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VOLTAGE STABILITY ANALYSIS BY SIMULATED ANNEALING ALGORITHM

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Abstract:

Power system is facing new challenges as the present system is subjected to severely stressed conditions. In order to avoid systemblackouts, power system is to be analyzed in view of voltage stability for a wide range ofsystem conditions.In voltage stability analysis, the main objective is to identify the system maximumloadability limit and causes of voltage instability.In this study, critical bus values in a power system are determined by using Simulated Annealing (SA) algorithm.Firstly, load value of the selected load bus is augmented step-by-step and load flow analysis is done for each case. This process iscontinued till there is no solution and in this way the critical bus values that are limit values of voltage stability are obtained.This study demonstrates the use of minimum singular value method order to determine the maximum loadability in power system.The reactive power at a particular bus is increaseduntil it reaches theinstability point at bifurcation. At this instability point, the connected load loadability. Secondly, by using SA algorithm, maximum loadability limit are directly determined without increasing the load of the selected load bus. The results show that the critical values can be easily determined using SA.This technique is tested on the IEEE-57 bus system.

Keywords— **Maximum loadability, Simulated Annealing, Voltage collapse, Stability index**

INTRODUCTION

The problems that come along at the planning and management of power systems which extend in requirement and dimension have had a complex nature more and more. In this way, these systems are modeled with nonlinear equations and computers are needed for analysis Power demands of consumers in the electric power systems are also increased. In a power system, sources, lines and load which is varying continually constitute a dynamic structure. In this dynamic structure, voltage and power values of the buses, which are also called the critical values, are needed to recognize. Because the system must be operated that these critical values are never attained. Otherwise voltage collapse that causes the serious economic losses may be observed. Voltage stability is directly related to maximum loading of the energy transmission system and is a measure of ability of fixing the load bus values in some predetermined values Voltage stability is examined statically with various methods. One of the most commonly used methods for finding the limits of the critical values in a power system is Newton- Raphson (NR) power flow analysis method [4]. In this method, load value of the load bus is augmented step-by-step till power flow algorithm produces no solution, namely till the case of the Jacobian matrix is singular[5]. In [6], Kessel and Glavitsch present a voltage stability analysis which uses L indicator. Thomas and Tiranuchit investigated a global voltage stability indicator based on the singular value of the Jacobian matrix[7]. Begovic et al also present a voltage stability analysis in [8] based upon the ratio of Thevenin equivalent impedance to load equivalent impedance.

This paper will first discus and describe some general aspects and facts concerning the singular value decomposition of a matrix, these conclusions will be applied to the power flow jacobian matrix. The following section represents a new fast method to calculate the minimum singular value and the corresponding singular vectors for a matrix .

The minimum singular value of the system jacobian was proposed in that the index decreases as the system loading increases toward its maximum value and by ensuring that this index is bounded from reaching zero, security margins can be ensured and voltage collapse may be prevented. However, when reactive power generation limits are considered in the modeling, such index may not be zero at the voltage collapse .

Therefore, although it would be desirable that VSIs have a predictable value and be smooth, limit-induced bifurcations cause them to be nonlinear and difficult to predict. In such work this function was obtained through a heuristic algorithm known as simulated annealing algorithm.This paper proposes the estimation of the MSV by means of NNs specially trained for determining these VSIs, using input signals the load and generation increase patterns. The effectiveness and the feasibility of the technique presented has led to the idea that VSIs at voltage collapse may be successfully represented by means of NNs.

In this study, the limit values of voltage stability are firstlydetermined based on the NR power flow algorithm.After this the critical values of the bus are determined with SA. The critical values are directlydetermined using SA without a continuous power flow effort, as in NR.

NEWTON RAPHSON (NR) POWER FLOW

NR is one of the power system analysis method used for the solution of multivariable nonlinear equations. In this method, initial values of the variables are selected randomly at starting. Using these random initial values, new values are derived with a certain analysis pattern as expressed in (5). In equations 1-7, *V* is bus voltage value, *δ* is bus angle, *J* is jacobian matrix of thepower system, *ΔP* and *ΔQ* represent active and reactive power equilibrium of the bus, *g* and *b* depict the real and imaginary values of bus admittance matrix, *P* and *Q* represent the active and reactive power values, *y* is admittance value of transmission line, *S* is complex power value. The samplepower system, which the equations are formed from this system, can be seen in Fig. 1

