International Journal of Electrical, Electronics and Computer Engineering 1(2): 93-97(2012)
ISSN No. (Online) : 2277-2626
Special Edition for Best Papers of Michael Faraday IET India Summit-2012, MFIIS-12

Modified Differential Evolution based Multi-Objective Congestion Management in Deregulatory Power Environment

S. Biswas (Raha), K.K. Mandal, and N. Chakraborty
Department of Power Engineering, Jadavpur University, Jadavpur, (WB)

(Received 15 October, 2012 Accepted 01 December, 2012)

ABSTRACT: Congestion Management (CM) is a very important aspect of present deregulatory power environment. In the restructured power market congestion occurs when the transmission network is unable to accommodate all the desired transaction due to violation of system operating limit. Increase of real power loss, increase of load demand compared to generated power, lack of Var sources or the fall of voltage level may be the different causes of CM problem. While solving the CM problem this paper minimises real power loss and reactive power generation aspect together as multi-objective solving problem with the concept of dominance and Pareto optimality. In this paper Thyristor Controlled Series Capacitor (TCSC) is inserted in the transmission line to settle multi-objective CM problem. The optimal location of the TCSC placement is suggested by the sensitivity factor analysis. The optimal size and the operating mode of the TCSC device are decided by the Modified Differential Evolution (MDE) method. As a test case IEEE 30-bus system is considered to solve the said problem.

Index Terms— Multi-Objective Congestion management (MOCM), Sensitivity Factor analysis, Thyristor Controlled Series Capacitor (TCSC), Differential Evolution with Random Localization (DERL), Pareto- Optimality.

I. INTRODUCTION

Deregulated power environment are frequently suffering from the problem of congestion which is a lack between the generation and transmission companies associated in the power market [1]. This problem is termed as Congestion Management (CM) problem [2]. This may happen due to many reasons. Among them line outage, additional load joining, reduced efficiency of power generating devices, voltage collapse etc are the main reasons behind the CM problem. This unavoidable phenomenon can be solved by generation rescheduling, topological changes or restructuring of the network or by incorporating power flow and voltage controlled devices like Flexible AC Transmission systems (FACTs). In solution to this, the expansion of the transmission system has resulted in reduction of stability margin and risk of grid failure or blackouts. In this situation the CM problem can efficiently be solved by the incorporation of FACTs devices [3] which is the most feasible and cheapest solution keeping the existing system without expanded and stressed. In this paper focus is given to solve CM problem by minimizing two important aspects of deregulated power environment. They are the real power loss [4] and reactive power generation aspects [5] which are closely coupled with the deregulated power environment. Real power loss minimization helps to enhance energy transfer capability to the connected loads where reactive power helps to provide requisite amount of voltage level along with the support to real power flow. Minimum real power loss enhances the efficiency of the deregulated power market where multi systems are operated together. Reactive power generation minimization saves the cost of the generating companies which is a very vital issue of the deregulated power market. While solving this one of the important FACTs devices i.e. Thyristor Controlled Series Capacitor (TCSC) is installed in the transmission line to resolve the MOCM problem. The major objective in applying TCSC is to increase real power transfer capacity in critical transmission lines (typically tie lines) under congested condition. Even sub-synchronous resonance can be mitigated by the installation of TCSC devices.

Now the optimal placement, size and the operating mode selection of the TCSC device is another important part of this research. The location of the TCSC may be determined by the sensitivity factor analysis [6]. This analysis is based on the total system VAR power loss versus the reactance of the system. In this paper optimal placement of TCSC device is settled based on such sensitivity factor (a_{ij}) analysis. According to the criteria of the mentioned factor TCSC should be placed in a line having most positive loss sensitivity index. The calculation of the factor 'a_{ij}' is discussed in the second section of the paper. Another part of the research is the optimum size and operating mode selection of the TCSC device. As this part of the MOCM problem belongs to non-linear, multi-constraint, multi-objective optimisation problem, implementation of metaheuristics [7] techniques will be most suitable option to resolve it. The CM problem is already achieved success by solving with various metaheuristics techniques [8] including Differential Evolution (DE). Although DE is a very efficient method sometime it suffers from the problem of slow convergence. Hence in this paper modified DE is applied to resolve the said problem of slow convergence. The modified DE technique is termed as differential evolution with random localization (DERL) [9] method. Pareto optimality based DERL method solves the MOCM problem by controlling the generator bus voltages along with the size, mode selection of the TCSC device.

