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ALLOCATION OF FACTS DEVICES FOR ATC ENHANCEMENT USING GENETIC ALGORITHM

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ABSTRACT

In this paper, a method using Genetic Algorithm is proposed to determine the optimal allocation of FACTS devices for maximizing the Available Transfer Capability (ATC) of power transactions between source and sink areas in the deregulated power system. Two types of FACTS are simulated in this study namely Thyristor Controlled Series Compensator (TCSC) and Unified Power Flow Controller (UPFC) for enhancing the available transfer capability of the interconnected power system. A Repeated Power Flow with FACTS devices including ATC is used to evaluate the feasible ATC value within real and reactive power generation limits, line thermal limits and voltage limits. An IEEE24- bus (single area) system is used to demonstrate the effectiveness of the algorithm as an optimization tool to enhance ATC. A Genetic Algorithm technique is used for validation purposes. The results clearly indicate that the introduction of FACTS devices in a right location could enhance ATC.

Keywords: available transfer capability, flexible AC transmission systems, genetic Algorithm, TCSC, UPFC.

INTRODUCTION

In recent years, power system operation faces new challenges due to deregulation and restructuring of the electricity markets. The old system known as monopoly based are substituted by a competitive marketplace. Hence the new structures of power system become more complex. These new structures have to deal with problem raised by the difficulties in building new transmission lines and the significant increase in power transactions associated to competitive electricity markets. Thus a large interconnected system has been built in order to be able to obtain a high operational efficiency and network security. In this situation, one of the possible solutions to improve the system operation is the use of flexible AC transmission technologies (FACTS). The implementation of the FACTS devices extends the possibility that current through a line can be controlled at a reasonable cost, enabling large potential of increasing the capacity of existing lines, and use of one of the FACTS devices to enable corresponding power to flow through such lines under normal and contingency conditions. Several studies [1-3] have found that FACTS technology not only provides solutions for efficiently increasing transmission system capacity but also increases ATC, relieve congestion, improve reliability and enhances operation and control.

However, it is hard to determine the optimal allocation and parameters of FACTS devices due to the complicated combinatorial optimization. Thus, attention is paid in this current work to study a technique to optimally allocate the devices to enhance ATC.

The task of calculating ATC is one of main concerns in power system operation and planning. ATC is determined as a function of increase in power transfers between different systems through prescribed interfaces. In this research, the ATC is calculated using Repetitive Power Flow (RPF) and the effectiveness of the devices to enhance ATC is investigated using IEEE24 bus test systems.

This paper is divided into several sections. Section II elaborates the Available Transfer Capability. Section III describes computational procedure for ATC determination while Section IV presents mathematical model of the TCSC Device and Section V describes modeling of UPFC. Section VI presents the background theory and the procedure of Genetic algorithm to allocate FACTS devices. The simulation results are presented and discussed briefly in Section VII. Section VIII concludes the paper.

AVAILABLE TRANSFER CAPABILITY

Mathematically, ATC is defined as [4, 5], the Total Transfer Capability (TTC) less the Transmission Reliability Margin (TRM), less the Capacity Benefit Margin (CBM) and the sum of existing transmission commitments (TC) which includes retail customer service. Transmission Reliability Margin (TRM) [4, 5] is defined as that amount of transmission transfer capability necessary to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system conditions. Capacity Benefit Margin (CBM) [4, 5] is defined as that amount of transmission transfer capability reserved by load serving entities to ensure access to generation from interconnected systems to meet generation reliability requirements.

$$ATC = TTC - TRM - CBM - TC \quad (1)$$

In this paper, the margins such as TRM and CBM are not considered. Therefore ATC here can be expressed as:

$$ATC = TTC-TC \quad (2)$$

The procedure proposed involves the method based on multiple load flow runs AC load flow for each increment of transaction between an interface and checks whether any of the operating conditions such as line flow limit or bus voltage limit is violated. The minimum out of the two critical transaction values is taken as the TTC for the system in that condition.

