FULL PAPER
International Journal of Recent Trends in Engineering, Vol 2, No. 5, November 2009

DE Based Optimal Power Flow for Location of UPFC Considering Voltage Stability

M. Saiveerraju[1], B.V. Sankar Ram[2], and K. Vaisakh[3]
[1] SRKR Engineering College, EEE Department, Bhimavaram, AP, India
Email: saiveerraju@yahoo.co.in
[2] JNT University Hyderabad, EEE Department, Hyderabad, , AP, India
[3] Andhra University, AU College of Engineering, EE Department, Visakhapatnam, AP, India
Email: {bvsram4321@yahoo.com, vaisakh_k@yahoo.co.in}

***Abstract*—Optimal Power Flow (OPF) has been widely used in power system operation and planning. This paper presents Differential Evolution (DE) method to solve optimal power flow in power system incorporating a powerful and versatile Flexible AC Transmission Systems (FACTS) device such as Unified Power Flow Controller (UPFC). Unlike other FACTS devices, UPFC has a great flexibility that can control the active power, reactive power and voltage simultaneously. In the solution process, DE, coupled with AC power flow, selects the best regulation to minimize the total generation fuel cost and keep the power flows within their security limits. The optimization process with DE is presented with case study examples using IEEE 30-bus test system to demonstrate its applicability. The results are presented to show the feasibility and potential of this new approach.**

***Index Terms*—Optimal power flow, differential evolution, flexible AC transmission systems, unified power flow controller.**

I. INTRODUCTION

The power flow control [1-3] and economic operation such as optimal power flow including the FACTS devices has become an important aspect in the present day power system operation and planning. OPF is part of the standard tools of the supervisory, control and data acquisition (SCADA) and energy management system (EMS). It schedules power system controls to optimize an objective function while satisfying non-linear equality and linear equality constraints.

In steady state operation of power system, unwanted loop flow and parallel power flow between utilities are problems in heavily loaded interconnected power systems. These two power flow problems are sometimes beyond the control of generators or it may cost too much with generator regulations. However, with UPFC and/or other control facilities based on power electronics components in network, the unwanted power flow can be easily regulated. In this context, more control facilities may complicate the system operation. As control facilities influence each other, a good coordination is required in order to bring all devices to work together, without interfering with each other. Therefore, it becomes necessary to extend available system analysis tools, such as optimal power flow to represent FACTS controls. It has also been noted that the OPF problem with series compensation may be a non-convex and non-linear problem, which will lead the conventional optimization method stuck into local minimum.

Many classical techniques have been reported in the literature [5–8], such as nonlinear programming (NLP), quadratic programming (QP) and linear programming (LP). The gradient based methods [8,9] and Newton methods [10] suffer from the difficulty in handling inequality constraints. Moreover, these NLP and QP methods rely on convexity to obtain the global optimum solution and as such are forced to simplify relationships in order to ensure convexity. To apply linear programming [11], input–output function is to be expressed as a set of linear functions, which may lead to loss of accuracy. Moreover they are not guaranteed to converge to the global optimum of the general non-convex OPF problem. These days, genetic algorithm (GA) and evolutionary programming techniques (EP) [12-15] has been suggested to overcome the above-mentioned difficulties of classical methods. However, problems arise with the considerations of FACTS devices in OPF. The controllable parameters of UPFC cannot be added directly to those existing OPF techniques because these parameters will change the admittance matrix.

This paper proposed a new method based on DE[16] technique to incorporate the power flow control needs with active power OPF using AC power flow model considering UPFC and voltage stability. The total generation fuel cost is used as the objective function and the operation and security limits are considered. Simulation studies are carried out in a modified IEEE 30-bus system to show the effectiveness of the method.

II. VOLTAGE STABILITY L-INDEX

Consider an n-bus system having 1, 2…g, generator buses (g), and g+1,g+2…n the load buses(r=n-g-s) and t number of OLTC transformers. The transmission system can be represented using a hybrid representation, by the following set of equations

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = H \begin{bmatrix} I_L \\ V_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \tag{1}$$

V_L, I_L are the voltage and current vectors at the load buses.

V_G, I_G are the voltage and current vectors at the generator buses.

$Z_{LL}, F_{LG}, K_{GL}, Y_{GG}$ are the sub-matrices of the hybrid matrix H.

