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VOLTAGE CONSTRAINED AVAILABLE TRANSFER CAPABILITY ENHANCEMENT WITH FACTS DEVICES

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ABSTRACT

The Available Transfer Capability (ATC) of a transmission system is a measure of unutilized capability of the system at a given time. The computation of ATC is very important to the transmission system security and market forecasting. While the power marketers are focusing on fully utilizing the transmission system, engineers are concern with the transmission system security as any power transfers over the limit might result in system instability. One of the most critical issues that any engineers would like to keep an eye on is the voltage collapse. Recent blackouts in major cities throughout the world have raised concerns about the voltage collapse phenomenon. FACTS devices such as thyristor controlled series compensators and thyristor controlled phase angle regulators, by controlling the power flows in the network, can help to reduce the flows in heavily loaded lines resulting in an increased loadability of the network and improves the voltage stability. This paper presents the aspects of enhancement of ATC limited by the voltage with and without contingency by simple and efficient models of FACTS devices. The effectiveness of the proposed methods is demonstrated on IEEE-14 bus and IEEE-30 bus system and the results are compared.

Keywords: voltage stability, transfer capability, thyristor controlled, series compensators, phase angle regulators.

INTRODUCTION

Power system transfer capability indicates how much inter-area power transfers can be increased without compromising system security. Accurate identification of this capability provides vital information for both planning and operation of the bulk power market. Repeated estimates of transfer capabilities are needed to ensure that the combined effects of power transfers do not cause an undue risk of system overloads, equipment damage, or blackouts. However, an overly conservative estimate of transfer capability unnecessarily limits the power transfers and is a costly and inefficient use of the network. There are a very strong economic incentive to improve the accuracy and effectiveness of ATC computations for us by system operators, planners and power marketers. The goal of the methods described here is to improve the accuracy and realism of ATC.

Aspects of availability transfer capability

Available Transfer Capability (ATC) is the measurement of the transfer capability remaining in the physical transmission network for further commercial activity, over and above already committed uses. The reasoning behind the development of ATC is based on several principles developed by the North American Electric Reliability Council's (NERC) [1]. ATC must recognize time-variant power flow conditions and the effects of simultaneous transfers/parallel path flow from reliability Viewpoint. The electric utilities' ATC strategy must include flexibility in allowing for different transfer capabilities over time and reasonably capture these capabilities in a time variant posting. ATC calculations must be dependent on the points of electric power injection, the directions of transfers across the network and the points of delivery. In short, ATC can be defined as, [1]

ATC = TTC – CBM – TRM – "EXISTING TC"

Where, TTC represents total transfer capability. The amount of power that can be transferred over the interconnected transmission network in a reliable manner while meeting a specific set of pre-and post-contingency system conditions. This capacity is defined by the worst contingency for the defined point-to-point path and the thermal, voltage and/or stability limits of the path.

CBM represents capacity benefit margin. The amount of transmission transfer capability reserved by load serving entities to ensure access to generation from interconnected systems to meet generation reliability requirements.

TRM represents transmission reliability margin. The amount of transmission transfer capability needed to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system conditions.

Aspects of voltage stability

As power systems become more complex and heavily loaded, voltage collapse becomes an increasingly serious problem. Voltage collapse has already occurred in real-world electric power systems. Fortunately, practical analytical tools will soon be making their ways from researchers to system designers and operators [2]. A large, nonlinear, interconnected power network can exhibit very complex dynamic phenomena when the system is disturbed from a steady-state operating condition. To complicate things even more, power systems are becoming more heavily loaded as the demand for electric power rises, while economic and environmental concerns limit the construction of new transmission and generation capacity. Under these stressful operating conditions, we are encountering a new instability problem called voltage collapse, which has led to blackouts in electric utilities around the world.

Aspects of FACTS devices

The limitations of a power transmission network arising from environmental, right-of-way and cost problems are fundamental to both bundled and unbundled power systems. Patterns of generation that results in heavy flows tend to incur greater losses, and to threaten stability and security, ultimately make certain generation patterns economically undesirable. Hence, there is an interest in better utilization of available power system capacities by installing new devices such as Flexible AC Transmission Systems (FACTS). Thyristor controlled series capacitors, thyristor controlled phase angle shifters can be utilized to change the power flow in lines by changing their parameters to achieve various objectives [13-14]. FACTS devices [15-17] provide new control facilities, both in steady state power flow control and dynamic stability control. The possibility of controlling power flow in an electric power system without generation rescheduling or topological changes can improve the performance considerably [15-17]. Using controllable components such as controllable series capacitors and phase shifters line flows can be changed in such a way that thermal limits are not violated, losses minimized, stability margin increased, contractual requirement fulfilled etc, without violating specified power dispatch. The increased interest in these devices is essentially due to two reasons.

