Improving voltage collapse point under transmission line outage by optimal placement and sizing of SVC using genetic algorithm

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ABSTRACT

In many power systems, voltage instability can increase the risk of voltage collapse and, as a result, turn the power system toward a blackout. Therefore, increasing the voltage collapse point is required. A transmission line outage is an emergency condition in power systems that can lead to voltage instability and voltage collapse. Thus, it is expected to employ shunt-connected flexible AC transmission systems (FACTS) such as the static var compensator (SVC) to increase the voltage collapse point when lines outage. This paper presents the genetic algorithm (GA) application to optimal placement and sizing of an SVC for increasing voltage collapse points following lines outage. The continuation power flow (CPF) technique has been used to determine the maximum loading point (MLP) corresponding to the point of voltage collapse. Also, to reduce the number of scenarios when line outages occur, a list in ascending order is established based on the line outage priority (LOP). The IEEE 14-bus test system is chosen to carry out simulations, and an SVC will be installed in the system based on the GA results. Simulation results confirm the effectiveness of an SVC for improving voltage stability as well as increasing voltage profile.

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1. INTRODUCTION

An increase in consumer demand as well as unforeseeable circumstances within the power system, also known as emergency conditions or contingencies, are potential contributors to voltage instability within a power system. The failure of transmission lines or generators can bring about conditions that are considered emergency situations. Transmission line outages can be caused by a number of factors, including the deterioration of individual components or unfavorable weather conditions. In addition, there is the possibility of a single or multiple line outage happening at the same time, which would result in a drop in voltage. In this scenario, the capacity to immediately supply reactive power to compensate for voltage drop and prevent voltage collapse is an important factor in determining whether or not blackouts will occur on the power grid [1]–[3]. Both the steady state and the transient state offer opportunities for research into voltage stability issues. The maximum loading point (MLP), also known as the voltage collapse point, is a placement "in the steady-state category" that is determined with the help of the continuation power flow (CPF) technique [2].

It is common practice to raise the MLP and voltage stability margins by controlling the system's reactive power through the application of two different solutions.

The first method is to control the flow of power by utilizing flexible AC transmission systems (FACTS) devices that are connected in series, such as the thyristor-controlled series capacitor (TCSC), or tap-changing transformers. The second method is to control the amount of reactive power in the system by employing shunt capacitors or shunt-connected FACTS devices like the static var compensator (SVC) [2]. Despite this, the results presented in [2] show that shunt-connected FACTS devices provide outstanding performance in terms of voltage stability. Both SVC and the static synchronous compensator (STATCOM), are shunt-connected FACTS devices that operate identically, with the exception that the STATCOM can inject and absorb reactive power more quickly. In comparison to SVC, STATCOM offers a greater number of benefits, including less power loss and quicker response times. However, putting together a STATCOM system is not only difficult but also very expensive. As a result, in a transmission system, SVC is utilized more frequently than STATCOM [3].

In recent years, a great number of articles have been written on the topic of applying the SVC to improve the performance of power systems [4]–[14]. Notably, the optimal placement of the SVC devices in order to improve voltage stability is investigated in [15]–[21]. For instance, preview study [15], the genetic algorithm (GA) is used to determine the best possible placement of the SVC in order to improve the voltage profile and reduce the amount of power that is lost. Aghaebrahimi *et al.* [16] outlines the effective siting and sizing of wind farms and the SVC in a power system through the application of the non-dominated sorting genetic algorithm (NSGA). NSGA-A has taken into consideration all of the goals simultaneously, such as lowering costs and enhancing the voltage profile of the buses. Preview study [17], a genetic algorithm is used to find the optimal location and setting of the SVC in order to improve voltage stability. This is accomplished by increasing the distance to the collapse point while simultaneously decreasing the total amount of power that is lost.

The purpose of this paper is to demonstrate how the genetic algorithm can be utilized to determine the optimal placement and sizing of an SVC in order to raise the voltage collapse point in the event that a transmission line fails. The following is how this paper is organized from a structural standpoint: i) The SVC is discussed in detail in section 2 of this document; ii) Sections 3 and 4, respectively, an introduction is provided to the concept of continuation power flow and the genetic algorithm; iii) The method for positioning and determining the size of the SVC is described in section 5; and iv) Section 6, the results of the simulation, along with some observations, are broken down and explained. In this part of the article, the method that was introduced will be investigated using the IEEE 14-bus test system. In the final section of the paper, a summary conclusion is presented as the conclusion.

