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# Cat Swarm Optimization for optimal placement of multiple UPFC's in voltage stability enhancement under contingency

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ABSTRACT

Voltage stability categorized under various classifications of power system stability is considered one of the important subjects in power systems stability studies. A power system, experiencing disturbances, is at risks of voltage instability. Main reason for the cause of voltage instability is the sag in reactive power at various locations due to circuit contingencies classified under large disturbance voltage stability. The aim of this paper is to identify the optimal location of Unified Power Flow Controller in an interconnected power system under N-1 contingency. As the size and the cost of the FACTS devices are high, an optimal location and size has to be identified before they are actually installed. We are trying to improve the voltage profile and Maximum Loading Parameter using Unified Power Flow Controller while determining their optimal location based upon Cat Swarm Optimization.



## 1. Introduction

Due to continuous expansion of power system in accordance with the growing demand, stability studies have become a fascinated area for research in the modern day. Power system stability [13,14] is a very complex subject that has been challenging the power system engineers from the past three decades. Due to the continuous expansion of power systems to cater the needs of growing population, power system stability problems also are a continuous and fascinating area of study. When we operate a bulk power transmission network close to the voltage stability limit, it becomes difficult to control the reactive power demand for that system. Voltage stability is of major concern in power systems stability [10,11]. Main reason for the cause of voltage instability is due to the sag in reactive power at various locations in an interconnected power system network. Voltage stability is a problem in power systems which are heavily loaded, have a shortage of reactive power or faulted [19]. Although it usually has an involvement in one critical area, the problem of voltage stability concerns the whole power system. Voltage stability is concerned with the ability of a power system to maintain steady voltages at all buses in the system under normal operating conditions, and after being subjected to a disturbance. Instability may occur in the form of a progressive fall or rise of voltages at some buses. The possible outcome of voltage instability is a loss of integrity of the power system network or loss of load in the area where voltages reach unacceptably low values [17]. A power system at a given operating state is small disturbance voltage stable if, following any small disturbance such as unbalanced loads and load variations, voltages near loads are identical or close to the pre-disturbance values. Large disturbance voltage stability [10,11] refers to the system's ability to maintain steady voltages following large disturbances such as system faults, circuit contingencies or loss of generation. The voltages at various points after such a disturbance may reach the pre-disturbance values or not, leading to voltage sag at certain points. Though in India, power transmission and distribution systems have been centralized and cause of power system instability is very minimal, the line outages caused due to weather conditions is still being considered a serious problem. Reactive power deficiency and voltage degradation is serious during such situations. There is a necessity to throw light in this area to assess the voltage stability of an interconnected power system affected by such a contingency.

Using FACTS controllers [12] one can control the variables such as voltage magnitude and phase angle at chosen bus and line impedance where a voltage collapse is observed. Introducing FACTS devices is the most effective way for utilities to improve the voltage profile and voltage stability margin of the system. With the ongoing expansion and growth of the electric utility industry, including deregulation in many countries, numerous changes are continuously being introduced to a once predictable business. Although electricity is a highly engineered product, it is

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increasingly being considered and handled as a commodity. Flexible AC Transmission Systems (FACTS), provide proven technical solutions to address these new operating challenges being presented today. FACTS technologies allow for improved transmission system operation with minimal infrastructure investment, environmental impact, and implementation time compared to the construction of new transmission lines. Traditional solutions to upgrading the electrical transmission system infrastructure have been primarily in the form of new transmission lines, substations, and associated equipment. However, as experiences have proven over the past decade or more, the process to permit, site, and construct new transmission lines has become extremely difficult, expensive, time-consuming, and controversial. FACTS technologies [12] provide advanced solutions as cost-effective alternatives to new transmission line construction. The potential benefits of FACTS equipment are now widely recognized by the power systems engineering and T&D communities.

The aim of this paper is to identify the optimal location and size of Unified Power Flow Controller in an interconnected power system under N-1 contingency for voltage stability analysis. As the size and the cost of the FACTS devices are high, an optimal location and size has to be identified before they are actually installed. We are trying to improve the voltage profile and Maximum Loading Parameter using the FACTS controllers. Optimization techniques find a variety of use in many fields. As artificial intelligence techniques are improving day by day, the use of these techniques in power systems is playing an important role for the optimal location of FACTS devices. We are using Cat Swarm Optimization [5,6] to identify the optimal location and size of FACTS controllers. This is the first paper to introduce Cat Swarm Optimization technique for voltage stability analysis under contingency for the optimal placement of Unified Power Flow Controller.

## 2. Problem statement

A contingency is a failure or loss of an element (e.g., generator, transformer, transmission line, etc.), or a change of state of a device (e.g., the unplanned opening of a circuit breaker in a transformer substation) in the power system. Contingency analysis is essentially a “preview” analysis. It simulates and quantifies the results of problems that could occur in the power system in the immediate future. CA is used for the off-line analysis of contingency events, and show operators what would be the effects of future outages. This allows operators to be better prepared to react to outages by using pre-planned recovery scenarios. An “outage” is the removal of equipment from service. Line contingency refers to the removal of transmission line from the system. Where as in the case of generator contingency we assume that the particular generator is no longer a part of the system and usually the voltage variation is high. Both line contingency and generator contingency come under large disturbances. In this paper we are doing (N-1) line outage contingency analysis and we are trying to improve the voltage profile and Maximum Loading Parameter through the use of FACTS devices. (N-1) contingency refers to removal of transmission lines individually for (N-1) cases. At any instant only one particular line can be removed.

