International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 14, No. 3, September 2023, pp. 1876~1884
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v14.i3.pp1876-1884

Optimal location of multiple FACTS devices in N-1 contingency conditions using traditional genetic algorithm

Tanuja Koppa Shankaregowda, Shankaralingappa Channappa Byalihal
Department of Electrical and Electronics Engineering, Dr. Ambedkar Institute of Technology, Bengaluru, India

Article Info

Article history:

Received Sep 2, 2022
Revised Jan 9, 2023
Accepted Feb 6, 2023

Keywords:

FACTS
Genetic algorithm
N-1 contingency
SVC
TCSC

ABSTRACT

Transmission systems are prone to contingency conditions that would either occur using a generator outage or line outage. Placing and sizing the flexible ac transmission systems (FACTS) devices appropriately can reduce the effects of the contingency condition. This paper optimally locates FACTS devices in a transmission system under the N-1 contingency condition. The genetic algorithm (GA) technique is used to locate different, multiple FACTS devices (thyristor-controlled series capacitor and static VAR compensator) optimally in a power system. This optimization technique is used to locate FACTS devices on the IEEE 9 bus system. MATLAB simulation is developed and checked for both single and multiple FACTS placements. Simulation results obtained for generator outage and line outage are tabulated with the type of FACTS device/rating, location, and generation cost with line loss reduction. The optimized results observed for the cost-optimized FACTS placement problem are found to be satisfactory. The results obtained in the IEEE 9 bus system have shown improvement in a decrease of generation cost and system loss component while placement and sizing of both the FACTS devices.

Corresponding Author:

Tanuja Koppa Shankaregowda
Department of Electrical and Electronics Engineering, Dr. Ambedkar Institute of Technology
Outer Ring Rd, near Gnana Bharathi, Bengaluru, Karnataka 560056, India
Email: tanujaksresearch2022@gmail.com

1. INTRODUCTION

The availability of a stable and high-quality power supply is critical for fast-developing countries like India. The mathematical analysis of power system optimization with security is more sophisticated and challenging. Power system security also involves power system reliability, which helps to prevent blackouts. When a generator fails, it must maintain a lower frequency and voltage departure from the actual grid code. The spinning reserve is used to keep the power system loaded and prevent blackouts. Contingency analysis, as a critical security component of the power system, necessitates timely and efficient countermeasures. These contingency conditions can be compensated by flexible ac transmission systems (FACTS) devices. Static synchronous compensator (STATCOM), thyristor controlled synchronous compensator (TCSC), static var compensator (SVC), and unified power flow controller (UPFC) are examples of FACTS devices that are incorporated into transmission systems by optimizing compensation using evolutionary computational algorithms [1]. the allocation of facts devices using a genetic algorithm (GA) is presented in this study with the goal of increasing the capacity of a networked power system's power transfer. The loading variation between the base load and 200% load is applied on the IEEE 30 BUS system to check the performance of FACTS devices when placed optimally using the GA-based approach [2]. Optimal placement of thyristor-controlled series compensator (TCSC), static var compensator (SVC), and static synchronous compensator (STATCOM) using particle swarm optimization (PSO) and genetic algorithm (GA), are explored and compared in this study. The objective function of, generation cost, active power loss, and voltage stability. are compared among aforementioned FACTS devices [3]. On the IEEE 14 bus system, a new technique employing improved teaching learning-based optimization (ITLBO) and weight improvement of particle swarm optimization WIPSO has been proposed and implemented for Optimal power flow during the N-1 contingency condition [4]. Biogeography based optimization (BBO) [5] is used to alleviate power system problems, including overloading and voltage limit violations, by placing the UPFC and interline power flow controller (IPFC). The "artificial algae algorithm" (AAA) [6] optimizes the placement of UPFC in the implementation. A comparison between real coded GA and PSO, [7] which optimizes the hourly generator cost to match load demand and system losses carried out in the literature. Optimal power flow (OPF) using PSO and GA algorithm is compared in the literature [8]. While the network configurations are set to minimize active power losses under pre-contingency conditions, the optimization's goal is to minimize the average load ability on all energy transmission lines [9]. The goal is to reduce all transmission lines' average load ability. The optimal placement of FACTS devices to alleviate line overload during a contingency is determined by monitoring the real power flow performance index (PI) and the contingency severity index (CSI) [10]. TCSC and UPFC are modeled for and GA determines the type, best parameters, and installation cost for the devices. Optimal generator reallocation for managing power system contingencies using the Krill Herd algorithm sizes the system for optimal power flow while placing TCSC using rapid contingency ranking [11]. Placement of TCSC under N-1 contingency condition is developed in the literature considering the power flow limits as constraints [12] using reformulation technique that linearizes the nonlinear power flow problem with limits [12]. SVC placement [13] using power loss minimization and voltage stability as the constraint is developed using GA algorithm. Multiple FACTS devices are placed with the overloading minimization as the constraint using PSO algorithm in the study [14]. The optimized placement for the TCSC is determined by calculating performance indices to minimize the overloading of each transmission line in both standard and contingency situations [15]. Optimizing FACTS devices, ratings, and installation costs for single and multiple contingencies for TCSC, SVC, and UPFC are modeled for steady-state analysis to improve system security criteria. Calculating performance indices prevents the overloading of transmission lines in regular and emergency scenarios is carried out [16], Under N-1 contingency, PSO is used to find the ideal TCSC placement and sizing [17]. In a power system, contingency analysis identifies and ranks the of worst line faults. In the study wind generation system, with optimal allocation of FACTS maximizes profit by minimizing device investment and running expenses [18]. The differential harmony search algorithm is evolutionary-based is developed for OPF problem [19] and different differential algorithms are used [20]–[23]. To improve the system's static load ability, a GA-based optimization technique finds the ideal FACTS placements and ratings. Mixed FACTS devices are used by combining any of the FACTS devices including SVC, TCSC, TCVR, TCPST, and UPFC. Placement of these mixed FACTS devices are applied in numerous sites and analyzed for better performance characteristics in IEEE test systems up to 300 buses [24]. An optimization-based mitigation strategy is given to strategically deploy alternative FACTS devices based on PQ performance and sensitivity analysis. The greedy algorithm and GA determine the best mitigation strategy to provide different PQ levels. A large-scale generic distribution network [25] demonstrates the mitigating mechanism's viability.

