THE INTERNATIONAL JOURNAL OF SCIENCE & TECHNOLEDGE

Optimal Location of Multi Type FACTS Devices for Single Contingency Using Genetic Algorithm

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Abstract:
In any power system, unexpected outages of lines or transformers occur due to faults or other disturbances. These events, referred to as contingencies, may cause significant overloading of transmission lines or transformers, which in turn may lead to outages. This paper presents a procedure based on the contingency severity index (CSI) described by a real power flow performance index (PI) to place multi type FACTS devices (Flexible AC Transmission System) in order to eliminate or alleviate the line over loads, resulting in an increased loadability, reduced system loss, improved stability of the network, by controlling the power flow in the network. TCSC (Thyristor Controlled Series Compensator) and SVC (Static Var Compensator) are considered and modeled for steady state analysis. Once the location is determined, their type, their optimal settings and cost of installation can be obtained by solving the optimization problem using genetic algorithms (GA). The proposed approach is tested on 9- bus test system.

Keywords: *Performance Index, Contingency Severity Index, FACTS devices, TCSC, SVC, GA*

1. Introduction
The increasing industrialization, urbanization of life style has lead to increasing dependency on the electrical energy. This has resulted into rapid growth of power systems. This rapid growth has resulted into few uncertainties. Power disruptions and individual power outages are one of the major problems and affect the economy of any country. In contrast to the rapid changes in technologies and the power required by these technologies, transmission systems are being pushed to operate closer to their stability limits and at the same time reaching their thermal limits due to the fact that the delivery of power have been increasing. If the exchanges were not controlled, some lines located on particular paths may become overloaded. The major problems faced by power industries in establishing the match between supply and demand are:

- Transmission & Distribution supply the electric demand without exceeding the thermal limit.
- In large power system, stability problems causing power disruptions, voltage instability and blackouts leading to huge losses.

These constraints affect the quality of power delivered. However, these constraints can be suppressed by enhancing the power system control[1]. Many measures are taken to enhance power system control such as, (i) Placement of series and shunt capacitors, (ii) Generation rescheduling, (iii) Installation of synchronous condensers, (iv) Under- Voltage load shedding, (v) Blocking of Tap-Changer under reverse operation, (vi) Placement of FACTS controllers. The last method is considered in this study[2].

FACTS is a terminology that embrace a wide range of power electronics controllers. These devices use no delay and high current power electronic devices available today for safe and accurate responses. They are able to control the parameters such as voltage magnitudes and their angles, line impedances, active and reactive power flows.

There are many types of FACTS such as, Superconducting magnetic energy storage (SMES), Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Thyristor Controlled Series Capacitor (TCSC), Interline Power Flow Controller (IPFC), and Unified Power Flow controller (UPFC)[3],[4].

TCSC and SVC is considered in this paper. Thyristor Controlled Series Capacitor (TCSC) is a variable impedance type FACTS device and is connected in series with the transmission line to increase the power transfer capability, improve transient stability, and reduce transmission losses. The SVC is defined as a shunt connected Static Var Compensator whose output is adjusted to exchange capacitive or inductive so as to maintain or control specific parameters of electrical power system, typically a bus voltage[5],[6].

In this proposed paper, the essential idea of multi type FACTS devices, TCSC and SVC placement is to determine a branch which having the most sensitivity for single contingency. After placing FACTS devices, their type, optimal settings and cost of installation can be obtained by solving the optimization problem. The nonlinear optimization problem is solved by Genetic Algorithms (GA).

2. Problem Formulation

2.1. Placement of FACTS devices

The essential idea of the proposed multi type FACTS devices, TCSC and SVC placement approaches is to determine a branch which is the most for the large list of single contingency. This section will describe the definition and calculation of the contingency severity index and the optimal placement procedure for the TCSC and SVC.