## 3. Objective function

The objective function is defined as follows

$$F = \{F_1, F_2, F_3\} \tag{1}$$

The functions $F_1$, $F_2$ and $F_3$ are defined and used in optimization process.

$$F = \Phi_1 F_1 + \Phi_2 F_2 + \Phi_3 F_3 \tag{2}$$

In our study, the fitness function is defined as a sum of three terms with individual criteria. The first part of the objective function concerns the voltages level. It is favorable that buses voltages be as close as possible to 1 p.u. Eq. (3) shows the voltage deviation in all buses.

$$F_1 = F_v = \left[\sum_{i=1}^{n_b} (V_i - 1)^2\right]^{1/2} \tag{3}$$

where $n_b$ is the number of buses and $V_i$ is the voltage of bus i.

F2-this function represents the optimal location and size of UPFC which has its dependence on $F_1$. This is related to having the minimum possible UPFC sizes regarding to the control of UPFC and is given by (4):

$$F_2 = F_S = \alpha \sum_{j=1}^{m} Q_j \tag{4}$$

where ‘$m$’ is the number of UPFCs and ‘$Q_j$’ is the value of UPFC’s kvar and ‘$\alpha$’ is a weight in order that the terms in the fitness function are comparable in magnitude. Value of UPFC’s kvar considering the control strategy and UPFC’s model is achieved.

The maximum loadability of power system is extremely important and hence it is considered as the third part of the objective function. The third issue in our problem is determining inverse of maximum loadability, given as follows:

$$F_3 = F_{SM} = 1/\lambda_{\text{Critical}} \tag{5}$$

Therefore, the objective function is given by the following equation.

$$F = \Phi_1 F_V + \Phi_2 F_S + \Phi_3 F_{SM} \tag{6}$$

The parameter that is used to examine system proximity to voltage collapse is called Maximum Loading Parameter, $\lambda$. In the bifurcation theory, it is assumed that system equations depend on a set of parameters together with state variables as shown in the equation below:

$$\Psi(\rho, \lambda) = 0 \tag{7}$$

Here, “$\rho$” is power system state variable and “$\lambda$” represents loading parameter. Stability or instability properties are assessed varying “slowly” these parameters.

The reason behind improving the Maximum Loading Parameter is to understand the maximum loadability limits of the interconnected power network and to determine the stability limits for run-up under secure conditions.

## 4. Test systems & software used

We are testing our algorithm here on two test systems: the 3-bus system and IEEE 14-bus system. The specifications of 3 bus system can be given as: Total number of buses used here are 3, total number of Lines used is 3, total Number of Generators is 1 and the total number of Loads is 2. The specifications of IEEE 14 bus system can be given as: the number of buses being 14, the number of Lines being 16, the generator count is 5 (including slack bus) and the number of loads being 11. Base MVA of 100 is assumed for the two test cases. All the analysis and testing here is performed in MATLAB [1]. Fig. 1 shows the 3 bus network and Fig. 2 displays the IEEE 14 bus network.

## 5. Cat Swarm Optimization and FACTS

### 5.1. Introduction to Cat Swarm Optimization

Optimization techniques find a variety of use in many fields. The use of these techniques in power systems is playing an

