Optimal Power Flow in the Presence of Generalized Interline Power Flow Controller

M. Balasubba Reddy, Y.P. Obulesh, S.Sivanaga Raju, Venkata Suresh

***Abstract*—In this paper a novel non-linear optimization problem is formulated to minimize the generation fuel cost and transmission power losses in the presence of generalized interline power flow controller (GIPFC). This paper presents a methodology to optimally allocate the device in a give power system by minimizing the system severity system buses and total transmission line power flows in order to maximize the system security. The formulated objectives are optimized individually while satisfying equality, in-equality, practical and device operational constraints. A new optimization method, based on cuckoo search algorithm and genetic algorithm cross over operations is proposed to test the effectiveness on IEEE-14 bus system, and the detailed analysis is carried out.**

***Index Terms*—Optimal power flow, Generalized interline power flow controller, Power injection model, Practical constraints, HCSA.**

I. INTRODUCTION

The Optimal Power Flow (OPF) is a popularly used method in electrical power system for effective controlled operation and proper planning towards meeting the load growth subjected to meeting various objectives. The chief necessity of the optimization of the power flow is to estimate the proper combination of the controllable parameters like voltage and real power generation at generator buses, tap setting of the transformers in transmission lines, value of compensating capacitors towards minimization of the specific objective functions. A problem with more number of controllable parameters makes the system non-linear and discontinues. So, traditional solution methodologies failed to give an optimized global solution. With the development in semi-conductor technology, the new convertible static compensators are developed using two or more series converters and coordinated with one shunt converter. The most popularly used Convertible Static Compensator (CSC) devices are Generalized Unified Power Flow Controller (GUPFC) and GIPFC. The basic circuit configuration and working principle of GIPFC are discussed in [1]. The power injected by the series converters is supplied by the shunt converter. The elementary GIPFC system model is developed by using d-q orthogonal coordinates [2] and is used to control direct and quadrature components of the ideal sources representing the converters.

A simple modeling approach based on quadrature equation is proposed to analyze the effect of series connected multi-line VSC based FACTS controllers is presented in [3]. In the past, much effort has been made in the modeling of the Unified Power Flow Control (UPFC) for power flow analysis [4, 5]. UPFC compensate a single transmission line, whereas the IPFC is used for the compensation and power flow control of multi-line transmission system. In most of the FACTS devices employs the Voltage Sourced Converter (VSC) as a basic building block reported in [6]. A steady state control of power system parameters with current and voltage operating constraints has been presented in [7]. Mathematical models of GUPFC, IPFC and their implementation in newton power flow are described in [8] to demonstrate the device performance. An OPF method with IPFC is proposed in [9] to optimize generation fuel cost. An injection model for congestion management and total active power loss minimization in electric power system was developed in [10]. A current based model of SSSC and IPFC has presented in [11, 12]. An evolutionary cuckoo optimization algorithm suitable for continuous nonlinear optimization problems is presented [13]. A meta-heuristic algorithm, called Cuckoo Search Algorithm for solving optimization problems is initiated in [14]. The main contribution of this paper is that, presenting detailed mathematical modeling of GIPFC power injection model to incorporate in NR load flow. To prove effectiveness of the device, generation fuel cost and total power loss objectives are optimized individually while satisfying equality, in-equality, practical constraints and device operating limits. For this, a new evolutionary algorithm based on hybrid cuckoo search algorithm (HCSA) is proposed. This method is developed by combining genetic algorithm along with conventional cuckoo search algorithm to start the iterative process with good initial and final best solution is obtained in less number of iterations than the existing methods for single objective. The effectiveness of the proposed method is tested for different test systems but only the results are given for IEEE 14 bus system, due to the restriction on number of pages.

II. MATHEMATICAL MODELING OF GIPFC

The basic configuration of GIPFC consist of two series converters connected in two separate transmission lines and are coordinated with shunt converter connected at sending end of one of the considered transmission lines. This device has five/more degrees of freedom to control power system parameters.

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Such as it can control active and reactive power flows in series converter connected transmission lines and it can control voltage magnitude of the shunt converter connected bus. It can have two/more number of series converters and one shunt converter. The basic configuration of GIPFC is shown in Fig.1.

