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OPTIMUM SIZING AND SITING OF TCSC USING RANDOM WEIGHTED - GENETIC ALGORITHM IN POWER SYSTEM

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This paper presents a voltage stability index based method to locate series compensation of transmission lines using random weighted Genetic Algorithm (rw-GA) to improve the loading margin by incorporating elitism and Dynamic Crowding Distance (DCD). Minimization of total loss and load bus voltage deviation is considered as the main objective and minimization of the investment cost of Thyristor Controlled Series Compensator (TCSC) and overall annual operating cost is taken as sub objective to maximize the social welfare. This proposed method is validated in IEEE 30 bus and a practical Tamil Nadu Electricity Board (TNEB) 69 bus system in India.

Keywords: New Voltage Stability Index (NVSI), TCSC, rw-Genetic Algorithm, Voltage stability, optimization

1. Introduction

In many power systems, voltage instability is considered the major cause of blackout, as important as thermal overloads and the associated risk of cascaded line outages. Many different remedial measures have been proposed and implemented to enhance power system voltage stability. Some of these measures are VAR compensation, load shedding and active power control. Voltage instability researches deal with two main aspects: proximity to voltage instability and mechanism of voltage instability. The first deals with the physical estimation of the distance to voltage instability and the current status of the power system and the later deals with strategies to prevent voltage instability and the factors involving areas of voltage instability [1].

In Steady State Stability (SSS) the steady state Jacobian matrix is obtained by solving the set of equations which is linearized around the operating point, where the power system is modeled based on algebraic and differential equations. The maximum loadability of the power system including effects of generators and other voltage dependent devices are determined to evaluate the singularity of the Jacobian matrix [2]. In literature, many static voltage assessment

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techniques have been proposed, such as the minimum singularity value, mode analysis and sensitivity method [3], [4] & [5].

The main disadvantages of these techniques include considerable computational efforts making implementation difficult in on-line application. In this paper, a New Voltage Stability Index (NVSI) based method is proposed to find the optimum value and location of TCSC for improving the loading margin. The rw-GA is used to obtain the best individual which satisfies the main objective and run the load flow for best individual to obtain top 10 weak buses based on NVSI values. The TCSC is placed one by one with various compensation percentages within their limit. When the installation cost is minimum which is considered as sub objective, the optimal value and location can be obtained.

2. Index Formation

A New Voltage Stability Index (NVSI) has been proposed which originates from the equation of a two-bus network, neglecting the resistance of transmission line, resulting in appreciable variations in both real and reactive loading [6]. NVSI is mathematically explained as follows

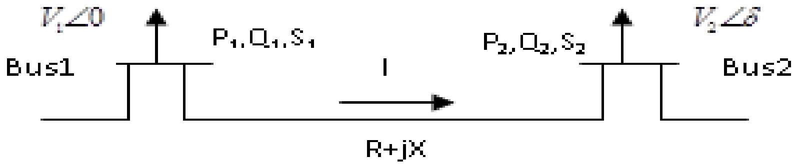

Fig.1 line model

From the Fig.1, current flowing between bus 1 and 2 is given by

$$I = \frac{V_1\angle 0 - V_2\angle\delta}{R + jX} \tag{1}$$

$$I^* = \frac{\overline{V}_1^* - \overline{V}_2^*}{R - jX} \tag{2}$$

Comparatively resistance of transmission line is negligible. So the above equation may be rewritten as

$$I^* = \frac{\overline{V}_1^* - \overline{V}_2^*}{-jX} \tag{3}$$

And the receiving end power

$$S = V_2 I^* \tag{4}$$

Incorporating Equation (3) in (4) and solving

$$P_2 = -\frac{V_1 V_2}{X}\sin\delta \tag{5}$$

$$Q_2 = -\frac{V_2^2}{X} + \frac{V_1 V_2}{X}\cos\delta \tag{6}$$

Elimination of δ from Equations (5) & (6) yields

$$\left(V_2^2\right)^2 + (2Q_2 X - V_1^2)V_2^2 + X^2(P_2^2 + Q_2^2) = 0 \tag{7}$$

This is an Equation of the fourth order of V_2. Consider
$V_2^2 = x$ then the Equation (7) is written as

$x^2 + (2QX - V_1^2)x + X^2(P^2 + Q^2) = 0$, the roots are

$$x = \frac{-(2QX - V_1^2) \pm \sqrt{(2QX - V_1^2)^2 - 4X^2(P^2 + Q^2)}}{2} \tag{8}$$

$$V_2 = \sqrt{\frac{-(2QX - V_1^2) \pm \sqrt{(2QX - V_1^2)^2 - 4X^2(P^2 + Q^2)}}{2}} \tag{9}$$

The condition to have at least one solution is:

$$(2Q_2 X - V_1^2)^2 - 4X^2(P_2^2 + Q_2^2) \geq 0 \tag{10}$$

Equation (10) can be rewritten as

$$\frac{2X\sqrt{(P_2^2 + Q_2^2)}}{2Q_2 X - V_1^2} \leq 1 \tag{11}$$

Taking the suffix "i" as the sending bus & "j" as the receiving bus, NVSI can be defined by

$$NVSI_{ij} = \frac{2X\sqrt{(P_j^2 + Q_j^2}}{2Q_j X - V_i^2} \tag{12}$$

Variable definition follows.

Z: line impedance

X: line reactance

Qj: reactive power at the receiving end

Vi: sending end voltage

θ: line impedance angle

δ: angle difference between the supply voltage and the receiving voltage.

Pi: sending end real power

Pj: real power at the receiving end. The value of NVSI must be less than 1.00 in all transmission lines to maintain a stable system.