This paper shows the application of the genetic algorithm to optimal placement and sizing of an SVC for increasing the voltage collapse point under transmission lines outage. The proposed solution employed the CPF method to determine the maximum loading point. Also, the number of scenarios under transmission line outages is reduced by establishing a list in ascending order based on the line outage priority. Simulation results performed on the IEEE 14-bus test system show the SVC can increase the maximum loading point and voltage levels of all buses.

The structure of this paper is arranged as follows; the SVC is described in section 2. An overview of continuation power flow and genetic algorithm is given in sections 3 and 4, respectively. The placement and sizing method for the SVC is presented in section 5. Simulation results, along with some observations, are explained in section 6. In this section, the IEEE 14-bus test system is employed for investigating the introduced method. The paper ends with a summary conclusion in the final section.

2. STATIC VAR COMPENSATOR

The SVC is the most well-known FACTS device that regulates and controls the voltage magnitude by injecting/absorbing reactive power. This device has been employed for over four decades and installed in about 100 places [2], [22]. The standard configuration of an SVC device and its equivalent circuit are displayed in Figure 1(a) and 1(b), respectively. The structure of the SVC includes a constant capacitor *C* in parallel with a thyristor-controlled reactor (TCR), which can be equivalent to a variable susceptance (B_{SVC}). The variable susceptance (B_{SVC}), the total effective reactance (X_{SVC}), and TCR reactance (X_{TCR}) are obtainable as demonstrated [23].

$$B_{SVC} = -\frac{1}{X_{SVC}} \tag{1}$$

$$X_{SVC} = \frac{X_C X_{TCR}}{X_C + X_{TCR}} \tag{2}$$

$$X_{TCR} = \frac{\pi X_L}{\sigma - \sin\sigma} \quad (3)$$

Where X_C, X_L, and σ denote the capacitive reactance, inductive reactance, and conduction angle respectively. The $\sigma=2(\pi-\alpha)$ *is the* relationship between the conduction angle and the firing angle (α) of thyristors. The reactive power injected/absorbed by the SVC at the bus n is [23].

$$Q_{SVC} = Q_n = -B_{SVC}V_n^2 \qquad If: \begin{cases} Q_{SVC} < 0 \rightarrow SVC\ injects\ reactive\ power \\ Q_{SVC} > 0 \rightarrow SVC\ absorbs\ reactive\ power \end{cases} \quad (4)$$

Where V_n represents the voltage amplitude of the SVC bus.

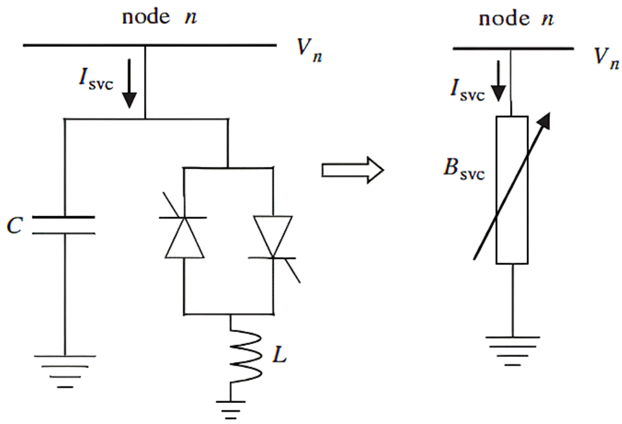

Figure 1. The SVC device: (a) standard configuration and (b) equivalent circuit [23]

3. CONTINUATION POWER FLOW

The CPF technique is a helpful procedure in finding the MLP corresponding to the voltage collapse point or critical point. In mathematical terms, the CPF technique examines the voltage stability of a system by changing the loading parameter (λ). According to Figure 2, the predictor-corrector steps are used to solve the PV curve in the CPF technique [16].