The previous implementation although having done regressive research on the placement of FACTS devices, the placement and sizing of FACTS devices with N-1 contingency for multiple FACTS needs to be compared and analyzed. The condition of contingency is added in the constraints of the FACTS placement paradigm and results are tabulated for multiple FACTS and single FACTS devices in this paper. Incorporating both generator outage and line outage N-1 contingency scenarios, this paper implements the location and sizing of a FACTS device or several FACTS devices in the power system. SVC, TCSC, and a mixture of these two FACTS devices for multiple FACTS device implementations were employed in the implementation. For the GA-based optimum FACTS placement implementation, operating cost convergence criteria are taken into account. The modeling of the FACTS devices employed in this study, as well as the formulation of the problem that determines the constraints and objective function for optimization, are covered in section 2. The recommended methodology of the task is discussed in section 3. The installation of different FACTS devices and numerous FACTS devices in the IEEE 9 bus system is discussed in length in section 4, followed by a conclusion and references.

2. SVC AND TCSC PLACEMENT FORMULATION IN N-1 CONTINGENCY CONDITION

A power injection model can be created for FACTS devices to use in the context of a linked and congested power network. The FACTS are utilized as a device within the injection model, which then injects a predetermined quantity of actual and reactive power into a node. By altering the reactance of the system, the TCSC and SVC devices can control the flow of power and the voltages respectively. The SVC is capable of operating in either a capacitive or an inductive mode, depending on the situation. Either adding reactive power to the bus where it is connected or drawing reactive power from the bus where it is attached is the function of the SVC when it is connected. It raises the voltage in both static and dynamic conditions and lowers the amount of active power that is lost. Figure 1(a) presents the variable susceptance model of the SVC for your reference. The variable impedance model of TCSC is shown in Figure 1(b). The effective reactance of the SVC The parallel combination of X_C and X_L is what establishes the value of X_{SVC}.

(a) (b)

Figure 1. FACTS model (a) SVC model and (b) TCSC model

The SVC is operated in both inductive and capacitive modes and controls bus voltage by absorbing or injecting reactive power. A shunt variable susceptance is added at both ends of the line to model the SVC. The injected reactive power at bus i is (1) and (2).

$$\Delta Q_{is} = Q_{svc} \quad (1)$$

$\mathrm{Q_{svc}}$ − reactive poweinjected

$$\mathrm{Q_{svc} - Q_{Min} \sim Qmax} \quad (2)$$

The TCSC which acts as the variable impedance in series with the line has the topology given in Figure 1(b). After placing the TCSC the line impedance between bus i and bus j are given as (3) and (4).

$$Z_{ij} = Z_L + jX_{TCSC} \quad (3)$$

$$X_{TCSC} = r_{TCSC} X_L \quad (4)$$

Were $Z_L - transmission\ line\ impedance,\quad X_{TCSC} - reatance\ of\ the\ line\ where\ TCSC\ is\ locate$ of $r_{TCSC} - compensation\ degree\ of\ TCSC\ (Coefficient).$

The constraint limit of the TCSC into $X_{TCSC} = -0.2\ X_L\ to\ 0.7\ X_L$ (5)

$$Q_{svc} = -100\ MVAR\ to\ 100\ MVAR \quad (6)$$

2.1. Operation cost and optimization problem formulation

The problem is formulated with a combination of FACTS devices and their placement with sizing that provides optimal cost benefits. The objective function for cost optimization is operation cost, with relevant constraints. The minimization cost equation is given by (7):

$$Minimize\ F_{cost}(P_g) = a * \sum_{i=1}^{N_g} x{P_{g_i}}^2 + yP_{g_i} + z \quad (7)$$

where P_{g_i} is power generated at i^{th} generator, $F_{cost}(P_g)$ is the total fuel cost, x, y, z aisthe cost coefficient. In (7) is sum of fuel costs of N_g number of generators.