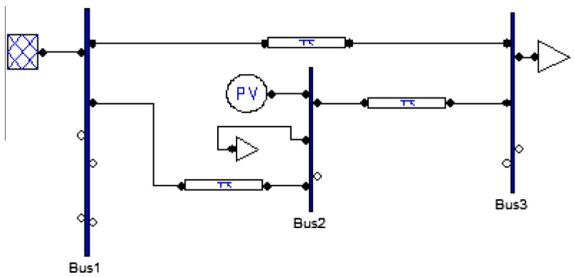


**Fig. 1.** 3-Bus power system.

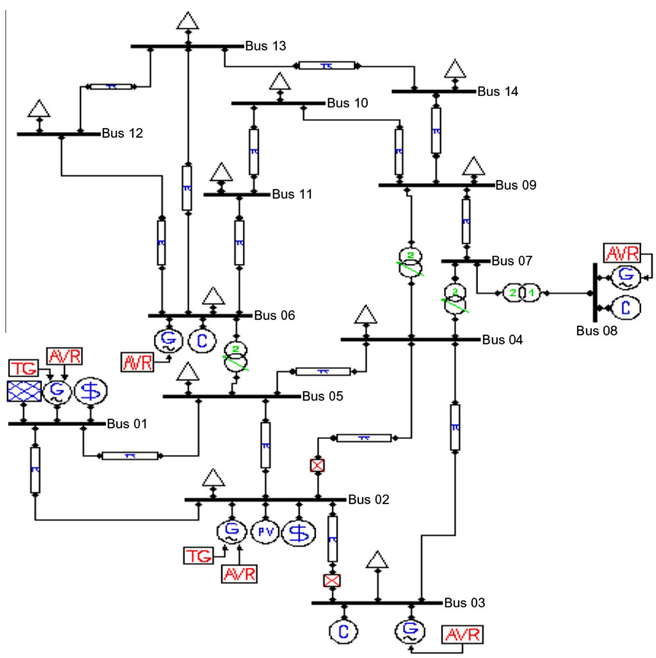


**Fig. 2.** Standard IEEE 14-bus system.

important role for the optimal location of FACTS devices. In the field of optimization, many algorithms were proposed in recent years. Examples include Genetic Algorithm (GA), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Simulated Annealing (SA). Some of these optimization algorithms were developed based on swarm intelligence. Cat Swarm Optimization in short CSO, the algorithm, is motivated from PSO and ACO. According to the literatures, PSO with weighting factor usually finds the better solution faster than the pure PSO. But according to the experimental results, Cat Swarm Optimization (CSO) presents even much better performance [7].

### 5.2. Proposed algorithm

In Cat Swarm Optimization, we first model the behavior of cats into two sub-models, namely, seeking mode and tracing mode [6,18].

#### 5.2.1. The solution set in the model – cat

Solution set must be represented in some manner. We use cats and the model of behaviors of cats to solve the optimization problems, i.e., we use cats to portray the solution sets. In CSO, we first decide how many cats we would like to use. Then we apply the cats into CSO to solve the problems. Every cat has its own position composed of M dimensions, velocities for each dimension and a flag to identify whether the cat is in seeking mode or in tracing mode. The final solution would be the best position in one of these cats because CSO keeps the best solution till it reaches the end of iterations.

#### 5.2.2. Seeking mode

This sub-model [6] is used to model the situation of the cat, which is resting, looking around and seeking the next position to move to. In seeking mode, we define four essential factors: seeking range of the selected dimension (SRD), counts of dimension to change (CDC), and self-position considering (SPC). SMP is used to define the size of seeking memory for each cat, which indicates the points sought by the cat. The cat would pick a point from the memory pool according to the rules described. SRD declares the mutative ratio for the selected dimensions. These factors are all playing important roles in the seeking mode. SPC is a variable, which decides whether the point, where the cat is already standing will be one of the candidates to move to.

The seeking mode can be described in 5 steps as follows:

Step 1: select the total number cats that have to be considered.
Step 2: for each cat, a fixed range of velocities has to be assumed.
Step 3: calculate the fitness values (FS) of all candidate points.
Step 4: select how many cats to be available in seeking mode.
Step 5: randomly pick the cat from the total number of cats and apply in seeking mode according to the following equation [5]:

$$P_{kn} = [(1 \pm 0.3)R_{and}()] * P_k \quad (8)$$

where, $n$ = 1, 2, 3, 4, 5, etc. Where $R_{and}$ ( ) is a random value in the range of [0, 1].

Here, '$P$' is the pick-up of the cat from a random number of cats and $P_k$ is the total number of cats available for application.

$$P_i = (FS_i - FS_b)/(FS_{max} - FS_{min}), \quad 0 < i < j \quad (9)$$

If the goal of the fitness function is to find the minimum solution,

$$FS_b = FS_{max}, \text{ otherwise } FS_b = FS_{min} \quad (10)$$

#### 5.2.3. Tracing mode

Tracing mode is the sub-model [6] for modeling the case of the cat in tracing some targets. Once a cat goes into tracing mode, it moves according to its own velocities for every dimension. The action of tracing mode can be described in 3 steps as follows:

Step 1: update the velocities for every dimension ($V_{k,d}$) according to equation.
Step 2: check if the velocities are in the range of maximum velocity. In case the new velocity is over range, set it be equal to the limit.
Step 3: update the position of cat$_k$ and again calculate the best fitness value. Proceed till the best fitness value is obtained and correspondingly, the cat location and the velocity.

$$V_{k,d} = V_{k,d} + r1 \cdot c1 \cdot (P_{best,d} - P_{k,d}), \quad d = 1, 2, \ldots, M \quad (11)$$

where $P_{best,d}$ is the position of the cat, which has the best fitness value. $V_{k,d}$ the velocity for every dimension. $P_{k,d}$ the position of cat$_k$, $c_1$ is a constant and $r_1$ is a random value in the range of [0, 1].

$$P_{k,d} = P_{k,d} + V_{k,d} \quad (12)$$

#### 5.2.4. Algorithm for the Cat Swarm Optimization

As described in the above subsection, CSO includes two sub-models, the seeking mode and the tracing mode. To combine the

