Indian Streams Research Journal
ISSN 2230-7850
Volume-4 | Issue-5 | June-2014 Available online at www. isrj.net

APPLICATION OF DE BASED WAFGP IN MULTI OBJECTIVE OPTIMAL POWER FLOW USING TCSC

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Abstract:- This paper proposes the application of Differential Evolution (DE) algorithm based Weighted Additive Fuzzy Goal Programming (WAFGP) in solving a Multi objective Optimal Power Flow (MOPF) problem. The multiple objectives considered are maximizing the loadability, minimizing the total real power loss and minimizing the overall system cost which comprises of installation cost of FACTS devices and generation fuel cost. The optimal solution for this MOPF problem is obtained by optimally sizing and placing a Thyristor Controlled Series Capacitor (TCSC) in the power system. The constraints considered in this MOPF are the generators' real and reactive power limits and their voltage limits, transmission lines' loading capability limits, TCSC limits along with system's equality and inequality constraints. The Line Stability Index (LSI) is used to determine the critically loaded transmission lines in the power system. IEEE 30 bus system is used for testing and validating the results.

Keywords: Differential Evolution Algorithm, Weighted Additive Fuzzy Goal Programming, Multi-objective, Thyristor Controlled Series Capacitor, Cost Minimization, Line Stability Index.

1. INTRODUCTION

The efficient and economical utilization of existing power grid is always a challenging task. The emergence of Flexible AC Transmission Systems (FACTS) devices in power systems paves an easy and efficient way to achieve a stable and secure power grid [1]. FACTS devices are power electronics dynamic controllers which alter transmission line impedance, maintain real and reactive power balance and thereby increase the loading capability of transmission lines; maintain voltage stability and reduce the real and reactive power losses occurring in the power grid [2].

The utilization of FACTS devices in an efficient and economical manner is achieved by setting their control parameters optimally and placing them in an optimal location in the power grid. The evolution of intelligent algorithms like Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Bacterial Foraging Algorithm (BFA), Differential Algorithm (DE) and Immune Algorithm (IA) helps in achieving this optimization [3] – [10] .

The various objectives considered in this paper are maximizing the loadability of the system; minimizing the total real power loss of the system and minimizing the overall system cost which comprises of installation cost of FACTS devices and generation fuel cost. When these objectives are individually addressed the above intelligent algorithms will provide an optimal solution. When all the objectives are to be considered together, more than one optimal solution exists and these are called pareto - optimal solutions.

Several conventional methods like Weighted Sum method, Penalty Function method and Є-constrained method are available for finding the best compromise solution from pareto - optimal solutions[11] [12]. Zadeh introduced fuzzy logic solving multi objective optimization problems and it paved a new way for addressing it. Several multi objective problems were addressed using fuzzy theory as Fuzzy Goal Programming (FGP) and some were coupled with Weighted Sum method as Weighted Additive Fuzzy Goal Programming (WAFGP) [13] [14]. In WAFGP method, the significance of each individual objective is preserved by optimizing each objective individually.

In this paper, series compensation device TCSC is considered for the study and DE algorithm is used for obtaining the optimal solution for individual objectives. Further, in this paper, for multi objective optimization, the weights for objectives used in WAFGP are chosen optimally using DE Algorithm to find the best optimal solution satisfying all the objectives considered.

This paper is organized into seven sections: this section providing an introduction, section 2 presenting the steady state modelling of TCSC device, section 3 formulating this study's problem, section 4 describing the LSI, section 5 describing the application of DE based WAFGP method, section 6 presenting and discussing the results, and section 7 concluding the benefits of this study.

2. **STEADY STATE MODELLING OF TCSC**

TCSC is one of the static series compensators which comprises of a series capacitor bank shunted by a Thyristor controlled reactor. The desired transmission line impedance can be achieved for smoother reactive power control by controlling the TCSC both in inductive and capacitive modes. By adjusting the line impedance, improvements in voltage stability and real power flow can be achieved [15]. Fig.1 depicts the equivalent circuit of TCSC.