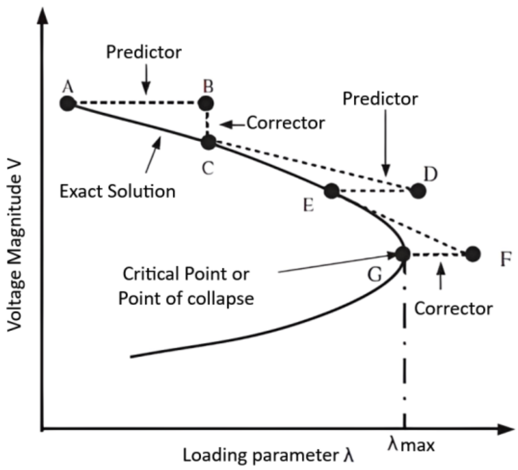

Figure 2. The continuation power flow method [24]

4. GENETIC ALGORITHM

The scope of work of genetic algorithms is extensive, and the use of this method in optimization and problem-solving is prevalent. The genetic algorithm can be called a general search method that mimics the laws of natural biological evolution. Commonly, genetic algorithms include chromosomes, population, and fitness function. In the GA, genetic operators are used during the reproduction phase. With the effect of these operators on a population, the next generation of that population is produced. Selection, crossover, and mutation operators are usually the most widely used in genetic algorithms [17]–[25].

5. PLACEMENT AND SIZING METHOD FOR SVC

This section presents a new method that uses the genetic algorithm and CPF technique to find the optimal placement and sizing of an SVC. The goal of the method is to increase voltage collapse points following transmission lines outage. The following parts explain the presented method.

5.1. Objective function

The optimization approach in this article is focused on the optimal placement of SVC for maximizing the maximum loading point (λ_{max}) corresponding to the point of voltage collapse. The objective function has been considered in the fitness function that formulated as (5).

$$Maximize\ (Fitness\ function) = \lambda_{max,iteration} - \lambda_0 \quad (5)$$

Where λ_0 is the maximum loading point at the base case and $\lambda_{max,iteration}$ is the maximum loading point that generates by the genetic algorithm in the presence of the SVC. The constraints for the optimization problem are defined as (6)-(10).

$$P_{Gi,min} \leq P_{Gi} \leq P_{Gi,max} \qquad i=1,\dots,N_G \quad (6)$$

$$Q_{Gi,min} \leq Q_{Gi} \leq Q_{Gi,max} \qquad i=1,\dots,N_{G,C} \quad (7)$$

$$V_{i,min} \leq V_i \leq V_{i,max} \qquad i=1,\dots,n \quad (8)$$

$$S_{i-j,min} \leq S_{i-j} \leq S_{i-j,max} \qquad i=1,\dots,N_L \quad (9)$$

$$Q_{SVC,min} \leq Q_{SVC} \leq Q_{SVC,max} \quad (10)$$

Where $P_{G,I}$ is active power generation at bus I; N_G is number of generators; $Q_{G,I}$ is reactive power generation at bus I; $N_{G,C}$ is number of generators and compensator; V_i is voltage amplitude at bus i ; n is number of buses; S_{i-j} is transmitted power through buses i and j; N_L is number of transmission lines; and Q_{SVC} is reactive power injected/absorbed by SVC.

5.2. Line outage priority

Since the number of transmission lines in a power system is many, it is better to reduce the number of simulation scenarios by establishing a list. In this paper, the line outage priority is used to establish a list in ascending order to reduce the number of simulation scenarios. The line outage priority (LOP) is the same as the maximum loading point obtained using the CPF by removing transmission lines separately [26].

5.3. Steps of method

The seven steps are used to find the optimal placement and sizing of an SVC for increasing voltage collapse points:
- Step 1: Power flow is carried out in the base case to obtain the voltage profile of buses and network losses.
- Step 2: The CPF is carried out in the base case to obtain the maximum loading point (λ_0) and voltage collapse point of buses.
- Step 3: Transmission lines are removed separately, and the CPF is carried out to obtain the LOP.
- Step 4: LOP is arranged in ascending order and a list is established.
- Step 5: Scenarios are determined for performing the genetic algorithm program.
- Step 6: Power flow is carried out in all scenarios without the SVC.
- Step 7: After setting the genetic algorithm parameters, the program is run for the specified scenario.
  a) The optimal placement and sizing of an SVC and MLP are determined.
  b) Power flow is carried out in the specified scenario in the presence of the SVC.

6. SIMULATION RESULTS

An open-source MATLAB-language M-files known as MATPOWER 7.0 are used for modeling the power system and continuation power flow solution [27]. Also, the SVC model and genetic algorithm are implemented by MATLAB coding. The IEEE 14-bus system has been employed as the power grid, consisting of five synchronous machines, 16 lines, four transformers, and 11 loads [28].

