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RESEARCH ARTICLE

Security Constrained Unit Commitment Incorporating Interline Power Flow Controller

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Abstract

Security-constrained unit commitment (SCUC) problem is solved using Artificial Bee Colony (ABC) algorithm incorporating Interline Power Flow Controller (IPFC). The objective of the SCUC problem is to obtain the minimum operating cost simultaneously maintaining the system security. The SCUC problem involves unit commitment as the main problem and security-constrained Economic Dispatch (SCED) as the sub problem. The solution of the SCUC problem is also investigated during contingency with a single line outage. Binary coded artificial bee colony (BABC) is used for solving the UC problem (master problem) and real coded artificial bee colony algorithm (RABC) is used for solving the SCED sub problem. The effectiveness of the proposed methodology is tested and validated on a 6 bus system and an IEEE 118 bus test system. The effectiveness of IPFC in a power system network ensuring system security is thoroughly investigated and the results are compared with that of existing methods available in the literature.

Keywords

SCUC, security constraints, IPFC, power flow, line outage

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1 Introduction

Unit Commitment (UC) is one of the critical decision making processes performed by the power system operators in the deregulated market. The main objective of UC problem is to find an optimal schedule to commit the generating units which minimizes the dispatch cost for meeting the forecasted system load, while satisfying various constraints. Only when the unit commitment schedule is optimal, economic operation of the system is possible. Under normal operating conditions, the system operator dispatches the committed generation resources to satisfy the actual demand and reliability requirements. When the actual system condition deviates from the expected or forecasted condition, the operator has to take necessary measures such as committing expensive fast-start generators or load shedding in emergency situation to maintain system security. In an electricity market, profit motive makes the transmission network to run more close to its security margin. For achieving this, security constraints have to be considered in UC, which is then called as Security Constrained Unit Commitment (SCUC). The main aim of SCUC is to obtain a commitment schedule without compromising the system security [1].

During last decade FACTS devices are extensively used for maximizing the loadability of already available power system transmission networks. As the power transmission increases, the power system becomes more complex to operate resulting in loop flows, unscheduled outages and more losses. The possibility of operating the power system at the minimal cost while satisfying all constraints is one of the main issues in stretching transmission capacity by the use of Flexible AC Transmission Systems [FACTS] [2, 3]. The objective of FACTS device is to control the power flow through designated routes and increase the transmission capability to the thermal limit. Incorporating FACTS devices into a power system network improves the power flow and loadability of the line during variable load conditions. This will reduce the burden of generators which are committed to meet the sudden load demand thus making the generation more economical. In this paper IPFC is incorporated in a power system network and its performance based on obtaining minimum generation cost and preventing the overloading of transmission lines are investigated. Interline Power Flow Controller, which is the latest evolved FACTS device for transmission network, is used to compensate a number of transmission lines in a given network [4]. The number of inverters in the IPFC will be equal to the number of transmission lines required to be compensated in a power system network. Each inverter in the IPFC can facilitate transfer of real power among other inverters and independently control the reactive power flow in the line [5]. IPFC is used to transfer power from overloaded lines to under loaded lines. During the outage of lines in power system network, there is a chance for violation of constraints, since the actual load has to be met by the existing transmission lines. In this condition, the power generated by certain source has to be changed, and the lines may get overloaded because of an outage occurring in transmission lines. By placing IPFC in the proper location, the power flow in the lines can be improved and the overloading of the lines due to outage can be alleviated.

Due to the complication of mathematical model of SCUC problem, several techniques have been proposed in order to solve the problem effectively. Dynamic programming, Lagrangian Relaxation (LR) [6, 7] and mixed-integer programming methods are applied in solving the unit commitment problem. Hybrid PSO [8] and social Evolutionary Programming [9] techniques are used for solving UC problem. In Ref. [10] genetic algorithms, tabu search, and simulated annealing are integrated to solve UC problem. In [11] Benders decomposition technique is applied to solve the SCUC problem. Ruiz et al. [12] proposed a hybrid approach, which combines the reserve requirement and stochastic optimization methods to improve the robustness of stochastic UC solutions. In [13] authors developed and implemented an integer coded genetic algorithm (ICGA) to solve the UC problem. In [14], a scenario based SCUC model without reserves was established, considering load forecast errors and system contingencies. A comparison between Mixed integer Programming (MIP) and LR is presented in [15, 16, 17] solved the unit commitment problem using a stochastic model without considering transmission security constraints, or fuel and emission limits. The SCUC problems encounter some inherent limitations that of the unreasonable relaxations for the discrete variables and unstable computing efficiency while applying the above said methods. However based on the literature survey, very few works have been carried out in the area of UCP incorporating FACTS devices. In the restructured power system environment where security and economic criteria's are considered to be the topmost priority, this paper investigates the incorporation of IPFC in UCP.

1.1 Proposed Work

This paper solves SCUC using ABC algorithm proposed by Karaboga [18]. IPFC is incorporated in the power system network to investigate the following two conditions:

(a) The role of IPFC for improving the power flow and thereby minimizing the total operating cost and
(b) To investigate the role of IPFC for system security during the occurrence of contingency, (i.e), in this paper contingency is simulated by randomly opening a loaded transmission line.

The capability of IPFC to handle the power flow in transmission lines without violating the constraints during outages is also demonstrated. IPFC is incorporated in the power system network by Power Injection (PI) modeling. Comparative analysis is carried out in 6 bus system with and without IPFC, and IPFC with single line outage.

In Ref. [18, 31], it is clearly proven that ABC algorithm can be efficiently used for solving constrained optimization problems. Therefore in this proposed methodology ABC algorithm is used as an optimization tool. Binary coded ABC is used to solve the master UC problem and real coded ABC is used to solve the security constrained economic dispatch sub-problem. All the above mentioned analysis are performed in a benchmark 6 bus test system available in the literature [19, 20]. The following 5 case studies are investigated in 6 bus test system and IEEE 118 bus test system.