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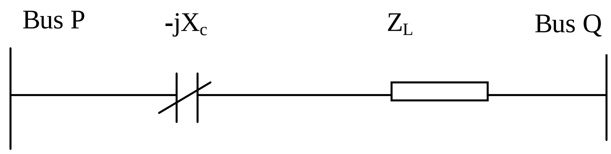

Fig. 1 Equivalent circuit of TCSC

The power flow equations of the transmission line after the insertion of TCSC are:

$$P_{pq} = v_p^2 g_{pq} - v_p v_q \left(g_{pq} \cos \delta_{pq} + b_{pq} \sin \delta_{pq} \right) \quad (1)$$

$$Q_{pq} = -v_p^2 b_{pq} - v_p v_q \left(g_{pq} \sin \delta_{pq} - b_{pq} \cos \delta_{pq} \right) \quad (2)$$

$$g_{pq} = \frac{r_{pq}}{r_{pq}^2 + \left(x_{pq} - x_c \right)^2} \quad (3)$$

$$b_{pq} = \frac{-\left(x_{pq} - x_c \right)}{r_{pq}^2 + \left(x_{pq} - x_c \right)^2} \quad (4)$$

Where x_c is the controllable reactance of TCSC device.

3. **PROBLEM FORMULATION**

Multi-objective Optimal Power Flow (MOPF) is a non-linear constrained optimization problem used to maximize or minimize a set of objectives satisfying all their equality and inequality constraints.

Minimize/Maximize $\left(f_1(y), f_2(y), \ldots\ldots\ldots\ldots f_t(y) \right)^T$ (5)

Subject to:

$U_i(y) = 0$; $V_j(y) \le 0$; i=1, 2 …m; j=1, 2 …n (6)

Where m and n are number of equality and inequality constraints.

The objective functions chosen in this paper are (i) maximizing the loadability of the power system, (ii) minimizing the total real power loss in the power system and (iii) minimizing the overall system cost which comprises of the installation cost of TCSC device and generation fuel cost. This is done by optimally placing the TCSC device in the power system with its optimal control settings.

Maximize loadability (λ) (7)

Where λ is the load factor

Minimize total real power loss (P_{Loss})

$$P_{Loss} = \sum_{p=1}^{nl} G_{p,q}\left[v_p^2 + v_q^2 - 2v_p v_q \cos\left(\delta_p - \delta_q\right)\right] \tag{8}$$

Where P_{Loss} is the total real power loss; $G_{p,q}$ is the conductance for (p - q)th transmission line; v_p and v_q are the magnitudes of voltages at bus p and bus q respectively; δ_p and δ_q are the angles of the voltages at pth and qth bus respectively ; and nl is the number of transmission lines.

Minimize overall system cost of the power system (TC)

$$TC = \sum_{i=1}^{ng} C_{gi}\left(P_{gi}\right) + IC_{TCSC} \tag{9}$$

$$\sum_{i=1}^{ng} C_{gi}\left(P_{gi}\right) = a_i + b_i P_{gi} + c_i P_{gi}^2 (\$/hr) \tag{10}$$

Based on Siemens AG database [16], the cost function for TCSC is:

$$C_{TCSC} = 0.0015(QR)^2 - 0.7130(QR) + 153.75(US\$/KVAR) \tag{11}$$

$$QR = \left|Q_2 - Q_1\right| \tag{12}$$

The unit of generation fuel cost is US$/hr and that of installation cost of TCSC device is US$. To find the overall system cost, both units must be similar. Though TCSC device remains in the power system for a long time, its service to regulate power and voltage will be limited. In this paper, for evaluating the installation cost of TCSC, five years of fruitful service of TCSC is taken into consideration.

$$IC_{TCSC} = C_{TCSC} * QR * 1000/(8760*5)\left(US\$/\text{hr}\right) \tag{13}$$

Where TC is the overall system cost of the power system; $\sum_{i=1}^{ng} C_{gi}\left(P_{gi}\right)$ is the total generation fuel cost; a_i, b_i, c_i are the cost coefficients of the ith generator; P_{gi} is the active power generation of the ith generator; ng is the total number of generator buses; C_{TCSC} is the cost equation of TCSC; QR is the operating range of TCSC in MVAR; IC_{TCSC} is the installation cost of TCSC in US$/h; Q_1 and Q_2 are the reactive power flows in a line branch before and after placing TCSC in MVAR.

