Social Welfare Improvement by TCSC using Real Code Based Genetic Algorithm in Double-Sided Auction Market

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Abstract—**This paper presents a genetic algorithm (GA) to maximize total system social welfare and alleviate congestion by best placement and sizing of TCSC device, in a double-sided auction market. To introduce more accurate modeling, the valve loading effects is incorporated to the conventional quadratic smooth generator cost curves. By adding the valve point effect, the model presents nondifferentiable and nonconvex regions that challenge most gradient-based optimization algorithms. In addition, quadratic consumer benefit functions integrated in the objective function to guarantee that locational marginal prices charged at the demand buses is less than or equal to DisCos benefit, earned by selling that power to retail customers. The proposed approach makes use of the genetic algorithm to optimal schedule GenCos, DisCos and TCSC location and size, while the Newton–Raphson algorithm minimizes the mismatch of the power flow equations. Simulation results on the modified IEEE 14-bus and 30-bus test systems (with/without line flow constraints, before and after the compensation) are used to examine the impact of TCSC on the total system social welfare improvement. Several cases are considered to test and validate the consistency of detecting best solutions. Simulation results are compared to solutions obtained by sequential quadratic programming (SQP) approaches.**

Index Terms—**congestion management, real code based-GA, rescheduling, social welfare maximization, TCSC.**

I. Introduction

Competition in a deregulated power system will set a fair market structure and motivate all participants to maximize their own individual profit. This will allow the market to behave in a manner which maximizes profit for all participants. In addition to the deregulation challenges, electrical loads are rapidly growing and some transmission lines are reaching their thermal limits. Congestion can be relived by building new transmission lines; however, this is an expensive solution that requires years for approval and construction. An accepted solution for the Independent System Operator (ISO) to perform congestion management which is the process of ensuring transmission system does not violate its operating limits. If congestion management is not properly implemented, it can impose a barrier to electricity trading by preventing new contracts, leading to additional outages, increasing electricity prices in some regions and threatening system security and reliability [1].

Numerous methods have been reported for social welfare maximization and congestion management, which are based on market model [1], particle swarm optimization (for generation rescheduling and/or load shedding) [2], genetic algorithms [3] and sensitivity analysis using transmission line susceptances [4].

Recent solutions for managing power flow in transmission lines are based on flexible AC transmission systems (FACTS) [5]. Different approaches, based on sensitivity method, have been proposed for optimal locating of FACTS devices in both vertically integrated and unbundled power systems [6-8].

Congestion management by interline power flow controller (IPFC) and unified power flow controller (UPFC) are performed in [7-9]. Application of series FACTS for congestion management in deregulated electricity markets is discussed in [10].

These references simplify the optimization problem by assuming given sizes of FACTS devices and/or using second order objective benefit functions without considering the sine components due to the valve point loading effects.

This paper proposes a real code-based genetic algorithm for alleviating congestion and maximizing social benefit in a double-sided auction market by optimal locating and sizing of one Thyristor-Controlled Series Capacitor (TCSC) unit. Simulations are performed to investigate the impact of TCSC on congestion levels of the modified IEEE 14-bus and 30-bus test systems with quadratic smooth and quadratic nonsmooth (with sine components due to valve point loading effect) generator cost curves and quadratic smooth benefit functions for loads. The proposed method shows the benefits of TCSC in a deregulated power market and demonstrates how they may be utilized by ISO to prevent congestion and improve the total social welfare.

II. Mathematical Model of TCSC

This paper, the Newton-Raphson (N-R) power flow formulation is used and TCSC is represented using the Power Injection Model [10]. This will allow easy integration of TCSC devices into the existing power system software tools and retains the symmetrical structure of the admittance matrix. The change in the line flow due to series capacitance is represented as a line without series capacitance with powers injected at receiving and sending ends (Figure. 1).

The real and reactive power injections at buses i and j with a TCSC connected in line ij can be expressed as [10]:

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

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

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

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

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

Eqs. 1 to 4 are added to Jacobin matrix in N-R load flow formulations.

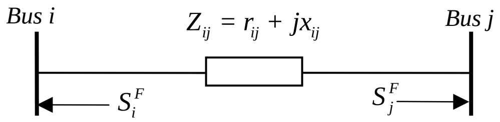

Figure 1. Power Injection Model of Transmission Line with a TCSC

III. 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 [13]:

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

where P_{Dj} and P_{Gi} are dispatched loads and generations at nodes j and i, respectively, N_D and N_G are the number of loads and generators, respectively, " a_{dj}, b_{dj}, c_{dj} " and " a_{gi}, b_{gi}, c_{gi}, e_{gi}, f_{gi} " are benefit functions coefficients in DisCos and cost coefficients in GenCos, respectively. The first component of Eq. 5 presents the benefit functions of DisCos which are expressed by quadratic functions. The second component presents the cost functions of GenCos considering their nonsmooth behavior. The objective function (Eq. 5) is subjected to the following constraints:

(i) Power injection: the net injections of real and reactive power at each bus are set to zero.

(ii) Generation limits: the limits on the maximum and minimum active power (P_G) and reactive (Q_G) power generation of the generators are included as:

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max},\ Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max},\ i = 1,...,N_G \quad (6)$$

where P_{Gi} and Q_{Gi} are the active and reactive power generation vectors for bus G_i, respectively.