1. The recent development in high power electronics has made these devices cost effective.

2. Secondly, increased loading of power systems, combined with deregulation of power industry, motivates the use of power flow control as a very cost effective means of dispatching specified power transactions. It is important to ascertain the location for placement of these devices because of their considerable costs. There are several methods for finding optimal locations of FACTS devices in both vertically integrated and unbundled power systems [16-17]. In [17], a sensitivity approach based on the loss has been proposed for placement of series capacitors, phase shifters. If there is no congestion, the placement of FACTS devices, from the static point of view, can be decided on the basis of reducing losses but this approach is inadequate when congestion occurs. A method based on the real power performance index (PI) has been considered, in this paper, for this purpose due to security and stability reasons. A method to determine the optimal locations of thyristor controlled series compensators (TCSC) and thyristor controlled phase angle regulators (TCPAR) has been suggested, in this paper. The approach is based on the sensitivity of these objectives loss on a transmission line in which a device is installed, the total system real power loss and the real power flow performance index. The proposed algorithm has been also demonstrated by line loss sensitivity method on IEEE 14-bus system and IEEE 30-bus system.

MATHEMATICAL MODELING

ATC-continuation method

One way to compute transfer capability with a software model is called continuation. From the solved base case, power flow solutions are sought for increasing amounts of transfer in the specified direction [1]. The quantity of the transfer is a scalar parameter, which can be varied in the model. The amount of transfer is gradually increased from the base case until a binding limit is encountered [1]. This continuation process requires a series of power system solutions to be solved and tested for limits [1]. The transfer capability is the change in the amount of transfer from the base case transfer at the limiting point. Continuation can be simply done as a series of load flow calculations for increasing amounts of transfers [1]. However, when convergence could be poor, such as the case for transfers approaching voltage instability, methods that allow the transfer parameter to become a dependent variable of the model are the most successful [1].

Continuation Power Flow (CPF) is a method for finding the maximum value of a scalar parameter in a linear function of changes in injections at a set of buses in a power flow problem [4]. Originally introduced for determining maximum loadability, CPF is adaptable, without change in principle, for other applications, including ATC. The CPF algorithm effectively increases the controlling parameter in discrete steps and solves the resulting power flow problem at each step [4]. The procedure is continued until a given condition or physical limit preventing further increase is reached [4]. Because of solution difficulty and the need for the Jacobean matrix at each step, the Newton power flow algorithm is used. CPF yields solution even at voltage collapse points [4].

Continuation power flow formulation

The polar form power flow equations are:

$$P_i = \sum_{j=1} V_i V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) \quad (1)$$

$$Q_i = \sum_{j=1} V_i V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) \quad (2)$$

For calculating ATC the injections, *Pi* and *Qi* at source and sink buses are functions of λ.

$$P_i = P_{io}(1 + \lambda K_{pi}) \quad (3)$$

$$Q_i = Q_{io}(1 + \lambda K_{Qi}) \quad (4)$$

Where P_{io}, Q_{io} are the base case injections at bus i and K_{Pi}, K_{Qi} are the participation factors. At PV buses, the K_{Qi} are zero; at PQ buses the ratios K_{pi}/K_{po} are constant to maintain constant power factor. The nonlinear equations (1), (2) augmented by an extra equation for λ, are expressed compactly as:

$$f(x, \lambda) = 0 \quad (5)$$

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Where x is the n-vector of state variables (voltage magnitudes and angles at all the buses), and λ is the parameter for changes in injections. To highlight the role of λ in CPF, (5) is written as:

$$f(x,\lambda) = F(x) + \lambda b \tag{6}$$

Where b is the direction vector of sensitivity of bus injections to change in. CPF has four important elements predictor, step length control, parameterization strategy and corrector.

Predictor and Step Length Control

The predictor with step length control provides an initial estimate of the state variables for power flow solution for the next step increase in transfer power. Without a good starting approximation for each step, the power flow algorithm will fail to converge or converges to an extraneous solution. Once a solution has been found $\lambda = \lambda^i$ a prediction of the next solution is made by taking an appropriate sized step in the direction tangent to the solution path. The tangent is derived by taking the differential of both sides of (5)

$$df = f_x dx + f_\lambda d\lambda \tag{7}$$

To solve for the tangent vector from (7) a magnitude (say 1.0) is assigned to one of its components.