- Coefficients of the fuel cost equation

Inequality constraints used for the problem are voltage regulation constraint as given in (8), impedance constraints for TCSC as given in (9) and MVAR injection constraint used in (10).

$$\mathrm{V_{i\,min} < V_i < V_{i\,max}} \quad (8)$$

$\mathrm{V_{i\,min}}$ – Minimum voltage

$\mathrm{V_{i\,max}}$ – Maximum voltage

V_i – Actual voltage measured at 'i^{th}' bus. The rating of TCSC is limited to 70% of the line impedance in capacitive and 20% inductive mode. The impedance range is represented in (9).

$$X_{TCSC} = -.2\, X_L \leq X_L \leq\ .7\, X_L \tag{9}$$

MVAR injection of SVC at bus limited to 100 MVAR in both directions which means that it can inject or absorb maximum of 100 MVAR from and to the line.

$$Q_{svc} =\ -28.5\, MVAR \leq Q_{svc} \leq\ 100\, MVAR \tag{10}$$

Equality constraints used are given in (11), (12) and (13).

$$P_{Load} + P_{Loss} - \sum_{i=1}^{N_g} P_{gi} = 0 \tag{11}$$

P_{Load} – Total demand in entire power system (summation of total demand)
P_{Loss} – Total line loss in entire power system. The constraint of SVC placement is given in (6).

$$\Delta Q_{is} = Q_{svc} \tag{12}$$

$$Q_{svc} - reative\ power\ injected\ by\ SVC\ in\ MVA$$

$$Q_{svc} - Q_{Min} \sim Qmax \tag{13}$$

3. FACTS SIZING AND PLACEMENT

The sizing and placement of FACTS devices must be optimized to reduce the power system's operating costs. The GA optimization technique is used for the placement and sizing of FACTS devices in the IEEE 9 bus system using the N-1 contingency condition. The generator and line outage are considered as N-1 contingency on GA technique for single and multiple FACTS placements. The IEEE 9 bus system data used are generation cost information, such as starting cost, shutdown, and maintenance costs including generation constraints. The flow chart of FACTS sizing and placement optimization is given Figure 2 (see Appendix). The SVC and TCSC location and sizing act as the search space for the GGA-based FACTS placement problem. The objective function for the problem is the power system operation cost defined in (7). The iterative process of selection, crossover, and mutation is applied to the search space. Newly calculated genes (location and type) are used to find the cost then this process continues till the end of the final iteration count. This process is represented in Figure 2.

4. RESULTS AND DISCUSSION

MATLAB-based simulation is carried out with different cases listed below. To analyze the best FACTS device placement between SVC, TCSC, and, a combination of both the FACTS devices analyzed. Thus, multiple cases are considered for the placement and sizing problem discussed in the previous section: i) Case 1 – without any FACTS devices, ii) Case 2 – with SVC, iii) Case 3 – with TCSC, iv) Case 4 – with TCSC and SVC, v) Case 5 – with two TCSC, vi) Case 6 – with two SVC, vii) Case 7 – with two TCSCs and one SVC, viii) Case 8 – with two TCSCs and two SVC, and each case discusses three scenarios: i) Scenario-I – base case with and without FACTS devices and no contingency applied; ii) Scenario II- with line outage Scenario-III- with generator outage; iii) The results obtained for placement of 50% and 70% compensation of SVC/TCSC and SVC-TCSC (either single or multiple) are provided in Table 1, Table 2, Table 3, and Table 4 for the scenarios mentioned.

Table 1. Transmission loss in MW for all the cases with 50% compensation

Outage	SVC	TCSC	SVC TCSC	2TCSC	2SVC	2TCSC 1SVC	2TCSC 2SVC
Without	3.664	3.7496	3.6783	3.7134	3.5827	3.6424	3.53
Line-2	4.941	5.2154	5.0049	5.2001	4.8068	5.0108	4.8912
Line-3	7.043	7.3142	7.1132	7.2698	6.9769	7.1476	6.9658
Line-5	4.876	5.1186	5.0652	5.1563	4.7321	4.987	4.9531
Line-6	7.291	7.7006	7.2182	7.7527	7.2113	7.3071	7.3581
Line-8	8.879	9.4962	9.0613	9.329	9.0004	8.8134	8.5295
Line-9	7.949	7.9	7.4989	7.9739	7.9028	7.5071	7.4843
Gen2	3.962	3.8708	3.8209	3.8697	3.9185	3.8126	3.8088
Gen3	4.01	3.9763	3.842	3.8968	4.0132	3.7595	3.8301

Table 2. Transmission loss in MW for all the cases with 70% compensation

Outage	SVC	TCSC	SVC TCSC	2TCSC	2SVC	2TCSC 1SVC	2TCSC 2SVC
without	3.6641	3.7293	3.5794	3.6986	3.5827	3.598	3.4972
Line-2	4.9413	5.1633	4.9216	5.1747	4.8068	4.9451	4.8796
Line-3	7.0429	7.2593	6.82	7.2288	6.9769	7.0808	6.7626
Line-5	4.8759	5.0963	4.9351	5.1234	4.7321	4.8657	4.8224
Line-6	7.2905	7.6897	7.1712	7.6252	7.2113	7.0929	7.0841
Line-8	8.8789	9.0642	8.7461	8.8909	9.0004	8.7182	8.1456
Line-9	7.9491	7.9169	7.2635	7.666	7.9028	7.2174	7.3048
Gen2	3.9618	3.8634	3.7994	3.8419	3.9185	3.8099	3.7977
Gen3	4.0104	3.9331	3.7945	3.8787	4.0132	3.7148	3.7562