A method based on continuation power flow [4] incorporating limits of reactive power flows, voltage limits as well as voltage collapse and line flow limits is described. However, with this method the computational effort and time requirement are large. The topological information of a system is stored in matrix form and constants for different simultaneous cases and critical contingencies have been calculating before hand and used for determination of ATC values. For very large systems, the method may be quite cumbersome. The localized linearity of the system is assumed and additional load required to hit the different limits are separately calculated and the minimum of all these is taken as ATC.

Method based on linear sensitivity factors offer a great potential for real time calculation of ATC. Use of these factors offers an approximate but extremely fast model for the static ATC determination. The DC power transfer distribution factors are derived (DCPTDFs) based on DC load flow assumptions and hence are provide less accurate results. The new set of AC power transfer distribution factors [2] (ACPTDFs) to determine static ATC more accurately.

It is highly recognized that FACTS devices, specially the series devices such as thyristor controlled series capacitor (TCSC), thyristor controlled phase angle regulator (TCPAR), the unified power flow controller (UPFC) etc. can be applied to increase the ATC of power network. If FACTS device is placed randomly in any line, the ATC between seller bus/area and the buyer bus/ area will increase. But if FACTS device is placed at a particular line [10, 11], ATC of that line will be increased.

COMPUTATIONAL METHODS

A. ATC Determination using DC power transfer distribution factors

1) Computation of DC distribution factors

A method based on DC power transfer distribution factors is proposed. From the power flow point of view, a transaction of a specified amount of power that is injected into the system at one zone by a generator and removed at another zone by a load. The linearity property of the DC power flow model can be used to find the transaction amount that would give rise to a specified power flow, such as an interface limit. The coefficient of the linear relationship between the amount of a transaction and the flow on a line is called the power transfer distribution factor (PTDF). PTDF is also called sensitivity because it relates the amount of one change transaction amount to another change line power flow [6-8].

The PTDF is the fraction of amount of a transaction from one zone to another that flows over a given transmission line. $PTDF_{iij-mn}$ is the fraction of a transaction from zone m to zone n that flows over a transmission line connecting zone i to zone j. The equation for the PTDF is

$$PTDF_{ij-mn} = (X_{im} - X_{jm} - X_{in} + X_{jn}) / X_{ij} \quad (3)$$

Where

X_{ij} - reactance of the transmission line connecting zone i and zone j.
X_{im} - entry in the i^{th} row and the m^{th} column of the bus reactance matrix X.

2) ATC Determination using DC power transfer distribution factors

The ATC from seller bus/area to buyer bus/ area could be found using a DC power flow by varying the amount of transaction until a limit is reached, but this is computationally inefficient. Instead, the DC power transfer distribution factors described above can be used to quickly calculate the maximum allowable flow.

The PTDF can be used to directly calculate the ATC. A transaction from zone m to zone n creates a change in the flow on a line from zone i to zone j of ΔP_{ij}. The new flow on the line is the sum of the original flow p_{ij}^{0} and the change, and it must be less than the line's flows limit $P_{ij}^{max.}$

$$P_{ij}^{new} = P_{ij}^{0} + \Delta P_{ij} \leq P_{ij}^{max} \quad (4)$$

Applying equation (4) and solving for the transaction amount,

$$P^{max}_{mn,ij} \leq (P_{ij}^{Max} - P^{0}_{ij}) / PTDF_{ij,mn} \quad (5)$$

$P^{max}_{mn,ij}$ is the maximum allowable transaction amount from zone m to zone n constrained by the line from zone i to zone j is the minimum of the maximum allowable transaction over all lines

$$ATC_{mn} = \min \{P^{max}_{mn,ij}\} \quad (6)$$

B. ATC determination using AC power transfer distribution factors

Consider a bilateral transaction t_p between a seller bus, m and buyer bus, n. Further consider a line l, carrying a part of the transaction power. Let the line be connected between a bus-i and a bus-j. For a change in real power transaction between the above seller and buyer say by Δt_p MW, if the change in transmission line quantity q_l is Δq_l, the AC power transfer distribution factors can be defined as [6-8]:

$$(ACPTDF)_{ql-tp} = \frac{\Delta q_l}{\Delta t_p} \quad (7)$$

In this paper, the transmission quantity q_l is taken as real power flow from bus-i to bus-j.