Let $z = (dx, d\lambda)^I$ and $z_k = \pm 1$, then

$$\left(\frac{f_x\, f_\lambda}{e_k}\right)(z) = e_{n+1} \tag{8}$$

where e_k is a row vector with all elements zero except for k^{th}, which equals one. Letting $z_k = \pm 1$ imposes a non-zero norm on the tangent vector and guarantees the augmented Jacobian will be non-singular at the critical point. The prediction is computed from:

$$\left[\frac{x^*}{\lambda^*}\right] = \left[\frac{x}{\lambda}\right] + \sigma\left[\frac{dx}{d\lambda}\right] \tag{9}$$

where * denotes the predicted solution of the next value of λ and σ is a scalar for step size.

Corrector and Parameterization

The corrector is a slightly modified Newton power flow algorithm in which the Jacobian matrix is augmented by an equation for λ. Because the number of state variables for power flow solution is unchanged, it is necessary, at each step of CPF, to select and assign a value to one variable of x or to λ. This is called local parameterization. The selection and assigned value are made by CPF.

Letting $X = (x, \lambda)^I$ the new set of equation is:

$$\left[\frac{f'(x)}{X_k - \eta} = \frac{0}{0}\right] = \left[\frac{0}{0}\right] \tag{10}$$

Where η is an appropriate value for the k_{th} element of X. A modified Newton power flow is used to solve Eq. (10).

ATC Calculation

For each transfer case, ATC is determined so as to be secure with respect to a list of contingencies. Each contingency case is processed by CPF to find the maximum transfer power without causing a limit violation. [4] Suppose one is interested in finding the total transfer capability of a transmission interface, which can be shown as:

$$P_i = P_{io}(1 + \lambda K_{pi}) \tag{11}$$

an optimization algorithm can be formulated to solve it as follows:

$$\max P_i = P_{io}(1 + \lambda K_{pi}) \tag{12}$$

s.t $\lambda < \lambda_{critical}$

Where

λ is the parameter of changes in injections and

$\lambda_{Critical}$ is the point when voltage collapses at this point of the injection.

Voltage Stability–Continuation method

Continuation methods, sometimes called curve tracing or path following, are useful tools to generate solution curves for general nonlinear algebraic equations with a varying parameter.

Static Model

Consider a comprehensive (static) power system model expressed in the following form:

$$0 = f(x,\lambda) = f(x) - \lambda b \tag{13}$$

This model may also be called a parametric power flow model. Stating it differently the parameter λ varies slowly or quasi statically with respect to the dynamics of its counterpart which is the following:

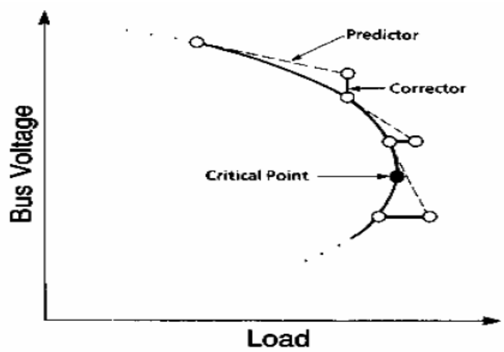

Figure-1. An illustration of the predictor-corrector scheme used in the continuation power flow

$$\dot{x} = f(x,\lambda) \tag{14}$$

It is clear that the PV and QV curves commonly used in the power industry to analyse voltage stability and voltage collapse are examples of saddle-node bifurcations.

$$f(x,\lambda) = 0, x \in R^n, f \in R^n, \lambda \in R \tag{15}$$

These n equations of n+1 variables define in the n+1-dimensional space a one dimensional curve $x(\lambda)$ passing

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through the operating point of the power system. The indirect method is to start from $x_{0,}\lambda_0$ and produce a series of solution points $x_{i,}\lambda_i$ in a prescribed direction, determined by participating load and generation variations, until the 'nose' point is reached. A straightforward such method is to differentiate (15) with respect to λ :

$$f_x(x,\lambda)\frac{dx}{d\lambda} + \frac{\partial f}{\partial \lambda} = 0 \qquad (16)$$

where,

$$\frac{\partial f}{\partial \lambda} = \left[\frac{\partial f_1}{\partial \lambda_1},.......\frac{\partial f_n}{\partial \lambda_n}\right]^T \qquad (17)$$

and then, solve (16) for $\frac{dx}{d\lambda}$:

$$\frac{dx}{d\lambda} = -fx^{-1}(x,\lambda)\frac{\partial f}{\partial \lambda} \qquad (18)$$

Integrating equation (18), one can get the solution curve *x* *(* λ *)* on some interval [λ *0*, λ *1*].

Parameterization

Parameterization is a mathematical way of identifying each solution on the solution curve so that 'next' solution or 'previous' solution can be quantified.

$$\Delta s = \sum_{i=1}^{n} \{\{x_i - x_i(s))^2 + (\lambda - \lambda(s))^2\}^{0.5} \qquad (19)$$

The so-called pseudo arc length parameterization uses different weighting factors (instead of an equal weighting factor) in the above equation.