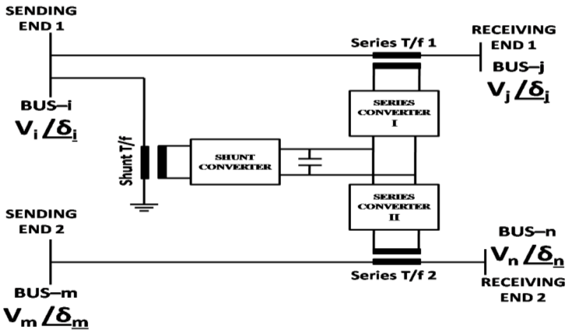

Fig.1: Principle Configuration of two Series Converter GIPFC

GIPFC series and shunt converters can be represented by an equivalent controllable voltage source in series with an equivalent reactance of converter transformers. Let us consider device is connected between buses i, j, m and n. The equivalent voltage source model of GIPFC is shown in Fig.2. The two controllable voltage sources can be expressed as

$$\bar{V}_{se,ij} = V_{se,ij} e^{j\theta_{se,ij}} \; ; \; \bar{V}_{se,mn} = V_{se,mn} e^{j\theta_{se,mn}} \qquad (1)$$

Where $\bar{V}_{se,ij}$, $\bar{V}_{se,mn}$ and $\theta_{se,ij}$, $\theta_{se,mn}$ are respective magnitude and phase angles of the series voltage sources operating within the limits $0 \le V_{se} \le V_{se,\max}$ and $0 \le \theta_{se} \le \theta_{se,\max}$. GIPFC power injection model can be developed in two voltage source models. The Voltages behind the series reactance are defined as

$$\bar{V}'_{se,ij} = \bar{V}_i + \bar{V}_{se,ij} \; ; \; \bar{V}'_{se,mn} = \bar{V}_m + \bar{V}_{se,mn} \qquad (2)$$

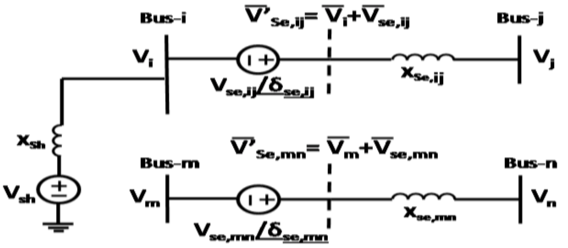

Fig.2. Voltage Source Model of GIPFC

A. Series Connected Voltage Source Model

The series connected voltage source converter can be modeled as an equivalent current source in parallel with corresponding susceptance as shown in Fig.3.

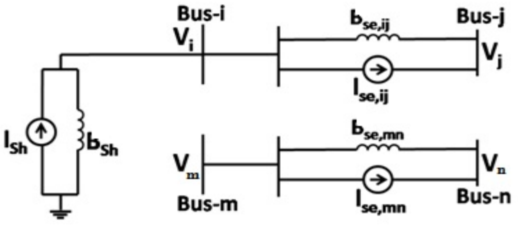

Fig.3. Equivalent Current Source Model of GIPFC

The amount of current flowing from the source can be given as,

$$\bar{I}_{se,ij} = -jb_{se,ij}\bar{V}_{se,ij} \; ; \; \bar{I}_{se,mn} = -jb_{se,mn}\bar{V}_{se,mn} \qquad (3)$$

Substitute Eq. (1) in Eq. (3) and can be solved for

$$\left(\bar{I}_{se,ij}\right)^* = jV_{se,ij}b_{se,ij}e^{-j\theta_{se,ij}} \; ; \; \left(\bar{I}_{se,mn}\right)^* = jV_{se,mn}b_{se,mn}e^{-j\theta_{se,mn}} \qquad (4)$$

Finally this current source can be modeled by injecting equivalent powers at GIPFC connected buses. The injection powers can be expressed as

$$\bar{S}_{i,se} = \bar{V}_i\left(-\bar{I}_{se,ij}\right)^* \; ; \; \bar{S}_{j,se} = \bar{V}_j\left(\bar{I}_{se,ij}\right)^* \qquad (5)$$

$$\bar{S}_{m,se} = \bar{V}_m\left(-\bar{I}_{se,mn}\right)^* \; ; \; \bar{S}_{n,se} = \bar{V}_n\left(\bar{I}_{se,mn}\right)^* \qquad (6)$$