(a) SCUC for 6 bus test system
(b) SCUC for 6 bus test system incorporating IPFC in line 2-3-4
(c) SCUC for 6 bus test system incorporating IPFC involving a single line outage.
(d) SCUC for IEEE 118 bus test system
(e) SCUC for IEEE 118 bus test system incorporating IPFC

2 Interline Power Flow Controller

2.1 Basic Operating Principle

STATCOM The Interline Power Flow Controller (IPFC) addresses the problem of compensating a number of transmission lines at the given substation. Series capacitive compensation is employed conventionally to increase the transfer of real power over a given line. However, series reactive compensators are unable to control the reactive power flow and thereby results in improper load balancing of transmission lines. This happens when the ratio of reactance to resistance of the line (X/R) is relatively low. Series reactive compensation significantly decreases the effective X/R ratio since it can reduce only the effective reactive impedance X, resulting in increased reactive power flow and losses in the line. The IPFC scheme, together with independently controllable reactive series compensation of each individual line enables the transfer of real power between the compensated lines. The IPFC can potentially provide a highly effective scheme for power transmission management at a multiline substation, where the other available FACTS devices can control the real and reactive power flow through single transmission line only. This capability makes it possible to:

1. Compensate against resistive line voltage drops and the corresponding reactive power demand
2. Increase the effectiveness of the overall compensating system for dynamic disturbances and
3. Reduce the burden of overloaded lines by real power transfer.

Interline Power Flow Controller employs a group of dc-ac converters each providing series compensation for different lines. In other words, the IPFC comprises a group of Static Synchronous Series Compensators (SSSC) linked together at dc terminals as shown in Fig. 1. With this scheme, along with providing series reactive compensation, any converter can be controlled to supply real power to the common dc link from its own transmission line. Thus an overall surplus power available from the under utilized lines, which then can be used by other lines for real power compensation. In this way, some of the overloaded lines or lines with heavy burden of reactive power flow can be equipped with full two- dimensional reactive and real power flow control capability. IPFC consists of two back-to-back dc-to-ac converters connected in series with two transmission lines through series coupling transformers and the dc terminals of the converters are connected together via a common dc link as shown in Fig. 1.

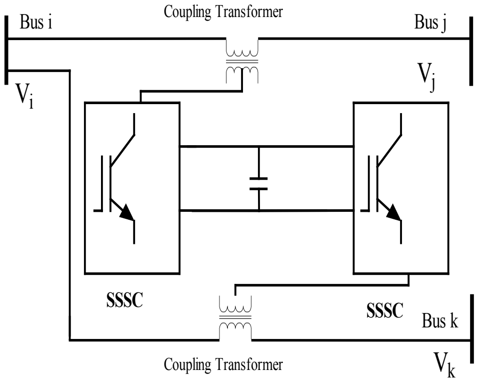

Fig. 1 Schematic diagram of IPFC

2.2 Mathematical Modelling of IPFC

IPFC is modelled using PI model which is helpful in understanding the impact of the IPFC on the power system in the steady state. Furthermore, this IPFC model can easily be incorporated in the power flow analysis. Usually, in the steady state analysis of power system, the Voltage Source Converters (VSC) may be represented as a synchronous voltage source injecting a sinusoidal voltage [21-25] with a controllable magnitude and angle. Power injection modeling technique is a method in which the FACTS devices are considered as synchronous voltage sources and the real and reactive powers are calculated accordingly. Here, the IPFC is considered as two voltage sources with series reactance and the equivalent circuit is shown in Fig. 2. The voltage magnitudes and phase angle of converters, series reactance and bus voltages are used for calculating the power flow with IPFC.

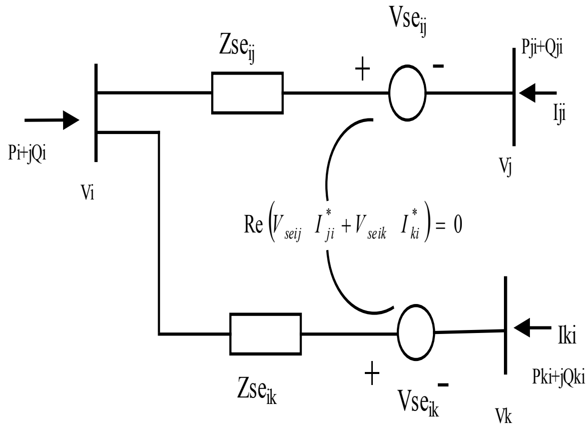

Fig. 2 Equivalent circuit of IPFC

In Fig. 2, Vi, Vj and V_k are the complex bus voltages at the buses i,j and k respectively, Vse_{in} is the complex controllable series injected voltage source, and Zse_{in} (n=j,k) is the series coupling transformer impedance. The complex power injected by series converter connected in between bus i and bus j as shown in Fig. 2 can be written as

$$P_{ij} = V_i^2 g_{ij} - \sum_{j=1, j\neq i}^{n} V_i V_j \left(g_{ij}\cos\theta_{ij} - b_{ij}\sin\theta_{ij} \right) - \sum_{j=1, j\neq i}^{n} V_i V_{seij} \left(g_{ij}\cos\left(\theta_{ij}-\theta_{seij}\right) - b_{ij}\sin\left(\theta_{ij}-\theta_{seij}\right)\right) \tag{1}$$

$$Q_{ij} = V_i^2 b_{ij} - \sum_{j=1, j\neq i}^{n} V_i V_j \left(g_{ij}\sin\theta_{ij} - b_{ij}\cos\theta_{ij} \right) - \sum_{j=1, j\neq i}^{n} V_i Vse_{ij} \left(g_{ij}\sin\left(\theta_{ij}-\theta se_{ij}\right) - b_{ij}\cos\left(\theta_{ij}-\theta se_{ij}\right)\right) \tag{2}$$

$$P_{ji} = V_j^2 g_{ij} - \sum_{j=1, j\neq i}^{n} V_i V_j \left(g_{ij}\cos\left(\theta_j-\theta_i\right)_{ij} - b_{ij}\sin\left(\theta_j-\theta_i\right)\right) - \sum_{j=1, j\neq i}^{n} V_j V_{seij} \left(g_{ij}\cos\left(\theta_{ij}-\theta_{seij}\right) - b_{ij}\sin\left(\theta_{ij}-\theta_{seij}\right)\right) \tag{3}$$

$$Q_{ji} = V_j^2 b_{ij} - \sum_{j=1, j\neq i}^{n} V_i V_j \left(g_{ij}\sin\left(\theta_j-\theta_i\right)_{ij} - b_{ij}\cos\left(\theta_j-\theta_i\right)\right) - \sum_{j=1, j\neq i}^{n} V_j V_{seij} \left(g_{ij}\sin\left(\theta_{ij}-\theta_{seij}\right) - b_{ij}\cos\left(\theta_{ij}-\theta_{seij}\right)\right) \tag{4}$$

where

$$g_{ij} = \mathrm{Re}\left(1/Zse_{ij}\right), b_{ij} = \mathrm{Im}\left(1/Zse_{ij}\right) \tag{5}$$

The same equations can be derived for bus k also.

