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CALCULATION OF THE EXTREME LOADING CONDITION OF A POWER SYSTEM FOR THE ASSESSMENT OF VOLTAGE STABILITY

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Abstract -- The Extreme Loading Condition (XLC) of a power system is defined by assuming a load increase (according to a predefined pattern for both active and reactive powers) until a maximum is reached for anyone of the loads. The XLC is significant for the assessment of voltage stability. Its calculation, as presented in the paper, is based on increasing the load admittances while first keeping the generator voltage phasors constant and then adjusting these phasors for satisfying operational requirements with respect to the generation powers. The secant method is used for the efficient and reliable determination of the maximal value of the loading parameter μ, while for the voltage adjustment a fast convergent Newton module is employed. The XLC can be calculated for both normal operation and for contingencies. The new approach is fast and simple and can be used on larger systems. Its features have been illustrated on the 39 bus New England test system. The calculation identifies the weakest bus where remedial action may be needed for voltage support.

Keywords: Voltage stability, Maximal load, Contingency analysis.

INTRODUCTION

The heavy loading of many power systems has spawned significant interest and much research regarding the conditions which may lead to loss of stable operation. The type of stability of concern is related to the complex phenomenon called voltage collapse. This is generally dynamic in nature, consisting of a sequence of events [1]-[5] which can only be examined computationally by time domain simulations. A simpler view may be obtained by approaching the voltage collapse phenomenon from the condition of increasing loading of the system network [6]-[9]. In the present paper we adopt this approach and focus on the main transmission system and its power transfer capabilities. Clearly, the problem is thus reduced to a pure algebraic one. While the tap changing dynamics of the transformers affect the way the load may react to voltage variations, our approach takes the load magnitudes at the high voltage side of the transformer as primary input variables. In this way all of the load dynamics, including that of the transformer, has been removed from the computations as irrelevant to the calculation of the loading condition leading to voltage collapse. The resultant critical situation will be called Extreme Loading Condition (XLC). Some authors assess the closeness to the XLC without actually calculating the critical point. This is done by either calculating the voltage sensitivity with respect to the reactive load power [6]-[8], or the determinant or the smallest eigenvalue or singular value of the load flow Jacobian [5],[10], or the closeness of a second load flow solution [11]-[13]. The advantage of these methods is that no loading pattern or scenario has to be defined. However, because of this, such indices may not provide satisfactory information regarding the closeness to the critical point.

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As the power system load is gradually increased, the voltages at the load buses decrease until the slope of the voltage-power curve becomes infinite. For given P,Q, as in the case of a conventional load flow program, in this extreme condition the magnitude of the voltage is (in a simplistic sense) not well defined. In a Newton-Raphson program this is reflected by the singularity of the Jacobian. The critical point could only be approached by this method but not accurately calculated. Of course the critical point, or turning point (on the nose portion of the characteristic) is in fact well defined and calculable. In a Newton-type approach, this simply requires to supplement the missing information contained in the rank deficient Jacobian by an equation equivalent to $\det(J)=0$ [10]. In order to avoid the singularity related to a turning point, it is however possible to choose a loading parameter different from the powers at the load buses. We chose for this purpose to express the increased loading by increasing the admittances of the loads. This of course does not imply an impedance type load and, indeed, the load can have any nature, as already mentioned. Since system loading implies a single parameter, we have specified an arbitrary loading pattern by means of a vector or diagonal matrix ΔY_{load} so that the total load admittance is $Y_{load}=Y_{load_0}+\mu\Delta Y_{load}$. Clearly, the admittance loading with parameter μ permits to move continuously along the nose portion of the voltage-power curve, even beyond a possible collapse point, without any problem of ill-conditioning or singularity if the generator voltage phasors remain constant. In fact, the detection of the XLC will now require the monitoring of the load powers. The XLC will be reached when the first load power (real or reactive) reaches a maximum or its derivative crosses the horizontal axis. The bus where this happens is the weakest in the system from the point of view of voltage stability. In the present paper, the value of μ for this zero crossing is calculated by means of the secant method.

As the load powers are increased, care must be taken to cover the total load by appropriate generation. For this purpose we use the simple device of keeping the generator bus voltages constant in both magnitude and phase. All generators act thus as slacks since physically they are all simple voltage sources. Consequently, for any given loading, the appropriate total power will be generated without consideration of realistic operational requirements related to capacities of individual generators and other operational limits, and to economic power scheduling. Therefore, as the loading progresses by increasing the loading parameter μ, the generator voltage phasors have to be adjusted for satisfactory (or optimal) power redistribution between generators. In our approach the voltage adjustment is obtained by a Newton computational module.

The XLC under normal operating conditions may often not be relevant for the secure operation of the system because normally enough loading margin is available. However, under contingencies the XLC is smaller since the network is weakened and the power may have to reach the load buses through longer paths. It is therefore important to calculate the XLC for contingencies with minimal additional computational effort. This has been achieved by using well known matrix modification techniques.

OUTLINE OF THE COMPUTATIONAL APPROACH

The calculation of the Extreme Loading Condition will first be shown for normal operating conditions and subsequently for contingencies.

Calculation of XLC for Normal Operation

The basic nodal system equation $YV=I$ in partitioned form for load and generator buses is

$$\begin{bmatrix} Y_{ll_\mu} & Y_{lg} \\ Y_{gl} & Y_{gg} \end{bmatrix} \begin{bmatrix} V_l \\ V_g \end{bmatrix} = \begin{bmatrix} 0 \\ I_g \end{bmatrix} \tag{1}$$

Note that the load has been represented as an admittance $Y_{load}=Y_{load_0}+\mu\Delta Y_{load}$ and this has been lumped with the diagonal elements of the respective submatrix Y_{ll} of the system admittance matrix Y, yielding Y_{ll_μ}. The expression $Y_{load}=Y_{load_0}+\mu\Delta Y_{load}$ describes the loading pattern as linear above the base load Y_{load_0}, with the loading parameter μ, following an arbitrary direction specified by the elements of ΔY_{load} with conductance and susceptance entries, proportional to the real and reactive powers. For example, the load can be increased more heavily on particular buses, and predominantly in its reactive part. ΔY_{load} is normalized to be equal in some sense to Y_{load_0}, for instance, by setting its largest entry equal to that of Y_{load_0}. Thus μ can be viewed as a per unit measure of admittance loading. The load powers are also proportional but scaled by the square of the voltage.

Proceeding Toward the XLC with Fixed Generation Voltages

In the following procedure only the upper (load) part of eqn.(1) is used

$$Y_{ll_\mu} V_l + Y_{lg} V_g = 0 \tag{2}$$

It serves for calculating, for a given set V_g and parameter μ, the load voltages V_l (and their derivatives). Then μ is modified until the first bus power becomes maximum. The selection of a new value for μ is made using the secant method with the power derivatives as mismatch functions. The generator powers will automatically match the load, since the generator buses act collectively as slack buses (voltage sources).