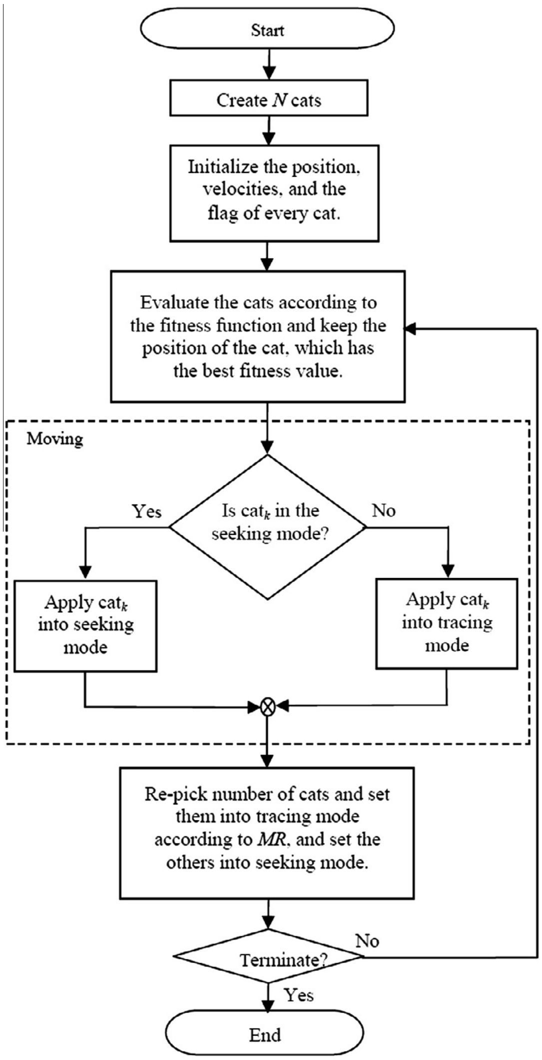


**Fig. 3.** Flow chart for the CSO technique.

two modes into the algorithm, we define mixture ratio (MR) of joining seeking mode together with tracing mode. While they are resting, they move their position carefully and slowly, sometimes even stay in the original position. The algorithmic flow routine for the CSO can be explained through the flow chart in Fig. 3.

### 5.3. FACTS

Flexible AC Transmission Systems (FACTS) [9] controllers have been used in power systems since the 1970s with the objective of improving system dynamic performance. Due to the environmental, right of-way, and cost problems in both bundled and unbundled power systems, many transmission lines have been forced to operate at almost their full capacities worldwide. FACTS controllers enhance the static performance viz. increased loading, congestion management, reduced system loss, economic operation, etc., and dynamic performance viz. increased stability limits, damping of power system oscillation, etc. The concept of FACTS involves a family of fast acting, high power, and electronic devices, with advanced and reliable controls. By using FACTS controllers' one can control the variables such as voltage magnitude and phase angle at chosen bus and line impedance. Flexible alternating-current transmission systems (FACTS) defined as "ac transmission systems incorporating power electronics based and other static controllers to enhance controllability and increase power transfer capability". Alternatively, a FACTS controller is defined as "a power electronics-based system or other static equipment that provides control of one or more ac transmission parameters". In recent years, many different FACTS controllers have been proposed, performing a wide variety of functions. Using FACTS controllers one can control the variables such as voltage magnitude and phase angle at chosen bus and line impedance where a voltage collapse is observed [2-4].

#### 5.3.1. UPFC-Unified Power Flow Controller

The Unified Power Flow Controller in short, UPFC [9,16] is a combination of STATCOM and SSSC, sharing a common dc link as shown in Fig. 4 below. The UPFC can control both the active and reactive power flow in the line. It provides independently controllable shunt reactive compensation. The UPFC is a two-port circuit (in series with a transmission line and parallel with a bus bar). The series voltage source and the shunt current source are defined as follows taken from [15]:

$$V_S = (V_p + V_q)e^{j\varphi} = rV_k e^{j\gamma} \tag{13}$$

$$i_{SH} = (i_p + i_q)e^{j\theta k} \tag{14}$$

The power equations that describe the power injection model of the UPFC are as taken from [15]:

$$P_{km} = b_r V_k V_m \sin(\gamma + \theta_k - \theta_m) \tag{15}$$

$$Q_{km} = b_r V_k^2 \cos\gamma - i_q V_k \tag{16}$$

$$P_{mk} = -b_r V_k V_m \sin(\gamma + \theta_k - \theta_m) \tag{17}$$

$$Q_{mk} = -b_r V_k V_m \cos(\gamma + \theta_k - \theta_m) \tag{18}$$

The POD controller can be used to modulate whatever of UPFC variables ($v_p$, $v_q$, $i_q$). The set of differential equations are as follows as depicted in [15]:

$$V_p = (V_{po} + u_1 V_{POD} - V_p)/T_r \tag{19}$$

$$V_q = (V_{qo} + u_2 V_{POD} - V_q)/T_r \tag{20}$$

$$I_q = [K_r(V_{ref} + u_3 v_{POD} - V_k) - i_q] \tag{21}$$

where, $u_1$, $u_2$ and $u_3$ are 1 if the correspondent stabilizing POD signal is enabled, '0' otherwise. '$\gamma$' is the relative UPFC angle. $V_{po}$ is the initial compensation voltage. $V_{qo}$ is the initial compensation voltage.where, $V_p$ represents the component of the series voltage $V_s$ that is in phase with the line current. In steady-state, the input $V_{po}$ is set to zero so that the exchange of active power between the UPFC and the ac system only takes place when this variable is modulated by the POD controller (i.e., during transients). $V_q$ represents the component of series voltage $V_s$ that is in quadrature with line current. The input $V_{qo}$ determines the value of the variable $V_q$ in steady-state [15].

