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Analysis of Optimal Power Flow with IPFC Using Differential Evolution Algorithm

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Abstract: This paper investigates the Optimal Power Flow (OPF) in a power system network incorporating Interline Power Flow Controller (IPFC). Here Differential Evolution Algorithm (DEA), a non-conventional computational intelligence approach is reframed to find the optimal settings of IPFC and OPF variables. IPFC can be placed in multiple lines for controlling the real and reactive power flow, which is the significant difference observed from other available FACTS devices. This paper aims to minimize the fuel cost of the generating units subjected to various operating constraints. The economic dispatch of power obtained through OPF, which utilizes DEA in an effective manner is also discussed. The proposed methodology is validated by testing on standard benchmark test systems like 5-bus and IEEE 30-bus systems. The advantages of the proposed OPF model over conventional Lagrangian based methods are discussed.

Keywords: FACTS, IPFC, Differential Evolution, Optimal Power Flow, Compensation, Modeling

1. Introduction

The optimal power flow is a non linear programming problem, which is used to optimize an objective function subject to certain set of physical and operational constraints. This is used to determine the optimal operating state of a power system and the corresponding settings of control variables for economic and secure operation. In the past three decades many conventional and non conventional methods have been developed to solve the optimal power flow problems. However, convergence and complexity are seen as the major issues. During last decade FACTS devices are extensively used for maximizing the loadability of already available power system transmission networks. The main purpose of transmission network is to pool power plants and load centers, such that it supplies the load at the required reliability, lower cost and with maximum efficiency. 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[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. 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 substation [4]. The number of inverters in the IPFC will be equal to the number of transmission lines required to be compensated at that substation. 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. In this paper the, interline power flow controller is modeled using power injection model (PI) [6] for optimal power flow incorporating IPFC. Conventional non linear programming based techniques like Newton Raphson method for OPF with Thyristor Controlled Series Compensator (TCSC) are investigated in [3], which lead to highly robust iterative solutions. Here power flow analysis is carried out with the firing angle model based TCSC using Newton's Method. Taronto et al [7] have proposed decomposition method to solve optimal power flow problem with Phase Shifters and series compensating devices, but this

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method did not consider the specified line flow constraints. Moreover, the optimal power flow problem with series compensation is a non convex problem , and there may be a chance for classical method to get stuck in to local minimum if applied [8]. Ongasakul proposed [9] hybrid tabu search and simulated annealing method to solve optimal power flow problem incorporating TCSC and Thyristor Controlled Phase Shifter (TCPS). The GA approach is applied to solve OPF problem incorporating TCPS by Chung and Li[10]. Basu [11] proposed an algorithm based on Differential Algorithm approach to solve optimal power flow problem incorporating TCSC, TCPS and obtained better results in terms of fuel cost and CPU timing. A.A.Abou El Ela et.al [12] have applied differential evolution algorithm for optimal reactive power dispatch. Teerathana.S [5] applied successive quadratic algorithm to solve the OPF incorporating IPFC in the network with an objective to reduce total capacity of installed IPFC in a power system. Khalid. H. Mohamed [13] had solved OPF problem incorporating IPFC using PSO, GA and SA, with an objective to reduce the real power loss in the network. But, in both these contributions [5,13], the economic dispatch of the generators and the minimization of real power generation cost are not considered. The reduction in operation cost of power system by suitably dispatching the load demand among the generators is mandatory for the economic operation of contemporary power system. Hence, an attempt is made in this paper for the first time to solve optimal power flow problem incorporating IPFC using DEA with due consideration to economic dispatch of generating units and fuel cost minimization, subject to the operating constraints such as real and reactive power generation limits, voltage limits, transmission line flow limits and IPFC parameters.The developed algorithm is tested on a standard 5-bus system and an IEEE 30-bus system. The results are compared with Lagrangian method to show the effectiveness of the proposed model in solving OPF with IPFC for controlling power flow in the network.

2. Interline Power Flow Controller

The Interline Power Flow Controller (IPFC) addresses the problem of compensating a number of transmission lines at the given substation. Conventionally, series capacitive compensation is employed 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 problem occurs when the ratio of reactive to resistance line impedance(X/R) is relatively low. Series reactive compensation reduces only the effective reactive impedance X and, thus, significantly decreases the effective X/R ratio and thereby increases the 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. This capability makes it possible to 1.Equalize both real and reactive power flow between the lines 2.Reduce the burden of overloaded lines by real power transfer 3.Compensate against resistive line voltage drops and the 4.corresponding reactive power demand and 4.Increase the effectiveness of the overall compensating system for dynamic disturbances. In other words, 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

2. 1. Basic Operating Principle

Interline Power Flow Controller employs a number of dc-ac converters each providing series compensation for different lines. In other words, the IPFC comprises of a number of Static Synchronous Series Compensators linked together at dc terminals. With this scheme, in addition to provide 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 can be made available from the underutilized 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 consist of two back-to-back dc-to-ac converters, which are 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. Evidently, this arrangement mandates the rigorous maintenance of the overall power balance at the common dc terminal by appropriate control action, for suitable real power transfer from overloaded lines to under loaded lines.

