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Intelligent stability margin improvement using series and shunt controllers

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ABSTRACT

Electric market always prefers to use full capacity of existing power system to control the costs. Flexible alternate current transmission system (FACTS) devices introduced by Electric Power Research Institute (EPRI) to increase the usable capacity of power system. Placement of FACTS controllers in power system is a critical issue to reach their maximum advantages. This article focused on the application of FACTS devices to increase the stability of power system using artificial intelligence. Five types of series and shunt FACTS controllers are considered in this study. Continuation power flow (CPF) analysis used to calculate the collapse point of power systems. Controlling parameters of FACTS devices including their locations are determined using real number representation based genetic algorithm (RNRGA) in order to improve the secure margin of operating condition of power system. The 14 and 118 buses IEEE standard test systems are utilized to verify the recommended method. The achieved results manifestly proved the effectiveness of proposed intelligent method to increase the stability of power system by determining the optimum location and size of each type of FACTS devices.

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1. INTRODUCTION

Environmental considerations such as pollutions, greenhouse gases and landfills are the major issues in recent years [1]. Flexible AC transmission system (FACTS) devices have the capability of modifying heavily loaded area, control the power flows, reduce the losses of power system, increase stability, improve loadability of system, decrease the overall cost and environmental benefits. FACTS devices provide rapid and smooth control for the interdependent parameters of power system such as current, voltage, reactive and active powers, impedance and phase angle by utilizing high speed power electronics elements [2]-[5]. The energy consumption, major interruptions and collapse phenomena are increasing in different power systems around the world. Accordingly, power system optimization and voltage stability enhancement, efficiency improvement of main devices in industry such as electrical machines and an effective maintenance strategy are highly concerned in electric industry [6]. Main source of voltage instability and collapse phenomenon is due to the operation of power systems close to their stability limit. The shareholders of power industry are more interested in reconstruction of existing network capacities rather than establishment of new generation stations and new transmission lines. Advantages of FACTS technology can be one of the best options to use the full potential of existing resources [7]-[9]. Location of FACTS controllers in transmission system is a critical issue to use their maximum capacity and advantages. Based on the structure of FACTS devices, each series or shunt controller has different effect on power system. Hence, identification of optimal location and control setting of FACTS devices are important [10], [11].

Identification of FACTS parameters are including several variables which should be optimized concurrently that causes complexity and difficulty [12]. There is some limitation to solve this combinatorial problem using the classic approaches. Artificial intelligence (AI) method such as genetic algorithm (GA) has been introduced as a significant solver of the combinatorial problems and applied in various aspects of industry and science [13], [14]. Nadeem *et al*. [15] proposed a method to find the best location and size of thyristor controlled series capacitor (TCSC), static var compensator (SVC) and unified power flow controller (UPFC) in IEEE 14 and 30 bus systems using whale optimization algorithm (WOA). The operating cost of power network has been considered to be minimized as objective function. The costs and losses have been reduced using this heuristic technique. Mohammed *et al*. [13] carried a research out on the application of SVC and TCSC for power system loss reduction using GA. The proposed method is applied on IEEE 24 bus system. In [10] an optimization algorithm has been proposed to minimize the generation and FACTS devices costs. Cuckoo search algorithm (CSA) in corporation with particle swarm optimization (PSO) is used to find the best place for installation of SVC, TCSC and UPFC in IEEE 14 bus test system. Zarkani *et al*. [16] developed a research based on differential evolution (DE) technique to minimizing the losses of power system and voltage profile improvement using TCSC, SVC and UPFC. The proposed algorithm is evaluated on IEEE 30 bus system. A heuristic method based on autonomous groups particle swarm optimization (AGPSO) is discussed in [17] for active power loss reduction in transmission system. Application of SVC is examined in IEEE 14 and 30 bus test systems to examine the efficiency of algorithm.

This article proposed a real number representation based genetic algorithm (RNRGA) to make an acceptable gap between the operating point and collapse margin of power system in order to improve the stability condition. Five types of series and shunt FACTS controllers such as Static Synchronous compensator (STATCOM), Static synchronous series compensator (SSSC), TCSC, SVC and UPFC are simulated in IEEE 14 and 118 bus test systems by MATLAB software to examine the effectiveness of proposed method. The results prove that the placement of controllers at optimum locations and capacities is a key element in optimization of transmission system.

