DETERMINATION OF VOLTAGE STABILITY CRITICAL LOADING VALUES USING SIMULATED ANNEALING

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Abstract

In this study, critical bus values in a power system are determined by using Simulated Annealing (SA) algorithm. As an example, a power system which contains the slack, generator and load buses is analyzed. Firstly, load value of the selected load bus is augmented step-by-step and load flow analysis is done for each case. This process is continued till there is no solution and in this way the critical bus values that are limit values of voltage stability are obtained. Secondly, by using SA algorithm, critical values are directly determined without augmenting the load of the selected load bus. The results show that the critical values can be easily determined using SA.

1. Introduction

The problems that come along at the planning and management of power systems which extend in qualification and dimensions have had a complex nature more and more. In this manner, these systems are modeled with nonlinear equations and computers are needed for analysis [1]. Power demands of consumers in the electric power systems are also increased. In a power system, sources, lines and load which increase and decrease 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 know. Because the system must be operated that these critical values are never reached. Otherwise voltage collapse that causes the serious economic losses may be observed [2]. Voltage stability is directly related to maximum loading capacity of the energy transmission system and is a measure of ability of fixing the load bus values in some pre-determined values [3].

Voltage stability is examined statically with various methods. One of the commonly used methods for determining 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. Another method for voltage stability analysis is to determine the critical values with the formulation produced from the case of singularity of the Jacobian matrix. In this method, the power system with N-buses is redacted to a 2-buses system by bus elimination, and after this, the critical values are determined by using this 2-buses simple system formulation [9].

In their SA-based study, Belhadj and Abido determined the optimum values of voltage stability indicator [10]. Lin et al also present voltage stability analysis based on SA [11]. Chang and Huang implemented a Static VAR Compensator (SVC) planning using SA [12].

In this study, the limit values of voltage stability are firstly determined with Power World environment which is based on the NR power flow algorithm. After this, the critical values of the bus are determined with SA. The critical values are directly determined using SA without a continuous power flow effort, as in NR method.

2-NR Power Flow Method

NR is an 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 the power 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 sample power system, which the equations are formed from this system, can be seen in Fig. 1.

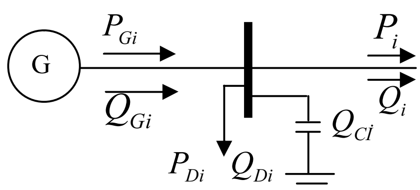

Fig. 1. Sketch of a general purpose bus

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

$$\left[\frac{V_i}{\delta_i}\right]^{(n+1)} = \left[\frac{V_i}{\delta_i}\right]^{(n)} - [j]^{-1(n)} x \left[\frac{\Delta P_i}{\Delta Q_i}\right]^{(n)}$$
(5)

$$\left[\frac{V_i}{\delta_i}\right]^{(n+1)} - \left[\frac{V_i}{\delta_i}\right]^{(n)} \leq \kappa$$
(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.

$$S_{ij} = p_{ij} + q_{ij=} v_i (v_i^* - v_j^*) y_{ij}^* + v_i v_i^* (\frac{y_{ij}}{2})^* \quad (7)$$

Objective of the NR power flow analysis is determination of voltage 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 this summation depicts the active power loss between *i* th and *j* th buses. Imaginary part, on the other hand, depicts the reactive power loss [13].

3. Simulated Annealing Algoritm

SA uses an analogy to physical annealing process of finding low energy states of solids and uses global optimization method. This approximation is also called Metropolis algorithm and this approach is firstly proposed by Kirkpatrick and his friends in 1983[14]. SA is a global optimization algorithm inspired by physical annealing process of solids [15].
Annealing is cooled down slowly in order to keep the system of the melt 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 possible lowest energy state. The initial temperature must not be too low and the cooling must be done sufficiently slow so as to avoid the system getting stuck in a meta-stable state representing a local minimum of energy. SA is originally based on statistical Metropolis algorithm. SA aims to find global minimum without getting trapped local minimums. So if object function is a maximization problem, the problem is converted to minimization problem by multiplying minus 1. The algorithm of SA is as in Table 1.

Table 1. SA Algorithm

```
s ← Produce initial solution()
T ← T0
while  stopping criteria not true  do
        for i=1 to k
s' ← Produce a random solution
if f(s') < f(s)
 then
'Simple Local Search
s ← s'  (s' is new solution)
else
'Metropolis Algorithm
x  Produce a random number between (0,1)
x < p ( T, s', s)
then s' is also new solution even if
s ← s'
end if
        next
Update (T)
end while
```

Algorithm starts with an initial solution and an initial temperature. Search process continues as long as stopping criteria is true. Maximum run time and maximum iteration number may be selected as stopping criteria. For each *T*, *s'∈N(s)* is selected randomly. And if *f(s')<f(s)* then s' is accepted as new solution like local search. But if *f(s')>f(s)* then *x= U(0,1)* is produced and if *x* is smaller than *P(s',s,T)* then *s'* is also accepted as new solution for diversification.

$$P = e^{-(\frac{f(s') - f(s)}{T})}$$
(8)

So firstly the possibility of bad solutions acceptance or (hill-climbing moves) is high for diversification.

$$\lim_{T\to\infty} e^{-(\frac{f(s') - f(s)}{T})} = e^0 = 1$$
(9)

T is decreased along the search process. The possibility of bad solution acceptance is approach to zero. And the process converges to local search method for intensification.

$$\lim_{T \to 0} e^{-(\frac{f(s')-f(s)}{T})} = e^{-\infty} = 0 \qquad (10)$$

The proper annealing process is related to initial temperature, iteration for each temperature, temperature decrement coefficient and stopping criteria. All these criterion can be found in related articles [16].