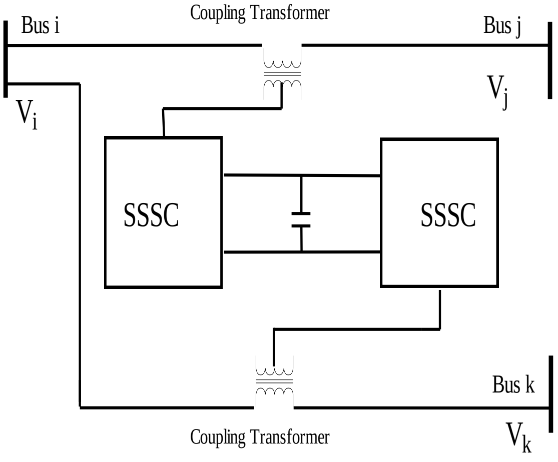


Fig. 1. Schematic diagram of IPFC

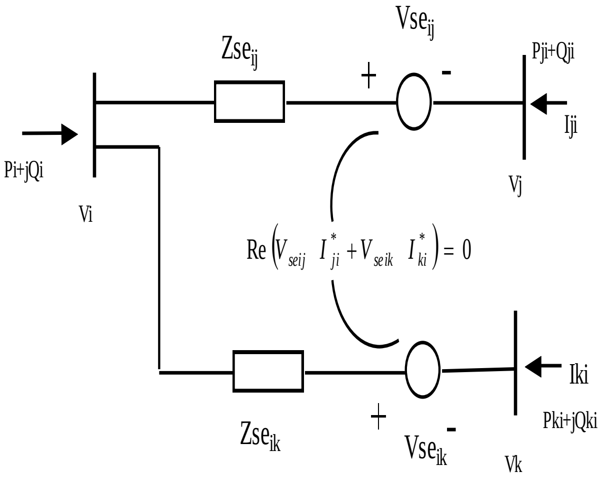


Fig. 2. Equivalent circuit of IPFC

2. 2. Mathematical Modeling of IPFC

Mathematical model for IPFC, which will be referred to as power injection model, 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 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 an almost sinusoidal voltage with controllable magnitude and angle[5]. Based on this, the equivalent circuit of IPFC is shown in Figure 2.In Figure 2 Vi,Vj and Vk are the complex bus voltages at the buses i,j and k respectively, Vsein is the complex controllable series injected voltage source, and Zsein (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 in Fig.2 can be written as

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

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

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

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

where

$$g_{ii} = g_{ij} = \operatorname{Re}\left(1/Zse_{ij}\right)$$
$$b_{ii} = b_{ij} = \operatorname{Im}\left(1/Zse_{ij}\right)$$

The active power exchange between series connected inverters via the common dc link is

$$P_{sum} = \sum_{j=1,\, j\neq i}^{n} \left\{\operatorname{Re}\left(Vse_{ij} \; I_{ij}^{*}\right)\right\} \tag{5}$$

The same equations can be derived for bus k also. P, Q are the active and reactive power flow through the branches in which the IPFC is connected

3. Optimal Power Flow

The OPF problem is to optimize the steady state performance of a power system in terms of an objective function while satisfying several equality and inequality constraints. The objective function is minimization of the total fuel cost. Mathematically the OPF problem can be formulated as

$$Min\ F = \sum_{m=1}^{N_G} a_m + b_m P_{Gm} + c_m P_{Gm}^2 \qquad (6)$$

where F is the total fuel cost, PGm is the output of the 'mth' generating unit, am, bm ,cm are the cost coefficients of 'mth, generating unit , N G is the number of generators in the test system, subject to

(a)Load flow constraints

$$P_{Gm} + P_{Dm} - \sum_{n=1}^{N_B} V_m V_n Y_{mn} \cos(\theta_{mn} + \delta_m - \delta_n) = 0 \forall m \in N_B \qquad (7)$$

$$Q_{Gm} + Q_{Dm} - \sum_{n=1}^{N_B} V_m V_n Y_{mn} \sin(\theta_{mn} + \delta_m - \delta_n) = 0 \forall m \in N_B \qquad (8)$$

where N B is the total number of system buses; PGm and QGm are the active and reactive power generations of generator 'm' ; PDm and QDm are the active and reactive power loads of bus Vm and Vn is the voltage magnitude of bus 'm' and 'n', θmn is the voltage angle difference between bus 'm' and 'n' ; Ymn is the transfer admittance matrix

(b) Power balance constraints

$$\sum_{m=1}^{N_G} P_{Gm} - P_D - P_L = 0 \qquad (9)$$

$$\sum_{m=1}^{N_G} Q_{Gm} - Q_D - Q_L = 0 \qquad (10)$$

where PD and QD are the real and reactive load demands, PGm, and QGm are the real and reactive power generation and PL and QL are the real and reactive power losses. The total power generated should meet the total load and the line loss

