Static Economic Dispatch Incorporating UPFC Using Artificial Bee Colony Algorithm

S. Sreejith, Velamuri Suresh and P. Ponnambalam

Abstract Static economic dispatch is a real-time problem in power system network. Here, the real power output of each generating unit is calculated with respect to forecasted load demand over a time horizon while satisfying the system constraints. This paper explains the impact of unified power flow controller (UPFC) in static economic dispatch (SED) using artificial bee colony (ABC) algorithm. UPFC is a converter (shunt and series)-based FACTS device, which can control all the parameters in a transmission line individually or simultaneously. ABC algorithm that imitates the foraging behavior of honey bees is used as an optimization tool. The impact of UPFC in reducing the generation cost, loss, and improving voltage profile, power flow are demonstrated. The studies are carried out in an IEEE 118 bus test system and a practical South Indian 86 bus utility.

Keywords Economic dispatch · Artificial bee colony · Unified power flow controller · Voltage source converter

1 Introduction

Economic dispatch of generating units is one of the significant functions of contemporary energy management system. The static economic dispatch problem (SED) can be formulated as a constrained optimization problem which reduces the

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M. Pant et al. (eds.), *Proceedings of Fifth International Conference on Soft Computing for Problem Solving*, Advances in Intelligent Systems and Computing 436, DOI 10.1007/978-981-10-0448-3_63

total generation cost within committed units satisfying system equality and inequality constraints. In conventional methods the cost curves of power generators are usually assumed to be quadratic and monotonically increasing functions. A variety of nonlinearities are present in the cost curves of modern generating units due to valve point loading. This results in inaccurate assumptions and the results in approximate solutions. On other hand, the evolutionary methods such as differential evolution (DE)¸ particle swarm optimization (PSO), genetic algorithms (GA), and bacterial foraging (BF) are free from these convexity assumptions and perform better since they have excellent parallel search capability. Therefore, the above methods are particularly popular for solving nonlinear and nonconvex optimization problems. In dynamic programming [1] the shape of cost curves is unrestricted, but it consumes more time and suffers from dimensional issues. Optimization methods like dynamic programming [1], genetic algorithm [2–4], evolutionary programming [3], and particle swarm optimization [5–7] solve nonconvex optimization problems in a faster rate and efficient manner. ABC algorithm is used efficiently [8] for solving constrained optimization problems [9], so ABC algorithm is used as an optimization tool in the proposed methodology. It is a well-known fact that the consumption of power is increasing day by day. Simultaneously, there is a slow growth in the generation sector also. The growth in the power generation should be met with the necessary infrastructures added to the transmission system. The transmission system should be capable of handling the maximum power flow through the transmission lines without exceeding the permissible MVA limits. In order to use the existing transmission corridor efficiently, by transmitting maximum power through the transmission lines, FACTS (flexible AC transmission systems) devices are suitably incorporated into the power system network. Installation of FACTS devices in the network will improve the real power flow by providing reactive power support to the lines. In 1988, Hingorani [10] initiated the concept of FACTS devices with their applications. The UPFC is one of the multipurpose devices of the FACTS family which is used for improving power system stability and damping power system oscillations [11–13]. A current injected UPFC model of UPFC for improving power system stability is discussed in [14]. In [15] PSO algorithm is applied to locate the optimal position of UPFC considering the cost of installation and system loadability. The optimal location is identified by calculating the maximum system loadability (MSL) index.

2 Economic Dispatch Problem

The economic load dispatch is used to allocate the active power demand among the committed generating units. This is carried out by satisfying the system and unit constraints. In reality, the load demand changes with respect to time. Thereby, the entire dispatch period is divided into number of subintervals and static economic dispatch problem (EDP) is employed for each interval. The objective of EDP is to reduce the fuel cost simultaneously satisfying the constraints. The objective function is given as follows:

$$F(P_i) = \sum_{i=1}^{N} a_i + b_i \cdot P_i + c_i \cdot P_i^2 \tag{1}$$

subjected to the following constraints:

2.1 System Constraint

2.1.1 Real Power Constraint

To satisfy the load demand, the sum of the system load and the transmission line losses must be equal to the total generation. The power balance constraint is

$$\sum_{i=1}^{N} P_i - P_D - P_L = 0 \tag{2}$$

Kron's loss formula is used to find the approximate value of the losses, which is given by

$$P_L = \sum_{i=1}^{N} \sum_{i'=1}^{N} P_i B_{ii} P_i + \sum_{i=1}^{N} B_{io} P_i + B_{oo} \tag{3}$$