2. RESEARCH METHOD

Generally, the steady state situation of power systems at specific load level can be determined by conventional power flow procedures [18]. Continuation power flow (CPF) analysis is one of the accurate methods for voltage collapse calculation. The voltages of buses can be drawn versus active power at crucial loading condition. CPF analysis consists two phases including predictor and corrector. The predictor step seeks an approximation point for the next solution by an equilibrium point of the nose curve. The predictor operator generates an initial guess for the corrector step. Accordingly, the existing error should be corrected before it accumulated in the corrector stage [19].

The power systems can be expressed with the ordinary differential equations (ODE). Bifurcation theory is a tool to handle the investigation on the stability of ODE systems which in motion between equilibrium to equilibrium. Bifurcations phenomena are very famous in nonlinear systems (e.g. interconnected power system) based on their ability to drive the system to chaotic manner [20]. There are different types of bifurcations pertinent to voltage instability in power system as saddle-node bifurcation (SNB), limit-induced bifurcation (LIB) and Hopf bifurcation. Among these bifurcations, SNB and LIB have been introduced to be forcefully related to voltage collapse phenomena [7]. SNB is the outcome of a singularity of the Jacobian or state matrix when the normal solution at steady state condition are vanishing. There are two well-known methods to compute SNB point of power system such as direct method (DM) and CPF technique. The CPF analysis is more applicable in comparison with DM. Increasing the distance of the system operating point to collapse is an effective solution to prevent instability problems.

2.1. Real number representation based genetic algorithm

The GA is introduced as an optimization tool to solve the combinatorial problem. The real number (continuous) representation of GA has some prominences such as faster calculation and less storage requirement. Various parts of proposed RNRGA are described in detail as follows.

2.1.1. Initialization

The RNRGA starts with an initial population by N chromosomes. A matrix of population will be created randomly with N row and N_{var} column where N_{var} includes the variables of chromosome. Therefore, each chromosome contains an array of variable values to be optimized. The variables values are generated between P_{Lo} and P_{Up} bound by (1).

$$Population = P_{Lo} + (P_{Up} - P_{Lo}) \times rand\ (N, N_{var}) \quad (1)$$

2.1.2. Selection

The roulette wheel selection technique is very common in most of the practical RNRGA where a chromosome will be selected from mating pool based on the probability proportional to its fitness. The fitness value of each chromosome is divided by the actual fitness of the population then calculated as the expected value of that chromosome. The roulette wheel slices are composed from the individuals and the size of each slice is proportional to the fitness of individual. The roulette wheel is spun equal to population size N and a chromosome is selected on each stop for new population. The roulette wheel technique is performed as (2). Calculate the values of objective function f for each chromosome v_i.

$$Eval\ (v_i) = f\ (x)\ I = 1, 2, \ldots, N \quad (2)$$

compute the sum of objective function values of population.

$$Sum = \sum_{i=1}^{N} eval(v_i)\ I = 1, 2, \ldots, N \quad (3)$$

compute the selective probability SP_i for each chromosome v_i.

$$SP_i = eva\ l\ (v_i) / Sum\ I = 1, 2, \ldots, N \quad (4)$$

calculate the cumulative probability Q_i for each chromosome v_i.

$$Q_i = \sum_{j=1}^{i} SP_j\ I = 1, 2, \ldots, N \quad (5)$$

While the process mentioned above is carried out for all the chromosomes, the selection of a chromosome will be performed as:
1). Generate random number r between zero and one.
2). The chromosome v_i will be selected if $Q_{i-1} \leq r \leq Q_i$ where $1 \leq I \leq N$.