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1) Computation of AC distribution factors

The distribution factors have been computed with the base case load flow results using the sensitivity properties of the NRLF Jacobean. The procedure for calculation of these distribution factors is described below. Consider the sensitivity relationship provided by the Newton-Raphson load flow equations in the polar coordinates for a base case load flow as:

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} S_T \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \qquad (8)$$

Where, $S_T = [J_T]^{-1}$ is a sensitivity matrix and J_T is the full Jacobean defined for all the buses except for the slack bus. At a base case load flow, if only one of the bilateral transactions, say the p^{th} transaction, between a seller bus, m and a buyer bus, n is changed by Δt_p, only the following two entries in the mismatch vector $[\Delta P, \Delta Q]^T$ of (8) will be non-zero.

$$\Delta P_m = \Delta t_p, \ \Delta P_n = -\Delta t_p$$

With the above mismatch vector, changes in the voltage angle and voltage magnitude at all the buses can be computed from (8), and hence, a new voltage profile can be calculated. These can be utilized to compute new values of transmission quantity q_l and thus the change in the quantity Δq_l from the base case. Once Δq_l is known for all the lines and change in the voltage magnitude is computed at all the buses corresponding to a transaction Δt_p, the ACPTDFs for each line and buses, respectively, can be obtained from (7).

2) ATC determination using AC distribution factors

ATC from a bus/zone m to another bus/zone n can be found using the AC load flow by varying the amount of transaction until one or more line flows in the transmission system considered or a bus voltage at some bus reaches the limiting value. However this method is computationally involved. Instead, the distribution factors described above can be used to quickly calculate ATC considering both the line flow limits and voltage limits, as follows.

ATC for base case, between bus/zone m and bus/zone n using the line flow limit criterion has been calculated using ACPTDFs as,

$$ATC_{mn} = \min\left\{ \frac{(P_{ij}^{max} - P_{ij}^{0})}{PTDF_{ij,mn}} \ ij \in N_l \right\} \qquad (9)$$

Where

P_{ij}^{max} is the MW power flow limit of a line between bus-i and bus-j.

P_{ij}^{0} is the base case power flow in the line between bus-i and bus-j. $PTDF_{ij\text{-}mn}$ is the Power Transfer Distribution Factor for the line between bus-i and bus-j, when N_l is the total no. of lines.

MODELING OF TCSC

Transmission lines are represented by lumped π equivalent parameters. The series compensator TCSC is simply a static capacitor/reactor with impedance jx_c. Figure-1 shows a transmission line incorporating TCSC.

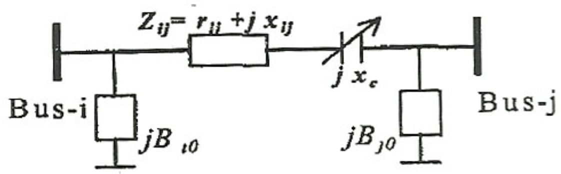

Figure-1. Equivalent circuit of a line with TCSC.

Where X_{ij} is the reactance of the line, R_{ij} *is* the resistance of the line, B_{io} and B_{jo} are the half-line charging susceptance of the line at bus-i and bus-j [9, 10].