2.1.1. Performance Index: PI

The severity of the system loading under normal and contingency cases can be described by a real power line flow performance index, as given in the following:

$$PI=\sum_{m=1}^{N_b}\frac{\omega_m}{2n}\left(\frac{P_{lm}}{P_{lm}^{max}}\right)^{2n} \quad (1)$$

Where P_{lm} is the real power flow and P_{lm}^{max} is the rated capacity of the branch-m, ω_m a real nonnegative weighting coefficient of the branches and n is the exponent. N_b is the total number of branches in the network.

The value of the exponent has been taken as 2 and ω_i =1.

The real power flow PI sensitivity factors with respect to the control parameters of TCSC and SVC can be defined as

$$\alpha_k = \frac{\partial PI}{\partial x_c}\Big|_{X_c=0}, \quad \beta_k = \frac{\partial PI}{\partial B_{svc}}\Big|_{B_{svc}=0} \quad (2)$$

The sensitivity of PI with respect to FACTS(TCSC, SVC) parameter X_k (x_c and B_{svc}) connected between bus-i and bus-j can be written as

$$\frac{\partial PI}{\partial X_k} = \sum_{m=1}^{N_b}\omega_m \; P_{lm}^3 \left(\frac{1}{P_{lm}^{max}}\right)^4 \frac{\partial P_{lm}}{\partial X_k} \quad (3)$$

2.1.2. Contingency Severity Index: CSI

The CSI for branch '*m*' is defined as the most of the sum of the sensitivities of branch '*m*' to all the considered single contingency, and is expressed as

$$CSI_m = \max\left(\sum_{p=1}^{c}|\alpha_k^p| \,;\, \sum_{p=1}^{c}|\beta_k^p|\right) \quad (4)$$

Where 'c' is the number of contingencies CSI values are calculated for every branch by using (4). The branch with the largest CSI is considered as the best location for Facts devices.

2.2. Optimal setting of FACTS devices

After fixing the location, to determine the best possible setting of FACTS devices for all possible single contingencies, the optimization problem will have to be solved using GA.

The objective function for this work is,

Obj=minimize

$$SOL=\sum_{c=1}^{N_s}\sum_{k=1}^{N} a_k\left(\frac{P_k}{P_k^{max}}\right)^4 \quad (5)$$

Where :

N: Number of lines.

Ns: Number of single contingency considered.

: Weight factor =1.

P_k: Real power transfer on branch k.

: Maximum real power transfer on branch k.

SOL: represents the severity of overloading.

IC: Installation cost of FACTS devices.

Installation cost includes the sum of installation cost of all the devices and it can be calculated by:

C_{TCSC} =0.0015S^2 – 0.71S+153.75(US$/KVAR) (6)

C_{SVC} =0.0003S^2 – 0.3051S+127.38(US$/KVAR) (7)

Where, *S* is the operating range of FACTS in MVAR

S= Q_2 – Q_1

Q_1 : MVAR flow through the branch before placing FACTS devices.

Q_2 : MVAR flow through the branch after placing FACTS devices.

The objective function is solved with the following constraints:

2.2.1. Security limits

Two inequality constraints are considered. The first constraint includes voltage limits at load buses as shown in (13)

$$V_{Li}^{min} \leq V_{Li} \leq V_{Li}^{max}, \text{ i= 1,....N} \quad (8)$$

Where V_{Li}^{min} and V_{Li}^{max} are respectively lower and upper limits voltage at load buses.

The second is represented by the line flow limits. It considers that the real power flow P_{li} in each transmission line i among the N_{line} lines of the power system must be lower than its maximum value P_{li}^{max}. Mathematically, it can be written as:

$$P_{li} \leq P_{li}^{max}, \ i= 1,....N_{line} \quad (9)$$

2.2.2. Voltage Stability Constraint

VS includes voltage stability constraints in the objective function and is given by:

$$VS=\begin{cases} 0 & if \quad 0.9 < Vb < 1.1pu \\ 0.95 - Vb & if \quad Vb < 0.9 \\ Vb - 1.05 & if \quad Vb > 1.1 \end{cases} \quad (15)$$

Where, Vb : voltage in per unit (pu) at bus b.