The obtained results improve the real power flow capability with satisfied voltage profile. Overall a contented stability is established due to incorporation of the TCSC device.

The paper is organized as follows. The second section of the paper focuses the state of art of the MOCM problem and sensitivity factor. The third section explains the multi-objective optimization criteria. The modeling part of the TCSC devices is shown in the forth section. The fifth section explains the DERL solution methodology. Pareto optimality based MOCM problem formulation with DERL technique is expressed in the sixth section. Seventh section demonstrates the result including comparative study followed by conclusion, acknowledgement and references.

II. STATE OF ART OF THE MOCM PROBLEM

In this paper two objective functions are solved together as a multi-objective congestion management problem (MOCM). While formulating the objective function equality and inequality constraints with few control and state variables are considered.

A. Objective Function Formulations

The MOCM problem is expressed as:

$$\min\ f_{\min}(x,u) = \min\ \left(\sum_{i=1}^{nbus} P_{LOSS} + \sum_{i=1}^{ng} Q_{Gen}\right) \quad \ldots(1)$$

Where the first part of the objective function is shows the real power loss minimization (P_{LOSS}):

$$\min P_{Loss} = \sum_{i=1}^{ng} P_{GEN} - \sum_{\substack{i=1,\\ i \neq \text{slack bus}}}^{nbus} P_{LOAD} \quad \ldots(2)$$

Second part of the objective function is gives the expression for the Reactive power generation minimization (Q_{Gen}):

$$\min Q_{Gen} = \sum_{i=1}^{ng} Q_i \quad \ldots(3)$$

Here P_{GEN} and P_{LOAD} represent the generated power at the *ng* number of generator buses and load power connected to the different buses i.e. *nbus*. Q_i represents the net generated power across the connected generator buses. Now $f(x,u)$ is the multi-objective function with few state (x) and control variables (u). x includes excitation angle (θ), load bus voltage(V_L), generated real power at the slack bus (P_{g1}), transformer tap settings (T), connected Shunt capacitors if any (Q_C) and u represents generator bus voltages (V_G) and placed TCSC device reactance (x_{TCSC}).

The minimization of the above multi-objective function is subjected to a number of equality and inequality constraints. Equality constraint consists of the real and reactive power flow balance equation comprising of the generation, load and losses. Equality Constraints are represented by (4) and (5)

$$P_{GENi} - P_{Di} - V_i \sum_{j=1}^{NB} V_j \left[G_{ij} \cos\left(\delta_i - \delta_j\right) + B_{ij} \sin\left(\delta_i - \delta_j\right)\right] = 0 \quad \ldots(4)$$

$$Q_{GENi} - Q_{Di} - V_i \sum_{j=1}^{NB} V_j \left[G_{ij} \sin\left(\delta_i - \delta_j\right) - B_{ij} \cos\left(\delta_i - \delta_j\right)\right] = 0 \quad \ldots(5)$$

Where *NB* is the number of buses, P_D is the active load demand, Q_D is the reactive load demand, δ_i and δ_j is the voltage angle of bus *i* and *j* respectively and G_{ij} and B_{ij} are the conductance and the susceptance between bus *i* and *j* respectively.

Inequality constraint comprises of different inequalities like generation constraints, transformer constraints, shunt Var constraints, security constraints and the reactance constraints.
Inequality Constraints are:

1. Generation constraints: Generation bus voltages, reactive power outputs are restricted by their lower and upper limits as:

$$V_{Gi}^{min} \le V_{Gi} \le V_{Gi}^{max}, \qquad i = 1,\ldots, G \quad \ldots(6)$$

$$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max}, \qquad i = 1,\ldots, G \quad \ldots(7)$$

2. Transformer constraints: Transformer tap settings are restricted by their lower and upper limits as:

$$T_i^{min} \le T_i \le T_i^{max}, \qquad i = 1,\ldots, NT \quad \ldots(8)$$

3. Shunt VAR constraints: Shunt VAR compensators are restricted by their lower and upper limits as:

$$Q_{Ci}^{min} \le Q_{Ci} \le Q_{Ci}^{max}, \qquad i = 1,\ldots, NC \quad \ldots(9)$$

4. Security Constraints: This includes the constraints of voltage at load buses as:

$$V_{Li}^{min} \le V_{Li} \le V_{Li}^{max}, \qquad i = 1,\ldots, NL \quad \ldots(10)$$

5. Reactance Constraints: This includes the constraints of the reactance to the TCSC placed lines:

$$-0.5 \times x_L \le x_{TCSCi} \le 0.5 \times x_L, \qquad i = 1,\ldots, Np \quad \ldots(11)$$

Where *NT*, *NC*, *NL*, *Np* , x_L and V_L are transformer tap settled buses, shunt capacitor connected buses, load buses, TCSC placed lines, inductive reactance of the TCSC placed lines and load bus voltages respectively. Once the objective function is fixed Pareto optimality based DERL Technique is applied to solve the problem in hand.

