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Multi Objective Optimal Power Flow with STATCOM using DE in WAFGP

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Abstract

FACTS devices are used in power systems to increase the loadability of the system or to optimize other objective, like to reduce the power loss in the system. When only a single objective is considered in the introduction of the FACTS device, other end results of the system are adversely affected leading to increase in the total cost of the system. This paper proposes a method for considering multiple objectives and to arrive at a solution optimal for all considered objectives. The method proposed in this paper uses application of Differential Evolution (DE) algorithm in Weighted Additive Fuzzy Goal Programming (WAFGP) method. Use of STATCOM in Indian utility Neyveli Thermal Power Station (NTPS) 23 bus system is used for testing and validating the proposed method.

Keywords: Differential Evolution Algorithm, Fast Voltage Stability Index, Installation Cost Minimization, Multi-Objective, STATCOM, Weighted Additive Fuzzy Goal Programming

1. Introduction

In deregulated power systems, power distributors have a choice to choose their power producers. Due to competitive marketing, multiple power distributors could sign up with few power producers, leading to unequal power flow in existing power grids with few transmission lines getting overloaded and threatening the stability of the power grid.

Flexible AC Transmission Systems (FACTS) are the power electronic dynamic devices which when installed in power grid regulate the power flow and maintain the stability of the system[1]. They provide the desired impedance (inductive/capacitive), real and reactive power and thereby maintain the voltage stability at all buses; increase the loadability of the power system and decrease the real and reactive power losses in the power system[2].

Optimal Power Flow (OPF) was first introduced by Carpentier in the year 1962. OPF is a Non- Linear Programming problem (NLP) used to minimize/maximize a desired objective function subject to certain equality and in-equality system constraints. Several methods are available for solving OPF[3]. In recent years, inspired by nature, several intelligent techniques like Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Bacterial Foraging Algorithm (BFA), Ant Colony Optimization (ACO) algorithm and DE Algorithm are used in obtaining optimized solutions [4-10].

In this paper, the objectives considered for OPF are: maximize the loadability of the system; minimize the total real power loss of the system; minimize the installation cost of the FACTS device used. DE algorithm is used in obtaining the optimal solution for this OPF. Among the various FACTS devices, STATCOM is considered in this study. When all the objectives are to be considered

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together, the OPF problem turns into a multi objective OPF problem providing a set of feasible solutions named Pareto optimal solutions.

Weighted Sum method, Penalty Function method and Є-constrained method are some of the conventional methods used in finding the best compromise solution for a multi-objective problem[11, 12]. The introduction of fuzzy logic by Zadeh paves a new way to find the best optimal solution for Pareto optimal solutions. 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 individual objective is preserved by optimizing each objective individually. Further, in this paper, the weights for objectives are chosen optimally using DE Algorithm to find the best feasible 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 STATCOM device, section 3 formulating this study's problem, section 4 describing the FVSI, section 5 describing the application of DE in WAFGP method, section 6 presenting and discussing the results, and section 7 concluding the benefits of this study.

2. Steady State Modelling of STATCOM

STATCOM is a static shunt FACTS device connected in parallel to the transmission grid buses. It consists of a Voltage Source Converter (VSC) and a capacitor coupled to the transmission lines through a coupling transformer. The primary function of STATCOM is to control the bus voltages by reactive power compensation. STATCOM can absorb or supply reactive power to the connected bus depending on the magnitude of output voltage of VSC with respect to the connected bus. The steady-state power injection model of STATCOM[15] is shown in Figure 1.

If a STATCOM is connected in shunt to a bus p in a power system, then the power flow equations of the bus that gets altered and can be written as:

$$P_p = P_s + \sum_{q=1}^{nb} |V_p||V_q||Y_{pq}|\cos(\delta_p - \delta_q - \theta_{pq}) \qquad (1)$$