A. Representation of TCSC for power flow

The difference between the line susceptance before and after the addition of TCSC can be expressed as:

$$\Delta y_{ij} = y'_{ij} - y_{ij} = (g'_{ij} + jb'_{ij}) - (g_{ij} + jb_{ij}) \qquad (10)$$

$$g_{ij} = \frac{r_{ij}}{\sqrt{r_{ij}^2 + x_{ij}^2}}, \ b_{ij} = -\frac{x_{ij}}{\sqrt{r_{ij}^2 + x_{ij}^2}} \qquad (11)$$

$$g'_{ij} = \frac{r_{ij}}{\sqrt{r_{ij}^2 + (x_{ij} + x_c)^2}}, \ b'_{ij} = -\frac{x_{ij} + x_c}{\sqrt{r_{ij}^2 + (x_{ij} + x_c)^2}} \qquad (12)$$

After adding TCSC on the line between bus i and bus j of a general power system, the new system admittance matrix Y_{bus}' can be updated as:

$$Y_{bus}' = Y_{bus} + \begin{bmatrix} 0 & 0 & 0 & & 0 & 0 & 0 \\ 0 & \Delta Y_{ij} & 0 & \cdots & 0 & -\Delta Y_{ij} & 0 \\ 0 & 0 & 0 & & 0 & 0 & 0 \\ & \vdots & & \ddots & & \vdots & \\ 0 & 0 & 0 & & 0 & 0 & 0 \\ 0 & -\Delta Y_{ij} & 0 & \cdots & 0 & \Delta Y_{ij} & 0 \\ 0 & 0 & 0 & & 0 & 0 & 0 \end{bmatrix} \qquad (13)$$

Because the Y_{bus} has to be updated for each of different locations and the amount of compensation of TCSC, the above formulation is applied in each iteration.

B. Power flow procedure with TCSC

The procedure for the proposed algorithm using TCSC can be summarized as:

Step 1: Read the system line data, bus data and TCSC data.
Step 2: Form Y_{bus} using sparsity technique.
Step 3: Modify the Y_{bus} elements with the value of TCSC reactance.
Step 4: Form conventional Jacobean matrix.

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Step 5: Use the Jacobean matrix to solve bus voltage until the convergence is achieved. When the mismatch at every bus is less than prescribed error, the power flow converges.
Step 6: Out put system voltages and line flows.

MODELING OF UPFC

UPFC is considered as a universal tool for power flow control because it has an ability to simultaneously and independently control all the three parameters which affect power flow, i.e., transmission angle, terminal voltage and system reactance. According to its impact on the system it might be modeled as a combination of a series voltage source, an active and a reactive current source.

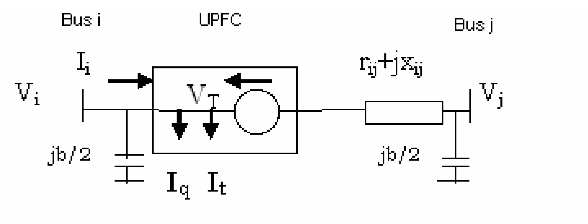

Figure-2. Power injection model of UPFC.

The equivalent circuit of UPFC placed in line k, which is connected between bus-i, and bus-j as shown in Figure-2. According to its structure, UPFC resemble phase shifting transformers. However, when active and reactive losses are neglected, their apparent power is not balanced. The active power inserted into the system via V_T is balanced by the current source IT. Here Iq represents a reactive current source and is independent of VT. The control parameters of the UPFC are the voltage (V_T), current (I_q) and the phase angle (Φ_T). The two voltage source model of the UPFC is converted into two power injections in polar form for power flow studies.

The advantage of power injection representation is that it does not destroy the symmetric characteristics of the admittance matrix.

A. Representation of UPFC for power flow

UPFC modified Jacobean matrix elements In power flow, the two power injections (P_{is},Q_{is}) and (P_{js},Q_{js}) of a UPFC can be treated as generators. However, because they vary with the connected bus bar voltage amplitudes and phases, the relevant elements of the jacobean matrix will be modified at each iteration. The formation of the jacobean matrix is

$$\begin{bmatrix} H & N \\ M & L \end{bmatrix} \quad (14)$$

The following equations are representing the additional elements of the Jacobean matrix owing to the injections of the UPFC at the bus bars i and j.

