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Full Length Research Paper

Investigation of critical bus values in electric power system using simulated annealing and Tabu search algorithms

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The critical values of a power system are the limit values of voltage stability. These are: the values of the highest active power that load busses can take and the values of voltage amplitude and angle of the busses in this condition. In this research, the critical values in electric power systems are defined with Simulated Annealing (SA) and Tabu Search (TS) algorithms. These algorithms are known as heuristic techniques in the literature. The research is executed on a sample of 6-bus power system. At first, as the load value in a selected load bus increased step by step, load flow is executed anytime. This process was kept until an unsolvable condition was reached, so critical bus values which are limited values of voltage stability were obtained. Secondly, using (SA) and (TS) algorithms, without increasing the load on selected bus step by step, the critical value was reached directly. It was seen that the critical bus values can be obtained easier through (SA) and (TS) which are heuristic techniques.

Key words: Tabu search, power system, voltage stability, simulated annealing.

INTRODUCTION

Voltage stability is directly related to the maximum load capacity of power system transmission line and it is defined as the ability of keeping load busses in determined limit values (Taylor, 1994; Anderson and Fouand, 1986). In electric power systems, load demands of the consumers that are related to developments are on the increase. In load system of in and out loads, lines and sources create a dynamic structure. In this dynamic structure, load, angle and voltage values which are the critical value of load busses, the connection points of the system need to be determined. System not reaching these critical values should be designed and operated. Otherwise, voltage would collapse, of which the samples can be seen from time to time and can cause economic losses (Yalcin, 1995).

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Glower and Sarma (2000) defined the critical bus values of voltage stability through the (NR) load flow analyzing technique. In this study, they reached the critical values through an increase in the load of related bus step by step until the load flow can not provide a solution. They stated that the algorithm can not provide a solution when the Jacobian matrix is singular (Glower and Sarma, 2000).

Thomas and Tiranuchit (1988) developed a global voltage indicator based on singular value of Jacobian matrix. Similar studies of various techniques were reported in the literature to identify and estimate the maximum loadability to indicate its importance in the study of power system (Kundur et al., 2004; Morison et al., 1993; Rahman et al., 1997; Yome et al., 2006; Musirin and Rahman, 2002). Begovic et al. (1999) studies on voltage stability reported that Thevenin equivalent impedance is based on qualification and rate of load equivalent impedance.

One of the studies on voltage stability is that the critical

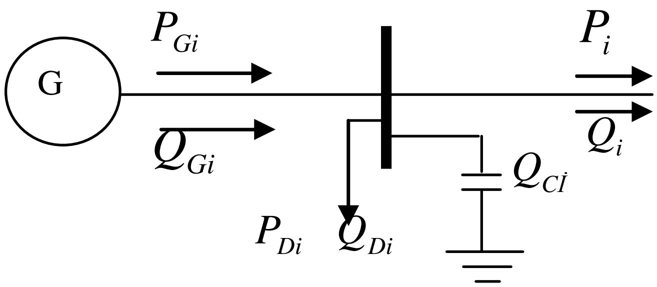

Figure 1. Displaying a general purpose bus.

values are defined using formulas produced considering the singularity of Jacobian matrix. According to this technique, critical values are estimated with formulas reducing power system into two busses system with bus elimination when it consists of N bus (Yalcın, 1995).

One of the popular and fast search techniques is the use of the Artificial Intelligence (AI) search techniques. Musirin and Rahman (2002a) developed a new algorithm to execute the Evolutionary Programming (EP) base optimi-zation technique for estimating maximum loada-bility or critical loading condition in power system for one load bus (Kalil et al., 2002). Other optimization techni-ques which can also perform similar task are linear programming, Genetic Algorithm, quadratic progra-mming, Ant Colony Optimization and Artificial Immune System (Musirin et al., 2005).

In this study SA and TS algorithms are used to esti-mate critical values. Voltage stability border values are obtained using NR load flow algorithm, firstly. According to this technique, to find the critical value, voltage stability critical value for the bus is obtained by reducing load until an unsolvable condition is reached; in other words, until the condition of the active power of load bus is at its maximum. In the next step of the study, the critical value in the same bus is obtained by using SA and TS algorithms. Through SA and TS algorithms, which are heuristic techniques, as a result of a study based on optimization logic, critical values are reached directly without any need of step by step load flow as in NR algorithm.

