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A novel accelerated genetic algorithm-based technique for optimal placement of multiple FACTSDEV in power systems under N-1 contingency

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ABSTRACT

The liberalization of the energy market has led to a surge in unforeseen power exchanges, which could jeopardize the security of the power system by overloading transmission lines. Flexible AC transmission system devices (FACTSDEV) has been developed in order to improve voltage profiles, reduce losses, and solve power system instability. However, because FACTSDEV devices have such high initial costs, careful planning and ideal placement are essential to maximizing their benefits. This paper proposes a genetic algorithm-based approach to arrange multiple FACTSDEV devices in a power system optimally under N-1 contingency conditions. The IEEE standard (IEEESTD) 14 bus network is where FACTSEDV are located using this optimization technique. The study makes use of MATLAB simulations to evaluate how different FACTSDEV and their placements affect the performance of the power system. The results of the generator and line outage simulations show how FACTDEV have an impact on generation costs, system loss components, and line loss reduction. The cost-optimized placement findings for FACTSDEVs in the IEEESTD 14 bus system are satisfactory and show an improvement in generation cost and system loss component with appropriate positioning and sizing of FACTDEVs.

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1. INTRODUCTION

Due to society's rapid urbanization and expanding industrialization, the demand for power from the power systems has recently expanded dramatically. The capacity of the transmission systems must be increased to handle this increase in electricity usage. The development of new transmission lines in this situation is all but impossible due to the high investment costs, in addition to additional restrictions like the lengthy construction period and disruption to the existing system. It is necessary to utilize all of the current transmission lines' capacity as a result. The mathematical analysis required for power system optimization with security is more challenging and sophisticated. Electricity system security also encompasses electricity reliability in order to stop blackouts. A generator must fail in order to keep the frequency and voltage deviation from the actual grid code at a decreased level. The spinning reserve is employed to manage system load and prevent blackouts. The security of the electrical system depends critically on contingency planning, thus quick and efficient defenses are needed. Flexible AC transmission system devices (FACTSDEV) devices for flexible ac gearbox systems can account for these unanticipated events. FACTSDEV devices can regulate a range of electrical properties in gearbox circuits while being ecologically friendly. A few of the FACTSDEV devices that have been suggested include the TCSCDEV, static VAR compensator, unified power flow controller, and static compensator. It is well known that when power demand rises, transmission loss increases and bus voltages decrease. As a result, it becomes important to consider other objectives such as minimizing transmission loss and the voltage deviation at the load buses in a power system in addition to the goal of boosting the loadability of transmission lines. These objectives can be accomplished by carefully positioning FACTSDEV devices inside the gearbox system, that will boost system performance and pave the way for a reduction in the cost of electrical energy supplied to customers. Given the high cost of FACTSDEV devices, location decisions must also take their price into account. Over the past few decades, the creation of cutting-edge techniques for distributing FACTSDEVs and its grading has served as a driving force.

The usage of heuristic methods [1] to solve problems of this nature is growing. This research proposes the allocation of fact devices using a genetic algorithm (GA) to enhance the power transfer capacity of a networked power system. The decomposition method, mixed integer programming, linear programming, and nonlinear programming have all been used in the past to handle reactive power optimization problems. However, the majority of these conventional methods can lead to a local minimum and are unable to handle integer problems. The design and execution of evolutionary algorithms, which are computer-based approaches [2], [3] to problem solving, however, heavily rely on computational models of the evolutionary process. Simulated annealing (SA), tabu search (TS), genetic algorithm (GA), particle swarm optimization (PSO), hybrid techniques (GAPSO, HPSO), and genetic algorithm (GA). All of these techniques are effective at enhancing the performance of the power system, whether there are just one or several goals. To reduce system overloads and increase the system security margin during single and double contingencies, [4] recommended placing different types of FACTSDEV controllers along the system branches based on contingency severity index (CSI) values (PSO). They have noticed that once the ideal number of different kinds of FACTSDEV controllers have been placed, the system security margin cannot be further improved. Examined the PSO technique's use to increase system loadability and put FACTSDEV controllers in the best possible spots with the least amount of money spent on installation. After a certain number of FACTSDEV controllers were installed, they noticed that the system loadability could not be further improved [5].

Review of FACTSDEV technologies' operational and reliability effects for improving the power quality and security of contemporary cyber-physical power systems is done in [6]. This paper discusses FACTSDEV based on various generational and connectional setups. Additionally, the significance of cyber-physical power systems is analyzed, as well as how they integrate with distributed FACTSDEV technology. An analysis of the best reactive power dispatch utilizing FACTSDEV is done in [7]. The reactive power dispatch design is examined in this paper with an eye towards minimizing line loss, overall voltage deviation, and cost. Additionally, modelling of FACTSDEV for reactive power dispatch, including Thyristor-controlled series compensator (TCSCDEV) and static VAR compensators (SVCDEV), is covered. An overview of congestion control using FACTSDEV is available in reference [8]. The operational and reliability implications of FACTSDEV technologies for enhancing the power quality and security of modern cyber-physical power systems are reviewed in [9]. The FACTSDEV depending on different generational and connectional setups are discussed in this study. Analyses of the significance of cyber-physical power systems and their integration with distributed FACTSDEV technology are also included. [10] does a study of the optimal reactive power dispatch using FACTSDEV. This study examines the reactive power dispatch design with a focus on reducing line loss, overall voltage deviation, and cost. For reactive power dispatch, modelling of FACTSDEV, including TCSC and SVCDEV, is also covered. The [11] provides a summary of congestion control utilizing FACTSDEV.