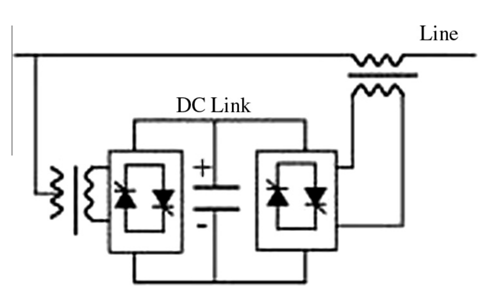


**Fig. 4.** Structure of UPFC.

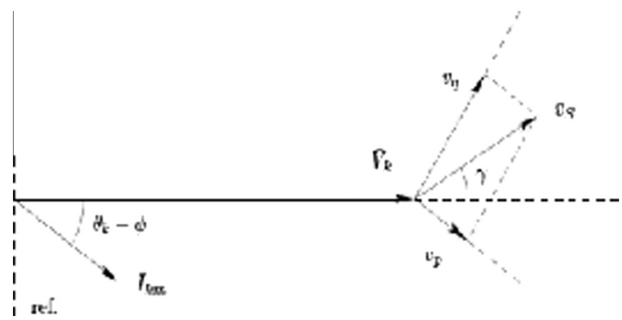

**Fig. 5.** UPFC phasor diagram.

Two control modes are implemented for this variable:

(1) Constant voltage: the magnitude of voltage $V_q$ is constant independently of the line current.
(2) Constant reactance: the magnitude of the voltage $V_q$ varies proportionally to the line current keeping constant the total impedance of the transmission line.

$I_q$ represents the component of shunt current $I_{sh}$ which is in quadrature with the bus voltage $V_k$. This current keeps the bus voltage around a specified level through the regulator gain $K_r$.

The above data and the Phasor diagram depicted in Fig. 5 below are taken from [15].

## 6. Implementation, results and discussions

The implementation of the present problem and its solution can be explained as follows. We run the CPF for the base case that is the pre-disturbance case and the voltage magnitudes at various buses are noted. And now we introduce the circuit contingency i.e., the line outage and rerun the CPF routine to know the deterioration of voltages. Similarly we continue this for N-1 cases and the Maximum Loading Parameter and the voltages at the respective buses is noted. From the N-1 line contingency analysis we identify the critical cases for which there is maximum deviation in the voltages. On analysis we found that line 16 outage shows a higher rate of deterioration of voltages. After identifying the worst locations for line contingencies, the UPFC's are introduced into the system at appropriate places applying CSO technique, which is used to decide both location and VAR requirements for the FACTS device. The maximum load-ability limit and voltage magnitude profile of the system at the weakest buses have been brought back to the pre disturbance values.

### *6.1. Case 1: 3-bus network*

Three bus system: The theoretical and practical results of a 3-bus system without considering line outage are shown. The theoretical values were found out using Newton–Raphson method. In N–R method the active and reactive power equations are given as follows:

$$P_i = \Sigma V_i V_k Y_{ik} * \cos(\delta_i - \delta_k - \theta_{ik}) \quad (22)$$

$$Q_i = \Sigma V_i V_k Y_{ik} * \sin(\delta_i - \delta_k - \theta_{ik}) \quad (23)$$

Using the above equations the voltages at their respective buses are obtained as shown in Table 1.

For the line outage contingency case, we find the theoretical values and simulate the same for a practical system using Newton–Raphson Technique. We assume that for this case the transmission line between bus-1 and bus-3 is eliminated. The results are shown in Table 2. Now we place the UPFC controller between bus-3 and bus-2 using CSO technique, simulate and note down the respective voltages and line flows between the buses as displayed in Table 3.

**Table 1**
3-Bus network results without line outage.

| Bus | Theoretical values *V* (p.u.) | Simulation results *V* (p.u.) |
|---|---|---|
| 1 | $1.05\angle 0$ | $1.05\angle 0$ |
| 2 | $1.03\angle -2.8517$ | $1.03\angle -2.8517$ |
| 3 | $1.0248\angle -1.947$ | $1.0248\angle -1.946$ |

**Table 2**
3-Bus network results with line outage.

| Bus | Theoretical values *V* (p.u.) | Simulation results *V* (p.u.) |
|---|---|---|
| 1 | $1.05\angle 0$ | $1.05\angle 0$ |
| 2 | $1.03\angle -0.2298$ | $1.03\angle -0.23305$ |
| 3 | $0.9475\angle -0.3202$ | $0.93896\angle -0.3301$ |

**Table 3**
3-Bus network results with UPFC installed between bus-3 and bus-2.

| Bus | *V* (p.u.) with UPFC between buses 3 and 2 |
|---|---|
| 01 | $1.05\angle 0$ |
| 02 | $1.03\angle -0.22596$ |
| 03 | $1.0256\angle -0.236189$ |

### *6.2. Case 2: IEEE 14-bus network*

#### *6.2.1. FACTS used: UPFC (for Line 16 outage)*

The following Table 4 shows the results for N-1 contingency analysis where in for each line outage, only the worst cases of voltage magnitude profiles at particular buses in p.u. are shown. The remaining blocks represent Acceptable Values (AL) of voltage magnitude profiles. N-1 contingency for 16 lines on IEEE 14-bus test network was performed to determine the worst case and the weakest buses. We found that Line-3, Line-7 and Line-16 outages have reported very low voltage profiles and the solution using CSO has been applied to one of these cases in this paper i.e., Line-16 outage.