The L-indices for a given load condition are computed for all load buses. The equation for the L-index for j-th node can be written as[17]

$$L_j = \left| 1.0 - \sum_{i=1}^{i=g} \left| F_{ji} \right| \frac{|V_i|}{|V_j|} \angle \theta_{ji} + \delta_i - \delta_j \right| \tag{2}$$

It can be seen that when a load bus approaches a steady state voltage collapse situation, the index L approaches the numerical value 1.0. Hence for an overall system voltage stability condition, the index evaluated at any of the buses must be less than unity. Thus the index value L gives an indication of how far the system is from voltage collapse.

III. FACTS MODELING

The UPFC is an advanced power systems device capable of providing simultaneous control of voltage magnitude and active and reactive power flows, and, it is well placed to solve most issues relating to power flow control while enhancing considerably transient and dynamic stability [18].

Considerable progress has been made for a realistic UPFC model [18-22] suitable for efficient load flow studies. These models are only valid for the purpose of conventional load flow studies. A comprehensive UPFC model suitable for OPF solutions is presented in [24, 25] and, very robust iterative solutions are achieved since the optimization process is carried out via Newton’s method. Hence, large-scale power networks are solved very reliably. The UPFC model has been developed to control active and reactive power flow at either the sending or receiving end nodes. Furthermore, the model is very flexible and can be set to simulate different UPFC operating modes very easily. The voltage source-based model [22] is used as the basis of the UPFC-OPF formulation.

1) *Voltage source-based UPFC model*

The UPFC equivalent circuit shown in Fig. 1 [32, 33] is used to derive a very flexible UPFC model, which can be used for OPF solutions. As far as power flow solutions are concerned, the only restriction which this model may have is that the UPFC converter valves are taken to be lossless. However, active power losses in the converter valves are expected to be negligible and this is expected to be a reasonable assumption. In this situation, the active power supplied to the shunt converter $\mathrm{Re}\{V_{vR} I_{vR}^*\}$ satisfies the active power demanded by the series converter $\mathrm{Re}\{V_{cR} I_r^*\}$.

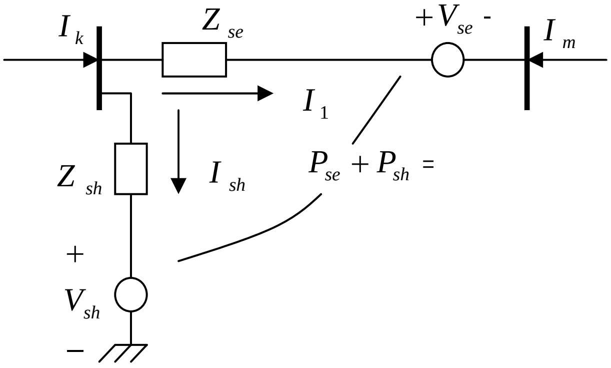

Figure 1. Equivalent circuit of UPFC

The circuit is made up of two ideal voltage sources representing the fundamental Fourier series component of the switched voltage wave forms at the AC converter terminals. The impedance of the series and shunt transformers, z,, and ,,z,, are included in the model.

The ideal voltages sources are

$$\mathbf{V}_{vR} = V_{vR}(\cos\theta_{vR} + j\sin\theta_{vR}) \tag{3}$$

$$\mathbf{V}_{cR} = V_{cR}(\cos\theta_{cR} + j\sin\theta_{cR}) \tag{4}$$

where

V_{vR} and θ_{vR} are the controllable magnitude $(V_{vR\min} \le V_{vR} \le V_{vR\max})$ and angle $(0 \le \theta_{vR} \le 2\pi)$ of the ideal voltage source representing the shut converter. The magnitude V_{cR} and angle θ_{cR} of the ideal voltage source representing the series converter are controlled between limits $(V_{cR\min} \le V_{cR} \le V_{cR\max})$ and $(0 \le \theta_{cR} \le 2\pi)$ respectively.

IV. OPTIMAL POWER FLOW PROBLEM

The objective function to be minimized for the determination of UPFC location is the sum of square of voltage stability indices of load buses, and is given below

$$f = \sum_{j=g+1}^{nb} L_j^2 \tag{5}$$

The optimization is subjected to the following constraints:

i) The inequality constraints on real power generation at bus i.