$H_{i,j}$=-2$V_iV_TG_{ij}$ sin(Φ_T-δ_j) + V_jV_T (G_{ij} sin(Φ_T-δ_j)- B_{ij} cos (Φ_T-δ_j)

$H_{j,j}$= V_jV_T(G_{ij}sin(Φ_T-δ_j)+B_{ij}cos(Φ_T-δ_j))

N_{ii}=-2 $V_iV_TG_{ij}$cos (Φ_T-δ_j)

$N_{i,j}$=V_jV_T(G_{ij}cos(Φ_T-δ_j)-B_{ij}sin(Φ_T-δ_j))

$M_{i,i}$= V_iV_T(-G_{ij} cos(Φ_T-δ_i)+(B_{ij}+B/2)sin(Φ_T-δ_i)

$M_{j,j}$=-V_jV_T(-G_{ij} cos(Φ_T-δ_i)+B_{ij}sin(Φ_T-δ_i))

$L_{i,i}$=V_iI_q+V_iV_T(G_{ij}sin(Φ_T-δ_i)+(B_{ij}+B/2)cos(Φ_T-δ_i))

$L_{j,j}$== -V_jV_T(G_{ij} sin(Φ_T-δ_j)+ B_{ij} cos(Φ_T-δ_j))

B. Power flow procedure with UPFC

The procedure for the proposed algorithm can be summarized as:

Step 1: Input data needed by the conventional power flow, form the admittance matrix, input the parameters of the UPFC i.e., V_T, Φ_T and I_q.
Step 2: Form conventional Jacobean matrix; modify the jacobean matrix using UPFC injection elements to become the enhanced jacobean matrix according to the above equations.
Step 3: Use the enhanced jacobean matrix to solve bus voltage until the convergence of all power injections are achieved. When the mismatch at every bus is less than prescribed error, the power flow converges. Otherwise go to step2.
Step4: Out put system voltages and line flows.

CONSTRUCTION OF GENETIC ALGORITHM

In genetic algorithms [9, 11], individuals are simplified to a chromosome that codes the control variables of the problem. The strength of an individual is the objective function (fitness) that must be optimized. A random start function might generate the initial population size. After the start, successive populations are generated using the GA iteration process, which contains three basic operators: reproduction, crossover and mutation. Finally, the population stabilizes, because no better individual can be found. When algorithm converges, and most of the individuals in the population are almost identical, it represents a sub-optimal solution. A genetic algorithm has three parameters: the population size, crossover rate and mutation rate. These parameters are important to determine the performance of the algorithm.

A. Presentation of control variables

To apply GA to solve a specific problem, one has to define the solution representation and the coding of control variables. The optimization problem here is to use Continuation Power Flow (CPF) to find the Total Transfer Capability for different FACTS devices locations and compensations. Every individual chromosome should contain FACTS device location and compensation level, as shown in Figure-3.

An Individual Chromosome

Location code	*Compensation level*

Figure-3. Chromosome presentation for control variables.

In this study, real code Genetic Algorithm is used. Compared with binary GA, it offers higher accuracy of the control variables. As for location information, we use a series of integrals to express different placement of FACTS devices. For example, if the location for FACTS device has 6 choices, six integrals 1, 2, 3, 4, 5, 6 are used as candidates for this control variable. In every procedure of GA (initialization, reproduction, crossover, mutation), the resulting location code will be held as one of those integers.

B. Initialization

The initialization procedure will select the initial population within the range of the control variables with a random number generator. The user can specify the population number in this procedure.

C. Fitness evaluation

After control variables are coded, the objective function (fitness) will be evaluated. These values are measures of quality, which is used to compare different solutions. The better solution joins the new population and the worse one is discarded. The fitness value of an individual will determine its chance to propagate its features to future generations. Here ATC is used as the fitness in the genetic algorithm.

D. Reproduction

Reproduction is a process in which individual chromosomes are copied according to their objective function (fitness), This operation is an artificial version of the Darwinian Process of natural selection. The first stage of the reproduction process is to select chromosomes for mating. Two different techniques, roulette wheel selection and stochastic universal sampling are tested here. It is seen that stochastic universal sampling exhibits better convergence.