Table 3. Total operating cost ($/hr) for all the cases with 50% compensation

Outage	SVC	TCSC	SVC TCSC	2TCSC	2SVC	2TCSC 1SVC	2TCSC 2SVC
without	5305.5	5307.2	5305.3	5307.1	5304.6	5305	5304.4
Line-2	5338.2	5342.4	5338.6	5342.4	5336.2	5339.2	5337.2
Line-3	5398	5402.9	5397.3	5402.7	5396.6	5396.4	5393.1
Line-5	5339.8	5345.2	5341.9	5344.8	5337	5339.9	5338.3
Line-6	5409.6	5416	5406.4	5415.4	5407.5	5404.2	5401.7
Line-8	5270.3	5461.3	5456.5	5454.8	5465.5	5449.1	5449.1
Line-9	5413.9	5417	5399.9	5410.6	5412.1	5400.8	5399.2
Gen2	7955.4	7951.9	7949.7	7951.9	7953.7	7949.8	7949.2
Gen3	6858.1	6857.6	6852.4	6854.4	6858.1	6849.6	6851.7

Table 4. Total operating cost ($/hr) for all the cases with 70% compensation

Outage	SVC	TCSC	SVC TCSC	2TCSC	2SVC	2TCSC 1SVC	2TCSC 2SVC
without	5305.5	5306.8	5304.6	5306.7	5304.6	5304.4	5304.2
Line-2	5338.2	5341.9	5336	5342	5336.2	5337.9	5334.7
Line-3	5398	5402.4	5394.7	5402.6	5396.6	5394.9	5391.9
Line-5	5339.8	5345	5339.2	5344.6	5337	5339.8	5337
Line-6	5409.6	5415.5	5404.8	5415.1	5407.5	5403.5	5400.9
Line-8	5270.3	5452.6	5447.7	5451.9	5465.5	5447.8	5445
Line-9	5413.9	5410.1	5397.6	5407	5412.1	5396.5	5395.7
Gen2	7955.4	7951.4	7949.5	7951.2	7953.7	7949.5	7948.7
Gen3	6858.1	6855.8	6851.3	6854	6858.1	6849.1	6849

Table 1 and Table 2 indicate solutions for 50% and 70% compensation. Table 3 and Table 4 indicate power system operation costs for 50% and 70% compensation. The minimum power loss is shown in Table 1 and Table 2. It can be observed that the minimum loss occurs with minimum cost for the location of 2TCSC and 2SVC cases. Similarly, for 50% compensation, the minimum cost is in 2TCSC and 2SVC cases. But with 70% compensation 2TCSC and 2SVC case incurs a minimum cost for all the contingencies. Coding is developed using MATLAB on IEEE 9 bus system with GA technique as per the flowchart given in Figure 2. The network consists of three different types of generators and nine branches (3 transformers and 6 transmission lines). The total cost of generation can be determined by performing optimal power flow (OPF) without any FACTS devices. The simulation is carried out in the absence and presence of a contingency situation (line failure, generator outage). The overall cost of generation for the base case study (Case-1) is determined. The total generation cost, the total system loss, and the real power generation of the generators for each case are computed for individual and combined FACTS controllers (SVC and TCSC). The individual and combined FACTS controller's location is found to be satisfactory for all the cases.

Generation cost and system loss waveforms for different scenarios are depicted in Figure 3, Figure 4, Figure 5, and Figure 6. Generator costs for 50% compensation configuration for all three scenarios and eight cases are given in Figure 3. Line outages at lines 2, 3, 5, 6, 8, 9 and generator outages at generators 2 and 3 are analyzed and depicted. Similarly, in Figure 5, outputs for the same conditions with 70% compensation are depicted. Power system loss for 50% compensation configuration for all three scenarios and eight cases are given in Figure 4. Line outages at Lines 2, 3, 5, 6, 8, 9 and generator outages at generators 2 and 3 are analyzed and depicted. Similarly, in Figure 6, outputs for the same conditions with 70% compensation are depicted. Analysis from the observation made from the tables and the figures are as discussed below.

- Case-1: In this case, the TSL is found to be 3.80744 MW, and the associated generation cost is found to be 5309.486 dollars per hour. It has been found that the TSL will be significantly high whenever there is a Line failure or a generator outage and that the cost of generation would also rise accordingly.
- Case-2: Scenario I: SVC installed at bus 5 with 74.6237 MVAR results in improved cost savings for generation at 3.986 dollars per hour (34917.36 dollars per year). The reduction in system loss is found to be 0.14334 MW.