2.1.3. Crossover

The intermediate recombination method is one of the most practical crossover techniques in RNRGA which is usable for real number representation only. This technique combines the variable values of two parent chromosomes by utilizing the (6) and (7) to generate the new variable values of offspring chromosomes.

$$Off_1 = \alpha . P_{1n} + (1-\alpha) . P_{2n} \quad (6)$$

$$Off_{2n} = \alpha . P_{2n} + (1-\alpha) . P_{1n} \quad (7)$$

The variables of first and second parent chromosomes in the above equations can be combined by using the same α for each variable of both parents or by selecting the different α for each variable, but it is faster and simpler if the same α is chosen for each variable.

2.1.4. Mutation

The mutation operator for real number representation of RNRGA is applied randomly to the population and changed the variable values of chromosomes inside the population. The variable is changed by adding a random value known as mutation step within its domain given by a lower P_{Lo} and upper P_{Up} bound with the mutation probability P_m. The size of step S_m can be determined by using (8).

$$S_m = (P_{Up} - P_{Lo}) \times scale \times rand \quad (8)$$

If the mutation operator is applied on a variable, the value of S_m is added to that variable. After the influence of crossover and mutation operators, the new population will be generated and their fitness value will be determined based on objective function. The process described is iterated until the maximum iteration is reached.

2.2. Optimization strategy

The optimization goal is to find the closest margin to collapse point of power system and maximizing the distance of operating point to the instability limit considering the smooth variation of the loading parameter (λ) by installation of series and shunt FACTS devices on the best location with their optimum capacities. The IEEE 14 and 118 bus test systems is used to evaluate the proposed method. Various types of FACTS devices including STATCOM, SSSC, TCSC, SVC and UPFC are employed for stability analysis in the MATLAB environment.

2.2.1. Problem formulation

The nearest margin to the collapse point of power system can be calculated accurately by (9) [21].

$$\mathcal{F}_{x,p,\lambda,\omega,u,v} = Min\ -\frac{1}{2}\|\lambda - \lambda_0\|^2 \tag{9}$$

subjected to:

$$\begin{aligned} &f(x,p,\lambda) = 0 \\ &J^T(x,p,\lambda)u + \omega v = 0 \\ &J^T(x,p,\lambda)v + \omega u = 0 \end{aligned}$$

where x is involving with the state and algebraic variables, p is the parameters of power network, λ is referred to the load, ω is the imaginary part of a system eigenvalue, u is the real part and v refers to the imaginary portion of the eigenvector, λ_0 is the primary operating point of power system, $f(x,p,\lambda)$ is the load flow parameters and J is the system Jacobian. The function $\mathcal{F}$ computes the nearest margin to the collapse point of power system. By increasing the gap between the instability margin and operating point, the power system stability will guarantee a secure working condition. The stability margin can be improved by regulating the controllable parameters of power system. The constraints and boundaries of power system parameters such as voltage, current and load will be considered in the analysis.

2.2.1. Optimization algorithm

The RNRGA is used as an optimization tool to solve this complex problem. Collapse point of power system is calculated by CPF analysis. Then, the stability margin is improved through the installation of FACTS devices at the best locations and optimal capacities. FACTS devices are represented by variables of location and controlling parameters. The location involves the number of bus or line where the device should be installed. The control variables are defined based on the type of device. RNRGA consists of some chromosomes which are composed of a variable string. The variables are contained the values within their given bounds. Configuration of chromosomes is displayed in Figure 1.

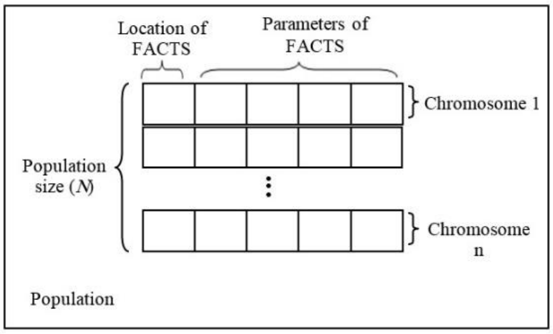

Figure 1. The configuration of chromosomes inside the population

The flowchart of optimization is displayed in Figure 2. An individual includes the location and control setting of a FACTS device is generated randomly and inserted into the population. The production will be iterated N times to create the given size of initial population. The fitness of each participant will be computed based on the objective function and constraints. An individual will be selected for the next generation according to its fitness value using Roulette Wheel technique. Then, a pair of individuals will be selected for crossover step and creation of new offspring with a probability P_c. Mutation functor is exerted to the population randomly to make amendment in the values of individuals with the probability P_m. After this stage, the most valuable individuals will be considered for the next generation. The number of 50 chromosomes is considered as population size and 100 iterations are set. The values 0.9 and 0.1 are set for P_c and P_m, respectively.

