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Optimal Locating and Sizing of TCSC for Social Welfare Maximization in Deregulated Power Markets

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Introduction

The restructuring in electric power industries from the last two decades was introduced with privatization in their sectors to improve their efficiency. However, as the deregulation progresses among power utilities, the utility operators face new problems and challenges [1]. Moreover, the provision of bilateral transaction, that allows GENCO and DISCO pairs to negotiate power transactions, has lead to uncertainty in the amount and direction of power flows. Evidently, the overall consequence of this issue is the congestion in transmission network. The issue of transmission congestion is more pronounced in deregulated and competitive markets and it needs a special treatment [1]. In this environment, independent system operator (ISO) has to maximize social welfare and relieve the congestion, so that the system is maintained in secure state. To maximize social welfare and relieve the congestion ISO can use mainly two types of techniques, which are as follows [1–4]:

A. Cost free means:

- Out-ageing of congested lines;
- Operation of transformer taps/phase shifters;
- Operation of FACTS devices particularly series devices.

B. Non-Cost free means:

- Re-dispatching the generation amounts. By using this method, some generators back down while others increase their output. The effect of re-dispatching is that generators no longer operate at equal incremental costs;
- Curtailment of loads and the exercise of load interruption options.

Among the above two main techniques cost free means do have advantages such as not touching economical matters, so GENCO and DISCO will not be involved.

This paper deals with the optimal locating and sizing of a TCSC, for social welfare maximization in competitive power markets. Up to now, different approaches have been proposed for optimal locating of FACTS devices in both vertically integrated and unbundled power systems [1-4]. Sensitivity-based congestion management with optimally placed FACTS controllers is presented in [1-4]. However, there are some disadvantages for this method such that it may not capture the non-linearity associated with the power system. Genetic algorithm as an evolutionary method can be applied as a good solution for optimization of OPF problem by incorporating FACTS devices and consequently considering the non-linearity of the system into account. However, various optimization techniques are available to OPF problem. Distributed generators locating for social welfare maximization is presented in [5]. Maximization social welfare is represented as marginal benefit versus demand function in [6]. [7] discovered a method for increasing social welfare under congestion probability in transmission network.

Mathematical model Of TCSC

In this paper, the Newton-Raphson (N-R) power flow formulation is used and TCSC is represented using the Power Injection Model (Fig. 1). The real and reactive power injections at buses i and j with a TCSC connected in line ij can be expressed as [7]:

$$P_i^F = V_i^2 \Delta G_{ij} - V_i V_j [\Delta G_{ij} \cos\delta_{ij} + \Delta B_{ij} \sin\delta_{ij}], \quad (1)$$

$$P_j^F = V_j^2 \Delta G_{ij} - V_i V_j [\Delta G_{ij} \cos\delta_{ij} - \Delta B_{ij} \sin\delta_{ij}], \quad (2)$$

$$Q_i^F = -V_i^2 \Delta B_{ij} - V_i V_j [\Delta G_{ij} \sin\delta_{ij} - \Delta B_{ij} \cos\delta_{ij}], \quad (3)$$

$$Q_i^F = -V_j^2 \Delta B_{ij} + V_i V_j [\Delta G_{ij} \sin\delta_{ij} + \Delta B_{ij} \cos\delta_{ij}], \quad (4)$$

where $\Delta G_{ij} = x_c r_{ij}(x_c - 2x_{ij})/(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)$ and $\Delta B_{ij} = -x_c(r_{ij}^2 - x_{ij}^2 + x_c x_{ij})/(r_{ij}^2 + x_{ij}^2)(r_{ij}^2 + (x_{ij} - x_c)^2)$.

(1)–(4) are added to Jacobin matrix in N-R load flow formulations.