3. Optimal Location of TCSC placement

Loading Margin is the most basic and widely accepted method to approximate voltage collapse in the power system. For a current operating point, the total increment of load in a specified pattern of load increase that would cause a voltage collapse is called the loading margin to voltage collapse [12]. Series compensation of transmission lines is one of the best ways to improve the loading margin of an interconnected system. Nowadays researchers have interested to recommend new techniques for selecting the best location for the placement of FACTS devices. Three various methods available for best location identification are sensitivity analysis [7] & [8], stability index based analysis [9]& [10], optimization technique [11]& [12]. A reactive power dispatch optimization algorithm for improving voltage stability margin based on the L-index is proposed [13]. The new methodologies based on the use of LMP differences and congestion rent for proper location of Thyristor Controlled Series Capacitor (TCSC) devices for congestion management in deregulated electricity markets has been presented [14]. The modal analysis method was utilized to calculate the critical nodes and bus participation factors corresponding to these critical nodes are used to identify the weakest buses in the system, which was treated as candidate's buses for VAR compensation [15].

A. *Model of TCSC*

The model of transmission line with TCSC connected between lines i and j is shown in Fig.2.The controllable reactance X_{TCSC} is directly used as control variable in power flow equations. The corresponding power injection model of TCSC incorporated within transmission line is shown in Fig. 3[16]. When the TCSC is placed between lines i and j, the resultant bus admittance matrix can be updated as:

$$Y_{bus}^{'} = Y_{bus} + \Delta Y_{bus}$$

$$Y_{bus}^{'} = Y_{bus} + \begin{bmatrix} 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & \Delta y_{ij} & 0 & \dots & 0 & -\Delta y_{ij} & 0 \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & -\Delta y_{ij} & 0 & \dots & 0 & \Delta y_{ij} & 0 \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 \end{bmatrix} \begin{matrix} \\ row_i \\ \\ \\ \\ row_j \\ \\ \end{matrix} \quad (13)$$

where Col_i Col_j

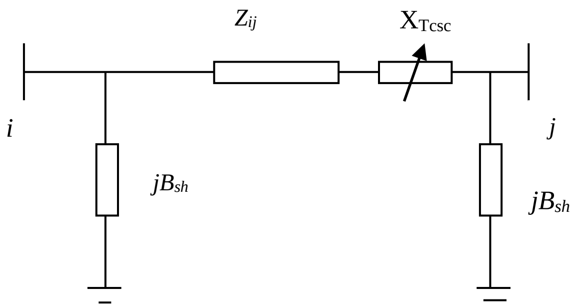

Fig. 2 TCSC located in transmission line

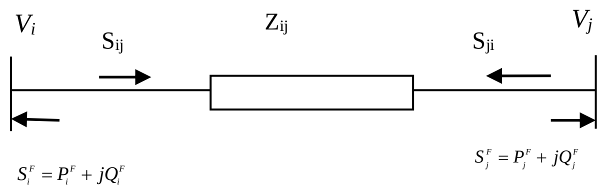

Fig.3 Power injection model of TCSC

The change of admittance between two lines is calculated by using the equation (14).

$$\Delta y_{ij} = y_{ij}^{'} - y_{ij} = (g_{ij}^{'} + jb_{ij}^{'}) - (g_{ij} + jb_{ij}) \tag{14}$$

Where

$$g_{ij} = \frac{r_{ij}}{\sqrt{r_{ij}^2 + x_{ij}^2}}, \qquad b_{ij} = \frac{-x_{ij}}{\sqrt{r_{ij}^2 + x_{ij}^2}}$$

$$g_{ij}^{'} = \frac{r_{ij}}{\sqrt{r_{ij}^2 + (x_{ij} + x_{T\mathrm{csc}})^2}}, \qquad b_{ij}^{'} = \frac{-(x_{ij} + x_{T\mathrm{csc}})}{\sqrt{r_{ij}^2 + (x_{ij} + x_{T\mathrm{csc}})^2}}$$

4. Proposed Algorithm Formulation

A. *random -weighted Genetic Algorithm (rw -GA)*

rw-GA proposed in [17], uses the weight to build an objective function in this paper. The weights are changed frequently during the running time, a tendency to demonstrate a variable search direction, therefore enable to sample the area uniformly over the entire frontier. Minimization of weighted sum objective for q objective functions is

$$z = \sum_{k=1}^{q} w_k f_k(x) \tag{15}$$

The random weighted can be calculated as follows,

$$w_k = \frac{r_k}{\sum_{j=1}^{q} r_j}, \qquad k = 1,2,3...q \tag{16}$$

where r_k is the random number which is generated between (0, 1). In rw-GA, the selection probability P_i for individual can be used to select a pair of parents for crossover and this is then defined by the following linear scaling function:

$$P_i = \frac{z_{\max} - z_i}{\sum_{i=1}^{Np-\max} \left(z_{\max} - z_i \right)} \tag{17}$$

where z_{max} is the worst fitness value in the current population.

B. *Main Objective*

The objective of this paper is divided into main and sub objective which is clearly shown in Fig. 4. The main objective is to find the best random string using random weighted -Genetic Algorithm (rw-GA), which has minimum of z when subjected to a variety of constraints.

$$\min z = w_1 f_1(x) + w_2 f_2(x) \tag{18}$$

where f_1 and f_2 are objective functions, they denote the real power loss and deviation in voltage magnitude at load buses respectively. The network real power loss and voltage deviation (VD) at all load buses can be calculated as follows

$$P_{loss} = \sum_{K=1}^{N_l} G_K [V_i^2 + V_j^2 - 2V_i V_j cos(\delta_i - \delta_j)] \tag{19}$$

$$VD = \sum_{i=1}^{N_{PQ}} (V_{ref} - V_i)^2 \tag{20}$$

w_1 and w_2 are random weights, calculated using (16) and G is the conductance of transmission line.