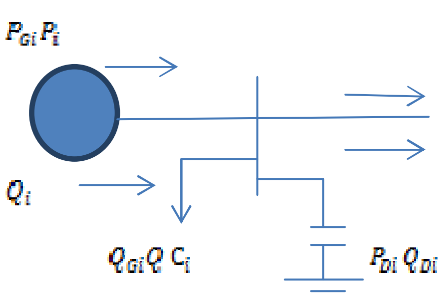

Fig1.Sketch of a general purpose bus

$P_i = V_i \sum_{j=1}^{n} V_j (g_{ij}\cos\delta_{ij} + b_{ij}\sin\delta_{ij})$ (1)

$Q_i = V_i \sum_{j=1}^{n} V_j (g_{ij}\sin\delta_{ij} - b_{ij}\cos\delta_{ij})$

(2)$P_i = (P_{Gi} - P_{Di}) = \Delta P_i = 0$(3)

$Q_i = (Q_{Ci} - Q_{Di}) = \Delta Q_i = 0$(4)

(n+1) (n) (n) (n)

$\begin{bmatrix} V_i \\ \delta_i \end{bmatrix} = \begin{bmatrix} V_i \\ \delta_i \end{bmatrix} - [J]^{-1} \times \begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix}$ (5) $\begin{bmatrix} V_i \\ \delta_i \end{bmatrix} = \begin{bmatrix} V_i \\ \delta_i \end{bmatrix} \le K$(6)

Iteration is continued until the difference between the last two derived values reach to an acceptable value, (κ) , as in (6).Final values obtained from this algorithm depict the solution of the problem.

$S_{ij} = p_{ij} + q_{ij} = V_i(V_i^* - V_j^*)Y_{ij}^* + V_i V_i^* \left(\left(\frac{Y_{ij}}{2}\right)\right)^*$ (7)

Objective of the NR power flow analysis is determination ofvoltage amplitude values of all load buses, and angle values of all buses except the slack bus. Voltage amplitude and angle values of the buses are determined via substituting Eqs. (1-4) into (5) till (6) is satisfied. After this, the expression S_{ij}+ $S_{ji}$is calculated using (7). Real part of the summation show the active power loss between *i* th and *j* th buses. Imaginary part, on the other hand, shows the reactive power loss [13].
The voltage stability critical value can be defined with the NR load flow technique, and as the active power value of load bus increases step by step, load flow is executed. This process was kept until the load flow could no longerproffer any solution. The values in the first unsolvable condition indicate the loadability limit values of the load bus.

THE MAXIMUM LOADING PROBLEM

The maximum loading of a power system is determined by including a variable that represents the system loading, i.e., the loading parameter λ, into the power flow equations. The modified power flow equations are given by:

$PG_{oi} + (\lambda + K_G).Ps_i - (PL_{Oi} + \lambda.PD_i) - \Sigma p_{ij}(V_i, V_j, \delta_i, \delta_j, G_{ij}, B_{ij}) = 0$ (8)

and

$QG_i - (QL_{Oi} + \lambda.K_L.PD_i)$

$- \Sigma Q_{ij}(V_i, V_j, \delta_i, \delta_j, G_{ij}, B_{ij}) = 0$ (9)

Where PG_0, PL_0 and QL_o stand for base generation. One of the possible methods for determining the maximum loading of a power system is through the algorithm of the continuation power flow. In this technique the power flow model is solved for automatic changes in the loading parameter λ using a predictor-corrector scheme.

SINGULAR VALUE DECOMPOSITION

The singular value decomposition is an important and practically useful orthogonal decomposition method used for matrix compositions. If the matrix A is an n by n quadratic real matrix, then the singular value decomposition is given by

$$A = U\Sigma V^T = \sum_{i=1}^{n} \sigma i U i V i^T \quad (10)$$

Where U and V are n by n orthogonal matrices, the singular vectors U_i and V_i are the columns of the matrices U and V respectively, and Σ is a diagonal matrix with