When deciding where to place FACTSDEV controllers to increase system loadability, researchers have not taken into account factors like changing seasonal demand or the introduction of renewable energy. By demonstrating how various FACTSDEV controllers can affect one or more electrical parameters and the active power flow in the transmission line, [12] demonstrated the application of FACTSDEV controllers for power flow regulation. The [13] displays the optimal FACTSDEV allocation and selection in multi-machine power systems. The objective is to efficiently dispatch and allocate generation for the power system in the deregulated energy market. By limiting the system loss, the FACTSDEV placement problem in their study took into account the upper and lower bound limitations of voltage at different load levels [14] for information on PSO and GA. Biogeography-based optimization (BBO) [15] is used to resolve power system issues like overloading and voltage limit violations using the unified power flow controller (UPFCDEV) and interline power flow controller (IPFC). The optimal generator reallocation method is presented in [16] for handling power system emergencies in the presence of the TCSCDEV. When applying the differential harmony search algorithm, which is developed for the OPF problem, it is necessary to compare and contrast the placement and dimensions of FACTSDEV with N-1 contingency for multiple FACTSDEVS [17]. A method for quick contingency analysis is rapid contingency ranking. By calculating performance indices, overloading of transmission lines can be prevented in both ordinary and emergency circumstances [18]. The worst line problems in an electrical system are analyzed and categorized using contingency analysis. The wind generation system maximizes revenue while reducing equipment purchases and running expenses thanks to the study's optimal FACTSDEV allocation [19]. A paper is displayed red deer algorithm (RDA) to manage emergency situations for enhancing power system security [20]. The optimal power flow (OPF) is solved using the suggested approach using multi-objective functions. FACTSDEV like the UPFCDEV and dynamic voltage restoration (DVR) are used in the power system to control the contingency condition. The RDA algorithm is used to determine the best distribution of the UPFCDEV and DVR.

The ideal placement improves system security, dependability, and stability during contingency scenarios in the power system. The multi-objective genetic algorithm (MOGA) has been presented by [21] for computing the best TCSCDEV allocation in the power system. Convergence, however, is a constraint of this approach. To manage contingency analysis in the power system for security enhancement utilizing UPFCDEV, [22] has provided a CSA method. It might, however, drop during an early convergence. The reference [23] has presented a hybrid JMFO method that combines the best elements of a powerful algorithm. The hybrid algorithm takes a long time to get the best results, though. The references [24]-[27] have developed a DE approach to address power system congestion control by strategically placing FACTSDEV. The local optima solutions are structured in this DE approach, nevertheless. Results for both multiple FACTSDEV and a single FACTSDEV device are studied in this work, which also adds the contingency condition to the restrictions of the FACTSDEV placement paradigm. In this study, a FACTSDEV device or several FACTSDEV devices are placed and sized in the power system while accounting for N-1 contingency scenarios for both generator outages and line outages. For various FACTSDEV device implementations, the implementation used SVCDEV, TCSCDEV, as well as a combination of these two FACTSDEV devices. For the GA-based ideal FACTSDEV implementation, operating cost convergence criteria are taken into account. The modelling of the FACTSDEV utilized in this study is explained in section 2, and the formulation of the problem that sets the constraints and objective function for optimization is covered in section 3. The suggested methodology for the task is covered in section 4. The installation of several FACTSDEV and varied FACTSDEV in the IEEE 14 bus system is thoroughly discussed in section 5, which will be followed by a conclusion and references.

2. MODELING OF POWER SYSTEM COMPONENTS

2.1. Transmission line model

The transmission line model in the power system components is one of the important components. The simple transmission line between buses i and j is depicted in Figure 1 by its lumped Π equivalent parameters. From bus-i to bus-j, the actual and reactive power flow can be expressed as (1) and (2).

$$P_{ij} = V_i^2 G_{ij} - V_i V_j [G_{ij} \cos(\delta_{ij}) + B_{ij} \sin(\delta_{ij})] \tag{1}$$

$$Q_{ij} = -V_i^2 (B_{ij} + B_{sh}) - V_i V_j [G_{ij} \sin(\delta_{ij}) - B_{ij} \cos(\delta_{ij})] \tag{2}$$

Where δ ij = δi-δj, similarly, the real and reactive power flow from bus-j to bus-i.

$$P_{ji} = V_j^2 G_{ij} - V_i V_j [G_{ij} \cos(\delta_{ij}) + B_{ij} \sin(\delta_{ij})] \tag{3}$$

$$Q_{ji} = -V_j^2 (B_{ij} + B_{sh}) - V_i V_j [G_{ij} \sin(\delta_{ij}) - B_{ij} \cos(\delta_{ij})] \tag{4}$$

2.2. Modelling of FACTSDEV

A power injection model can be created to include FACTSDEV in a connected and congested power network. These tools can be incorporated into the injection model as a means of injecting certain nodes with specified amounts of active and reactive power. The TCSCDEV and SVCDEV devices can manage voltage and power flow, respectively, by modifying the system's reactance. This approach enables efficient FACTSDEV device integration into a complicated power network and gives users more system performance control.

2.2.1. TCSCDEV model

A power system device known as the TCSCDEV provides the dynamic control of gearbox line reactance to ensure proper load compensation [25]. Figure 2 shows the structure of the TCSCDEV device, which acts as a variable impedance in series with the transmission line. Placing the TCSCDEV device results in the following line impedance across bus i and bus j.

$$\mathrm{Z_{ij}} = \mathrm{Z_L} + \mathrm{jX_{TCSCD}}_{EV} \tag{5}$$

$$\mathrm{X_{TCSCDEV}} = \mathrm{r_{TCSCDEV}} \mathrm{X_L} \tag{6}$$

Where, Z_L: transmission line impedance; $X_{TCSCDEV}$: reactance of the line where TCSCDEV is located; r_{TCSC}: compensation degree of TCSCDEV (coefficient). The constraint limits of the TCSCDEV are (7) and (8).