The two UPFC's used are taken in seeking and tracing modes respectively and their size in terms of VAR requirement is sorted based on the number of iterations run with various number of VAR ratings induced in them based on Cat Swarm Optimization. The location is decided according to the picture obtained from contingency analysis given in Table 4. 50 Numbers of iteration are run for this technique, of which the global best solution is taken into consideration. The best location and optimal size of UPFC for line 16 contingency is between the bus locations 13–14 and 14–09 with size equal to 0.8 kvar, 1 kvar for the test network. If we compare the present implemented CSO technique with PSO that was implemented in [8], we see a significant reduction in computational effort needed to solve for the voltage stability problems for choosing the optimal placement and size of FACTS controllers for the same number of iterations. Also this was proved in [5]. In [8] TCSC was used to solve for the voltage stability problems using PSO, but an advanced device, UPFC which shows the properties of both series and shunt compensation has been successfully utilized here to solve for the problem. PSO is a primitive technique in comparison with CSO and implementation of latest AI technique i.e., CSO is a proof for the results obtained that are illustrated using Figs. 7–11 and Tables 1–7 in the paper.

**Table 4**
N-1 contingency analysis for IEEE 14 bus network.

| Bus no. | Voltage magnitude profile | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | LO-1 | LO-2 | LO-3 | LO-4 | LO-5 | LO-6 | LO-7 | LO-8 | LO-9 | LO-10 | LO-11 | LO-12 | LO-13 | LO-14 | LO-15 | LO-16 |
| 1 | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL |
| 2 | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL |
| 3 | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL |
| 4 | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | **0.81681** | **AL** | **0.86382** | AL | AL |
| 5 | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | **0.83362** | AL | AL |
| 6 | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL |
| 7 | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL |
| 8 | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL | AL |
| 9 | | **0.71577** | **0.65886** | | | **0.66099** | | **0.62245** | **0.73489** | **0.69143** | **0.73255** | **0.8388** | **0.7604** | AL | **0.70855** | AL |
| 10 | **0.69903** | **0.70793** | **0.66336** | | **0.63381** | **0.63157** | **0.58774** | **0.63909** | **0.73115** | **0.68326** | **0.72736** | | **0.75621** | AL | **0.7** | AL |
| 11 | AL | AL | AL | AL | **0.70354** | AL | **0.56107** | AL | AL | AL | AL | AL | AL | AL | AL | AL |
| 12 | **0.63827** | AL | AL | **0.75873** | AL | AL | | AL | AL | AL | AL | AL | AL | AL | AL | **0.66922** |
| 13 | AL | AL | AL | **0.71185** | AL | AL | | AL | AL | AL | AL | AL | AL | AL | AL | **0.50774** |
| 14 | **0.63193** | **0.65267** | **0.48452** | **0.50283** | **0.67456** | **0.62299** | **0.60413** | **0.63047** | **0.69626** | **0.63035** | **0.68693** | **0.81645** | **0.72091** | **0.88596** | **0.65043** | **0.53445** |

LO: line outage.
AL: acceptable limit.
Bold values indicate the low voltage magnitude in P.U.

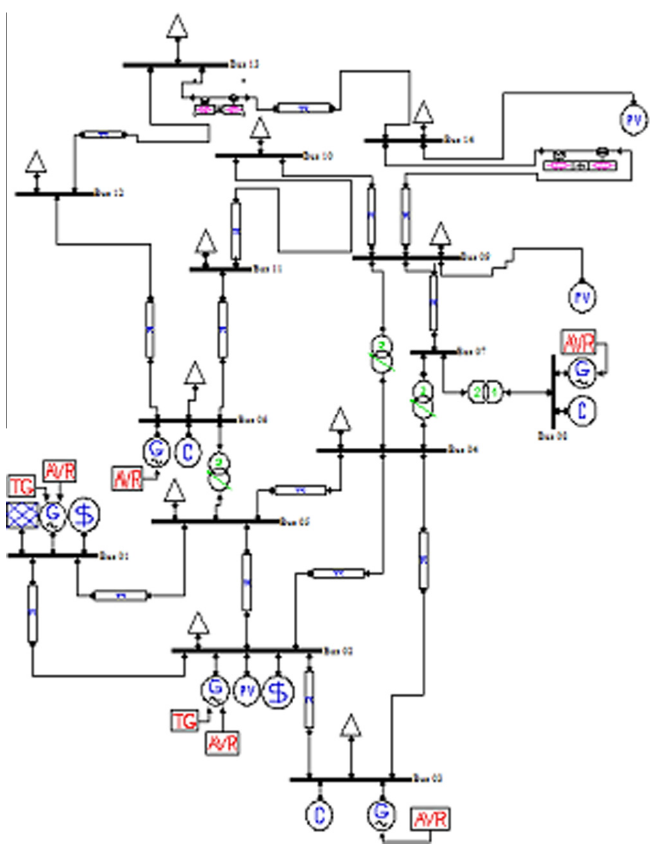

**Fig. 6.** 14-Bus system with UPFC's placed in the optimal location (for line 16 outage).

We are attempting to show that UPFC used here is better compared to a series device. TCSC is a primitive device, very popular even today and has got a very good performance. But we have to throw light on latest trends in FACTS technology and this is the sole idea behind using UPFC owing to its use both as a series and shunt device even though its operation is complicated and is expensive. The results presented here are better because CSO is superior to PSO in the fast convergence and better performance to find the global best solution. The series and shunt converters of the UPFC