Subjected to:

Apparent line flow limit

$$\left| S_{ij}(\theta, V) \right| \le S_{ij}^{\max} \tag{21}$$

Power generation lim

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \tag{22}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \tag{23}$$

Bus voltage limit

$$V_i^{\min} \le V_i \le V_i^{\max} \tag{24}$$

TCSC reactance limit

$$x_c^{\min} \le x_c \le x_c^{\max} \tag{25}$$

Voltage stability index limit

$$NVSI \le NVSI_{\max} \text{ at all buses.} \tag{26}$$

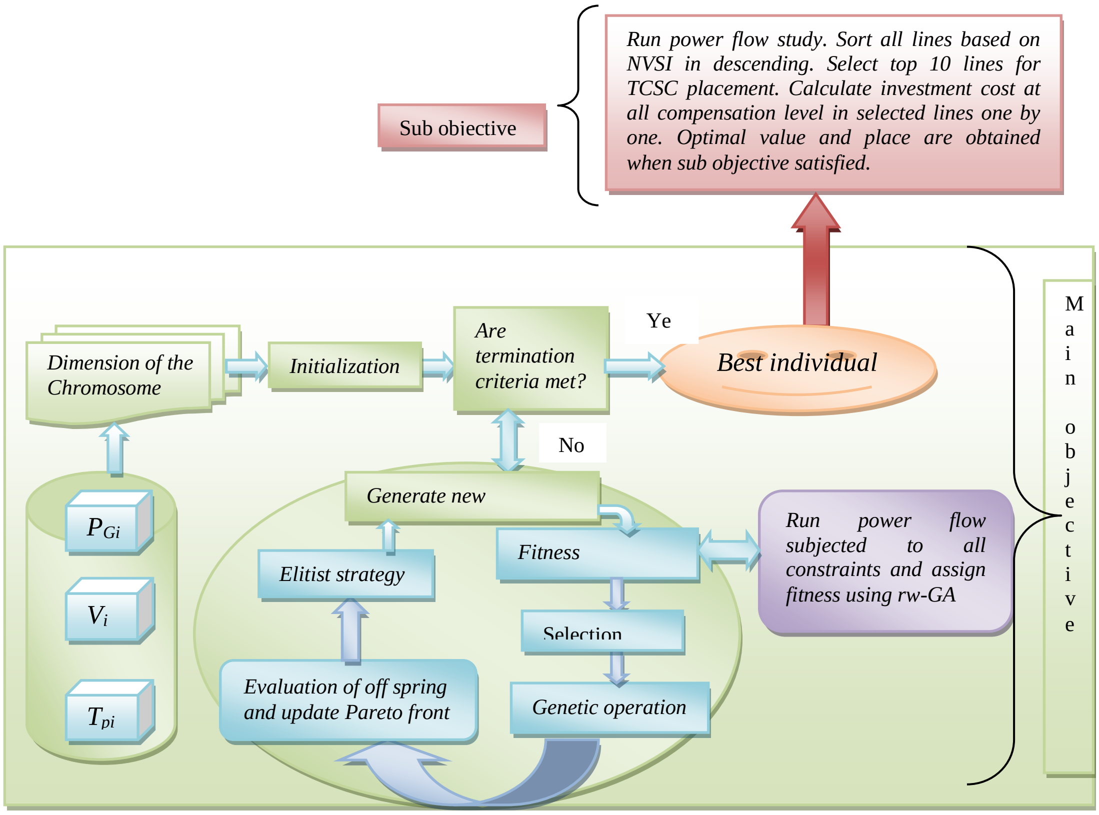

Fig. 4 Architecture for proposed algorithm

C. *Sub Objective*

The sub objective function is to minimize the investment cost of TCSC and overall annual operating cost under normal and contingency states, where each state is separately computed by local power flow study for best string obtained by rw-GA, satisfying main objective subjected to all constraints. According to [18], the investment cost (C_{TCSC}) and investment cost in annual term (IC_{TCSC}) can be formulated as follows:

$$C_{TCSC} = 0.0015 S_{TCSC}^2 - 0.7130 S_{TCSC} + 153.73 \quad \text{\$/KVAR} \tag{27}$$

$$IC_{TCSC} = \frac{[C_{TCSC} * S_{TCSC} * 1000]}{8760} \quad \text{\$/hr,} \tag{28}$$

S is the operating range of TCSC device in MVAR and it can be calculated as follows:

$$S = |Q_2| - |Q_1| \tag{29}$$

where Q_1 and Q_2 are the reactive power flow in the line before and after installing TCSC device in MVAR, respectively.

5. Methodology

a. *Initial population*

The initial population chromosomes are generated using a random number generator within the range of control variables. The real values are used for generating chromosomes; provide a higher accuracy as compared with binary coding.

Each variable in the chromosome structure shown in Fig. 5, is randomly generated using equation (30)

$$R = cv_{\min} + (cv_{\max} - cv_{\min})r \tag{30}$$

R- new value of chromosome, cv_{min}-minimum value of control variable, cv_{max}-maximum value of control variable and r- Numerical value between 0-1.