2.2.3. Facts Devices Constraints

The FACTS devices limit is given by:

$0.5XL < x_c < 0.5XL$ (10)

$-200MVAR \leq Q_{SVC} \leq 200MVAR$ (11)

Where :

X_L: Original line reactance in (pu).

x_c: Reactance in (pu) added to the line where TCSC is placed.

Q_{SVC}: reactance power injected at SVC placed in MVAR.

2.2.4. Power Balance Constraints

The power balance equations are given by:

$$\sum P_G = \sum P_D + P_L$$

Where

$\sum P_G$: Total power generation.

$\sum P_D$: Total power demand.

P_L: Losses in the transmission network. (12)

3. Overview of GA

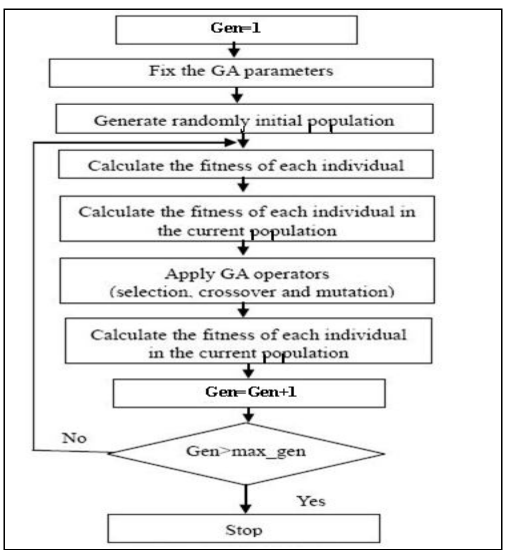


Figure 1: Flow chart of the GA

In this paper, GA has been used for choice and setting parameters of the FACTS devices. The first step GA is to fix a random initial population, which is a set of candidate solutions. In general, candidate solutions are represented as coded number corresponding to each variable of the optimization problem, called chromosome. Also, for each individual, a fitness function, related to the objective function, is affected. GA operates in generations.
One generation is as follows :

- For each individual of the current population, a fitness function is affected.
- One or more parents are chosen according to their fitness function.
- GA operators, such as, crossover and mutation are applied to parents to produce children.
- Theses children are inserted into the following population.

This process is repeated until the population size is reached.
The optimal configuration of the FACTS devices is encoded by its location and control parameter.

4. Results and Discussions

Load flow calculations are done with Newton Raphson method for the 9 bus system[9]using MATLAB. By N R method, the parameters i.e, voltage magnitude, real and reactive power flow from bus- i to bus - j and from bus- j to bus- i, real power loss and reactive power loss are calculated, for convergence of above parameters it took 6 iterations. The total real power loss is 4.65 MW and total reactive power loss is -92.77 MVAR.

Line No.	Bus			
	From	To	Real power in MW	Reactive power in MVAR
1	1	4	71.65	-26.86
	4	1	-71.65	23.76
2	4	6	32.71	-1.11
	6	4	-32.52	16.51
3	6	9	-57.48	13.49
	9	6	58.74	18.37
4	3	9	85	8.63
	9	3	-85	-12.71
5	8	9	-26.15	27.17
	9	8	26.26	-5.66
6	7	8	74.30	4.01
	8	7	-73.85	7.83
7	2	7	163	-3.99
	7	2	-163	-11.82
8	5	7	-86.3	11.41
	7	5	88.70	7.81
9	5	4	-38.70	38.59
	4	5	38.94	-22.65

Table 1: The real and reactive power flow from bus- i to bus - j and from bus- j to bus- i.

4.1. Determine the Location of FACTS Devices

In this paper for determining the location of FACTS devices we have considered the single contingency analysis by removing the branches one by one and then calculated the PI value for each branch through load flow calculations. The real power flow PI sensitivity factors with respect to the control parameter of TCSC and SVC can be defined as α_K and β_k as mentioned in the equation (3).
CSI values are calculated for every branch by using equation (4). The branch with the largest CSI is considered as the best location for Facts devices.
Table 3 shows that branch number 2-7 and 7-8 is chosen as best location to place the multi type FACTS devices for single contingency.. The best location for TCSC is branch 2-7 and it is connected in series, then SVC is located at bus 7 connected in shunt.