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \tag{6}$$

where $P_{gi}^{\min}$ and $P_{gi}^{\max}$ are respectively minimum and maximum values of real power generation allowed at generator bus i.

ii) The power flow equation of the power network

$$g(V, \phi) = 0 \tag{7}$$

where $g(V,\phi) = \begin{cases} P_i(V,\phi) - P_i^{net} \\ Q(V,\phi) - Q_i^{net} \\ P_m(V,\phi) - P_m^{net} \end{cases}$ for each PQ bus i

where P_i and Q_i are respectively calculated real and reactive power for PQ bus i.

P_i^{net} and Q_i^{net} are respectively specified real and reactive power for PQ bus i.

P_m and P_m^{net} are respectively calculated and specified real power PV bus m.

V and ϕ are voltage magnitude and phase angles at different buses.

iii) The inequality constraint on reactive power generation Q_{gi} at each PV bus

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} \tag{8}$$

where $Q_{gi}^{\min}$ and $Q_{gi}^{\max}$ are respectively minimum and maximum value of reactive power at PV bus i.

iv) The inequality constraint on voltage magnitude V of each PQ bus

$$V_i^{\min} \le V_i \le V_i^{\max} \tag{9}$$

where $V_i^{\min}$ and $V_i^{\max}$ are respectively minimum and maximum voltage at bus i.

v) The inequality constraint on phase angle ϕ_i of voltage at all the buses i

$$\phi_i^{\min} \le \phi_i \le \phi_i^{\max} \tag{10}$$

where $\phi_i^{\min}$ and $\phi_i^{\max}$ are respectively minimum and maximum voltage angles allowed at bus i.

vi) MVA flow limit on transmission line

$$MVAf_{ij} \le MVAf_{ij}^{\max} \tag{11}$$

where $MVAf_{ij}^{\max}$ is the maximum rating of transmission line connecting bus I and j.

vii) Voltage stability constraint

$$L_j < L_{\max} \tag{12}$$

Where $L_{\max}$ is the maximum voltage stability index at bus j

viii) The inequality constraint on series voltage source magnitude of UPFC

$$V_{se}^{\min} \le V_{se} \le V_{se}^{\max} \tag{13}$$

where $V_{se}^{\min}$ and $V_{se}^{\max}$ are respectively minimum and maximum series voltage source magnitude of UPFC.

ix) The inequality constraint on shunt voltage source magnitude of UPFC

$$V_{sh}^{\min} \le V_{sh} \le V_{sh}^{\max} \tag{14}$$

where $V_{sh}^{\min}$ and $V_{sh}^{\max}$ are respectively minimum and maximum shunt voltage source magnitude of UPFC.

x) The inequality constraint on series voltage source angle of UPFC

$$\phi_{se}^{\min} \le \phi_{se} \le \phi_{se}^{\max} \tag{15}$$

where $\phi_{se}^{\min}$ and $\phi_{se}^{\max}$ are respectively minimum and maximum series voltage source angle of UPFC

xi) The inequality constraint on shunt voltage source angle of UPFC

$$\phi_{sh}^{\min} \le \phi_{sh} \le \phi_{sh}^{\max} \tag{16}$$

where $\phi_{sh}^{\min}$ and $\phi_{sh}^{\max}$ are respectively minimum and maximum shunt voltage source angle of UPFC

V. OVERVIEW OF DE

The DE algorithm is a population based algorithm like genetic algorithms using the similar operators; crossover, mutation and selection. The main difference in constructing better solutions is that genetic algorithms rely on crossover while DE relies on mutation operation. This main operation is based on the differences of randomly sampled pairs of solutions in the population. The algorithm uses mutation operation as a search mechanism and selection operations to direct the search toward the prospective regions in the search space. The DE algorithm also uses a non-uniform crossover that can take child vector parameter from one parent more often than it does from others. By using the components of the existing population members to construct trial vectors, the recombination (crossover) operator efficiently shuffles information about successful combinations, enabling the search for a better solution space [16].

The main DE algorithm is described as follows:

Initialization

The initial population of NP vectors is randomly selected based on uniform probability distribution for all variables to cover the entire search uniformly. Each individual X_i is a vector that contains as many parameters as the problem decision variables D. Random values are assigned to each decision parameter in every vector according to:

$$x_{ij}^0 \sim U(x_j^{\min},\ x_j^{\max}) \tag{17}$$

where i =1,...,NP and j =1,...D; $x_j^{\min}$ and $x_j^{\max}$ are the lower and upper bounds of the j^{th} decision variable; U($x_j^{\min}$, $x_j^{\max}$)denotes a uniform random variable ranging over [$x_j^{\min}$, $x_j^{\max}$].

x_{ij}^0 is the initial j^{th} variable of i^{th} population .All the vectors should satisfy the constraints.