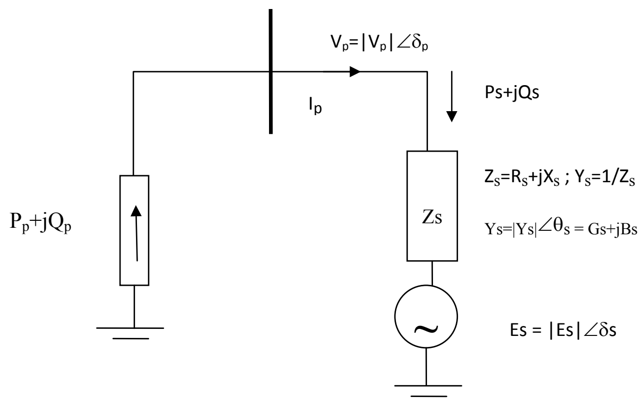

Figure 1. Steady state model of STATCOM.

$$Q_p = Q_s + \sum_{q=1}^{nb} |V_p||V_q||Y_{pq}|\sin(\delta_p - \delta_q - \theta_{pq}) \qquad (2)$$

$$P_s = G_s|V_p|^2 - |V_p||E_s||Y_s|\cos(\delta_p - \delta_s - \theta_s) \qquad (3)$$

$$Q_s = -B_s|V_p|^2 - |V_p||E_s||Y_s|\sin(\delta_p - \delta_s - \theta_s) \qquad (4)$$

Where $|E_S|$, δ_S, $|Y_S|$, θ_S are shown in Figure 1.

|Es| and δs are the two new variables added in the mathematical modelling due to introduction of STATCOM in the system. The size of the Jacobian matrix is altered to add these new variables in the conventional power flow computations[15].

3. Problem Formulation

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

Minimize/Maximize $(f_1(y), f_2(y), \ldots\ldots\ldots\ldots f_t(y))^T$ (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 numbers of equality and inequality constraints.

The objective functions chosen in this paper are (i) maximizing the loadability of a network, (ii) minimizing the total real power loss in the network and (iii) minimizing the installation cost of STATCOM device used. This is done by optimally placing the STATCOM device with its optimal control settings.

3.1 Maximize Loadability (λ) (7)

Where λ is the load factor

3.2 Minimize Total Real Power Loss (PLoss)

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

Where P_{Loss} is the 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.

3.3 Minimize Installation Cost of STATCOM (IC)

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

$$C_{STATCOM} = 0.000375(S)^2 - 0.3041(S) + 162.4(US\$/KVAR) \quad (9)$$

$$IC = C_{STATCOM} * S * 1000(US\$) \quad (10)$$

Where S is the size of STATCOM in MVAR; IC is the Installation Cost of STATCOM in US$.

The various constraints chosen in the problem are:

3.4 Equality Constraint: Power Flow Equation

$$P_{Gp} - P_{Dp} - \sum_{q=1}^{nb}\left|V_p\right|\left|V_q\right|\left|Y_{pq}\right|\cos\left(\theta_{pq} - \delta_p + \delta_q\right) = 0 \quad (11)$$

$$Q_{Gp} - Q_{Gp} - \sum_{q=1}^{nb}\left|V_p\right|\left|V_q\right|\left|Y_{pq}\right|\sin\left(\theta_{pq} - \delta_p + \delta_q\right) = 0 \quad (12)$$

Where $P_{Gp \text{ and}}$ 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.

3.5 Inequality Constraints

$$P_{Gp}^{\min} \le P_{Gp} \le P_{Gp}^{\max} \quad (13)$$

$$Q_{Gp}^{\min} \le Q_{Gp} \le Q_{Gp}^{\max} \quad (14)$$

$$V_p^{\min} \le V_p \le V_p^{\max} \quad (15)$$

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.

3.6 STATCOM Constraint

$$x_S^{\min} \le x_S \le x_S^{\max} \quad (16)$$

Where x_S is the STATCOM parameter.

3.7 Security Constraints

$$BOL = \begin{cases} 1 & ; ifBL \le 100 \\ P1 & ; otherwise \end{cases} \quad (17)$$

$$VL = \begin{cases} 1 & ; 0.95 \le V \le 1.1 \\ P2 & ; otherwise \end{cases} \quad (18)$$

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. Fast Voltage Stability Index (FVSI)

FVSI helps in identifying the critical buses and lines under loaded conditions. It is the index framed from the analysis of two bus system model[17].

$$FVSI_{p,q} = \frac{4z^2 Q_p}{v_p^2 x} \quad (19)$$

Where, p is the sending end bus; q is the receiving end bus; z is the line impedance; x is the line reactance; Qp is the reactive power at sending end and vp is the sending end voltage.