Removed line		α_k	β_k
From bus	To bus		
1	4	0.12664	0.13832
4	6	0.13437	0.13828
6	9	0.14399	0.13811
3	9	0.12588	0.13790
8	9	0.14956	0.138154
7	**8**	0.12589	**0.138477**
2	**7**	**0.15332**	0.138368
5	7	0.12316	0.138104
5	4	0.14678	0.138104

Table 2: Selection of branches for single contingency

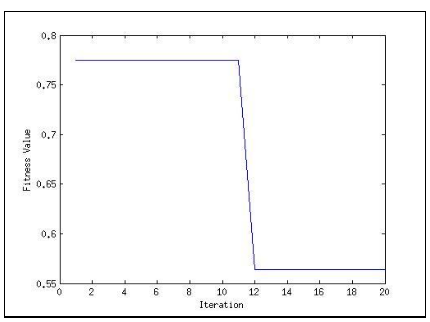
4.2. Applying Genetic Algorithm

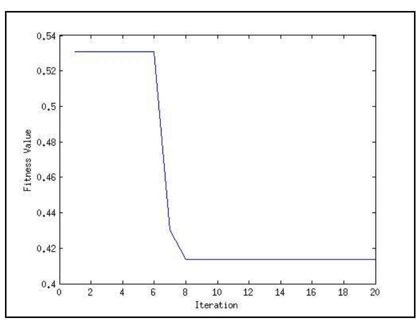
After determining location of FACTS devices, by applying the GA we calculate the size of the FACTS devices, severity of over loading (SOL), cost of installation(IC) can be obtained by solving the optimization problem as in table 3 and then the parameters i.e., voltage magnitude, real and reactive power flow from bus- i to bus- j and from bus- j to bus- i, real power loss and reactive power loss can be calculated by using N R method.

Devices/Type	TCSC		SVC		SOL	IC
	location	x_c (pu)	location	B_{SVC}(pu)		
TCSC	2-7	0.0545	-	-	56.38	176.18
SVC	-	-	7	-0.59378	41.37	156.06
Multi type	2-7	0.15845	7	-0.39378	36.14	235.05

Table 3: Installation cost of The FACTS devices and SOL results with genetic algorithm.

Below figures shows the Severity of over loading convergence for single contingency in different iterations.





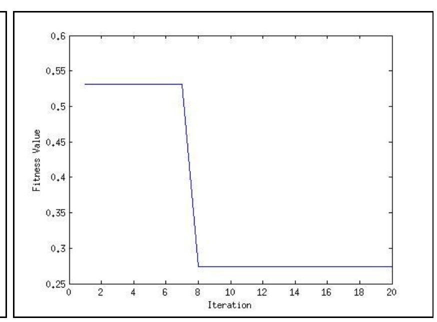


Figure 2. Severity of over loading convergence for single contingency in different iterations For TCSC
Figure 3. Severity of over loading convergence for single contingency in different For SVC
Figure 4. Severity of over loading convergence for single contingency in different for TCSC and SVC

Fig.2, Fig.3, and Fig.4 represent the fitness convergence curve for single contingency.

After placing the FACTS devices such as TCSC alone at bus 2-7, real and reactive power flow from bus- i to bus- j and from bus- j to bus- i as shown in below table.

Line No.	Bus		Real power in MW	Reactive power in MVAR
	From	To		
1	1	4	71.64	-26.97
	4	1	-71.64	23.85
2	4	6	30.71	-1.02
	6	4	-30.54	16.54
3	6	9	-59.46	13.46
	9	6	60.81	18.07
4	3	9	85	10.94
	9	3	-85	-15.03
5	8	9	-24.10	24.22
	9	8	24.19	-3.03
6	7	8	76.37	0.73
	8	7	-75.90	10.78
7	2	7	163	-5.74
	7	2	-163	-2.17
8	5	7	-84.32	11.37
	7	5	86.62	8.33
9	5	4	-40.68	38.63
	4	5	40.93	-22.83

Table 4: The real and reactive power flow from bus- i to bus - j and from bus- j to bus- i with TCSC

After placing SVC alone at bus 7, real and reactive power flow from bus- i to bus- j and from bus- j to bus- i as shown in below table. The injected reactive power Q_{SVC} to the bus 7 is 16.7MVAR.

