Indonesian Journal of Electrical Engineering and Computer Science
Vol. 32, No. 2, November 2023, pp. 664~675
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v32.i2.pp664-675

Economic flexible AC transmission system devices placement/sizing with (N-1) contingency using genetic algorithm

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Article Info

Article history:

Received Oct 26, 2022
Revised Jul 19, 2023
Accepted Aug 25, 2023

Keywords:

Genetic algorithm
N-1 contingency
Optimal placement
Static VAR compensators
TCSC

ABSTRACT

The rise in demand for electricity and the high cost of constructing new power networks reckons optimal utilization of electric power overloading and excessive power transfer along transmission lines, high losses, voltage instability, poor power quality, reliability issues. Flexible AC transmission system (FACTS) boosts the static and dynamic performance of power systems. Although efficient power transmission by improving power quality and voltage profile enhancement is controlled using the FACTS devices the placement, types, and sizing are important parameters to be optimized for the power system. This paper develops the economic multiple FACT placements and sizing solution during N-1 contingency conditions. Placement and sizing being the stochastic problem meta-heuristic algorithm genetic algorithm (GA) is used and applied on the standard IEEE 9 bus system. MATLAB-based simulation is developed for economic placement of multiple FACTS and single FACTS devices in different scenarios (without FACTS devices, with single FACTS devices, and with multiple FACTS devices). Both static VAR compensators (SVC) and thyristor-controlled series capacitors (TCSC) are used (either single or multiple) to optimize the transmission loss and total cost. The results show that transmission loss and cost reduction with 70% compensation is working better with about 0.1 MW lesser loss in many cases.

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1. INTRODUCTION

Nowadays, power electronics are more appropriate than electromechanical approaches, for dynamic and economic power quality enhancement in the transmission system [1]. In 1999, Hingorani and Gyugyi presented the ideas of flexible AC transmission system (FACTS) for the first time allowing for accurate, rapid, and precise control of the power flow in the power system [2]. Therefore, the utilization of FACTS devices to achieve efficient utilization of existing electrical networks is possible without expanding the power system [3]. The FACTS device technology adopts efficient energy utilization, demand control, voltage stabilization, power quality enhancement, power factor correction, and harmonic reduction [4], [5]. Additional uses include managing congestion, controlling power flow, reducing power loss, regulating voltage, planning reactive power, and improving power quality [6], [7]. The process of locating and configuring FACTS devices in power systems in the most efficient manner is quite difficult, and comprehensive data collection is invariably necessary. Even an applied method that delivers the precise optimal solution to the problem may not be successful in a simulation scenario [8] due to the difficulty of its size in terms of either time or space. Analytic approaches, arithmetic programming methods, conventional optimization techniques, meta-heuristic optimization techniques, and hybrid methods are the different ways that approaches and techniques have been used in the past to determine the optimal locations and settings of FACTS devices in previous literature studies. The flexibility of FACTS controllers to accept control algorithms that are organized to fulfill various objectives is one of the defining characteristics of these controllers [9]. Metaheuristics are the methods that are utilized the most frequently and are also thought to be the methods that are the most effective. Because of their adaptability, metaheuristics are currently being utilized in an effective manner to tackle a variety of difficult engineering optimization issues [10]–[18]. This multi-objective optimization problem, also known as the optimal allocation of FACTS devices, can be solved by taking into account the multi-equality and inequality of static and dynamic constraints in a transmission system. Some examples of these types of constraints include the power balance equation, generator active and reactive power, bus voltage, FACTS devices ratings, transmission line thermal limits, power loss equation, power flow equations, and demand limits [19].

An investigation into important parameters has to be carried out in order to demonstrate the viability of the strategy that has been suggested as a method for determining the best placement of FACTS devices within transmission systems or distribution systems. The voltage profile, bus voltage phase angle, percentage of transmission line power losses, cost of power generation, FACTS device installation and operating cost, FACTS devices (location, type, number, and capacity), overloaded lines, severity index, line utilization, voltage deviation, voltage stability, and harmonics reduction are some of the parameters that have been analyzed [20]–[23]. These assessments need to be carried out in a particular power network under particular contingency conditions. The power network in question should primarily be the IEEE bus system standard network or a real-world case study. The following are examples of contingency conditions: load variation; single or multiple line outages; single or multiple generator faults; ignorance of line limits; three-phase faults; and the intermittent nature of renewable sources [24], [25]. This paper develops the economic placement of multiple FACTS devices in the IEEE 9 bus system with total operation cost as the objective function. Total operation cost or total cost as it is denoted in the rest of the paper is the sum of the generation cost and the FACTS cost. Economic placement and sizing of the FACTS device optimize the objective function to obtain the economic solution. The problem formulation of the solution is given in the following section. In section 2 discusses the problem formulation of the economic FACTS placement and sizing solution. In section 3 has the genetic algorithm (GA) based FACTS placement methodology based on the formulation. The section 4 discusses the results obtained from the implementation on the IEEE 9 bus system.