$$X_{TCSCDEV} = -0.2\ X_L \text{ to } 0.7\ X_L \tag{7}$$

$$Q_{svcDEV} = -100 \text{ MVAR to } 100 \text{ MVAR} \tag{8}$$

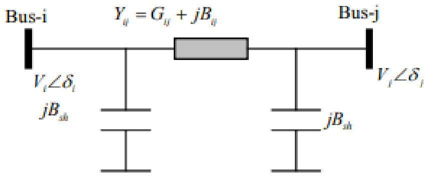

Figure 1. Transmission line model

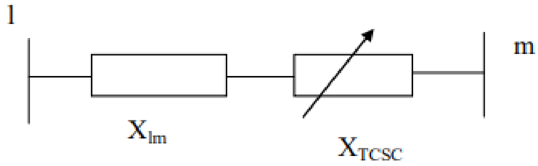

Figure 2. TCSCDEV model

The benefits of TCSCDEV may be observed in its capacity to regulate the level of compensation on a gearbox line and in its versatility in functioning in three different modes: thyristor blocked, bypassed, and operating in Vernier mode. It is uncommon to use the thyristor-blocked mode operation, which is the waiting mode with only the capacitor reactance acting as the TCSCDEV module impedance and no firing pulse delivered to the thyristor. The reactor receives no current, while the capacitor receives the entire transmission line current. In thyristor bypass mode, a firing pulse is continuously provided to the thyristor to produce a fully conducting mode of 180 degrees. The thyristors receive the majority of the transmission line current in this operating mode, and the TCSCDEV serves as a minor, net inductive impedance, mostly protecting the capacitor from high voltages. The thyristor valve is intermittently operated in vernier mode with partial thyristor conduction. This mode can be produced by correctly changing the delay angle of the thyristor pair in the TCR branch. Usually, the thyristor valves are opened by about 90 degrees. Instead of the inductive region, vernier control is often used in the capacitive zone.

2.2.2. SVCDEV model

Devices called SVCDEVs are capable of accurately and swiftly controlling line voltages [26], [27]. In the event of system exigencies (such as network short circuits, line and generator disconnections), an SVCDEV will normally regulate and control the voltage to the desired set point in regular steady-state and emergency conditions. An SVCDEV can also increase transfer efficiency, decrease losses, stop active power oscillations, and guard against over-voltages in the case that the load is lost. Depending on the circumstance, the SVCDEV can operate in either a capacitive or an inductive mode. The SVCDEV's role when connected is to either provide reactive power to the bus where it is connected or drain reactive power from the bus where it is attached. Both in static and dynamic circumstances, it increases voltage and reduces active power loss. Figure 3 presents the variable susceptance model of the SVCDEV for your reference. The effective reactance of the SVCDEV is the parallel combination of X_C and X_L is what establishes the value of X_{SVCDEV}.

The SVCDEV controls bus voltage by absorbing or injecting reactive power while being operated in both inductive and capacitive modes. At both ends of the line, shunt variable susceptibility is added to simulate the SVCDEV. The injected reactive power at bus i is (9) and (10).

$$\Delta Q_{is} = Q_{SVCDEV} \tag{9}$$

$$Q_{SVCDEV} - \text{reactive power injected by SVCDEV in MVAR}$$
$$Q_{SVCDEV} - Q_{Min} \sim\ Qmax \tag{10}$$

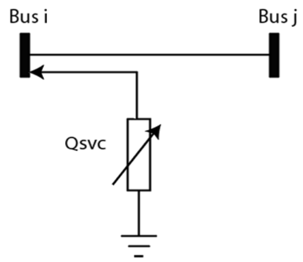

Figure 3. Model of SVCDEV

3. PROBLEM FORMULATION

The problem is formulated as the cost function. The cost of electricity is considered here as the operational cost. A combination of FACTSDEV is used to formulate the issue, and their placement is chosen for its best cost-benefit ratio. Operation cost serves as the objective function for cost optimization under pertinent limitations.

3.1. Operation cost and optimization of FACTSDEV

The minimization cost equation is given by (11).

$$\text{Minimize } F_{cost}(P_g) = a * \sum_{i=1}^{N_g} xP_{g_i}^{\ 2} + yP_{g_i} + z \quad (11)$$

Where: P_{g_i} is power generated at i^{th} generator; and $F_{cost}(P_g)$ is the total fuel cost x, y, z are the cost coefficients. In (11) is the sum of fuel costs of N_g number of generators. a, b, and c are coefficients of the fuel cost equation.

3.2. Inequality and equality constraints

Voltage regulation requirements, impedance constraints for TCSCDEV, and MVAR injection constraints are employed as inequality constraints in the issue. These constraints are described in (12)-(14).

$$V_{i\,min} < V_i < V_{i\,max} \quad (12)$$

Where: $V_{i\,min}$: minimum voltage, $V_{i\,max}$: maximum voltage, and V_i : actual voltage measured at 'i^{th}' bus.

Rating of TCSCDEV is capped at 20% inductive mode and 70% of the line impedance in capacitive mode. The impedance range is represented in (13). The reactance of the TCSC device is depicted here as the inequality constraint.

$$X_{TCSCDEV} = -.2\,X_L \leq X_L \leq .7\,X_L \quad (13)$$

MVAR injection of SVCDEV at bus limited to 100 MVAR in both directions, which means that it can inject or absorb a maximum of 100 MVAR from and to the line. Equality constraints used are given in (15- (17).

$$Q_{SVCDEV} = -28.5\text{ MVAR} \leq Q_{SVCDEV} \leq 100\text{MVAR} \quad (14)$$

$$P_{Load} + P_{Loss} - \sum_{i=1}^{N_g} P_{gi} = 0 \quad (15)$$

Where: P_{Load}: total demand in entire power system (summation of total demand) and P_{Loss}: total line loss in the entire power system. The constraint of SVCDEV placement is given in (16).

$$\Delta Q_{is} = Q_{SVCDEV} \quad (16)$$

Q_{SVCDEV} − reactive power injected by SVCDEV in MVAR

$$Q_{SVCDEV} - Q_{Min} \sim Q\max \quad (17)$$

4. OVERVIEW OF ACCELERATED GENETIC ALGORITHM

The genetic algorithms are a subset of the family of computer models known as evolutionary algorithms that get their inspiration from nature. The powerful stochastic search algorithms known as genetic algorithms are built on the principles of natural selection and genetics. In the genetic population optimization issue, the choice variables are commonly represented as binary strings, regardless of their nature. The Hamming cliff problems of the conventional binary-coded GA can occasionally be problematic when coding continuous variables. Additionally, using a fixed-length binary coding to represent all allowed values becomes challenging for discrete variables whose total number of possible options is less than 2 k (where k is an integer). These problems are avoided in this chapter by representing continuous variables as floating-point numbers and discrete variables as integers. In a mixed form of representation, crossover operation is carried out variable by variable, but the evaluation process and reproduction operator are the same as in a binary-coded GA. The real parameter mutation operator is also used. In this setting, individuals are considered as chromosomes, and the fitness function is used to estimate the value of each one. There will be a match between the fitness function and the optimized objective function.

