0.0106	0.1750	0.1756	0.1543	0.1556
6	Qc_{24}	0.0040	0.0380	0.0372	0.0356	0.0375
7	V1	1.0842	1.0820	1.0768	1.0833	1.0710
8	V2	1.0476	1.0317	1.0266	1.0352	1.0194
9	V5	1.0112	1.0097	1.0011	1.0111	0.9980
10	V8	1.0262	1.0141	1.0140	1.0261	1.0234
11	V11	1.0845	1.0838	1.0833	1.0846	1.0768
12	V13	1.0928	1.0912	1.0807	1.0921	1.0875

Table-7. Reactive power reserve at generator buses and fitness function using Jaya, TLBO, DE and CAPSO techniques for IEEE 30-bus system $(S_{dt}) = 4.6759pu$..

Sr. No.	**Methodology**	**Reactive Power Reserve (pu)**						**Total Reactive Power Reserve (pu)**	**Fitness Function**
		Qgk(res)1	Qgk(res)2	Qgk(res)5	Qgk(res)8	Qgk(res)11	Qgk(res)13		
1	**JAYA**	**0.9759**	**0.2228**	**0.0337**	**0.3076**	**0.0547**	**0.0313**	**1.6260**	**1.4692**
2	TLBO	0.9908	0.2099	0.0804	0.2292	0.0441	0.0589	1.6133	1.5119
3	DE	1.0301	0.2027	0.0791	0.1897	0.0684	0.038	1.608	1.5409
4	CAPSO	0.9931	0.3677	0.0855	0.0303	0.0716	0.0397	1.5879	1.5897
5	Base Case	1.2278	0.2272	0.0729	0.0965	-0.0749	-0.2348	1.3147	2.2925

Table -8. Comparison of Jaya with TLBO, DE and CAPSO techniques based on statistical interence for IEEE 30-bus system.

Optimization methods	**Arithmetic mean value of the objective function**	**Median value of the objective function**	**Mean deviation of objective function**	**Variance of objective function**	**Standard deviation of objective function**	**Best value of objective function**	**Worst value of objective function**	**Frequency of convergence**	**Confidence level**	**Determined value for the Eng. Application**	**Standard error of the mean objective function**	**Confidence interval of the objective function**	**Length of confidence interval of the objective function**
	$(\bar{F})$	(m)	(d)	(s)	(σ)	(F_{best})	(F_{worst})		(γ)	(c)	(ε)	(μ)	(L)
JAYA	**1.4814**	**1.4787**	**2.00E-05**	**1.40E-04**	**0.0118**	**1.4692**	**1.5142**	**12**	**0.95**	**2.0452**	**0.0054**	**1.4760≤ μ ≤1.4868**	**0.0221**
TLBO	1.5348	1.5298	4.50E-05	4.02E-04	0.0200	1.5119	1.5849	11	0.95	2.0452	0.0091	1.5257≤ μ ≤1.5439	0.0372
DE	1.5781	1.5751	5.00E-05	7.64E-04	0.0276	1.5409	1.6479	10	0.95	2.0452	0.0126	1.5655≤ μ ≤1.5907	0.0515
CAPSO	1.6461	1.6476	-5.00E-05	1.38E-03	0.0371	1.5897	1.7177	9	0.95	2.0452	0.0169	1.6292≤ μ ≤1.6630	0.0691