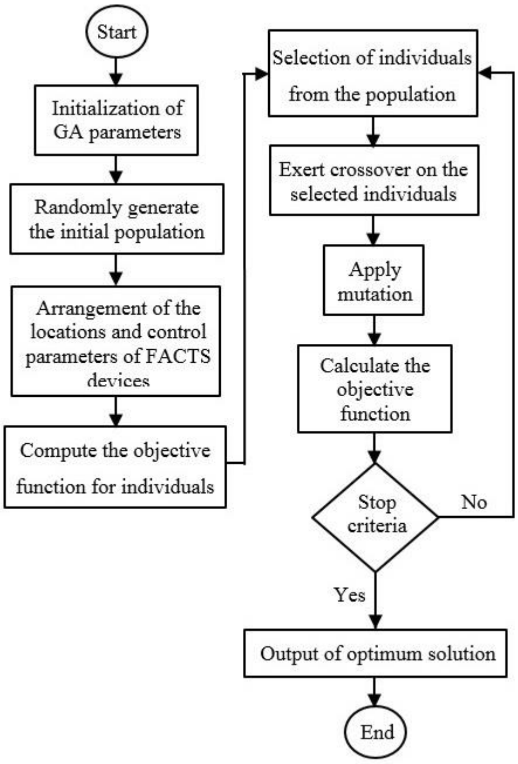

Figure 2. The flowchart of optimization

3. RESULTS AND DISCUSSION

An optimization method based on RNRGA is applied to investigate the location and parameters of controllers in test systems for increment of the gap with collapse point. The trace of RNRGA for is indicated in Figure 3. The calculation process after 100 generations reached to the optimum solution. In the first assessment four SVCs are located at buses number 4, 5, 9 and 14 of IEEE 14-bus test system. Nose curve of the systems without any FACTS devices is named base case. The nose curve of the weakest bus which is number 5 plotted in Figure 4. It is shown that the collapse point is moved from 4 p.u in the Base Case to 5.3 p.u at the optimal condition with SVC.

In IEEE 118-bus test system, eight SVCs are located at buses number 21, 30, 38, 44, 45, 52, 75 and 95. The PV curve of weakest bus which is number 44 is displayed in Figure 5. It is obvious that the collapse point of system altered from 3.2 (p.u) to 3.6 (p.u). In the second investigation, a TCSC is installed at line number 2 where is between buses 1 and 5 of IEEE 14-bus test system. As shown in Figure 6, the stability margin of system is improved about 0.75 p.u.

Three TCSC is located at lines number 38, 51, 60 of IEEE 118-bus system with optimum parameters. The stability margin of this case is changed to 3.5 (p.u). The PV curve of bus 44 is indicated in Figure 7.