Predictor

The purpose of the predictor is to find an approximation point for the next solution. Several different predictors have been proposed in the literature of numerical analysis. They can be divided into two classes:

1. ODE based methods, which use the current solution and its derivatives to predict the next solution. The tangent method, a popular one as a predictor, is a first order ODE-based method;
2. Polynomial extrapolation based methods; which use only current and previous solutions to find an approximated solution. The secant method, a popular polynomial-based predictor, uses the current solution and the previous one to predict the next one.

Tangent Method

The Tangent method calls for the calculation of the derivatives of x_1, x_2… x_n, x_{n+1} with respect to the arc length *s*:

$$\frac{dx_1}{ds},.....,\frac{dx_n}{ds},\frac{dx_{n+1}}{ds} \qquad (20)$$

To find these derivatives, differentiate both sides of equation (15) with respect to *s*:

$$0 = fx\frac{dx}{ds} + fx_{n+1}\frac{d_{x+1}}{ds} \qquad (21)$$

Equation (21) is an implicit system of *n* linear algebraic equations in *n*+ 1 unknowns

$$\frac{dx_i}{ds}, i = 1,2,.....,n,n+1 \qquad (22)$$

with the coefficients being the elements of the matrix:

$$Df = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \cdots & \frac{\partial f_1}{\partial x_k} & \cdots & \frac{\partial f_1}{\partial x_{n+1}} \\ \frac{\partial f_2}{\partial x_1} & \cdots & & \cdots & & \cdots \\ \vdots & \vdots & & \vdots & & \vdots \\ \frac{\partial f_n}{\partial x_1} & \frac{\partial f_n}{\partial x_2} & \cdots & \frac{\partial f_n}{\partial x_k} & \cdots & \frac{\partial f_n}{\partial x_{n+1}} \end{bmatrix} \qquad (23)$$

the following equation is required to make sure that *s* is the arc length on the curve.

$$\frac{dx_1}{ds} + ... + \left(\frac{dx_n}{ds}\right)^2 + \left(\frac{dx_{n+1}}{ds}\right)^2 = 1 \qquad (24)$$

A trivial predictor is the zero order polynomial which uses the current solution as an approximation point for the next solution; i.e.

$$(\hat{x}^{i+1}, \hat{\lambda}^{i+1}) = (x^i, \lambda^i) \qquad (25)$$

A slightly modified predictor based on the zero-order polynomial is:

$$(\hat{x}^{i+1}, \hat{\lambda}^{i+1}) = (x^i, \lambda^{i+1)}) \qquad (26)$$

A predictor, known as the secant predictor, uses a first-order polynomial (a straight line) passing through the current and previous solutions to predict the next solution;

$$(\hat{x}^{i+1}, \hat{\lambda}^{i+1}) = (x^i, \lambda^{i)}) + h(x^i - x^{i-1}, \lambda^i, \lambda^{i-1}) \qquad (27)$$

where h_i is an appropriate step-size.

The Corrector

One strategy for step length control is to set up an upper limit $h_{max,\ I}$ for each variable *xi*. The actual step length *h* along the arc length *s* is the thus chosen such that:

$$h\frac{dx_i}{ds} \leq h_{\max,i}, i = 1.......n+1 \qquad (28)$$

the motivation for such an implementation is that the curve *x(* λ *)* under consideration may be "flat" with respect to some *xi*, while turning sharply with respect to some other *xj*. The success of this step length control method depends greatly on the proper value of *hmax,I,* which requires prior knowledge of the problem under consideration.

STATIC MODELING OF FACTS DEVICES

In this section we look at treating enhancing the voltage constrained available transfer capability with the help of flexible AC transmission (FACTS) devices. Two main types of devices are considered here, namely, thyristor controlled series compensators (TCSC) and thyristor controlled phase angle regulators (TCPAR). The

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concept of flexible AC transmission systems (FACTS) was first proposed by Hingorani [15]. FACTS devices have the ability to allow power systems to operate in a more flexible, secure, economic, and sophisticated way. Generation patterns that lead to heavy line flows result in higher losses, and weakened security and stability. Such patterns are economically undesirable. Further, transmission constraints make certain combinations of generation and demand unviable due to the potential of outages. In such situations, FACTS devices may be used to improve system performance by controlling the power flows in the grid. Studies on FACTS so far have mainly focused on device developments and their impacts on the power system aspects such as control and stability enhancement, and damping of oscillations [16-17].With the increased presence of independent Gencos in the deregulated scenario, the operation of power systems would require more sophisticated means of power control. FACTS devices can meet that need.