3 Problem formulation

The objective of the security-constrained unit commitment problem is to minimize the total generation cost of committed generators in addition with the start up cost of initially committed units in that particular hour. Here, after determining the set of committed generation units, economic dispatch is carried out with this set of units. This generation pattern is again checked with the network security constraints using the standard load flow model for any violation in dispatch or line over load. Unit commitment program will re-run until the system security is not jeopardized. The objective function of the SUCP is given by

$$\text{Min}\sum_{t=1}^{T}\left\{\sum_{t=1}^{I}\left[Fi\left(P_{i,t}\right)\cdot u_{i,t}+ST_{i,t}+SD_{i,t}\right]\right\} \tag{6}$$

where

t = Time index

T = Number of hours for the scheduling period

I = Denotes a thermal unit

$P_{i,t}$ = Active power generation of unit "i" at time "t"

F_i = Production cost function of unit "i"

$ST_{i,t}$ = Start up cost of "i" at time "t"

$SD_{i,t}$ =Shut down cost of "i" at time "t"

Subjected to

1. System energy balance constraints

$$\sum_{i=1}^{I}P_{i,t}=P_D\left(t\right)+P_L\left(t\right) \qquad \forall t \tag{7}$$

where

$P_D(t)$ = Forecasted load at time "t"

$P_L(t)$ = system losses at time "t"

2. Spinning reserve constraints

$$\sum_{i=1}^{I}rs_{i,t}\geq R_s\left(t\right) \qquad \forall t \tag{8}$$

where

$rs_{i,t}$ = Spinning reserve of unit "i" at time "t"

$R_s(t)$ = System Spinning reserve requirement at time "t"

3. Non Spinning reserve constraints

$$\sum_{i=1}^{I}nr_{i,t}\geq R_N\left(t\right) \qquad \forall t \tag{9}$$

where

$nr_{i,t}$ = Non Spinning reserve of unit "i" at time "t"

$R_N(t)$ = System Non Spinning reserve requirement at time "t"

4. Regulation up and down constraints

$$\sum_{i=1}^{I}ru_{i,t}\geq R_{RU}\left(t\right) \qquad \forall t \tag{10}$$

$$\sum_{i=1}^{I}rd_{i,t}\geq R_{RD}\left(t\right) \qquad \forall t \tag{11}$$

where

$ru_{i,t}$ = Regulation up time of unit "i" at time "t"

$rd_{i,t}$ = Regulation up time of unit "i" at time "t"

$R_{RU}(t)$ = System regulation up requirement at time "t"

$R_{RD}(t)$ = System regulation down requirement at time "t"

5. Ramp limits

$$P_{i,t+1}-P_{i,t}\leq RU_i\left(1-y_{i,t}\right)+P_{i,\min}y_{i,t} \quad \forall i,\forall t \tag{12}$$

$$P_{i,t}-P_{i,t+1}\leq RD_i\left(1-z_{i,t}\right)+P_{i,\min}z_{i,t} \quad \forall i,\forall t \tag{13}$$

where

RU_i, RD_i = Ramping up/down limit of unit "i"

$y_{i,t}$ = Startup indicator

$z_{i,t}$ = Shutdown indicator

6. Minimum ON/OFF time limits

$$y_{i,t}+\sum_{j=t+1}^{\max\{T,t+MU_t-1\}}z_{i,j}\leq 1, \quad \forall i,\forall t=UT_i+1,....,T \tag{14}$$

where

$UT_i=MAX\left\{0,MIN\left[T,\left(MU_i-TU_{i,0}\right)u_{i,0}\right]\right\}\ \forall i$

MU_i = minimum up time of unit "i"

UT_i = Number of hours a unit need to remain ON at the beginning of the scheduling period

TU_i = Number of hours a unit has been ON at the beginning of the scheduling period

7. Active and reactive power generation limits

$$P_{i,\min}\cdot u_{i,t}\leq P_{i,t}\leq P_{i,\max}\cdot u_{i,t} \quad \forall i,\forall t \tag{15}$$

$$Q_{i,\min}\cdot u_{i,t}\leq Q_{i,t}\leq Q_{i,\max}\cdot u_{i,t} \quad \forall i,\forall t \tag{16}$$

where

$P_{i,t}$ = Active power generation of unit "i" at time "t"

$Q_{i,t}$ = Reactive power generation of unit "i" at time "t"

$P_{i,\min}$, $P_{i,\max}$ = Minimum and maximum active power generation of unit "i" at time "t"

$Q_{i,\min}$, $Q_{i,\max}$ = Minimum and maximum reactive power generation of unit "i" at time "t"

8. Transmission line flow Limits

$$-FL_l^{\min}\leq -FL_{l,t}\leq -FL_l^{\max} \ \forall l,\forall t \tag{17}$$

where

$FL_{i,t}$ = Line flow at line "l"

$FL_i^{\min}, FL_i^{\max}$ = Maximum and minimum line flow

9. Bus voltage Limits

$$-V_b^{\min}\leq -V_{b,t}\leq -V_b^{\max} \ \forall b,\forall t \tag{18}$$

where

$V_{b,t}$ = Voltage magnitude at bus "b"

$V_b^{\min}, V_b^{\max}$ = minimum and maximum Voltage magnitude at bus "b"

10. IPFC constraints

$$Vse_{mn}^{\min} \le Vse_{mn} \le Vse_{mn}^{\max} \quad (19)$$

$$\theta se_{mn}^{\min} \le \theta se_{mn} \le \theta se_{mn}^{\max} \quad (20)$$

where

$Vse_{mn}^{\min}, \theta se_{mn}^{\min}$ are the minimum value of the magnitude and angle of series voltage source in IPFC.

$Vse_{mn}^{\max}, \theta se_{mn}^{\max}$ are the maximum value of the magnitude and angle of series voltage source in IPFC.

All the above constraints should be satisfied while running the UCP.