P_{G2}	$\cdots$	P_{Gn}	V_{G2}	$\cdots$	V_{Gn}	T_{P1}	$\cdots$	T_{Pn}

Fig.5 Chromosome structure

b. *Selection process*

This process selects the chromosome in population for reproduction. The more fit the chromosome, higher its probability of being selected for reproduction. Roulette Wheel Selection (RWS) is one of the best-known selection process type, used to determine selection probability or survival probability for each chromosome proportional to the objective value. In this algorithm, the selection method is preferred because it is more effective for combinational optimization problem.

c. Crossover process

Many researchers have proposed different crossover operators for real number encoding. After the selection process, the population is enhanced with better individual using extended intermediate recombination between pair of individuals with 0.8 crossover probability for this simulation.

d. Mutation process

Mutates each element with given probability and returns the resulting population. Integer representation mutation with 0.1 probability is used in this simulation.

e. Termination Criteria

The maximum generation or repeated solution is considered as stopping criterion for this simulation.

f. Dynamic Crowding Distance(DCD)

In this Multi Objective Evolutionary Algorithm (MOEA), Dynamic Crowding Distance [19] is used to remove excess individual when number of selected individuals exceeds population size. DCD give good horizontal diversity of Pareto-front. The individuals are sorted based on DCD value and those which have highest DCD value are selected for further process. The DCD of individual 'i' is calculated as follows:

$$DCD_i = \frac{CD_i}{\log\left(\frac{1}{Var_i}\right)} \tag{31}$$

Where,

$$CD_i = \frac{1}{N_{obj}}\sum_{j=1}^{N_{obj}}\left| f_{i+1}^{j} - f_{i-1}^{j}\right|$$

N_{obj}- Number of objectives.

f_{i+1}^{j}- j^{th} objective of the i+1th individual

f_{i-1}^{j}- j^{th} objective of the i-1th individual after sorting the population to CD values.

$$Var_i = \frac{1}{N_{obj}}\sum_{j=1}^{N_{obj}}\left(\left| f_{i+1}^{j} - f_{i-1}^{j}\right| - CD_i\right)^2 \tag{32}$$

Var_i - Variance of CDs of individuals which are neighbors of the i_{th} individual. In order to find the candidate lines for the most effective series compensation, the proposed methodology is illustrated in the flow chart of Fig.6.