Static modeling of FACTS devices

For the optimal power dispatch formulation using FACTS controllers, only the static models of these controllers have been considered here [17]. It is assumed that the time constants in FACTS devices are very small and hence this approximation is justified.

1) Thyristor -controlled series compensator (TCSC)

Thyristor-controlled series compensators (TCSC) are connected in series with the lines. The effect of a TCSC on the network can be seen as a controllable reactance inserted in the related transmission line that compensates for the inductive reactance of the line. This reduces the transfer reactance between the buses to which the line is connected. This leads to an increase in the maximum power that can be transferred on that line in addition to a reduction in the effective reactive power losses. The series capacitors also contribute to an improvement in the voltage profiles. Figure-2 shows a model of a transmission line with a TCSC connected between buses i and j. The transmission line is represented by its lumped π-equivalent parameters connected between the two buses. During the steady state, the TCSC can be considered as a static reactance $-jX_C$. This controllable reactance, X_C, is directly used as the control variable to be implemented in the power flow equation.

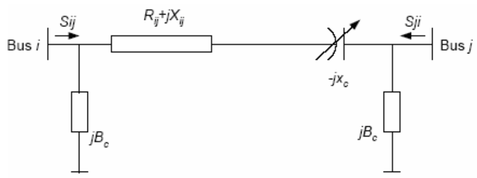

Figure-2. Model of TCSC.

Let the complex voltages at bus *i* and bus *j* be denoted as $V_i\angle\delta_i$ and $V_j\angle\delta_j$ respectively.

The complex power flowing from bus *i* to bus *j* can be expressed as

$$S^*_{ij} = P_{ij} - jQ_{ij} = V_i^* I_{ij} = V_i^2[G_{ij}+j(B_{ij}+B_c)] - V_i^* V_j (G_{ij}+jB_{ij}) \quad (29)$$

The active and reactive power loss in the line can be calculated as

$$P_L = P_{ij} + P_{ji} = V_i^2 G_{ij} + V_j^2 G_{ij} - 2ViVjGij\cos(\delta_i - \delta_j) \quad (30)$$

$$Q_L = Q_{ij} + Q_{ji} = -V_i^2(B_{ij} + B_c) - V_j^2(B_{ij} + B_c) + 2ViVjGij\cos(\delta_i - \delta_j) \quad (31)$$

These equations are used to model the TCSC in the power flow formulations.

2) Thyristor-controlled phase angle regulator (TCPAR)

In a thyristor-controlled phase angle regulator, the phase shift is achieved by introducing a variable voltage component in perpendicular to the phase voltage of the line. The static model of a TCPAR having a complex tap ratio of $1{:}a\angle\alpha$ and a transmission line between bus i and bus j is shown in Figure-3.

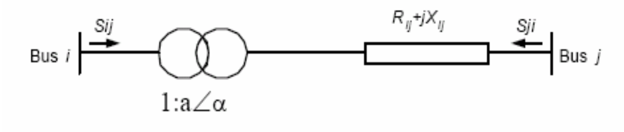

Figure-3. Model of TCPAR.

The real and reactive power loss in the line having a TCPAR can be expressed as

$$P_l = P_{ij} + P_{ji} = a^2 V_i^2 G_{ij} + V_j^2 G_{ij} - 2V_i V_j G_{ij}\cos(\delta_i - \delta_j + \alpha) \quad (32)$$

$$Q_l = Q_{ij} + Q_{ji} = -a^2 V_i^2 G_{ij} - V_j^2 B_{ij} + 2aV_i V_j B_{ij}\cos(\delta_i - \delta_j + \alpha) \quad (33)$$

These equations will be used to model the TCPAR in the power flow formulation. The injection model of the TCPAR is shown in Figure-4.

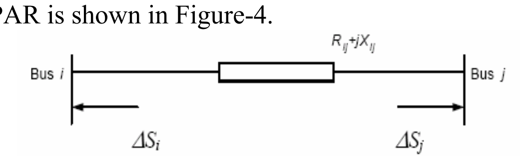

Figure-4. Injection model of TCPAR.

FACTS DEVICES LOCATIONS

We look at static considerations here for the placement of FACTS devices in the power system. The objectives for device placement may be one of the following:

1. Reduction in the real power loss of a particular line
2. Reduction in the total system real power loss
3. Reduction in the total system reactive power loss
4. Maximum relief of congestion in the system

For the first three objectives, methods based on the sensitivity approach may be used. If the objective of

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FACTS device placement is to provide maximum relief of congestion, the devices may be placed in the most congested lines or, alternatively, in locations determined by trial-and-error.