(iii) Demand limits: the maximum and minimum limits of consumers active power (P_D) and reactive power (Q_D) demands are considered as:

$$P_{Di}^{min} \le P_{Di} \le P_{Di}^{max},\ Q_{Di}^{min} \le Q_{Di} \le Q_{Di}^{max},\ i = 1,...,N_D \quad (7)$$

where P_{Di} and Q_{Di} are the active and reactive power demand vectors for bus D_i ,respectively.

(iv) Transmission limits: the line MVA limit is included as:

$$\left| S_l(\theta, V) \right|^2 \le (S_l^{max})^2 \quad (8)$$

$$S_l(\theta, V) = Max\ (S_{ij}, S_{ji}) \quad (9)$$

$$S_{ij}(\theta, V) = V_i^*(V_i - V_j) y_{ij} + V_i^* V_i y_{i_0} \quad (10)$$

where y_{i_0} is the line charging admittance and y_{ij} is the admittance of line ij. Eq. 8 ensures that no congestion occurs in lines in the procedure of double action market clearing.

(v) Voltage limits: voltage limit at each bus is expressed as:

$$V_i^{min} \le V_i \le V_i^{max} \quad (11)$$

(vi) Compensation limit: the maximum and minimum values of equivalent TCSC reactance (x_c) are included as:

$$x_c^{min} \le x_c \le x_c^{max} \quad (12)$$

IV. PROPOSED REAL CODE BASED-GENETIC ALGORITHM

Genetic Algorithm (GA) is a global search technique, based on the mechanisms of natural selection and genetics capable of searching several possible solutions simultaneously [12]. GA has been applied to many problems including stability studies, load frequency control, unit commitment, reactive power compensation, and V/Q/THD control [14].

The optimization problem, Eq. 5 is a complex, large-scale nonlinear programming dilemma that cannot easily be solved by the conventional approaches. This paper proposes a real code based GA approach to capture the best solution.

V. DEVELOPMENT OF THE PROPOSED METHOD

The optimization problem consists of solving Eq. 5 with the incorporation of one TCSC device for social welfare maximization in power systems based on a pool market.

A. Initial Population and Structure of Chromosomes

A random number generator is used to select the initial population chromosomes within the range of the control variables. The selected chromosome structure contains generation and demand levels, as well as TCSC location and compensation level (Figure. 2). Real codes are used to provide a higher accuracy as compared with binary coding.

P_{G_1}	P_{G_2}	…	P_{G_N}	P_{D_1}	P_{D_2}	…	$P_{D_{ND}}$	$TCSC_{Size}$	$TCSC_{Location}$

Figure 2. Chromosome structure for the GA

B. Proposed Fitness Function

GA procedure involves the evaluation of objective (fitness) functions to measure the quality of the solutions. A solution with a better quality (e.g., higher fitness value) will be included in the new population, while low quality solutions are discarded. In this paper, exponential penalty functions for each generated chromosome are calculated for lines that have power overflows and/or reach voltage, generation and load limits, based on respective penalty functions as follows:

$$F_{fitness} = F_{line\ flow} . F_{busvoltage} . F_{generation} . F_{load} \quad (13)$$

where $F_{lineflow} = \prod_{j=1}^{N_L} F_L$, $F_{bus voltage} = \prod_{j=1}^{N_B} F_V$, $F_{generation} = \prod_{j=1}^{N_G} F_G$,and $F_{load} = \prod_{j=1}^{N_D} F_D$.

N_L , N_G , N_D and N_B are the number of branches, generators, loads and buses in the power system, respectively, and $F_{fitness}$ is the fitness function value for each chromosome. The proposed penalty functions are:

$$F_L = \begin{cases} 1 & line\ flow < line\ flow_{Max} \\ e^{\alpha_l (line\ flow_{Max} - line\ flow)} & line\ flow > line\ flow_{Max} \end{cases} \quad (14)$$

$$F_G = \begin{cases} e^{-\alpha_{G1}(P_{generation})} - 1 & P_{generation} < P_{generation\_Min} \\ 1 & P_{generation\_Min} \le P_{generation} \le P_{generation\_Max} \\ e^{\alpha_{G2}(P_{generation_{Max}} - P_{generation})} & P_{generation} > P_{generation\_Max} \end{cases} \quad (15)$$

$$F_V = \begin{cases} e^{-\alpha_{V1}(V_{Bus})} - 1 & V_{Bus} < V_{Min} \\ 1 & V_{Min} \le V_{Bus} \le V_{Max} \\ e^{-\alpha_{V2}(V_{Max} - V_{Bus})} & V_{Bus} > V_{Max} \end{cases} \quad (16)$$

$$F_D = \begin{cases} e^{-\alpha_{L1}(P_{Load})} - 1 & P_{Load} < P_{Load\ Min} \\ 1 & P_{Load\ Min} \le P_{Load} \le P_{Load\ Max} \\ e^{-\alpha_{L2}(P_{Load_{Max}} - P_{Load})} & P_{Load} > P_{Load\ Max} \end{cases} \quad (17)$$

where $\alpha_l, \alpha_{G1}, \alpha_{G2}, \alpha_{L1}, \alpha_{L2}, \alpha_{V1}$ and α_{V2} are the coefficients used to adjust the slope of penalty functions (Figure. 3).