2.2 Unit Constraint

2.2.1 Generation Capacity Limit

The active power generated is limited by minimum and maximum power limits.

$$P_{i,\min} \le P_i \le P_{i,\max} \tag{4}$$

where F—Fuel cost function, a_i, b_i, c_i—Generator cost coefficients of ith unit,
N—Number of generating units, P_i—Generation power output of unit i,
$P_{i,\min}$ and $P_{i,\max}$—Minimum and maximum real power outputs of unit i, P_D—Total load demand, P_L—Total losses, and B_{00}, B_{i0}, $B_{ii'}$—B loss coefficients.

2.3 UPFC Constraints

$$V_{vR\min} \leq V_{vR} \leq V_{vR\max} \tag{5}$$

$$V_{cR\min} \leq V_{cR} \leq V_{cR\max} \tag{6}$$

$$\delta_{vR\min} \leq \delta_{vR} \leq \delta_{vR\max} \tag{7}$$

$$\delta_{cR\min} \leq \delta_{cR} \leq \delta_{cR\max} \tag{8}$$

where

$V_{vR\min}, V_{vR\max}$	Minimum and maximum amplitudes of shunt voltage source
$V_{cR\min}, V_{cR\max}$	Minimum and maximum amplitudes of series voltage source
$\delta_{vR\min}, \delta_{vR\max}$	Minimum and maximum phase angles for shunt voltage sources
$\delta_{cR\min}, \delta_{cR\max}$	Minimum and maximum phase angles for series voltage sources.

3 Implementation of ABC Algorithm for Static Economic Dispatch

ABC algorithm is a metaheuristic algorithm for optimizing numerical problems [8, 9]. The performance of ABC algorithm is significant in solving various researches and engineering problems. The main components of ABC model are employed bees, food sources, onlooker or unemployed bees, and the dancing area. The employed bees fly round the search space and find the food sources using their experience. After completing their search process, the information on food source is shared to the unemployed bees which are in the hive. The information is shared by waggle dancing performed in the dancing area. By this dance, the information such as distance, direction, and the quality of the food sources are shared. The distance of the food source depends on the duration of the dance. The dancing time period will give the distance from the current position. In this work, the ABC algorithm is applied to determine the output power of all generation units for a specified load demand at a particular time horizon (T) to reduce the total generation cost. Here, solution of the problem is given by the position of the food source. The nectar amount will determine the quality of the solution. The steps for the proposed work are as follows:

Step 1 Specify the system and network parameters (generation power limits, ramp limits cost coefficients). Initialize the ABC algorithm parameters and the termination criteria.

Step 2 Initialize the population with m solutions in the solution space (food source positions), where m is the size of population. The solutions are represented by a

D-dimensional vector individually, where D is the total number of parameters which is to be optimized. In this work D is the number of generators. The elements of each solution denoted as x_{ij} is the real power output of generators which are distributed uniformly between their limits. This is given in (9).

$$P_{ij} = P_{j\min} + \text{rand}(0,1) * (P_{j\max} - P_{j\min}) \tag{9}$$

For each interval within the scheduling time, an initial population can be generated as in (10).

$$M = \begin{bmatrix} P_{11} & P_{12} & \ldots & P_{1N} \\ P_{21} & P_{22} & \ldots & P_{2N} \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ P_{m1} & P_{m2} & \ldots & P_{mN} \end{bmatrix} \tag{10}$$

where P_{ij} is the real power output of the jth generator for the ith individual, N is the generating units. The size of employed bees will be half of the colony size.

Step 3 Fitness function evaluation
The fitness value evaluated for each food source in the colony is carried out using (11).

$$\text{Fitness} = \text{A} * [1 - \%\text{Cost}] + \text{B} * [1 - \%\text{Error}] \tag{11}$$

$$\text{Error} = \left| \sum_{i=1}^{N} P_i - P_L - P_D \right| \tag{12}$$

$$\%\text{Error} = \frac{\text{String error} - \text{Min error}}{\text{Max error} - \text{Min error}} \tag{13}$$

where

Stringcost	Generation cost of individual string,
Mincost	Minimum value of objective function,
Maxcost	Maximum value of objective function,
Stringerror	Error of individual string in meeting the power balance,
Minerror	Minimum error of constraints, and
Maxerror	Maximum error of constraints.