4- Definition of the Problem

The system to be analyzed in view of voltage stability is given in Fig. 2. In this system, buses 1, 2 and 3 represent slack, PV and load buses respectively. Line data of the system are shown in Table 2.

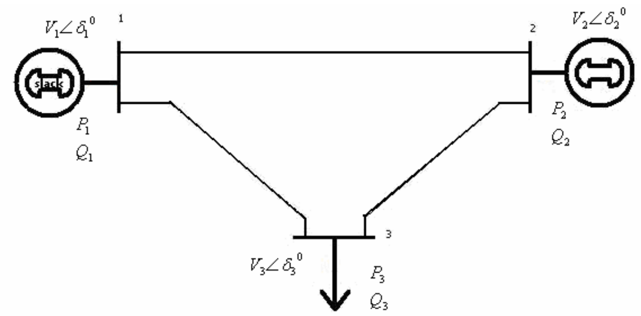

Fig. 2. System to be analyzed in the sense of voltage stability

Table 2. Line data

Line		Line Empedance	
From	**To**	**R(pu)**	**X(pu)**
1	2	0,07	0,2
1	3	0,05	0,3
2	3	0,08	0,3

The bus 3, which is the load bus, is examined in the sense of voltage stability. It is assumed that power factor of the load bus is constant. The problem is solved by both Power World and SA algorithm.

4-1 Solution of the Problem Using NR Algorithm

Power World environment is used for the solution of the problem. This software can be used for load flow analysis based on NR algorithm. To find the solution of the problem, by increasing the power consumed by the load bus step by step, the values shown in Fig. 3 are reached. These values also represent the maximum power values that can be supplied from the load bus. If maximum power is consumed by load bus, then voltage amplitude and angle values depict the critical values.

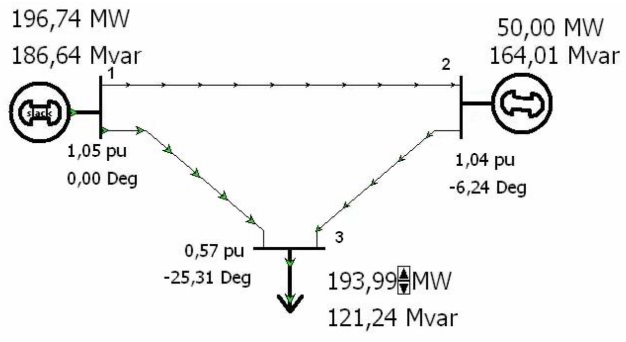

Fig. 3. Given values and calculated values with load flow analysis.

Table 3. Critical values calculated with Power Word

Bus	Voltage	Angle	Power	
	V(pu)	*δ (deg)*	*P(MW)*	*Q(MVAr)*
1	1,05	0	196,74	186,64
2	1,04	-6.24	50,00	164,01
3	**0,57***	**-25.31***	**193,99***	121,24

In the system given in Fig. 3, to get PV curve of the load bus, consumed active power value is increased step-by-step. In each step, the voltage value is recorded. Bu using these values, the curve in the Fig. 4 is obtained. In this curve, the maximum active power value represents the critical power value, and the corresponding voltage value is the critical voltage value. Mentioned values are shown in the curve.

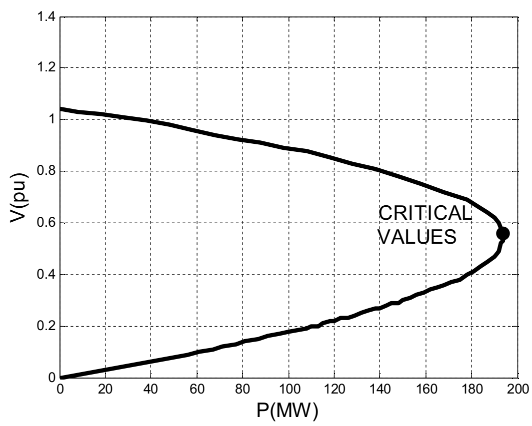

Fig. 4. P-V curve and critical values calculated with power flow analysis for bus-3

Table 4. Critical values calculated with SA

Bus	Voltage	Angle	Power	
	V(pu)	δ *(deg)*	*P(MW)*	*Q(MVAr)*
1	1,05	0	196,17	184,53
2	1,04	-6,30	50,00	159,30
3	**0,57**	**-25,3**	**193,68**	121,22

Power World environment produce the P-V curve shown in Fig. 4. There are two voltage values for each power value at the curve. At the critical voltage point, however, there is only one solution. This point is assumed critical voltage point in view of voltage stability.

