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Multi-Objective Optimization incorporating TCSC with ramp-rate limits and prohibited operating zones using NSHCSA

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This paper mainly concentrates in finding enhanced optimal solution for Multi-Objective Problem (MOP) with Thyristor Controller Series Compensator (TCSC) formulated using generation fuel cost, emission, and loss objectives with practical and operating constraints. Here, the optimal location is selected to enhance the system security in terms of minimizing line overloads and bus voltage violations under severe contingency. Cuckoo Search Algorithm (CSA) along with genetic algorithm cross over operation treated as Hybrid Cuckoo Search Algorithm (HCSA) is proposed to select best value as compared with existing evaluation algorithms. Optimizing multiple objectives simultaneously and selecting a best compromised solution as per the requirements of decision maker needs an application of MOP along with fuzzy decision making tool. The proposed Non-dominated Sorting Hybrid Cuckoo Search Algorithm (NSHCSA) with TCSC is tested on IEEE test system and corresponding results are analyzed. The OPF results obtained using proposed method is compared with the existing methods.

Keywords: *Optimal location, Non-dominated Hybrid Cuckoo Search Algorithm, Installation cost of device, Multi objective optimization.*

1.0 INTRODUCTION

In present days, most of the research activities are towards maximizing the utilization of transmission lines up to their thermal limits by using Flexible AC Transmission System (FACTS) controllers as they are in built with the efficient power semiconductor devices [1]. In contingency operation, system security is the major concern and needs to be enhanced by placing FACTS controllers in suitable location. Since the installation cost of the device has a great impact on economics of the system, needs to be analyzed along with regular objectives. As the fuel prices are increasing day by day, it is necessary to operate the generating units at optimum levels to minimize the total generation fuel cost of the system while satisfying the system operating and practical constraints [2, 3]. In this [4], proposed Improved Colliding Bodies Optimization (ICBO) algorithm to solve efficiently the Optimal Power Flow (OPF) problem. Several objectives, constraints and formulations at normal and preventive operating conditions are used to model the OPF problem. In [5], proposed Water cycle algorithm (WCA) is one of the metaheuristic optimization algorithms inspired by hydrological cycle in nature.

In this [6], presents the use of a recent developed algorithm inspired by the hunting mechanism of ant lions in nature, called ant lion optimizer (ALO) algorithm for solving optimal reactive power dispatch problem. M A Abido [7] he proposed Tabu search algorithms for the solution of optimal power flow problems for the minimization of overall generation cost, minimization of active power losses. Carlos A. coello coello [8] reviewed most of the important evolutionary base multi objective optimization techniques such as weighted sum approach sum; goal programming

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and e-constraint methods with applications, strengths and weakness are presented. In this [9], presented a novel Moth Swarm Algorithm (MSA), inspired by the orientation of moths towards moonlight to solve constrained Optimal Power Flow (OPF) problem.

In this [10], proposed Differential Search Algorithm (DSA) for optimizing the power system parameters sequentially and simultaneously. X in-She Yang et. Al. [11], proposed basic Cuckoo Search Algorithm (CSA), for solving the optimal power flow problems. Multi objective optimal power flow problem has been formulated in [12]. Hybrid optimization algorithm is proposed to solve multi objective optimal power flow problems in [13].

The main contribution of this paper is to solving OPF problem with various single and multi-objective functions using a new hybrid GA and CSA optimization (HCSA) algorithm. The proposed hybrid GA and CSA algorithm combines both individual algorithm strengths, to get the balance between global and local search capability. Generally, most of the multi-objective based optimization methods use non-dominated sorting and strength Pareto approaches for achieving the optimal trade-off curve. This paper uses non-dominated sorting and crowding distance approach to maintaining a diverse in Pareto optimal points. Finally, a fuzzy membership approach is used to get compromising solution over the trade-off curve. The proposed multi objective NSHCSA algorithm with TCSC is tested on IEEE 30-bus systems. The simulation results show that the proposed method is more robust and efficient than the standard multi-objective literature.

2.0 MATHEMATICAL MODEL AND OPTIMAL LOCATION OF TCSC

To study the impact of TCSC on a given system, in this paper TCSC Power Injection Model (PIM) should be incorporated in NR load flow formulation. In this model, the power flows in a line due to TCSC can be represented as equivalent power injections at TCSC connected buses (Bus-i and Bus-k) shown in Figure.1.

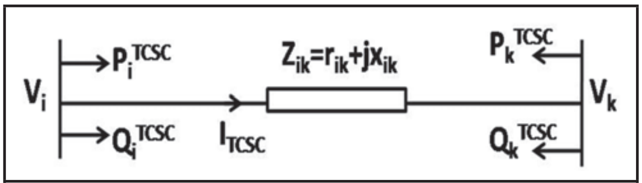

FIG. 1. EQUIVALENT POWER INJECTION MODEL OF TCSC INCLUDED IN A TRANSMISSION LINE

Consider TCSC is connected in line between bus-i and bus-k, the expressions for equivalent real and reactive power injections can be expressed as

$$P_i^{TCSC} = V_i^2 \Delta G_{ik} - V_i V_k \left[\Delta G_{ik}\cos\delta_{ik} + \Delta B_{ik}\sin\delta_{ik}\right] \quad ...(1)$$

$$P_k^{TCSC} = V_k^2 \Delta G_{ik} - V_i V_k \left[\Delta G_{ik}\cos\delta_{ik} - \Delta B_{ik}\sin\delta_{ik}\right] \quad ...(2)$$

$$Q_i^{TCSC} = -V_i^2 \Delta B_{ik} - V_i V_k \left[\Delta G_{ik}\sin\delta_{ik} - \Delta B_{ik}\cos\delta_{ik}\right] \quad ...(3)$$

$$Q_k^{TCSC} = -V_k^2 \Delta B_{ik} + V_i V_k \left[\Delta G_{ik}\sin\delta_{ik} + \Delta B_{ik}\cos\delta_{ik}\right] \quad ...(4)$$