6.1. Step 1 and step 2: Results of power flow and CPF in base case

The results of executing power flow and CPF in the base case are provided in Table 1. The results show that buses 4, 5, and 14 are the weakest, with a stronger desire to experience voltage collapse. The PV curves for the weakest buses are presented in Figure 3.

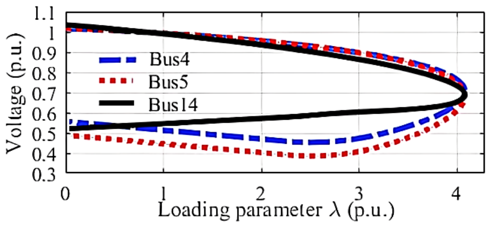

Figure 3. The PV curves for three weakest buses

Table 1. Power flow and CPF results in base case

	Power flow		CPF
Bus No.	Amplitude (p.u.)	Phase (Deg.)	Voltage collapse point (p.u.)
1	1.06	0	1.06
2	1.045	-4.98	1.045
3	1.01	-12.72	1.01
4	1.018	-10.31	0.7
5	1.02	-8.77	0.68
6	1.07	-14.22	1.07
7	1.062	-13.36	0.8
8	1.09	-13.36	1.09
9	1.056	-14.94	0.71
10	1.051	-15.1	0.73
11	1.057	-14.8	0.88
12	1.055	-15.08	0.98
13	1.05	-15.16	0.93
14	1.036	-16.03	0.69
Network losses		13.4 MW 54.54 MVar	MLP (λ_0)= 4.08 p.u.

6.2. Step 3 and step 4: Determining line outage priority (LOP) and establishing a list

Transmission lines are removed separately, and the CPF is executed to obtain the LOP (maximum loading point). In other words, the LOP is determined by CPF when transmission lines are out of the system one by one. The results are shown in Table 2 and the LOP is arranged in ascending for establishing a list.

Table 2. List in ascending order based on LOP

Transmission line (from bus-to bus)	Line outage (line number)	LOP (p.u.)
1-2	1	0.46
2-3	3	1.7
7-9	11	2.59
6-13	10	3.03
2-4	4	3.07
13-14	16	3.09
2-5	5	3.26
6-11	8	3.44
1-5	2	3.57
9-14	13	3.6
10-11	14	3.71
4-5	7	3.94
3-4	6	3.96
6-12	9	4.01
9-10	12	4.04
12-13	15	4.07

6.3. Step 5: Determining scenarios

This step is used to determine scenarios for performing the genetic algorithm program. Based on Table 2, lines number 1 and 3 have the lowest value of LOP, which results in a low voltage stability margin. Therefore, these lines are chosen to form scenarios according to Table 3.

Table 3. Scenarios for simulations

Scenario 1	Scenario 2	Scenario 3
Outage of line number 1	Outage of line number 3	Simultaneous outage of line number 1 and 3

6.4. Step 6: Power flow results in all scenarios without SVC

Power flow is carried out in all scenarios without an SVC to show the effectiveness of the SVC on improving voltage profile after installation in the system. The voltage amplitude and network losses are shown in Figures 4 and 5, respectively. As can be seen, in scenario 3, the maximum voltage drop is achieved, and the network losses are increased significantly.