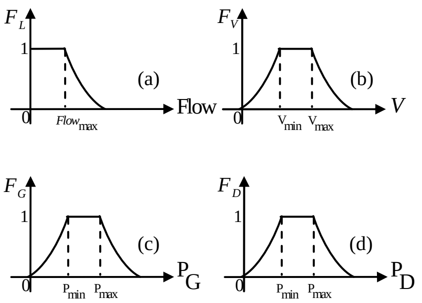

Figure 3. Proposed penalty functions used to compute fitness (EQ.13); (A) $F_{line\ flow\_Limit}$, (B) $F_{bus voltage\_Limit}$, (C) $F_{generation\_Limit}$, (D) F_{load_Limit}

C. Genetic Operators

The selected GA operators are shown in Table I. Note that the probabilities of crossover and mutation are 0.9 and 0.1, respectively.

VI. Solution Methodology

The problem defined by Eqs. 5-12 is solved using the proposed GA of Figure. 4. The main steps are as follows:

Step 1: 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}). Set initial counters and parameter values (e.g., $N_{ch} = N_{it} = 1$). Generate random chromosomes by real coding.

Step 3 (Fitness Process):

Step 3A: Run power flow for each set of chromosome and determine voltage magnitudes and phase angles at all buses. Calculate power flow in each transmission line of the system.

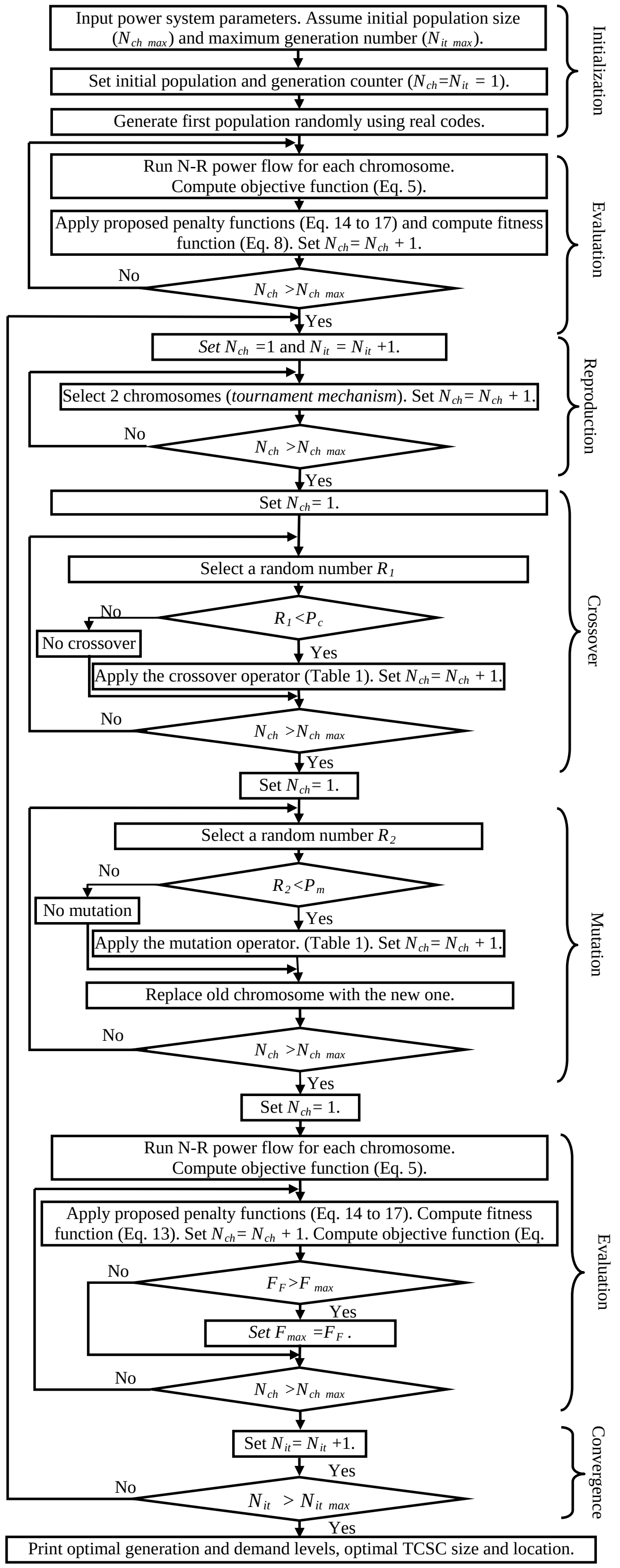

Figure 4. Proposed real code based-ga algorithm for congestion management by optimal locating and sizing of one tcsc device

Step 3B: Compute proposed penalty functions (Figure. 3) using outputs of the applied power flow. Compute fitness functions (Eq. 8) for chromosome N_{ch} . Set $N_{ch} = N_{ch} + 1$.

Step 3C: If $N_{ch} \le N_{ch\_max}$ go to Step 3A.