Where

$$\Delta G_{ik} = \frac{X_{TCSC} r_{ik}\left(X_{TCSC} - 2x_{ik}\right)}{\left(r_{ik}^2 + x_{ik}^2\right)\left(r_{ik}^2 + \left(x_{ik} - X_{TCSC}\right)^2\right)},$$

$$\Delta B_{ik} = -\frac{X_{TCSC}\left(r_{ik}^2 - x_{ik}^2 + X_{TCSC}x_{ik}\right)}{\left(r_{ik}^2 + x_{ik}^2\right)\left(r_{ik}^2 + \left(x_{ik} - X_{TCSC}\right)^2\right)} \quad ...(5)$$

X_{TCSC} is the reactance added to the line by placing TCSC.

2.1 Installation cost of FACTS devices

The installation cost of FACTS devices place a vital role in power system operation. In this paper it is considered over a period of 15 years during analysis, and described as follows:

2.2 Installation Cost of TCSC

The Installation Cost (IC) of TCSC [14] is

$$IC_{TCSC} = \frac{C_{TCSC} \times S_{TCSC} \times 1000}{n \times 8760} \quad \$/h \quad ...(6)$$

Where,

$$C_{TCSC} = \left[0.0015\, S_{TCSC}^2 - 0.713\, S_{TCSC} + 153.75\right] \$/KVAr \quad ...(7)$$

S_{TCSC} = Operating range of TCSC

$$= \left|Q_2\right| - \left|Q_1\right| \; MVAr \quad ...(8)$$

Q_1 and Q_2 are the reactive power flows in the line without and with TCSC. n is life time in years

3.0 PROBLEM FORMULATION

The problem can be formulated mathematically as a constrained nonlinear optimization problem as follows

$$Min[A_1(x,u), A_2(x,u), \ldots, A_m(x,u)]; \quad m = 1,2,3,\ldots,m \qquad (9)$$

Subject to
$$g(x,u) = 0$$
$$h(x,u) \leq 0$$

Where $'g'$ and $'h'$ are the equality and inequality constraints respectively, $'x'$ is a dependent variable and $'u'$ is control variable.

In multi objective optimization problem, a reasonable solution demoted by vector p is said to be non-dominated if and only if, for any other vector denoted q.

i) Each and every objective function value represented by vector p is less than or at most equal to that determined by vector q.

ii) At least one of the objective functions determined by vector p is strictly less than the corresponding objective function determined by vector q.

A Pareto-optimal solution cannot be improved with respect to any objective without worsening at least one other objective. For a given domain of possible solutions, there is only one Pareto-optimal vector which satisfies both (i) and (ii).

In this paper, the NSGA-II [15], which incorporates the concept of Pareto optimality into its search algorithms and can find optimal trade-offs among the multiple conflicting objectives simultaneously, has been implemented.

3.1 Objective function

The objective functions namely generation fuel cost including installation cost of TCSC device, emission and the total power loss are considered for the analysis. The mathematical expressions for these objective functions are as follows:

i. Generation fuel cost

The simplified quadratic cost expression for i^{th} unit for real power output of $'P_{G_i}'$ subjected to different constraints can be expressed as

$$F_i(P_{Gi}) = a_i P_{Gi}^2 + b_i P_{Gi} + c_i \ \$/h$$

Where a_i, b_i and c_i are the fuel cost-coefficients of i^{th} unit. The total generation fuel cost (F_T) of all $'N_G'$ number of units can be mathematically expressed as

$$A_1 = \min(F_T) = \sum_{i=1}^{N_G} F_i(P_{G_i}) + IC_{TCSC} \ \$/h \qquad \ldots(10)$$

ii. Emission

The emission generated can be approximated as

$$A_2 = \min\left(E(P_{G_i})\right) = \sum_{i=1}^{N_G} \alpha_i + \beta_i P_{G_i} + \gamma_i P_{G_i}^2 + \xi_i \exp^{(\lambda_i P_{G_i})}$$

ton/h ...(11)

Where α_i, β_i, γ_i, ξ_i and λ_i are emission coefficients of the i^{th} generator.

iii. Total transmission loss

This objective can be expressed as

$$A_3 = \min(TPL) = \sum_{i=1}^{N_{line}} P_{Loss,i} \quad MW \qquad \ldots(12)$$

Where $P_{Loss,i}$ is the real power loss in i^{th} line.