The process of optimization is made easier by the construction of chromosomes. This is made possible by the migration of chromosomes from one location to another. This method alters the mobility of genes, which can be utilized to assess the resistance of a chromosome and carry out optimization. These three restrictions must be considered in the AGA. They are using random methods and encoding population size. Numerous chromosomal combinations, voltages, and actual power flows are initially considered for computations. We look at these different chromosomes and chromosomal combinations to see which one has the most activity. This method can be repeated to obtain different outcomes by using additional chromosomes. The values are then evaluated to further identify the power flows for each combination. The effective power flow is increased and the network's power flow is balanced as a result of the AGA selecting which transmission line will be connected to which FACTSDEV. The fundamental processes of the approach are initialization, application of the fitness function, crossover, mutation, and termination. Figure 4 depicts the genetic algorithm's flowchart. The acceleration factor is added to the traditional genetic algorithm for the fast and accurate results.

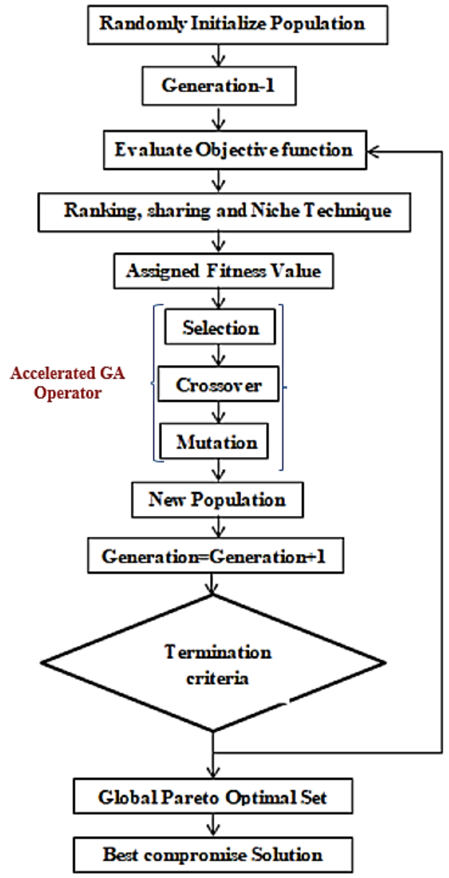

Figure 4. Flow chart for accelerated genetic algorithm

5. PROPOSED IMPLEMENTATION

To lower the operational expenses of the electricity system, FACTSDEV placement and sizing must be optimized. The placement and sizing of FACTSDEV in the IEEE standard (IEEESTD) 14 bus system utilizing the N-1 contingency condition is done using the AGA optimization technique. When using the AGA technique for both single and multiple FACTSDEV placements, the generator and line outages are categorized as N-1 contingencies. The inner loop will imitate the load flow algorithm of the Newton Raphson (NR) approach, and the outer loop will employ AGA to reduce costs overall. The data from the IEEESTD 14 bus system utilized for generation costs include beginning expenses, shut-down costs, and maintenance costs, as well as generation limits. Figure 5 shows the flow chart for FACTSDEV placement and sizing optimization. The search space for the GAGA-based FACTSDEV placement problem is determined by the positioning and dimensions of the SVCDEV and TCSCDEV. The cost of operating the power system, as specified in (7), serves as the problem's objective function. The search space is subjected to the iterative process of selection, crossover, and mutation. The cost is determined using newly calculated genes (location and type), and this process is repeated until the end of the ultimate iteration count. Figure 5 illustrates this procedure.

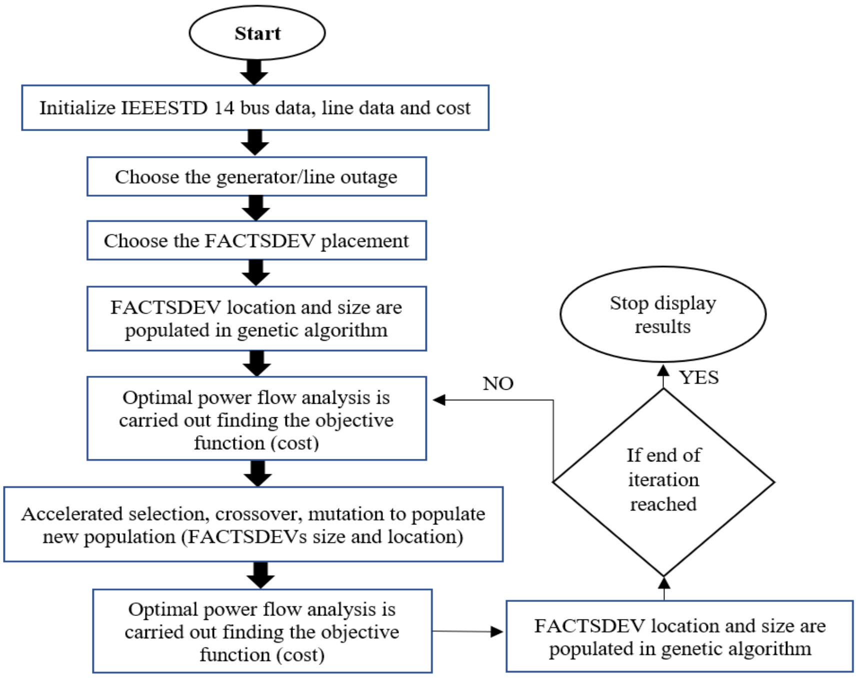

Figure 5. Proposed method of implementation

6. SIMULATION RESULTS

Different cases are used for MATLAB-based simulation, as listed below. To determine where SVCDEV, TCSCDEV, or a mix of both analyzed, FACTSDEV should be placed. As a result, several circumstances are taken into account for the placement and sizing issue covered in the preceding section: i) Case 1 represents a system with no FACTSDEV; ii) Case 2 represents a system with SVCDEV; iii) Case 3 represents a system with TCSCDEV; iv) Case 4 represents a system with TCSCDEV and SVCDEV; v) Case 5 represents a system with two TCSCDEVs; vi) Case 6 represents a system with two SVCDEVs; vii) Case 7 represents a system with two TCSCDEVs and one SVCDEV; and viii) Case 8 represents a system with two TCSCDEVs and two SVCDEVs. Table 1 lists the eight situations taken into consideration.