Step 4 (Reproduction Process):

Step 4A: Define total fitness as the product of all fitness values for all chromosomes.
Step 4B: Run a tournament for selection process. Select a new combination of chromosomes.
Step 5 (Crossover Process):
Step 5A: Select a random number (R1) for mating two parent chromosomes.
Step 5B: If R1 is less than the values of crossover, then combine the two parents, generate two offspring and go to Step 5D.
Step 5C: Else, transfer the chromosome with no crossover.
Step 5D: Repeat steps 5A to 5D for all chromosomes.
Step 6 (Mutation Process):
Step 6A: Select a random number (R2) for mutation of one chromosome.
Step 6B: If R2 is less than the values of mutation, then apply the mutation process and go to Step 6D.
Step 6C: Else, transfer the chromosome with no mutation.
Step 6D: Repeat Steps 6A to 6C for all chromosomes.
Step 7 (Updating Populations): Replace the old population with the improved population generated by Steps 2 to 6. Check all chromosomes, if there is any chromosome with $F_L = 1, F_G = 1, F_V = 1, F_D = 1$ and $F_F > F_{\max}$, set $F_{\max} = F_F$ and save it. Set $N_{it} = N_{it} + 1$.
Step 8 (Convergence): If the maximum number of iterations is achieved then print solution and stop, else go to Step 3.

TABLE I. THE SELECTED GENETIC OPERATORS FOR THE PROPOSED ALGORITHM

GA Operators	Method
Reproduction	Tournament selection.
Heuristic Crossover	$p_{new} = \beta(p_{mn} - p_{dn}) + p_{mn}$ β is a random number on interval (0,1), p_{mn} and p_{dn} are the nth variables in the parent chromosomes. Probability of crossover is selected to be 0.9.
Dynamic Mutation	$x'_k = x_k \times [1 + (-1)^t \times (1 - r^{(1-\frac{t}{T})^b})]$ *r* is a uniform random number on interval (0,1), *t* is the current generation number, *T* is the maximum number of generations and *b*=2. The probability of mutation is selected to be 0.1.
Steady-State Replacement	Creating a number of offspring to replace the least fit individuals.
Convergence Criterion	Iterations are continued until all of the generated chromosomes become equal or $N^{max}=1000$

VII. SIMULATION RESULTS

Operations of the modified IEEE 14-bus [10, 11] and the modified IEEE 30-bus test systems [15] without and with TCSC are studied to demonstrate the ability of proposed GA method (Figure. 4). The imposed modifications are nonsmooth cost curves (Eq. 5) for generators G1 and G7 (e.g., e_g=50, f_g=0.063), as well as generators G2 and G8 (e_g=40, f_g=0.098). Five cases and are studied (Table II) as follows:

Cases A: Base operation of the modified IEEE 14-bus test system with/without line flow constraints & with/without TCSC using smooth and nonsmooth generation cost function, respectively.

Cases B: Base operation of the modified IEEE 30-bus test system with/without line flow constraints & with/without TCSC using smooth and nonsmooth generation cost function, respectively.

Cases C1: Considering the line outage between buses 2 & 4 in the modified IEEE 30-bus test system with/without line flow constraints & with/without TCSC using smooth and nonsmooth generation cost function, respectively.

Cases C2: Considering the unit outage on bus 2 in the modified IEEE 30-bus test system with/without line flow constraints & with/without TCSC using smooth and nonsmooth generation cost function, respectively.

Cases C3: Considering load increasing at bus 4 in the modified IEEE 30-bus test system with/without line flow constraints & with/without TCSC using smooth and nonsmooth generation cost function, respectively.

TABLE II. SIMULATED CASES OF THE IEEE 14-BUS AND IEEE 30-BUS SYSTEMS

Test System	Simulated Cases		Results
IEEE 14-Bus (Figure 5)	A	Base operation without/with TCSC	Tables III-V, 7,8,10 Figure 6
IEEE 30-Bus (Figure 7)	B	Base operation without/with TCSC	Tables V-X
	C1	Outage of line 2-4 (between buses 2 & 4)	Tables V, VII-X
	C2	Outage of unit 4 at bus 2	
	C3	Increase of load 3 (by 150%) at bus 4	

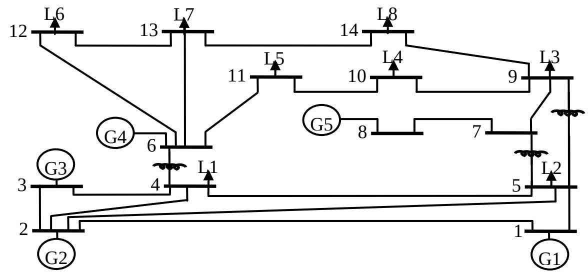

Figure 5. The modified IEEE 14-bus test system with nonsmooth cost curves (eq. 5) for g1 (eg=50, fgi=0.063) and g2 (eg=40, fg=0.098)

The optimal location and size of a TCSC unit is estimated by maximizing the total social benefit function of Eq. 5. The minimum and maximum series capacitive compensation levels are limited to 0% and 70% of the compensated line reactance, respectively. Both smooth (when $e_g = f_g = 0$ in Eq. 5) [10] and nonsmooth [13] generator cost curves are considered and consumer benefit curves are assumed to be quadratic [15]. For IEEE 30-bus, the second consumer benefit coefficient (b_d) is multiplied by 5 to increase the benefit function.