(c)Operation constraints

$$P_{Gm}^{\min} \le P_{Gm} \le P_{Gm}^{\max} \quad \forall m \in N_G \qquad (11)$$

$$Q_{Gm}^{\min} \le Q_{Gm} \le Q_{Gm}^{\max} \quad \forall m \in N_G \qquad (12)$$

$$V_m^{\min} \le V_m \le V_m^{\max} \quad \forall m \in N_B \qquad (13)$$

$$|S_m| \le S_m^{\max} \quad \forall m \in N_L \qquad (14)$$

where

Where NL is the total number of lines in the system $P_{Gm}^{\min}$, $P_{Gm}^{\max}$, $Q_{Gm}^{\min}$ and $Q_{Gm}^{\max}$ are the minimum and the maximum values of real and reactive power generations of the 'm^th' generator, respectively. $V_m^{\min}$ and $V_m^{\max}$ are the minimum and maximum voltage magnitude of the mth bus respectively. S_m is the transmission line loading which should be below its maximum limit

(d) **IPFC limits**

$$Vse_{mn}^{\min} \le Vse_{mn} \le Vse_{mn}^{\max} \qquad (15)$$

$$\theta se_{mn}^{\min} \le \theta se_{mn} \le \theta se_{mn}^{\max} \qquad (16)$$

Where $Vse_{mn}^{\min}$, $\theta se_{mn}^{\min}$ are are the minimum value of the magnitude angle of series voltage source and in IPFC. $Vse_{mn}^{\max}$, $\theta se_{mn}^{\max}$ are the maximum value of the magnitude and angle of series voltage source in IPFC. During optimal power flow analysis, all constraints from (7) to (16) should be satisfied. All the parameters should be within its minimum and maximum limits

4. Differential Evolution Algorithm

Differential Evolution (DE)[11,12] is an evolutionary algorithm proposed by Price and Storn for solving optimization problems which are non-differential. Differential evolution solves real valued problems based on the principle of natural evolution. The selection process and the mutation in DE scheme makes it self adaptive and exceptionally simple, faster, robust. Basically DE generates new vectors of parameters by adding the weighted difference between two population vectors to the third one. If the resulting individual provides a smaller objective function value, a new individual replaces the one with which it is compared, otherwise the old individual is retained. The key parameters for control in DEA are population size (Np), scaling factor (F) and crossover constant (CR).

4.1Implementation of DEA for OPF incorporating IPFC

Step: 1.Initialization

The initial population X with population size of Np is initialized randomly such that X = [N_1, N_2, N_3, ...N_{Np}]. Each solution is given by Nn = [P_{n1} P_{n2}……….. P_{nN}, V_{sen1} V_{sen2}, θ_{sen1} ,θ_{sen2}], (where n = 1, 2…N_p , N is the number of real power generations in the problem and N_p is the Number of population.The size of the solution is D, which includes the number of real power generations and the IPFC parameters. The variables should bound within their upper and lower limits. Let the nth component of the mth population member

$$x_{mn}^{(0)} = x_n^l + rand(0,1)*\left(x_n^u - x_n^l\right) \quad (17)$$

where x_n^u and x_n^l are the upper bound and the lower bound of the n_{th} variable of the problem, rand (0,1) is a uniformly distributed number within the limits (0 ,1), $x_{mn}^{(0)}$ is the initial nth variable of the mth population. The random values should be within the limits specified as in equations from (11) to (16)

Step:2.Mutation

A new population named mutant population is generated whose size is same as that of the initial population Np. Among the various strategies used for mutation in DE, the addition of the various strategies used for mutation in DE, the addition of the weighted difference vector between the two population members to the third member is adopted in this approach. Here three different members namely x_{r1},x_{r2} and xr3 are chosen from the current population .Then the difference between any two of these members are scaled by a scalar number F, which is then added to the third member. The value of F is usually in between 0.4 and 1. In each generation, a donor vector is created in order to change the population member vector. Therefore the mth member of the donor vector is expressed as $\vec{V}_n(t)$, the value of F is selected as 0.6 for the present study.

$$V_{mn}(t+1) = x_{r1}\,m(t) + F*\left(x_{r2}\,m(t) - x_{r3}\,m(t)\right) \quad (18)$$

Step:3.Crossover

A new population is created by suitably combining the parent population and the mutant population. The process of crossover is based on the CR which is in between (0,1). In this study, the value of CR is taken as 0.8. Binomial crossover scheme is used and performed on all D variables, which can be expressed as:

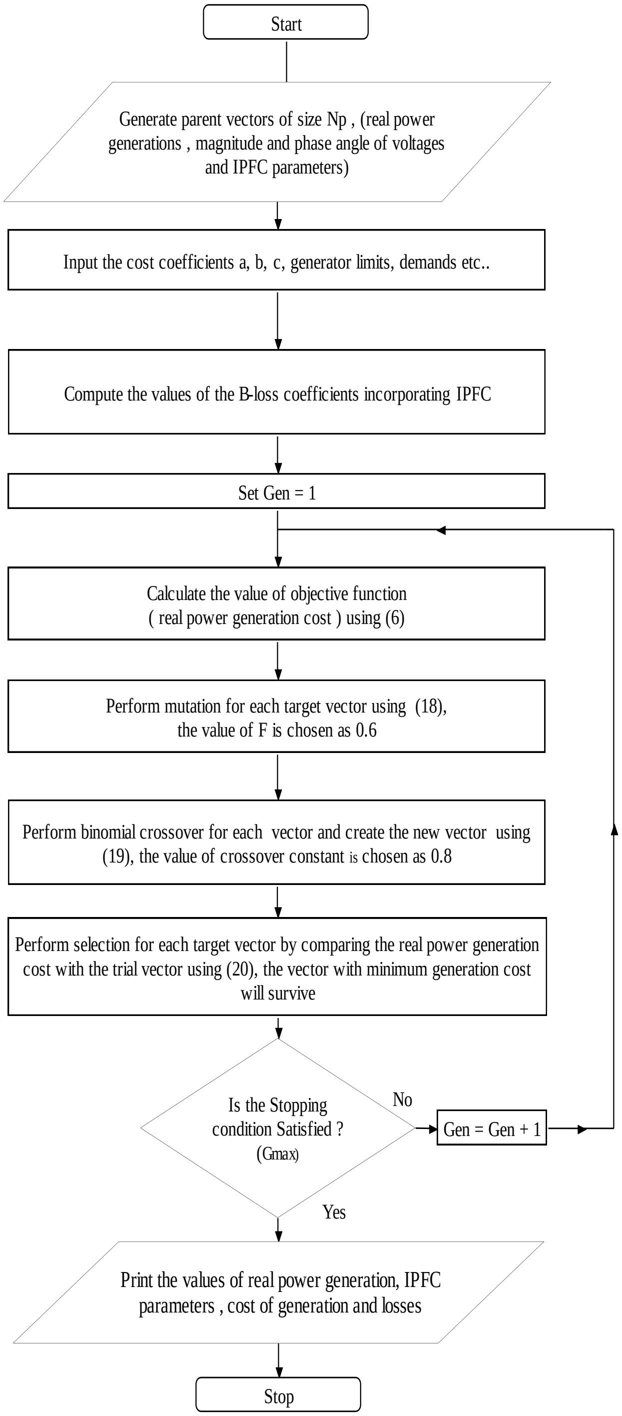


Fig. 3. Flowchart for OPF incorporating IPFC using DEA

$$U_{mn}(t) = \begin{Bmatrix} V_{mn}(t) \ if \ \ rand(0,1) < CR \\ X_{mn}(t) \ else \end{Bmatrix} \qquad (19)$$

where $V_{mn}(t)$ is the child which is obtained after crossover operation, m = 1,2,…Np, n = 1,2,…..D. Here, rand ensures that the newly generated vector is different for both $V_{mn}(t)$ and $X_{mn}(t)$

Step:4.Selection

After calculating the objective function F(t) using D number of variables using initial and crossover population , a new population with the least objective function (minimum fuel cost) is formed for the next generation. This is given by

$$\vec{X}(t+1) = \begin{Bmatrix} \vec{U}_n(t) \ if \ \ f(\vec{U}_n(t)) \le f(\vec{X}_n(t)) \\ \vec{X}_n(t) \ if \ \ f(\vec{U}_n(t)) > f(\vec{X}_n(t)) \end{Bmatrix} \qquad (20)$$

This process is repeated until the maximum number of generations or no improvement is seen in the real power generation cost after many generations of DEA.

5. Results And Discussions

The optimal power flow incorporating IPFC using DEA is implemented in MATLAB 7.4 version running in Pentium IV processor with 3.2GHz speed and 1GB RAM. The OPF using DEA incorporating IPFC is tested on standard 5-bus system and standard IEEE 30-bus system. The minimum and maximum angles of converters in IPFC are taken as -1800 and 1800. The minimum and maximum value of converter voltages are taken as 0.001 p.u. and 0.2 p.u. respectively. The OPF is carried out with and without IPFC using both DE and Lagrangian method. The results are compared and discussed. The global optimum searching capability and the convergence speed of DE are very sensitive to the choice of control parameters NP, F and CR [22]. Mutation factor (F) should not be smaller than a certain value to prevent premature convergence. A larger F increases the probability for escaping a local optimum. However for F>1, the convergence speed decreases. A good initial choice for the scaling factor is 0.6. A large CR often speeds up convergence. However, beyond a certain value, the convergence speed may decrease or the population may converge prematurely. A good choice for the crossover constant is a value between 0.3 and 0.9[34].Depending on these facts the mutation constant is selected as 0.6 and the crossover constant CR is chosen as 0.8. The population size Np is taken as 20 ,Gmax is taken as 100 which is taken as the stopping criteria for the OPF problem.