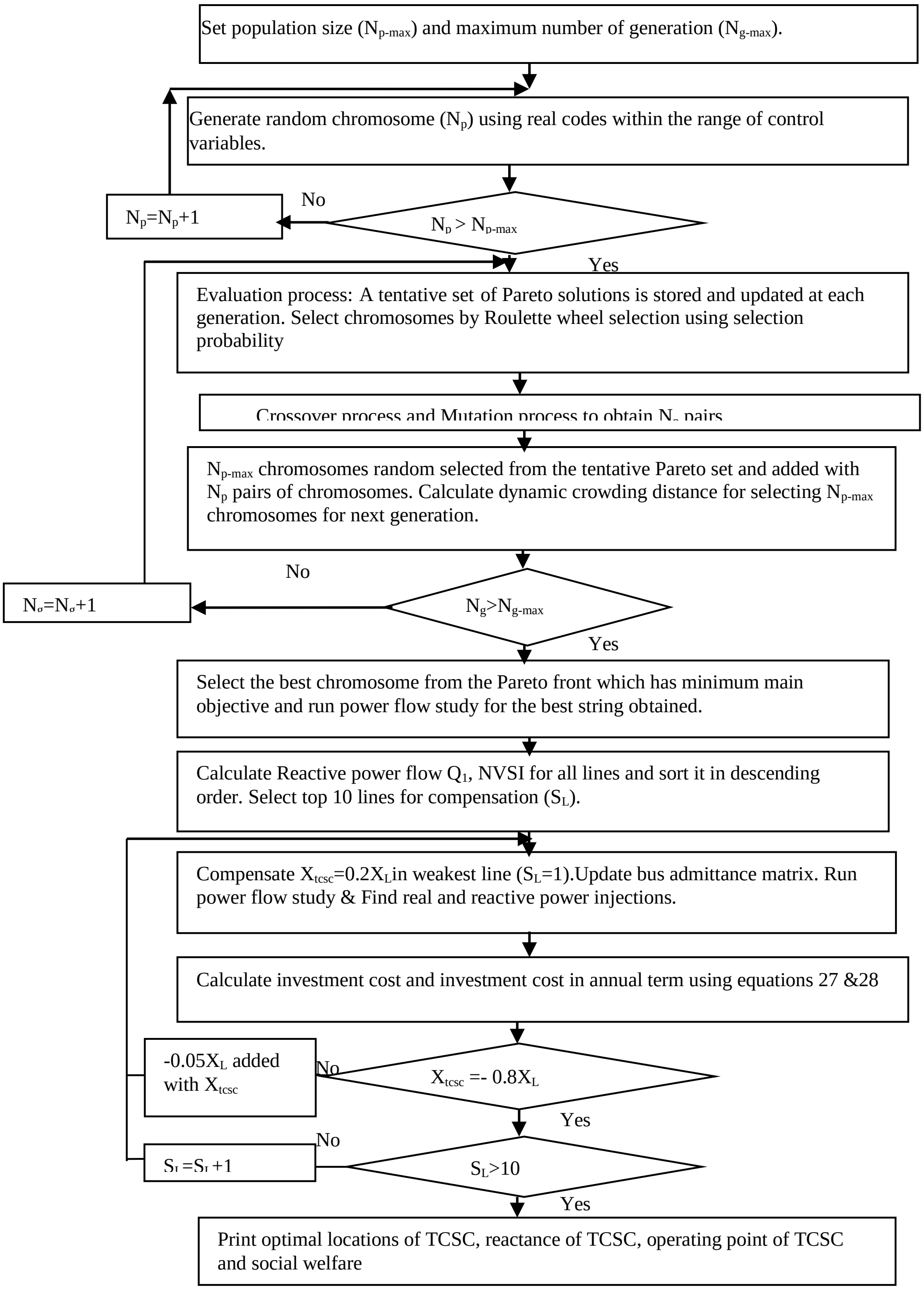

Fig.6 Methodology for selection of the optimal location and sizing of TCSC

6. Results and Discussion

Case A: IEEE 30 bus system

The proposed algorithm is evaluated using MATLAB environment on a PC with Pentium core 2 duo processor operating at 2 GHz with 2 GB RAM. In the simulations, the following conditions are implemented unless stated otherwise. Loads are modeled as constant power. Reactive power output limits of generator are modeled. The system MVA base is 100.The power factor of load remains constant when load increases. IEEE 30 bus system consists of 6 generator buses and 24 load buses.

The network has 41 branches and 4 tap changing transformers in (6-9), (6-10),(4-12) and (28-27) branches .The active and reactive power loads are set at base load P_{load} = 2.384 p.u and Q_{load} =1.0445p.u respectively. The dimension of the chromosome is 14, which consists of five real power generators, five generator voltages and four transformer tap setting ratios varied within their respective limits as given in Table 1. Number of generations considered for this simulation is 200. The values of real power generation, generator terminal voltages and tap settings are allowed to vary within their respective limits during the optimization process. The base load and heavily loaded conditions are considered for this work. In heavily loaded case, the base case real and reactive loads are multiplied by loading factor =1.4 with maintaining constant power factor.

Table1

Control variable limits

Parameter	Limits
P_{G2}	(20-80) MW
P_{G5}	**(15-50) MW**
P_{G8}	(10-35) MW
P_{G11}	(10-30) MW
P_{G13}	(12-40) MW
Generator voltage magnitude(V_G)	0.9-1.1pu
Transformer tap setting	0.9-1.1pu

Table 2

GA parameters for optimal solution

Parameter	Values
Generation	200
Population size	20
Crossover rate	0.9
Crossover fun	Extended intermediate
Selection fun	Roulette
Mutation process	Integer representation
Mutation rate	0.1
Termination criteria	Maximum generation or repeated solution.

For the base case, the loading factor (λ) is taken as 1. The GA parameters have utilized for this algorithm to obtain optimal siting and sizing of TCSC is shown in Table 2.

Case 1: Base loading condition

This algorithm randomly generates ($N_{p\text{-}max}$) 20 initial solutions. Then each solution is evaluated using power flow analysis and also makes initial tentative set of nondominated solutions. N_{elite} is taken as 3for this work. Hence $N_{p\text{-}max}$ - N_{elite} =17 pairs of parents are selected from current population by randomly specifying the weight values (w_1, w_2) 17 times and apply crossover and mutation,17 pairs of new solutions are generated. Dynamic crowding distance is used to remove excess individuals from these solutions ie., only 17 new solutions. N_{elite} solutions 3 are randomly selected from tentative set of nondominated solutions and added to the set of the new solutions to form a population of 20 solutions. Repeat the procedure up to termination criteria meet. 20 independent trails are used in this algorithm. The best compromised solution has obtained which satisfies the main objective from final set of nondominated solution is shown in Fig.7 using TOPSIS method.

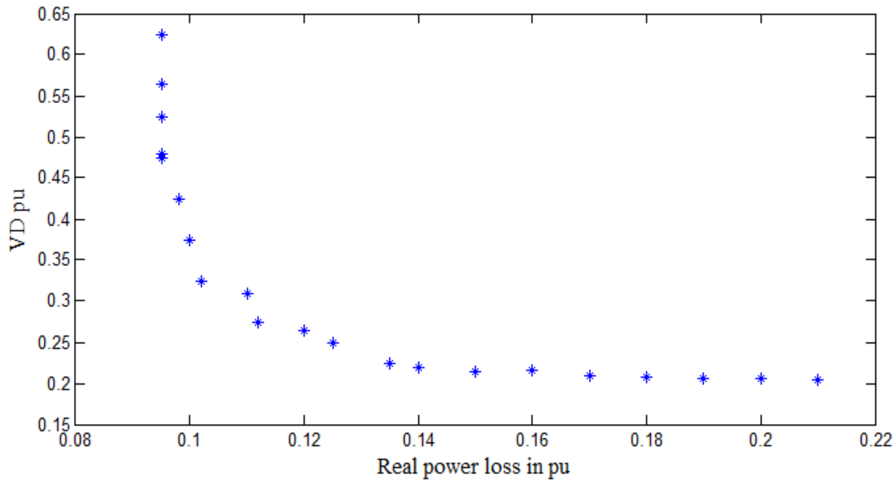

Fig.7 Final set of non-dominated solution for base case loading

The concept of TOPSIS [20] is that in the absence of a natural course of action for overall summary measure and ranking, the most preferred alternative should not only have the shortest distance from the positive ideal solution, but also have the longest distance from the negative ideal solution. The best values of individual and corresponding real power loss, voltage deviation and main objective for base load and heavy load case are obtained as shown in Table.3 and it is used to find optimal location of TCSC with optimum value.