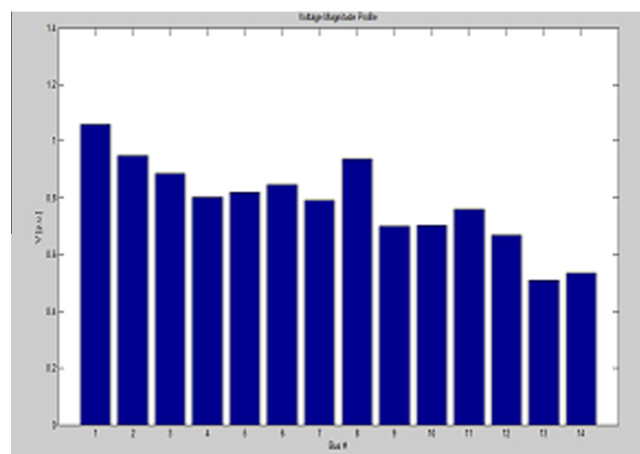

**Fig. 7.** Voltage magnitude profile before placement of UPFC's.

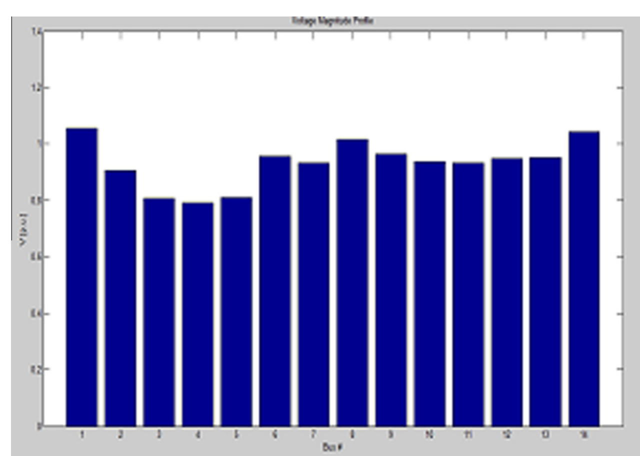

**Fig. 8.** Voltage magnitude profile after placement of UPFC's.

device were used in constant voltage mode, where the magnitude of voltage $V_q$ is constant independently of the line current.

The results are displayed in Tables 5 and 6. Table 7 shows the improvement in voltage profile and Maximum Loading Parameter for line 16 contingency when 2 UPFC's are used in the location 13–14, 14–09. The optimum size of the two UPFC's used here in

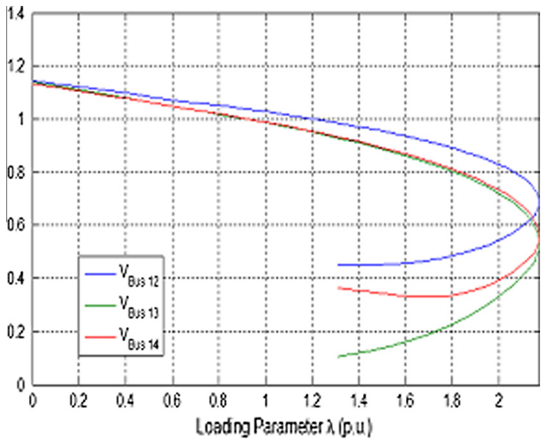


**Fig. 9.** PV curves before placement of UPFC's.

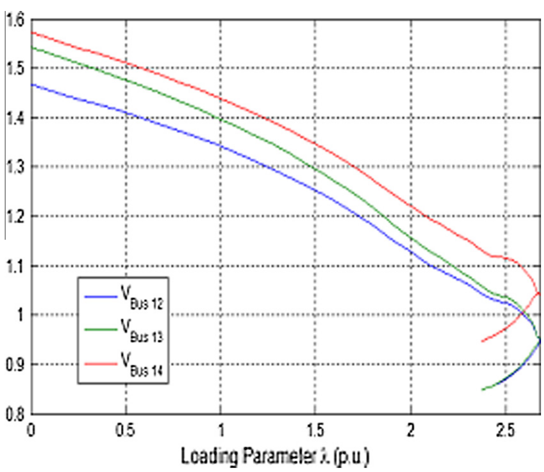


**Fig. 10.** PV curves after placement of UPFC's.

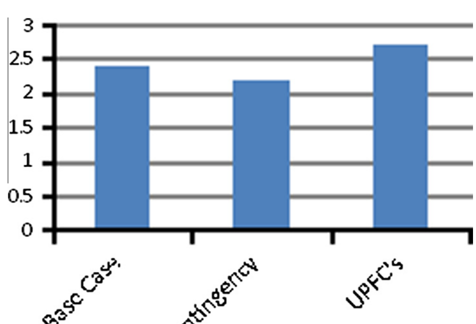


**Fig. 11.** Maximum Loading Parameter for different cases.

terms of its converter ratings is 0.8 kvar and 1 kvar respectively with 50% gain and a time constant of 0.1. The UPFC is utilized here in constant voltage mode. Maximum values of $V_p$, $V_q$ and $I_q$ are 1.15, 1.15 and 1.1 in p.u. and minimum values of $V_p$, $V_q$ and $I_q$ are 0.85, 0.85 and 0.9 respectively.