Substitute Eqn. (4) in Eqns. (5) and (6), the individual power injections can be derived as

$$P_{i,se} = V_iV_{se,ij}b_{se,ij}\sin\left(\delta_i - \theta_{se,ij}\right) \; ;$$
$$Q_{i,se} = -V_iV_{se,ij}b_{se,ij}\cos\left(\delta_i - \theta_{se,ij}\right) \qquad (7)$$

$$P_{j,se} = -V_jV_{se,ij}b_{se,ij}\sin\left(\delta_j - \theta_{se,ij}\right) \; ;$$
$$Q_{j,se} = V_jV_{se,ij}b_{se,ij}\cos\left(\delta_j - \theta_{se,ij}\right) \qquad (8)$$

$$P_{m,se} = V_mV_{se,mn}b_{se,mn}\sin\left(\delta_m - \theta_{se,mn}\right) \; ;$$
$$Q_{m,se} = -V_mV_{se,mn}b_{se,mn}\cos\left(\delta_m - \theta_{se,mn}\right) \qquad (9)$$

$$P_{n,se} = -V_nV_{se,mn}b_{se,mn}\sin\left(\delta_n - \theta_{se,mn}\right) \; ;$$
$$Q_{n,se} = V_nV_{se,mn}b_{se,mn}\cos\left(\delta_n - \theta_{se,mn}\right) \qquad (10)$$

The equivalent power injections are shown in Fig.4.

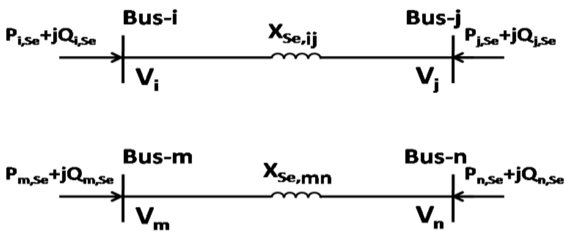

Fig.4. Equivalent Series Connected Voltage Source Model of GIPFC

B. Shunt Connected Voltage Source Model

The amount of apparent powers supplied by the series converters can be expressed as

$$\bar{S}_{se,ij} = \bar{V}_{se,ij}\left(\bar{I}_{ij}\right)^* = jV_{se,ij}b_{se,ij}e^{j\theta_{se,ij}}\left(\bar{V}'_{se,ij} - \bar{V}_j\right)^* \qquad (11)$$

$$\bar{S}_{se,mn} = \bar{V}_{se,mn}\left(\bar{I}_{mn}\right)^* = jV_{se,mn}b_{se,mn}e^{j\theta_{se,mn}}\left(\bar{V}'_{se,mn} - \bar{V}_n\right)^* \qquad (12)$$

Substitute Eqn. (2) in (11 & 12) and solve for supplied powers

$$P_{se,ij} = V_i V_{se,ij} b_{se,ij} \sin\left(\theta_{se,ij} - \delta_i\right) - V_j V_{se,ij} b_{se,ij} \sin\left(\theta_{se,ij} - \delta_j\right) \tag{13}$$

$$Q_{se,ij} = -V_i V_{se,ij} b_{se,ij} \cos\left(\theta_{se,ij} - \delta_i\right) + V_j V_{se,ij} b_{se,ij} \cos\left(\theta_{se,ij} - \delta_j\right) - V_{se,ij}^2 b_{se,ij} \tag{14}$$

$$P_{se,mn} = V_m V_{se,mn} b_{se,mn} \sin\left(\theta_{se,mn} - \delta_m\right) - V_n V_{se,mn} b_{se,mn} \sin\left(\theta_{se,mn} - \delta_n\right) \tag{15}$$

$$\begin{aligned} Q_{se,mn} = {} & -V_m V_{se,mn} b_{se,mn} \cos\left(\theta_{se,mn} - \delta_m\right) + \\ & V_n V_{se,mn} b_{se,mn} \cos\left(\theta_{se,mn} - \delta_n\right) - V_{se,mn}^2 b_{se,mn} \end{aligned} \tag{16}$$

The shunt connected voltage source can be modeled as an equivalent power injection from GIPFC shunt branch to the series branches through series converters I and II. This model is also used to provide the converter switching losses. The reactive power injection at shunt converter is used to control/maintain the voltage level at sending end within limits. The total switching losses of one of the converters is about 0.8-1.0% of the power transferred through the converter. If these losses are considered, the real power injections at shunt branch is

$$P_{sh} = -1.03\left(P_{se,ij} + P_{se,mn}\right)$$

C. Power Injection Model of GIPFC

The final steady state model of GIPFC shown in Fig.5 can be derived by combining the above two voltage source models. The resultant active and reactive power injections can be expressed as

$$P_{i,GIPFC} = P_{i,se} + P_{sh}\,; \quad Q_{i,GIPFC} = Q_{i,se} + Q_{sh} \tag{17}$$