When one of the mismatches becomes sufficiently small, a sidestep is made to adjust the generator voltage phasors in order to redistribute the generated powers in a near-optimal and operationally feasible way.

The process of obtaining new values for μ is based on monitoring the loading on all buses and, more precisely, the load derivatives with respect to μ, since the first occurrence of a zero crossing will indicate that the XLC has been reached (at $\mu=\mu_{XLC}$). The load powers on bus k are

$$S_k^* = P_k - jQ_k = Y_{load_k} V_{l_k} V_{l_k}^* = (Y_{load_0}+\mu\Delta Y_{load})_k V_{l_k} V_{l_k}^* \tag{3}$$

or

$$\begin{aligned} P_k &= G_{load_k} V_{l_k} V_{l_k}^* = (G_{load_0}+\mu\Delta G_{load})_k V_{l_k} V_{l_k}^* \\ Q_k &= -B_{load_k} V_{l_k} V_{l_k}^* = -(B_{load_0}+\mu\Delta B_{load})_k V_{l_k} V_{l_k}^* \end{aligned} \tag{3a}$$

Their derivatives w.r.t. μ are

$$\begin{aligned} P'_k &= \Delta G_{load_k} V_{l_k} V_{l_k}^* + 2G_{load_k} \mathrm{Re}(V'_{l_k} V_{l_k}^*) \\ Q'_k &= -\Delta B_{load_k} V_{l_k} V_{l_k}^* - 2B_{load_k} \mathrm{Re}(V'_{l_k} V_{l_k}^*) \end{aligned} \tag{3b}$$

In general, the (real and reactive) powers of eqn.(3a) do not reach simultaneously their maxima w.r.t. μ. To obtain V_l we use eqn.(2) and for obtaining V'_l we take the derivative w.r.t. μ of eqn.(2a)

$$(Y_{ll_0} + \mu\Delta Y_{load})V_l + Y_{lg} V_g = 0 \tag{2a}$$

obtained from eqn.(2). The derivative is

$$Y_{ll_\mu} V'_l + \Delta Y_{load} V_l = 0 \tag{2b}$$

Clearly, the same factorization (of Y_{ll_μ}) is needed for the calculation of both V_l and V'_l. With the elements of these calculated vectors all derivatives expressed in eqn.(3b) can be computed. The functions of eqn.(3a) will be denoted by y and their derivatives by y'. Figure 1 shows the variation with μ of several of these functions y and of their derivatives y'.

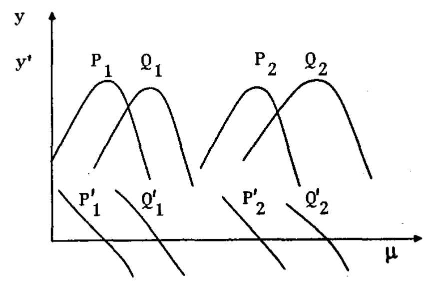

Fig.1 Variation with μ of some y and y'.

The values of y' serve to obtain the new value μ_{new} from the secant updating formula

$$\mu_{new} = \frac{\mu_1 y'_2 - \mu_2 y'_1}{y'_2 - y'_1} \tag{4}$$

This process is repeated until y' which has the first zero crossing is sufficiently small. This does not mean that the XLC has necessarily been reached. Let μ_{adj} be the corresponding value of μ. This μ_{adj} will be used in the sidestep for voltage adjustment.

Before performing the voltage adjustment, we use the lower part of equations (1) to calculate the generator currents I_g. These yield the powers S_g which permit to compute the total generator power P_{total}. We use P_{total} for obtaining (see Appendix 1) an economically optimal set of powers P_g such that $\Sigma P_g=P_{total}$ and satisfy the operational limits. These powers P_g are used as inputs for the voltage adjustment.

Sidestep: Adjustment of Generator Voltages

The adjustment of generator voltages is performed at $\mu=\mu_{adj}$ before calculating the derivative V'_l from eqn.(2b). The latter will only be used after the adjustment process has produced new voltages V_l in addition to the adjusted generator voltages V_g.

At first, a decoupled approach for the calculation of V_g may seem appealing. It uses, with fixed V_g, the lower (generator) part of eqn.(1) (modified to express powers). Then eqn.(2) gives a new vector V_l, and so on. Unfortunately, this process converges very slowly. Therefore, the voltage adjustment is performed using both V_g and V_l as variables. The corresponding Newton equation is

$$\begin{bmatrix} Y_{ll_\mu} & Y_{lg} \\ J_{gl} & J_{gg} \end{bmatrix} \begin{bmatrix} \Delta V_l \\ \Delta V_g \end{bmatrix} = \begin{bmatrix} \Delta I_l \\ \Delta S_g^* \end{bmatrix} \tag{5}$$

where J stands for Jacobian matrices and the right hand side vector represents mismatches of currents and (conjugates of) powers. It results directly from (1) by premultiplication of the lower (generator) part by $\mathrm{diag}(V_g^*)$ and then calculating the corresponding Jacobians. For details, see Appendix 2. We note that eqn.(2) is implicitly satisfied when the Newton equation (5) has been solved to convergence. Therefore, with the obtained V_l, the calculations starting with eqn.(2b) for obtaining new values of μ, can be directly continued until, in a few more steps, μ_{XLC} is obtained with a high degree of accuracy.

We note that in its full form the matrix of eqn.(5) is singular because the complete set of complex voltages can be arbitrarily rotated for a given set of prescribed powers. Therefore, one of the generator buses is chosen as a slack. This removes the singularity and facilitates keeping the generator voltages in an acceptable range.

The need for a generator bus with its voltage phasor as reference angle brings us closer to the traditional load flow problem formulation. This means that the rows of the Jacobian related to specified Q are removed and replaced by constraints for given voltage magnitudes $|V|$. If the reactive power limit for a generator is exceeded, then the row with the reactive power constraint is reintroduced for that generator.

Calculation of XLC for Contingencies

Contingencies are of paramount interest for the assessment of the security of the operating conditions because they bring the XLC closer to the actual loading. The computational methodology outlined above permits the calculation of the XLC without refactorizations if instead of the exact matrices approximate ones are used. This leads to iterative solution of the linear equations. However, in the case of contingencies, in order to avoid new factorizations for each case, matrix modification techniques [14],[15] have been used. The next section will deal in more detail with computational considerations.

COMPUTATIONAL CONSIDERATIONS

In the computations described above, linear equations have to be solved with changing coefficient matrices A. In the secant method A changes because of μ taking different values. Even though the secant method has superlinear convergence, a number of 5 to 10 factorizations may be needed just for the normal condition and similarly for any contingency. This can be avoided by an iterative procedure where $Ax=b$ is solved by using an approximation A' to A. This is used to obtain a first solution of $A'x=b$ and then to successively correct it by calculating Δx from $A'\Delta x=r$ (where $r=b-Ax$ is the residue for x during the iteration process). The iterative process converges fast if A' is close to A. This means that in the process for secant updates, where μ varies from 0 to perhaps 4 to 8, at least two or three factorizations should be performed for the base values μ_{base_1}, μ_{base_2} and, possibly, μ_{base_3}. These should be as close as possible to the actual values of μ resulting from the secant process.