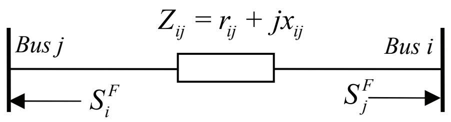

Fig. 1. Power Injection Model of transmission line with a TCSC

Problem formulation

In the double-sided auction market model, both DisCos and GenCos participate in the market and offer their bid-quantity packages to the market operator. The objective of market operator is to maximize the social welfare, including load flow equality and operational inequality constraints [7]:

$$Max \left\{ \begin{array}{l} \sum_{j=1}^{N_D} (a_{dj} + b_{dj}P_{Dj} + c_{dj}P_{Dj}^2) - \\ - \left\{ \begin{array}{l} \sum_{i=1}^{N_G} (a_{gi} + b_{gi}P_{Gi} + c_{gi}P_{Gi}^2) + \\ + \left| e_{gi} \times Sin(f_{gi} \times (P_{Gi} - P_{min\,i})) \right| \end{array} \right\} \end{array} \right\}, \qquad (5)$$

$$\begin{cases} F(V, \delta, P, Q) = 0, \\ P_{\min\_g} \le P_g \le P_{\max\_g}, & g = 1,...,N_G, \\ P_{\min\_D} \le P_D \le P_{\max\_D}, & D = 1,...,N_D, \\ Q_{\min\_g} \le Q_g \le Q_{\max\_g}, & g = 1,...,N_G, \\ Q_{\min\_D} \le Q_D \le Q_{\max\_D}, & D = 1,...,N_D, \\ 0.95 \le V_b \le 1.05 \quad p.u., & b = 1,...,Nb, \\ \left| S_l(\theta, V) \right|^2 \le (S_l^{\max})^2, & l = 1,...,NL, \\ x_c^{\min} \le x_c \le x_c^{\max}. \end{cases} \qquad (6)$$

Proposed algorithm

A detailed step by step procedure for the proposed GA based social welfare maximization by incorporating all the constraint in the objective function is expressed as follows:

Step 1. Prepare input power system parameters (e.g., system topology, line and load specifications, generation limits, line flow limits and cost coefficient parameters).

Step 2. Assume a suitably population size (N_{ch_max}) and maximum number of generations (N_{it_max}), crossover rate (Pc), and mutation rate (Pm)). Set initial counters and parameter values (e.g., $N_{ch} = N_{it} = 1$).

Step 3. Generate random chromosomes by real coding which include power generation schedule, Location and size of TCSC, as follow:

- The values of power generation corresponding to the i^{th} generator may be expressed

$$P_{gi} = \lambda \times P_{g\max i}, \qquad 0 \le \lambda \le 1. \qquad (7)$$

- The location and size of TCSC device is described by:

$$FACTS_{Location} = INT[NL \times \lambda] + 1, \quad 0 \le \lambda \le 1, \qquad (8)$$

$$TCSC_{Size} = \lambda \times X_{FACTS_{Location}}, \; 0 \le \lambda \le 0.7, \qquad (9)$$

where NL is the number of transmission lines.

Step 4. Run power flow. Check the equality and non-equality constraints of the system as described before.

Step 5. If any of the constraints is violated compute proposed penalty functions (Fig.2) using outputs of the applied power flow. Compute objective function for chromosome N_{ch}. Set $N_{ch} = N_{ch} + 1$.

Step 6. If $N_{ch} \le N_{ch\_\max}$ go to Step *4*.