NEWTON RAPHSON (NR) POWER FLOW

NR algorithm is an analyzing technique used in solving multi-variable non-linear equation. According to this method, the values of the equation are determined randomly at the beginning. Using a specific method with the use of this value, new values are produced; this is shown in Equation 1. In the Equation 2, the study is sustained iteratively until an acceptable little distinction (κ) between the two values produced lastly is provided. As a result, the resolution of the problem is provided through these obtained values. Sample power system that obtained power flow equations, was given in Figure 1. According to NR algorithm, the unknown value in power system is found using Equation 1:

$$\begin{bmatrix} V_i \\ \delta_i \end{bmatrix}^{(n+1)} = \begin{bmatrix} V_i \\ \delta_i \end{bmatrix}^{(n)} - \left[\overbrace{\begin{matrix} \dfrac{\partial P_i}{\partial \delta_i} & \dfrac{\partial P_i}{\partial V_i} \\ \dfrac{\partial Q_i}{\partial \delta_i} & \dfrac{\partial Q_i}{\partial V_i} \end{matrix}}^{(n)}\right]^{-1} \times \begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix}^{(n)} \quad (1)$$

V_1 and δ_1 values in Equation 1 indicate that voltage amplitude and angle values of busses are required to find NR algorithms. ΔP_i and ΔQ_i values indicate the non-linear equations that are formed to find the unknowns. These are the active and reactive power balance equations of busses. Achieving the solution of NR algorithm depends on providing Equation 2.

$$\begin{bmatrix} V_i \\ \delta_i \end{bmatrix}^{(n+1)} - \begin{bmatrix} V_i \\ \delta_i \end{bmatrix}^{(n)} \leq K \quad (2)$$

The purpose of NR power is to define voltage amplitude values of the entire load busses and angle values of the whole busses, except beat bus. Voltage amplitude and angle value of busses are obtained as a result of keeping on the process iteratively in Equation 1, until Equation 2 is provided in the expression of Equations 3-6. If Equation 7 is placed, value of active and reactive power flows through the whole lines. At the same time $S_{ij} + S_{ji}$ values are estimated with the help of this equation. The real part in total shows the active power loss between i-j busses, while the imaginary part of it demonstrates the reactive power loss (Powel, 2005):

$$P_i = v_i \sum_{j=1}^{n} v_j (g_{ij} \cos \delta_{ij} + b_{ij} \sin \delta_{ij}) \quad (3)$$

$$Q_i = v_i \sum_{j=1}^{n} v_j (g_{ij} \sin \delta_{ij} - b_{ij} \cos \delta_{ij}) \quad (4)$$

$$P_i - (P_{Gi} - P_{Di}) = \Delta P_i = 0 \quad (5)$$

$$Q_i - (Q_{Cİ} - Q_{Dİ}) = \Delta Q_i = 0 \quad (6)$$

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

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 longer proffer any solution. The values in the first unsolvable condition indicate the loadability limit values of the load bus.

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 which one 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 to keep 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:

$$P(\Delta E) = \begin{pmatrix} 1, & if & \Delta E \langle 0 \\ e^{\left(-\Delta E / T*k\right)}, & & otherwise \end{pmatrix}$$

Thus, if $\Delta E \langle 0$, the probability, P, is one and the change - the new point- is accepted. Otherwise, the modification is accepted at some finite probability. Each set of points of all atoms of a system is scaled by its Boltzmann probability factor $e^{-\Delta E / T*k}$ where ΔE is the change in the energy value from one point to the next; k is the Boltzmann's constant and T is the current temperature as a control parameter. The general procedure (steps) for employing 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 new solution $X_i^{new} = X_i + r * SL_i$, where r is random number and SL_i at each move should be decreased with the reduction of temperature. Evaluate $F_i^{new} = F\left(X_i^{new}\right)$

Step 3

Choose accept or reject the move. The probability of acceptance (depending on the current temperature) if $F_i^{new} \langle F_{i-1}$, go to Step 5; or else accept F_i as the new solution with probability $e^{\left(-\Delta E / T*k\right)}$, where $\Delta E = F_i^{new} - F_{i-1}$ new 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 $\left(T^{new} = Tr_T\right)$, 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 the SA are its ability to avoid being trapped in a local optimum, and it also deals with a highly nonlinear problem with many constraints and multiple points of optimum (Saruhan, 2009).