4 Implementation of ABC Algorithm for SCUC

The ABC algorithm belongs to a class of swarm intelligence algorithms that are inspired by the intelligent behavior of the honey bees in finding nectar sources around their hives [26-28]. The total number of bees in the colony is categorized into three groups: employed, onlookers and scout bees. The colony is equally divided into employed bees and onlooker bees. Each solution consists of a set of parameters to be optimized which represent a food source position. The total number of employed bees will be equal to the number of food sources. The fitness value corresponds to the quality of food source and is associated with its position. The process of searching the better food source is used to find the optimal solution. From these bees employed bees starts its search process by its own experience and followed by the onlooker bees by getting the information exchange from the employed bees and update their new positions by probabilistically. Scout bees finds new food sources using randomness. The food sources represent the possible solution and the nectar amount represents the quality of the solution obtained. The onlooker bees evaluate the nectar information available and choose a food source depending on the probability value associated with that food source given by Eq. (21).

$$\Pr_p = \frac{fit_p}{\sum_{p=1}^{N_e} fit_q} \quad (21)$$

where fit_p is the fitness value of the solution p which is proportional to the nectar amount of the food source in the position p and is the number of food sources which is equal to the number of employed bees. Now the onlookers produce a modification in the position selected by it using Eq. (22) and evaluate the nectar amount of the new source.

$$v_{pq} = x_{pq} + \varphi_{pq}\left(x_{pq} - x_{kq}\right) \quad (22)$$

where k ∈ {1 2. . . n_e} and q ∈ {1 2 . . . D} are are randomly chosen indexes. Although k is determined randomly it has to be different from is a random number between [−1,1]. It controls the production of neighborhood food sources. If the nectar amount of the new source is higher than that of the previous one the onlookers remember the new position; otherwise it retains the old one. In other words, greedy selection method is employed as the selection operation between the old and the new food sources. If a solution representing a food source is not improved by a predetermined number of trials, then that food source is abandoned and the employed bee associated with that food source is changed to a scout. The scout bee discovers a new food source x_{ij} using Eq. (23).

$$x_{pq} = x_{q\min} + \mathrm{rand}(0,1) \times \left(x_{q\max} - x_{q\min}\right) \quad (23)$$

where $x_{q\min}$ and $x_{q\max}$ are the of the parameter to be optimized. There are four control parameters used in ABC algorithm. They are the number of employed bees, number of unemployed or onlooker bees, the limit value (MCN) and the colony size.

4.1 Repair Strategy for Constraint Management

When an initial solution is randomly generated or whenever a modification in the positions is made by the employed and onlooker bees the strings may not satisfy the spinning reserve and Minimum Up Time and Minimum Down Time (MUT/MDT) constraints.

If spinning reserve constraints are violated then less expensive unit should be turned on randomly. This process is continued until the spinning reserve constraints are satisfied. The minimum UP/DOWN constraints are checked for their new status, if any violation occurs, then repair mechanism is used to overcome this. For instance, let us assume that the minimum up and down time of unit 1 is 4 h. During the scheduling of 12 hours, if the off time of unit "1" is 3 h (5th -7th), which is less than 4 h thus violating the MDT constraint. In this case, the unit status before 5th h or after 7th h can be made '0'. By doing so, if it violates the minimum up time constraint, then the status of the units are made 1 during the violated down time period. But, this repairing strategy and UP/DOWN time violation affects the spinning reserve and power balance constraints. In this condition, the committed units may be surplus or insufficient. Therefore if the committed units are in surplus, some units can be turned off. In doing so, the units that have the least UP/DOWN time can be selected. Again the minimum UP/DOWN time constraint has to be checked. A minimum number of trials can be set for the repair mechanism. This is represented in Fig. 3.

4.2 Procedure For Binary/Real Coded ABC

4.2.1 Binary coded ABC

Step 1: Initialize the ABC parameters such as the colony size, number of employed and onlooker bees, limit value and maximum cycle number (MCN) and IPFC parameters.

Step 2: Initial generation of population

Generate M random population of binary strings as bits of 1 or 0, which represents the ON/OFF status of generators.

Step 3: Repair and solve SCED

The randomly generated commitment status for each time interval is checked for spinning reserve constraint (8) and minimum up/down time (10-11) constraints violation. If any violation occurs, binary strings are repaired as in Section 4.1. Then security constrained economic load dispatch is done as in Section 4.2.2 for the feasible positions and constraints (12-13) and (15-16) are satisfied.

Step 4: Evaluation of fitness of the population

For calculation of fitness function Eq. (24) is used.

$$\text{Fitness} = A\left[1 - \%\text{Cost}\right] \tag{24}$$

$$\%\cos t = \frac{String\cos t - Min\cos t}{Max\cos t - Min\cos t} \tag{25}$$

where A is a positive weighting coefficient. String cost is the individual string's cost of generation. Mincost and Maxcost are the minimum and maximum objective function value within the population. In Eq. (24) the individual with the lowest total cost has the highest fitness. The best fitness among the individuals is determined and the corresponding minimum cost and the parameters responsible for the minimum total cost. The cycle count is set to one and repeat the following steps until the maximum cycle number (MCN) which is the termination criteria is reached.

Step 5: Modification of position and selection of site by employed bees:

The current position of employed bees is modified using Eq. (22) ,the new modified position is checked for constraints in Eqs. (7), (8), (12), (13). If any of these constraints are violated, then the repair strategy for spinning reserve and MUT/MDT as discussed in step 3 is employed. SCED is done and the fitness value of the new food source position is calculated. The fitness of the new modified position is compared with the fitness of the old position computed in step 3. Here a greedy selection mechanism is employed as the selection operation between the old and the new position. In case if fitness value of the new position is better than the old one, then a limit count is set.

Step 6: Recruit onlooker bees for selected sites

The onlooker bee evaluates the nectar information which is taken from all employed bees and chooses a food source with a probability Prp using Eq. (21) according toits fitness value. Onlookers are placed onto the food source sites by using a fitness based selection technique (tournament selection).

Step 7: Modification of position by onlookers

As in the case of the employed bees discussed in step 4 the onlookers produce a modification on their position in its memory using Eq. (22). As discussed in step 4 the modified positions are changed to the corresponding on/off status of the units. Constraints (14) and (8) are checked for MUT/MDT and spinning reserve violations. If there is any violation in these constraints, then repair mechanism is done as mentioned in Section 4.1. Then SCED is performed and the fitness is evaluated. Again greedy selection mechanism is employed as the selection operation between the old and new position.

Step 8: Abandon sources exploited by the bees

If a solution representing a food source is not improved by a predetermined number of trials, then that food source is abandoned and the scout discovers a new food source to be replaced with Xp. The number of trials for releasing a solution is equal to the value of limit. This operation is performed using Eq. (23). For the UCP can be either '0'or '1'.

Step 9: Memorize the best solution achieved so far. Increment the cycle count.