3.2 Constraints

Minimization of the objectives is subjected to the following equality, inequality and device constraints.

i) *Equality constraints are simply power flow equations*

$$\sum_{i=1}^{N_G} P_{G_i} - P_D - P_L = 0 \ ;$$

$$\sum_{i=1}^{N_G} Q_{G_i} - Q_D - Q_L = 0$$

Where, P_D, Q_D and, P_L, Q_L are total active and reactive power demands and its corresponding total power losses.

ii) *In-equality constraints*

These constraints represent the system operating constraints. The self restricted constraints satisfied within OPF are

Generator bus voltage limits:

$$V_{G_i}^{\min} \le V_{G_i} \le V_{G_i}^{\max}; \qquad \forall\, i \in N_G$$

Active Power Generation limits:

$$P_{G_i}^{\min} \le P_{G_i} \le P_{G_i}^{\max}; \qquad \forall\, i \in N_G$$

Transformers tap setting limits:

$$T_i^{\min} \le T_i \le T_i^{\max}; \qquad i = 1,2,...,n_t$$

Capacitor reactive power generation limits:

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

Transmission line flow limit:

$$S_{l_i} \le S_{l_i}^{\max}; \qquad i = 1,2,....,N_{line}$$

Reactive Power Generation limits:

$$Q_{G_i}^{\min} \le Q_{G_i} \le Q_{G_i}^{\max}; \qquad \forall\, i \in N_G$$

Bus voltage magnitude limits:

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

Where n_t total number of taps, n_C total number of VAr sources, N_{load} total number of VAr sources.

iii) *TCSC constraint*

$$-0.8\,X_{line} \le X_{TCSC} \le 0.2 X_{line}\ p.u.$$

3.3 Prohibited Operating Zones (POZ) (practical constraints)

In practice when adjusting the output of a generator unit one must avoid the operation in the prohibited zones to increase the performance of a thermal unit during vibrations in the shaft or other machine faults. This feature can be included in the problem formulation as follows:

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

Where n_i the number of prohibited zones and k index of prohibited zone of unit-i. $P_{i,k}^L$ and $P_{i,k}^U$ are the respective lower and upper limit of k^{th} prohibited zone of i^{th} generator.

3.4 Ramp rate limits (Practical constraint)

The operating range of the generating units is restricted by their ramp rate limits to operate generators continuously between two adjacent periods forcibly. The inequality constraints due to ramp limits are $\max\left(P_{G_i}^{\min}, P_i^0 - DR_i\right) \le P_{G_i} \le \min\left(P_{G_i}^{\max}, P_i^0 + UR_i\right)$

Where P_i^0 is the power generation of i^{th} unit at previous hour. DR_i and UR_i are the respective decreasing and increasing ramp-rate limits of i^{th} unit.

The Eqn (9) can be written in more generalized form by including the constraints with penalty factors as

$$A_{m,aug}(x,u) = A_m(x,u) + R_1\left(P_{g,slack} - P_{g,slack}^{\lim}\right)^2 + R_2\sum_{i=1}^{N_{Load}}\left(V_i - V_i^{\lim}\right)^2 + R_3\sum_{i=1}^{N_G}\left(Q_{G_i} - Q_{G_i}^{\lim}\right)^2 + R_4\sum_{i=1}^{N_{line}}\left(S_{l_i} - S_{l_i}^{\max}\right)^2 \quad .(13)$$

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

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

4.0 OPTIMAL LOCATION

The device installation location will enhance the system security either by minimizing line loadings or bus voltage limit violations under contingency operations. Here the system severity function $\left(F_{severity}\right)$ can be expressed as

$$F_{Severity} = \sum_{i=1}^{N_{line}}\left(\frac{S_i}{S_i^{\max}}\right)^{2q} + \sum_{j=1}^{N_{bus}}\left(\frac{V_{j,ref} - V_j}{V_{j,ref}}\right)^{2r} \quad ...(14)$$

Where $N_{line,}$ N_{bus} are the total number of lines and buses in a given system. S_i and $S_i^{\max}$ are the present and maximum apparent powers of i^{th} line. $V_{j,ref}$ and V_j are the nominal voltage and present voltage values at j^{th} bus. q and r are two coefficients used to penalize more or less over loads and voltage violations. These are considered to be equal to 2.

To enhance security of the system under contingencies TCSC should be placed in a proper location. Initially contingency analysis is performed by removing single transmission line at a time due to which the total Number of Voltage Violation Buses (NVVB) and total Number of Over Loaded Lines (NOLL) are identified. Calculate performance index by adding NVVB and NOLL. Finally the contingency with highest performance index value is identified as most critical one.

Then, this critical line is removed from the system and TCSC is placed in one of the possible TCSC installation locations discussed in section 8 and the severity function $\left(F_{severity}\right)$ is minimized subjected to satisfy equality, in-equality and operational constraints as well as TCSC control settings. This process is repeated at all possible installation locations, and finally, identifies the best location for placing TCSC which has less severity value for enhancing the system security.

In this paper, the following rules are considered, to identify the proper possible device location so as to reduce the possible number of locations.