Figure 6 shows the scenario and case representation of the study conducted. Each case includes three scenarios: i) Scenario I, which is the base case without FACTSDEV or backup plans; ii) Scenario II, which includes a line outage; iii) Scenario III, which includes a generator outage; and Scenario IV, which includes a transformer outage.

- Transmission loss for all the cases: Table 1 shows the outcomes of transmission loss for the placement of 70% compensation of SVCDEV/TCSCDEV and SVCDEV-TCSCDEV (either single or multiple) for the aforementioned scenarios.
- Total operating cost for all the cases: Table 2 shows the outcomes of the total operating cost for the placement of 70% compensation of SVCDEV/TCSCDEV and SVCDEV-TCSCDEV (either single or multiple) for the aforementioned scenarios.

Tables 1 and 2 show the costs of operating the power system and transmission loss for 70% of the total. According to the flowchart shown in Figure 5, coding is created using MATLAB on the IEEESTD 14 bus system with the AGA technique. Three different generator types, six transmission lines, and nine branches make up the network. The optimal power flow program (OPFP) procedure can be used to calculate the overall cost of generating without the need for any FACTSDEV. The simulation is run both without and with a contingency situation (such as a line outage, generator outage, or transformer outage) present. For the base case study (case-1), the total cost of generating is calculated. For both individual and combined FACTSDEV controllers (SVCDEV and TCSCDEV), the total generation cost, total system loss, and real power generation of the generators are calculated for each scenario. Cases 2 to 8 are a discussion of the analysis based on the observations made from Figure 6, Table 1, and Table 2.

6.1. Case-1: system with No FACTSDEV

The total loss in this instance is calculated to be 7.79 MW, and the hourly generation cost is calculated to be $130.86. It has been discovered that anytime there is a line or generator outage, the overall loss will be quite high, and the cost of generating would increase proportionately.

6.2. Case-2: system with SVCDEV

- Scenario I: The process is uninterrupted on either a line or a bus in this situation since the static VAR compensator (SVCDEV) controller is situated at generator 3. The system has lost 266.1541 MW in total. Reactive power worth 7.1541 MVA is being compensated by the SVCDEV. The system's projected hourly running cost is $1,129.6.
- Scenario II: The functioning of an SVCDEV FACTSDEV controller in this instance during a line loss. During such an event, the SVCDEV is installed on a specific line and used to control voltage and enhance power factor. Because it must cover the entire reactive power demand during the outage, the SVCDEV is rated at its full size (MVA). The table provides the overall system loss for each line, which ranges from 7.0742 MW for line 20 to 7.5062 MW for line 6. For all lines, it is anticipated that running the system will cost $1,129.7 per hour. The voltage on the gearbox system may become unstable during a line outage, requiring reactive power support from the SVCDEV to keep voltage levels stable. Reactive power demand of the load during the outage determines how much reactive power support the SVCDEV needs to provide. Given that the total system loss is quite low across all lines, the data in the table implies that the SVCDEV is successfully correcting for the reactive power demand.
- Scenario III: The type of outage in this instance is that generators 2 and 3 are affected by the generator outage. The table provides the overall system loss during the outage, which is 7.372 MW for generator 2 and 11.0012 MW for generator 3. Operating the system is expected to cost $1,162.0 per hour during the downtime. The SVCDEV FACTSDEV controller can be used to keep the voltage level constant and increase system stability during a generator outage.
- Scenario IV: This instance demonstrates the effects of a transformer outage on a system's multiple transmission lines. Transformer 1, transformer 2, transformer 3, and transformer 4 are just a few of the transmission lines in the system that are being impacted by the transformer outage. The table provides the overall system loss experienced during the outage, which differs for each transmission line. Losses for transformer 4 and transformer 1 range from 7.1926 MW to 7.3276 MW. The table provides the expected cost of maintaining the system during the outage, which varies for each transmission line. Transformer 4 is priced at $1,129.4 per hour, while transformer 1, transformer 2, and transformer 3 are priced at $1,129.7 per hour.

6.3. Case-3: system with TCSCDEV

- Scenario I: The electrical system in this instance has a TCSCDEV FACTSDEV controller installed, but no particular line or bus is affected by the outage. 7.2252 MW are lost in total as a result of the TCSCDEV's presence, and this loss costs $1,129.4 per hour overall.
- Scenario II: In this case, the outage is a line outage. For each line, the overall loss as a result of the outage varies and spans from 6.7718 to 7.4808 MW. Each line's cost per hour due to the outage varies and ranges from $1,128.8 to $1,129.3.
- Scenario III: In this case, the outage is a generator outage. This results in an overall loss of 7.2079 MW in generator 2 and an overall cost of $1161.4 per hour. Generator 3 has a total loss of 10.911 MW and an hourly cost of $1,148.8.
- Scenario IV: In this case, the outage is a transformer outage. Transformer 1, transformer 2, transformer 3, and transformer 4 are particularly affected in this instance of a transformer-related outage. Transformer 1 lost a total of 6.8050 MW and cost $1,128.9 per hour during the transformer outage transformer 2 lost a total of 7.3381 MW and cost $1,128.9 per hour, transformer 3 lost a total of 7.1802 MW and cost $1,129.2 per hour, and transformer 4 lost a total of 7.2740 MW and cost $1,128.8 per hour.