The parameters that constitute the dimensions of the position of the CAT in this case are listed below:

No. of iterations carried for CSO: 50
No. of cats used: 02
No. of cats in seeking mode: 01
No. of cats in tracing mode: 01

**Table 5**
UPFC2 between bus 14 and bus 9 applied in tracing mode.

| UPFC1 bt. buses 13 and 14 in kvar | UPFC2 bt. buses14 and 9 in kvar | $\lambda_{max}$ |
|---|---|---|
| 2 | 2 | – |
| 1.5 | 1.5 | – |
| 1.2 | 1.2 | – |
| **1** | **1** | **2.6762** |
| 1 | 0.9 | 2.6749 |
| 1 | 0.8 | 2.6749 |
| 1 | 0.7 | 2.6741 |
| 1 | 0.5 | 2.6705 |
| 1 | 0.3 | 2.6686 |
| 1 | 0.2 | 2.6692 |
| 1 | 0.15 | 2.6697 |

**Table 6**
UPFC1 between bus 13 and bus 14 applied in tracing mode.

| UPFC1 between buses 13 and 14 in kvar | UPFC2 between buses14 and 9 in kvar | $\lambda_{max}$ |
|---|---|---|
| 1.2 | 1 | – |
| 1 | 1 | 2.6762 |
| 0.9 | 1 | 2.6767 |
| **0.8** | **1** | **2.679** |
| 0.7 | 1 | 2.6786 |
| 0.5 | 1 | 2.6771 |
| 0.3 | 1 | 2.6757 |

**Table 7**
Voltage profile before and after contingency.

| Bus no. | *V* (p.u.) before contingency (with-out UPFC) | *V* (p.u.) after contingency (line 16) | *V* (p.u.) after contingency (with 2 UPFC's) |
|---|---|---|---|
| 01 | 1.0572 | 1.0577 | 1.0567 |
| 02 | 0.93179 | 0.94915 | 0.90569 |
| 03 | 0.85811 | 0.88577 | 0.80674 |
| 04 | 0.77903 | 0.80139 | 0.79135 |
| 05 | 0.79614 | 0.82107 | 0.80904 |
| 06 | 0.82196 | 0.8462 | 0.95657 |
| 07 | 0.79451 | 0.79031 | 0.93273 |
| 08 | 0.93818 | 0.93788 | 1.0168 |
| 09 | 0.72039 | 0.70069 | 0.96335 |
| 10 | 0.71231 | 0.70156 | 0.93772 |
| 11 | 0.75452 | 0.76107 | 0.93384 |
| **12** | **0.7663** | **0.66922** | **0.9495** |
| **13** | **0.74451** | **0.50774** | **0.9511** |
| **14** | **0.66134** | **0.53445** | **1.0438** |
| **MLP ($\lambda_{max}$)** | **2.375** | **2.1732** | **2.679** |
| **$Q_{GEN}$** | **7.1003** | **6.463** | **6.5647** |

Figs. 6, 7 and 10 show us the improvement in voltage magnitude profile and Maximum Loading Parameter (MLP) before and after placement of UPFCs using CSO for the contingency case. This proves for the achievement of $F_1$ in the objective function. $F_2$ and $F_3$ which defines the second and third part of the objective function is achieved from $F_1$, as it is evident that the optimal placement of the two UPFC's using CSO itself indicates the improvement of the steady state voltage stability limit in these test cases. Figs. 8 and 9 display the PV curves obtained of continuation power flow (CPF) routine.

Table 7 shows that the voltage magnitude profile for buses 3, 4 and 5 are below 0.80614, 0.79135 and 0.80904 p.u. respectively. Out of this, voltage at bus-4 can be seen as unacceptable. This can be considered as a layback/error or disadvantage but can be addressed as a separate issue in the future research work on this topic.

## 7. Conclusion

In this paper, a novel method is presented to determine the optimal placement of multiple UPFC's to enhance the power system voltage stability under large disturbance contingency. The Maximum Loading Parameter and bus voltage magnitude profile are employed as the measure of power system performance in optimization algorithm. This method is based on Cat Swarm Optimization (CSO). Apart from optimal location, size of the UPFC's is also determined using CSO. We choose UPFC compared to the other available FACTS controllers owing to its operational benefits though it is costly. This algorithm was found to be easy and effective in implementing in comparison with earlier AI techniques. It is capable of finding multiple optimal solutions to the constrained multi objective problem, giving more flexibility to make the final decision about the location of the FACTS controller. It can be concluded that for large power systems, CSO algorithm can have a significant advantage, compared to exhaustive search and PSO techniques, by giving better solutions with lesser computational effort.

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