- It should be located between two load buses and there should not be any shunt power injections.
- It should not be placed in a line where there exists tap changing transformer

5.0 HYBRID CUCKOO SEARCH ALGORITHM (HCSA)

HCSA is population based evolutionary computation technique. It has been applied to many optimization problems and observed that it yields to better performance. Main steps of cuckoo search optimization can be described as follows

i) Initialization

Randomly generate a population of specified size for each control variable is given by

$$x_{pq} = x_q^{\min} + rand\left(0,1\right)\times\left(x_q^{\max} - x_q^{\min}\right)$$

Where, $p=1,2,..,n$ and $q=1,2,..,m$
n number of host nests and m number of control variables

$x_q^{\min}$ and $x_q^{\max}$ are minimum and maximum limits of q^{th} control variable

rand(0,1) is uniformly distributed random number between 0 and 1

Population vector is of size $\left(n\times m\right)$ generated and it is used for evolutionary operations.

ii) Levy flights

The cuckoo randomly chooses the nest position to lay egg is given in equations (15) and (16). for i^{th} cuckoo, while generating new solutions levy flight is performed.

$$x_i\left(t+1\right) = x_i\left(t\right) + S_{pq}\times\alpha\oplus Levy\left(\lambda\right) \quad ...(15)$$

Where

α is generated randomly between -1 and 1; ⊕ gives entry wise multiplication

Hence step size $\left(S_{pq}\right)$ is calculated by

$$S_{pq} = x_{pq}^t - x_{fq}^t$$

Where $p,f=1,2,..,n$ and q=1,2,...m

levy flights in which the step lengths are distributed according to heavy tailed probability distribution mathematically.

$$Levy(\lambda)=\left|\frac{\Gamma(1+\lambda)\times\sin\left(\frac{\pi\times\lambda}{2}\right)}{\Gamma\left(\frac{1+\lambda}{2}\right)\times\lambda\times 2^{\left(\frac{\lambda-1}{2}\right)}}\right|^{1/\lambda};$$

$$1<\lambda\leq 3; \qquad ...(16)$$

Above levy flight equation gives modified variables in the population vector x_{pq}^{t+1} i.e, belongs to p^{th} nest and q^{th} control variable. Here old x_{pq} variable is modified with respect to f^{th} neighborhood's nest, and the egg laid by cuckoo is evaluated

iii) Cross over

Once population of random set of points is created, a reproduction operator can be used to select good population. Recently new efficient crossover operators have been designed for searching process [16].

$$x_{pq}^{new}=(1-\lambda)\times x_{1q}^{ref}+\lambda\times x_{pq}^{old}$$

Where 'λ' is random number between 0 and 1

Modified value of x_{pq} is obtained by the crossover of old value and its reference value. After getting new values of control variables for total number of nests, whose limits has to be checked if control variable obtained is beyond its maximum limit equate it to maximum and below its minimum limit equate it to minimum otherwise keep the value same as obtained.

iv) Selection

After sorting and ranking processes based on fitness values, the lowest fitness value and its corresponding population value are treated as best, and best population vector is considered for the next generation until the stopping criteria is reached.

v) Stopping criteria

The stopping criteria will be, if the number of generations equals to the specified maximum number of generations.

6.0 SELECTION OF COMPROMISED SOLUTION

Because of multiple solutions for a multi-objective optimization problem, it is necessary to choose an optimal solution as per the requirements of decision maker. Fuzzy membership function (μ_m) for minimization of objective functions is [17]

$$\mu_m^n=\begin{cases}1 & ; \quad A_m^n\leq\min(A_m)\\ \dfrac{\max(A_m)-A_m^n}{\max(A_m)-\min(A_m)} & ; \quad \min(A_m)\leq A_m^n\leq\max(A_m)\\ 0 & ; \quad A_m^n\geq\max(A_m)\end{cases} \qquad ...(17)$$

where A_m^n and μ_m^n are the respective values of the i^{th} objective function in the n^{th} Pareto optimal solution and its membership function. The most preferred degree of the Pareto optimal solutions can be defined as

$$\mu_{opt}=\underbrace{\sup}_{n\in j}\frac{\sum_{i=1}^{p}W_i\mu_m^n}{\sum_{n=1}^{M}\sum_{i=1}^{p}W_i\mu_m^n}$$ Where

$$W_i\geq 0;\sum_{i=1}^{p}W_i=1 \qquad ...(18)$$

where W_i is the weight value of the i^{th} objective function. Therefore, the best optimal Pareto solution and the corresponding settings are obtained by the proposed algorithm based on the adopted weight factors.

7.0 MULTI OBJECTIVE SOLUTION FLOW CHART

The complete Non-dominated sorting procedure is described in [18]. After completion of this sorting, the distance between each of the two points is calculated and after this all the generated solutions are arranged based on the crowding distances explained in [19]. The flow chart is given in Figure. 8.

8.0 RESULTS AND ANALYSIS

This section clearly describes the results on IEEE-30 bus test system. The complete IEEE 30 bus data, ramp rate-limits and prohibited operating zones data taken from [20,21] For electrical test system, primarily single objectives are optimized individually using proposed HCSA and later extended to multi-objective optimization problems are solved using proposed NSHCSA and corresponding results are analyzed. The input parameters of proposed HCSA for two test systems are given in Table 1.

TABLE 1 INPUT PARAMETERS USED FOR PROPOSED HCSA	
PARAMETERS	QUANTITY
Number of host nest	50
Recombination constant	rand(0,1)
Number of Iteration	100
Levy flight constant (λ)	
Levy flight constant (α)	rand(-1,1)
Cross over constant (λ_{cross})	rand(0,1)

8.1 Optimal Location

Optimal location is identified by using the proposed procedure described in Section-4. To maintain the continuity supply, the three lines connected between buses (9-11, 12-13, 25-26) should not be considered as contingency lines. Hence for this system only 38 possible transmission line contingencies are considered out of 41. The top 2 contingency rankings are tabulated in Table 2.