$$\Sigma(A) = \mathrm{diag}\{\sigma_i(A)\} \; i = 1,2,\ldots..,(11)$$

Where $\sigma_i \geq 0$ for all i. the diagonal elements in the matrix Σ are usually ordered so that $\sigma_1 \geq \sigma_2 \geq \ldots \geq \sigma_n \geq 0$. If the matrix A has rank r($r \leq n$) its singular values are the square roots of the r positive eigenvalues of A^TA, which also are the r positive eigenvalues of AA^T. these square roots are $\sigma_1, \sigma_2, \ldots \sigma_r$ are the only nonzero entries in the n by n diagonal matrix Σ. U and V are orthogonal matrices of order n, and the columns contain the eigenvectors of AA^T and A^TA respectively. If thus σ_i is the ith singular value of A, the vector U_i is the ith left singular vector and the vector V_i is the ith right singular vector, then the following relations between the singular values the left and right singular vectors and the matrix A can be written

$$AV_i = \sigma_i U_i (12) \quad A^T u_i = \sigma_i v_i (13)$$

The relations between the singular values and the eigenvalues of a matrix comes as has been indicated in the text above, from the fact that the entries σ_i in the diagonal matrix Σ are the singular values of A could also be described by the following relations

$$A(A^TA) = A(AA^T) = \Sigma^2(A) \quad (14)$$

Where

$$A(A) = \mathrm{diag}\{\lambda_i(A)\} \quad i = 1,2,\ldots..,n (15)$$

Is a diagonal matrix containing the eigen values of the matrix A^TA or AA^T and Σ is the diagonal matrix, defined above, which contains the singular values of the matrix A. further, let $A = U\Sigma V^T$ be the singular value decomposition of A^TA and AA^T are given by the following two equations

$$A^TA = V(\Sigma^T\Sigma)V^T (16)$$

$$AA^T = U(\Sigma\Sigma^T)U^T \; (17)$$

To use the above theory on power systems a literalized relation between the active and reactive power at nodes versus the voltage magnitudes and node angles has to be found, which is established by the power flow jacobian matrix.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = J \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} = \begin{bmatrix} F\theta & Fv \\ G\theta & Gv \end{bmatrix} \begin{bmatrix} \Delta \Theta \\ \Delta v \end{bmatrix} (18)$$

The jacobian matrix J in the above equation thus contains the first derivatives of the active power part F and the reactive power part G, of the power flow equations with respect to voltage magnitudes V and node angle θ.

If the singular value decomposition is applied to the power flow jacobian matrix J, then the so obtained matrix decomposition can be written as

$$J = U\Sigma V^T \quad (19)$$

MINIMUM SINGULAR VALUE

The minimum singular value, $\sigma_n(J)$ is a measure of how close to singularity the power flow jacobian matrix is. If the minimum singular value is equal to zero, then the studied matrix is singular and no power flow solution can be obtained. The singularity of the jacobian matrix corresponds to that the inverse of the matrix does not exist. This can be interpreted as an infinite sensitivity of the power flow solution to small perturbations in the parameter values. This point is called a static bifurcation point of the power system.

The effect on the $[\Delta\Theta \quad \Delta V]^T$ vector of a small change in the active and reactive power injections . according to the above theory of singular value decomposition of matrix, be computed as

$$\begin{bmatrix}\Delta\theta \\ \Delta v\end{bmatrix} = V\Sigma^{-1} U^T \begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} (20)$$

The inverse of the minimum singular value σ_n^{-1}, will thus from a small disturbance point of view, indicate the largest change in the static variable. Let

$$\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} = U_n (21)$$

Where U_n is the last column of U, then

$$\begin{bmatrix}\Delta\theta \\ \Delta v\end{bmatrix} = \sigma_n^{-1} V_n (22)$$

Where V_n is the last column of V. By the above given formulas and discussion about the singular value decomposition of the power flow jacobian matrix the following interpretations can be made for the minimum singular value and the corresponding left and right singular vectors

1. The smallest singular value, σ_n, is an indicator of the proximity to the steady state stability limit.
2. The right singular vector, V_n, corresponding to σ_n indicates sensitive voltages.
3. The left singular vector, U_n, corresponding to σ_n indicates the most sensitive direction for changes of active and reactive power injections .