In the Newton process for voltage adjustment the parameter μ remains constant ($=\mu_{adj}$) and therefore the matrix of eqn.(5) is modified during the iterations only due to the changing Jacobian matrices in the lower part of the coefficient matrix. If a factorization with μ_{adj} would be performed then, for a true Newton process, the required matrix factorization could be obtained simply by a partial refactorization. However, since μ_{adj} will generally not coincide with any of the values μ_{base} for which factorizations are available, eqn.(5) should preferably also be solved iteratively. Instead of quadratic convergence, fast linear convergence will still be achieved if the Jacobian submatrices are frozen after the first factorization. The computational procedure consists then in obtaining the factorization for eqn.(5) by simply completing the already available factorization with some μ_{base} for the remainder of the complete matrix.

TEST RESULTS

The XLC calculations have been tested on a 9 bus system and on the 39 bus New England test system. The following results pertain to the 39 bus system (see Fig.2). It has 10 generator buses, 17 load buses, and 12 connection buses without loads.

The tests have examined two types of loading conditions:

(1) System-wide loading, e.g., loading of all buses in proportion to their initial load.

(2) Single bus loading for all load buses sequentially, with either real, or reactive, or both real and reactive loads (at $\cos\phi=0.8$) on the selected bus.

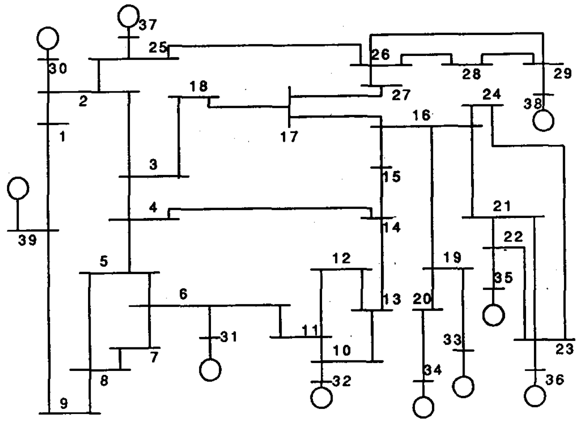

Fig.2 Diagram of the 39 bus New England test system.

For each of these conditions a no-contingency case and a case with different contingencies have been examined. Ten contingencies have been used: eight with single line outages, one with a two line outage, and one with a generator outage.

Fig.3 shows the load bus voltages and powers for the initial (μ=0) and the XLC condition without contingency. The XLC has been reached with system-wide loading at μ_{XLC}=3.66. The critical or "weakest" bus is #12. It can be seen that the powers do not increase proportionally with μ because of the voltage drop. Still the XLC for this case shows a significant margin with respect to the initial or normal loading.

Fig.4 represents the effect of contingencies on the loading parameter μ_{XLC} under system-wide loading. As expected, it is smaller than in the no-contingency case (μ_{XLC}=1.64 in case A of a double line outage). In case B, representing a single line outage, μ_{XLC}=2.04, and the weakest bus is #15. The 39 bus system, often used for testing power system analysis programs, is tightly meshed and not too heavily loaded. This is why the voltage stability margin is high even in the case of contingencies. The result obtained suggests that the voltage stability of the system could be improved by voltage support measures at bus #15. Indeed, by increasing the load power factor at that bus from 0.9022 to 0.98, the value of μ_{XLC} increases from 2.04 to 2.3.

Fig.5 represents the effect of loading only one bus at a time, with either real, or reactive, or real and reactive power at $\cos\phi=0.8$, without contingency. The value of μ_{XLC} versus the bus number is shown. The figure indicates the location (bus #12) of loading to which the system is most sensitive.

Fig.6 represents the effect of loading only one bus at a time, with either real, or reactive, or real and reactive power at $\cos\phi=0.8$, considering different contingencies. The value of $\mu_{XLC_{min}}$ is shown versus the bus number, corresponding to the most severe contingency for that particular bus.

The CPU time for non-contingency type calculations on a VAX-8600 is of the order of 10 seconds. For an XLC calculation including 10 contingencies, the total CPU time is around one minute. Fundamentally, the method does not have problems of ill-conditioning in the main procedure which calculates V_l and V'_l since it involves only the solution of linear equations. The voltage adjustment is a nonlinear process and may lead to ill-conditioning if it is performed too close to the XLC. At this point it is however of no practical significance. Consequently, on the whole, the method is computationally both fast and robust.

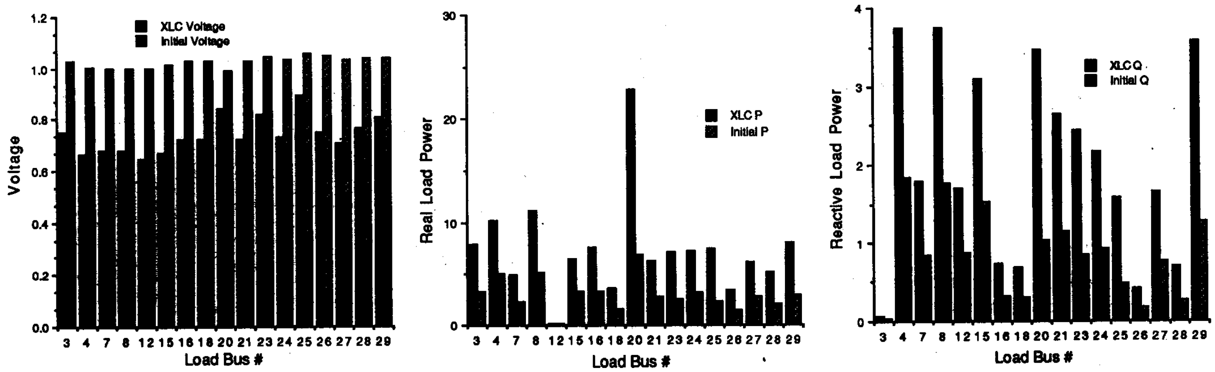

Fig.3 Bar graphs of V, P, and Q, for load buses with initial and XLC system-wide no contingency loading (μ_{XLC}=3.66, weakest bus: #12).

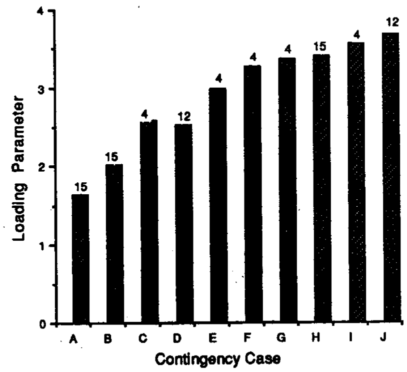

Fig.4 Bar graph of loading parameters μ_{XLC} for system-wide loading with different contingencies (A, B, ... J); the numbers indicate the weakest bus.