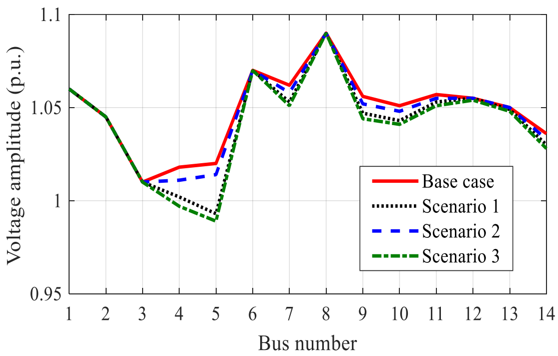

Figure 4. Voltage amplitude in base case and all scenarios without SVC

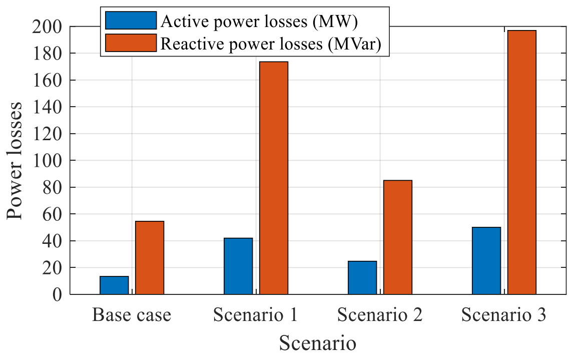

Figure 5. Network losses in base case and all scenarios without SVC

6.5. Step 7: Running genetic algorithm program

The power system constraints and genetic algorithm parameters have to be set as inputs. Constraints related to the power system can be extracted from IEEE 14-bus system data. Also, other constraints and genetic algorithm parameters are taken from Table 4.

Table 4. Constraint of the SVC and genetic algorithm parameters for all scenarios

Constraint of the voltage amplitude of buses	Constraint of the SVC	Population size	Number of iterations
$0.9 \leq V_i \leq 1.1$ p.u.	$0 \leq Q_{SVC} \leq 4$ p.u.	40	500

6.5.1. Scenario 1: Outage of line number 1

An outage of line number 1 is created, and inputs are set in the GA program. After executing 500 iterations of the GA program, the optimal location of the SVC is bus number 5, with compensation of 399.4 MVar. The fitness function versus the number of iterations is illustrated in Figure 6. As can be seen, the value of the fitness function is nearly has been converged after the 65th iteration, and a minor change in the fitness function at iteration 399 is achieved.

The GA results show the maximum loading point is 0.93 p.u., which a 202.2% increase has been obtained compared to before installing SVC. Also, based on Figure 7, the voltage amplitude of all buses is improved while a line outage has occurred. In addition, a comparison of network losses with and without the SVC reveals that the losses have been increased. After employing the SVC, the network losses are 42.67 MW and 181.85 MVar.

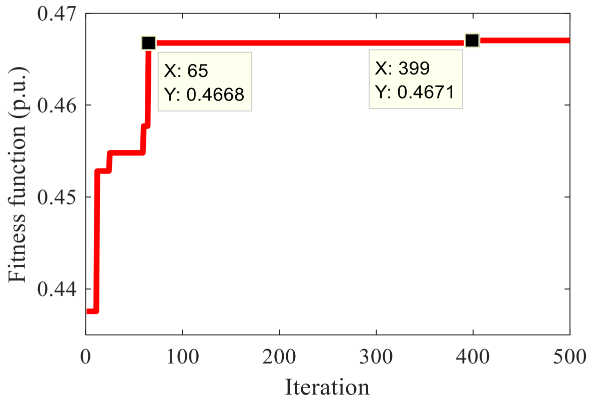

Figure 6. Fitness function versus the number of iterations for scenario 1

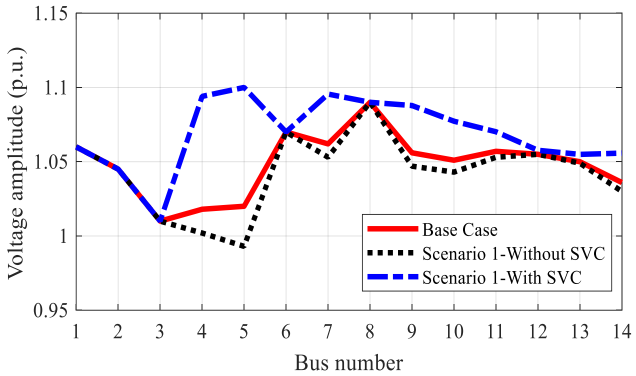

Figure 7. Voltage amplitude in base case and scenario 1

6.5.2. Scenario 2: Outage of line number 3

After an outage of line number 3 and running the GA program for 500 iterations, the optimal placement of the SVC has been found at bus number 4, and the injected reactive power by the SVC is 399.6 MVar. After installing the SVC, the maximum loading point is 3.49 p.u., which shows significant improvement in the voltage stability margin. The voltage amplitude of all buses in scenario 2 after using the SVC is shown in Figure 8. Results show that an improvement in voltage amplitude is obtained. Also, buses 4, 5, 7, and 9 are not above 1.1 p.u., so that the constraint of the voltage amplitude has been met.