The following steps are done to determine critical buses and critical transmission lines:

1. Load flow analysis is carried out using Newton Raphson (NR) method.
2. The reactive power loading is gradually increased for each load bus until the load flow solution fails to converge and for each loadability condition determine the FVSI for all transmission lines.
3. Determine the maximum reactive power loading for each load bus. At this maximum loadability condition,

determine the transmission line having maximum FVSI value.

4. Sort the load buses in the ascending order of their maximum loadability.
5. The load bus which has the smallest value as its maximum loadability is considered as a critical bus and the transmission line which has the maximum FVSI value closer to unity is considered as the critical transmission line corresponding to the critical bus.

5. Differential Evolution (DE) Algorithm in Weighted Additive Fuzzy Goal Programming (WAFGP) Method

WAFGP is a goal programming method based on Fuzzy theory and was proposed by Zimmermann & Tiwari et.al in 1987. In WAFGP method, the weight assigned to each goal plays a significant role in determining the best optimal solution[18,19]. In this paper, DE algorithm is used for optimizing the individual goals and is also used in determining the optimal weight of each goal. The procedure for implementing DE algorithm in WAFGP is explained in detail below:

Step I:

The first step in WAFGP is determining the minimum (W_m) and maximum (W_n) goals. In this paper, DE algorithm is used to determine the goals for each individual objective (W_i). The significance of each objective is preserved in this step. The basic DE algorithmic steps are explained in brief below[20]:

1. *Initialize the population vector*
2. *Evaluate the fitness of each member of the population vector*
3. *Start the Mutation process and determine the mutated vector*
4. *Determine the trial vector using recombination process*
5. *Evaluate the fitness of each member of the population vector*
6. *Select the members of population vector for next generation using selection process*
7. *Repeat the steps 3 to 6 till the termination criteria are met*

Step II:

In the second step, fuzzy membership functions are used to convert the crisp goals into fuzzy goals [18].

$$\mu_{W_m}(y)=\begin{cases} 1 & W_m \le W_m^{\min} \\ \dfrac{\left(W_m^{\max}-W_m(y)\right)}{\left(W_m^{\max}-W_m^{\min}\right)} & W_m^{\min}\le W_m(y)\le W_m^{\max};\quad \mathrm{m}=1,2\ldots \mathrm{p} \\ 0 & W_m \ge W_m^{\max} \end{cases} \tag{20}$$

$$\mu_{W_n}(y)=\begin{cases} 1 & W_n \ge W_n^{\max} \\ \dfrac{\left(W_n(y)-W_n^{\min}\right)}{\left(W_n^{\max}-W_n^{\min}\right)} & W_n^{\min}\le W_n(y)\le W_n^{\max} \\ 0 & W_n \le W_n^{\min}\quad ;\ \mathrm{n}=\mathrm{p}+1,\mathrm{p}+2\ldots \mathrm{q} \end{cases} \tag{21}$$

Where p & q: p^{th} minimization & q^{th} maximization goal

μ_{Wm} & μ_{Wn} : membership value of m^{th} minimization & n^{th} maximization goal.

Step III:

In the third step the fuzzy goals are combined using WAFGP model.

$$\text{Maximize } \sum_{j=1}^{q} x_j FG_j \tag{22}$$

Subject to: $FG_j \le \mu_{W_j}(y)$; j=1,2& .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 denotes the number of objectives and *FG* is the individual Fuzzy Goal.

Step IV:

In the Fourth and final step, DE algorithm is used in determining the optimal weights in WAFGP to obtain a single optimal solution satisfying all the constraints for a multi objective problem.

6. Result and Discussion

A practical Indian utility NTPS 23 bus system which has 22 transmission lines, 4 generators and 19 load buses is taken for the study[21]. Simulation of the system scenarios with and without STATCOM device and optimization using DE algorithm is done by coding in MATLAB 7.5. In this study, the population size (P) chosen is 50; number of generations (G) is 100 and number of control parameters are 15 in number. The control parameters chosen are P_{G1}, P_{G2}, P_{G3}, P_{G4}, Q_{G1}, Q_{G2}, Q_{G3}, Q_{G4}, V_1, V_2, V_3, V_4, location, X_s, λ.