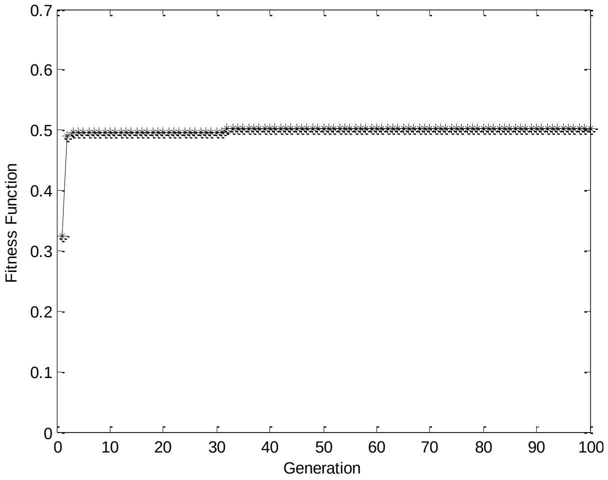

Figure 3. The calculation trace of RNRGA

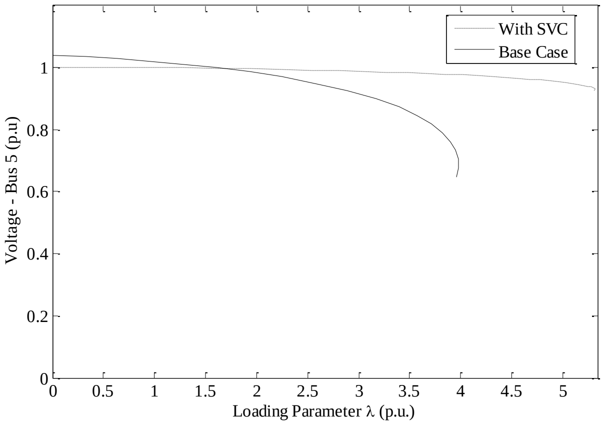

Figure 4. PV curve of bus 5 of IEEE 14-bus system with SVC

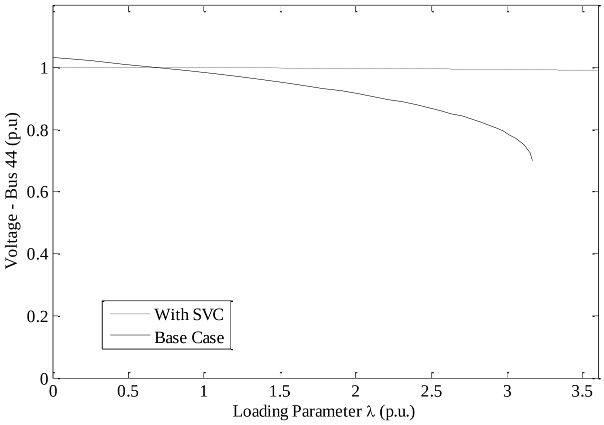

Figure 5. PV curve of bus 44 of IEEE 118-bus system with SVC

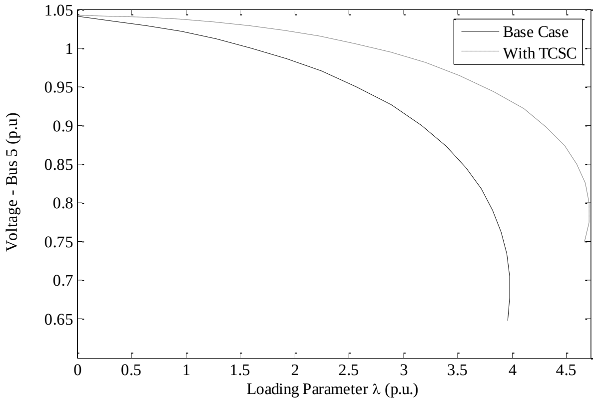

Figure 6. PV curve of bus 5 in IEEE 14-bus system with TCSC at line 2

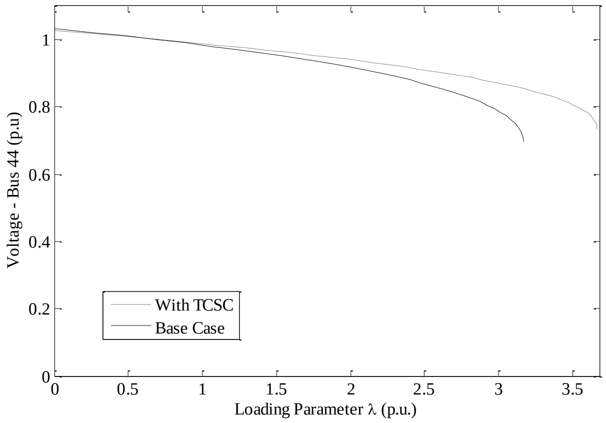

Figure 7. PV curve of bus 44 for IEEE 118-bus system with TCSC

In the next case, IEEE 14-bus test system is analyzed with four STATCOM. The RNRGA is proposed buses number 4, 5, 9 and 14 for installation of the controllers. The PV curve of bus 5 clarified that the stability margin of IEEE 14-bus system moved from 4 to 5.3 p.u compare to the same system without STATCOM as shown in Figure 8. In the next part, eight STATCOM is installed in IEEE 118-bus system at buses 22, 30, 38, 44, 45, 52, 75 and 95. The collapse point of test system in the presence of given STATCOMs changed from 3.2 to 3.6 p.u. The PV curve of bus 44 with STATCOM is displayed in Figure 9.