2. PROBLEM FORMULATION

The problem formulation of economic placement and sizing of multiple FACTS devices involves objective function which is the cost function and constraints. Operation cost is considered as the thermal system cost curve so the cost curve can be represented as [9], generation cost of the ‘ith generator is as given in (1):

$$F_i(P_{gi}) = a_i + b_i P_{gi} + c_i P_{gi}^2 \quad (1)$$

the incremental cost can be represented as given in (2),

$$IC_i(P_{gi}) = b_i + 2c_i P_{gi} \quad (2)$$

the power system optimal power flow is given in (3). Generation cost of all the ‘n’ generators are cumulatively summed up to get the objective function.

$$Minimize: \sum_{i=1}^{n} F_i(P_{gi}) \quad (3)$$

$$subjectedto: \sum_{P_{gi}}^{N_g} P_{gi} = P_d \quad (4)$$

$$P_{imin} < P_{gi} < P_{imax}, i \in [1, N_g] \quad (5)$$

When $\sum_{i=1}^{N_g} P_{imin} > P_d or \sum_{i=1}^{N_g} P_{imax} = P_d$, no feasible solution, when $\sum_{i=1}^{N_g} P_{imin} = P_d$,-every customer has a contract that is a minimum of his ability. When $\sum_{i=1}^{N_g} P_{imin} < P_d$ and $\sum_{i=1}^{N_g} P_{imin} > P_d$-non-trivial case. Here,

$F_i(P_{gi}) - costofgeneration$
$P_{gi} - PowerinMWofi^{th}generator$
$a_i, b_i, c_i - constantco - ordinate$

$P_{imin}, P_{imax} - minimumandmaximumlimitsof i^{th} generator$
$P_d - PowerdemandinMW$
$n, N_g - Numberof generators$

since the problem formulation of the proposed implementation involves the cost of the FACTS devices to be added in the total cost along with the generation cost, the FACTS devices cost must be defined. Facts devices costs for thyristor-controlled series capacitors (TCSC) and static VAR compensators (SVC) are defined in (6) and (7) respectively.

$$C_{TCSC} = 0.0015S_{TCSC}^2 - 0.713S_{TCSC}^2 + 153.75 \quad (6)$$

$$C_{SVC} = 0.0003S_{SVC}^2 - 0.3051S_{SVC} + 127.38 \quad (7)$$

Where, $IC_{devices} - investment\ cost\ of FACTS\ devices\ in\ \$$,$C_{TCSC} - TCSC\ cost\ per\ KVAR\ installed$ in \$,$C_{SVC} - SVC\ cost\ per\ KVAR\ installed\ in\ \$\ S_{TCSC} - TCSC\ capacity\ in\ MVAR$,$S_{SVC} - SVC\ capacity\ in\ MVAR$. Considering the above constraints entire cost function can be represented as [6]. According to the selection of the FACTS devices either single or multiple there are nine cases involved in the solution. Different cases involved are tabulated in the Table 1.

Table 1. Different FACTS device combinations cases

Case number	Objective function	FACTS devices involved
Case I:	Base case without outage, with outage without FACTS	
Case II:	$minimizeTotalCost = \sum_{i=1}^{n} F_i(P_{gi}) + IC_{SVC}$ (8)	SVC
Case III:	$minimizeTotalCost = \sum_{i=1}^{n} F_i(P_{gi}) + IC_{TCSC}$ (9)	TCSC
Case IV:	$minimizeTotalCost = \sum_{i=1}^{n} F_i(P_{gi}) + IC_{SVC+TCSC}$ (10)	SVC+TCSC
Case V:	$minimizeTotalCost = \sum_{i=1}^{n} F_i(P_{gi}) + IC_{2TCSC}$ (11)	2 TCSC
Case VI:	$minimizeTotalCost = \sum_{i=1}^{n} F_i(P_{gi}) + IC_{2SVC}$ (12)	2 SVC
Case VII:	$minimizeTotalCost = \sum_{i=1}^{n} F_i(P_{gi}) + IC_{SVC+2TCSC}$ (13)	SVC+2TCSC
Case VIII:	$minimizeTotalCost = \sum_{i=1}^{n} F_i(P_{gi}) + IC_{2SVC+2TCSC}$ (14)	2SVC+2TCSC

Here, the equality constraints are as given in (15) to (21):

$$IC_{SVC} = C_{svc} \quad (15)$$

$$IC_{TCSC} = C_{TCSC} \quad (16)$$

$$IC_{SVC+TCSC} = C_{SVC} + C_{TCSC} \quad (17)$$

$$IC_{2TCSC} = 2 * C_{TCSC} \quad (18)$$

$$IC_{2SVC} = 2 * C_{svc} \quad (19)$$

$$IC_{SVC+2TCSC} = C_{SVC} + 2 * C_{TCSC} \quad (20)$$

$$IC_{2SVC+2TCSC} = 2 * C_{SVC} + 2 * C_{TCSC} \quad (21)$$

with the objective's functions defined in the Table 1 the optimization algorithm is applied to minimize the total cost as given in (8) to (14). The GA implementation for multiple FACTS placement problem is solved as given in the following section.