TABLE 2 CONTINGENCY ANALYSIS RESULT						
LINE NO.	OUTAGE LINE	OVER LOADED LINES	NOL	NVVL	PI	RANK
5	2 to 5	1-2, 2-4, 2-6, 4-6, 5-7, 6-8	6	0	6	1
36	28 to 27	1-2, 22-24, 24-25	3	3	6	2

From Table 2 it is very clear that, the line connected between buses 2 and 5 is the most critical one. By following the rules given in section 4, the severity function value is defined in 19 possible locations with TCSC are tabulated in Table.3.

TABLE 3 SEVERITY FUNCTION VALUES UNDER RANK-1 CONTINGENCY WITH TCSC			
SL.NO	TCSC SE	TCSC RE	SEVERITY
1	3	4	1.4951
2	4	6	1.5091
3	6	7	1.5943
4	6	28	1.499
5	12	16	1.4875
6	**12**	**14**	**1.4393**
7	12	15	1.497
8	14	15	1.4857
9	15	18	1.5089
10	15	23	1.4866
11	16	17	1.4815
12	18	19	1.4947
13	19	20	1.5085
14	21	22	1.4882
15	25	27	1.4869
16	25	26	1.4847
17	27	29	1.4974
18	27	30	1.4898
19	29	30	1.4836

From Table.3, it is observed that, when TCSC is placed in location number 6, the severity function value is 1.4393 which is very less when compared with other. The further analysis with TCSC is performed by placing TCSC in 6^{th} location i.e. between buses 12-14.

8.2 Single objective optimization

The generation fuel cost without ramp rate and POZ constraints is optimized using existing PSO, CSA and the proposed HCSA along with settings of eighteen control variables are considered and results are tabulated in Table.4.

From Table.4, it is observed that the generation fuel cost is minimum for the proposed method in compared with the existing methods. Also compared the proposed method with different existing method in Table 5, it is observed that the proposed method gives the best solution.

The convergence characteristics of the proposed method along with the existing methods can be observed in Figure.2 and it is very clear that, the proposed method started with best starting value and reached final solution with less number of iterations as compared with the existing methods.

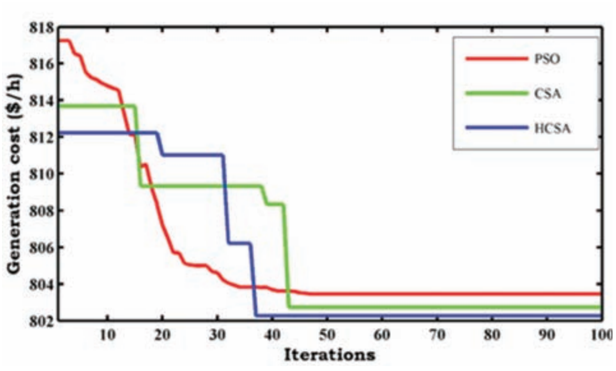

FIG. 2. CONVERGENCE CHARACTERISTICS FOR FUEL COST

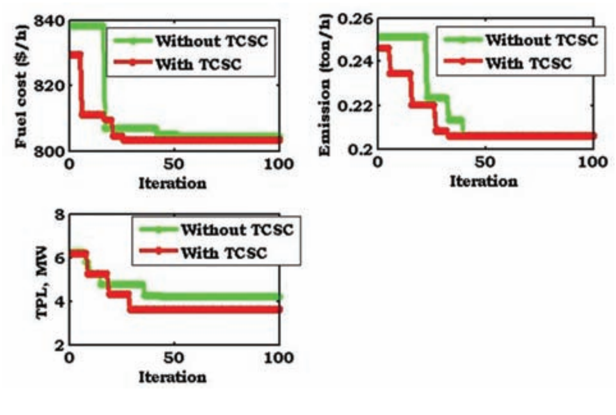

FIG. 3. CONVERGENCE PATTERNS OF THREE OBJECTIVES WITHOUT AND WITH TCSC

Further the analysis is performed for the generation fuel cost, emission and total power loss as objectives without and with TCSC by considering practical and operational constraints. The consolidated results of these objectives are tabulated in Table.6. From this table the following points are noticed:

- While minimizing generation fuel cost without TCSC, it is observed that the generators at 5, 8, 11, 13 buses are following down ramp rates and operating below the POZ lower limit. While slack bus generator is following up ramp rate and operating above the POZ upper limit. Similarly, 2nd generator is following up ramp rate and operating below the POZ lower limit.
- In the presence of TCSC, the generation fuel cost decreases from 804.5387 $/h to 803.2860 $/h with the net saving of 1.2527 $/h, emission is reduced from 0.20618 ton/h to 0.20592 ton/h and power loss is reduced from 4.2004 MW to 3.5941 MW.