Reduction of total system VAr power loss

Here we look at a method based on the sensitivity of the total system reactive power loss (Q_L) with respect to the control variables of the FACTS devices. For each of the three devices considered in Section 3, we consider the following control parameters: net line series reactance (X_{ij}) for a TCSC placed between buses i and j, phase shift (α_{ij}) for a TCPAR placed between buses i and j. The reactive power loss sensitivity factors with respect to these control variables may be given as follows:

1. Loss sensitivity with respect to control parameter X_{ij} of TCSC placed between buses i and j,

$$a_{ij} = \frac{\partial Q_L}{\partial X_{ij}} \tag{34}$$

2. Loss sensitivity with respect to control parameter θ_{ij} of TCPAR placed between buses

$$b_{ij} = \frac{\partial Q_L}{\partial \theta_{ij}} \tag{35}$$

These factors can be computed for a base case power flow solution. Consider a line connected between buses i and j and having a net series impedance of X_{ij}, that includes the reactance of a TCSC, if present, in that line. θ_{ij} is the net phase shift in the line and includes the effect of the TCPAR. The loss sensitivities with respect to X_{ij} and θ_{ij} can be computed as

$$\frac{\partial Q_L}{\partial X_{ij}} = \left[V^2{}_i + V^2{}_j \; - 2V_iV_j\cos(\delta_i - \delta_j)\right]\frac{R^2{}_{ij} - X^2{}_{ij}}{(R^2{}_{ij} + X^2{}_{ij})^2} \tag{36}$$

$$\frac{\partial Q_L}{\partial \theta_{ij}} = \left[-2aV_iV_jB_{ij}\sin\theta_{ij}\right] \tag{37}$$

Selection of optimal placement of FACTS devices

Using the loss sensitivities as computed in the previous section, the criteria for deciding device location might be stated as follows:

1. TCSC must be placed in the line having the most positive loss sensitivity index a_{ij} .

2. TCPAR must be placed in the line having the highest absolute value of loss sensitivity index b_{ij}.

RESULTS AND DISCUSSIONS

Testing has been done with the help of Power world simulator. The limit of the ATC is the voltage collapse point. One definition of voltage collapse and maximum loadability is when the Jacobean singularity condition to the continuation problem. In most systems, there are many practical and operational reasons why a simple constraint on the voltage magnitude is a more significant and limiting constraint. The ATC is just limited by the steady-state voltage stability.

Sensitivity Index

Here, we simulated the Voltage Collapse for two different cases namely Voltage collapse with contingency and Voltage collapse without contingency. In each case, one of the two FACTS controllers, viz., TCSC and TCPAR is included in the problem formulation. The static models of these devices, as developed in Section 3, are considered, i.e., a TCSC is represented as static impedance, a TCPAR as a transformer with a complex tap ratio. The optimal locations for placing of these devices can be determined by sensitivity analysis are shown in Table-1.

Case 1: IEEE-14 Bus system

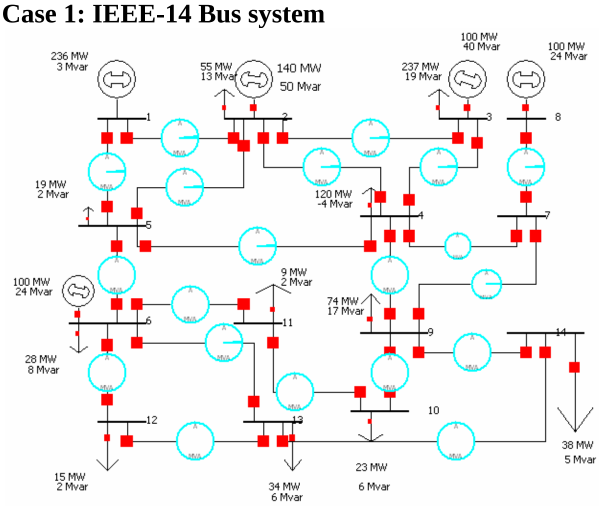

Figure-5. IEEE-14 Bus system.

Table-1. VAr loss sensitivity index of IEEE-14 bus system.

Line	From bus	To bus	Sensitivity index	
			TCSC a_{ij}	TCPAR$_{bij}$
1	1	2	-1.779	**2.9294**
2	1	5	-0.4562	**1.4216**
3	2	3	-0.4382	1.3542
4	2	4	-0.2329	1.03196
5	2	5	-0.126	0.7571
6	3	4	-0.04031	-0.4206
7	4	5	-0.318	-1.2048
8	4	7	-0.0917	0.5859
9	4	9	-0.02626	0.3307
10	5	6	-0.17145	0.8503
11	6	11	-0.002519	0.0916
12	6	12	-0.00359	0.10493
13	6	13	-0.0183	0.2233
14	7	8	-0.049	0
15	7	9	-0.08911	0.5838
16	9	10	-0.005254	0.06543
17	9	14	-0.007528	0.12817
18	10	11	**-0.0005368**	-0.0504
19	12	13	**-0.0000234**	0.00821
20	13	14	-0.00146	0.0757

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In this problem we consider these two cases:

1. A TCSC placed in the lines 18 and 19, operated with an inductive reactance of 6.5 and 6.5 are replaced with the line reactance existing in that case.
2. A TCPAR placed in the lines 1, 2 operated with a phase shift of 0.5, 3.5 degrees and unity tap ratio.