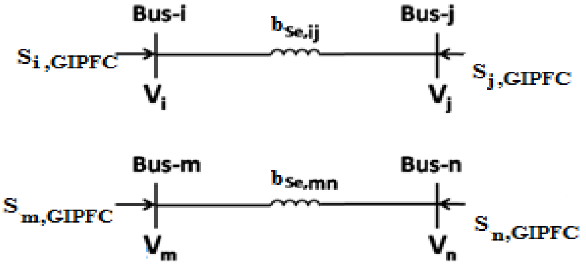

Fig.5. Injection Model of two Series Converter GIPFC

Similarly, GIPFC power injections at j,m and n buses is the power injected by the series voltage sources only since there is no effect of shunt branch.

D. GIPFC Power Mismatches Equations

The power mismatch equations in NR method can be modified by using the following equations.

$$\Delta P_{i,new} = \Delta P_{i,old} + P_{i,GIPFC} \tag{18}$$

$$\Delta Q_{i,new} = \Delta Q_{i,old} + Q_{i,GIPFC} \tag{19}$$

Where, $\Delta P_{i,old}$ *and* $\Delta Q_{i,old}$ are the real and reactive power mismatches without FACTS device. Similar modifications can be obtained for the remaining GIPFC buses.

E. GIPFC Jacobian Elements

The Jacobian elements can be modified in the NR iterative process using the following equations

$$\left(H^{new} = H^{old} + H^{'}\right)$$

$$H_{ii}^{'} = \frac{\partial P_{i,GIPFC}}{\partial \delta_i} = -Q_{i,GIPFC} + 1.03 \times V_i V_{se,ij} b_{se,ij} \cos\left(\theta_{se,ij} - \delta_i\right) \tag{20}$$

$$H_{qq}^{'} = -Q_{q,GIPFC} \qquad \forall\, q = j, m, n \tag{21}$$

$$H_{ij}^{'} = -1.03\, Q_{j,GIPFC} \;; \qquad H_{im}^{'} = 1.03\, Q_{m,GIPFC} \;;$$

$$H_{in}^{'} = -1.03\, Q_{n,GIPFC}\,; \tag{22}$$

$$H_{ji}^{'} = H_{mn}^{'} = H_{nm}^{'} = 0 \tag{23}$$

Where, H^{old} are the jacobian elements without FACTS device. Similar modifications can be obtained for the remaining elements.

III. PROBLEM FORMULATION

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

$$Min\left[A_m(x,u)\right]; \qquad \forall\, m = 1,2,\ldots., J \tag{24}$$

$$\text{Subjected to} \quad \begin{aligned} g(x,u) &= 0 \\ h(x,u) &\le 0 \end{aligned}$$

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

A. Objective Functions

The objective functions namely generation fuel cost and the total power loss are considered for the analysis. The mathematical expressions for these objective functions are as follows:

1) Generation Fuel Cost

The simplified quadratic cost expression for ith unit for real power output of 'P_{Gi}' subjected to different constraints can be expressed as

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

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

$$A_1 = \min\left(F_T\right) = \sum_{i=1}^{N_G} F_i\left(P_{G_i}\right) \;\text{\$/h} \tag{25}$$

2) Total Transmission Loss

This objective can be expressed as

$$A_3 = \min(TPL) = \sum_{i=1}^{N_{line}} P_{Loss,i} \quad MW \tag{26}$$

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

B. Constraints

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

1) Equality Constraints are Simply Power Flow Equations

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

$$\sum_{i=1}^{N_G} Q_{G_i} - Q_D - Q_L = 0 \quad (27)$$

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

2) 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:

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

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.

3) IPFC Limits

$$0 \le V_{se\,A} \le 0.1\,p.u.,\ 0 \le V_{se\,B} \le 0.1\,p.u.,$$
$$0 \le \theta_{se\,A} \le 360^0, 0 \le \theta_{se\,B} \le 360^o,$$
$$0 \le X_{se\,A} \le 0.1\,p.u.,\ 0 \le X_{se\,B} \le 0.1\,p.u.$$

4) GIPFC Limits

$$0 \le V_{se\,A} \le 0.1\,p.u., 0 \le V_{se\,B} \le 0.1\,p.u.,$$
$$0 \le \theta_{se\,A} \le 360^0, 0 \le \theta_{se\,B} \le 360^o,$$
$$0 \le X_{se\,A} \le 0.1\,p.u.,\ 0 \le X_{se\,B} \le 0.1\,p.u.$$

C. 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:

$$P_i = \begin{cases} P_i^{\min} \le P_i \le P_{i,1}^L \\ P_{i,k-1}^U \le P_i \le P_{i,k}^L & k = 2,3,...,n_i \\ P_{i,n_i}^U \le P_i \le P_i^{\max} \end{cases} \qquad (28)$$

Where n_i is 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.