TABLE 4

COMPARISION OF OPF RESULTS FOR FUEL COST MINIMIZATION

Control Variables	Existing methods			Proposed
	TS [7]	PSO	CSA	HCSA
P_{G1}(MW)	176.04	178.5558	170.7789	173.6794
P_{G2}(MW)	48.76	48.6032	48.3696	44.4255
P_{G5}(MW)	21.56	21.6697	18.3135	22.9575
P_{G8}(MW)	22.05	20.7414	32.6057	25.953
P_{G11}(MW)	12.44	11.7702	10	13.221
P_{G13}(MW)	12	12	12	12
V_{G1}(p.u.)	1.05	1.1	1.1	1.1
V_{G2}(p.u.)	1.0389	0.9	1.0567	1.0499
V_{G5}(p.u.)	1.011	0.9642	1.0912	1.0877
V_{G8}(p.u.)	1.0198	0.9887	1.0725	1.0985
V_{G11}(p.u.)	1.0941	0.9403	1.0465	1.1
V_{G13}(p.u.)	1.0898	0.9284	1.1	1.1
T_{6-9}(p.u.)	1.0407	0.9848	1.0531	1.0323
T_{6-10}(p.u.)	0.9218	1.0299	1.007	1.0151
T_{4-12}(p.u.)	1.0098	0.9794	1.0395	0.9793
T_{28-27}(p.u.)	0.9402	1.0406	0.9707	1.0588
Q_{C10}(MVAr)	-	9.0931	30	30
Q_{C24}(MVAr)	-	21.665	6.7556	5.4662
Cost ($/h)	**802.29**	**803.4548**	**802.7283**	**802.2545**
Emission (ton/h)	-	0.3701	0.3508	0.3557
TPL (MW)	-	9.9403	8.6677	8.8364

TABLE 5

SUMMERY OF TEST RESULTS FOR GENERATION FUEL COST

Method	EP [22]	TS/SA [23]	ITS [24]	IEP [25]	GA [26]	Proposed HCSA
Fuel cost ($/h)	802.907	802.788	804.556	802.465	803.050	802.2545

From Table.6, it is also observed that, TCSC device installation cost is less in emission minimization when compared to two objectives. The convergence patterns for all objectives are shown in Figure.3. It is observed that, with TCSC the proposed method has started with good initial value and converged in less number of iterations.

TABLE 6

SINGLE OBJECTIVE OPF RESULTS OF GENERATION FUEL COST, EMISSION AND TOTAL POWER LOSS WITHOUT AND WITH TCSC

Control Variables	Generation cost ($/h)		Emission (ton/h)		Total power loss (MW)	
	Without TCSC	With TCSC	Without TCSC	With TCSC	Without TCSC	With TCSC
P_{G1}(MW)	170.3015	176.7243	66.1230	65.123	66.3574	51.9941
P_{G2}(MW)	46.2830	50	70.0013	70.2123	75.4412	80
P_{G5}(MW)	19	19	50	50	50	50
P_{G8}(MW)	30	20.4031	35	35	35	35
P_{G11}(MW)	13	13	30	30	30	30
P_{G13}(MW)	14	14	40	40	30.8018	40
V_{G1}(p.u.)	1.0625	1.0998	1.1	1.1	1.1	1.001
V_{G2}(p.u.)	1.0122	1.0598	1.1	1.1	0.9017	0.9558
V_{G5}(p.u.)	1.0013	1.0181	1.0975	1.0919	0.9	0.9679
V_{G8}(p.u.)	1.1	1.0731	1.098	1.1	1.1	1.1
V_{G11}(p.u.)	0.9	1.1	0.9	1.1	1.0286	1.0639
V_{G13}(p.u.)	1.0984	1.1	1.0059	1.0579	1.0988	1.1
T_{6-9}(p.u.)	0.9	0.9	1.1	1.1	0.9882	0.9058
T_{6-10}(p.u.)	0.9	1.0451	1.1	1.1	0.9707	0.9
T_{4-12}(p.u.)	0.9067	1.1	1.0063	0.9228	1.0468	0.9
T_{28-27}(p.u.)	0.9	0.9083	1.0681	1.0565	1.0234	0.9000
Q_{C10}(MVAr)	29.9967	23.3372	30	29.9776	27.0536	28.6647
Q_{C24}(MVAr)	5	5	5	5	28.0595	11.7065
X_{TCSC}, , p.u.	-	0.0412	-	0.03934	-	0.0414
Net saving, $/h	-	1.2527	-			
Cost ($/h)	**804.5387**	**803.2860**	959.6139	958.0087	939.6890	968.8423
Emission (ton/h)	0.35426	0.36483	**0.20618**	**0.20592**	0.21020	0.20721
TPL (MW)	9.1845	9.7274	7.7243	6.9353	**4.2004**	**3.5941**
Severity value	3.6418	3.2877	1.6677	1.2185	1.8947	1.4711

8.3 Multi objective optimization

In this optimization problem, considered objectives can be solved using the proposed NSHCSA for the following four cases with TCSC.

Case-I: Cost-Emission objectives

Case-II: Cost-TPL objectives

Case-III: Emission-TPL objectives

Case-IV: Cost-Emission-TPL objectives

Cases I, II and III can be considered as two objectives optimization problem, and Case-IV is the three objectives optimization problem. The generated two dimensional Pareto front for the

Case-I, Case-II and Case-III are shown in Figure 4, Figure 5 and Figure 6 respectively.