Selected parameters are: number of generations= 1000, number of populations= 73, crossover rate= 0.9 and mutation rate= 0.1.

Case A. Operation of IEEE 14-Bus System with TCSC

This section presents the basic operation of the IEEE 14-bus system (Figure. 5) and optimal locating and sizing of one TCSC unit with smooth/nonsmooth generators cost curves (Eq. 5), without/with transmission line flow constraints (Eq. 5) to illustrate the ability of proposed method. The objective function consists of 15 variables for 5 generation nodes (G5 only generates reactive power), 8 demand nodes and 2 TCSC parameters. There are 20 possible locations to place one unit of TCSC. Simulation results (Tables III-V, VI-VII, X and Figure.6) are analyzed as follows:

- Transmission line limits (Eq. 8) overcome the congestion problem; however, social benefit decreases from 1972.3$/h to 1523.9$/h and from 1956.6$/h to 1529.67$/h for smooth and nonsmooth cost curves, respectively (Table VI rows 1, 6).
- In addition, total generation and total load decreases from 381.9MW/h and 357.7MW/h to 336.9MW/h and 327.64MW/h for nonsmooth cost curves, respectively (Table VI, row 1).
- As expected, line flow constraints cause a significant decrease in social welfares. They are the main causes of low social benefit and low loading levels. Moreover, some power consumers will have to bid higher prices in power markets since they cannot access cheaper power due to transmission limits.
- To alleviate the overload, ISO will have to sacrifice cost to some extent. Therefore, it is necessary for ISO to encourage competition and reduce the waste. FACTS devices can be used to direct power through un-congested transmission line(s) and provide cheaper power to be transferred from generators to consumers. Figure 6 shows the individual welfare of each consumer without and with the line flow constraints using nonsmooth cost curves.

These simulation results also demonstrate the impact of one TCSC unit (including its optimal location and size) on the social benefit. Note that the benefits to individual consumers are not uniformly distributed and some participants may actually face reduction in their welfare/profit. However, TCSC will provide overall benefit to the system as a whole, while some market participants may benefit more the others. Further discussions are as follows:

- According to Table VI (row 11), optimal sizing and placement of one TCSC will decrease the generation cost. It will also improve social benefit from 1523.9$/h to 1604.57$/h and from 1529.6$/h to 1595.32$/h for smooth and nonsmooth cost curves, respectively.
- The main reason is the increase in load demands at nodes 11-13. Therefore, optimal placement/sizing of TCSC has proven to be beneficial for the IEEE 14-bus system.
- According to Table III (rows 11-14, columns 2 and 5), without any line flow constraints, there are very high load demands at nodes 11-14 (corresponding to loads 5-8) due to higher benefit coefficients (Eq. 5). However, when the line flow constraints are considered (Table III, rows 11-14, columns 3 and 6), there is substantial reductions in load demands and social benefit at theses nodes (Figure. 6).
- Line flow constraints will substantially increase loading levels (Table III) at nodes 4-5 (corresponding to loads 1-2) and increase their social benefits (Figure.6). In addition, the generation level of generator G4 (located at bus 6) is decreased and therefore, the total system generation cost is increased (Table III, row 4).
- Furthermore, after the placement of TCSC, load levels at nodes 4 and 5 -previously elevated due to the line flow constraints- are now decreased (Table III, rows 5-6). This is due to their lower benefit coefficients compared to the other loads.

TABLE III. THE OPTIMAL GENERATION AND LOAD LEVELS FOR IEEE 14-BUS SYSTEM WITH SMOOTH AND NONSMOOTH GENERATION COST CURVE AND WITH/WITHOUT OPTIMAL LOCATING/SIZING OF ONE TCSC DEVICE.

Generator or Load (in MW)	**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	94.22	97.25	88.84	90.07	90.64	88.84
G2	100	100	100	100	100	100
G3	100	100	100	100	100	100
G4	92.83	48.9	63.59	91.82	46.26	63.59
L1	58.10	116.90	107.7	55.15	121.01	107.7
L2	55.63	125.14	116.2	52.49	112.86	116.2
L3	5.63	8.02	5	5.02	5.94	5
L4	21.54	16.86	26.8	29.73	16.08	26.8
L5	35.79	22.15	15.4	26.32	23.97	15.4
L6	51.88	31.23	25.9	54.10	30.18	25.9
L7	71.90	7.16	9.2	71.49	6.68	9.2
L8	62.33	7.604	29.5	63.45	10.88	29.5

TABLE IV. OPTIMAL LOCATION AND SIZE OF ONE UNIT TCSC IN THE MODIFIED IEEE 14-BUS SYSTEM WITH SMOOTH AND NONSMOOTH GENERATION COST CURVES.