3. GENETIC ALGORITHM BASED FACTS PLACEMENT

The problem formulation thus developed in the previous section is considered for the solution using GA. The optimization method uses the objective function that is considered in (8) to (14). The cost of generation and installation cost both are combined to form the objective function for each test case. These objective functions act as the test cases for the optimization problem. Solution for this optimization problem is tabulated and observed for improvement in cost minimization using GA. The load flow algorithm of Newton Raphson method will be simulated as the inner loop with minimization of the total cost using GA as the outer loop of the solution. Population of mega-volt- amperes reactive (MVAR) injection is iterated using GA to find the cost incurred by the power system. MVAR injection for SVC and impedance variation for TCSC is populated for multi facts placement solution. Population vector is updated using the velocity vector for every iteration to reach the convergence of minimized cost. The flowchart that defines the convergence process of the multi-FACTS placement problem is as given in Figure. FACTS sizing and placement are the independent variables of the optimization problem. Fitness function depends on these variables. These variables are populated and updated for each iteration using the GA algorithm with the cost objective function defined in (8) to (14). Each objective function is a test case which is defined in the previous section. Minimization of these cost equations is iterated using GA as given in flowchart given in Figure 1. According to the flowchart the independent variables of the optimization problem is the placement and sizing of the FACTS devices. First the selection of any one of the cases given in Table 1 is chosen. Corresponding objective function with the constraint is chosen. The chosen objective function depends on the capacity of the FACTS device since the cost of the FACTS device depends on its size. Placement of the FACTS device varies the size thus indirectly affecting the cost of FACTS. Thus, both the size and placement of the FACTS devices affect both the total cost and the transmission loss. But since the objective function is the total cost the iteration of the GA algorithm optimizes the total cost.

Initial population of size of the FACTS devices are used to find the total cost for all the population. The best cost which is the minimized cost is used as the comparative cost for the next iteration. Both placement and size of the FACTS devices is updated using the mutation and crossover process in the GA algorithm.

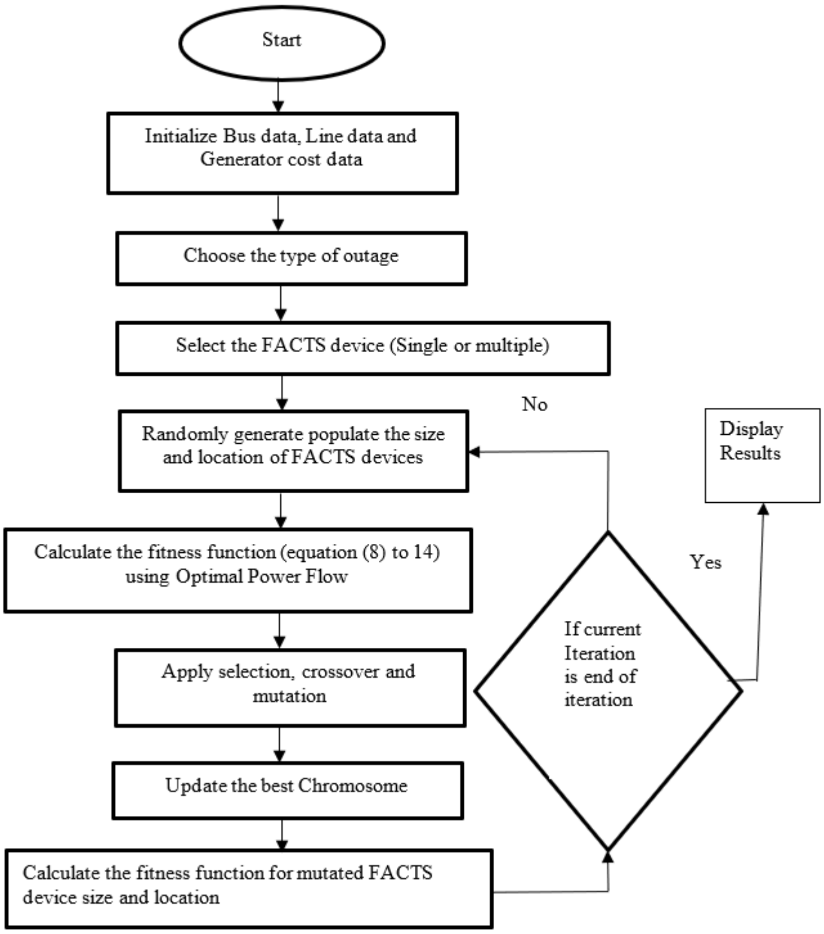

Figure 1. Flowchart of GA implementation for total cost minimization

The independent variables in the GA implementation being size and location of the FACTS devices, these two variables are populated to obtain the optimized placement of single and multiple FACts devices. For every iteration the GA is applied to populate these variables and find the new cost and transmission loss values. The updated population is again used for total calculation and the best cost for the current iteration is found and compared with the previous iteration's best value. This is continued for total number of iteration and the global best values for each type of FACTS devices are tabulated to analyse the placement and sizing solutions.