Step 10: Stop the process if the termination criteria are satisfied. Termination criteria used in this work is the specified maximum number of cycles. Otherwise go to step 4. The best fitness and the corresponding position of the food source retained in the memory at the end of the termination criteria is selected as the optimum commitment schedule of generating units involved in the power generation process for the scheduling time interval. For the optimum commitment schedule obtained economic dispatch is performed for each interval. Compute the total cost for the 24 h time interval.

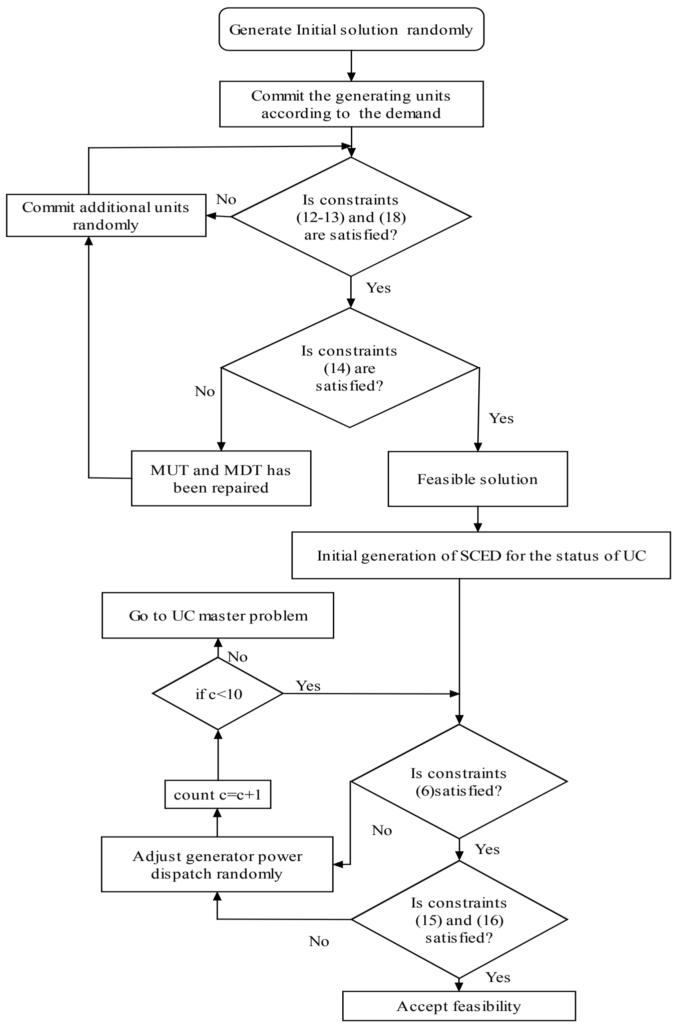

Fig. 3 Flowchart of constraint handling in SCED

Pseudo-code of the real-coded ABC algorithm to solve SCED problem Binary coded ABC

The . Initialize the control parameters and read system data.

2. Set time interval "t" to 1
3. Repeat.
4. Generate the initial population as in Step 1
5. Evaluate the fitness of the population as in Step 2
6. Set cycle to 1.
7. For each employed bee - produce new solution using Eq. (22) and check for constraints. calculate the fitness value using (24) and apply greedy selection process.
9. Calculate the probability values Prp for the solutions using Eq. (21).
10. For each unemployed or onlooker bee - select a solution depending on Prp and produce new solution using Eq. (23) and check for constraints. Calculate the fitness value using (24) and apply greedy selection process.
11. Abandon sources exploited by the bees using Eq. (23).
12. Memorize the best solution achieved so far.
13. cycle = cycle + 1.
14. Until cycle = MCN (Termination criteria).

The best fitness and the corresponding position of the food source retained in the memory at the end o the termination criteria is selected as the optimum output powers of generating units involved in the economic dispatch process for that time interval. The overall SCUC procedure is given in Fig. 4.

5 Numerical Results

The proposed methodology is implemented using 2.33 GHz Pentium IV, Windows XP with 1 GB of RAM and has been simulated in the MATLAB 7.5 environment. Two test cases (6 bus system, IEEE 118 bus system) are carried out over a scheduling horizon of 24 hours. SCUC incorporating IPFC is carried out in both the test systems and the impact of IPFC is clearly demonstrated. Single line outage contingency is carried out in the 6 bus system, and the performance of IPFC in alleviating the violation of constraints are described. The ABC parameters are obtained by trial and error method for both the test systems. For 6 bus test system, for both UC and SCED, the colony size is taken as 20 and the maximum cycle number is taken as 300. For IEEE 118 bus system the colony size is taken as 200 and the maximum cycle number is 300. Both test systems are subject to (n-1) security criterion [29-30] characterized by the loss of a generation unit. The unit shut down cost is not included because the cost is considered as negligible and can be assumed to be zero.

5.1 6 -Bus Test System

The 6 bus three generator system shown in Fig. 5 is used to demonstrate the effectiveness of the proposed SCUC algorithm in this case. The 6 bus test system has three units, five transmission lines, two tap-changing transformers and three demand sides. The following cases mentioned in Section 1.1 are simulated and the results are discussed in the following sections.

5.1.1 SCUC in 6 Bus System Without IPFC

The SCUC problem is solved by considering power flow constraints, transmission flow and bus voltage violations using the ABC algorithm. While solving a normal UC problem without incorporating security constraints such as MVA limits and voltage constraints, two kinds of violations are observed. The first one is a line flow violation occurring at the line 1-4 at 9th and 10th hours, the second one is the violation of bus voltage at buses 2 and 4 .This is because the power flow in the transmission line is above 100 MW, exceeding its maximum capacity of 100MW. The bus voltage violations are encountered on buses 2 and 4, because the amplitude values of the voltage are lower than the lower limit of the bus voltage on the two buses.

These two problems are eliminated in SCUC model. The commitment schedule of SCUC for a time horizon of 24 hours are given in Table 1. The daily operating cost of the SCUC is $84,228.51. This cost is slightly higher than the operating cost of traditional UC as security constraints are considered. Similarly violations in the Economic dispatch are rectified in the SCED. The generation dispatch schedule of SCUC problem is given in Table 3.

The cost convergence characteristics for 10 trials is shown in Fig. 6, which gives the best, worst and average cost for the first hour. From Fig. 6 it is clear that the average cost with ABC is much closer to the best cost obtained. Table 2 shows the superiority of the proposed method with the other methods which are available in the literature.