	Smooth cost curve	**Nonsmooth cost curve**
TCSC location	6-13	6-13
Compensation rate (%)	25.445	25.305
Social welfare improvement ($/h)	80.650	65.650

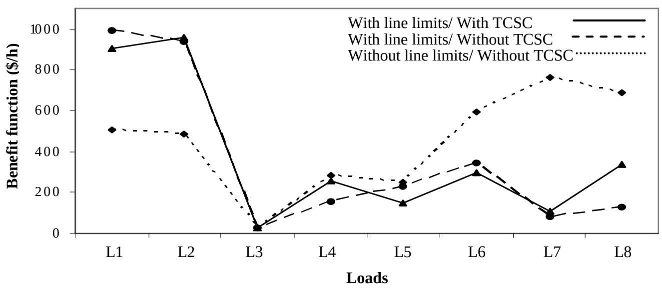

Figure 6. Impact of line flow constraints and TCSC on the individual welfare of each market participant using nonsmooth generation cost curve

Case B: Operation of IEEE 30-Bus System with TCSC

Basic operation of the IEEE 30-bus system (Figure. 7) will be demonstrated before and after TCSC compensation. The objective function consists of 32 variables for 9 generation nodes, 21 demand nodes and 2 TCSC parameters. There are 41 possible locations to place one TCSC unit. Therefore, the optimization problem has become too complex and get as a large-scale problem to be solved with conventional approaches. The proposed GA is applied and simulation results are presented in Tables V-X. General comments are:

With unconstrained conditions, congestion occurs in lines 1-2, 1-3, 2-4 and 3-4 (Table V).

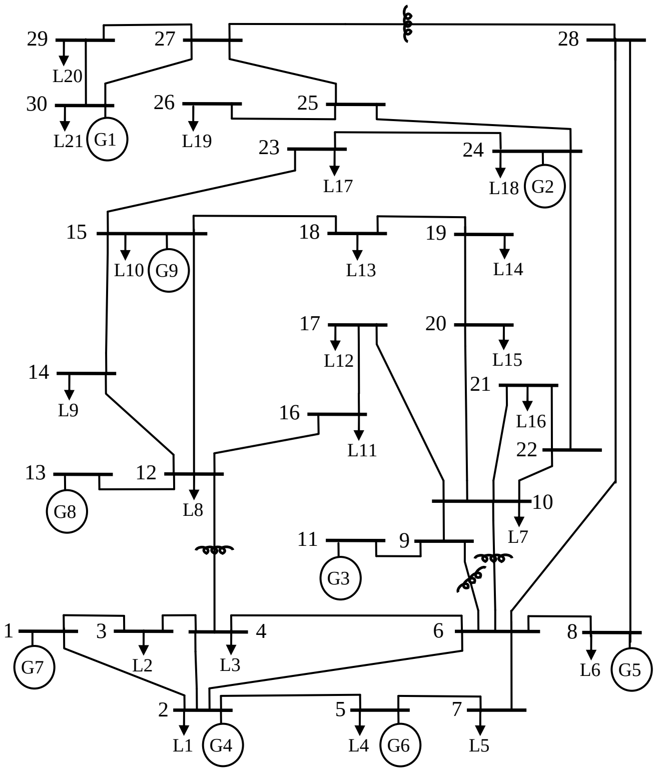

Figure 7. M odified IEEE 30-bus test system; nonsmooth cost curves (eq. 5) for g1 and g7 (eg=50, fg=0.063), g2 and g8 (eg=40, fg=0.098)

- According to Table V, without line flow constraints, generators G1, G2, G3 and G8 are lightly loaded while generators G5, G6 and G7 are reaching there maximum capacity. This is due to the different cost benefit coefficients (Eq. 5), being lower for G5, G6 and G7 and relatively high for the other generators.
- With line constraints, generation level of G7 is substantially decreased to about 60MW. This is the maximum capacity of the lines connected to this generator at node 1. In contrast to G7, loading levels of G4, G8 and G9 are significantly increased to fulfill load requirements. As a result, overall social benefit is decreased (Table VI).
- After optimal placement and sizing of TCSC, a considerable increase in generation of G7 (to transfer more power from node 1 to node 2) reduces the generation cost and increases the social benefit (Table VI). These results demonstrate the ability of TCSC in improving system operation with line flow constraints.
- After TCSC compensation, social benefit increases and the total generation cost decreases for both smooth and nonsmooth cost curves. This demonstrates the effectiveness of optimal sizing and placement of TCSC.

Case C. Operation of IEEE 30-Bus System with Congestion

Three additional cases (Table II, rows 4-6) are presented to further illustrate the ability of the proposed method and the impact of TCSC in overcoming congestion. Congested lines (without line constraints) are listed in Table VIII.

TABLE V. THE OPTIMAL GENERATION AND LOAD LEVELS IN MW FOR IEEE 30-BUS SYSTEM WITH SMOOTH AND NONSMOOTH GENERATION COST CURVE AND WITH/WITHOUT OPTIMAL LOCATING/SIZING OF ONE TCSC DEVICE FOR CASE B.

Generator	**Smooth generation cost curve**						**Nonsmooth generation cost curve**		
	Proposed method			SQP [16]			Proposed method		
	Without line flow constraints &	With line flow constraints & without TCSC	With line flow constraints &	Without line flow constraints &	With line flow constraints & without TCSC	With line flow constraints &	Without line flow constraints &	With line flow constraints & without TCSC	With line flow constraints &
G1	10	10	10.14	10	10	10	10	10	10
G2	5	5	5.02	5	5	5	5	5	5
G3	5	5.01	5.04	5	5	5	5	5.06	5
G4	29.50	53.94	10	25.17	50.82	10	29.50	54.86	10
G5	50	46.83	47.38	50.00	50.00	50.00	50	48.67	42.26
G6	50	48.06	46.75	50.00	50.00	50.00	50	47.70	44.99
G7	100	58.23	92.07	100.00	59.98	83.71	100	57.87	97.88
G8	10	21.44	36.13	10	10	17.14	10	27.87	38.91
G9	27.80	37.73	35.65	31.57	45.18	55.57	27.80	29.17	35.40

TABLE VI. COST-BENEFIT ANALYSIS BY COMPARISON OF RESULTS GENERATED BY THE PROPOSED GA AND SQP FOR THE IEEE 30 BUS TEST SYSTEMS WITH SMOOTH AND NONSMOOTH COST CURVES.