Evaluation

Evaluate the fitness value of each individual (in this work, the goal is to minimize the cost function)

Mutation

For each target vector $x_{i,G}$

, a mutant vector is produced by

$$v_{i,G+1} = x_{i,G} + K.(x_{r1,G} - x_{i,G}) + F.(x_{r2,G} - x_{r3,G}) \tag{18}$$

where $i, r_1, r_2, r_3 \in \{1, 2, ..., NP\}$ are randomly chosen and must be different from each other.

In Eq (23), F is the scaling factor which has an effect on the difference vector $(x_{r2,G} - x_{r3,G})$, K is the combination factor.

Crossover

The parent vector is mixed with the mutated vector to produce a trial vector $u_{ji,G+1}$

$$u_{ji,G+1} = \begin{cases} v_{ji,G+1} & if\ (rnd_j \le CR)\ or\ j = rn_i, \\ q_{ji,G} & if\ (rnd_j > CR)\ or\ j \ne rn_i \end{cases} \quad (19)$$

where

$j = 1, 2, ..., D;\ r_j \in [0,1]$ is the random number; CR is crossover constant $\in [0,1]$ and $rn_i \in (1, 2, ..., D)$ is the randomly chosen index.

Selection

All solutions in the population have the same chances of being selected as parents without dependence of their fitness value. The child produced after the mutation and crossover operations is evaluated. Then, the performance of the child vector and its parent is compared and the better one is selected. If the parent is still better, it is retained in the population.

VI. SIMULATION RESULTS WITH DE

This DE-OPF algorithm is applied to IEEE-30 bus test system whose data has been given in Ref. [23]. For this analysis the DE control parameters as given in Table I have been considered. Table II gives the UPFC location and the corresponding real power, reactive power and bus voltage settings of UPFC.

TABLE I. DE CONTROL PARAMETERS

S.No.	DE Parameter	Value
1	Population size	20
2	Maximum generations	150
3	CR(Crossover Ratio)	0.5

TABLE II. **IEEE 30-BUS RESULTS**: LINE FLOW SETTINGS OF UPFC IN EACH LOCATION

S.No.	UPFC Location	$\sum_{j=g+1}^{nb} L_j^2$	PM	1.5(PM)	PM	QM	1.5(QM)	QM Final	VLine
			Initial(Range)		Final	Initial(Range)			
1	8 - 11	0.1225	0.5865	0.8798	0.5904	-0.0574	-0.0861	-0.0379	1.05
2	11 - 13	0.1336	0.5138	0.7707	0.4543	-0.0309	-0.04635	-0.0227	1.0445
3	13 - 7	0.1358	0.3473	0.52095	0.2026	0.03	0.045	0.045	1.0411
4	9 - 10	0.0956	0.3072	0.4608	0.4608	-0.0282	-0.0423	-0.0126	1.0417
5	12 - 14	0.1338	0.0739	0.11085	0.0751	-0.0006895	-0.00103	-0.001	1.05
6	12 - 15	0.1267	0.1789	0.26835	0.2405	-0.0299	-0.04485	-0.0449	1.0417
7	12 - 16	0.1306	0.069	0.1035	0.1035	0.017	0.0255	0.0073	1.05
8	14 - 15	0.1351	0.0113	0.01695	0.017	-0.018	-0.027	-0.0236	1.0446
9	16 - 17	0.1349	0.0336	0.0504	0.0504	-0.0019	-0.00285	0.0029	1.0413
10	15 - 18	0.1311	0.0562	0.0843	0.0843	0.0109	0.01635	0.01	1.0428
11	18 - 19	0.1381	0.0239	0.03585	0.0359	0.0012	0.0018	0.0018	1.0367
12	19 - 20	0.1294	-0.0712	-0.1068	0.1068	-0.0329	-0.04935	0.0153	1.05
13	10 - 20	0.1237	0.0941	0.14115	0.1218	-0.0081	-0.01215	-0.0121	1.0457
14	10 - 17	0.1302	0.0566	0.0849	0.0849	0.039	0.0585	0.0253	1.05
15	10 - 21	0.1256	0.1609	0.24135	0.2414	0.0314	0.0471	0.0087	1.0462
16	10 - 22	0.131	0.0777	0.11655	0.1166	0.0125	0.01875	-0.016	1.0465
17	21 - 22	0.135	-0.0149	-0.02235	-0.0223	-0.0104	-0.0156	0.0156	1.042
18	15 - 23	0.1319	0.05	0.075	0.075	-0.0206	-0.0309	-0.0221	1.0429
19	22 - 24	0.1271	0.0623	0.09345	0.0935	0.0013	0.00195	-0.0015	1.0392
20	23 - 24	0.1386	0.0177	0.02655	0.0266	0.0377	0.05655	0.0511	1.0427
21	24 - 25	0.1306	-0.0076	-0.0114	-0.0114	0.0249	0.03735	-0.0106	1.05
22	25 - 27	0.1234	-0.0432	-0.0648	0.0648	0.0011	0.00165	0.0017	1.05
23	27 - 29	0.1156	0.0619	0.09285	0.0929	0.0159	0.02385	0.0059	1.0422
24	27 - 30	0.1161	0.0709	0.10635	0.1064	0.0163	0.02445	0.0061	1.0419
25	29 - 30	0.1333	0.037	0.0555	0.0555	0.0063	0.00945	0.0073	1.0357
26	13 - 28	0.1136	0.1552	0.2328	0.2328	0.177	0.02655	0.0266	1.04