- Scenario II: The associated decrease in system loss is also shown in Figure 3. The reduction in generation cost per year and the equivalent reduction in system loss is calculated manually.
- Scenario III: It is noticed that the cost of generation and system loss decrease. It is demonstrated in Figure 3 that for each generator outage, there is a reduction in the cost of generation per hour and a proportional reduction in system loss (Figure 4).
- Case-3: Scenario I – It is observed that the placement of TCSC in Lines 9-4 does not change regardless of the sizing for the TCSC. An increase in the TCSC compensation will result in a decrease in the TSL and the generation cost. It is observed that transmission Line 9-4 is the location of TCSC with 51.56 MVAR compensation, which results in optimal cost reduction of 2.686 dollars per hour (980.39 dollars per year), and reduction of system loss is found to be 0.07814 MW.
- Scenario II: It is observed that the location of the TCSC shifts between Lines 2 and 4-5 depending on the compensation settings used. It is observed that TCSC with 8-9 and 9-4 offered a promising reduction in generation cost per hour as well as a reduction in TSL.
- Scenario III: The location of the TCSC remains the same regardless of the compensation setting. The use of TCSC in Lines 9-4 results in higher generation cost savings as well as a decrease in TSL.
- Case-4: Scenario-I The placement of the TCSC will fluctuate depending on the compensation settings used in the transmission Line (9-4 for minimum compensation and 5-6 for maximum compensation), but there will be no shifts in the SVC's position. It is determined that placing the TCSC in Lines 5-6 will result in better generation cost reduction (4.886 dollars per hour/1783.39 dollars per year). There is a corresponding decrease in TSL that is found to be 0.22804 MW.
- Scenario II: It is observed that the placement of the TCSC moves about in Line 5 depending on the type of line outage, however, the location of the SVC remains the same regardless of the compensation setting. In compensation settings of 70 percent (maximum), there is a more promising reduction in generation cost per hour as well as a reduction in system loss.
- Scenario-III: The position of the TCSC is not the same in the event of a generator-3 power failure because of the varied compensation settings for the TCSC. However, the location of the SVC remains unchanged. When compensation is increased to the maximum of 70 percent, there is a significant drop in generation cost and a reduction in losses.
- Case-5: Scenario-I Location of the first TCSC varies with different compensation settings. TCSC with transmission Lines 9-4 and 8-9 are found to be better generation cost savings with 2.786 $/hr (1016.89$ per year) and TSL reduction is found to be 0.10884 MW.
- Scenario-II: It is observed that for different compensation settings, the location of TCSC changes in Line-2, Line-5 and Line-6 outages. But in Line-3, Line-8, and Line-9 outage both TCSCs are located in the same line giving a better reduction in cost savings and reduction in system losses.
- Scenario-III: It is observed that in the bus-2 outage location of both TCSCs is the same when the compensation is minimum, and when compensation is the maximum location of the TCSC is different. In Gen-3 outage location of two TCSCs is different, but it is the same when the compensation setting is increased. For maximum compensation, the setting gives better generation cost/hr and a loss red.
- Case-6: Scenario-I SVC located at bus 5 and bus 3 with 68.7149 MVAR, and 64.6314 MVAR respectively gives better generation cost savings with 4.886 $/h (42,801.36 $/yr). Also, the corresponding system loss reduction is found to be 0.22474 MW.
- Scenario-II: Savings of generation costs for two different SVCs at different buses are found to be more promising in generation cost savings and reduce the system loss.
- Scenario-III: It is observed that placing both SVC in different buses in generator-2 outage but in generator-3 outage placement of SVC in the same bus gives better generation cost savings and system losses are also reduced.
- Case-7: Scenario-I Location of SVC at bus 5 and both TCSC at Line 9 (9-4) for different compensation settings. An increase in the TCSC compensation setting will reduce the generation cost and TSL. The compensation setting of the first TCSC is 43.62%, the conduction TCSC is 14.58%, and the ratings of SVC is 54.6316 MVAr gives an optimal generation cost of 5.086 $/hr (1856.39 $/hr) its loss reduction is 0.20944 MW.
- Scenario-II: It is observed that in Line 2, Line 5 and Line 6 outage location of both TCSCs is not the same, in Line 3, Line 8 & Line 9 location of the TCSC is the same when the compensation setting is different & location of the SVC is the same. By increase in compensation gives a more promising reduction in generation cost/hr and a corresponding reduction in loss.
- Scenario-III: It is observed that the increase in TCSC compensation setting the location of both TCSC is different under gen-2 & gen-3 outage. The location of SVC is the same concerning the TCSC compensation setting GIA ves morge promising reduction in generation cost/hr and reduction in loss.
- Case-8: Scenario-I The savings of generation cost for different compensation settings are almost the same. This indicates that minimum compensation is found to be more promising i.e., TCSC with 50%

compensation setting in Lines 8-9 & 9-4, SVC is located at bus-5 & bus-3. Corresponding ratings of SVC are found to be 69.8777 MVAr and 51.2089MVAr respectively.

- Scenario-II: It is observed that the location of both SVCs is the same at the bus-5 outage and the location of both TCSCs is the same in Line 8 outage for different compensation settings. Under each line outage, the maximum compensation setting gives more promising savings in generation cost/hr and a corresponding reduction in loss.
- Scenario-III: Location both SVCs is the same in bus-5 for the generator-3 outage and the location of TCSC is not the same in both generator outage for different compensation setting. The savings of generation cost & reduction in the loss for different TCSC and SVC settings are almost the same.