Minerror, Maxerror, and Stringerror are determined using (12). In (12) the individual with the highest fitness value will have the lowest cost. The best fitness value within the individuals and the cost corresponding to that are determined. The

parameters accountable for the minimum cost are memorized. The cycle count is set and the following steps are carried out till it reaches the termination criteria MCN
Step 4 Position modification and site selection
The position of employed bees is modified for searching a new food source. The new food source is calculated by changing the value of any one of the D parameters (position of old food source) selected while all other parameters are kept unchanged. For the proposed problem this can be represented as in (14).

$$P_{ij} = P_{ij} + \phi_{ij} * (P_{ij} - P_{kj}) \tag{14}$$

where j is the index of the randomly generated selected parameter. If the n solution resulting from the modified position value violates the constraints, they are set to the maximum limits. Using (11) the fitness value of the new source is calculated. Here greedy selection method is employed as the selection mechanism. If the fitness of the new position is less, then the old population is retained.

Step 5 Recruiting onlooker bees for selected sites
After the completion of the search process by the employed bees they will share the information regarding the food sources to the onlooker bees. The onlooker bee evaluates the nectar information and finds out a food source depending on the fitness value probability. Roulette wheel selection technique is employed to place the onlookers onto the food source sites.

Step 6 Position modification by onlookers
The onlookers position is modified and the nectar amount of the candidate source is checked. Greedy selection mechanism is applied to select between the old and the new positions here. The nector information is evaluated by the onlooker bee and selects a food source with a probability. Roulette wheel selection technique is employed to place the onlookers onto the food source sites.

Step 7 Abandon sources
If there is no improvement in a solution representing a food source for a specified number of trials, then that food source will be abandoned. The scout bee discovers a new food source (Xi).

Step 8 The best solution achieved so far is memorized and the cycle count is incremented.

Step 9 Termination of the process
If the cycle count reaches the maximum number of cycles (MCN) the process is terminated. Otherwise, go to Step 4. The best fitness value and its corresponding food source are retained once the termination criteria are reached. This is the optimum output power of generating units for that time horizon.

Step 10 The count is incremented and the Steps from 2 to 9 are repeated for the time intervals. The total generation cost is computed for all the subintervals of the total time period T.

4 Mathematical Modeling of UPFC

Unified power flow controller comprises of two voltage source converters (VSC), one of them in series with the transmission line and the another in parallel with the line. Figure 1 shows the equivalent circuit of UPFC. Using UPFC, the active, reactive power flow and the magnitude of voltage in the UPFC terminals can be controlled individually or simultaneously. The magnitude of the inverter output V_{CR} decides the voltage regulation. The phase angle of the output voltage δ_{cR} decides the mode of power flow control in UPFC. The shunt converter may generate or absorb reactive power to provide independent control of voltage magnitude in its terminal in addition to its supportive role for active power exchange between series converter and the line. Figure 1 consists of two voltage sources (shunt and series) and a real power constraint equation that links the two VSC. The power flow equations for a three-phase UPFC is given as

$$E_{vR} = V_{vR}(\cos\delta_{vR} + j\sin\delta_{vR}) \tag{15}$$

$$E_{cR} = V_{cR}(\cos\delta_{cR} + j\sin\delta_{cR}) \tag{16}$$

The active power and reactive power equations at bus i are

$$\begin{aligned} P_i = {} & V_i^2 G_{ii} + V_i V_j \big(G_{ij}\cos(\theta_i - \delta_j) + B_{ij}\sin(\theta_i - \delta_j)\big) \\ & + V_i V_{cR}\big(G_{ij}\cos(\theta_i - \delta_{cR}) + B_{ij}\sin(\theta_i - \delta_{cR})\big) \\ & + V_i V_{cR}(G_{vR}\cos(\theta_i - \delta_{cR}) + B_{vR}\sin(\theta_i - \delta_{cR})) \end{aligned} \tag{17}$$