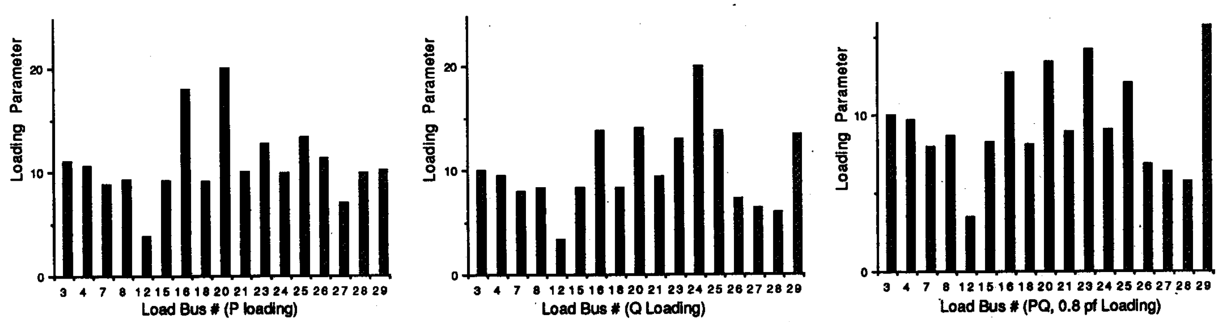

Fig.5 Bar graph of loading parameters μ_{XLC} versus bus number for single bus no contingency loading with either P, or Q, or P,Q at $\cos\phi$=0.8.

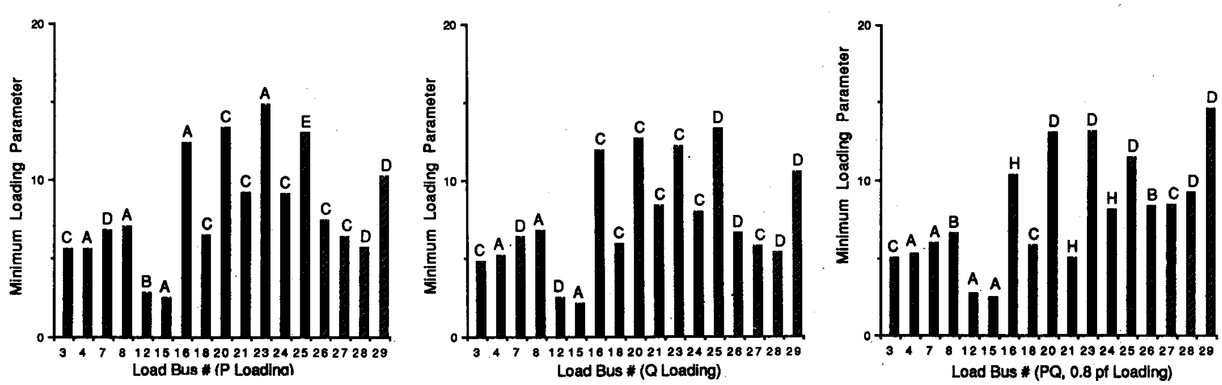

Fig.6 Bar graphs of $\mu_{XLC_{min}}$ versus bus number for single bus loading with different contingencies (marked as in Fig.4), with either P, or Q, or P,Q at $\cos\phi$=0.8.

CONCLUSIONS

The paper has presented a methodology for the calculation of the Extreme Loading Condition (XLC) of a power system. The following are the features of the method:

- The XLC is approached gradually by a coherent increase of all loads using a single loading parameter μ. The XLC is reached when anyone of the loads first attains its maximum. This condition is believed to be conducive to voltage collapse.
- The first bus where the load has reached its maximal value may be viewed as the weakest from the point of view of voltage stability. That bus is of particular interest for possible remedial action.
- The pattern of the increase of loads is given by an arbitrarily chosen direction ΔY_{load}. Thus the loads do not have to be modified according to their present distribution pattern. This way the closeness of the XLC can be assessed for load increases on particular buses and also in relation to the reactive loading on those buses. The voltage collapse can be due to a real or reactive power, whichever first reaches its extreme value.
- The method uses the increase of the load admittances as the computational mechanism for loading. This does however not reflect on and does not restrict the nature of the loads (which may include tap changing transformers). The dynamics of the loads, including that of the related tap changing transformers, is beyond the scope of the present program which is purely algebraic in nature. However, this choice of loading, by means of variables other than powers, has eliminated difficulties due to ill-conditioning and singularity of a Jacobian matrix. The calculated XLC may lead to voltage collapse only if the load powers are in fact fixed at the critical values of the XLC. Dynamic, small disturbance instability of the system may occur before the XLC is reached. The algebraic approach of the XLC calculations does not give any indication on whether the XLC condition can in fact be approached in a dynamically stable manner.
- The method is based on the calculation of the load voltages with a set of fixed generator voltage phasors V_g. This assures that the generation will automatically follow the load and only a redistribution of generator powers is necessary for achieving a measure of optimality during the simulation of the loading process. The redistribution of generations is obtained by the adjustment of the generator voltages.
- For computational efficiency, the method avoids repeated factorization of matrices. It consistently uses for this purpose an iterative approach for solving linear equations. Still, for the calculation of the voltage adjustment, the problem is formulated in terms of Jacobians in order to assure fast and reliable solution, even though the matrix is kept constant during the iterations.
- It is essential for the usefulness of the method that it has the ability to handle contingencies without much computational burden by using matrix modification techniques. The identification of the "weakest bus" is particularly important in the presence of contingencies.
- The method uses sparsity based solutions and is thus applicable in principle to large size system. Its features have been examined on systems with up to 39 buses. The results obtained show good convergence characteristics and small computer times.
- The 39 bus test system, used for testing the XLC calculation method, did not display any particular weakness in terms of voltage stability. The practical usefulness of the XLC calculation method is expected to be significant in systems where voltage instability has been found to be imminent.

We conclude by noting that the calculation of XLC as outlined in this paper represents one of several computational alternatives. It is hoped that its future application will indicate directions for refinement and improvement.

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APPENDICES

Appendix 1: Economic Generation Redistribution

A simplified, approximate approach will be described below. It assumes known, quadratic generation cost functions which include in a rough, approximate way the effect of transmission loss penalties (by increased values of the coefficients):

$$F_i = a_i P_i^2 + b_i P_i + c_i \tag{A1-1}$$

With the constraint

$$\Sigma P_i = P_{total} \tag{A1-2}$$

the Lagrangean minimization approach leads to the conditions

$$\frac{dF_i}{dP_i} = 2a_i P_i + b_i = \lambda \tag{A1-3}$$

yielding

$$P_i = \frac{\lambda - b_i}{2a_i} \tag{A1-4}$$

Adding up all equations (A1-4) and taking (A1-2) into account, we obtain

$$\lambda = \frac{2P_{total} + \Sigma(b_i/a_i)}{\Sigma(1/a_i)} \tag{A1-5}$$

The individual optimal powers P_i can then be calculated from eqn.(A1-4).