D. Ramp-Rate Limits (practical constraints)

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

$$\max\left(P_{G_i}^{\min}, P_i^0 - DR_i\right) \le P_{G_i} \le \min\left(P_{G_i}^{\max}, P_i^0 + UR_i\right) \qquad (29)$$

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. (28) can be written in more generalized form by including the constraints with penalty factors as

$$A_{m,aug}(x,u) = A_m(x,u) + R_1\left(P_{g,slack} - P_{g,slack}^{\lim}\right)^2 + R_2\sum_{i=1}^{N_{Load}}\left(V_i - V_i^{\lim}\right)^2 + R_3\sum_{i=1}^{N_G}\left(Q_{G_i} - Q_{G_i}^{\lim}\right)^2 + R_4\sum_{i=1}^{N_{line}}\left(S_{l_i} - S_{l_i}^{\max}\right)^2 \qquad (30)$$

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 $P_{g,slack}, V_i$ and Q_{G_i}

IV. PROPOSED 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.

A. Initialization

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

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

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

‘n’ is the number of host nests and ‘m’ is the 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 $(n \times m)$ generated and it is used for evolutionary operations.

B. Levy Flights

The cuckoo randomly chooses the nest position to lay egg is given in equations (20) and (21). For i^{th} cuckoo, while generating new solutions levy flight is performed [13]

$$x_i(t+1) = x_i(t) + S_{pq} \times \alpha \oplus Levy(\lambda) \tag{31}$$

Where

α is generated randomly between -1 and 1; $\oplus$ gives entry wise multiplication

Hence step size (S_{pq}) 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.

$$Levy(\lambda) = \left| \frac{\Gamma(1+\lambda) \times \sin\left(\frac{\pi \times \lambda}{2}\right)}{\Gamma\left(\frac{1+\lambda}{2}\right) \times \lambda \times 2^{\left(\frac{\lambda-1}{2}\right)}} \right|^{1/\lambda} \quad ; \quad 1 < \lambda \le 3 \tag{32}$$

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

C. *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.

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

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.

D. *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.

E. *Stopping Criteria*

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

V. RESULTS AND ANALYSIS

This section clearly describes the results on IEEE-14 bus test systems. For electrical test systems, primarily single objectives are optimized individually using proposed HCSA. The input parameters of proposed HCSA for test system are given in Table 1.

Table 1 Input Parameters of Proposed HCSA

Parameters	Quantity
Number of host nest	50
Recombination constant	rand(0,1)
Number of Iteration	100
Levy flight constant (λ)	$1 \le \lambda \le 3$
Levy flight constant (α)	rand(-1,1)
Cross over constant (λ_{cross})	rand(0,1)

The efficiency of the proposed method is tested on IEEE-14.

A. *Single Objective Optimization*

The generation fuel cost and total power losses are considered as objective functions. The solution of the individual objective function is determined using proposed HCSA method and the results are compared with existing methods. The OPF results for fuel cost minimization are given in Table 2. The comparison of convergence characteristics of the proposed method with existing methods is shown in Fig.6.
From Tables 2, it is observed that the generation fuel cost is minimized for the proposed method compared to the existing methods. From Fig.6 it is clear that the proposed method starts with good function value and converges with less number of iterations compared to existing methods.

Table 2 OPF results for fuel cost minimization of IEEE-14 bus system

Control variables	PSO	CSA	Proposed HCSA
P_{G1}(MW)	170.4400	168.2136	167.5522
P_{G2}(MW)	48.6746	46.1794	48.1076
P_{G3}(MW)	19.3274	25.1688	20.9467
P_{G6}(MW)	19.3783	18.7853	22.6890
P_{G8}(MW)	10.25355	8.71160	7.7768
V_{G1}(p.u.)	1.1000	1.0964	1.1000
V_{G2}(p.u.)	0.9614	0.9000	0.9734
V_{G3}(p.u.)	0.9006	0.9000	1.1000
V_{G6}(p.u.)	0.9843	0.9000	1.1000
V_{G8}(p.u.)	0.9000	0.9550	0.9000
$T_{4\text{-}7}$(p.u.)	0.9916	0.9586	0.9330
$T_{4\text{-}9}$(p.u.)	0.9499	0.9229	0.9000
$T_{5\text{-}6}$(p.u.)	1.0190	0.9000	0.9516
Q_{C9}(MVAr)	17.3325	30.0000	5.0000
Cost ($/h)	**718.6326**	**717.4570**	**716.3141**
Emission (ton/h)	0.2956	0.2893	0.2889
TPL (MW)	9.0737	8.0585	8.0722