Case 2: IEEE-30 Bus system

Similarly after calculating the Var loss sensitivity index of IEEE-30 Bus system for 41 lines, we consider these two cases:

1. A TCSC placed in the lines 26 and 35, operated with an inductive reactance of 75 and 20% of the line reactance
2. A TCPAR placed in the lines 5, 7 and 22, operated with a phase shift of 4.5, 0.5, 9.5 degrees and unity tap ratio. The following Tables, PV-Curves shows a comparison between the data obtained with and without FACTS devices in the system.

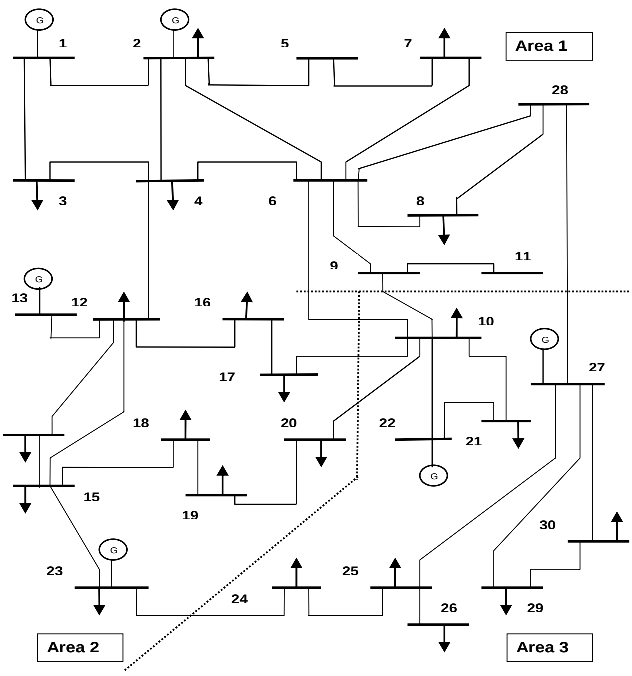

Figure-6. Three area IEEE-30 bus system.

1. IEEE 14 BUS SYSTEM

Table-2. Comparison of ATC with and without FACTS devices.

From -To area	ATC in MW					
2 - 1	without contingency			with contingency (between buses 5-4)		
	without FACTS	with TCSC	with TCPAR	without FACTS	with TCSC	with TCPAR
	85.85	86.10	85.89	85.93	94.90	86.15

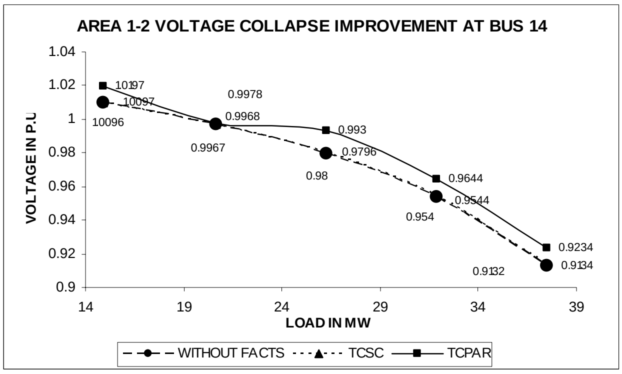

Figure-7. Comparison of voltage with and without FACTS devices at bus 14.

For the IEEE-14 and 30 bus system, the comparison between with and without contingency and the comparison between with and without incorporating the FACTS devices are shown in table 2, 3 and 4 for different areas.

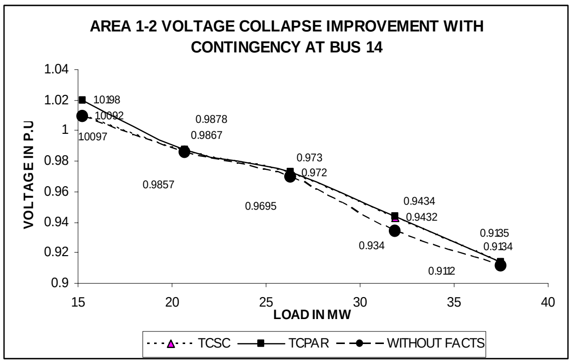

Figure-8. Comparison of voltage with and without FACTS devices at bus 14.