B. Sensitivity Factor Analysis

Due to high cost of the FACTs devices the optimal placement is so necessary. Hence the sensitivity factor is calculated to determine the proper optimal placement of the corresponding TCSC devices. In this paper the said factor is meant the sensitivity of the total system reactive power loss with respect to the control variable of the TCSC [6]. The a_{ij} factor is given as:

$$a_{ij} = \frac{\partial Q_L}{\partial x_{ij}} = \left[V_i^2 + V_j^2 - 2V_i V_j \cos\delta_{ij}\right]\left[\frac{r_{ij}^2 - x_{ij}^2}{(r_{ij}^2 + x_{ij}^2)^2}\right] \quad \ldots(12)$$

Where Q_L is the total reactive power or VAR power loss , x_{ij} is the respective reactance between the i^{th} and j^{th} line, V_i and V_j are the ith and jth bus voltages, δ_{ij} is the difference in excitation angle between the i^{th} and j^{th} bus and r_{ij} is the respective resistance between the i^{th} and j^{th} line. In this paper most positive loss sensitivity factor based line is selected as the optimal position for the TCSC device.

III. MULTI-OBJECTIVE OPTIMIZATION CRITERION

In these paper multi-objective optimization criteria is fulfilled by the concept of Dominance and Pareto-Optimality [10]. While more than one objective functions are to be solved simultaneously, compromised solution between both the functions are to be made. Now the level of compromisation is dependent on the priority of the objectives in the practical field. In this paper the real power loss minimization is prioritized over the reactive power generation minimization aspect. According to the applied evolutionary technique the solution ($x^{(1)}$) dominates the solution ($x^{(2)}$) if both the following conditions are satisfied. First condition is that the solution ($x^{(1)}$) is no inferior than the solution ($x^{(2)}$) in all objectives. Second condition is that the solution ($x^{(1)}$) is strictly superior than ($x^{(2)}$) in at least one objective. While solving the multi-objective CM problem in this paper these two conditions are strictly maintained throughout the simulation process. The obtained best non dominated solution is termed as Pareto optimal solution. In this process Ideal solution for real power loss minimization is also determined. Finally a collective set of non dominated solutions are plotted as Pareto optimal curve showing Pareto optimal solution and Ideal solution.

IV. MODELING OF TCSC DEVICES

The major advantages of implementing TCSC devices in the deregulated power network is enhanced loadability, improved power system thermal stability and system security, reliability along with a smooth, continuous cycling. In this paper the modeling of the TCSC device in line *i-j* is represented in the Fig. 1. And Fig. 2. TCSC device comprises of a fixed capacitor (X_c) in parallel with a thyristor controlled reactor (X_{TCR}). The equivalent circuit is given in Fig. 1. The impedance of the TCSC (X_{TCSC}) is given by (13).

$$X_{TCSC} = \frac{X_C}{1 - \frac{X_c}{X_{TCR}}} \qquad \ldots(13)$$

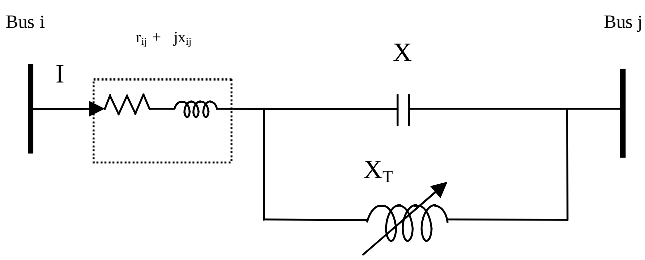

Fig. 1. Equivalent circuit of the placed TCSC in the line i-j

If $X_c < X_{TCR}$, current flowing through the TCR (I_{TCR}) will be 180^0 out of phase with the line current (I_L) indicating the capacitive operating mode of the TCSC device. If $X_c > X_{TCR}$, the effective reactance of TCSC will become negative. This will imply the inductive behavior of the TCSC device. Both the cases are shown in Fig. 2.