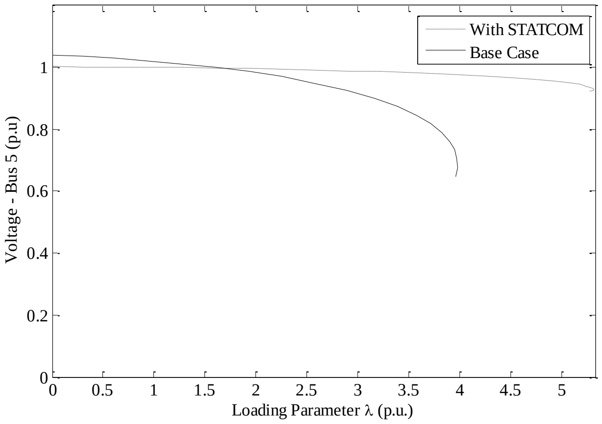

Figure 8. PV curve of bus 5 of IEEE 14-bus system with STATCOM

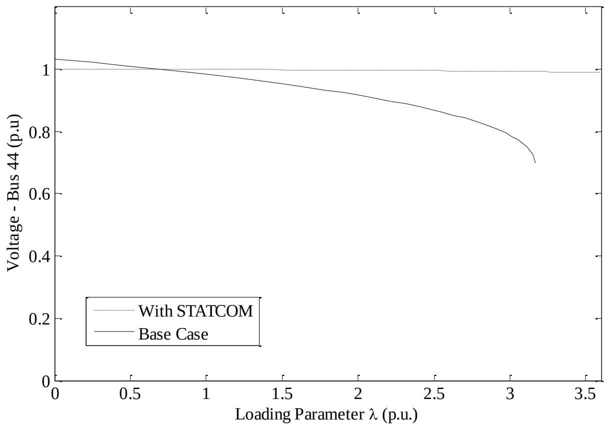

Figure 9. PV curve of bus 44 of IEEE 118-bus system with STATCOM

In the following investigation, three SSSCs are located in IEEE 14-bus system and RNRGA determined the lines 4, 9, 17 as optimum locations. The PV curve of bus number 5 of the system with three SSSC is indicated in Figure 10. Installation of SSSCs at given locations improved the stability limit of system from 4 to 6.3 p.u. On the other hand, eleven SSSCs are installed in IEEE 118-bus system at lines 25, 29, 36, 54, 59, 60, 62, 63, 74, 148 and 186. The collapse point of system is changed from 3.2 to 3.9 (p.u) at the optimal case. The PV of weakest bus at both condition and are shown in Figure 11.