TABU SEARCH ALGORITHM

This technique is one of the most used methods of intuitive optimization techniques that inquire solution space to find optimal or near optimal solutions. Tabu search (TS) concept was first claimed by Glover (1986). The method was improved by Hansen (1986). TS is a process that inquires any solution as long as there are no inquired points. So, avoiding local minimum required solution can be reached through inquiring a new solution space. The algorithm begins movement through the local minimum. The method retains one or more tabu list to prevent turning back to the movements that it did before. If a neighbour solution candidate is the same as a solution placed in tabu list, this solution is left out of order. While forming the tabu list, the best solution in each circle is taken into the list. If the list eventually gets occupied, the first records in the list (the solutions at the beginning) are omitted and the solutions got from the last circle are included in the list. Tabu list is made up through the retain method, forming first best solution cluster. An important rule of making up tabu list is processed with various filters (Mori and Usami, 1998).

Getting new solution with a change that is developed from an existing solution is executed with the use of movement mechanism. The possible movements in the movement mechanism make up the neighbours of the existing solution. Because movement mechanism is important in the activity of the algorithm, it should be selected appropriately, depending on the structure of the problem.

The memory is one of the basic elements of (TS) algorithm. The situation appears during when the search is recorded. The movements that are not allowed are called tabu, and are recorded under the tabu list category. These movements are removed from the tabu list after a short time. Tabu breaking criterion expresses the situations that tabu can disappear. The most general tabu breaking criterion is to allow tabu movement which gives a better result than the current situation does. Using this criterion increases the activity of TS algorithm. Also, if all the probable movements are tabu, a tabu movement is allowed when its timing is about to be over. Stopping condition remains searching until algorithm provides one or more stoppage condition. Some of these conditions are: not having selected neighbour, reaching a significant iteration number, reaching a significant solution value, blocking of the algorithm and not being able to produce better results.

The general algorithm of TS can be described in steps as explained below.

Step 1

Set the iteration counter $k = 0$ and randomly generate an initial solution $X_{initial}$. Set this solution as the current solution as well as the best solution, X_{best},, that is, $X_{initial} = X_{current} = X_{best}$.

Step 2

Randomly generate a set of trial solutions X_{trial} S in the neighborhood of the current solution, that is, create $S(x_{current})$. Sort the elements of S based on their objective function values in ascending order as the problem is a minimization one. Let us define X_{trial}^{i} as the i^{th} trial solution in the sorted set, $1 \leq i \leq nt$. Here, X_{trial}^{1} represents the best trial solution in S in terms of objective function value associated with it.

Step 3

Set $i = 1$. If $J(X_{trial}^{i}) > J(X_{best})$ go to Step 4;
Or else set $X_{best} = X_{trial}^{i}$ and go to Step 4.

Step 4

Check the tabu status of X_{trial}^{i}. If it is not in the tabu list then put it in the tabu list; set $X_{current} = X_{trial}^{i}$, and go to Step 7. If it is in tabu list then go to Step 5.

Step 5

Check the aspiration criterion of X_{trial}^{i}. If satisfied, then override the tabu restrictions, update the aspiration level, set $X_{current} = X_{trial}^{i}$, and go to Step 7. If not set $i = i+1$ and then go to Step 6.

Step 6

If $i > nt$ go to Step 7; or else go back to Step 4.

Step 7

Check the stopping criteria. If one of them is satisfied then stop; or else set $k = k+1$ and go back to Step 2.