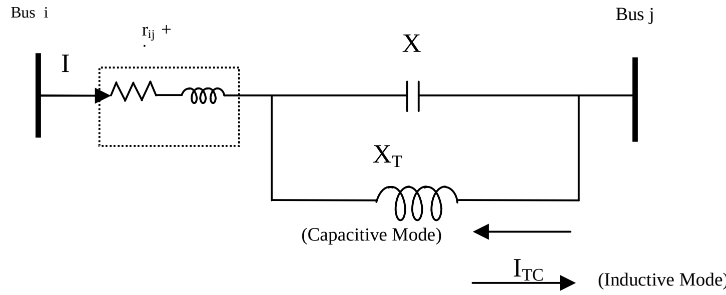

Fig. 2. Equivalent circuit of the placed TCSC with its different operating mode in the line i-j.

The power flow equation while inserting TCSC device in the line *i-j* is given bellow:

$$P_{ij} = V_i^2 G_{ij} - V_i V_j G_{ij}\cos(\delta_i - \delta_j) - V_i V_j B_{ij}\sin(\delta_i - \delta_j) \quad \ldots(14)$$

$$Q_{ij} = -V_i^2 B_{ij} - V_i V_j G_{ij}\sin(\delta_i - \delta_j) + V_i V_j B_{ij}\cos(\delta_i - \delta_j) \quad \ldots(15)$$

$$P_{ji} = V_j^2 G_{ij} - V_i V_j G_{ij}\cos(\delta_i - \delta_j) + V_i V_j B_{ij}\sin(\delta_i - \delta_j) \quad \ldots(16)$$

$$Q_{ji} = -V_j^2 B_{ij} + V_i V_j G_{ij}\sin(\delta_i - \delta_j) + V_i V_j B_{ij}\cos(\delta_i - \delta_j) \quad \ldots(17)$$

Where $Gij = \dfrac{r_{ij}}{r_{ij}^2 + (x_{ij} - X_{TCSC})^2}$,

$$Bij = -\frac{x_{ij} - X_{TCSC}}{r_{ij}^2 + (x_{ij} - X_{TCSC})^2}$$

V. DERL SOLUTION METHODOLOGY

This paper applies a new modified DE termed as differential evolution with random localization (DERL) [9] for solving the said problem. This modification includes randomly chosen scaling factor (f_m) instead of a fixed value and tournament best value selection. DERL technique comprises of five steps i.e. Initialization, Tournament best value selection, Mutation, Crossover and Selection.

Step 1: At the initialization step alike the DE technique DERL generates a set of target vector using the uniform probability distribution function.

Step 2: In the second step, tournament best value selection is procured where best fitness value providing vector among the entire population pool is determined as one of the perturbation vector among the three vectors. The fitness value is calculated utilizing the each vector of the entire population pool. Best value providing vector among them is considered as tournament best vector and it is deemed as base perturbation vector for the mutation process (x_{tb}). This approach makes the DERL technique faster as well as efficient compared to the conventional DE.

Step 3: In the mutation step, the mutant vector v_{ij} is framed as the summation of the base vector x_{tb} and weighted difference of the two randomly chosen vectors from the entire population pool.

For every generation f_m is selected by random number generation ($f_m \in \text{rand}(0,1)$). $x_{ij}(r_2)$ and $x_{ij}(r_3)$ are the randomly chosen vectors where r_2, r_3 are the unequal random numbers and the mutant vector presented by Eq. (5)

$$v_{i,j}(t+1) = x_{tb}(t) + f_m \times \left(x_{r2,j}(t) - x_{r3,j}(t)\right) \quad \text{… (18)}$$

Step 4: In the crossover stage new offspring or trial vector is generated between target vector and mutant vector depending upon the crossover factor ($C_R \in$ rand). Trial Vector (y_{ij}) is expressed as:

$$y_{i,j}(t) = \begin{cases} v_{i,j}(t) \text{ if } rand(0,1) < C_R \\ x_{i,j}(t) \text{ else} \end{cases} \quad \text{…(19)}$$

Step 5: At the selection stage, DERL determines the efficient offspring among the target vector and the trial vector depending upon the fitness value. The better solution providing vector among the two will be chosen as fit vector. It will be passed to the next generation. While solving the multi objective optimization problem two conditions will be strictly followed to get a multi objective dominant solution as earlier discussion [section III.].