Table 3

Optimized results of IEEE 30 bus system

Parameters	Base load condition(pu)	Heavy load condition (pu) (λ =1.4)
P_{G2}	0.3421	0.3529
P_{G5}	0.4603	0.8466
P_{G8}	0.3103	0.5905
P_{G11}	0.1251	0.3573
P_{G13}	0.2215	0.1142
V_{G2}	1.0667	1.0250
V_{G5}	1.0228	0.9980
V_{G8}	1.0843	0.9820
V_{G11}	1.0438	1.0460
V_{G13}	1.0402	1.0600
T_{P1}	0.9878	0.9760
T_{P2}	0.9291	0.9700
T_{P3}	0.9362	0.9320
T_{P4}	0.9517	0.9680
P_{loss}	0.1703	0.2041
VD	0.2064	0.3009

The best individual is utilized for compensation purpose. For that, power flow analysis is run and New Voltage Stability Index (NVSI) is found for all lines.

Table 4

Selected transmission lines for TCSC placement for IEEE 30 Bus system

Rank	**line**		**NVSI**	
	Base load condition	**Heavy load condition** (**λ** =1.4)	**Base load condition**	**Heavy load condition** (**λ** =1.4)
1	6-10	6-10	0.2327	0.2536
2	2-5	27-30	0.1784	0.1959
3	27-30	2-5	0.1210	0.1932
4	29-30	9-11	0.0940	0.1710
5	4-12	29-30	0.0682	0.1557
6	5-7	4-12	0.0574	0.1037
7	12-13	5-7	0.0560	0.0854
8	9-11	23-24	0.0462	0.0759
9	23-24	12-13	0.0403	0.0731
10	6-7	6-7	0.0384	0.0611

It is sorted in the descending order and first 10 lines are selected for TCSC location for base and heavy loading conditions that are shown in Table.4. Each line is compensated with 20 steps of -0.05pu each and it covers the compensation range from $0.2X_L$ to $-0.8X_L$.

Optimal location of TCSC with optimum value is obtained when the sub objective is satisfied. In each step of compensation, the Q_2 and the investment cost of TCSC are calculated.

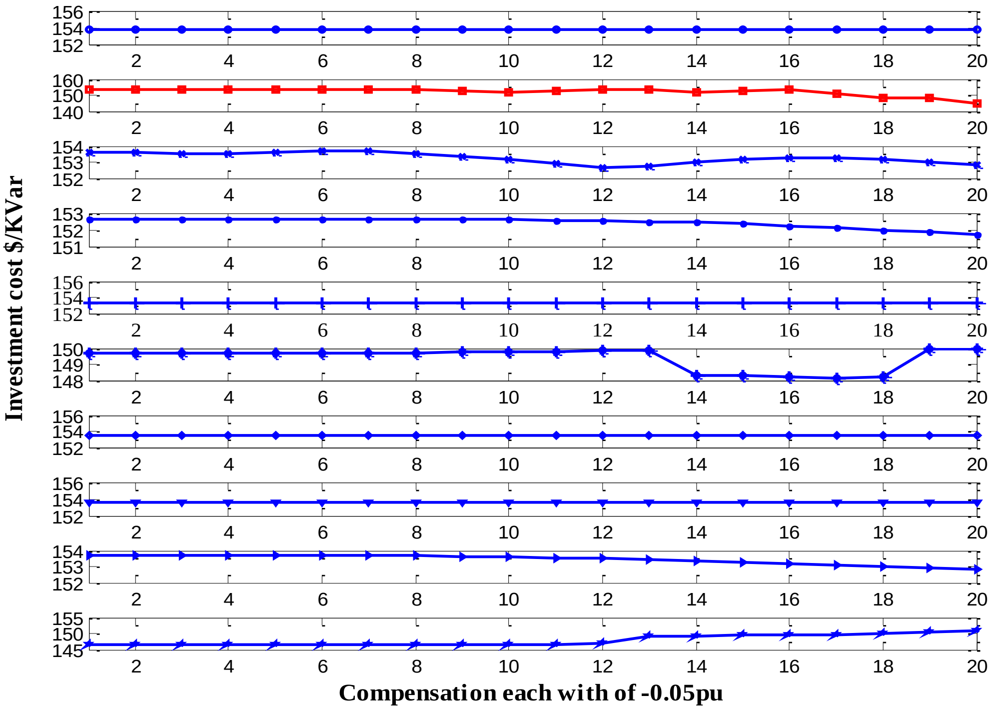

Fig.8 Compensation level in 20 steps verses investment cost of TCSC at top 10 rank lines for base loading condition

The investment cost at all 20 compensation levels for top ranking 10 lines are shown in Fig.8.