5.1 Case. 1: Standard 5 -bus system

In the standard 5-bus system, 2 buses (bus no 6 and 7) are added to incorporate IPFC in it . The optimal power flow is carried out using both Lagrangian method and DE method incorporating IPFC and the results are compared. The OPF is also carried out without placing IPFC in the test system and the effectiveness of the FACTS device is also demonstrated. The maximum and minimum limits for voltage magnitude of all buses, generated power and reactive power limits are taken as 1.1 p.u and 0.9 p.u, 200MW and 10MW, 300MVAR and -300MVAR respectively . Table.1 gives the various results of the 5-bus system without incorporating IPFC. The real power generated by the two generators are given in Table.1. The total system loss is 5.3498MW and the generation cost is 759.81$/hr. Fig.4 shows the real and reactive power flow in various lines in the 5 bus system without IPFC. Fig. 5 shows the convergence characteristics of both DEA and lagrangian method for a 5 bus system without IPFC

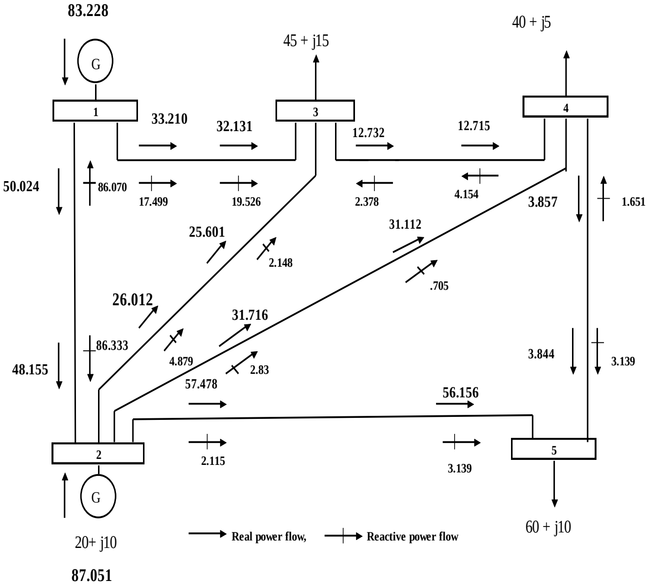
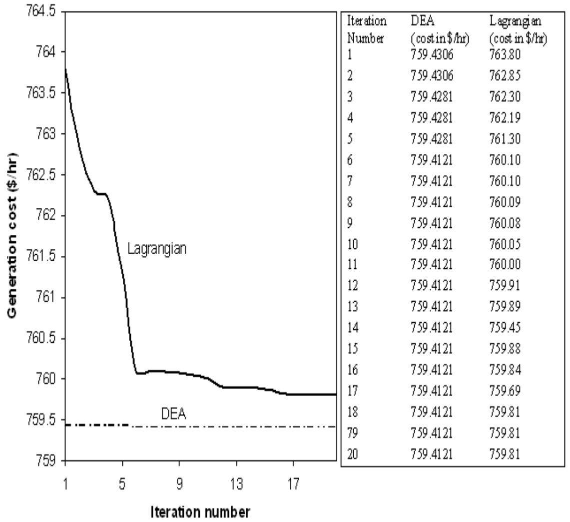


Fig. 4 Power flow (MW) in a 5- bus system without IPFC.



Iteration Number	DEA (cost in $/hr)	Lagrangian (cost in $/hr)
1	759.4306	763.80
2	759.4306	762.85
3	759.4281	762.30
4	759.4281	762.19
5	759.4281	761.30
6	759.4121	760.10
7	759.4121	760.10
8	759.4121	760.09
9	759.4121	760.08
10	759.4121	760.05
11	759.4121	760.00
12	759.4121	759.91
13	759.4121	759.89
14	759.4121	759.45
15	759.4121	759.88
16	759.4121	759.84
17	759.4121	759.69
18	759.4121	759.81
79	759.4121	759.81
20	759.4121	759.81

Fig. 5 Convergence graph of a 5-bus system without IPFC

The optimal power flow is carried out by incorporating IPFC as shown in Fig.6, using both Lagrangian and DE algorithm.The bus voltages and angles of the 5 bus system are furnished in Table.1. From Table.1 it is clear that the voltage profile is better in DE method compared to Lagrangian method. To assess the potential of the DEA , a comparison between the results of fuel cost obtained by the DEA and Lagrangian method is carried out. The results of this comparison are given in Table.1. The real power generated by both the generators (G1 and G2) are given, which shows that the real power generation required to meet the load demand is less in case of DEA, and hence the generation cost is also reduced from 757.28($/hr) to 756.66($/hr) with DEA. The real power loss is reduced from5.25MW to 5.197MW with DEA.The active power flow through the line (3-4) is increased from 12.715MW to16MW when IPFC is placed in the network. The power flow in that line is increased by 25.5% with the incorporation of IPFC. Fig.6 shows the active and reactive power flow in the standard 5-bus system incorporating IPFC using DE algorithm. From Table.1, it is clear that the loss and generation cost are reduced in differential evolution method compared to Lagrangian method. Fig.7.shows the convergence characteristics of DEA and Lagrangian method for a 5 bus system ith IPFC. In this case DEA has converged in 8 iterations where as Lagrangian needs 20 iterations for convergence.