The various constraints chosen in the problem are:

Equality Constraint: Power flow equation

$$P_{Gp} - P_{Dp} - \sum_{q=1}^{nb} \left|V_p\right|\left|V_q\right|\left|Y_{pq}\right| \cos\left(\theta_{pq} - \delta_p + \delta_q\right) = 0 \tag{14}$$

$$Q_{Gp} - Q_{Gp} - \sum_{q=1}^{nb} \left|V_p\right|\left|V_q\right|\left|Y_{pq}\right| \sin\left(\theta_{pq} - \delta_p + \delta_q\right) = 0 \tag{15}$$

Where P_{Gp} and Q_{Gp} are real and reactive power generation at sending bus p; P_{Dp} and Q_{Dp} are real and reactive power demand at sending bus p; θ_{pq} and Y_{pq} are the angle and magnitude of bus admittance element p,q ; and nb is the total number of buses.

Inequality Constraints:

$$P_{Gp}^{\min} \le P_{Gp} \le P_{Gp}^{\max} \tag{16}$$

$$Q_{Gp}^{\min} \le Q_{Gp} \le Q_{Gp}^{\max} \tag{17}$$

$$V_{p}^{\min} \le V_{p} \le V_{p}^{\max} \tag{18}$$

Where V_p^{max}, P_{Gp}^{max}, Q_{Gp}^{max} and V_p^{min}, P_{Gp}^{min}, Q_{Gp}^{min} are upper and lower limits of voltage magnitude, real and reactive power generation at bus p.

TCSC Constraints:

$$x_{TCSC\min} \le x_{TCSC} \le x_{TCSC\max} \tag{19}$$

Where x_{TCSC} is the TCSC parameter.

Security Constraints

$$BOL = \begin{cases} 1 & ; if BL \le 100 \\ P1 & ; otherwise \end{cases} \tag{20}$$

$$VL = \begin{cases} 1 & ; 0.95 \le V \le 1.1 \\ P2 & ; otherwise \end{cases} \tag{21}$$

Where BOL is branch overloading index; BL is branch loading; VL is voltage limit index; V is per unit values of bus voltages; p1 & p2 are penalty factors.

4. LINE STABILITY INDEX

LSI helps in identifying the critically loaded transmission lines during loaded condition of the system. It helps in optimal placement of the FACTS controllers to maintain voltage Stability and system security. It is the index derived from the two bus system model [17].

$$LSI_{p,q} = \left(\frac{R_{pq}P_q + X_{pq}Q_q}{0.25V_p^2} \right) \tag{22}$$

Where R_{pq} & X_{pq} are the resistance and reactance of the transmission line between bus p and bus q; P_q & Q_q are the real and reactive powers of bus q; V_p is the voltage at bus p.

LSI provides more accurate results than other voltage stability indices as it uses both the real power and reactive power in determination of voltage stability. In a system, the largest positive value of LSI close to one determines the critical line which is nearing its stability limit.

5. Differential Evolution (DE) algorithm based Weighted Additive Fuzzy Goal Programming (WAFGP) method

WAFGP is a popular method used for finding solutions to multi–objective optimization problems [18]. It is based on fuzzy set theory and was proposed by Zimmermann & Tiwari et.al in 1987. The algorithmic steps for DE in WAFGP are described below:

Step I

DE algorithm is used to optimize each individual objective (W_i) to obtain its minimum (W_m) and maximum (W_n) goals. This step preserves the significance of each objective. The well known basic algorithm for DE is as follows [19]:

Initialization

Evaluation

Repeat

Mutation

Crossover

Evaluation

Selection

Until (termination criteria are met)

Step II:

The crisp goal of each objective (W_i) is converted into fuzzy goal using membership functions. The linear membership function for minimization goals (W_m) and maximization goals (W_n) [18] are defined as follows:

$$\mu_{W_m}(y) = \begin{cases} 1 & W_m \le W_m^{\min} \\ \dfrac{\left(W_m^{\max} - W_m(y)\right)}{\left(W_m^{\max} - W_m^{\min}\right)} & W_m^{\min} \le W_m(y) \le W_m^{\max} \\ 0 & W_m \ge W_m^{\max} \end{cases} ; \quad m = 1, 2 \ldots p \tag{23}$$

$$\mu_{W_n}(y) = \begin{cases} 1 & W_n \ge W_n^{\max} \\ \dfrac{\left(W_n(y) - W_n^{\min}\right)}{\left(W_n^{\max} - W_n^{\min}\right)} & W_n^{\min} \le W_n(y) \le W_n^{\max} \\ 0 & W_n \le W_n^{\min} \end{cases} ; \quad n = p+1, p+2 \ldots q \tag{24}$$

Where p and q are p^{th} minimization and q^{th} maximization goal; μ_{Wm} and μ_{Wn} are the membership value of m^{th} minimization and n^{th} maximization goal.

Step III:

The WAFGP model is formulated as:

$$\text{Maximize} \quad \sum_{j=1}^{q} x_j FG_j \tag{25}$$

Subject to:

$$FG_j \le \mu_{W_j}(y);\ \mathrm{j} = 1,2\ldots\mathrm{q};\ g_j(y) = 0;\ h_k(y) \le 0;\ 0 \le FG_j \le 1;\ 0 \le \mu_{W_j} \le 1;\ 0 \le x_j \le 1$$

Where q is all objectives; FG is the Fuzzy goal.

Step IV:

A single optimal solution satisfying all the constraints is obtained by choosing the optimal weights using DE algorithm.

6. **RESULTS AND DISCUSSIONS**

The multiple objectives chosen in this MOPF study are the maximum loadability, minimum total real power loss and minimum overall system cost which includes installation cost of TCSC and generation fuel cost. The optimal sizing and placement of TCSC is used to achieve this desired objectives. As a first step, the suitability of TCSC for use in solving this MOPF is evaluated.

IEEE 30 bus system which has six generators, 24 load buses and 41 transmission lines is taken for the study [20]. DE algorithm is used for optimization and the results with and without TCSC device in the power system is compared. Coding for DE based optimization is done in MATLAB 7.5. In this study, the population size (P) chosen is 100; number of generations (G) is 50 and number of control parameters are 21 in number. The control parameters chosen are P_{G1}, P_{G2}, P_{G5}, P_{G8}, P_{G11}, $P_{G13,}$ Q_{G1}, Q_{G2}, Q_{G5}, Q_{G8}, Q_{G11}, $Q_{G13,}$ V_1, V_2, V_5, V_8, V_{11}, V_{13}, location, X_{TCSC}, λ. For this study, real power loading is considered.

TCSC has to be installed in the critical transmission lines for achieving the optimization objectives. LSI is used in determining the critical transmission lines. The critical lines are ranked and tabulated in Table 1.

Table 1 Rankings of the critical lines

Line No	**p-q**	**Rank**
13	6-10	1
4	2-5	2
17	9-10	3
1	1-2	4
16	9-11	5

IEEE 30 bus system is used to determine the total real and reactive power loss of the system for different loadability conditions with and without TCSC device and the results are compared in Fig. 2 and Fig. 3. The graphical comparisons show that TCSC device reduces total system real and reactive power losses.