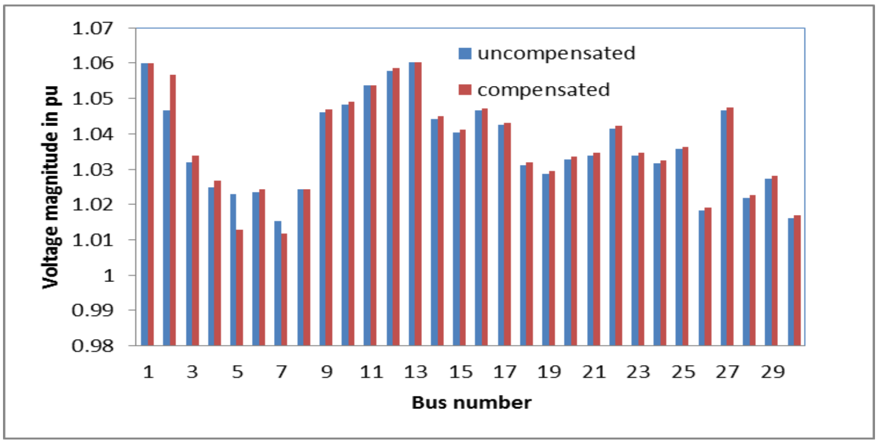

Fig. 9 Voltage magnitudes at all the buses before and after TCSC placement

The X axis represents that compensation level at each line in 20 steps varies from 0.2 line reactance to -0.8 line reactance of respective lines. It also show that the sub objective is satisfied at the compensation level of X_{tcsc}= -0.8X_L (20th step of compensation) in line 2-5. The $Q_1$and Q_2 values are obtained as 3.6395 MVAr and 17.0208MVAr respectively. Compensation value = 13.3813 MVAr, investment Cost =144.4577 $/KVAr, overall investment cost= 220.66$/hr. Hence the 2-5 is optimized line and the value is -0.8 X_L for the base loading condition. The voltage at all buses before and after compensation in line 2-5 are shown in Fig.9.

Case 2: Heavy loading condition

The voltages at all buses and voltage stability index are improved and real power loss is reduced. When the load increases by 40% with constant power factor the investment costs at all 20 compensation levels for top ranking of 10 lines are shown in Fig.10. From this, X_{tcsc}= -0.2X_L at line 6-7, compensation value = 19.4837 MVAR, investment Cost =140.0001 $/KVAr, overall investment cost= 311.38$/hr are optimized line and value for the heavy loading condition. The losses are reduced from 20.1376 MW to 15.410 MW after compensation and voltage magnitudes are improved. All possible (N-1) contingencies are executed to find the possible TCSC placement. The lines (27-30), (2-5), (12-13) are found to occur respectively for most of the line outages.

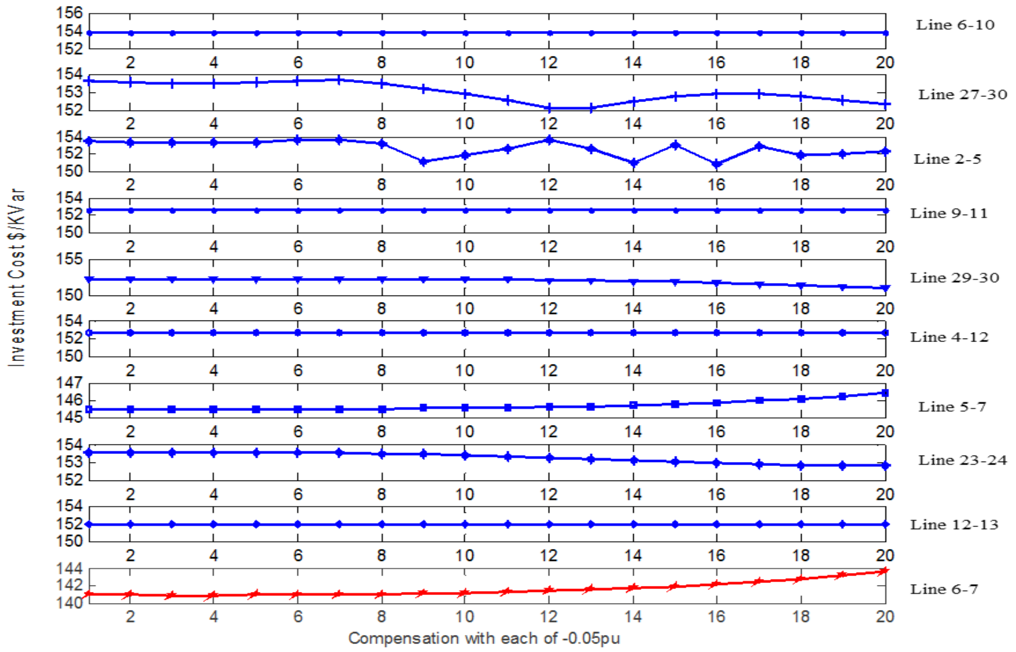

Fig.10 Compensation level in 20 steps versus investment cost of TCSC at top 10 rank lines for heavy loading condition

Under base loading condition the line (2-5), heavy loading conditions the line (6-7) are selected. Consequently the lines (2-5),(6-7),(27-30),(12-13) have been identified as suitable lines for TCSC placement in IEEE 30 bus system for considering various conditions of the system.

Case B: TNEB 69 bus system

The 12 generator bus real power generations, voltage and 11 transformer rating decide the dimension number. The dimension of control variables is 35. The final set of nondominated solution for TNEB system is shown in Fig.11 and the best compromised solution is obtained using TOPSIS method.

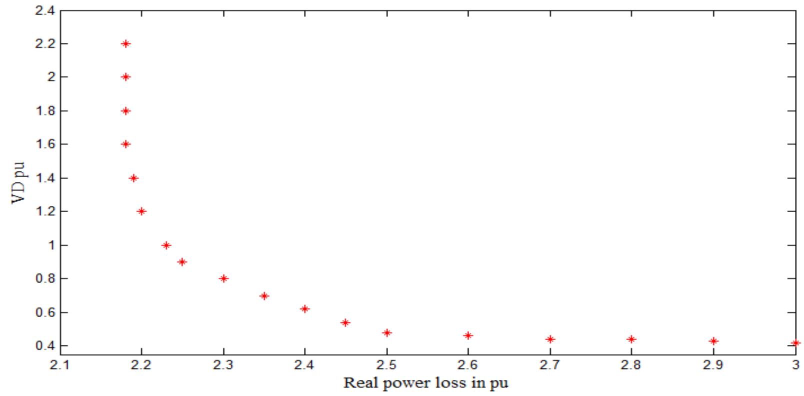

Fig. 11 Final set of nondominated solution for TNEB 69 bus system

The best compromised solutions attained are forwarded for power flow study, top 10 ranking of transmission lines are tabulated in Table 5 with NVSI values.