Table 1 Commitment schedule of SCUC in 6 bus system

Hour	G1	G2	G3	Hour	G1	G2	G3	Hour	G1	G2	G3
1	1	1	0	9	1	1	0	17	1	1	1
2	1	0	0	10	1	1	1	18	1	1	1
3	1	0	0	11	1	1	1	19	1	1	1
4	1	0	0	12	1	1	1	20	1	1	1
5	1	0	0	13	1	1	1	21	1	1	1
6	1	0	0	14	1	1	1	22	1	1	1
7	1	0	0	15	1	1	1	23	1	0	0
8	1	0	0	16	1	1	1	24	1	0	0

Table 2 Comparison of results for 6 bus system

Solution methods	Total operating cost ($)
	SCUC
SDP [29]	84,268.79
HybridABPSO-ARCGA [30]	84,243.46
Proposed method	84,228.51

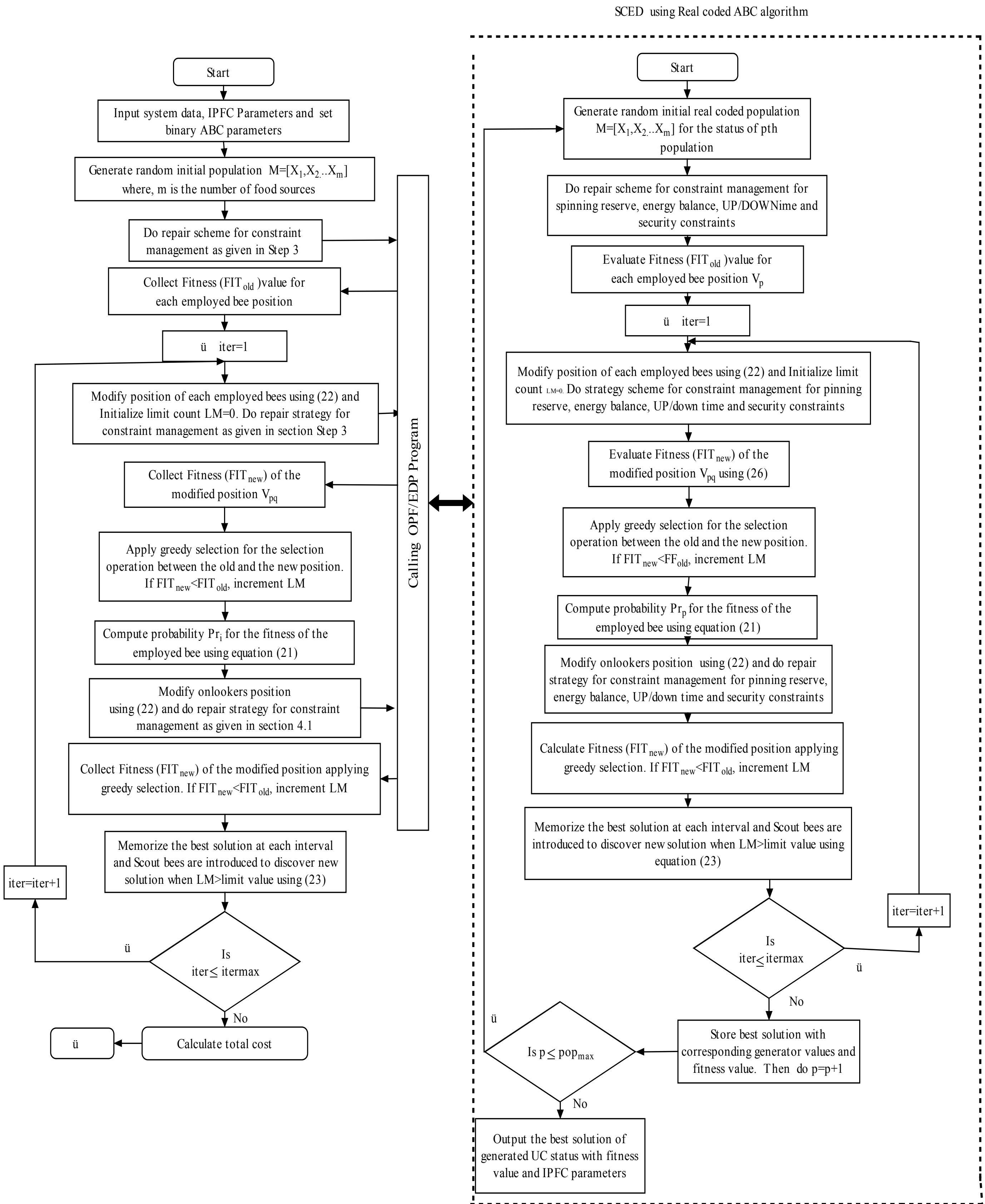

Fig. 4 Flowchart of the ABC algorithm for SCUC

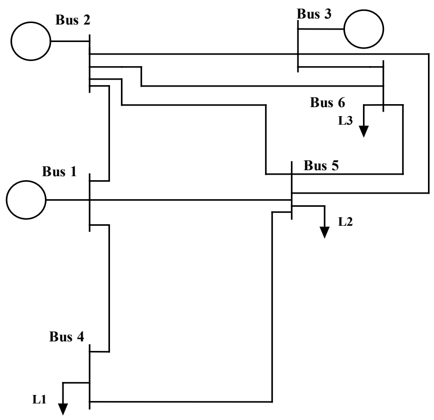

Fig. 5 6 bus 3 generator test system

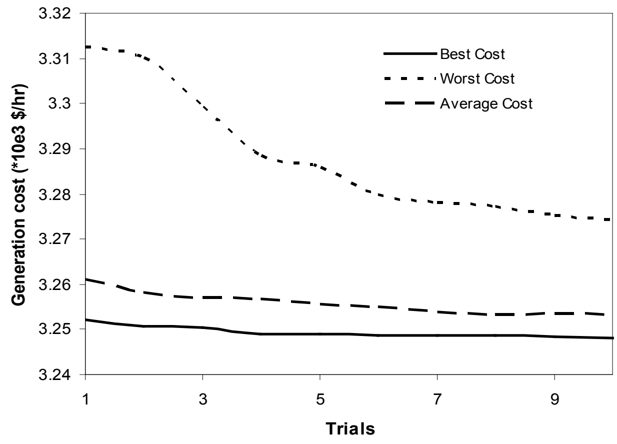

Fig. 6 Cost convergence of 6 bus system

Table 3 Generation dispatch schedule of SCUC in 6 bus system with and without IPFC