Appendix 2: Calculation of Jacobian Matrices

Let

$$YV = I_g \tag{A2-1}$$

be the condensed representation of the lower (generator) part of Eqn.(1). Here Y is a rectangular matrix and V includes both V_l and V_g. Denote

$$W = V^* \tag{A2-2}$$

and premultiply (A2-1) by diag(W) (a diagonal matrix formed with the elements of the vector V^*). We obtain

$$f(V,W) = \mathrm{diag}(W)YV - S^* = 0 \tag{A2-3}$$

The (complex) Jacobian of the function f is

$$J = \begin{bmatrix} J_V & J_W \end{bmatrix} = \begin{bmatrix} \frac{\partial f}{\partial V} & \frac{\partial f}{\partial W} \end{bmatrix} = \begin{bmatrix} \mathrm{diag}(W)Y & \mathrm{diag}(YV) \end{bmatrix} \tag{A2-4}$$

For eqn.(A2-3) Newton's method gives

$$J_V \Delta V + J_W \Delta W = -f \tag{A2-5a}$$

This becomes in terms of the real and imaginary components of the variables

$$(J'_V + jJ''_V)(\Delta V' + j\Delta V'') + (J'_W + jJ''_W)(\Delta V' - j\Delta V'') = -f' - jf'' \tag{A2-5b}$$

or, in matrix form,

$$\begin{bmatrix} J'_V + J'_W & -J''_V + J''_W \\ J''_V + J''_W & J'_V - J'_W \end{bmatrix} \begin{bmatrix} \Delta V' \\ \Delta V'' \end{bmatrix} = - \begin{bmatrix} f' \\ f'' \end{bmatrix} \tag{A2-6}$$

The above equation corresponds to the Newton iteration for the generation part of eqn.(3). The coefficient matrix gives the Jacobian matrices of eqn.(3).

Adam Semlyen (F'87) was born and educated in Rumania where he obtained a Dipl. Ing. degree and his Ph.D. He started his career with an electric power utility and held an academic position at the Polytechnic Institute of Timisoara, Rumania. In 1969 he joined the University of Toronto where he is a professor in the Department of Electrical Engineering. His research interests include steady state and dynamic analysis of power systems, electromagnetic transients, and power system optimization.

Baofu Gao was born in China in 1962. He received his B. Eng. degree in 1982 from Xian Jiaotong University , Xian , China, and an M.A.Sc. degree in 1986 from the University of Toronto, both in Electrical Engineering. Presently he is working towards his Ph. D. degree at the Department of Electrical Engineering, University of Toronto. His research interest is in the area of power system dynamics and control.

Wasyl Janischewskyj (F'77) was born in Prague, Czechoslovakia in 1925. He studied Electrical Engineering at the Ukrainian Technical-Husbandry Institute, the Technical University Hanover and the University of Toronto, graduating with a BASc in 1952 and an MASc in 1954. He spent five years at the Aluminium Laboratories, Ltd., Kingston, Ontario. Since 1959, he has been with the University of Toronto as Lecturer, Professor, and Associate Dean. His main research interest are electric power transmission, corona, electromagnetic interference, lightning, and power system stability. Professor Janischewskyj is involved in many national and international technical committees, is a former chairman of the IEEE Subcommittee on Corona and Field Effects, member of the IEEE Working Group on Transmission Line Lightning Performance and a Professional Engineer in the Province of Ontario.

Discussion

Y. Tamura, (Waseda University, 3-4-1 Ohkubo, Shinjuku-ku, Tokyo, Tokyo 169 Japan): The authors are very much commended for the integrated algorithm for assessing voltage margin, for identifying the weakest node under the reasonable scenario of increasing " " for system conditions with and without contingencies. The algorithm gives much information to the field engineer/practioners from the practical viewpoint. Indeed, the proposed method is very efficient to compute the XLC (Extreme Loading Condition) for moderately large power systems.

Would the authors express their thoughts/perspective on the following items?

(a) Two kinds of scenarios of increasing loads towards the XLC (system-wide basis and single-bus basis *with* and *without* contingencies) taken up in the paper are very typical and will be accepted by most people. It is true at the same time that a number of different load-increasing scenarios exist between the two extreme scenarios being following in the paper.

What would be the authors' view on this point for the successful implementation of the proposed method?

(b) As shown in Fig. 6 of the paper, the method of detection of the weakest node/a set of weak nodes is again practical. Would the authors suggest any idea on what types of control actions should be taken at these weak nodes to prevent the system from falling to voltage collapse, e.g. connection of shunt capacitor banks, load shedding, etc.?

The authors are again commended for their very fine work of engineering interest.

H. Glavitsch, (Swiss Federal Institute of Technology, Zuerich, Switzerland): The authors are to be commended for an unconventional but powerful contribution to the problem of voltage stability.

The powerful item in the proposed method lies in the simple calculation of the maximum power transfer which is not confined to the area of voltage stability but has more general applications.

The specific use of the method in the paper, however, needs some considerations. The coherent increase of the loads by a real factor μ gives a power limit but need not necessarily be relevant for the stability of the voltage of the particular load condition. The main point is that the load will not increase this way. In practice, the voltage stability limit will be reached by a single load or by the increase of a group of loads. The voltage limits determined this way will be different from those found by a coherent increase. If one really wants to work out limits by a coherent increase the method in [1] will give a faster answer.

It is to be realized, however, that the computational method in the paper lends itself for raising the loads in any desirable manner. This way it may have its merits. In this connection it would be of interest to know what the computational efficiency is. How does it compare with a load flow which has been augmented to give an answer near the stability limit? Have there been any checks made as far as the accuracy of the method is concerned, i.e. in comparison to a load flow solution? A comment will be appreciated.

Reference

[1] P. Kessel, H. Glavitsch; Estimating the Voltage Stability of a Power System, IEEE Trans. on Power Delivery, Vol. PWRD-1, Nr. 3, July 1986, pp. 346-354.

Manuscript received March 5, 1990.

K.Iba, H.Suzuki, M.Egawa and T.Watanabe : The authors are to be commended on preparing an interesting paper on calculating the extreme loading condition. That the numerical difficulties caused by the singularity of the Jacobian matrix has been overcome by using admittance loads is considered in this paper,as are operating limits of generators. The following four questions are risen for clarification.

The aim of the proposed method is to obtain the XLC directly. It might be fast, but the shape of the nose curves is not available. It is desired by system operators and/or planners to watch the process of the voltage decline, monitoring both of the upper and the lower sides of the curves. Is it more visual to draw the curves by solving multiple solutions[13] ?