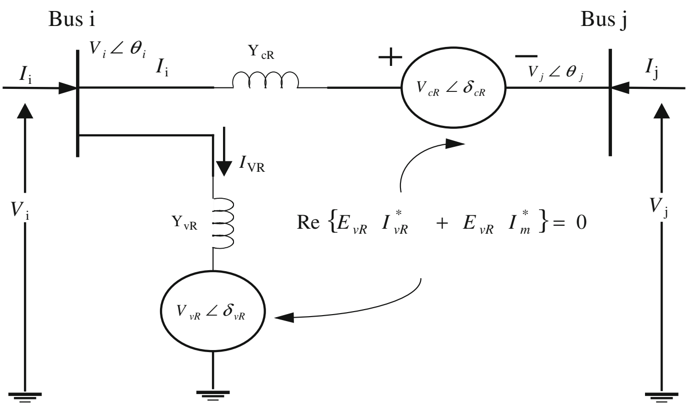

Fig. 1 Equivalent circuit of UPFC

$$Q_i = -V_i^2 B_{ii} + V_i V_j \big(G_{ij}\sin(\theta_i - \delta_j) + B_{ij}\cos(\theta_i - \delta_j)\big) + V_i V_{cR}\big(G_{ij}\sin(\theta_i - \delta_{cR}) + B_{ij}\cos(\theta_i - \delta_{cR})\big) + V_i V_{cR}(G_{vR}\sin(\theta_i - \delta_{cR}) + B_{vR}\cos(\theta_i - \delta_{cR})) \quad (18)$$

$$P_j = V_j^2 G_{jj} + V_j V_i \big(G_{ji}\cos(\theta_j - \delta_i) + B_{ji}\sin(\theta_j - \delta_i)\big) + V_j V_{cR}\big(G_{jj}\cos(\theta_j - \delta_{cR}) + B_{jj}\sin(\theta_j - \delta_{cR})\big) \quad (19)$$

The active power and reactive power equations at bus j are

$$Q_j = -V_j^2 B_{jj} + V_j V_i \big(G_{ji}\sin(\theta_j - \delta_i) + B_{ji}\cos(\theta_j - \delta_i)\big) + V_j V_{cR}\big(G_{jj}\sin(\theta_j - \delta_{cR}) + B_{jj}\cos(\theta_j - \delta_{cR})\big) \quad (20)$$

In a series converter,

$$P_{cR} = V_{cR}^2 G_{jj} + V_{cR} V_i \big(G_{ij}\cos(\delta_{cR} - \delta_i) + B_{ij}\sin(\delta_{cR} - \delta_i)\big) + V_{cR} V_j \big(G_{jj}\cos(\delta_{cR} - \delta_j) + B_{jj}\sin(\delta_{cR} - \delta_j)\big) \quad (21)$$

$$Q_{cR} = -V_{cR}^2 B_{jj} + V_{cR} V_i \big(G_{ij}\sin(\delta_{cR} - \delta_i) - B_{ij}\cos(\delta_{cR} - \delta_i)\big) + V_{cR} V_j \big(G_{jj}\sin(\delta_{cR} - \delta_j) - B_{jj}\cos(\delta_{cR} - \delta_j)\big) \quad (22)$$

Also in a shunt converter,

$$P_{vR} = -V_{vR}^2 G_{vR} + V_{cR} V_i (G_{vR}\cos(\delta_{vR} - \delta_i) + B_{vR}\sin(\delta_{vR} - \delta_i)) \quad (23)$$

$$Q_{vR} = V_{vR}^2 B_{vR} + V_{cR} V_j \big(G_{vR}\sin(\delta_{vR} - \delta_j) - B_{vR}\cos(\delta_{vR} - \delta_j)\big) \quad (24)$$

The initial parameter settings for UPFC and ABC algorithm are furnished in Table 1.

Table 1 Parameter settings for UPFC and ABC algorithm

Parameter	Values	Parameter	Values
Shunt source—reactance	0.1 Ω	Min voltage of series source	0.001 p.u.
Series source—reactance	0.1 Ω	Max voltage of series source	0.2 p.u.
Series source—initial voltage	0.04 p.u.	Min voltage of shunt source	0.9 p.u
Series source—initial angle	90°	Max voltage of shunt source	1.1 p.u.
Shunt source—initial voltage	1.0 p.u.	Colony size	250
Shunt source—initial angle	0.0°	Termination criteria (MCN)	100

5 Results and Discussion

5.1 SED Without UPFC in IEEE 118 Bus System

In this case, static economic dispatch is done without incorporating UPFC in IEEE 118 bus system. The data for the test system are obtained from https://www.ee.washington.edu/research/pstca/pf118/pg_tca118bus.htm. The dispatch is carried out for one hour and the real power dispatch is given in Table 2. The generation cost without FACTS devices is $99699.05. The voltage profile is shown in Fig. 2. It is evident that the voltages in certain buses are below 1.0 p.u.