Hr	SCUC-six-bus			SCUC-six-bus with IPFC		
	Total cost $ 84228.51			Total cost $ 84224.43		
	G1	G2	G3	G1	G2	G3
1	169.34	10	0	169.21	10	0
2	169.09	0	0	169.03	0	0
3	162.43	0	0	162.12	0	0
4	158.39	0	0	158.28	0	0
5	158.72	0	0	158.39	0	0
6	164.29	0	0	164.33	0	0
7	177.56	0	0	177.51	0	0
8	199.09	0	0	199.12	0	0
9	200.54	10.00	0	200.50	10.00	0
10	204.44	10.00	10.00	204.44	10.28	10.00
11	213.72	10.44	10.00	212.99	10.44	10.00
12	219.26	10.00	18.81	219.26	10.00	18.73
13	220.00	10.51	17.58	220.02	10.51	17.58
14	219.61	10.00	19.90	219.33	10.01	19.90
15	219.60	15.62	20.00	218.32	15.62	20.12
16	219.94	32.00	20.00	219.88	32.00	20.03
17	219.66	51.50	20.00	219.66	51.30	20.03
18	219.21	13.50	20.00	219.21	13.50	20.00
19	218.41	13.50	20.00	218.55	13.43	19.46
20	212.95	10.00	20.00	212.38	10.08	20.21
21	219.59	10.00	13.50	219.59	10.01	13.50
22	211.74	10.00	10.89	210.82	9.89	11.45
23	198.95	0	0	198.92	0	0
24	191.51	0	0	191.56	0	0

5.1.2 Case: 2 SCUC for 6 bus test system incorporating IPFC line 2-3-4

In this case, IPFC is placed in line 2-3-4 of the 6 bus system and SCUC is carried out using ABC algorithm. The maximum and minimum amplitude of voltages of both the converters in IPFC are chosen as 0.001 and 0.2 p.u respectively. The maximum and minimum value of converter angles in both the converters of IPFC are taken as -180 and 180 degree respectively. The parameters for ABC are chosen as given in Section 5. The power flow targets are fixed to the IPFC depending on the flow of power in the line.

Along with the security constraints, the IPFC constraints are also considered in this case. The commitment statuses of the generators are same as that of the previous case. The dispatch schedule for the 6 bus system with IPFC is given in Table 2. Incorporation of IPFC into the network improves the power flow and reduces the burden of the generators. It is clear from Table 2, that the real power generation is reduced in most of the cases with the incorporation of IPFC to meet a constant load demand. The real power losses are also reduced. The total generation cost is $84224.43 which is less compared to that of SCUC without IPFC. All the constraints including the IPFC constraints are satisfied in this case. The total generation cost is $84224.43 which is less compared to that of SCUC without IPFC. All the constraints including the IPFC constraints are satisfied in this case.

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Table 4 shows the IPFC parameters for certain hours of dispatch, which shows that the IPFC parameters are within their limits as specified. The cost convergence characteristics for 10 trials incorporating IPFC in the network is shown in Fig. 7, which shows the best , worst and average cost for the first hour. From Fig. 7 it is clear that the average cost using ABC algorithm is much closer to the best cost obtained in all trials.

Table 4 IPFC parameter of SCUC 6 bus system

Hours/ IPFC parameters	Vse1 (p.u)	Vse2 (p.u)	θse1 (Deg)	θse2 (Deg)
1	0.0294	0.1432	-83.95	69.89
6	0.0276	0.001	-85.67	-71.74
8	0.1291	0.1687	-69.39	-176.38
10	0.001	0.001	-69.1	-120.6
12	0.001	0.008	-175	-147.26
15	0.0724	0.0994	-180	-89.3
16	0.0154	0.00832	-180	165.3
19	0.01488	0.1712	-90.18	150.26
22	0.0171	0.001	-98.3	128.36

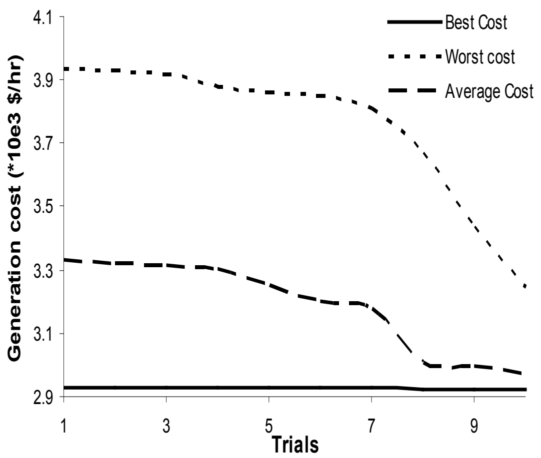

Fig. 7 Cost convergence of 6 bus system with IPFC

5.1.3 Case: 3 SCUC for 6 Bus Test System with IPFC Involving a Single Line Outage

In this case, SCUC problem is solved in a contingency environment with a random single line outage at line 3-6. Also the role of IPFC during its absence and presence in the power system network is investigated. The line 3-6 connects generator 3 and load L1, which has the maximum MW limit of 100. This limit is included in the security constraints. The outage of line 3-6 results in the overloading of other lines. When SCUC is solved without incorporating IPFC, the lines 2-3 and 2-4 got overloaded because of the outage occurred in line 3-6. It should be noted that the maximum MW limits of the above lines are 100MW. The power flowing during outage were 193.2MW and 178MW respectively. The power flowing at this condition is more than the specified limit, which violates the line flow constraints, so that SCUC fails to converge in this case. However SCUC is carried out by placing IPFC in lines 2-1-3 due to the line outage. It should be noted that the commitment schedule is same as that of Cases: 2, even during the occurrence of a transmission outage. The parameters of ABC and IPFC are kept same as in Case: 2. Convergence is obtained with a tolerance of 1e-12 when IPFC is incorporated. IPFC injects required amount of power into the system which minimizes the burden of the transmission lines due to the outage.

5.2 IEEE 118 Bus Test System

In this case SCUC is carried out in an IEEE 118 bus system incorporating IPFC using ABC algorithm. This test system has 54 thermal generating units and 186 transmission lines. The test data and the load data for 24 h duration along with reserves for IEEE 118 bus system are given in http://motor.ece.iit.edu/data/IEEE118data.xls and http://motor.ece.iit.edu/data/JEAS/IEEE118.doc respectively, in which the peak load demand is 6000 MW at 21st hour. The magnitude of voltage at each bus must be between 0.85 and 1.15. Ramp rate constraints are taken into account along with the spinning reserve and MUT/MDT constraints. The impact of IPFC is analyzed based on power flow improvement, reduction of line loss and active power generation cost.