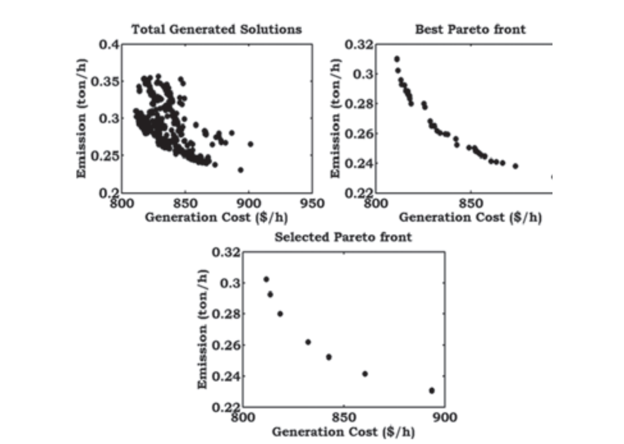

FIG. 4 TWO DIMENSIONAL PARETO FRONT OF CASE-I WITH TCSC

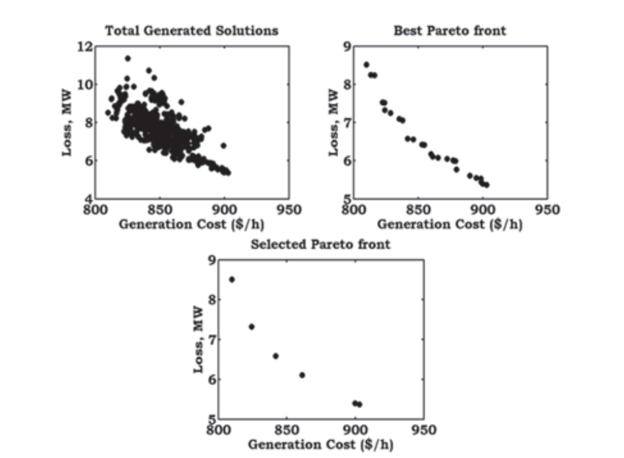

FIG. 5 TWO DIMENSIONAL PARETO FRONT OF CASE-II WITH TCSC

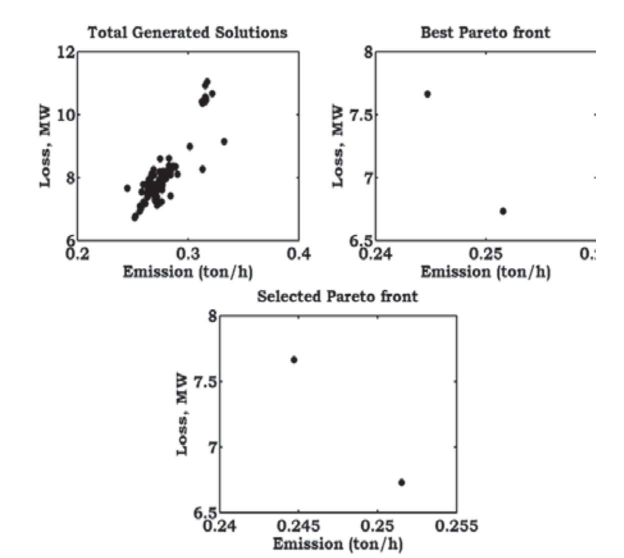

FIG. 6 TWO DIMENSIONAL PARETO FRONT OF CASE-III WITH TCSC

From Figures. 4, 5, 6 it is observed that the selected Pareto front using proposed NSHCSA confines the entire trade-off region and the fuzzy decision making tool proves its effectiveness in choosing best compromised solution than the exact solution. The selected Pareto solutions for first three cases are tabulated in Table.7.

TABLE 7

SUMMARY OF TEST RESULTS WHEN TWO OBJECTIVES ARE CONSIDERED WITH TCSC

Set No.	W1	W2	Case-I Cost (S/h)	Case-I Emission (ton/h)	Case-II Cost (S/h)	Case-II Loss (MW)	Case-II Emission (ton/h)	Case-III Loss (MW)
1	0.9	0.1	811.589	0.3024	809.949	85115	0.2447	7.6638
2	0.5	0.5	832.25	0.2619	841.922	6.5826	0.2447	7.6638
3	0.1	0.9	893.614	0.2307	902.989	5.373	0.2515	6.7308