Power injections from each generators are free in the first step of the method. In the second step, however, power generations should be redispatched. In the practical situation, many generators are operating with full power at a peak demand. Therefore power up is allowed at few generators. Suppose gen-A and gen-B are operating at full power and increase their output in the first step. The increased power might be redispatched to distant generator gen-C in the second step. The gap between the two processes seems to cause numerical difficulties. Would the authors care to comment on such a problem?

The proposed method could be able to handle any type of load in the second step, however, the parameter μ, which is calculated in the first step is based on the admittance load. In the practical system, loads behave as if they are constant with respect to voltages. If the authors have any experience related to the numerical problems caused by the gap between admittance load and constant load, comments would be appreciated.

The proposed method requires some loop calculations. Would the authors show us the numbers of iterations in each process? A flow chart would also be helpful for us to trace the method correctly.

Manuscript received April 11, 1990.

I. Dobson and L. Lu (University of Wisconsin, Madison, WI): The authors describe an interesting method to calculate the "extreme loading condition" and point of voltage collapse of a power system while avoiding singularity of the method. Voltage collapse is commonly associated with the critical point, or bifurcation point at which multiple solutions of the power system equations coincide. The authors seem to identify their extreme loading condition with the bifurcation point. We show by example that the extreme loading condition is usually different from the bifurcation point.

Consider a single generator modelled as a voltage source (slack bus), a lossless line and an admittance load $G_{load} + jB_{load} + \mu(\Delta G_{load} + j\Delta B_{load})$. Following the authors' equations (2) and (3a), the load voltage magnitude $V = |V_l|$ is given by

$$V = |Y_{lg}V_g/(G_{load} + jB_{load} + \mu(\Delta G_{load} + j\Delta B_{load}) - Y_{lg})| \quad (1)$$

and the load powers are

$$P = (G_{load} + \mu\Delta G_{load})V^2 \quad (2)$$

$$Q = -(B_{load} + \mu\Delta B_{load})V^2 \quad (3)$$

Circuit analysis gives the relation between V, P, Q as

$$0 = f(V,P,Q) = V^4 + (2QX - |V_g|^2)V^2 + (P^2 + Q^2)X^2 \quad (4)$$

where the line reactance $X = jY_{lg}^{-1}$. (Here we think of V as a variable and P and Q as parameters; we think this is consistent with the interpretation of the *outcome* of authors' calculation although in authors' *method* V, P and Q are the functions of μ given by equations (1-3).)

Equation (4) bifurcates and has multiple solutions for V when

$$\left.\frac{\partial f}{\partial V}\right|_{(V,P,Q)} = 0 \quad (5)$$

In the authors' formulation, $f(V(\mu), P(\mu), Q(\mu)) = 0$ and

$$\frac{\partial f}{\partial V}V' + \frac{\partial F}{\partial P}P' + \frac{\partial f}{\partial Q}Q' = 0 \quad (6)$$

where dash denotes differentiation with respect to μ. If we assume V' is nonzero then equation (6) shows that the bifurcation condition (5) is equivalent to

$$\frac{\partial f}{\partial P}P' + \frac{\partial f}{\partial Q}Q' = 0 \quad (7)$$

However the authors' extreme loading condition is at the first maximum in

P or Q as μ is increased; that is,

$$P' = 0 \quad \text{or} \quad Q' = 0 \tag{8}$$

which differs from (7) in general. Thus the extreme loading condition is generally different from the bifurcation point.

There are special cases where the extreme loading condition (8) does imply the bifurcation condition (7). If only one of P, Q varies with μ then (8) implies (7). If the load is constant power factor so that P and Q are proportional, then $P' = 0$ implies that $Q' = 0$ and hence $\frac{\partial f}{\partial V} = 0$. In this case, P and Q both attain their maxima at the value of μ at which equation (4) bifurcates. However, we expect that the discrepancy between (8) and (7) cannot be resolved in this way when the method is applied to more than one load. (Load powers for different loads will not be proportional even if $G_{load} = B_{load} = 0$ because of the dependence of the load voltage magnitudes on μ in equations (2) and (3).)

To illustrate the comments above we set $V_g = 1.0$, $Y_{lg} = -j4.0$, $G_{load} + jB_{load} = 0.5 - j1.0$, $\Delta G_{load} + j\Delta B_{load} = 2.0 - j0.5$ and plot P, Q and $\frac{\partial f}{\partial V}$ as functions of μ in Figure 1. The extreme loading condition (Q reaches a maximum) occurs at a smaller value of μ than the bifurcation $\left(\frac{\partial f}{\partial V} = 0\right)$.

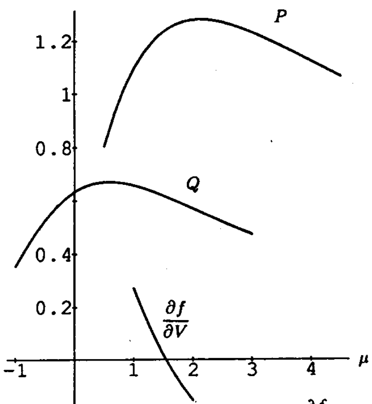

Fig. 1. Variation with μ of P, Q, $\frac{\partial f}{\partial V}$.

For a geometric view of the problem, we plot the surface defined by equation (4) in P, Q, V space in Figure 2.

As μ varies, $(V(\mu),\ P(\mu),\ Q(\mu))$ describes the path shown on the surface. Bifurcation occurs when the path encounters the fold shown on the surface where the normal to the surface has zero V component; that is, $\frac{\partial f}{\partial V} = 0$. For a general path, the maximum of P, the maximum of Q and the bifurcation occur at *different* values of μ. (It is necessary to consider paths not in a plane of constant ratio of P and Q to see this.) The projections of the path and the fold onto the $V = 0$ plane are also shown in Figures 2 and 3.

The fold projects onto a curve in the $V = 0$ plane called the bifurcation curves which is the values of P, Q at which equation 4 bifurcates. The bifurcation curve is easily found to be the parabola

$$X\,|V_g|^2 Q + X^2 P^2 = \frac{1}{4}\,|V_g|^4 \tag{9}$$

by eliminating V from equations (4) and (5). The projected path $(P(\mu),\ Q(\mu))$ in Figure 3 touches the bifurcation curve at the bifurcation and it is clear that the maxima of P, Q and the bifurcation occur at distinct values of μ. Figure 3 shows how the extreme loading condition (maximum of Q) depends on the function of μ specified by equation (3). Thus the extreme loading condition depends on the assumption of admittance loads.

Our observation that the extreme loading condition and the bifurcation point are different leads us to question how the extreme loading condition and voltage collapse are related. We would appreciate the authors' comments on our observation and their assessment of the relation of the extreme loading condition to voltage collapse.

Manuscript received February 23, 1990.