Line No.	Bus		Real power in MW	Reactive power in MVAR
	From	To		
1	1	4	71.50	3.01
	4	1	-71.50	-5.74
2	4	6	31.88	1.44
	6	4	-31.71	14.64
3	6	9	-58.30	15.36
	9	6	59.54	18.02
4	3	9	85	44.87
	9	3	-85	-50.02
5	8	9	-25.34	-9.47
	9	8	25.46	31.00
6	7	8	75.17	-31.27
	8	7	-74.66	44.47
7	2	7	163	115.62
	7	2	-163	-139.38
8	5	7	-85.52	36.57
	7	5	87.83	-13.27
9	5	4	-39.48	13.43
	4	5	39.62	4.30

Table 5: The real and reactive power flow from bus- i to bus - j and from bus- j to bus- i with SVC.

After placing both TCSC and SVC at bus 2-7 and bus 7 respectively, real and reactive power flow from bus- i to bus- j and from bus- j to bus- i as shown in below table. The injected reactive power Q_{SVC} to the bus 7 is 13.17MVAR.

Line No.	Bus		Real power in MW	Reactive power in MVAR
	From	To		
1	1	4	71.91	-37.54
	4	1	-71.91	34.03
2	4	6	30.36	-1.87
	6	4	-30.19	17.17
3	6	9	-59.81	12.82
	9	6	61.20	18.07
4	3	9	85	-9.90
	9	3	-85	-3.04
5	8	9	-23.66	35.22
	9	8	23.78	-15.03
6	7	8	76.85	10.83
	8	7	-76.34	-2.9
7	2	7	163	-49.12
	7	2	-163	31.88
8	5	7	-83.78	3.00
	7	5	86.16	15.10
9	5	4	-41.22	47.00
	4	5	41.55	-32.17

Table 6: The real and reactive power flow from bus- i to bus - j and from bus- j to bus- i with TCSC and SVC

Type of devices	P loss in MW	Q loss in MVAR
No FACTS devices	4.65	-92.77
SVC	4.5	-67.58
TCSC	3.65	-44.11
TCSC and SVC	1.58	-27.411

Table 7: Shows reduction of power losses by placing the FACTS devices.

\ From above table we conclude that the real and reactive power losses after placing the FACTS devices get reduced.
After the implementation of FACTS devices the voltage magnitude is maintained within the limits $0.9 \leq |V| \leq 1.1$ for all single contingency cases as shown in table 8.

Bus No.	Voltage Magnitude(pu) without FACTS devices	Voltage Magnitude(pu) for TCSC	Voltage Magnitude(pu) for SVC	Voltage Magnitude(pu) for TCSC and SVC
1	1.04	1.04	1.04	1.04
2	1.025	1.025	1.025	1.025
3	1.025	1.025	1.025	1.025
4	1.0259	1.0258	1.0424	1.02
5	0.99608	0.99572	1.0348	0.98195
6	1.0124	1.0127	1.0313	1.0062
7	1.0274	1.0259	1.1	1
8	1.0199	1.016	1.0688	0.99745
9	1.0311	1.0324	1.0518	1.0256

Table 8: Voltage magnitudes for the system with and without FACTS controllers.

5. Conclusion

In this paper, a sensitivity-based approach has been used for single contingency to find suitable placement of FACTS devices along the system branches based on the CSI values to alleviate system overloads and to improve the system security margin. Cost of installation and their settings were taken as the optimization parameters for single contingency. This optimization problem is solved using GA techniques. TCSC and SVC were considered in this work. It is observed that the real and reactive power losses, SOL and IC get reduced after placing multi type FACTS devices. 9-bus test system is used to evaluate the performance of these approaches.

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