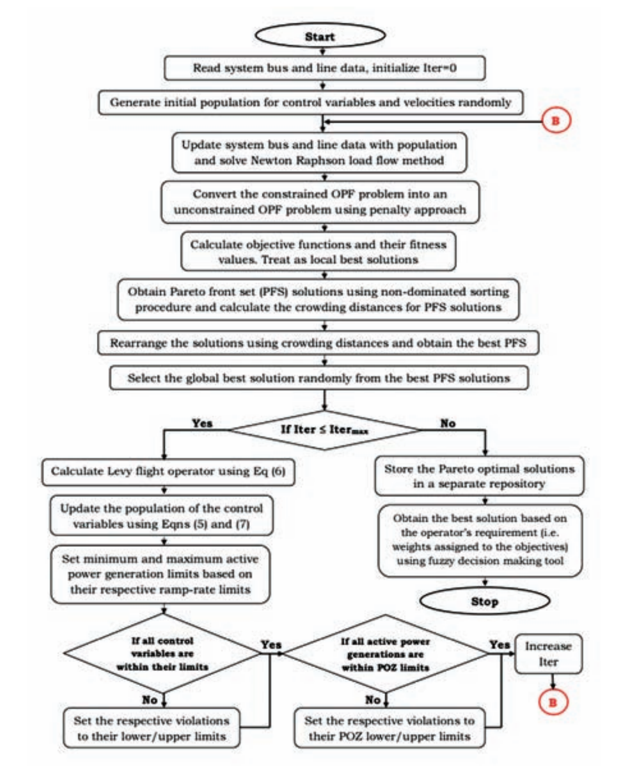

FIG. 8. FLOW CHART FOR MULTI OBJECTIVE OPTIMIZATION

From Tables 7, it is observed that the cost is less and emission is more for Case-I, the cost is less and total power loss is more for Case-II and the emission is less and total power loss is more for Case-III with respect to the weights W_1= 0.9 and W_2=0.1compared to other weight combinations. Similarly, the fuel cost is high and emission is low for Case-I, the fuel cost is high and total power loss is low for Case-II and the emission is high and total power loss is low for Case-III with respect to the weights W_1= 0.1 and W_2=0.9 compared to other weight combinations. It is also observed that the objective function value is depends upon the weights assign to the respective objectives. The optimal function values with TCSC are fuel cost is 811.5887 $/h and emission is 0.2307 ton/h for Case-I, fuel cost is 809.9489 $/h and total power loss is 5.373 MW for Case-II, emission is 0.2447 ton/h and total power loss is 6.7308 MW for Case-III. The objective function values are better with TCSC compared to without TCSC.

To extend this, all three objectives are combined together to show extended effectiveness of the proposed NSHCSA. The three dimensional Pareto front for the three objectives optimization is shown in Figure.7. Figure.7b shows the two dimensional best Pareto fronts of the corresponding objective functions. It is observed that these Pareto front are well distributed over the entire region.

With three objectives there are 34 possible sets as per the weights distribution among the objectives. Some of the important sets are given in Table.8.

TABLE 8						
SUMMARY OF TEST RESULTS WHEN THREE OBJECTIVES ARE CONSIDERED						
No.	W1	W2	W3	Cost (S/h)	Emission (ton/h)	Loss (MW)
1	0.1	0.1	0.8	896.1835	0.222677	4.586365
2	0.1	0.8	0.1	891.5975	02.11968	4.961325
3	0.8	0.1	0.1	808.1103	0.311099	7.973398

From Table.8, it is observed that minimum cost is 808.1103 $/h minimum emission is 0.211968 ton/h and minimum loss is 4.586365 MW.

9.0 CONCLUSIONS

In this paper, a methodology to install TCSC is proposed based on severity function formed by combining total bus voltage deviations and line limit violations to enhance the system security. Non-dominated Sorting (NS) methodology has been adapted to Hybrid Cuckoo Search Algorithm (HCSA) to solve multi-objective optimization problem with important objectives such as generation fuel cost, emission and total power loss in a given power system with TCSC. Device installation cost variation with respect to objective function values is also analyzed. Effect of the practical constraints such as, ramp-rate limits and prohibited operating zones on objectives has been analyzed without and with TCSC. The proposed fuzzy decision making tool helps in selecting better solution than the exact solution. The Pareto solutions confine the entire trade-off region because of effectiveness of the proposed methodology. The proposed method has been tested on standard test systems with the supporting results.

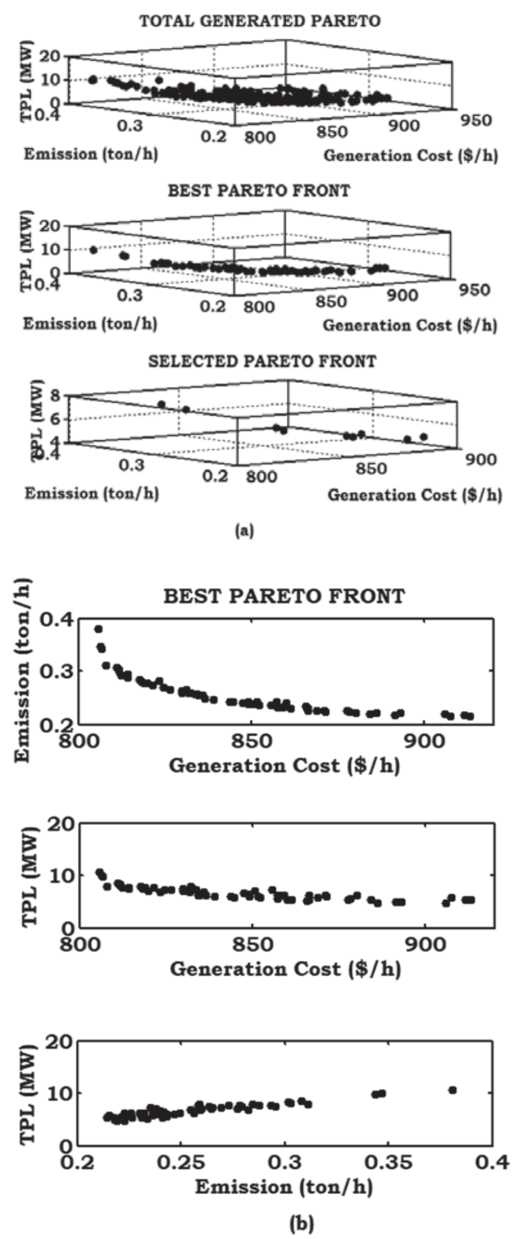

FIG.7. THREE DIMENSIONAL PARETO FRONT FOR THREE OBJECTIVES OPTIMIZATION

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