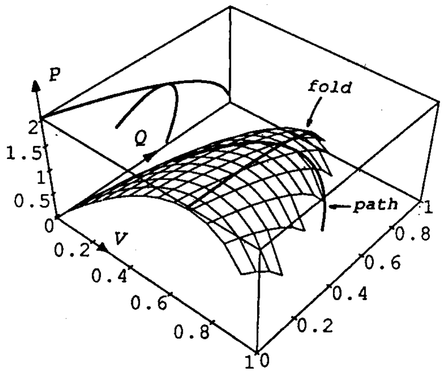

Fig. 2. Path and fold on the surface $f(P, Q, V) = 0$.

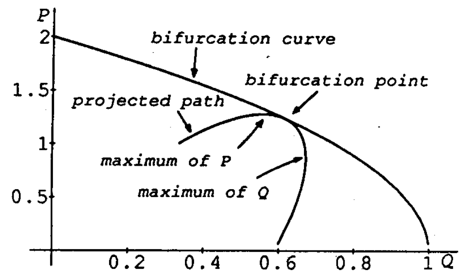

Fig. 3. Projected path on the plane $V = 0$.

F. Alvarado, (University of Wisconsin): This paper is a provocative one. The computational technique presented in this paper to determine the "extreme loading condition" is indeed fast and it is quite compatible with traditional power flow techniques. As such, it is likely to prove of value in many cases where one is interested in computing approximate limits of system operation. However, the technique is not equivalent to the Point of Collapse (PoC) methodology introduced in [10]. Replacing the load by a linear load changes not only its value as conditions change, but also affects its derivative. While the value of the linear load is iteratively adjusted by the proposed method to coincide with the correct value from a nonlinear load model, its derivative is not. A mathematically analogous problem is as follows: find the value of the parameter p at which the derivative of a nonlinear function $f(x,\ y,\ p)$ with respect to x becomes zero, given that an equality constraint $h(x,\ y,\ p) = 0$ must be satisfied. It is indeed tempting to guess x and p, solve the equality constraint h for a value of y that satisfies the constraint, then solve for a new value of x that makes the *partial* derivative of f with respect to x zero, and repeat iteratively. Unfortunately, the process does not converge to the value of p that makes the *total* derivative of f with respect to p zero (subject to $h = 0$). It is easy to demonstrate that cases where a legitimate solutions exist to the author's systems at loading levels beyond the author's "extreme loading condition".

The discusser is interested not only in the determination of not just the Point of Collapse of the system or some Extreme Loading Condition, but rather on how changes is system loading or interarea transactions affect the Point of Collapse of Extreme Loading Condition. This discusser's objective is to quantify the incremental effect of individual transactions on service reliability. This discusser would be quite interested in the author's opinion of the suitability of their XLC method for the computation of an *incremental* measure of system security; that is, can the derivative of the XLC be computed? And, given the concerns raised about the differences between the PoC and the XLC methodologies, what significance if any can be ascribed to the derivative of the XLC?

Manuscript received February 26, 1990.

Adam Semlyen, Baofu Gao, and Wasyl Janischewskyj (University of Toronto): We would like to thank the discussers for their interest in our paper and for their thoughtful questions and remarks. Our answers will be arranged in relation to each discussion.

Messrs. Kenji Iba, Hiroshi Suzuki, M.Egawa, and T.Watanabe:

The XLC approach may be used for obtaining the upper portion of the $Q-V$ curve. It is however not intended to provide this type of information. Instead it gives a measure for the proximity to the maximal loading of the system. The side-step for generator power redistribution does in general not produce difficulties if the XLC point is not very close. The XLC approach uses the load admittances rather than the load powers to simulate the increase of loading. This does however not reflect on the character of the load, whether it is constant power, constant impedance, or of any other type. The selection of the load admittance as input variable is computationally advantageous as repeated load flow solutions are avoided. The latter become more and more ill-conditioned if a conventional Newton-type method is used. The number of iterations for an XLC solution is between 5 and 10 steps with 3 to 6 iterations needed for a side-step.

Prof. Yasuo Tamura:

The choice of ΔY_{load}, which defines the direction along which the loads are increased, is totally arbitrary as far as the XLC method is concerned. For the purpose of illustration, we have tested two extreme cases: system-wide loading and individual bus loading. However, any loading pattern can be handled just as easily, e.g., loading of a particular area, loading of different zones within each area, etc. Since the selection of the direction ΔY_{load} is arbitrary, it will not lead to the closest XLC point. We are now examining a procedure for obtaining the most sensitive loading direction leading to voltage instability.

Among the possible remedial actions against impending voltage collapse, series capacitive compensation and load shedding are often viewed as the most acceptable.

Prof. Ian Dobson and Liming Lu:

We appreciate the care and thoroughness of the discussers' analysis of some fundamental aspects of our paper. Their small system example has provided very useful insight to the complex problem of the loadability of a power system. We agree with their analysis and find of particular interest the representation of a path in the $P-Q$ plane of their Figure 3 to show that the bifurcation point and the points for the maxima for P and Q do not coincide, in general. However, as the discussers have noted, coherent variation of all load powers, P and Q, leads to the XLC being also a point of the bifurcation hypersurface. This is achieved in the single bus case by choosing ΔY_{load} in phase with Y_{load_0}. Computed numerical results, for several fixed power factors, have confirmed that the nose points of the obtained $P-V$ curves coincide exactly with the bifurcation points of Figure 3 of the discussion. In the case of large systems, the coherency of load powers can be achieved by adjusting ΔY_{load_k} in inverse proportion to V_k^2. We would like to make further remarks to this problem.

The parabolic bifurcation curve of Figure 3 (of the discussion) is a universal curve for the simple system of the discussion if V_g and X are both assumed to be base values equal to 1 p.u. Then the parabola intersects the P and Q (per unit) axes at 0.5 and 0.25, respectively. It separates the P,Q plane into a feasible and infeasible domain for any given point P,Q. In the feasible portion, the load flow problem in terms of V and δ has a real solution, while in the infeasible part the load flow problem has no solution in R^2. The limit curve is structurally unstable because a small perturbation in the system parameters may leave the point P,Q in the infeasible area. It is the system that is unstable and speaking about voltage instability is somehow restrictive and justified mainly by using V as the most significant descriptor for the state of the system. Equivalently, the current I or any other algebraic variable could have been used, and all become unstable at the same time.

The feasible area of the P,Q plane can be viewed as a mapping of the V,δ plane. In an n load bus system, we have the mapping of V,δ in R^{2n} to the feasible domain of P,Q in R^{2n}. While we would be interested in this domain of the $2n$ dimensional P,Q space and, in particular, in the hyper-surface separating it from the infeasible domain, the solution of the problem appears to be practically very difficult. Because of this, we had to restrict ourselves to the simpler problem obtained by using a single parameter, μ. In any case, with fewer than $2n$ parameters, the size of the feasible domain is expected to be decreased.