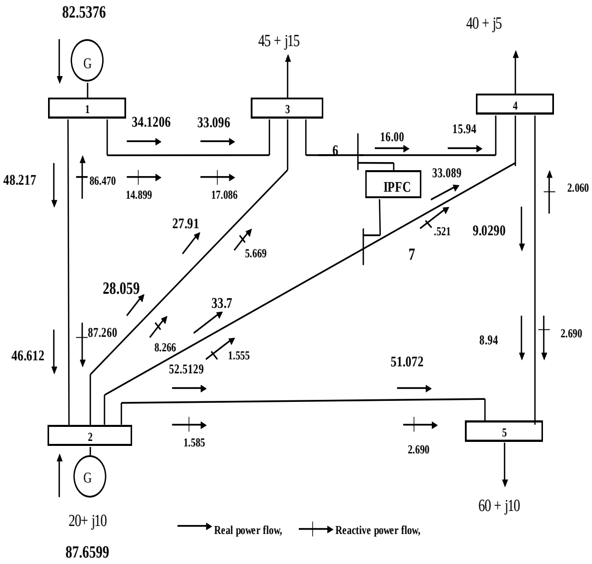
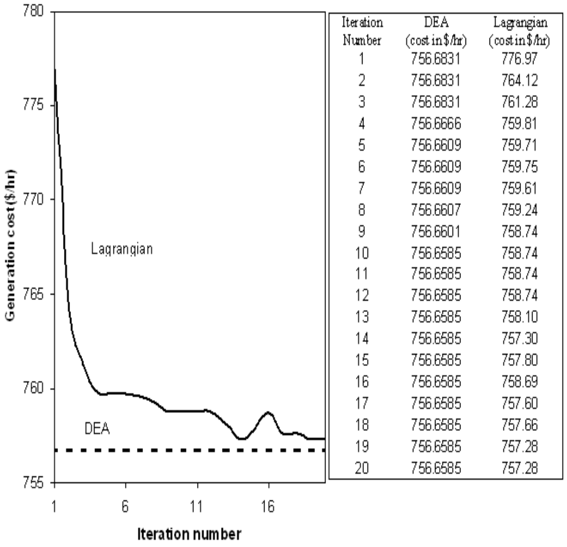


Fig. 6. Power flow (MW) in a 5-bus system with IPFC.



Iteration Number	DEA (cost in $/hr)	Lagrangian (cost in $/hr)
1	756.6831	776.97
2	756.6831	764.12
3	756.6831	761.28
4	756.6666	759.81
5	756.6609	759.71
6	756.6609	759.75
7	756.6609	759.61
8	756.6607	759.24
9	756.6601	758.74
10	756.6585	758.74
11	756.6585	758.74
12	756.6585	758.74
13	756.6585	758.10
14	756.6585	757.30
15	756.6585	757.80
16	756.6585	758.69
17	756.6585	757.60
18	756.6585	757.66
19	756.6585	757.28
20	756.6585	757.28

Fig. 7 Convergence graph of a 5-bus system with IPFC

6.2 Case. 2: IEEE 30-bus system

The optimal power flow using DE algorithm is tested in IEEE 30-bus standard test system. In order to demonstrate the effectiveness of IPFC, a comparison is made between power flows before and after incorporating IPFC in the test system. The results of optimal power flow analysis on IEEE 30-bus test system incorporating IPFC using DEA, are compared with Lagrangian

Table 1
Results of 5-bus system with IPFC

Bus	Without IPFC				With IPFC							
	Voltage (p.u.)	Real power Generation (MW)	Loss (MW)	Generation Cost ($/hr)	Voltage (p.u.)		Real power Generation (MW)		Loss (MW)		Generation Cost ($/hr)	
					Lag	DEA	Lag	DEA	Lag	DEA	Lag	DEA
1	1.06	83.28(G1)	5.35	759.81	1.06	1.06	86.0(G1)	82.54(G1)	5.25	5.19	757.2	756.6
2	1				1	1						
3	0.990	87.01(G2)			0.990	0.996	84.2(G2)	87.66(G2)				
4	0.983				0.983	0.984						
5	0.979				0.971	0.971						

method. For instance, in line 10-20, 39.3% increase in active power flow can be observed, and 28% of real power flow improvement is observed in line 10-22. The real and reactive power flows of both the lines in which IPFC is connected are simultaneously controlled. The real power generation, generation cost, power loss and the IPFC parameters for 5 cases (Lines 10-20-17, 10-17-21, 10-21-22,12-15-16, 25-26-28) are given in Table.2.From Table.2, the IPFC parameters (converter voltage and angle) are also found to be within the specified limits. P1 to P6 indicates the real power generated by all the generators. The losses are reduced in all the 5 cases as compared to Lagranian method, and the generation cost is also reduced using DEA. In the first case (line 10-20-17) the total generation of real power is less in DEA compared to Lagrangian method. The real power loss is reduced from 10.895MW to 10.646MW in DEA compared to the Lagrangian method. The generation cost is 4981.43 $/hr in Lagrangian method, and 4974.048$/hr in DEA , which shows that the real power generation , real power loss and generation cost are reduced in case of DEA compared to Lagrangian method. The IPFC converter parameters Vse1, Vse2 , θs1, θs2 are within the specified limits in both the methods. The voltage and angle profile for three lines (10-17-21, 10-20-17, 10-21-22) using both the methods are given in Table.3. The voltage profile of buses when IPFC is placed in lines 12-15-16 using both the methods are shown in Fig.8. The convergence graph of DEA when IPFC is placed in various lines of the network is shown in Fig.9, which confirms that the algorithm converges faster in less number of iterations and the oscillations between values are also less. The number of iterations taken for convergence also depends on the line in which the IPFC is placed.This is true for all other cases also.Based on the steady state analysis, the following observations are made: Fig.5,7 and 9 shows the strong convergence characteristics of DEA compared to Lagrangian method, and the oscillations in the value of objective function from initial iteration to the final is very small in DEA compared to Lagrangian method. From Table 1 and 2 it is clear that the real power generation, the real power loss and the generation cost are reduced in case of DEA and the bus voltages are also enhanced. These observations clearly indicate that the results obtained using DEA method is better than that of conventional Lagrangian method. The DEA provides better solution than the Lagrangian because DEA searches from a population of points and not from a single point as in the case of Lagrangian relaxation method. Therefore DEA is able to provide a globally near optimal solution and also able to prevent the solution from getting caught in the local optima. Therefore DEA is very much suitable when multiple solutions exist in a search . DE uses only objective function information, not derivatives and auxiliary knowledges. Therefore the complexity involved in deriving Jacobian matrix with IPFC in a network is eliminated. DEA has better performance not only over conventional Lagrangian relaxation optimization method, but also proved to be better than other population based approaches like GA and PSO. This is understood from the performance comparison of the above mentioned population based algorithms when tested on different benchmark optimization functions [12][18][35].