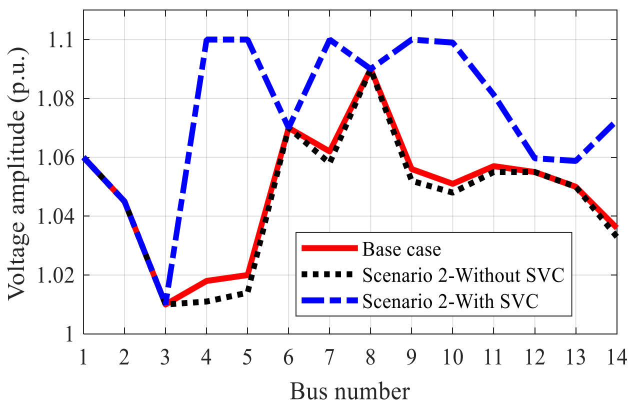

Figure 8. Voltage amplitude in base case and scenario 2

6.5.3. Scenario 3: Simultaneous outage of line number 1 and 3

Scenario 3 is the worst because it is a combination of scenarios 1 and 2. In other words, transmission lines 1 and 3 out from the power system together. In this scenario, to get the best result, only the number of iterations will change to 1000. In this condition, after completing the program, the SVC location is bus number 5, and the value of the injected reactive power is 399.41 MVar. Before and after installing the SVC, the maximum loading point is 0.38 p.u. and 0.83 p.u., respectively. That means a 218.4% improvement in the loading parameter has been gained. Therefore, better performance of SVC is provided than the other two scenarios. In Figure 9, the impact of the SVC to enhance voltage amplitude under transmission lines outage is shown.

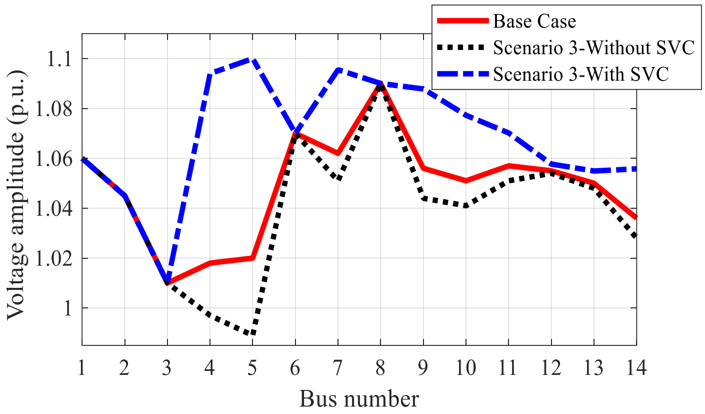

Figure 9. Voltage amplitude in base case and scenario 3

Based on summarized results in Table 5, the network losses in scenario 3 have been decreased while the improvement in voltage stability margin and voltage profile has been obtained. Therefore, by employing the genetic algorithm and selecting its parameters suitably, the best results can be taken. Please note that optimization aims to increase the MLP corresponding to the point of voltage collapse following transmission line outage and improve the voltage profile that after running the GA program in the presence of the SVC has been achieved.

Table 5. Summary of results with and without SVC under transmission line outage condition

Scenario	Maximum loading point (p.u.)		Network losses	
	Without SVC	With SVC	Without SVC	With SVC
Base case	4.08	---	13.4 MW 54.54 MVar	---
Scenario 1	0.46	0.93	41.97 MW 173.59 MVar	42.67 MW 181.85 MVar
Scenario 2	1.7	3.49	24.74 MW 85.05 MVar	34.68 MW 101.77 MVar
Scenario 3	0.38	0.83	50.04 MW 196.95 MVar	47.7 MW 181.85 MVar

7. CONCLUSION

In this study, a genetic algorithm program is used to determine the optimal placement of the SVC in order to maximize the voltage stability margin in the event of a transmission line failure. In order to ascertain the maximum loading point, the CPF method was put into practice. In addition to this, an ascending list is compiled based on the line outage priority (LOP) in order to cut down on the number of potential outcomes brought about by transmission line failures. The results of simulations performed on the IEEE 14-bus test system indicate that bus 5 is the optimal location for installing the SVC in the third-worst case scenario (scenario 3). Following the installation of the SVC, the maximum loading point and voltage levels of each bus were raised to their respective new levels. In addition, if the parameters of the GA are configured correctly, there will be less data loss on the network.

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