6.4. Case-4: system with one SVCDEV and one TCSCDEV

- Scenario I: In this case, the power system has one TCSCDEV and one SVCDEV FACTSDEV controller installed, but no particular line or bus is affected by the outage. The TCSCDEV's presence resulted in a 7.025 MW overall loss, which cost $1,129.2 per hour to compensate for.
- Scenario II: In this case, the outage is a line outage. For each line, the overall loss as a result of the outage varies and is between 6.9 and 7.7 MW. For each line, the total cost due to the outage varies and ranges from $1,129.1 to $1,161.6 per hour.
- Scenario III: In this instance, buses 2 and 3 are affected by a generator outage. On generator 2 and 3, respectively, the outage caused a total loss of 7.0718 MW and 10.9175 MW. The total price of the outage for generator 2 is $1,161.6 per hour, and for generator 3 is $1,148.6 per hour.
- Scenario IV: Transformer 1 lost a total of 7.2693 MW and cost $1,129.3 per hour during the transformer outage, transformer 2 lost a total of 7.2272 MW and cost $1,129.4 per hour, transformer 3 lost a total of 7.1742 MW and cost $1,129.4 per hour, and transformer 4 lost a total of 7.4238 MW and cost $1,129.5 per hour.

6.5. Case-5: system with two TCSCDEV

- Scenario I: Scenario I is the base scenario in this entire study. Here the case 5 discusses the two TCSCDEV functions in the system. The overall loss in this case is 7.2585 MW, and the total cost per hour is $1,129.2.
- Scenario II: In this case, the outage is a line outage. For each line, the overall loss as a result of the outage varies and is between 6.6 and 7.4 MW. For each line, the total cost in dollars per hour as a result of the outage varies and ranges from 1128.8 to 1129.4.
- Scenario III: In this instance, generators 1 and 2 are affected by a generator outage. The outage resulted in a power loss of 7.2284 MW and 10.7850 MW on Generators 2 and 3, respectively. Generators 2 and 3 will be affected at a total cost of $1,161.4 per hour and $1,148.4 per hour, respectively.
- Scenario IV: Transformer 1, transformer 2, transformer 3, and transformer 4 are all affected by a transformer outage, which is the type of outage that is occurring. For transformer 1, transformer 2, transformer 3, and transformer 4, the total loss as a result of the outage is 6.8600 for transformer 1, 7.4716 for transformer 2, 6.9546 for transformer 3, and 3.3055 for Transformer 4. For transformer 1, transformer 2, transformer 3, and transformer 4, the total cost of the outage is $1,129.2, $1,129.1, $1,129.0, and $1,121.6 per hour, respectively.

6.6. Case-6: system with two SVCDEV

- Scenario I: Scenario I is the base scenario in this entire study. In this case, there is no outage mentioned, and a total loss of 7.4662 MW is displayed. It is estimated that this circumstance will cost a total of $1,129.7 per hour.
- Scenario II: In this instance, there is a line outage. In comparison to the total cost numbers, which range from $1,129.6 per hour to $1,134.7 per hour, the total loss values for the line outage range from 5.8518 MW to 8.4378 MW.
- Scenario III: In this instance, generators 1 and 2 are affected by a generator outage. On generator 2 and generator 3, respectively, the interruption caused a total loss of 7.4422 MW and 10.9126 MW. The total price of the outage on generator 2 is $116 per hour, and on generator 3 it is $1,149 per hour.
- Scenario IV: The total loss for the transformer outage is between 6.1119 and 7.1601 MW, and the related total cost is between $1,130.2 and $1,133.2 per hour. Transformer 2 has the biggest total loss, while transformer 1 has the highest total cost.

6.7. CASE-7: System with two TCSCDEV, one SVCDEV

- Scenario I: With case 7, the two TCSCDEV and one SVCDEV are used here and the code is implemented for the given condition. The total loss is 6.8672 MW, and the total cost is 1128.8 USD per hour if there are no outages.
- Scenario II: The scenario II with the TCSCDEV and SVCDEV is used here for the analysis, and the condition as per this scenario provides that the total MW loss varies between 6.4985 and 7.5980 MW, and the total cost per hour varies between 1129.1 and 1129.7 USD.
- Scenario III: The scenario III with the TCSCDEV and SVCDEV are used here for the analysis and the condition as per this scenario provides the generator 2's overall loss as a result of the generator outage is 7.3060 MW, costing a total of $1,161.5 per hour; generator 3's total loss is 11.0728 MW, costing a total of $1,148.9 per hour.
- Scenario IV: Transformer 1 had the biggest overall loss during the transformer breakdown, totaling 6.9963 MW, and the overall cost is $1,129.5 per hour. The remaining impacted lines, transformer 2, transformer 3, and transformer 4, experienced lesser overall losses between 6.7977 MW and 7.2329 MW and comparable overall costs between $1,129.0 and $1,129.3 per hour, respectively.

6.8. Case-8: system with two TCSCDEV and two SVCDEV

- Scenario I: Scenario I is the base scenario in this entire study, and here, the two TCSCDEV and two SVCDEV are used for case 8. Total loss in the absence of an outage is 7.4061 MW, and the hourly cost is $1,129.2.
- Scenario II: Scenario II is the next scenario in this entire study, and here, the two TCSCDEV and two SVCDEV are used for case 8. Since the total cost per hour varies between $1,129.0 to $1129.8, the total loss in MW is between 7.0124 MW and 7.7273 MW.
- Scenario III: At generator 2 and generator 3, respectively, the generator outage resulted in total losses of 7.3717 MW and 10.9982 MW. At generator 2 and generator 3, the final cost of the outage was $1,161.9 and $1,148.8, respectively.

– Scenario IV: The affected lines include transformer 1, which will lose 7.2495 MW and cost $1129.7 per hour. Transformer 2, which will lose 7.1380 MW and cost $1129.6 per hour. Transformer 3, which will lose 7.1964 MW and cost $1129.6 per hour. Transformer 4, which will lose 7.0572 MW and cost $1129.4 per hour.