See Table 2.

Table 2 SED without UPFC in IEEE 118 bus system

Generator	Dispatch	Generator	Dispatch	Generator	Dispatch	Generator	Dispatch
G4 (MW)	14.90	G34(MW)	30.00	G69(MW)	176.74	G92(MW)	167.33
G6(MW)	30.00	G36(MW)	47.61	G71(MW)	40.14	G99(MW)	300.00
G8(MW)	30.00	G40(MW)	17.07	G72(MW)	30.00	G10(MW)	218.71
G10(MW)	300.00	G42(MW)	30.00	G73(MW)	8.43	G103(MW)	20.00
G12(MW)	300.00	G46(MW)	100.00	G74(MW)	13.40	G104(MW)	68.70
G15(MW)	20.26	G49(MW)	210.67	G76(MW)	59.34	G105(MW)	100.00
G18(MW)	100.00	G54(MW)	175.34	G77(MW)	47.78	G107(MW)	20.00
G19(MW)	30.00	G55(MW)	100.00	G80(MW)	253.19	G110(MW)	50.00
G24(MW)	30.00	G56(MW)	100.00	G82(MW)	100.00	G111(MW)	100.00
G25(MW)	300.00	G59(MW)	97.22	G85(MW)	30.00	G112(MW)	58.52
G26(MW)	350.00	G61(MW)	200.00	G87(MW)	223.80	G113(MW)	100.00
G27(MW)	30.00	G62(MW)	33.15	G89(MW)	200.00	G116(MW)	50.00
G31(MW)	30.00	G65(MW)	420.00	G90(MW)	17.50	Generation cost ($)	99699.05

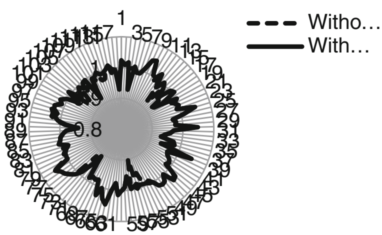

Fig. 2 Voltage profile without and with UPFC

Table 3 SED incorporating UPFC devices in 118 bus system

Generator	Dispatch	Generator	Dispatch	Generator	Dispatch	Generator	Dispatch
G4(MW)	22.62	G34(MW)	30.00	G69(MW)	300.00	G92(MW)	300.00
G6(MW)	5.74	G36(MW)	100.00	G71(MW)	80.00	G99(MW)	240.23
G8(MW)	30.00	G40(MW)	30.00	G72(MW)	24.88	G10(MW)	300.00
G10(MW)	196.04	G42(MW)	30.00	G73(MW)	30.00	G103(MW)	20.00
G12(MW)	300.00	G46(MW)	38.90	G74(MW)	20.00	G104(MW)	100.00
G15(MW)	30.00	G49(MW)	250.00	G76(MW)	100.00	G105(MW)	100.00
G18(MW)	71.25	G54(MW)	228.68	G77(MW)	53.64	G107(MW)	17.21
G19(MW)	30.00	G55(MW)	100.00	G80(MW)	169.98	G110(MW)	50.00
G24(MW)	28.15	G56(MW)	100.00	G82(MW)	41.54	G111(MW)	100.00
G25(MW)	179.74	G59(MW)	87.63	G85(MW)	30.00	G112(MW)	89.63
G26(MW)	350.00	G61(MW)	200.00	G87(MW)	156.45	G113(MW)	37.59
G27(MW)	30.00	G62(MW)	30.22	G89(MW)	171.35	G116(MW)	50.00
G31(MW)	30.00	G65(MW)	190.71	G90(MW)	20.00	Generation cost ($)	95924.00
G32(MW)	100.00	G66(MW)	420.00	G91(MW)	36.15		

Table 4 UPFC parameters in IEEE 118 bus system

Parameters	Values
V_{vR} (p.u.)	1.03
V_{cR} (p.u.)	0.58
$\delta_{vR}(°)$	−6.33
$\delta_{cR}(°)$	−94.12

5.2 *SED with UPFC in IEEE 118 Bus Test System*

Here, economic dispatch is carried out by incorporating UPFC in the test system. The initial parameter settings for UPFC are given in Table 1. The real power dispatch of generators incorporating FACTS devices is given in Table 3.