Accordingly, the DERL based simulation process continues till the terminating condition arises. In this paper the terminating condition is fixed as reaching to the maximum generation number. At the terminating point, obtained solution (offspring) is chosen as the final dominant or Pareto optimal solution.

VI. PARETO OPTIMALITY BASED MOCM PROBLEM FORMULATION WITH DERL TECHNIQUE

Before starting the Pareto Optimality based DERL programming, line wise sensitivity factor analysis are performed to find the most positive sensitive lines for the considered bus systems (IEEE 30-bus system). According to the sensitivity factor analysis suitable lines for the TCSC placement is decided. According to the DERL solution methodology (as said in section IV) the multi objective fitness value and corresponding vectors are calculated. This calculation is completely based on the optimal sizing and mode selection of the TCSC devices. Moreover generator bus voltages are controlled for better treatment. The ideal solution for the function 1 (real power loss minimization) and the final Pareto optimal solution can be marked after obtaining the Pareto front.

VII. SIMULATION RESULT & DISCUSSION

In this paper IEEE 30 bus system [11] is chosen for solving the MOCM problem by optimal placement of the TCSC devices. Initially sensitivity factor is calculated for all the connected 41 lines. From the sensitivity factor analysis 20[th] and 29[th] line has been found to be most positive sensitive line respectively. Hence these two lines are chosen for the optimal TCSC placements. In parallel with the TCSC placements generator bus voltages are controlled to keep within the system thermal stability limit. By controlling the bus voltages along with the size of the FACTs device, two functions (P_{LOSS} and Q_{Gen}) are minimized together. All the bus voltages are maintained between 0.9pu to 1.10pu. The size of the TCSC is con

trolled by the given inequality $-0.5 \times x_L \le x_{TCSC} \le 0.5 \times x_L$,[7] where x_L is the inductance of the congested line where TCSC will suppose to be placed. The size of the TCSC device is selected via DERL technique. The simulations are coded in house with the MATLAB 7.1 software. While solving the load flow study newton raphson method is utilized [12]. As this is a multi-objective optimisation problem, the solution vectors are dependent on a compromised value of the two functions. The obtained results in terms of the controlled variables are given in Table 1. The dominant solution for the prioritized function (real power loss minimization) has been obtained as 17.209 MW and other function (reactive power generation minimization) value optimizes at 17.7676 MVAR. Both the optimized result with respect to the generation number is given by Fig. 3 and Fig. 4. The Fig. 5 shows the Pareto optimal curve from which Pareto optimal solution as P_{LOSS}(MW)=17.216 and Q_{Gen}(MVAR)=17.74 can be concluded.

Controlled Variables	Obtained Value	Dominant Solution of function 1 and function 2	Pareto Optimal Solution of function 1 and function 2 from the Figure 3
V_{g2}	1.0639		
V_{g5}	1.0910		
V_{g8}	1.0885		
V_{g11}	1.0947	P_{LOSS}(MW)= 17.2109	P_{LOSS}(MW)= 17.216
V_{g13}	1.0975	Q_{Gen}(MVar)= 17.7676	Q_{GMIN}(MVar) =17.74
x_{TCSC20}	(+) 0.0128		
x_{TCSC29}	(-) 0.0012		

Table 1.Optimal Results.

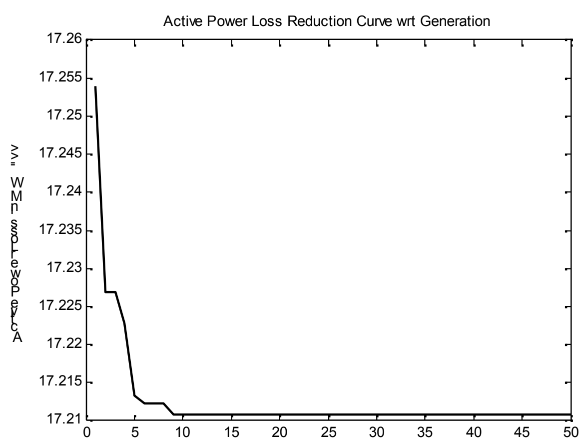

Fig. 3. Active Power Loss reduction Curve.