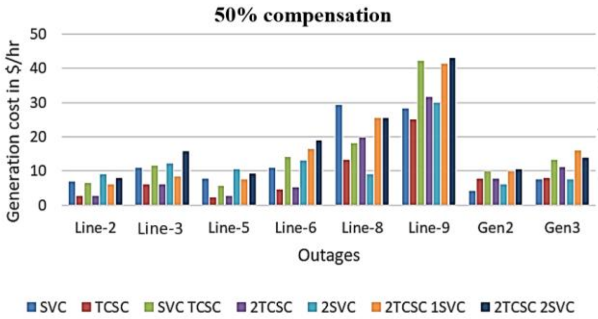

Figure 3. Generation cost for 50% compensation with different FACTS devices

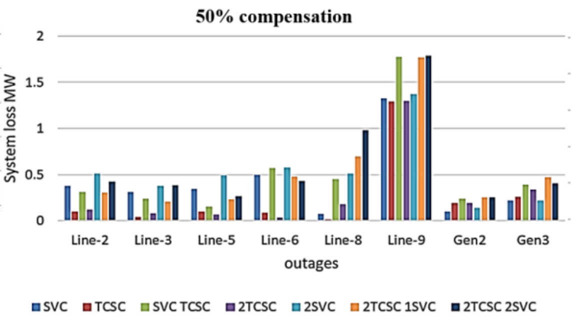

Figure 4. System loss in MW with 50% compensation of different FACTS devices

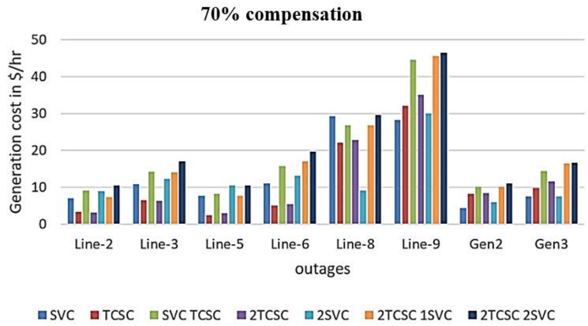

Figure 5. Generation cost with 70% compensation for different FACTS devices

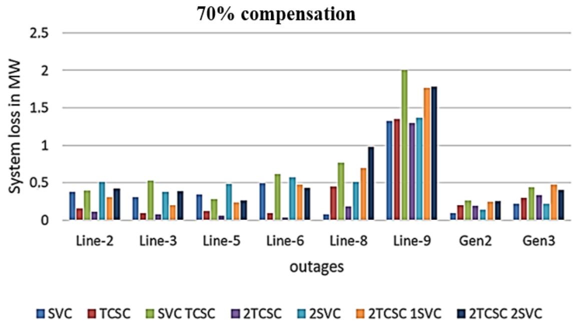

Figure 6. System loss in MW with 70% compensation for different FACTS devices

The line outage performance and the generator outage performance are better while the FACTS Controllers either SVC or TCSC placement are used. It can be inferred that the SVC has performed better for the line outage conditions and at the same time TCSC has performed during the generator outage conditions. But the combination of both TCSC and SVC is used and the performance under both line and generator outage conditions is found to be better compared to individual FACTS controllers incorporated. The single TCSC and SVC have better performance compared to two SVC, two TCSC, two SVC with one SVC, and two SVC with two TCSC. It can be observed that the contingency while both the line outage and the generator outage occur in the IEEE 9 bus system the total cost is observed to be reduced for SVC installation than the TCSC installation for the best possible set of each of the FACTS devices. Total power generated (PG), total loss, and the total cost/hr is also tabulated for different configuration of SVC, TCSC, and combined SVC and TCSC.

5. CONCLUSION

The optimal location of SVC and TCSC devices has been simulated for IEEE 9 bus system under contingency for both line outage and generator outage conditions for different scenarios and different case studies. The location of different FACTS devices with rating reduction in generation cost and reduction in system loss is shown. It is concluded that appropriate locations with ratings give better generation cost reduction and system power loss. All these analyses are carried out without the inclusion of capital costs that are incurred for the installation of the FACTS devices. Placement and sizing including the FACTS installation cost can be implemented as future work.