Table 2

Real power, cost, loss and IPFC parameters for IEEE 30-bus system with IPFC

IPFC Location / Parameters	Line (10-20-17)		Line (10-17-21)		Line (10-21-22)		Line (12-15-16)		Line (25-26-28)	
	Lagrangian	DEA	Lagrangian	DEA	Lagrangian	DEA	Lagrangian	DEA	Lagrangian	DEA
P1(MW)	200	200	200	200	200	200	197.3	198.9	200	200
P2(MW)	74.01	67.05	73.341	65.674	73.76	66.60	70.98	72.18	70.33	68.33
P3(MW)	50	50	50	50	50	50	50	50	50	50
P4(MW)	30.88	35	29.25	35	28.99	35	35	31.38	30.38	31.25
P5(MW)	30	30	30	30	30	30	29.12	29.45	29.22	30
P6(MW)	10	12	12	12.93	12	12	12	12	12	12
Loss(MW)	11.49	10.65	11.19	10.202	11.35	10.2	11.00	10..51	8.46	8.18
Generation cost ($/hr)	4981.43	4974.048	4978.63	4969.78	4980.51	4968.9	4997..32	4994.65	4976..32	4971.69
Vse1	0.03990	0.0387	0.0068	0.0072	0.0166	0.0042	0.00263	0.0298	0.0321	0.0358
Vse2	0.04212	0.046	0.0183	0.0177	0.0093	0.0116	0.0412	0.0392	0.0422	0.0497
θse1	-12.63	-37.88	-75.30	-71.10	-131.83	-106.11	-26.36	-22.89	-23.45	-25.89
θse2	-174.2	-172.78	-161.4	-163.6	-180	-170.02	-169.28	-172.36	-166.28	-170.36

.