Table 5

Selected transmission lines for TCSC placement in TNEB 69 bus system

Line	**Rank**	**NVSI**
55-56	1	0.3805
48-51	2	0.2890
32-41	3	0.2498
30-31	4	0.2264
5-6	5	0.2249
39-44	6	0.2145
1-8	7	0.2122
52-59	8	0.2043
65-68	9	0.1965
1-6	10	0.1786

The 69 bus system is a large practical system; therefore more than one line is selected for TCSC compensation to increase the loading margin. From Fig.12, the lines (55-56), (48-51), (32-41), (30-31), and (5-6) are selected and compensation levels based on the investment cost of individual line are also obtained and these are tabulated in Table.6 (Here one US dollar is taken as approximately Rs.55).

Table 6

Compensation level and investment cost in TNEB 69 bus system

Line	Degree of Compensation		Cost (Rs/KVAr)	Compensation Value (MVAr)
	$X_{l,old}$(before compensation)	$X_{l,new}$(after compensation		
55-56	0.0582	0.1164	7700.2695	18.7846
48-51	0.0701	0.0140	8111.334	36.3115
32-41	0.0722	0.0361	7761.083	5.641
30-31	0.0430	0.0086	8311.083	34.120
5-6	0.0884	0.0829	8117.56	1.012

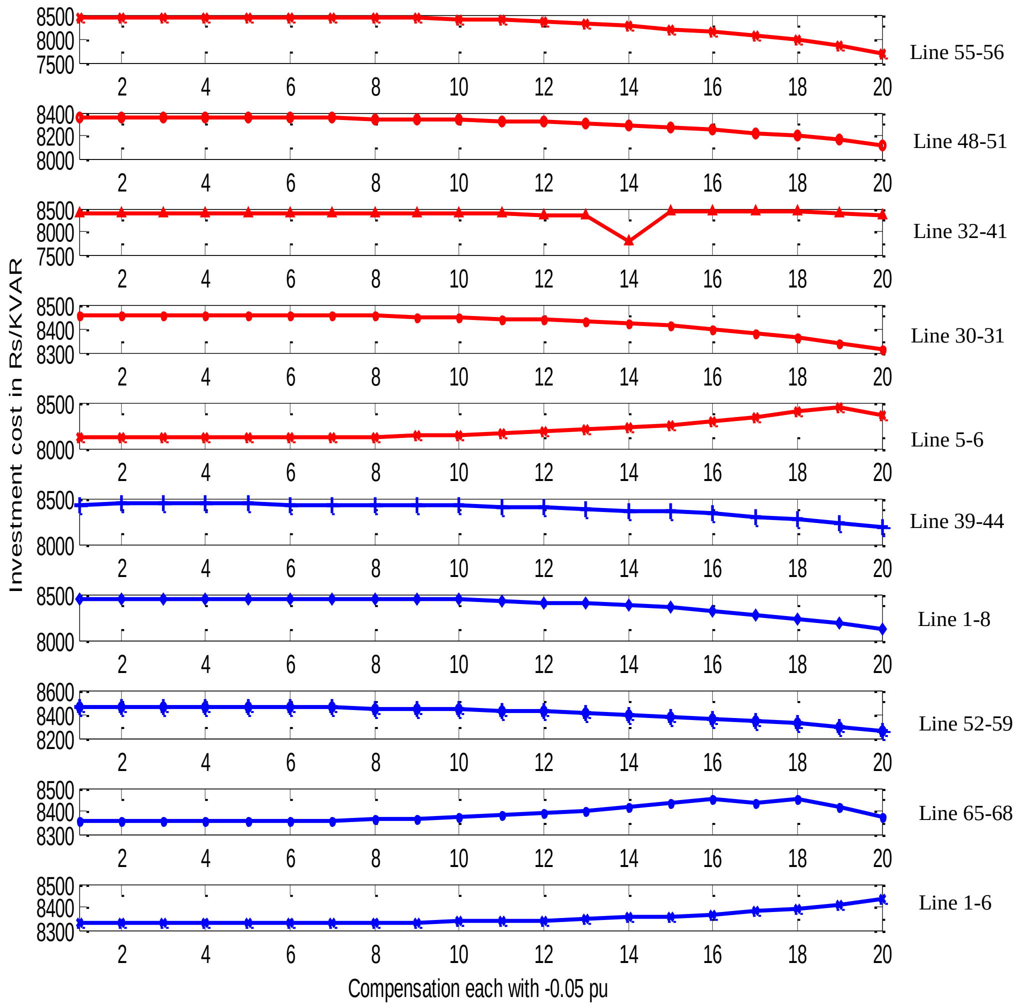

Fig.12 Compensation level in 20 steps versus investment cost TCSC at top 10 rank lines of TNEB 69 bus

7. Conclusion

The voltage stability index based method is presented to identity optimal location, size, and installation cost of TCSC considering normal, heavy loading and (N-1) contingency conditions for both IEEE 30 bus, and a practical Indian TNEB 69 bus system using rw-GA. The advantages of rw-GA are that the computation process is simplest and fastest in finding the best individual. Multiple solutions are arrived in parallel, keeping the weights not fixed to enable the genetic search to the sample uniformly from the whole area to whole frontier. This innovative algorithm can also be used in online monitoring for large power systems. All possible degrees of compensation are effectively determined for the selected lines which are very useful for perfect improvement of voltage magnitude at all lines and also reduction of losses.

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