SIMULATED ANNEALING

Early simulated annealing algorithms considered the combinatorial systems, where the state of the system depends on the configuration of variables. Perhaps the best known is the traveling salesman problem, in whichone tries to find the minimum trip distance connecting a number of cities (Goffe et al., 1994).
The SA was proposed by Kirkpatrick et al. (1983) to deal with complex non-linear problems. They showed the analogy between the simulated annealing of solid as proposed by Metropolis et al. 0(1953). The SA is an iterative improvement algorithm for a global optimization.
The optimization process in SA is essentially a simulation of the annealing process of molten metals (Corona et al., 1992; Miki et al., 2003; Wong and Wong, 1994; Saruhan,2009). Annealing was cooled down slowly, in order tokeep the system from melting in a thermodynamic equilibrium which will increase the size of its crystals and reduce their defects. As cooling proceeds, the atoms of solid become more ordered. If the cooling was prolonged beyond normal, the system would approach a "frozen"ground state at the lowest possible energy state. The initial temperature must not be too low and the cooling must be done sufficiently and slowly, so as to avoid the system getting stuck in a meta-stable state that represents a local minimum of energy. SA aims to find global minimum without getting trapped to local minimums. So, if object function is a maximization problem, the problem is converted to a minimization problem, thereby multiplying by minus 1. The simulated annealing makes use of the Metropolis et al. (1953) algorithm which provides an efficient simulation according to a probabilistic criterion stated as

$$P(\Delta E) = \begin{pmatrix} 1, & if & \Delta E < 0 \\ e^{\left(\frac{-\Delta E}{T \cdot K}\right)}, & & otherwise \end{pmatrix}$$

Thus, if $\Delta E < 0$, the probability P, is one and the change in is scaled by its Boltzmann probability factor$e^{\left(\frac{-\Delta E}{T \cdot K}\right)}$where ΔE is the change in the energy value from one point to the next; k is the Boltzmann's constant the new point- is accepted. Otherwise, the modification isaccepted at some finite probability. Each set of points of Tosun et al. 2675 all atoms of a system and T is the current temperature asa control parameter. The general procedure (steps) foremploying the SA is thus explained.

Step 1
It begins with a random initial solution, *X*, and an initial temperature, *T*, which should be high enough to allow all candidate solutions to be accepted and to evaluate the objective function.

Step 2
Set *i = i +1* and the generated newsolution $X_i^{new} = X_i + r * SL_i$,where r is random numberand SL_iat each move should be decreased with thereduction of temperature. Evaluate $F_i^{new} = F(X_i^{new})$.

Step 3

Choose accept or reject the move. The probability of acceptance (depending on the current temperature) if $F_i^{new} < F_{i-1}$, go to step 5 ; accept F_i as the new solution with probability $e^{\left(\frac{-\Delta E}{T \cdot K}\right)}$ where $\Delta E = Fi_i^{new} - F_{i-1}$ and go to step 4.

Step 4

If F_i was rejected in Step 3, set $F_i^{new} - F_{i-1}$ .Go to step 5.

Step 5

If satisfied with the current objective function value, F_i, is stopped. Otherwise, adjust the temperature

($T^{new} = Tr_T$ where r_T is the temperature reduction

rate called cooling schedule and go to Step 2.

The process is done until freezing point is reached.The major advantages of theSA are its ability to avoid being trapped in a localoptimum, andit also deals with a highly nonlinearproblem with many constraints and multiple points ofoptimum (Saruhan, 200)

PROBLEM SOLVING WITH SA ALGORITHM

In power system, if critical values are foundusing SA algorithm, the non-linear equations referring to the active power value in busses 4, 5, 6 are considered as the objective function. The maximum values are optimized with SA algorithm, using these equations. The circumstances required when searching for maximum value are considered as appropriate function, as shown in Equation 23:

$$F(x)= -P_k(x)+\sum_{\substack{j=1 \\ i \neq k}}^{m} w_{1i}(\Delta P_i^2(x) + \Delta Q_i^2(x) + \sum_{i=m+1}^{n} w_{2i}(\Delta P_i^2(x)) + w_{1k}\Delta Q_k^2(x) \qquad (23)$$

'm' refers to the number of the total load busses; n, thenumber of the total busses in power system; w is penalty factor and refers to a high number:

$$\Delta P_i(x) = P_i^{sp} - P_i(x) \text{(24Type equation here.)}$$

$$\Delta Q_i(x) = Q_i^{sp} - Q_i(x) \qquad (25)$$

The active power balance used in SA is shown in Equation 24; reactive power balance is shown in Equation 25.Active and reactive powers going in and out the bus are indicated in Equations 19 and 20. P^{sp} and Q^{sp}iin the Equations 26 and 27 refer to known bus powers

$$P_i = V_i \sum_{j=1}^{n} V_j (g_{ij} \cos\delta_{ij} + b_{ij} \sin\delta_{ij}) \qquad (26)$$

$$Q_i = V_i \sum_{j=1}^{n} V_j (g_{ij} \sin\delta_{ij} - b_{ij} \cos\delta_{ij}) \qquad (27)$$