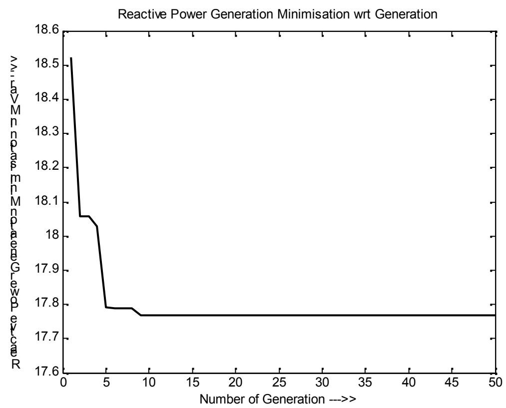

Fig 4. Reactive Power Generation Minimisation Curve.

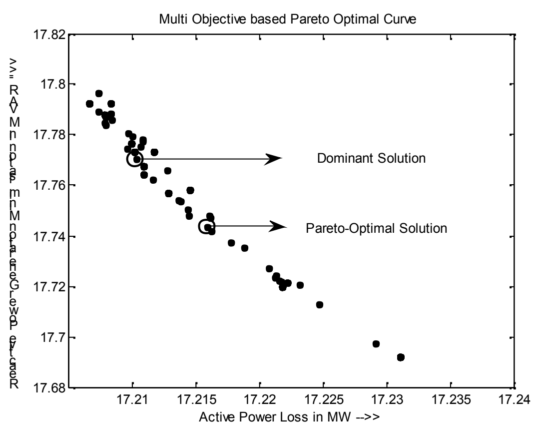

Fig 5. Multi objective based Pareto optimal Curve (Min-min).

Therefore from the test result and the obtained curves it is cleared that DERL based MOCM optimisation problem is solved with the satisfied results. Due to fast converging property of the applied algorithm optimal values converge within the 10^{th} generation. Overall one point must be mentioned that during the simulation runs no result violates the system stability.

VIII. CONCLUSION

Congestion is the major problem of deregulated power system which is tried to solve to some extent in this paper with a minor change in the existing system. In this paper incorporation of the TCSC device results minimized real power flow with minimum reactive power generation. Therefore the novelty of the research work (minimization of MOCM problem) is the optimal placement and size selection of the FACTs device with a rising modified optimisation technique. Altogether the chosen optimisation tool for the solved problem shows a satisfied Pareto optimal solution.

ACKNOWLEDGMENT

The authors acknowledge the DST INSPIRE Fellowship Programme for their cordial approach towards the research activity and the Jadavpur University for providing a smooth research environment.

REFERENCES

[1]. S. Nagalakshmi, N. Kamaraj, "Secured loadability enhancement with TCSC in transmission system using computational intelligence technique for pool and hybrid model", Applied Soft Computing, 11, pp. 4748-4756, (2011).

[2]. A. Yousefi, T. T. Nguyen, H. Zareipour, O. P. Malik, " Congestion management using demand response and FACTS devices", Electric power and Energy Systems, 37, pp. 78-85, (2012).

[3]. K. R. Padiyar, "FACTS controllers in power transmission and distribution", New Age International (P) Limited Publishers, (2007).

[4]. M. Varadarajan, K. S. Swarup, "Differential evolution approach for optimal reactive power dispatch", Applied Soft Computing, 8, pp. 1549-1561, (2008).

[5]. H. Wu, C. W. Yu, N. Xu and X. J. Lin, "An OPF based approach for assessing the minimal reactive power support for generators in deregulated power systems", Electric Power & Energy Systems, 30, pp. 23-30, (2008).

[6]. H. Besharat, T. S. Abbas, "Congestion management by determining optimal location of TCSC in deregulated power systems", Electrical Power and Energy Systems, 30, pp. 563-568 , (2008).

[7]. E. G. Talbi. "Metaheuristics from design to implementation". John Wiley & Sons, (2009) (Chapter 3, 4).

[8]. G. I. Rashed, H. I. Shaheen, X. Z. Duan, S. J. Cheng, "Evolutionary optimisation techniques for optimal location and parameter setting of TCSC under single line contingency", Applied Mathematics and Computation, 205, pp. 133-147, (2008).

[9]. P. Kaelo, M. M. Ali, "A numerical study of some modified differential evolution algorithms", European journal of operational research, 169, pp. 1176-1184, (2006).

[10]. K. Deb, "Multi-objective optimisation using evolutionary algorithms", John Wiley & Sons, (2001).

[11]. Power system test case archive, 2006, Decembar [Online], Available: http://www.ww.washington.edu/research/pstca.

[12]. H. Sadat. "Power system analysis", Fourteenth reprint, Tata McGraw-Hill Publishing Company limited, (2008).