4. RESULTS AND DISCUSSION

MATLAB based simulation is carried out for all the cases given in Table 1 and the optimized total cost obtained from the GA algorithm is observed in this section. The parameters of GA algorithm are as given in Table 2. The number of particles in Table 2 defines how many numbers of random size and location values of the FACTS are generated in every iteration. Total number of iterations are the number of times the 100 particles are updated to check the transmission loss and cost.

Table 2. GA parameter

Number of particles	Total number of iterations	Iteration of convergence
100	100	101

Three scenarios that is applied for the solution is as given in the following: i) scenario-I-base case with and without FACTS devices and no contingency applied, ii) scenario-II-with line outage, and iii) scenario-III-with generator outage. The cost coefficient used for the cost calculation is as given in Table 3.

Table 3. Cost coefficients of generator and generator limits

Gen. No	a	b	C	Pmin MW	Pmax MW
1	0.11	5.0	150	10	250
2	0.085	1.2	600	10	300
3	0.1225	1.0	335	10	270

The component of total cost includes both generation cost and installation cost of FACTS devices. Generation cost is the varying component while the FACTS installation component is dependent on the compensation level. Since the placement of FACTS (either single or multiple) affects the total amount of compensation the cost of the FACTS installation depends on the placement of FACTS. Although installation cost is a one-time investment the cost varies because of placing and sizing. The results obtained by minimizing the total cost for this placement and sizing problem are observed, with investment cost is converted to dollars per hour [26].

4.1. Case-1

Without any FACTS device placement transmission loss of 3.80744 MW and a generation cost of 5309.486 dollars per hour is observed. Line outage increases transmission loss significantly compared to generator failure is observed and tabulated in Table 4.

4.2. Case-2

- **Scenario-I:** although SVC installation at the placement lines is reducing the transmission losses cost is found to be higher since it includes the FACTS cost. SVC installed at different buses has decreased the total loss compared to the system without FACTS placement. Both line and generator are compensated by the SVC controller.
- **Scenario-II:** for example, total loss during line outage 5 is 5.22134 MW without SVC but it is 5.0572 MW with SVC placement. Total cost in this outage without SVC is 5347.46 $/hr while with SVC it is 5427.0 $/hr. It can be observed that for increase of around 80 $/hr increase in cost there is around 0.2 MW reduction is transmission loss.
- **Scenario-III:** generator outage is very costly compared to the line outage. It can be seen that for line outage the maximum cost is maintained within 5746.0 $/hr. While generator outage is increasing the cost to around 8083.5 $/hr.

4.3. Case-3

- **Scenario-I:** it is observed that placement of TCSC, total generation cost increases to 101.814 $/hr due to FACTS cost in 50% compensation but TSL reduces to 0.23394 MW. In 70% compensation total Generation cost increases to 77.314 $/hr, TSL increases to 0.11126 MW. 50% compensation gives better performance including FACTS cost.
- **Scenario-II:** during line outages a significant transmission loss reduction is evident in the 50% compensation for example for line 2 outage SVC placement is providing 5.0564 MW loss, 50% TCSC compensation shows 5.1628 MW loss and 70% TCSC compensation shows 5.1900 MW loss.
- **Scenario-III:** although the generator outage increases the total cost the transmission loss is the lowest for the 70% compensation TCSC. For example, generator outage in bus 2 transmission loss is 3.9676 MW for 70% TCSC, 4.0241 MW for TCSC 50% compensation.

4.4. CASE-4

- **Scenario-I:** SVC with TCSC with 50% compensation incurs the transmission loss of 3.7797 MW while for 70% compensation it is 3.6255 MW. The 70% compensation TCSC with SVC is showing a better performance which can be noticed in Table 5.
- **Scenario-II:** SVC with TCSC 70% compensation have clearly dominated in both the total cost and the transmission loss as shown in Table 6 except for line 8 and 9.
- **Scenario-III:** when compensation is increased to the maximum of 70 percent, there is a significant drop in generation cost and losses. The generator loss is evidently compensated in the TCSC 70% compensation scenario. For bus 3 generator outage 3.8652 MW loss is seen for 50% compensation but for 70% compensation it is observed to be 3.7759 MW.