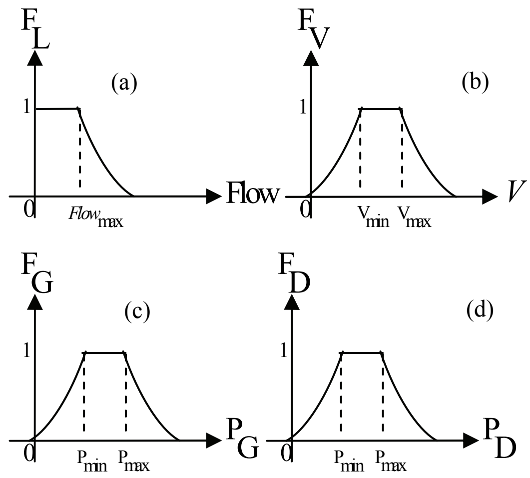

Fig. 2. Proposed penalty functions used to compute fitness: a – $F_{line\,flow\_Limit}$; b – $F_{bus\,voltage\_Limit}$; c – $F_{generation\_Limit}$; d – F_{load_Limit}

Step 7. Calculate the value of objective function corresponding to each set of a chromosome.

Step 8. Find and store maximum social welfare among all valid chromosomes and corresponding pattern.

Step 9. Set generation count *gen-count*=**1**.

Step 10. Select two chromosomes based on "*tournament*" mechanism. Set $N_{ch} = N_{ch} + 1$. If $N_{ch} \le N_{ch\_\max}$ go to Step *10*.

Step 11. Select a random number (RND_1) for mating two parent chromosomes.

Step 12. If RND_1 is less than the crossover rate (Pm) then combine the two parents, generate two offspring using Eq. 10 and go to Step 13. Else, transfer the chromosome with no crossover

$$p_{new} = \beta(p_{mn} - p_{dn}) + p_{mn}. \qquad (10)$$

Step 13. Repeat steps 11 to 12 for all chromosomes.

Step 14. Select a random number (RND_2) for mutation of one chromosome.

Step 15. If RND_2 is less than the mutation rate then apply the mutation process using (7) and go to Step 16, Else, transfer the chromosome with no mutation

$$x_k' = x_k \times \left\{ 1 + (-1)^t \times \left[1 - r^{(1-\frac{t}{T})^b} \right] \right\}, \qquad (11)$$

where r is a uniform random number on the interval (0,1), t is the current generation number, T is the maximum number of generations and b (e.g., b=2 in this paper) is a parameter determining the impact of mutation on the new generations.

Step 16. Repeat Steps 14 to 15 for all chromosomes.

Step 17. Replace the old population with the improved population generated by Steps 3 to 16.

Step 18. Run power flow. Check the equality and non-equality constraints of the system as described before.

Step 19. If any of the constraints is violated compute proposed penalty functions (Fig. 2) using outputs of the applied power flow. Compute fitness functions (5) for chromosome N_{ch} . Set $N_{ch} = N_{ch} + 1$.

Step 20. If $N_{ch} \le N_{ch\_\max}$ go to Step 18.

Step 21. Calculate and store the value of objective function.

Step 22. Find and store maximum social welfare among all valid chromosomes. Set $N_{it} = N_{it} + 1$.

Step 23. If the maximum number of iterations is achieved then print optimal generation and demand amount, optimal TCSC size and location and stop, else go to Step 9.

Results and discussions

This section presents the basic operation of the IEEE 14-bus system [4] and optimal locating and sizing of one TCSC unit with smooth/nonsmooth generators cost curves (5), without/with line flow constraints (6) to illustrate the ability of proposed method. Simulation results are analyzed as follows:

- Without line flow constraints by using smooth cost curve, lines 7–10, 12, 13, 15–17 are congested. The same lines (except for line 8) will be congested when nonsmooth cost curve are used (Table 1, columns 2 and 5);
- Transmission line limits (6) overcome the congestion problem; however, social benefit decreases from 1972.3$/h to 1490.8$/h and from 1956.6$/h to 1436.3$/h for smooth and nonsmooth cost curves, respectively;
- In addition, total generation and total load decreases from 381.9MW/h and 357.7MW/h to 326.1MW/h and 313.8MW/h for nonsmooth cost curves, respectively;
- As expected, line flow constraints cause significant decrease in social welfares. Therefore, line flow constrains are the main causes of low social benefit and low loading levels. Therefore, it is necessary for ISO to encourage competition and reduce the waste. FACTS devices can be used to direct power through uncongested transmission line(s) and provide cheaper power to be transferred from generators to consumers;
- According to Table 2, optimal sizing and placement of one TCSC (Table 3) will increases the generation cost; however, it will also improve social benefit from 1490.8$/h to 1504.2$/h and from 1436.3$/h to 1511.7$/h for smooth and nonsmooth cost curves, respectively. The main reason is the increase in total load from 331.1MW/h to 334.8MW/h and from 313.8MW/h and 331.2MW/h for smooth and nonsmooth cost curves, respectively. Therefore, optimal placement/sizing of TCSC has proven to be beneficial for IEEE 14-bus system;
- According to Table 2, without any line flow constraints, there are very high load demands at nodes 11-14 (corresponding to lines 5-8) due to higher benefit coefficients. However, when the line flow constrains are considered, there is substantial reductions in load demands and social benefit at theses nodes;
- According to Table 2, line flow constraints will substantially increase loading levels at nodes 4-5 (corresponding to lines 1-2) and increase their social benefits.

Table 1. Line flows in MVA and congestion status. Bold letters show congested lines

Line number	Smooth generation cost curve			Nonsmooth generation cost		
	Without line flow constraints & without TCSC	With line flow constraints & without TCSC	With line flow constraints & with TCSC	Without line flow constraints & without TCSC	With line flow constraints & without TCSC	With line flow constraints & with TCSC
1	31.61633	28.17257	30.93223	36.71299	32.7389	32.16095
2	71.04538	69.84794	61.25266	76.32502	71.04089	69.04305
3	13.45163	15.12874	13.46684	11.8827	13.24076	13.67735
4	73.48225	69.11777	62.51628	78.4612	73.39067	72.09152
5	77.56725	77.33662	68.08183	82.45477	77.18559	75.6154
6	89.80466	87.12907	88.94062	93.30313	89.59086	88.73285
7	**79.66307**	10.88447	11.54614	**88.89005**	30.23065	15.97631
8	**31.73317**	20.36393	19.93668	22.5029	19.87304	23.86974
9	**54.37408**	23.48075	23.63160	**63.28773**	22.48284	22.74126
10	**97.38573**	23.8493	24.31652	**107.5132**	24.99912	23.5227
11	11.36704	6.331729	5.645326	11.53664	6.433444	4.964561
12	11.91955	28.32349	16.59003	11.30399	10.62169	9.640333
13	**23.96059**	8.441359	8.848999	**25.17609**	14.03826	8.823108
14	27.88105	12.88797	12.61659	28.75304	17.03045	12.1077
15	**69.04419**	25.60867	26.48866	**72.13202**	40.74086	26.26042
16	**30.56769**	24.18584	23.66989	**41.35086**	24.51769	21.70305
17	**55.85606**	9.878545	10.41569	**49.4385**	12.79883	10.66079
18	9.115927	12.45922	11.01606	7.026041	9.646493	.7512248
19	4.237323	10.09426	10.02694	7.204359	8.693436	9.598461
20	15.09119	6.956587	6.944428	8.334585	10.18826	7.085112

Table 2. The optimal generation and load levels in MW

Generator or load	Smooth generation cost curve			Nonsmooth generation cost curve		
	Without line limits & without TCSC	With line limits & without TCSC	With line limits & with TCSC	Without line limits & without TCSC	With line limits & without TCSC	With line limits & with TCSC
G1	94.2208	89.8534	97.3523	90.079	96.8171	98.3452
G2	100	100.530	100.416	100	100.048	100.297
G3	100	100.200	100	100	100.084	100
G4	92.8325	51.1333	50.4080	91.8292	29.2006	45.0523
L1	58.1066	108.712	122.481	55.1504	110.855	114.638
L2	55.6328	135.506	124.456	52.4997	94.6358	122.789
L3	5.63115	6.63534	5.33135	5.02759	20.4422	5.01438
L4	21.5454	33.1993	30.7021	29.7315	30.6391	23.2145
L5	35.7925	5.67436	6.65414	26.3258	8.60749	19.7862
L6	51.8876	30.1815	29.4312	54.1041	26.9693	31.1336
L7	71.9098	5.31819	5.13937	71.4937	5.07251	6.81429