Case		**Smooth generation cost curve**						**Nonsmooth generation cost curve**		
		Proposed method			SQP [16]			Proposed method		
		Social Benefit ($/h)	Generation Cost ($/h)	Customer Benefit ($/h)	Social Benefit ($/h)	Generation Cost ($/h)	Customer Benefit ($/h)	Social Benefit ($/h)	Generation Cost ($/h)	Customer Benefit ($/h)
Without line flow constraints & without TCSC	A	1972.36	1665.13	3637.50	1942.64	1694.86	3637.50	1956.66	1646.15	3602.81
	B	8106.311	6109.912	14225.03	8127.360	6097.670	14225.03	8083.674	6134.477	14225.03
	C1	8101.320	6123.710	14225.03	8117.150	6107.880	14225.03	8094.399	6130.631	14225.03
	C2	8273.252	5951.779	14225.03	8329.860	5895.170	14225.03	8268.365	5956.666	14225.03
	C3	8434.290	6770.468	15204.76	8459.020	6745.74	15204.76	8429.859	6774.901	15204.76
With line flow constraints & without TCSC	A	1523.92	1407.15	2931.07	1502.6	1428.47	2931.07	1529.67	1369.59	2899.26
	B	7870.95	6354.08	14225.03	7854.920	6370.110	14225.03	7794.90	6430.13	14225.03
	C1	7768.00	6449.47	14225.03	7763.300	6461.730	14225.03	7753.77	6471.12	14225.03
	C2	7154.83	6976.92	14225.03	7128.870	7096.16	14225.03	7147.25	6984.60	14225.03
	C3	8077.65	7114.29	15204.76	8027.860	7176.90	15204.76	8052.61	7152.14	15204.76
With line flow constraints & with TCSC	A	1604.57	1436.26	3040.83	1604.57	1436.26	3040.83	1595.32	1445.51	3040.83
	B	7991.08	6233.94	14225.03	8000.500	6224.530	14225.03	7956.55	6268.47	14225.03
	C1	7901.07	6323.95	14225.03	7864.410	6360.620	14225.03	7878.03	6347.00	14225.03
	C2	8227.21	5977.90	14225.03	8242.800	5982.230	14225.03	8201.16	6023.86	14225.03

TABLE VII. SYSTEM ANALYSIS RESULTS FOR THE IEEE 30 BUS TEST SYSTEMS WITH SMOOTH COST CURVES (POWERS ARE IN MW).

Case	Smooth generation cost curve								Nonsmooth generation cost curve			
	Operation without TCSC				Operation with TCSC				Operation without TCSC		Operation with TCSC	
	Proposed method		SQP [16]		Proposed method		SQP [16]		Proposed method		Proposed method	
	Total generation	Total load	Total generation	Total load	Total generation	Total load	Total generation	Total Load	Total generation	Total load	Total generation	Total load
A	346.22	335.08	361.13	347.41	352.44	335.70	366.11	352.44	336.90	327.64	351.86	335.70
B	286.27	283.40	285.98	283.40	288.46	283.40	286.42	283.40	286.23	283.40	289.46	283.40
C1	286.23	283.40	286.73	283.40	289.24	283.40	286.78	283.40	286.16	283.40	289.03	283.40
C2	285.31	283.40	286.23	283.40	290.27	283.40	286.47	283.40	285.31	283.4	289.30	283.40
C3	320.63	317.20	321.07	317.20	323.55	317.20	321.07	317.20	320.57	317.2	323.27	317.20

TABLE VIII. CONGESTED LINES OF THE SIMULATED CASES BASED ON TABLE II WITHOUT LINE FLOW CONSTRAINTS AND WITHOUT TCSC.

Case	Smooth generation cost curves	Nonsmooth generation cost curves
A	4-6, 6-11, 6-12, 6-13, 5-7, 5-9, 9-10, 9-14	4-6, 6-12, 6-13, 5-7, 5-9, 9-10, 9-14
B	1-2, 1-3, 2-4 , 3-4	1-2, 1-3, 2-4, 3-4
C1	1-2, 1-3, 2-4 , 3-4	1-2, 1-3, 2-4, 3-4
C2	1-2, 1-3, 3-4	1-2, 1-3, 3-4
C3	1-2, 1-3, 2-4 , 3-4, 2-6	1-2, 1-3, 2-4, 3-4, 2-6

TABLE IX. NEAR-OPTIMAL LOCATION AND SIZE OF ONE TCSC UNIT IN THE IEEE 30-BUS SYSTEM WITH SMOOTH/NONSMOOTH GENERATION COST CURVES.