4.5. CASE-5

- **Scenario-I:** location of Two TCSC with 70% compensation performs better than the 50% compensation with 3.7035 MW and 3.7861 MW as transmission loss respectively.
- **Scenario-II:** it is observed that except for line outage at 2 and 3 the TCSC with 70% compensation shows a better transmission loss compared to that of 50% compensated TCSC.
- **Scenario-III:** both the generator outage with 3.8557 MW and 3.9083 MW as the transmission loss for TCSCs with 70% compensation has performed better than 50% percentage compensation.

Table 4. Optimal location of FACTS controllers with ratings and total cost/total loss

Case no.	Type of FACTS controller	Type of outage	Line/Bus no.	Total PG in MW	Total loss	Total cost in $/hr
1	Without FACTS	None	-----	318.809	3.80744	5309.486
	controllers	line outage	Line-2	320.319	5.31873	5345.16
			Line-3	322.35 2	7.3528	5408.87
			Line-5	320.197	5.22134	5347.46
			Line-6	322.790	7.78739	5420.54
			Line-8	324.515	9.51188	5474.59
			Line-9	324.271	9.27131	5442.12
		generator outage	Bus-2	319.063	4.06236	7959.66
			Bus-3	319.234	4.23363	6865.59
2	SVC	without outage	---------	318.69	3.6913	5393.3
		with line outage	Line-2	320.06	5.0564	5426.2
			Line-3	322.24	7.2400	5486.1
			Line-5	320.06	5.0572	5427.0
			Line-6	322.45	7.4531	5498.9
			Line-8	323.99	8.9924	5746.0
			Line-9	322.99	7.9956	5501.9
		generator outage	Bus-2	318.97	3.9681	8083.5
			Bus-3	319.03	4.0321	6929.5
3	TCSC			50% COMPENSATION		
		without outage	--------	318.57	3.5735	5411.3
		with line outage	Line-2	320.1628	5.1628	5428.3
			Line-3	321.7126	6.7126	5534.3
			Line-5	320.3808	5.3808	5446.7
			Line-6	323.36	8.3600	5501.8
			Line-8	324.3525	9.3525	5613.6
			Line-9	323.0917	8.0918	5567.3
		generator outage	Bus-2	319.0231	4.0241	8027.7
			Bus-3	319.2282	4.2292	6933.9
				70% COMPENSATION		
		without outage	-----	318.9187	3.9187	5386.8
		With line outage	Line-2	320.1900	5.1900	5427.7
			Line-3	322.1093	7.1093	5503.0
			Line-5	320.2995	5.3002	5424.2
			Line-6	322.7431	7.7430	5496.9
			Line-8	324.1354	9.1354	5605.2
			Line-9	322.9485	7.9485	5563.4
		generator outage	Bus-2	318.9667	3.9676	8034.0
			Bus-3	319.1763	4.1773	6933.8

4.6. CASE-6

- **Scenario-I:** between 2 SVC and 2 TCSC placement the 2 SVC performed better for the transmission loss but cost is higher compared to the 2 TCSC placement.
- **Scenario-II:** transmission loss during the line outage is clearly dominant for 2 SVC case as compared to that of 2 TCSC case.

– **Scenario-III:** 2 SVC placement while generator outage is giving higher transmission loss (4.0323 MW) compared to that of 2 TCSC (3.9083 MW).

4.7. CASE-7

– **Scenario-I:** 2 TCSC and SVC case gives better transmission loss with 70% TCSC compensation (3.6163 MW) compared to 50% compensation (3.6954 MW).
– **Scenario-II:** line outage is cheaper in the 70% compensation setting (Line-2 5732.3 $/hr) and also lesser transmission loss (5.0648 MW) in the same seting.
– **Scenario-III:** it is observed that increase in TCSC compensation setting location of both TCSC is different under gen-2 and gen-3 outage. Location of SVC is same with respect to TCSC compensation setting gives more promising generation cost/hr and loss.

Table 5. Optimal location of FACTS controllers with ratings and total cost/total loss with two facts devices