Figures 7 and 8 show the Generation cost in $/hr and Transmission loss in MW for all the cases, respectively. The position of the FACTSDEV controller, both individually and collectively, is deemed adequate in every instance. For the location of 2TCSCDEV, it can be seen that the minimum loss occurs at the lowest cost. By implementing FACTSDEV Controllers such as the SVCDEV and TCSCDEV, the performance of the power system during line and generator outages can be enhanced. When there is a line outage, SVCDEV performs better than TCSCDEV, and when there is a generator outage, TCSCDEV performs better than SVCDEV. However, it has been discovered that the combined performance of SVCDEV and TCSCDEV outperforms that of individual FACTSDEV controllers for both line and generator outages. Additionally, a single TCSCDEV and SVCDEV outperforms two SVCDEV, two TCSCDEV, two SVCDEV with one SVCDEV, and two SVCDEV with two TCSCDEV in terms of performance. When SVCDEV is implemented vs TCSCDEV for the best feasible set of each of the FACTSDEV, the system's overall cost is decreased in both line and generator outages.

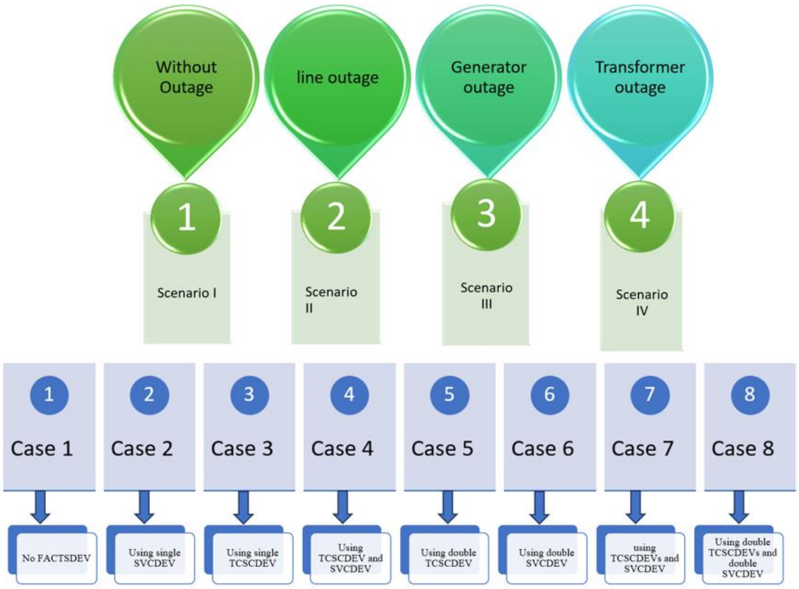

Figure 6. Scenario and case representation

Table 1. Transmission loss in MW for all the cases with 70% compensation

Outage	Line/Gen./ Trans.No.	Types of FACTSDEV controller							
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Scenario I	-----	7.797	7.1541	7.2252	7.0257	7.2585	7.4662	6.8672	7.4061
Scenario II	Line-1	11.7092	7.263	6.7718	7.3102	7.3573	8.0320	7.0617	7.7273
	Line-2	12.5557	7.2134	7.1647	6.9185	7.0259	7.5737	7.4450	7.1084
	Line-3	9.46131	7.4270	7.3213	6.8069	6.8759	7.9385	7.2623	7.5473
	Line-4	9.76587	7.3126	7.1378	7.7340	7.2118	7.1804	6.9783	7.5953
	Line-5	8.92986	7.4367	7.3960	7.2599	7.3798	7.1592	6.8423	7.7251
	Line-6	7.93211	7.5062	7.4361	6.9175	7.1279	8.0220	6.6253	7.1067
	Line-7	9.07521	7.2673	7.4808	7.2197	7.1611	7.2459	7.3255	7.0124
	Line-11	7.95206	7.3911	6.7479	7.1900	7.0119	7.8341	7.5980	7.0483
	Line-12	8.06037	7.2281	7.4106	7.0333	7.3482	6.9591	7.2044	7.6949
	Line-13	8.86115	7.1849	6.9209	7.4969	6.6766	6.5030	7.4034	7.3555
	Line-16	7.96997	7.4370	7.4423	7.3317	7.2126	6.7344	7.4226	7.1700
	Line-17	8.45334	7.3250	7.0816	7.5860	7.0467	5.8518	7.3286	7.3558
	Line-18	7.82793	7.2841	6.9188	7.1132	7.4093	7.1327	6.4985	7.4388
	Line-19	7.81669	7.3072	7.4145	7.1937	7.3190	7.0384	7.3622	7.4006
	Line-20	7.9247	7.0742	7.0879	7.2348	7.1781	8.4378	7.5199	7.4628
Scenario III	Generator 2	7.79355	7.372	7.2079	7.0718	7.2284	7.4422	7.3060	7.3717
	Generator 3	11.4843	11.0012	10.9111	10.917	10.7850	10.912	11.0728	10.9982
	Transformer-1	8.47426	7.3276	6.8050	7.2693	6.8600	6.1119	6.9963	7.2495
Scenario IV	Transformer-2	8.03749	7.2777	7.3381	7.2272	7.4716	7.1601	6.7977	7.1380
	Transformer-3	13.7135	7.2835	7.1802	7.1742	6.9546	6.9058	7.2329	7.1964
	Transformer-4	8.47426	7.1926	7.2740	7.4238	3.3055	6.5840	7.1657	7.0572