DEFINING THE PROBLEM

In Figure 2, six bus power systems of which critical values will be searched are seen. In this system, bus 1 is referred to as slack bus; busses 2 and 3 as generator busses; busses 4, 5, 6 as load busses. The line data of the six busses system given in Figure 2 are shown in Table 1.

Table 1. Line data of 6-bus system.

Line	From	1	1	1	2	2	2	2	3	3	4	5
	To	**2**	**4**	**5**	**3**	**4**	**5**	**6**	**5**	**6**	**5**	**6**
Line impedance	R(pu)	0.1	0.05	0.08	0.05	0.05	0.1	0.07	0.12	0.02	0.2	0.1
	X(pu)	0.2	0.2	0.3	0.25	0.1	0.3	0.2	0.26	0.1	0.4	0.3
	B(pu)	0.04	0.04	0.06	0.06	0.02	0.04	0.05	0.05	0.02	0.08	0.06

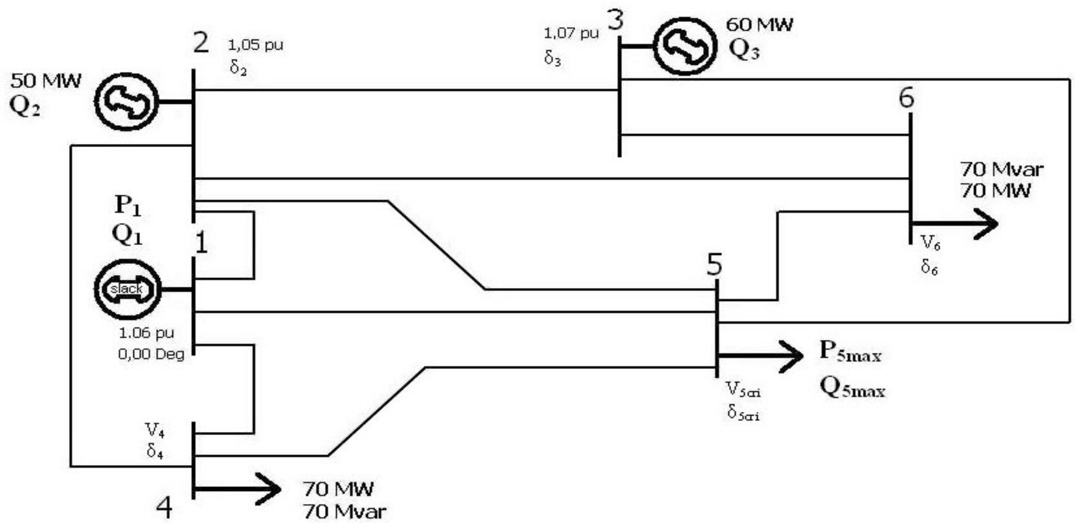

Figure 2. An example of 6-bus power system.

In this system, the loads on all the busses work under the stable power number. Also the study is executed through releasing reactive power borders of PV generators. Under these circumstances, the critical values of 4, 5, 6 busses are estimated. These critical values mean that the maximum active power values will be removed from the busses, voltage amplitude and angle values. NR power flow algorithm, which is one of the traditional methods, is used initially to obtain these critical values. Then those indicated critical values are obtained using SA and TS algorithms which are heuristic methods.

Problem solving with NR algorithm

NR power flow algorithm is applied on a three busses system, given in Figure 2. The critical values obtained with step by step power flow are shown in Table 2. As a result of step by step load, increased PV values obtained before reaching critical values are shown in Figure 3. The point where the graph ends is the first point that insolvability cannot be supplied, so it refers to the points where the critical values are reached.

In this case, power removed from the load bus means the maximum load value will be removed from that bus.