E. Crossover

Crossover is one of the main distinguishing features of GAs that make them different from other algorithms. Its main aim is to recombine blocks on different individual to make a new one. Convex crossover is used in this work as the following formulation.

$$x' = \lambda_1 x + \lambda_2 y$$

$$y' = \lambda_1 y + \lambda_2 x$$

$$\lambda_1 + \lambda_2 = 1, \lambda_1, \lambda_2 > 0$$

where x, y are the two parents, x', y' are their two offspring. λ_1 is obtained by a uniform random number generator between the range (0~l).

F. Mutation

Mutation is used to introduce some sort of artificial diversification in the population to avoid premature convergence to local optimum. An arithmetic mutation operator that has proved successful in a number of studies is dynamic or non uniform mutation, which is used in this study. This is designed for fine-tuning aimed at achieving a high degree of precision. For a given parent x, if the gene x_k is selected for mutation, then the resulting gene is selected with equal probability from the two choices:

$$x_k' = x_k + r(b_k - x_k)(1 - \frac{t}{T})^b$$

or

$$x_k' = x_k - r(x_k - a_k)(1 - \frac{t}{T})^b$$

where r is a uniform random number chosen between the range (0,1), t is the current generation number, T is the maximum number of generations and b is a parameter determining the degree of non uniformity. The amount of mutation decreases as the number of generations increases. In this study, the value b = 2 is used.

G. Population replacement

Two population replacement methods, non-overlapping generations and steady-state replacement are used in this work. When using non-overlapping generations, a generation was entirely replaced by its offspring created through selection, crossover and mutation. It is possible for the offspring to be worse than their parents and some fitter chromosomes may be lost from the evolutionary process. Steady-state replacement is used to overcome this problem. In this process, a number of offspring are created and these replace the same number of the least fit individuals in the population. In this work the steady-state replacement demonstrates better convergence than non-overlapping generations.

Figure-4 shows the flow chart of the proposed algorithm.

CASE STUDIES AND RESULTS

The IEEE 24-bus system is adopted as the test system. The ATC has been determined using AC power transfer distribution factors, DC power transfer distribution factors based on the line flow limit. Further ATC values are also determined for all the transactions using repetitive NRLF. ATC for the 24-bus system is determined for ten transactions, which are given in Table-1. Results obtained from repetitive AC load flow NRLF are also given for comparison. To determine ATC with the repetitive AC load flow, the NRLF was run for each increment of the transaction over its base value until any of the line flows or the bus voltages hit the limiting value. Results obtained from DC load flows are also included in Table-1.

The proposed method has been applied to sample system i.e., IEEE 24- bus system. By placing TCSC and UPFC at appropriate location, more power can be transferred.

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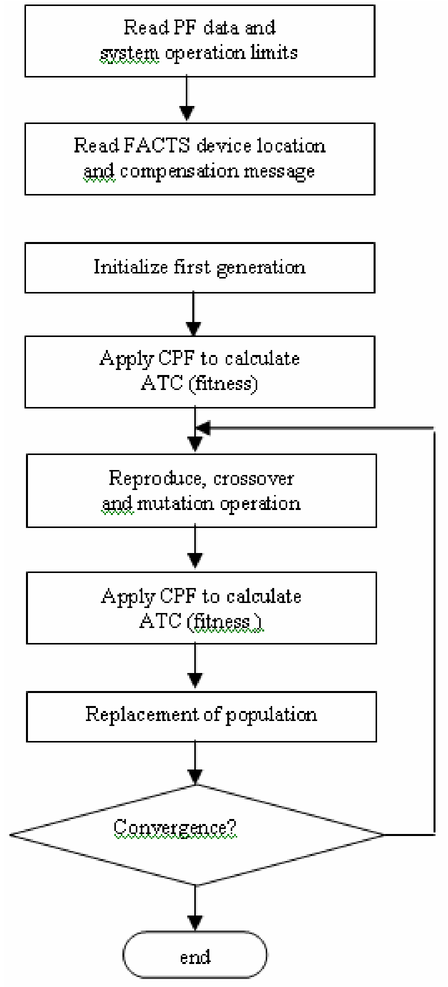

Figure-4. Flow chart of genetic algorithm.