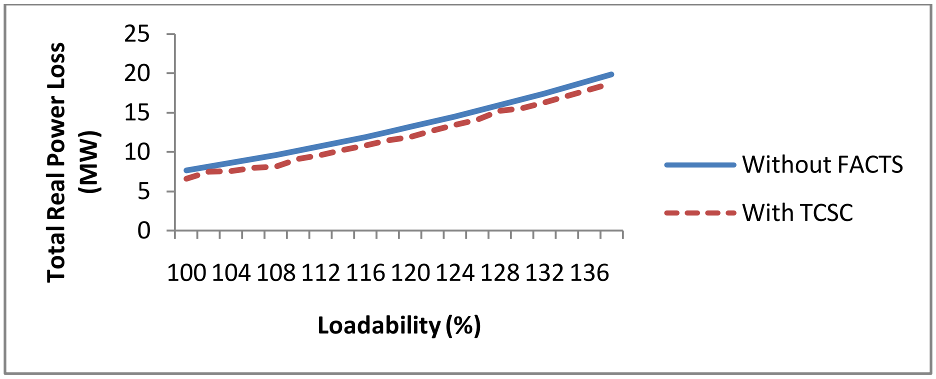

Fig. 2 Comparison results of total system real power loss in IEEE 30 bus system

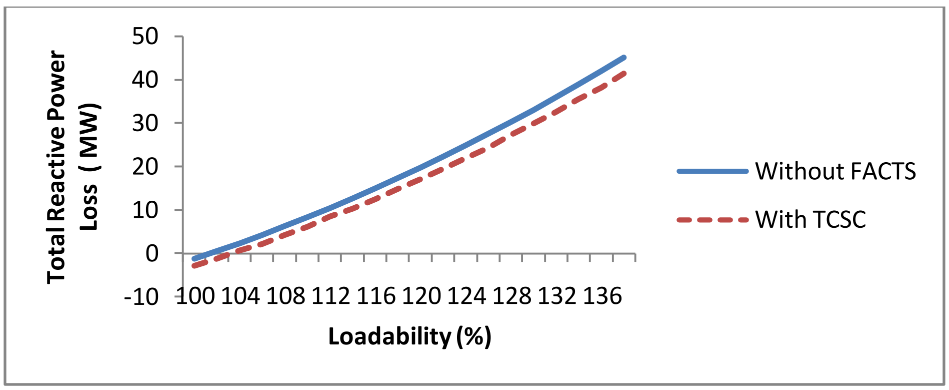

Fig. 3 Comparison results of total system reactive power loss in IEEE 30 bus system

To study the effect of TCSC device in maintenance of voltage stability, voltages at all buses in IEEE 30 bus system are determined for normal loading condition; with and without TCSC device and the results are compared in Fig. 4. The results show that an introduction of TCSC device in the system enhances the voltage profile of the buses.

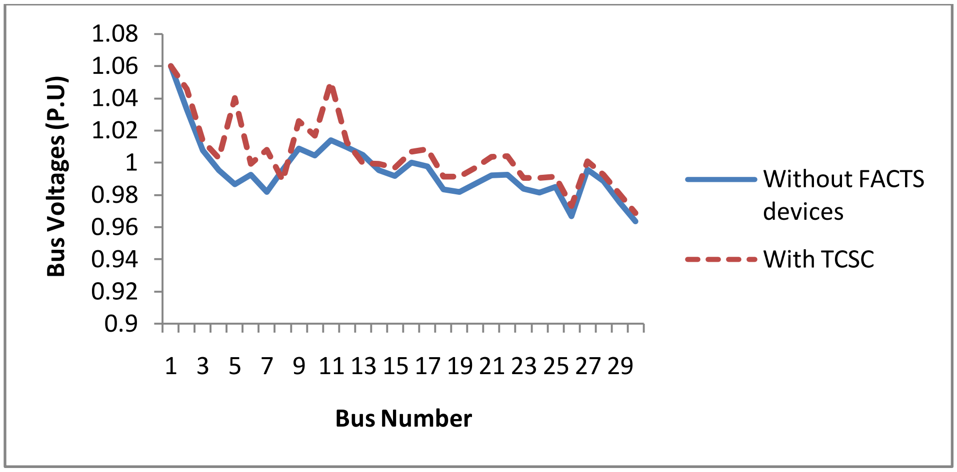

Fig. 4 Comparison results of bus voltages (P.U) in IEEE 30 bus system

To study the impact of TCSC device on generation fuel cost, an optimal power flow is conducted at a higher loadability condition (134%) in IEEE 30 bus system and the generation cost of the system with and without TCSC device are computed and tabulated in Table 2.