4.2. SA Algorithm-Based Solution of the Problem

If it is desired to find the critical values of the system shown in Fig. 2 with SA algorithm, one must consider the nonlinear equation of active power in bus-3 as goal function. It is tried to find the maximum value by applying SA-based optimization on this equation. While maximum value is being searched, the fitness function, when the conditions required to satisfied such as active and reactive power equilibrium are considered, will be

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

$$\sum_{i=M+1}^{n} w_{2i}(\Delta P_i^2(x) + w_{1k}\Delta Q_k^2(x) \quad (11)$$

In (11), m represents the number of load buses and n represents the total number of buses, w_{1i}, w_{2i} 's are called penalty factors and generally assigned as a great positive number.

$$\Delta P_i(x) = P_i^{SP} - P_i(x) \quad (12)$$

$$\Delta Q_i(x) = Q_i^{SP} - Q_i(x) \quad (13)$$

Active power equilibrium condition is given in (12) and reactive power equilibrium condition is given in (13). The active and reactive powers flowing towards or flowing away the bus are expressed as in (14) and (15). P^{SP} and Q^{SP} are the known bus powers. Limit values are expressed as $V_{\min} \leq V_i \leq V_{\max}$ for voltage and $\delta_{\min} \leq \delta_i \leq \delta_{\max}$ for angle. Voltage limits in power system are assigned as 0,5-1,1 pu and angle limits are assigned as -45° , +45° [17].

$$P_i = v_i \sum_{j=1}^{n} v_j (g_{ij} \cos\delta_{ij} + b_{ij} \sin\delta_{ij}) \quad (14)$$

$$Q_i = v_i \sum_{j=1}^{n} v_j (g_{ij} \sin\delta_{ij} - b_{ij} \cos\delta_{ij}) \quad (15)$$

As an example, initial temperature value of T is selected as $1*10^{35}$, a sufficiently great value. This satisfies the advantages of searching so many points in the space and examining more neighbor solutions. The final temperature of T is selected as $T<0.1$, which it is assumed that cost function is never changed at this value. In this way, a complete cooling is satisfied. Geometric decrement is used for temperature decreasing process, and the factor value is selected as *0.99* [18]. Iteration number for each temperature value is selected as *100*. In this wise, the best value for each T temperature is found.

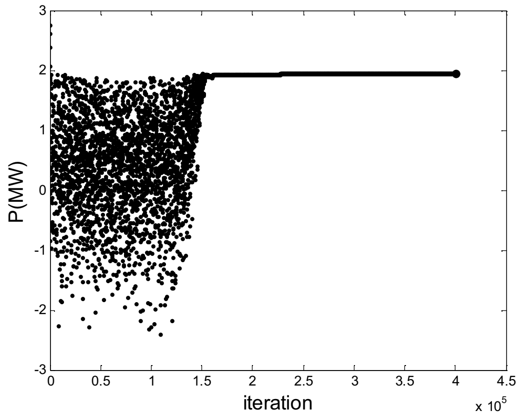

Fig. 5. Variation of maximum power (cost) versus iteration number

Table 4 shows the critical values calculated with SA and Fig. 5 shows the variation of maximum active power of the bus versus iteration number.

6. Conclusions

The results show that SA algorithm is an alternative and simple method to calculate the critical values. In a power system, it is important to know the critical values which are limit values of stability. As shown in Table 5, The critical values can be simply and correctly calculated with SA which is a heuristic method. Power flow analysis has a complex structure containing the solution of nonlinear differential equation systems. NR algorithm requires too many computational efforts to find the critical values. SA algorithm, on the other hand, searches the solution in a wide range of the space and finds the global maximum without getting trapped to the local minimums. The critical values of the desired bus are directly found with SA by optimizing the defined function. Namely, it is not needed to run a continuous load flow analysis to determine whether the singular values are reached, as in NR algorithm.

Table 5. Comparison of the critical values calculated with NR and SA for the system.

		N R	S A
BUS 1 (Slack)	Voltage *(V) (pu)*	1,05	1,05
	Angle *(δ) (deg.)*	0	0
	Active Power *(P) (MW)*	196,74	196,17
	Reactive Power *(Q) (MVAr)*	186,64	184,53
BUS 2 (P-V)	Voltage *(V) (pu)*	1,04	1,04
	Angle *(δ) (deg.)*	-6,24	-6,30
	Active Power *(P) (MW)*	50,00	50,00
	Reactive Power *(Q) (MVAr)*	164,01	159,30
BUS 3 (P-Q)	**Voltage *(V) (pu)***	**0,57**	**0,57**
	Angle *(δ) (deg.)*	**-25,31**	**-25,30**
	Active Power *(P) (MW)*	**193,99**	**193,68**
	Reactive Power *(Q) (MVAr)*	**121,24**	**121,22**

6. Acknowledgement

Authors would like to thank Ugur HASIRCI for his valuable discussion and peer-reviewing.

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