Case no.	Type of FACTS controller	Type of outage	Line/Bus no.	Total PG in MW	Total loss	Total cost in $/hr
			50% COMPENSATION			
4	SVC and TCSC	without outage	---------	318.7797	3.7797	5481.8
		With line outage	Line-2	318.8888	3.8888	5477.7
			Line-3	318.8723	3.8724	5489.6
			Line-5	319.2721	4.2720	5502.3
			Line-6	318.5299	3.5300	5503.6
			Line-8	318.7105	3.7104	5515.8
			Line-9	319.1453	4.0331	5510.6
		Generator outage	Bus-2	318.795	3.7959	7950.2
			Bus-3	318.8642	3.8652	6852.8
			70% COMPENSATION			
		without outage	--------	318.6255	3.6255	5469.0
		With line outage	Line-2	318.6894	3.6895	5494.4
			Line-3	318.5466	3.5466	5522.0
			Line-5	318.4379	3.4380	5507.4
			Line-6	318.4251	3.4251	5495.4
			Line-8	319.0706	4.0709	5491.7
			Line-9	318.4674	3.4675	5524.0
		Generator outage	Bus-2	318.8211	3.8221	7949.8
			Bus-3	318.7749	3.7759	6850.3
5	Two TCSC		50% COMPENSATION			
		without outage	---------	318.7862	3.7861	5476.5
		With line outage	Line-2	320.2129	5.2130	5510.5
			Line-3	322.3803	7.3803	5571.7
			Line-5	320.1000	5.1000	5512.0
			Line-6	322.9318	7.9318	5588.4
			Line-8	324.3386	9.3387	5625.6
			Line-9	322.8722	7.9722	5577.6
		Generator outage	Bus-2	318.8625	3.8635	8259.4
			Bus-3	318.9599	3.9609	7000.8
			70% COMPENSATION			
		without outage	---------	318.7035	3.7035	5476.4
		With line outage	Line-2	320.2237	5.2236	5511.1
			Line-3	322.4015	7.4015	5571.4
			Line-5	320.0709	5.0709	5511.9
			Line-6	322.8882	7.8882	5587.8
			Line-8	324.3230	9.3231	5623.5
			Line-9	322.7503	7.7503	5574.3
		Generator outage	Bus-2	318.8548	3.8557	8259.2
			Bus-3	318.9073	3.9083	6999.5
6	Two SVC					
		without outage	---------	318.2149	3.6455	5478.0
		With line outage	Line-2	319.841	4.8410	5506.7
			Line-3	322.1231	7.1231	5570.7
			Line-5	319.9065	4.9065	5510.9
			Line-6	322.5176	7.5176	5585.5
			Line-8	325.1392	10.1392	5655.4
			Line-9	322.8516	7.8515	5584.3
		Generator outage	Bus-2	318.9691	3.9180	8210.2
			Bus-3	319.0313	4.0323	6997.9

4.8. CASE-8

- **Scenario-I:** both transmission loss 3.6783 MW and cost 5784.3 $/hr is a competitive compared to 2 TCSC and 2 SVC condition.
- **Scenario-II:** except for the line, 6, 8, and 9 outage the transmission loss for this case is better compared to other 4 FACTS placement scenario.
- **Scenario-III:** with gen outage in bus 3 the transmission loss 3.7904 MW is the minimum.

Table 6. Optimal location of FACTS controllers with ratings and total cost/total loss with multiple facts devices

Case no.	Type of FACTS controller	Type of outage	Line/Bus no.	Total PG in MW	Total loss	Total cost in $/hr
7	Two TCSC and one SVC			50% COMPENSATION		
		without outage	--------	318.6953	3.6954	5631.3
		With line outage	Line-2	320.1289	5.1289	5733.8
			Line-3	322.3134	7.3134	5790.8
			Line-5	319.9298	4.9299	5732.3
			Line-6	322.6054	7.6055	5801.1
			Line-8	323.7493	8.7493	5841.9
			Line-9	322.5532	7.5532	5792.7
		Generator outage	Bus-2	318.813	3.8139	8358.3
			Bus-3	318.8209	3.8218	7143.8
				70% COMPENSATION		
		without outage	---------	318.6163	3.6163	5630.7
		With line outage	Line-2	320.0647	5.0648	5732.3
			Line-3	322.1324	7.1324	5789.5
			Line-5	319.9569	4.9568	5731.3
			Line-6	322.1410	7.1410	5799.8
			Line-8	323.7417	8.7417	5841.7
			Line-9	322.2144	7.2144	5786.5
		Generator outage	Bus-2	318.8363	3.8373	8358.8
			Bus-3	318.7727	3.7738	7142.9
8	Two TCSC and Two SVC			50% COMPENSATION		
		without outage	--------	318.7070	3.7071	5784.9
		With line outage	Line-2	320.0100	5.0100	5816.4
			Line-3	321.9445	6.9445	5869.4
			Line-5	319.8743	4.8743	5815.8
			Line-6	322.7605	7.7604	5886.0
			Line-8	323.7697	8.7696	5929.8
			Line-9	322.3630	7.3630	5929.8
		Generator outage	Bus-2	318.7992	3.8002	8511.6
			Bus-3	318.7930	3.7940	7297.0
				70% COMPENSATION		
		without outage	--------	318.6783	3.6783	5784.3
		With line outage	Line-2	319.9820	4.9820	5815.3
			Line-3	321.9050	6.9050	5872.0
			Line-5	319.8248	4.8248	5815.3
			Line-6	322.2486	7.2486	5888.2
			Line-8	323.5138	8.5138	5929.6
			Line-9	322.3384	7.3384	5874.0
		Generator outage	Bus-2	318.7894	3.7904	8511.1
			Bus-3	318.7851	3.7861	7296.5