APPENDIX

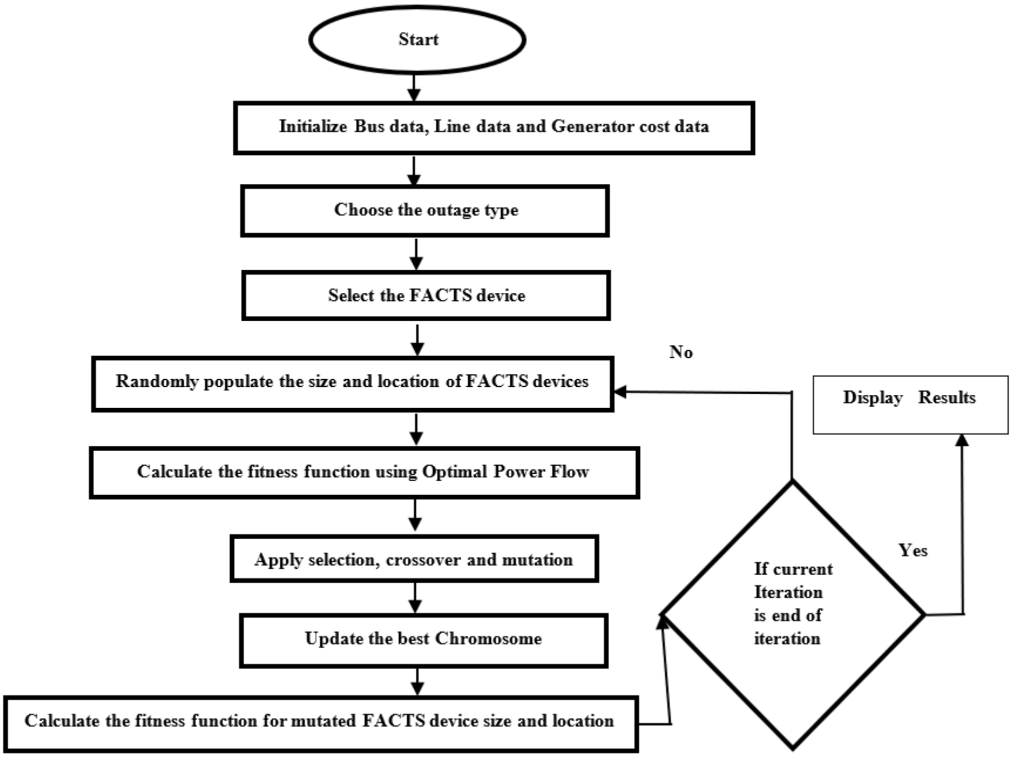

Figure 2. Overall implementation details of the optimization algorithm

REFERENCES

[1] M. Singh and S. Gupta, "Optimal placement of facts devices in power system for power quality improvement," *International Journal of Recent Technology and Engineering*, vol. 7, no. 6, pp. 605–610, 2019.

[2] M. K. Saifullah, M. M. Kabir, N. Mia, and T. Ahmed, "Optimal Placement of FACTS Devices in the Power System Using ANN to Increase the System Loadability," *Lecture Notes in Electrical Engineering*, vol. 686, pp. 89–98, 2020, doi: 10.1007/978-981-15-7031-5_9.

[3] D. Gaur and L. Mathew, "Optimal placement of FACTS devices using optimization techniques: A review," *IOP Conference Series: Materials Science and Engineering*, vol. 331, no. 1, 2018, doi: 10.1088/1757-899X/331/1/012023.

[4] H. A. Devi and S. Padma, "Optimal Location and Parameter Setting of FACTS Devices based on WIPSO and ITLBO for Power System Security Enhancement under Single Contingency," *International Journal of Engineering and Advanced Technology (IJEAT)*, vol. 6, no. 6, pp. 177–185, 2017.

[5] H. A. D. and S. Padma, "Power System Security Enhancement Using Optimal Placement and Parameter Setting of Multi-FACTS devices with BBO Algorithm," *International journal of pure and applied mathematics*, vol. 118, no. 5, pp. 785–804, 2018.

[6] R. B. Magadum, B. K. Patil, S. N. Dodamani, and V. J. Shetty, "Contigency based UPFC Placement for Steady State Analysis," *Proceedings of the 2019 2nd International Conference on Power and Embedded Drive Control, ICPEDC 2019*, pp. 450–453, 2019, doi: 10.1109/ICPEDC47771.2019.9036547.

[7] J. M. Home-Ortiz, W. C. De Oliveira, and J. R. S. Mantovani, "Optimal Power Flow Problem Solution through a Matheuristic Approach," *IEEE Access*, vol. 9, pp. 84576–84587, 2021, doi: 10.1109/ACCESS.2021.3087626.

[8] D. Ignatiev and V. Popovtsev, "N-1 Based Multi-Objective Optimization of Static Var Compensator Placement Using Heuristic Methods," in *2021 Ural-Siberian Smart Energy Conference (USSEC)*, Nov. 2021, pp. 143–146. doi: 10.1109/USSEC53120.2021.9655759.

[9] K. V. Kumar Kavuturu, K. N. V. Sai Tejaswi, and V. Janamala, "Performance and security enhancement using generalized optimal unified power flow controller under contingency conditions and renewable energy penetrations," *Journal of Electrical Systems and Information Technology*, vol. 9, no. 1, 2022, doi: 10.1186/s43067-022-00057-y.

[10] A. AL Ahmad and R. Sirjani, "Optimal placement and sizing of multi-type FACTS devices in power systems using metaheuristic optimisation techniques: An updated review," *Ain Shams Engineering Journal*, vol. 11, no. 3, pp. 611–628, 2020, doi: 10.1016/j.asej.2019.10.013.

[11] B. Sravana Kumar, M. Suryakalavathi, and G. V. Nagesh Kumar, "Thyristor controlled series compensator based optimal reallocation of generators for contingency management," *ECTI Transactions on Electrical Engineering, Electronics, and Communications*, vol. 16, no. 1, pp. 30–38, 2018, doi: 10.37936/ecti-eec.2018161.171327.

[12] X. Zhang, K. Tomsovic, and A. Dimitrovski, "Optimal allocation of series FACTS devices in large-scale systems," *IET Generation, Transmission and Distribution*, vol. 12, no. 8, pp. 1889–1896, 2018, doi: 10.1049/iet-gtd.2017.1223.

[13] C. H. Brillianto Apribowo, O. Listiyanto, and M. H. Ibrahim, “Placement Static Var Compensator (SVC) for Improving Voltage Stability Based on Sensitivity Analysis : A Case Study of 500 KV Java-Bali Electrical Power System,” *ICEVT 2019 - Proceeding: 6th International Conference on Electric Vehicular Technology 2019*, pp. 276–280, 2019, doi: 10.1109/ICEVT48285.2019.8993997.