Case		Smooth cost curve	Nonsmooth cost curve
B	TCSC location	Line 1-2	Line 1-2
	Compensation rate (%)	58.74	66.97
	Improvement in social welfare ($/h)	187.41	161.65
C1	TCSC location	Line 1-2	Line 1-2
	Compensation rate (%)	55.87	56.61
	Improvement in social welfare ($/h)	133.07	124.26
C2	TCSC location	Line 1-2	Line 1-2
	Compensation rate (%)	61.17	61.02
	Improvement in social welfare ($/h)	1072.40	1053.90
C3	TCSC location	Line 1-2	Line 1-2
	Compensation rate (%)	45.22	44.67
	Improvement in social welfare ($/h)	252.68	271.16

TABLE X. REQUIRED NUMBER OF ITERATIONS (N_{IT}) FOR OPTIMAL LOCATING AND SIZING OF ONE TCSC DEVICE USING THE PROPOSED GA FOR THE FIVE CASES OF TABLE III.

Case	Smooth cost curve	Nonsmooth cost curve
A	609	619
B	682	729
C1	703	745
C2	725	732
C3	691	751

Table IX shows the social welfare improvement by best locating and sizing TCSC. According to Table VII, for all cases, inclusion of TCSC does not considerably improve generation level and customer benefit. This indicates that the systems under consideration have the capability of supporting maximum load under the assumed congestion conditions.

- According to Table VI (row 5, column 11), after optimal rescheduling, social welfare is improved to 7878.03 $/h. This is done by optimal placement of one TCSC at line 1-2 with a composition level of 56.6% (Table IX; row 5, last column).
- Simulations are performed (Tables V-X) assuming outages of line 2-4, outage of unit 6 and a substantial increase in load 3.
- In Case C1, line 2-4 is not available and because of physical limitations on lines 1-2 and 1-3, generator G7 (at bus 1) will not be operating at an optimal point. Therefore, ISO needs to reschedule other generators.
- In Case C1, line 2-4 is not available and because of physical limitations on lines 1-2 and 1-3, generator G7 (at bus 1) will not be operating at an optimal point. Therefore, ISO needs to reschedule other generators. According to Table VI (row 5, column 11), after optimal rescheduling, social welfare is improved to 7878.03 $/h. This is done by optimal placement of one TCSC at line 1-2 with a composition level of 56.6% (Table IX; row 5, last column).
- Note that TCSC improves social benefits in all cases (Table VI, columns 2, 5, 8, 11) with nonsmooth/smooth generation curves. Therefore, optimal sizing and placement of TCSC is also justified and recommended for these cases.
- According to Table VI, the effect of sine components is to increase generation cost. Therefore, the ISO needs to consider the actual valve setting points in the objective function by including nonsmooth characteristics to get more accurate results and perform realistic cost.
- Note that all line loadings are at their near maximum levels due to their high cost benefit coefficients (Eq. 5), as well as the system ability in fulfilling load demands.
- Transmission line limits (Eq. 8) overcome the congestion problem; however, social benefit decreases from 8106.31$/h to 7870.95$/h and from 8083.674$/h to 7794.9$/h for smooth and nonsmooth cost curves, respectively (Table VI, row 7). Therefore, as with the IEEE 14-bus system, line flow constraints are the main causes of low social benefit and low loading levels.
- Therefore, it is easy to investigate the impact of generator curves. According to Table VI, inclusion of the sin component on the generator's characteristics increases the total generation cost from 6354.08$/h to 6430.1$/h and decreases the social benefit from 7870.95$/h to 7794.9$/h, respectively.
- In the Modified IEEE 30-bus test system, all loads are nearly at their maximum levels due to their high cost benefit coefficients, as well as the system ability in fulfilling load demands. Therefore, it is easy to investigate the impact of generator curves.
- According to Table VI, inclusion of the sin component on the generator's characteristics increases the total generation cost and decreases the total system social welfare.

- In addition, considering valve point loading effect in objective function changes the size and investment cost of the TCSC and affects the amount of social welfare. Therefore, the ISO needs to consider the actual valve setting points in the objective function by including nonsmooth characteristics to get results that are more accurate and perform realistic cost (Table VI).
- The required number of iterations for optimal locating and sizing of one TCSC device for the five simulated cases (Table II) are presented in Table X. It is shown, that considering valve point increases the required iteration.

VIII. Conclusions

A real code based genetic algorithm is proposed and implemented to perform congestion management and maximize social benefit with optimal locating (and sizing) of one TCSC unit and optimal rescheduling of generation and demand levels.

- A suitable formulation of TCSC is presented and included in the objective function.
- Using real code based in GA to guarantee fast convergence to the best solution for smooth and nonsmooth generator cost curves. Based on simulation results for the IEEE 14-bus and 30-bus systems, the following conclusions are obtained:
- TCSC has the ability to redistribute power flow, influence loads and generations levels at different buses, and significantly increase the social benefit (Tables III-IX). Installation of TCSC offers benefit that far exceeds its cost for the system conditions studied (Table IX).
- TCSC has different impacts on the welfare of individual participants and may affect the double-sided auction price of each bus differently. Therefore, some participants may benefit more than others (Table VI).
- The benefits of using TCSC may not be considerable at low levels of demand and generation. Simulation studies over an extended period of time would be required to evaluate the overall benefit of TCSC for an actual system.

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