It may seem that the loading parameter μ is equivalent (in the case of the simple system) to the voltage parameter V. In reality, μ defines not only V (equation (1) of the discussion), but also δ. Therefore, for a given μ we obtain a single point in the P,Q plane, while for a given V but with unspecified δ we obtain a circle of equation (4). The bifurcation curve is the envelope of the family of circles; see Figure A. Alternatively, the bifurcation curve can be obtained as the envelope of parabolas for δ = const; see Figure B. Along the arc of a circle of Figure A, the parameter is δ, and transversally, from circle to circle, it is V. On the path with μ as longitudinal parameter (in Figure 3 of the discussion) we have no transversal parameter to find the point where the path will touch the envelope. We may be able to use such a parameter (perhaps with a complex $\mu+j\varepsilon$ with $\varepsilon\rightarrow 0$) in order to find the bifurcation point on the path, but this will not be of any real significance in the multi-load case since the complete feasible domain is obtainable only through a $2n$-dimensional mapping. Thus, our (from a theoretical point of view) arbitrary definition of the XLC, as the point where a first maximum is reached, gives in fact a P,Q point at some distance from the limit point (which may not even be on the chosen path) where instability occurs. The XLC limit is thus more conservative for the assessment of stable operation than the limit obtained by a rigorous approach of bifurcation analysis. It may still not be conservative enough, as dynamic instability is likely to occur before the XLC point on the path having μ as parameter.

Prof. Hans Glavitsch:

We agree with the discusser that the voltage stability limit depends on the way the loads are increased. If ΔY_{load} is changed during the iterations, any prescribed load power path can be followed, at little extra computational expense. In general, the cost of computations is comparable to that of a load flow since the main effort goes into a small number of sparse factorizations. The accuracy of the results is not affected by ill-conditioning as in the case of load flows when the XLC limit is approached.

Prof. Fernando Alvarado:

As pointed out in our answer to Prof. I. Dobson and L. Lu, the methodology used for the calculation of the XLC permits to choose a loading path which corresponds to coherent loading. Then the XLC (Extreme Loading Condition) and the PoC (Point of Collapse) of [10] coincide. Thus, the theoretically correct voltage stability limit can be obtained with relatively small computational effort, even in the case of large systems.

The problem of the sensitivity of the maximal system load, raised by the discusser, is clearly of practical importance and favors Newton-like methods (as in [10]). The XLC procedure is based on the secant method which requires only function evaluations (no derivatives).

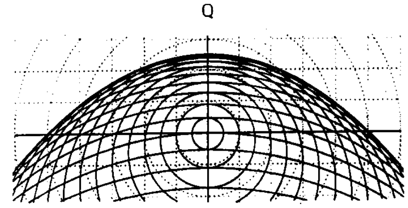

Fig.A Family of circles with V = const as parameter

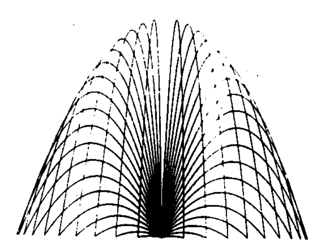

Fig. B Family of parabolas with δ = const as parameter

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VALUATION OF THE TRANSMISSION IMPACT IN A RESOURCE BIDDING PROCESS

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ABSTRACT

This paper presents a methodology for the valuation of the transmission impact of a new resource in a transparent resource bidding process sponsored by a vertically integrated electric utility company. The attribute of the resource considered for this evaluation is its location, defined as the point of interconnection of the resource to the transmission network. The objective is to send "correct economic signals" to potential new resources to connect to the "right" places in the network for an "optimum" transmission impact.The value of the resource location is estimated based on its impacts on losses and on potential loading and voltage problems in the system. This methodology has been implemented in a computer program currently in use within the company.

KEYWORDS: Competitive resource bidding and auction, Transmission impact analysis, Valuation of resource location attribute.

I. INTRODUCTION

Competitive bidding and auctions for the procurement of new generation capacity is receiving a great deal of attention in the U.S.A. Regulators at both federal and state levels have proposed rules [1] and adopted programs for the competitive resource bidding. Several research bodies have recommended structures for the bidding process [2,3,4].

In a resource bidding process, it is essential to devise the means to evaluate the relative merits of project bids. The evaluation should accurately take into account all attributes of the resource which could impact the overall cost/benefit to the utility customers. Resource attributes should, hence, be tied to customer benefits and bids should be awarded to the resources that provide the highest customer benefits.

At present, various technical and institutional limitations do not allow an accurate evaluation of the benefits of a new resource to be performed in a bidding system. Lack of sufficient data and/or analytical tools constitute the major technical limitations. Institutional limitations stem mainly from the need to prevent gaming in the bidding process. In order to prevent gaming and to ensure maximum economic benefit, the bidding process should be as transparent as possible. A transparent process would provide maximum information and minimum specifications, on a pre-bid basis. The information would enable bidders to self-score the merits of their projects; hence, they will be able to optimize their bids to enhance customer benefits and the profitability of their projects.

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Several utilities in the U.S.A have already sponsored competitive bidding for resource acquisitions. The self-scoring systems in all these bidding processes are based on point systems. A bidder will score points by providing attributes and features deemed desirable by the utility. Bidders with the highest points scored will win the bid. The main drawback of these bid scoring systems is that the award procedure for points is based on experience and engineering judgment of the utility planners rather than a direct analysis of the costs and benefits attributable to the resource.

In Pacific Gas and Electric Company (PG&E), we have developed a procedure for evaluating the total customer benefits due to a new resource based on its major attributes. Resource attributes considered in this procedure are:

- Capacity price
- Energy price
- Dispatchability/curtailability
- Location
- Start date flexibility
- Fuel diversity
- Project viability
- Environmental impact

Figure 1 demonstrates the overall framework of the PG&E's bid evaluation process. In this framework benefits from relevant attributes of a resouce are taken into account in evaluating the overall customer benefit from the resource. The details of the bid evaluation process are presented in [5].

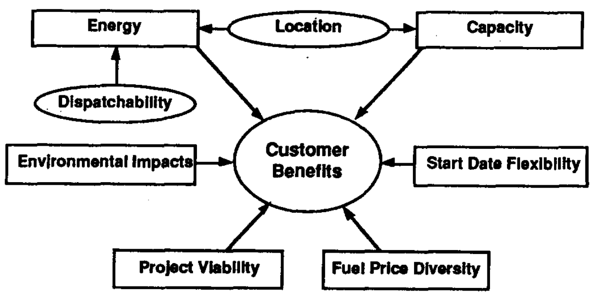

Figure 1. PG&E's bid evaluation framework

A PC-based software package, developed based on the bid evaluation procedure, is distributed to all potential bidders during the bid solicitation process. This software package enables the bidders to calculate the customer benefit of their projects on a pre-bid basis. Bidders will also be able to determine the influence of various attributes of their projects on the customer benefit; hence, they, will be able to optimize their resource bids by modifying these attributes. In this fashion, they will be able to improve the overall economic efficiency by enhancing customer benefit and increasing project profitability.

This bid evaluation procedure uses information associated with the transmission impact of a new resource due to its location. The location of a resource refers to its point of interconnection to the transmission network. The information on the location attribute will be distributed to the bidders as part of the overall package.