While SA algorithms processing the border values for voltage are referred to as$V_{min} \le V_i \le V_{max}$ and for angle as $\delta_{min} \le \delta_i \le \delta_{max}$, the values below the usual process of power system are considered as initial values in algorithm (Roa and Pavez,n2003). For sample application, the initial temperature of *T* is chosen as a high value like *1*$*10^{25}$. So, for this value ofT, it is supplied and searched in many points in the space and much more neighbour solution is required. The lost heat of T is defined as *T<0,001* accepted as a heat value of which cost function does not change. So, an entire cooling is provided. In the procedure of reduction of temperature, geometric decreasing algorithm is used and the factor value is defined as *0,99* (Lee and Mohamed,2002). The iteration number in each temperature degree is considered as *1000* algorithm. So the most appropriate value is obtained in each T temperature. The max power is removed from the load bus using SA algorithm and the critical values expressed as the voltage amplitude and angle values of load busses are obtained. Critical values obtained by SA Algorithm are given Table 1.

IEEE 57 BUS SYSTEM

The network shown in Figure 2 has seven generators and forty two load points.Criticalvalues obtained by using NR and SA are given in Table 1

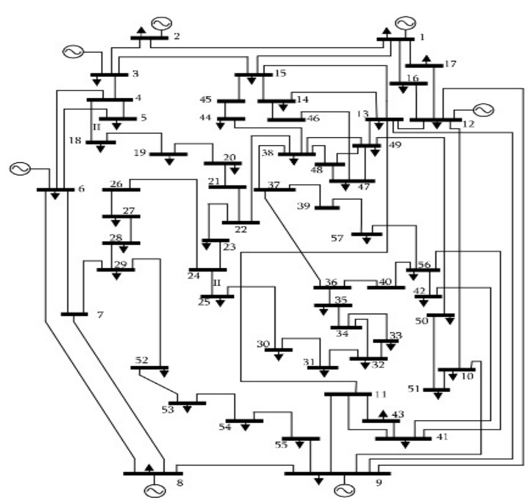

Table 1. Bus voltages at maximum loading of IEEE 57-bus system

BUS NO	NR METHOD		SA ALGORITHM	
	Magnitude (p.u)	Angle (deg)	Magnitude (p.u)	Angle (deg)
1	1.06	0.00	1.06	0.00
2	0.95	-9.31	0.50	-63.78
3	0.86	-14.65	0.50	-53.85
5	0.85	-24.03	0.59	-66.63
6	0.80	-22.38	0.68	-55.47
8	0.79	-23.83	0.83	-58.32
10	0.76	-41.09	0.67	-49.66
12	0.80	-38.47	0.67	-50.08
13	0.84	-38.47	0.68	-48.54
14	0.76	-42-27	0.67	-50.51
15	0.74	-42.84	0.68	-49.99
16	0.77	-40.97	0.67	-49.80
17	0.75	-41.86	0.67	-49.83
18	0.70	-45.84	0.69	-49.47
20	0.72	-45.46	0.69	-49.22
23	0.71	-45.44	0.67	-49.25
25	0.66	-48.27	0.67	-42.15
27	0.64	-45.32	0.68	-42.92
28	0.77	-24.73	0.72	-53.13
29	0.62	-52.62	0.69	-40.61
30	0.59	-55.63	0.66	-40.65

RESULT

The critical values obtained with NR, SA are shownin Table 1. This study states that intuitive SA algorithm method is an alternative and easy methodof estimation of critical value. This is shown in Table 1 clearly. It has a complex form for the solution of the equation system which has non-linear power flow. To reach the critical values with NR algorithm, a great deal is required of power flow by increasing the load step by step. Optimization of the function defined with SA the critical value for required bus is reached directly. SA do not require a great deal of power flow until the singular value of Jacobian matrix of the system as in NR algorithms is reached. So, these are easier way of defining voltage stability border values.Table 1 show the voltage stability critical valuesobtained from sample power system models. It is quite important to know these values before the planning and processing of power system. The results show that SA algorithm can directly reach the voltage stability limit values.

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