Table 6 tabulates the total loss and total cost when two Facts devices are placed and sized in the IEEE 9 bus system. The total cost is found to be optimum when the SVC and TCSC is used with 70% compensation. Total loss is best for the same case. While two SVC is the costliest pair of FACTS devices. In this two FACTS device category SVC ans 70% TCSC is a clear winner. The observation for all the eight cases and three scenarios is tabulated to infer the advantages of the GA based placement and sizing solution. Although the total cost increases due to FACTS installation the benefits observed because of the total loss reduction is observed for the different cases. Line outages and generator outages are applied on the IEEE 9 bus system and the compensation due to both SVC and TCSC is checked. The total cost observed in Table 5 is meant for the single FACTS device placement. Case-1 which is without the FACTS placement, followed by SVC and TCSC placement. TCSC placement has both the 50% and 70% compensation is involved. It can be observed that among the single FACTS placement the cheapest is the TCSC placement with 70% compensation. When it comes to the transmission losses the SVC has the better profile.

In order to analyse the overall placement and sizing solution of FACTS devices in the implementation thus developed, bar graphs of the observed total loss are drawn. From the bar graph in Figure 2 drawn it can be observed that the total loss is higher during both the line-8 and line-9 outage. This is observed for the cases with single FACTS devices placement.

The graph obtained in Figure 3 depicts the total loss obtained at different outages introduced in the buses with two FACTS devices. It can be observed that the outage of line-3, line-6, line-8, and line-9 are depicting very high total system loss compared to other outages. Although the 70% compensation of multiple TCSC is performing a little better than the 50% compensation in most of the cases. In every case the line outage is affecting the transmission loss higher compared to the generator outages.

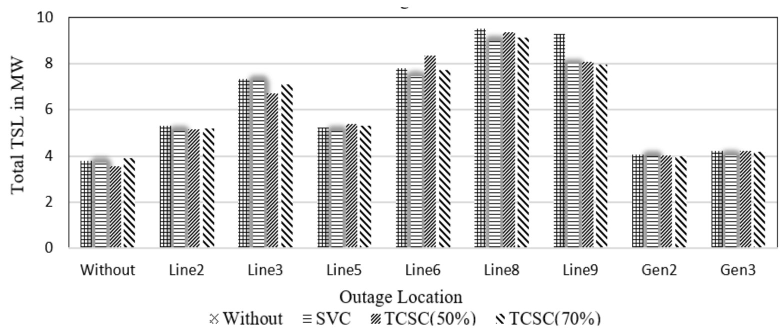

Figure 2. Total TSL with single FACTS device placement

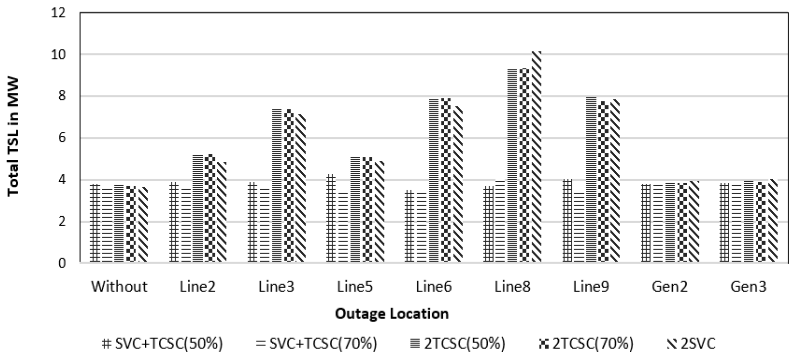

Figure 3. Total TSL with two FACTS device placement

The graph obtained in Figure 4 depicts the total loss obtained at different outages introduced in the buses with multi-FACTS devices. It can be observed that the outage of line-3, line-6, line-8, and line-9 are depicting very high total system loss compared to other outages. Although the 70% compensation of multiple TCSC is performing a little better than the 50% compensation in most of the cases. In every case the line outage is affecting the transmission loss higher compared to the generator outages.

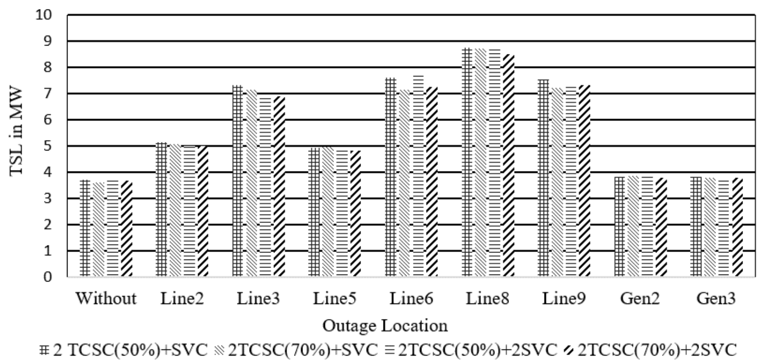

Figure 4. Total TSL with multi FACTS device placement

The cost of FACTS device installation is considered for the system. Bar graphs of the cost details for placement of FACTS device is depicted for single FACTS placement as shown in Figure 5. It can observe that the cost is having its highest values when generator outages occurs. Although the 70% compensation of multiple TCSC is performing a little better than the 50% compensation in most of the cases. In every case the generator outage is affecting the generator cost higher compared to the line outages. Total cost for multiple FACTS devices is as given in Figure 6. It can observe that the cost is having its highest values when generator outages occurs. But generator-2 outage incurs highest total cost among the generator cost.