Generator or load	Smooth generation cost curve			Nonsmooth generation cost curve		
	Without line limits & without TCSC	With line limits & without TCSC	With line limits & with TCSC	Without line limits & without TCSC	With line limits & without TCSC	With line limits & with TCSC
L8	62.3385	5.87836	10.6874	63.4563	16.6195	7.86693
Total generatio	387.053	341.717	348.176	381.908	326.150	343.694
Total load	362.844	331.105	334.883	357.789	313.841	331.258
Social benefit	1972.36	1490.86	1504.29	1956.66	1436.31	1511.77
Generation cost	1665.13	1382.07	1416.82	1646.15	1340.64	1410.47
Customer benefit	3637.50	2872.94	2922.11	3602.81	2776.95	2922.24

Table 3. Optimal location and size of one unit TCSC

	Smooth cost curve	Nonsmooth cost curve
TCSC location	Line 1	Line 14
Compensation rate	33.24946	15.57667

Table 4. Cost coefficient parameters for the generators and loads

Bus No.		a	b	c	e	f	P_{min}	P_{max}
G1	1	0.0245	1	0	50	0.063	20	100
G2	2	0.0351	1	0	40	0.098	100	500
G3	3	0.0389	1	0	0	0	100	500
G4	6	0.0372	1	0	0	0	20	100
G5	8	0	0	0	0	0	0	0
L1	4	-0.015	10	0	0	0	50	200
L2	5	-0.015	10	0	0	0	50	200
L3	9	-0.01	5	0	0	0	5	100
L4	10	-0.015	10	0	0	0	5	100
L5	11	-0.015	10	0	0	0	5	100
L6	12	-0.018	12	0	0	0	5	100
L7	13	-0.018	12	0	0	0	5	100
L8	14	-0.018	12	0	0	0	5	100

Conclusions

In this paper an algorithm for social welfare maximization with optimal locating (and sizing) of one TCSC unit and optimal rescheduling of generation and demand levels is proposed. Based on the simulation results for IEEE 14-bus system, the following conclusions are drawn:

- TCSC has the ability to redistribute power flow, influence loads and generations levels at different buses, and significantly increase the social benefit. Installation of TCSC offers benefit that far exceeds its cost for the system conditions studied.;
- TCSC may have different impacts on the welfare of individual participants and may affect the pool price of each bus differently. Therefore, some participants may benefit more than others;
- The smoothness of the generator cost curves shows no significant impact on the line congestions; however, it will increase generation cost. This needs to be considered by ISO to get more accurate results and realistic cost analysis.

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This paper presents a genetic algorithm GA to perform congestion management and maximize social welfare by placement and sizing of one TCSC device. Conventional quadratic smooth and augmented quadratic nonsmooth generator cost curves and quadratic smooth consumer benefit functions are considered. By adding the valve point effect, the model presents nondifferentiable and nonconvex regions that challenge most gradient-based optimization algorithms. The aim of this paper are locating/sizing of TCSC and inclusion of customer benefit in the congestion management objective function, consideration of nonsmooth generator characteristics. Ill. 2, bibl. 7, tabl. 4 (in English; abstracts in English and Lithuanian).

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Analizuojamas TCSC prietaiso, skirto socialinei aplinkai gerinti nereguliuojamose elektros rinkose, optimalios vietos ir dydžio nustatymas. Pateiktas apkrovos valdymo genetinis algoritmas. Il. 2, bibl. 7, lent. 4 (anglų kalba; santraukos anglų ir lietuvių k.).