Table 3
Voltage and angle of IEEE 30- bus system with IPFC

IPFC in Line 10-17-21				IPFC in Line 10-20-17				IPFC in Line 10-21-22			
Voltage (p.u.)		Angle (Degrees)		Voltage (p.u.)		Angle (Degrees)		Voltage (p.u.)		Angle (Degrees)	
Lagrangian	DEA	Lagrangian	DEA	Lagrangian	DEA	Lagrangian	DEA	Lagrangian	DEA	Lagrangian	DEA
1.06	1.06	0	0	1.06	1.06	0	0	1.06	1.06	0	0
1.043	1.043	-3.58	-3.63	1.043	1.043	-3.59	-3.65	1.043	1.043	-3.58	-3.65
1.017	1.017	-6.86	-6.76	1.018	1.017	-6.85	-6.73	1.017	1.017	-6.85	-6.75
1.00	1.01	-8.07	-7.94	1.01	1.009	-8.06	-7.90	1.009	1.01	-8.06	-7.92
1.01	1.01	-8.81	-8.73	1.01	1.01	-8.79	-8.74	1.01	1.01	-8.80	-8.75
1.012	1.013	-8.27	-8.06	1.013	1.012	-8.27	-8.06	1.012	1.012	-8.27	-8.09
1.003	1.003	-9.02	-8.87	1.004	1.003	-9.02	-8.87	1.003	1.003	-9.02	-8.90
1.01	1.01	-8.34	-8.00	1.01	1.01	-8.30	-7.99	1.01	1.01	-8.34	-8.03
1.052	1.052	-9.16	-8.89	1.058	1.052	-9.25	-9.04	1.054	1.051	-9.18	-9.15
1.047	1.047	-11.3	-11.0	1.059	1.047	-11.4	-11.2	1.050	1.046	-11.3	-11.4
1.082	1.082	-6.02	-5.75	1.082	1.082	-6.13	-5.90	1.082	1.082	-6.04	-6.0
1.056	1.056	-11.7	-11.7	1.057	1.055	-11.6	-11.3	1.056	1.056	-11.6	-11.3
1.071	1.071	-10.9	-10.8	1.071	1.07	-10.8	-10.4	1.071	1.071	-10.8	-10.4
1.038	1.037	-12.56	-12.52	1.045	1.041	-12.3	-12.1	1.041	1.042	-12.5	-12.1
1.03	1.03	-12.5	-12.5	1.045	1.039	-12.2	-12.0	1.036	1.038	-12.5	-12.1
1.058	1.056	-12.07	-12.27	1.048	1.037	-11.9	-11.8	1.047	1.045	-11.8	-11.6
1.066	1.063	-12.15	-12.54	1.046	1.027	-11.9	-12.1	1.044	1.040	-11.7	-11.7
1.024	1.024	-12.3	-12.7	1.044	1.031	-12.5	-12.6	1.03	1.03	-12.9	-12.5
1.023	1.023	-12.8	-12.6	1.047	1.029	-12.5	-12.7	1.02	1.02	-12.8	-12.6
1.028	1.029	-12.5	-12.3	1.054	1.034	-12.1	-12.5	1.033	1.030	-12.5	-12.4
1	0.999	-13.0	-12.9	1.042	1.032	-12.1	-11.9	1.021	1.030	-13.2	-12.1
1.032	1.032	-12.03	-11.8	1.049	1.038	-11.9	-11.8	1.035	1.034	-12.3	-11.9
1.003	1.002	-12.9	-12.8	1.041	1.031	-12.2	-12.0	1.022	1.030	-13.1	-12.2
1.011	1.011	-12.8	-12.6	1.035	1.026	-12.4	-12.2	1.020	1.023	-12.9	-12.4
1.011	1.011	-12.8	-12.5	1.027	1.020	-12.4	-12.2	1.018	1.018	-12.8	-12.3
0.994	0.994	-13.1	-12.9	1.009	1.003	-12.8	-12.6	1.000	1.001	-13.2	-12.7
1.02	1.02	-12.4	-12.2	1.030	1.026	-12.0	-11.9	1.024	1.024	-12.5	-12.1
1.01	1.011	-8.6	-8.5	1.012	1.011	-8.7	-8.5	1.011	1.011	-8.8	-8.5
1	1	-13.6	-13.4	1.010	1.006	-13.3	-13.1	1.005	1.005	-13.6	-13.3
0.989	0.989	-14.5	-14.3	0.999	0.994	-14.2	-14.0	0.993	0.993	-14.5	-14.1

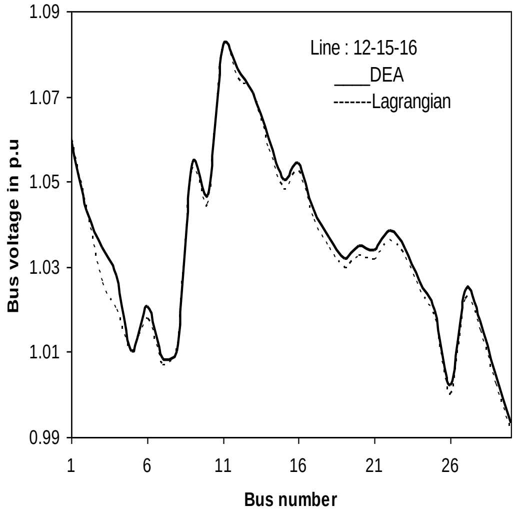


Fig. 8 Voltage profile of IEEE 30-bus system with IPFC (12-15-16)

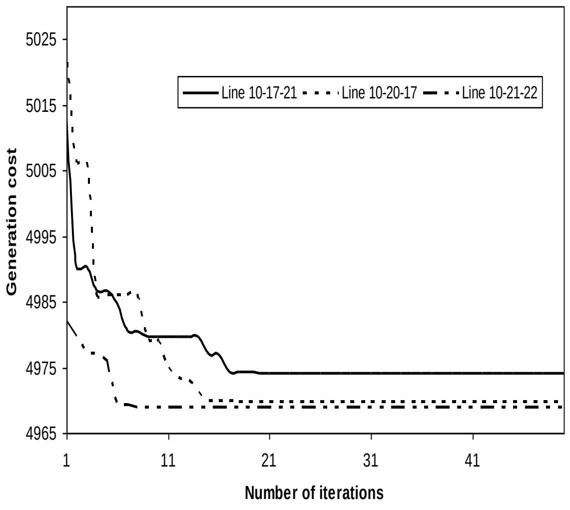


Fig. 9. DEA Convergence graph of IEEE 30-bus system with IPFC.

7. Conclusion

In this paper, differential evolution optimization algorithm has been successfully applied to solve optimal power flow problem incorporating

Interline Power Flow Controller (IPFC). The DE approach has been tested on the standard 5-bus system and standard IEEE 30-bus system. The IPFC is placed in various lines of the system and the corresponding results are tabulated. The results of the DE algorithm have been compared with that of Lagrangian method. The results demonstrate the effectiveness and robustness of the DE algorithm to solve OPF problem incorporating IPFC. From the results, the effectiveness of IPFC to improve the power flow in multiple lines is also understood. It is concluded that the DE algorithm has good convergence characteristics, high computational efficiency and the ability to find the better quality solution compared to Lagrangian method. This algorithm can be applied to solve the optimal power flow incorporating other FACTS devices also.

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