Table 2. Comparison Results for Generation Fuel cost in IEEE 30 bus system

Cases	Total Real Power Generation (MW/hr)	Total Real Power Loss (MW)	Total Generation Fuel cost ($/hr)
Without TCSC	393.0545	14.0	830.67
With TCSC	391.8481	12.7	810.08

In this study, total real power generation is obtained by optimal rescheduling of generators. The result with TCSC shown in Table 2 is obtained by optimally placing the TCSC in line 1-2 with an optimal value of X_{TCSC} as –47.35% of line reactance. From the results in Table 2, it is observed that the introduction of TCSC device in the system results in considerable reduction of total generation fuel cost by reducing the total real power loss in the system.

From the results in Fig. 2, Fig. 3, Fig. 4 and Table 2, it is concluded that TCSC is a suitable FACTS device candidate for resolving the MOPF being evaluated in this study.

For the purpose of comparative study, DE algorithm is used to determine the maximum loadability, minimum total real power loss and minimum overall system cost which includes installation cost of TCSC and generation fuel cost as individual objectives and the results are tabulated in Table 3. In addition to identifying the optimal location and optimal tuning of control parameter of TCSC, rescheduling of generators are performed to get their maximum capability.

Table 3. Optimal Results for Individual Objectives in IEEE 30 bus system

Objectives	**λ (%)**	**P_{Loss} (MW)**	**Overall System Cost (US$/hr)**	**Optimal Location of TCSC Device (p-q)**	**Optimal Control Parameter(X_{TCSC}) of TCSC Device**
Max λ	144	13.8	887.73	9-10	-0.5242
Min P_{Loss}	100	3.9	563.03	2-5	-0.3885
Min Overall System Cost	100	6.2	541.30	2-5	-0.0230

From the results in Table 3 it is observed that considering only one objective doesn't provide desired results for the other objectives. For obtaining desired results for all objectives, all objectives need to be considered together, resulting in a MOPF problem. WAFGP is used to obtain the optimal solution for this MOPF. DE is used for determining the optimal weights in WAFGP and the results are tabulated in Table 4.

Table 4.Optimal solution using DE based WAFGP in IEEE 30 bus system

Optimal λ (%)	**Optimal P_{Loss} (MW)**	**Optimal Overall System Cost (US$/hr)**	**Optimal Weights**			**Optimal Location of TCSC Device**	**Optimal Control Parameter (X_{TCSC}) of TCSC Device**
			W1	***W2***	***W3***		
141	10.5	642.345	0.4889	0.2362	0.2749	2-5	-0.0077

Comparing the results in Table 4 with that of Table 3 show that the use of DE based WAFGP method for this MOPF provides a balanced and optimized result for all the considered objectives.

7. **CONCLUSION**

From the results in this paper, it is observed that TCSC is effective in significantly reducing the overall system loss and in enhancement of voltage profiles of the buses in loaded condition. The reduction in overall system loss results in reducing the real power generation requirement and thereby reducing the generation fuel cost. In this paper, the main focus is to find the optimal location and sizing of a static series device TCSC to achieve maximum loadability and minimal total real power loss in a power system with least overall system cost which includes installation cost of TCSC and generation fuel cost. Line Stability Index (LSI) is used to determine the critical transmission lines in which the TCSC is to be installed to achieve the desired optimal goals. Differential Evolution (DE) is used to determine the optimal solution for the individual objectives. The results indicate that when only one objective is considered for optimization, it doesn't provide desired results for the other objectives. Use of DE algorithm in Weighted Additive Fuzzy Goal Programming (WAFGP) provides an excellent means for balancing multiple objectives and arrives at a solution optimal for all objectives.

ACKNOWLEDGEMENTS

The authors express their sincere thanks to the Management of Sathyabama University for providing necessary facilities to carry out this research work.

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