UPFC will inject power as required and maintains the power flow in the system, thus reducing the losses and burden of generators. The dispatch is very economical compared to the results without UPFC. The generation cost obtained with UPFC is given in Table 2. The generation cost is reduced compared to the results without incorporating UPFC. The use of ABC algorithm eliminates the complexity of forming Jacobian matrix. The parameters of UPFC are given in Table 4, which is in between its maximum and minimum limits. The voltage profile with UPFC is shown in Fig. 2. Form Fig. 2, it is evident that UPFC improves the voltage profiles of the buses in the test system.

5.3 *SED Without UPFC in South Indian 86 Bus System*

In this case, static economic dispatch is carried out in South Indian 86 bus system without incorporating UOFC. The line data, bus data, and generation coefficients

Table 5 Dispatch and cost with UPFC in SED (South Indian 86 bus)

Devices/generator	Without FACTS devices	With UPFC	Devices/generator	Without FACTS devices	With UPFC
G1	122.10	117.34	G10	106.21	88.641
G2	125.83	127.59	G11	75.779	64.401
G3	107.97	107.84	G12	89.164	74.766
G4	104.68	99.420	G13	109.85	100.15
G5	75.600	71.562	G14	135.30	94.036
G6	101.67	95.266	G15	127.98	101.64
G7	121.89	91.518	G16	132.35	110.53
G8	96.992	111.76	G17	95.103	93.466
G9	112.90	112.12	Generation cost without UPFC (₹)		359826.0
			Generation cost with UPFC(₹)		359294.3

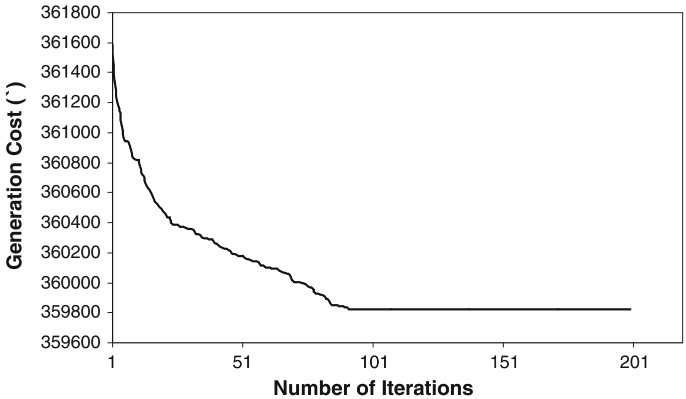

Fig. 3 Cost convergence for South Indian 86 bus system without UPFC

for the test system are obtained from [16]. The dispatch is carried out for 1 h. The real power dispatch of generating units is given in Table 5. The generation cost without FACTS devices is ₹36188.00. The graph of generation cost without FACTS device is shown in Fig. 3, which shows the better convergence property of ABC algorithm.

5.4 *SED with UPFC in South Indian 86 Bus System*

Here, economic dispatch is done by incorporating all FACTS individually in the test system. UPFC is incorporated and SED is done for a time horizon of one hour and the generator dispatch with FACTS devices are given in Table 5. The FACTS devices will inject power as required and maintain the power flow in the system, thus reducing the losses and burden of generators. Because of this, the dispatch is very economical compared to the case without UPFC. The generation cost obtained with UPFC is given in Table 5. The generation cost is reduced in this case compared to the results without incorporating FACTS devices. UPFC is the multi-converter device which has the combined shunt and series compensation has the generation cost of ₹359294.3, which is less compared to the case without UPFC. With the incorporation of UPFC, the power flow can be controlled without violating the economic optimal dispatch such that thermal limits of the transmission lines are not exceeded, losses and generation costs are minimized. The installation cost of UPFC is not considered in this paper.

6 Conclusion

Static economic incorporating UPFC using ABC algorithm is discussed in this paper. Two case studies are carried out in two standard test systems. The UPFC is placed in its optimal location in the test system. The results are compared with and without incorporating UPFC in the test system. It is clear that the incorporation of UPFC in the network reduces the burden of generators, improves power flow and voltage profile, and reduces the total real power generation cost. Significant amount of generation cost can be reduced by incorporating UPFC in the test system. ABC shows better convergence characteristics and eliminates the requirement of Jacobian matrix in economic dispatch. These studies can be applied to other FACTS devices also.

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