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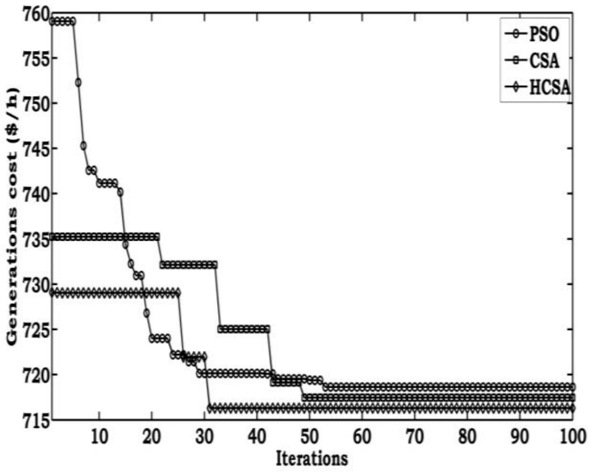

Fig.6 Comparison of convergence characteristics for IEEE-14 bus system

Further the analysis is performed for the generation fuel cost and total power loss as objectives without and with GIPFC by considering practical and operational constraints. By significantly, GIPFC is placed between buses 10-11 and 13-12. The consolidated results of these objectives are tabulated in Table 3.

From Table 4 it is observed that generation cost is reduced from **721.8330 $/h** to **718.6802 $/h** with GIPFC compared to without GIPFC also observed that total power losses is **4.0973MW** with GIPFC.

Table 4 Single objective OPF results of generation fuel cost and total power loss without and with FACTS

Control Variables	**Generation cost ($/h)**		**Total power loss (MW)**	
	Without FACTS	**With GIPFC**	**Without FACTS**	**With GIPFC**
PG1 (MW)	161.4779	169.231	75.0517	26.8723
PG2 (MW)	46.8931	43.9813	112.0794	134.0451
PG3 (MW)	20.0000	21.9891	43.9330	58.8273
PG6 (MW)	33.9437	25.8728	23.2024	18.9554
PG8 (MW)	5.0000	6.37	9.6166	24.3971
VG1 (p.u.)	1.05381	1.027	1.0560	1.0406
VG2 (p.u.)	0.9000	0.9879	0.9000	0.9683
VG3 (p.u.)	1.0079	1.0739	1.1000	1.0378
VG6 (p.u.)	0.9783	0.9968	1.0097	0.9676
VG8 (p.u.)	1.1000	1.016	1.1000	1.0003
T4-7 (p.u.)	1.0210	0.9349	1.1000	1.0296
T4-9 (p.u.)	0.9000	0.9928	1.0114	0.9888
T5-6 (p.u.)	1.0670	0.9784	0.9708	0.9709
QC9 (p.u.)	5.0000	17.7367	29.5561	11.0546
V_{se1} (p.u.)	-	0.0605	-	0.0797
V_{se2} (p.u.)	-	0.0196	-	0.0387
θ_{se1} (deg)	-	131.8762	-	235.1138
θ_{se2} (deg)	-	258.5553	-	207.0485
X_{se1} (p.u.)	-	0.089	-	0.0363
X_{se2} (p.u.)	-	0.0801	-	0.0552
$Q_{sh,GIPFC}$ (p.u.)	-	0.0058	-	0.0228
Cost ($/h)	**721.8330**	**718.6802**	862.8203	1033.265
TPL (MW)	8.314585	8.4442	**4.8830**	**4.0973**

VI. CONCLUSION

In this paper, a new power injection model has been developed for the basic GIPFC configuration. The equivalent power injections at the respective buses have been incorporated in NR load flow to analyze the effect of the same. The effect of device in optimizing the power system objectives such as generation fuel cost and transmission losses are compared with the effect of existing GIPFC device. A Hybrid Cuckoo Search Algorithm has been proposed for solving individual objectives while satisfying equality, in-equality and practical constraints. The obtained result supports that, the proposed method has good convergence characteristics than that of the existing methods. As the proposed method works independent of the nature of the problem and it can be applied to optimize any type of the objectives and for any size of the system.

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