First SCUC is carried out without incorporating IPFC. In this case, the economical units such as G4–G5, G10-G11, G24-25, G27-29, G36, G39-40 and G43-45 are used as base units. The expensive units such as G6, G8-9, G15, G17-18, G31-33, G38, G41-42, G49-50 and G54 are not committed at all. The remaining units are committed accordingly to satisfy hourly load demands. The daily operation cost is $1,713,370.01. In SCUC dispatch power flow violations are eliminated. Obviously, SCUC schedule can satisfy transmission, security and voltage constraints. The commitment schedule of the SCUC problem is presented in Table 5 in which1/0 represent hourly ON/OFF status of units. The cheaper units are always committed and dispatched to supply the base load. Daily generation dispatch cost is $1,713,370.01 without IPFC. The cost convergence characteristics for 10 trials without incorporating IPFC in the network is shown in Fig. 8, which shows the best , worst and average cost for the first hour. From Fig. 8 it is clear that the average cost with ABC is much closer to the best cost obtained in all trials. In this case, IPFC is placed in line 17-18-113 and SCUC is carried out. The maximum and minimum amplitude of voltages of both the converters in IPFC are chosen as 0.001 and 0.2 p.u respectively. The maximum and minimum value of converter angles in both the converters of IPFC are taken as -180 and 180 degree respectively. The parameters for ABC are same as that when IPFC is not placed in the network. The real and reactive power for target for IPFC is selected depending on the requirement. The commitment obtained for the generating units are same as that obtained without placing IPFC. It should be noted that the impact of IPFC is on the real power flow and the active power generation cost. The constraints are not violated with the incorporation of IPFC in the network. But the power flow in line 17-18-113 has increased with IPFC to a considerable level. Without IPFC the power flow in line 17-18 is 78.32MW and with IPFC it has improved to 81.22MW. The power flow in line 17-113 without IPFC is 1.18MW and 2.2 1MW with IPFC. There is an improvement of 3.70 % of real power in line 17-18 and 87.02 % of real power in 17-113 line. The IPFC parameters obtained are given in Table 6 which are also within their limits. The incorporation of IPFC into the network reduced the burden of generators in both real and reactive power generation. Since the IPFC injected power are specified, the real power generated by the sources in which IPFC is connected reduced the real power generation to meet the fixed load demand. This results in reduction in the total cost. The daily operating cost is $1,716,208.8 with IPFC, which is less compared to the daily operating cost of $1,713,370.01 without IPFC. The cost convergence characteristics for 10 trials incorporating IPFC in the network is shown in Fig. 8, which shows the best, worst and average cost for the first hour. The cost is less than the cost without incorporating IPFC in the network. From Fig. 8 it is clear that the average cost with IPFC is much closer to the best cost obtained in all trials.

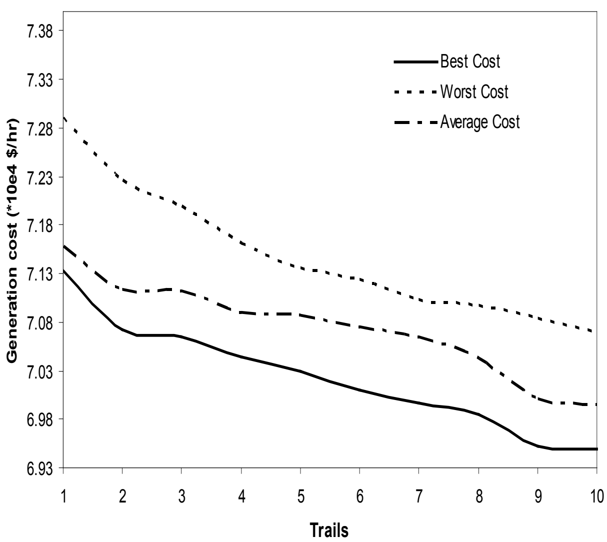

Fig. 8 Cost convergence without IPFC

Table 5 Commitment status for 118-bus system

Time (h)	Unit ON/ OFF status
1	0001100001100000000110011011100000010011001110000000000
2	0001100001100000000110011011100000010011001110000000000
3	0001100001100000000110011011100000010011001110000000000
4	0001100001100000000110011011100000010011001110000000000
5	0001101001100100000110011011100001010011001110000000100
6	000110100110010100111111101110000101001100111001001110
7	000110100110010100111111101111000111001100111011001110
8	000110100110010100111111111111000111101100111011001110
9	000110100110010100111111111111000111101100111011001110
10	000110100110010100111111111111000111101100111011001110
11	000110100110010100111111111111000111101100111011001110
12	000110100110010100111111111111000111101100111011001110
13	000110100110010100111111111111000111101100111011001110
14	000110100110010100111111111111000111101100111011001110
15	000110100110010100111111111111000111101100111011001110
16	000110100110010100111111111111000111101100111011001110
17	000110100110010100111111111111000111101100111011001110
18	000110100110010100111111111111000111101100111011001110
19	111110100110010100111111111111000111101100111111001110
20	111110100111110100111111111111000111101100111111001110
21	000110100110010100111111111111000111101100111011001110
22	000110100110010100111111111111000111101100111011001110
23	000110100110010100111111111111000111101100111011001110
24	0001100001100000000110011011100000010011001110000001000

Table 6 IPFC parameters of SCUC for 118-bus system

Hours/ IPFC parameters	2	6	10	12	16	22
Vse1 (p.u)	0.0082	0.025	0.031	0.033	0.001	0.0036
Vse2(p.u)	0.2	0.036	0.031	0.001	0.024	0.2
θse1(Degree)	-83.95	-85.67	-69.14	-175	-180	-98.26
θse2(Degree)	-128.3	119.9-	-157.4	-130.6	-130.9	-135.9

6 Conclusion

This paper investigates the role of IPFC in a solution of SCUC using ABC. UC and SCED are solved simultaneously to obtain the economic operation schedule of generators satisfying all security constraints. The proposed approach is validated by testing on a 6 bus system and an IEEE 118 bus system for a time horizon of 24 hours. The proposed methodology gives better solution a par with other methods available in the literature. The effect of installing IPFC in a power system network is clearly demonstrated in terms of power flow improvement. The results show that the IPFC can alleviate transmission line congestion by redirecting power flow and can prevent a contingency during the occurrence of a transmission line outage.

By incorporating IPFC, the transmission lines can be loaded to a higher level to meet the required load demand. The investigation on the role of IPFC in an SCUC problem will be useful for the system operators in the deregulated market.

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