Table-1. ATC values based on the line flow limit for 24-bus system.

S. No	Trans action	ATC from AC distribution factors	ATC from DC distribution factors	NRLF
1	23-15	7.6416	7.8363	7.6
2	10-3	2.9372	3.6876	2.8
3	22-9	4.0696	3.4903	3.4999
4	21-6	1.0437	1.0797	0.9999
5	18-5	2.5686	2.6504	2.4999
6	20-8	0.4614	0.337	0.4
7	19-5	2.5379	2.6076	2.5
8	10-6	0.9539	0.9896	0.9
9	22-5	2.5663	2.6513	2.4998
10	14-8	0.4617	0.3372	0.4

Table-2. ATC enhancement using TCSC for 24- bus system.

S. No	Transaction	ATC with out TCSC	ATC with TCSC	TCSC location (optimal)
1	22-9	4.0443	4.2010	line-28
2	18-5	2.5589	2.672	line-9
3	19-5	2.5262	2.6387	line-9
4	21-6	1.0398	1.1929	line-10
5	10-6	1.9532	1.5700	line-10

Table-3. ATC enhancement using UPFC for 24- bus system.

S. No	Transaction	ATC with out UPFC	ATC with UPFC	UPFC location (Optimal)
1	22-9	4.0474	4.2399	line-28
2	18-5	2.5951	2.999	line-3
3	19-5	2.5647	3.1	line-3
4	21-6	1.8672	2.199	line-10
5	10-6	1.5956	1.9	line-10

Table-2 presents details on the location of the TCSC and the corresponding ATC for IEEE 24 -bus (single area) system. Table-3 presents details on the location of the UPFC and the corresponding ATC for IEEE 24 -bus (single area) system.

The base case ATC values are also shown in the above Tables to observe the improvement with the placement of FACTS devices. The results in Table-2 shows that a significant improvement of ATC can be achieved using TCSC. The result in Table-3 shows the enhancement of ATC by placing UPFC at optimal locations.

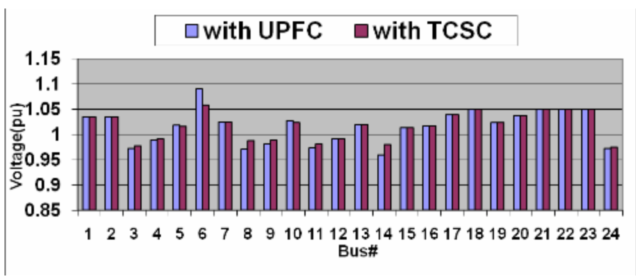

Figure-5. Bus voltage profile.

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CONCLUSIONS

The ATC is computed for different transactions of IEEE 24- bus system using power transfer distribution factor methods. AC and DC power transfer distribution factor (PTDF) methods have been used for ATC determination and the results are compared with the repeated NRLF method. The distribution factors can be recalculated at a base case operating point and can be utilized for determining ATC values based on line flow. The studies conducted on the two systems reveal that ATC determined using AC power transfer distribution factors method are quite accurate as compared to the DC power transfer distribution factors method and are close to those from AC load flows. FACTS devices can be effectively used to overcome some of the limitations of electric power transfer. The ATC enhancement using TCSC and UPFC has been analyzed for different transactions, and results are compared with and with out FACTS devices for the IEEE -24 bus reliability test system. Test results illustrate the effectiveness of the UPFC.

This paper has presented an optimization algorithm to optimally allocate FACTS devices to enhance ATC. The results tremendously prove that the proposed algorithm has remarkable robustness in maximizing the ATC.

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