where PM=UPFC Real Power setting
QM=UPFC Reactive power setting
Vline= UPFC Bus voltage setting

From the Table II it can be seen the UPFC location in the lines 9-10, 13-28, 27-29, 27-30, and 8-11 gives the best performance of the system with respect to the objective function values. Hence, they are designated as top 5 UPFC locations.

Figures 2 and 3 show the bus voltage magnitudes and voltage stability indices with the UPFC location in the top 5 locations.

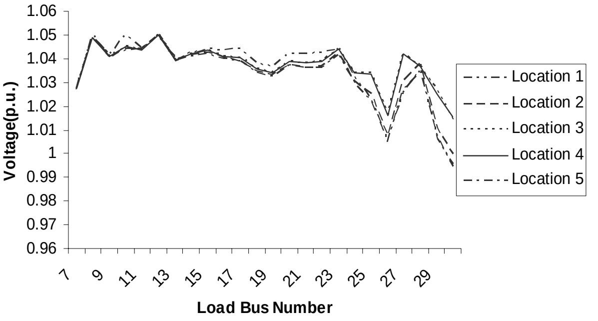

Figure 2. Bus voltage Profiles

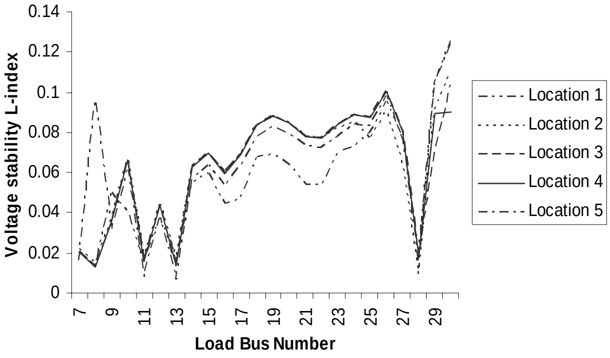

Figure 3. Voltage stability indices

VII. CONCLUSION

In this paper, a new DE method has been presented to solve the optimal power flow problem of power system with flexible AC transmission systems. The proposed method introduces the voltage source model of FACTS devices into a conventional AC optimal power flow problem to exploit the new characteristic of FACTS devices. Case studies on IEEE-30 bus test system show the potential for application of DE to determine the control parameter of the power flow controls with FACTS. It has been shown that the FACTS device can improve the voltage stability. Moreover, it can provide wider operating margin and higher voltage stability with higher reserve capacity.

REFERENCES

[1] I. Papic. P. Zunko, D. Povh and M. Weinhold, "Basic Control of Unified Power Flow Controller," *IEEE Transactions **ON** Power Systems.* Vo1.12, No.4, November 1997. pp.1734-1739.

[2] D.J. Gotham and G.T. Heydt, "Power Flow Control In Systems with FACTS Devices," Electrical Machine and Power Systems. N0.26, 1998, pp.951-962.