FVSI is used in determining the critical buses where STATCOM has to be installed for achieving the objectives. The critical buses are ranked and tabulated in Table 1.

In power systems, with the load always varying, the real and reactive powers of various buses are always varying with the loading getting closer to the maximum in some cases. In order to analyse a system in all the conditions, three different cases are considered for the study.

Case 1: Increase in real power loading
Case 2: Increase in reactive power loading
Case 3: Increase in real and reactive power loading

In each case, as the first step in WAFGP, DE algorithm is used to determine the maximum loadability, minimum total real power loss and minimum installation cost of STATCOM as individual objectives and the results are tabulated in Table 2, Table 3 and Table 4 respectively. In all cases, in addition to identifying the optimal location and optimal tuning of control parameter of STATCOM, rescheduling of generators are performed to get their maximum capability.

Table 1. Rankings of the critical buses

Bus	Rank
9	1
6	2
8	3
7	4
19	5

In Table 2, for all cases, comparing results with and without STATCOM shows that insertion of STATCOM increases the loadability, while reducing the total real power loss.

Results in Table 3 show that when minimization of total real power loss is considered as the only objective, loadability of the system decreases to 100%. Considering that increasing the loadability is one of the objectives of MOPF, this is not a suitable solution.

Similar to the observations in Table 3, results in Table 4 show that trying to minimize the installation cost of STATCOM as the only objective also reduces the loadability to 100%. Comparing the results in Table 4 with that of Table 3, minimum Installation cost of STATCOM is obtained for a minor increase in total real power loss.

The results in Table 2–4, where only one objective has been considered for optimization, shows that considering only one objective doesn't provide desired results for all the objectives. For desired results for all objectives, all objectives need to be considered together resulting in a MOPF problem. WAFGP method is used to obtain the best optimal solution for this MOPF. DE is used for determining the optimal weights in WAFGP and the results are tabulated in Table 5.

Comparing the results in Table 5 with that of Table 2-4 show that the use of DE and WAFGP methods for this MOPF provides a balanced and optimized results for all the considered objectives.

In practical deployment, there would be situations where one objective in a MOPF needs to be proritized without fully compromising the other objectives. DE

Table 2. Results for maximum loadability in NTPS 23 bus system

Cases	Max λ (%)	P_{Loss} (x 100 MW)	IC of STATCOM (x 10^6 US$)	Optimal location of STATCOM (Bus No)	Optimal control parameter (x_s) of STATCOM
Case 1 without STATCOM	133	0.282	-	-	-
Case 1 with STATCOM	137.5	0.265	0.8413	7	2.6782
Case 2 without STATCOM	144	0.286	-	-	-
Case 2 with STATCOM	152	0.270	1.2347	9	1.3980
Case 3 without STATCOM	127	0.348	-	-	-
Case 3 with STATCOM	132	0.334	1.5594	9	0.7328

algorithm comes very handy in providing this flexibility. Results for prioritizing maximum loadability objective among other objectives is tabulated in Table 6; prioritization of minimizing total real power loss is tabulated in Table 7; and priortization of minimzation of installation cost of STATCOM is tabulated in Table 8.

Comparing the results in Tables 6-8 with that of Tables 2-4 and Table 5 demonstrate that the DE algorithm and WAFGP provide an excellent flexibility to prioritize one objective in a MOPF with limited impact on other objectives and thereby providing a desired optimized result for all objectives.