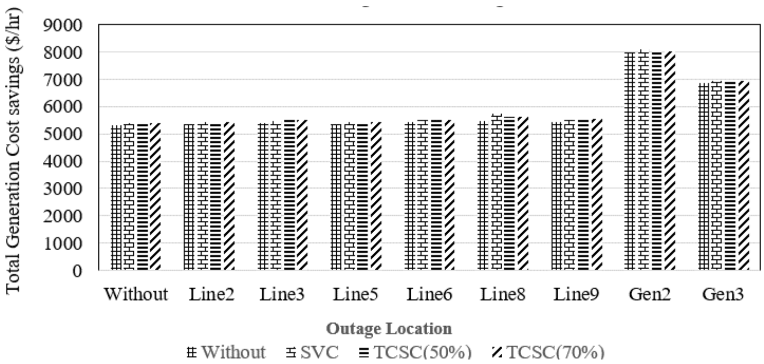

Figure 5. Total generation cost savings with single FACTS device placement

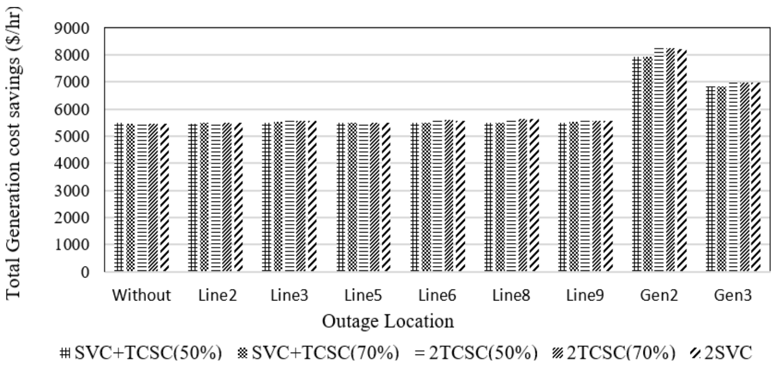

Figure 6. Total generation cost savings with two FACTS placement

Total cost for multiple FACTS devices is as given in Figure 7. It can observe that the cost is having its highest values when generator outages occurs. But generator 2 outage incurs highest total cost among the generator cost although the 70% compensation of multiple TCSC is performing a little better than the 50% compensation in most of the cases. In every case the generator outage is affecting the generator cost higher compared to the line outages.

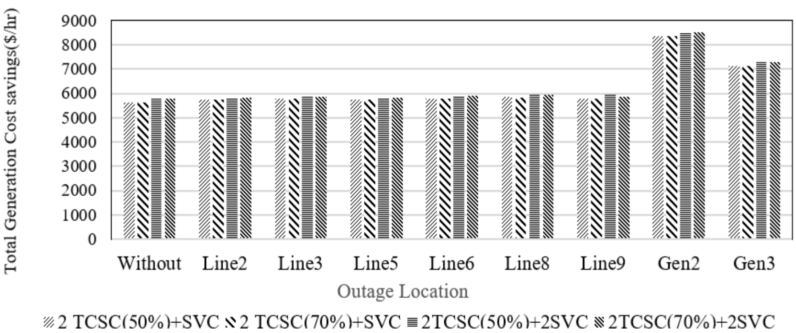

Figure 7. Total generation cost savings with multi-FACTS placement

Although there is an increase in cost for increase in number of FACTS devices the transmission loss values are to be considered for tradeoff. In the three and four FACTS device category also, it can be seen that the 70% compensated TCSC is showing better performance compared to any combination of FACTS devices. Since from the discussion and the observation this obtained for the proposed IEEE 9 bus system the TCSC with 70% compensation must be combined with any other FACTS device or individually used for compensation to obtain a better cost and loss characteristics in the system. Among all the outages the generator outage is providing the highest total cost as given in the above discussion.

5. CONCLUSION

MATLAB based economic placement and sizing of multiple FACTS devices is developed in the proposed implementation. GA based implementation for optimizing the total cost in the IEEE 9 bus system provided satisfactory results for both placement and sizing of both single and Multiple Facts devices. It is observed from to results that the TCSC with 70% compensation performed better when used individually or with the combination of other FACTS devices. The observed results also suggest that there is a trade-off between the cost and the transmission loss in many cases. But in the overall performance observed the TCSC with 70% compensation must be one of the FACTS devices while used in the IEEE 9 bus system to get a moderation between the transmission loss and the total cost.

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