[14] M. S. IQBAL and S. B.C., “Multiple Contingency Analysis for Optimal Placement and Estimate the Value of Svc for Power Loss Reduction Employing Genetic Algorithm,” *International Journal of Electrical Engineering and Technology*, vol. 10, no. 4, 2019, doi: 10.34218/ijeet.10.4.2019.007.

[15] M. Ahmadi Kamarposhti, H. Shokouhandeh, Y. Gholami Omali, I. Colak, P. Thounthong, and W. Holderbaum, “Optimal Coordination of TCSC and PSS2B Controllers in Electric Power Systems Using MOPSO Multiobjective Algorithm,” *International Transactions on Electrical Energy Systems*, vol. 2022, 2022, doi: 10.1155/2022/5233620.

[16] A. V. Sunil Kumar, Prakash, S. R. S. Aradhya, and G. Swetha, “Comprehensive Survey on Recent Trends in Optimization Methods and Different Facts Controllers-Based Power Quality Improvement System,” *Lecture Notes in Electrical Engineering*, vol. 939, pp. 971–985, 2022, doi: 10.1007/978-981-19-4364-5_69.

[17] O. Ziaee, O. Alizadeh-Mousavi, and F. F. Choobineh, “Co-Optimization of Transmission Expansion Planning and TCSC Placement Considering the Correlation Between Wind and Demand Scenarios,” *IEEE Transactions on Power Systems*, vol. 33, no. 1, pp. 206–215, 2017, doi: 10.1109/tpwrs.2017.2690969.

[18] A. Das, S. Dawn, S. Gope, and T. S. Ustun, “A Strategy for System Risk Mitigation Using FACTS Devices in a Wind Incorporated Competitive Power System,” *Sustainability (Switzerland)*, vol. 14, no. 13, 2022, doi: 10.3390/su14138069.

[19] M. Abbasi, E. Abbasi, and B. Mohammadi-Ivatloo, “Single and multi-objective optimal power flow using a new differential-based harmony search algorithm,” *Journal of Ambient Intelligence and Humanized Computing*, vol. 12, no. 1, pp. 851–871, 2021, doi: 10.1007/s12652-020-02089-6.

[20] B. G. Risi, F. Riganti-Fulginei, and A. Laudani, “Modern Techniques for the Optimal Power Flow Problem: State of the Art,” *Energies*, vol. 15, no. 17, 2022, doi: 10.3390/en15176387.

[21] C. B. Shankaralingappa and S. H. Jangamashetti, “FACTS controllers to improve voltage profile and enhancement of line loadability in EHV long transmission lines,” *2008 Joint International Conference on Power System Technology POWERCON and IEEE Power India Conference, POWERCON 2008*, 2008, doi: 10.1109/ICPST.2008.4745188.

[22] H. Hartono, M. Azis and Y. Muharni, "Optimal Capacitor Placement For IEEE 118 Bus System By Using Genetic Algorithm," *2019 2nd International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*, Denpasar, Indonesia, 2019, pp. 1-5, doi: 10.1109/ICHVEPS47643.2019.9011111.

[23] N. K. Sharma, A. Ghosh, and R. K. Varma, “A novel placement strategy for facts controllers,” *IEEE Transactions on Power Delivery*, vol. 18, no. 3, pp. 982–987, 2003, doi: 10.1109/TPWRD.2003.813874.

[24] E. Ghahremani and I. Kamwa, “Optimal placement of multiple-type FACTS devices to maximize power system loadability using a generic graphical user interface,” *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 764–778, 2013, doi: 10.1109/TPWRS.2012.2210253.

[25] H. Liao, S. Abdelrahman, and J. V. Milanović, “Zonal mitigation of power quality using FACTS devices for provision of differentiated quality of electricity supply in networks with renewable generation,” *IEEE Transactions on Power Delivery*, vol. 32, no. 4, pp. 1975–1985, 2017, doi: 10.1109/TPWRD.2016.2585882.

BIOGRAPHIES OF AUTHORS

Tanuja Koppa Shankaregowda was born in Koppa, Turuvekere (TQ), Tumakuru (DIST), Karnataka, India on June 22, 1978. received a Bachelor's degree in Electrical and Electronics Engineering from Bengaluru University in 2001, ME degree in Power and energy systems from Bengaluru University in 2008, respectively. Currently working as an Assistant Professor in the Department of Electrical & Electronics Engineering at Sridevi Institute of Engineering and Technology, Tumakuru, India. Her research areas include Power Systems, FACTS. She can be contacted at email: tanujaksresearch2022@gmail.com.

Shankaralingappa Channappa Byalihal was born in Raichur, Karnataka, India on June 01, 1969. He received his B.E (Electrical) and M.E(Energy systems) degrees from Karnatak University Dharwar, India in 1993 and 1994 respectively, and his Ph.D. (Power Systems) from Visveswaraya Technological University, Belgaum, Karnataka, India in 2011. Currently, he is working as a professor in the department of Electrical and Electronics Engineering at Dr. Ambedkar Institute of Technology, Bengaluru, India. His current research interests include renewable integration, electric vehicles, and metaheuristic algorithms. He is a life member of the Indian Society for Technical Education (ISTE). He can be contacted at email: shankarcbt@gmail.com.