Table 2. Total operating cost ($/hr) for all the cases with 70% compensation

Outage	Line/Gen./ Trans.No.	Types of FACTSDEV controller							
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Scenario I	-	1130.86	1129.6	1129.4	1129.2	1129.2	1129.7	1128.8	1129.2
Scenario II	Line 1	1157.67	1129.7	1129.0	1129.5	1129.4	1131.6	1129.3	1129.6
	Line-2	1154.17	1129.7	1129.0	1129.3	1129.0	1129.8	1129.4	1129.2
	Line-3	1144.30	1129.7	1129.0	1129.2	1129.0	1130.4	1129.1	1129.7
	Line-4	1139.78	1129.7	1129.0	1129.4	1128.9	1129.6	1129.1	1129.6
	Line-5	1135.86	1129.7	1128.8	1129.5	1128.8	1130.7	1129.5	1129.8
	Line-6	1131.63	1129.7	1129.1	1129.3	1129.0	1134.5	1129.5	1129.6
	Line-7	1137.17	1129.7	1129.1	1129.6	1128.9	1131.1	1129.7	1129.6
	Line-11	1131.49	1129.7	1129.3	1129.0	1129.0	1132.4	1129.3	1129.7
	Line-12	1131.92	1129.7	1129.2	1129.6	1128.8	1130.2	1129.5	1129.6
	Line-13	1135.46	1129.7	1128.9	1129.6	1129.0	1132.4	1129.6	1129.8
	Line-16	1131.52	1129.7	1129.2	1129.6	1129.1	1131.1	1129.5	1129.7
	Line-17	1133.73	1129.7	1129.3	1129.6	1128.9	1134.7	1129.6	1129.0
	Line-18	1130.98	1129.7	1128.9	1129.5	1129.2	1133.6	1129.3	1129.6
	Line-19	1130.92	1129.7	1129.2	1129.4	1128.9	1131.9	1129.3	1129.6
	Line-20	1131.37	1129.7	1129.2	1129.1	1129.0	1133.0	1129.2	1129.5
Scenario III	Generator 2	1163.65	1162.0	1161.4	1161.6	1161.4	1162.0	1161.5	1161.9
	Generator 3	1151.06	1149.1	1148.8	1148.6	1148.4	1149.0	1148.9	1148.8
Scenario IV	Transformer-1	1133.76	1129.7	1128.9	1129.3	1129.2	1133.2	1129.5	1129.7
	Transformer-2	1132.00	1129.6	1128.9	1129.4	1129.1	1130.6	1129.0	1129.6
	Transformer-3	1155.79	1129.7	1129.2	1129.4	1129.0	1130.2	1129.3	1129.6
	Transformer-4	1133.76	1129.4	1128.8	1129.5	1121.6	1131.2	1129.3	1129.4

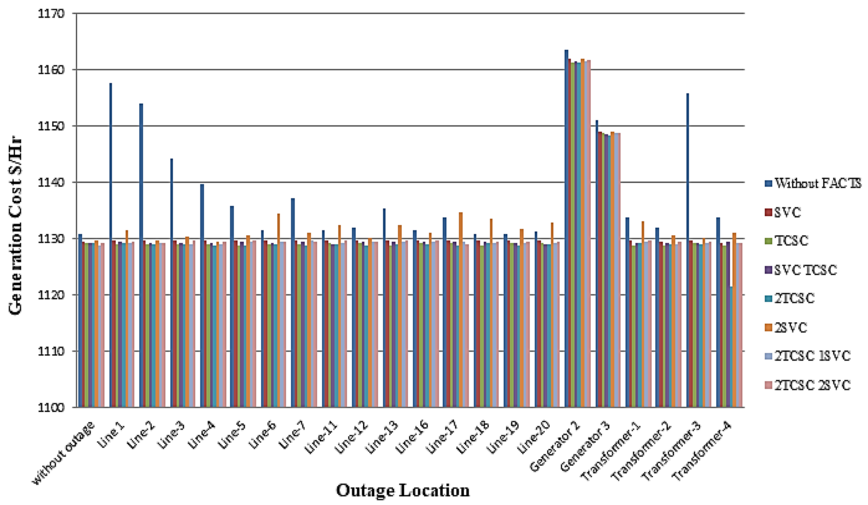

Figure 7. Generation cost for different FACTSDEV controllers

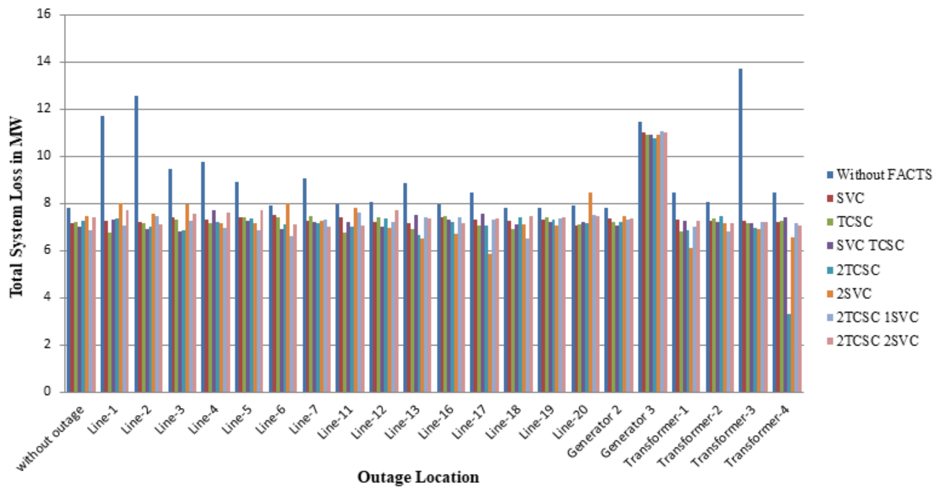

Figure 8. Total system loss for different FACTSDEV controllers

7. CONCLUSION

The goal of the study is to select the best location and SVCDEV and TCSCDEV device ratings for the IEEESTD 14 bus system during various outage scenarios. The findings indicate that optimal FACTSDEV placement and rating can lower generation costs and system power loss. The study, however, did not account for how much these devices cost to install. To produce a more realistic cost-benefit analysis, it would be crucial in future work to take into account the capital expenses related to FACTSDEV installation and sizing. Making this choice would enable the installation of FACTSDEV in power systems to be made more intelligently.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

There is no conflict of interest.

DATA AVAILABILITY

The data used in the code is a standard IEEE 14 bus system. The link is provided to get the data [http://www.ee.washington.edu/research/pstca/pf14/pg_tca14bus.html].

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