[3] M.Noroozian, L. Agquist, M. Ghandhari and G. Andersson, "Use of UPFC for Optimal Power Flow Control," *IEEE Tran.vactions **on** Power Delivery,* Vol.12, No.4, October 1997, pp.1629-1634.

[4] Walter DC, Sheble GB. Genetic algorithm solution of economic dispatch with valve point loading. IEEE Trans Power Syst 1993;8(3):1325–32.

[5] Momoh JA, Guo SX, Ogbuobiri EC, Adapa R. The quadratic interior point method solving power system optimization problems. IEEE Trans Power Syst 1994;9:1327–36.

[6] Momoh James A, El-Hawary ME, Adapa R. A review of selected optimal power literature to 1993. Part I: non-linear and quadratic programming approaches. IEEE Trans Power Syst 1999;14(1): 96–104.

[7] Momoh James A, El-Hawary ME, Adapa R. A review of selected optimal power literature to 1993. Part II: Newton, linear programming and interior point methods. IEEE Trans Power Syst 1999;14(1):105–11.

[8] Nagarth IJ, Kothari DP. Power system engineering. New Delhi: Tata McGraw-Hill Publishing Company Limited; 1996.

[9] Dommel HW, Tinney WF. Optimal power flow solution. IEEE Trans Power Appar Syst 1968;PAS-87(10):1866–76.

[10] Sun DI, Ashley B, Brewer B, Hughes A, Tinney WF. Optimal power flow by Newton approach. Trans Power Appar Syst 1984;PAS103(10):2864–80.

[11] Alsac O, Bright J, Prais M, Stott B. Further developments in LP-based optimal power flow. IEEE Trans Power Syst 1990;5(3): 697–711.

[12] Bakirtzis Anastasios G, Biskas Pandel N, Zoumas Christoforos E, Vasilios Petridis. Optimal power flow by enhanced genetic algorithm. IEEE Trans Power Syst 2002;17(2):229–36.

[13] Yang Hong-Tzer, Yang Pai-Chuan, Huang Ching-Lien. Evolutionary programming based economic dispatch for units with non-smooth fuel cost functions. IEEE Trans Power Syst 1996;11(1):112–8.

[14] Yuryevich Janson, Wong Po kit. Evolutionary programming based optimal power flow algorithm. IEEE Trans Power Syst 1999;14(4): 1245–50.

[15] Lo CH, Chung CY, Nguyen DHM, Wong KP. A parallel evolutionary programming based optimal power flow algorithm and its implementation. In: Proceedings of IEEE third international conference on machine learning and cybernetics, Shanghai, vol. 4, 26–29 August 2004. p. 2543–8.

[16] Storn R, Price K. Differential evolution - a simple and efficient heuristic for global optimization over continuous spaces. J. Global Optimization, 1997, 11: 341–359

[17] P Kessel, H Glavitsch, “Estimating the voltage stability of a power system”, IEEE Trans on Power Delivery, vol. PWRD-1, No.3, July 1986, pp. 346-354.

[18] IEEEKIGRE: ‘FACTS overview’. Special Issue, 95TP108, IEEE Service Center, Piscataway, NJ, 1995

[19] GYUGYI, L.: ‘A unified power flow control concept for flexible AC transmission system’, *IEE Proc. C,* 1992, **139,** (4), pp. 323-333.

[20] NOROOZIAN, M., ANGQUIST, L., GHANDHARI, M., and ANDERSON, G.: ‘Use of UPFC for optimal power flow control’.IEEE/KTH Stockholm *Power tech* conference, Stockholm, Sweden, 1995, pp. 506-511

[21] NABAVI-NIAKI, A., and IRAVANI, M.R.: ‘Steady-state and dynamic models of unified power flow controller (UPFC) for power system studies’ Presented at 1996 IEEE -PES Winter Meeting, 96 Baltimore, MD, 1996, WM 257-6 PWRS

[22] FUERTE-ESOUIVEL. C R . and ACHA. E ‘The unified Power flow controller; a critical comparison of Newton-Raphson UPFC algorithms in power flow studies’, *IEE Proc. C,* 1997, 144, (5), pp.437444.

[23] K Y Lee, Y M Park and J L Ortiz. ‘A United Approach to Optimal Real and Reactive Power Dispatch’. IEEE Transactions on Power Apparatus and System, vol 104, 1985, pp1147-1153.