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2. IEEE 30 BUS SYSTEM WITHOUT CONTINGENCY

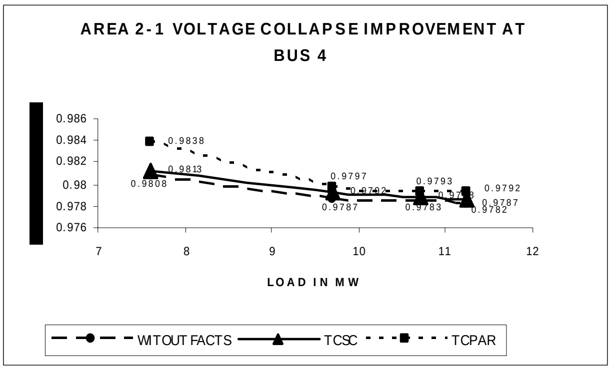

Figure-9. Comparison of voltage with and without FACTS devices at bus 4.

Table- 3. Comparison of ATC with and without FACTS devices.

S. #	From area	To area	ATC in MW		
			Without FACTS	**With TCSC**	**With TCPAR**
1	2	1	13.80	13.80	13.80
2	3	1	38.09	38.35	38.19
3	3	2	39.31	41.41	41.07

3. IEEE 30 BUS SYSTEM WITH CONTINGENCY

Table-4. Comparison of ATC with and without FACTS devices.

S. #	From area	To area	ATC in MW		
			Without FACTS	**With TCSC**	**With TCPAR**
1	2	1	13.80	13.80	13.80
2	3	1	39.79	40.03	39.81
3	3	2	40.53	43.10	42.22

It is observed that from PV curves, Figures 7, 8,9,10 and 11 the enhancement of ATC with voltage constraint by incorporating the FACTS devices at different buses.

CONCLUSIONS

This paper has described a simple, efficient and practical method for determining the voltage constrained.

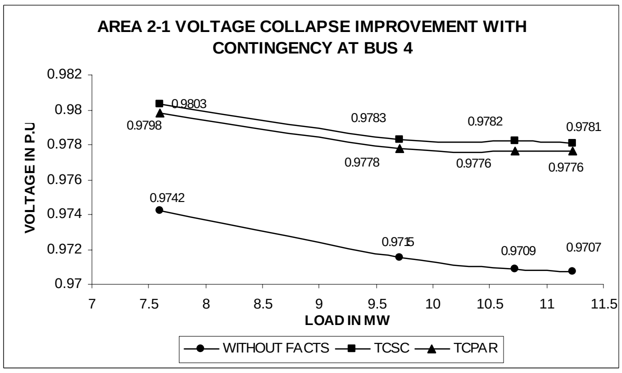

Figure-10. Comparison of voltage with and without FACTS devices at bus 4.
(Line between buses 4 and 12 is disconnected)

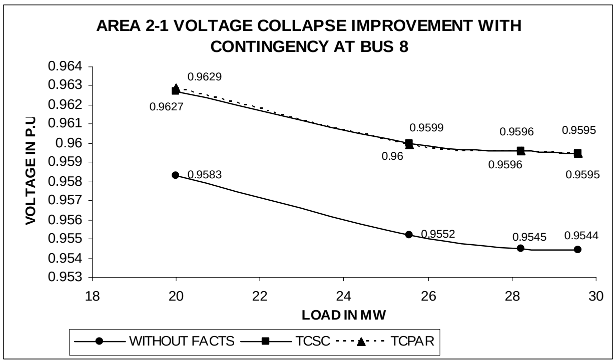

Figure-11. Comparison of voltage with and without FACTS devices at bus 8.
(Line between buses 4 and 12 is disconnected)

Available Transfer Capability with FACTS devices between two areas.

A sensitivity based approach has been developed for finding optimal placement of these devices. Test results obtained on two systems show that new sensitivity factors could be effectively used for optimal placement in response to required objectives. The ATC calculation is a CPF (Continuation Power Flow) routine based on a Newton Raphson power flow algorithm. The CPF is limited by the Jacobian matrix becoming singular and could not be converged. The amount of CPF processing is reduced using larger steps to find the initial ATC before it is reprocessed again using a smaller step to increase the accuracy.

New, more accurate models are developed to better predict how a realistic power system will react over a wide range of operating conditions. This kind of models will also help in the research of ATC.

An accurate ATC computation is also very important to the transmission system. If the computed ATC is less than the ATC of the system, the transmission of power will not be efficient economically, if the computed ATC is more than the ATC of the system, the transmission will be operating in a dangerous state and any power increased will stand a chance to collapse the whole system and the result of that is disastrous.

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