Table 3. Results for minimum total real power loss in NTPS 23 bus system

Cases	Min P_{Loss} (x 100 MW)	λ (%)	IC of STATCOM device (x 10^6 US$)	Optimal location of STATCOM (Bus No)	Optimal control parameter (x_s) of STATCOM
Case 1 with STATCOM	0.154	100	0.3895	8	2.8615
Case 2 with STATCOM	0.139	100	0.5452	6	2.250
Case 3 with STATCOM	0.168	100	0.7459	6	2.5755

Table 4. Results for minimum installation cost of STATCOM in NTPS 23 bus system

Cases	Min IC of STATCOM device (x 10^6 US$)	P_{Loss} (x 100 MW)	λ (%)	Optimal location of STATCOM (Bus No)	Optimal control parameter (x_s) of STATCOM
Case 1 with STATCOM	0.0916	0.167	100	7	2.2981
Case 2 with STATCOM	0.1324	0.146	100	6	3
Case 3 with STATCOM	0.2321	0.176	100	6	1.3100

Table 5. Results for optimal solutions using DE and WAFGP in NTPS23 bus system

Cases (With STATCOM)	Optimal λ (%)	Optimal P_{Loss} (x 100 MW)	Optimal IC of STATCOM (x 10^6 US$)	Optimal Weights			Optimal location of STATCOM (Bus No)	Optimal control parameter (x_s) of STATCOM
				W1	*W2*	*W3*		
Case 1	136	0.229	0.7541	0.5643	0.1956	0.2401	7	2.8364
Case 2	150	0.208	1.0047	0.4872	0.3212	0.1916	6	1.9833
Case 3	130.5	0.305	1.1679	0.5873	0.2432	0.1695	8	1.7947

Table 6. Results for prioritising loadability using DE and WAFGP in NTPS23 bus system

Cases (With STATCOM)	Optimal λ (%)	Optimal P_{Loss} (x 100 MW)	Optimal IC of STATCOM (x 10^6 US$)	Optimal Weights			Optimal location of STATCOM (Bus No)	Optimal control parameter (x_s) of STATCOM
				W1	*W2*	*W3*		
Case 1	137	0.235	0.8003	0.6031	0.1998	0.1971	7	2.9725
Case 2	151.5	0.224	1.1652	0.5923	0.2832	0.1245	8	2.0313
Case 3	131.5	0.312	1.3079	0.5548	0.2132	0.2320	9	2.436

Table 7. Results for prioritising total real power loss using DE and WAFGP in NTPS23 bus system

Cases (With STATCOM)	Optimal λ (%)	Optimal P_{Loss} (x 100 MW)	Optimal IC of STATCOM (x 10^6 US$)	Optimal Weights			Optimal location of STATCOM (Bus No)	Optimal control parameter (x_s) of STATCOM
				W1	*W2*	*W3*		
Case 1	113	0.160	0.4476	0.2478	0.5781	0.1741	8	2.8428
Case 2	127	0.147	0.6058	0.2072	0.4969	0.2959	6	2.6442
Case 3	110	0.174	0.8113	0.3108	0.4852	0.2040	6	2.854

Table 8. Results for prioritising IC of STATCOM using DE and WAFGP in NTPS23 bus system

Cases (With STATCOM)	Optimal λ (%)	Optimal P_{Loss} (x 100 MW)	Optimal IC of STATCOM (x 10^6 US$)	Optimal Weights			Optimal location of STATCOM (Bus No)	Optimal control parameter (x_s) of STATCOM
				W1	*W2*	*W3*		
Case 1	111	0.178	0.1134	0.2249	0.1520	0.6231	9	1.7642
Case 2	125	0.162	0.2247	0.2735	0.2442	0.4823	7	2.8992
Case 3	107	0.190	0.3948	0.2005	0.2341	0.5654	6	2.794

7. Conclusion

In this paper, from the results of application of Differential Evolution (DE) algorithm in determining the optimal solution for the individual objectives, it can be concluded that introduction of FACTS device to optimize only one network parameter would adversely affect the other network parameters, and hence this is not an optimal solution for the system. For taking multiple network parameters into account, use of DE algorithm in Weighted Additive Fuzzy Goal Programming (WAFGP) was studied. Results from this study indicate DE algorithm in WAFGP provides an excellent means for balancing multiple objectives and arrive at a solution optimal for all objectives. In addition to this, to meet practical necessities, this study also demonstrates the flexibility of the proposed method for prioritising one objective in a MOPF, while still producing optimal results for all objectives. Based on these results, it can be concluded that DE algorithm in WAFGP, with its capability to take all network parameters into consideration and flexibility in prioritising them, provides a holistic optimal solution for the system.

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