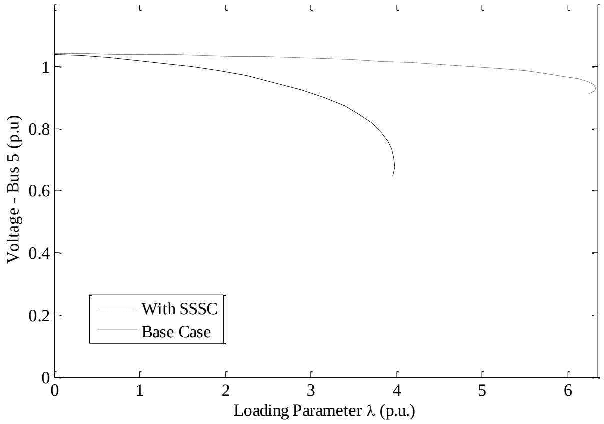

Figure 10. PV curve of bus 5 of IEEE 14-bus system with SSSC

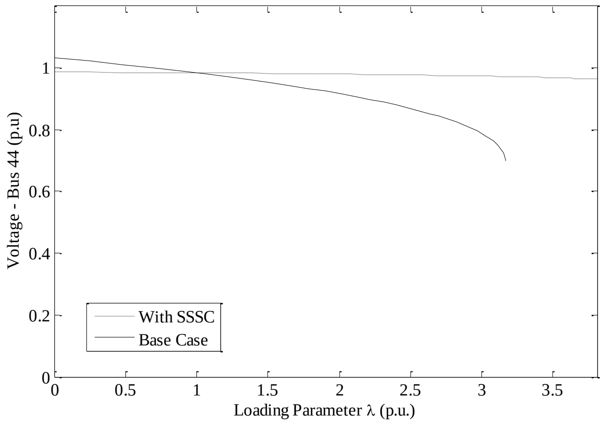

Figure 11. PV curve of bus 44 of IEEE 118-bus system with SSSC

The IEEE 14 bus test system is simulated with two UPFC at lines number 10 and 16. The PV curve of weakest bus of system is shown in Figure 12. It shows that the collapse point of system where occurred at 4 p.u in the Base Case improved to a new point close to 5.4 p.u. In another case, IEEE 118-bus system is simulated with UPFCs at lines number 9, 29, 51, 54, 61, 68, 83, 154 and 185. The stability margin of system changed from 3.2 to 3.7 p.u. The PV curve of bus 44 is displayed in Figure 13.

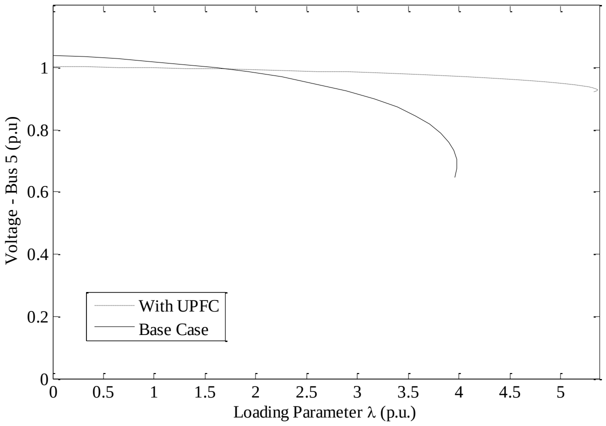

Figure 12. PV curve of bus 5 of IEEE 14-bus system with UPFC

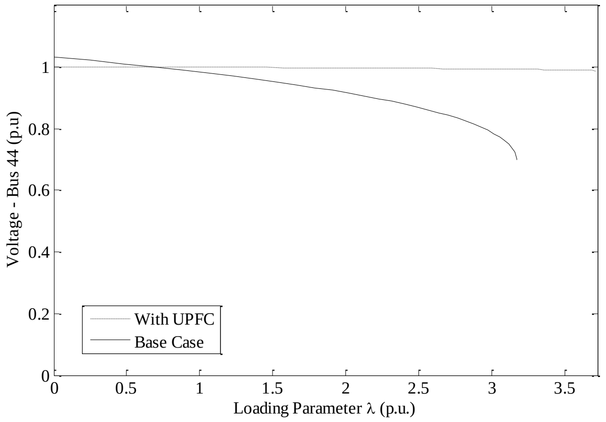

Figure 13. PV curve of bus 44 of IEEE 118-bus system with UPFC

4. CONCLUSION

The necessity of the placement of FACTS devices is studied as a significant issue for maximizing their benefits and obtain the high performance of these controllers. Different types of FACTS devices in various categories are used in this study for series compensation, shunt compensation and combination of both. Effect of each type of FACTS controllers is analyzed. The IEEE 14 and 118 bus test systems are simulated with given FACTS devices in MATLAB environment. The CPF analysis based on SNB is used to calculate the stability limit of the systems. RNRGA is described to determine the location and control parameters of given controllers simultaneously. The achieved results proved the efficiency of proposed technique.

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