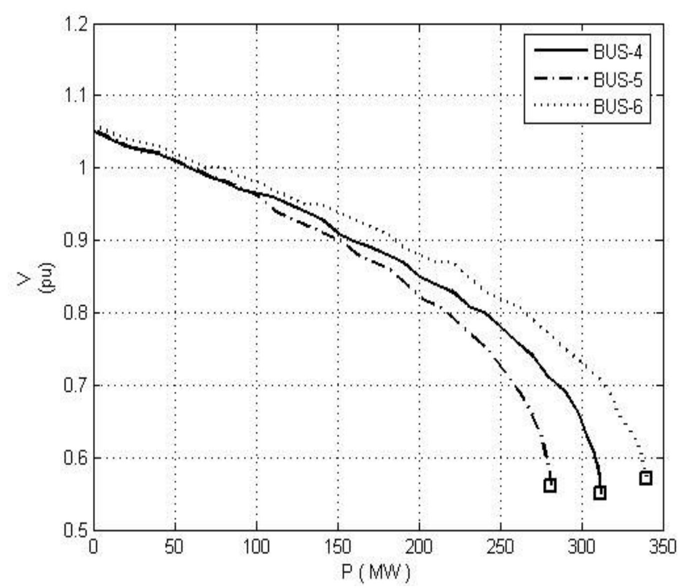

Figure 3. The critical values of 4, 5, 6 busses on the P-V curves.

Also, amplitude and angle values of the bus voltage refer to critical values.

Table 3. Stability critical values with using SA.

Bus	V(pu)	δ (deg)	P (pu)
4	0.53	-27.1	3.14
5	0.55	-30.6	2.78
6	0.55	-5.0	3.43

Table 4. Obtained critical values with using TS algorithm.

Bus	V(pu)	δ (deg)	P(pu)
4	0.54	-30	3.12
5	0.54	-32.3	2.83
6	0.57	-49.5	3.39

Problem solving with SA algorithm

In power system in Figure 2, if critical values are found using 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 8:

$$F(x) = -P_k(x) + \sum_{\substack{j=1 \\ i\neq k}}^{m} w_{1i}(\Delta P_i^2(x) + \Delta Q_i^2(x)) + \sum_{i=M+1}^{n} w_{2i}(\Delta P_i^2(x) + w_{1k}\Delta Q_k^2(x) \quad (8)$$

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

$$\Delta P_i(x) = P_i^{SP} - P_i(x) \quad (9)$$

$$\Delta Q_i(x) = Q_i^{SP} - Q_i(x) \quad (10)$$

The active power balance used in SA is shown in Equation 9; reactive power balance is shown in Equation 10. Active and reactive powers going in and out the bus are indicated in Equations 11 and 12. P^{SP} and Q^{SP} in the Equations 9 and 10 refer to known bus powers.

$$P_i = v_i \sum_{j=1}^{n} v_j (g_{ij} \cos\delta_{ij} + b_{ij} \sin\delta_{ij}) \quad (11)$$

$$Q_i = v_i \sum_{j=1}^{n} v_j (g_{ij} \sin\delta_{ij} - b_{ij} \cos\delta_{ij}) \quad (12)$$

While SA algorithms processing the border values for voltage are referred to as $V_{\min} \leq V_i \leq V_{\max}$ and for angle as $\delta_{\min} \leq \delta_i \leq \delta_{\max}$, the values below the usual process of power system are considered as initial values in algorithm (Roa and Pavez, 2003). For sample application, the initial temperature of *T* is chosen as a high value like *1*10*^{35}. So, for this value of T, 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 3

Problem solving with TS algorithm

As searching for solution with TS algorithms is shown in Figure 2, the objective function and limit values expressions given in Equations 8 - 12 are used. In this study the list determines how long a movement remains in tabu list. The length of tabu list is important. If the list is long, the movement ability of the algorithm decreases because most of the movements are tabu. On the contrary, if the short of it is chosen the risk of being captured by local values increases. In this case tabu list length is stable. If tabu renovation is the aspiration criterion, it is considered as depending on iteration. The short time memory is used in the algorithm. In the solution with TS algorithm, length of tabu list (5000) and the number of iterations were taken as *1000*. Using TS algorithms in Table 4, the max power removed from load bus and the critical values referred to as voltage amplitude angle values of load bus are obtained.

IEEE 14-bus system

The network shown in Figure 4 has five generators and twelve load points. Three of these load points are PV-buses, besides one of the generators. The other generator is taken as the slack bus. The operation conditions of the system are shown in Table 5. Critical values obtained by using NR, SA and TS algorithms are given in Table 7.

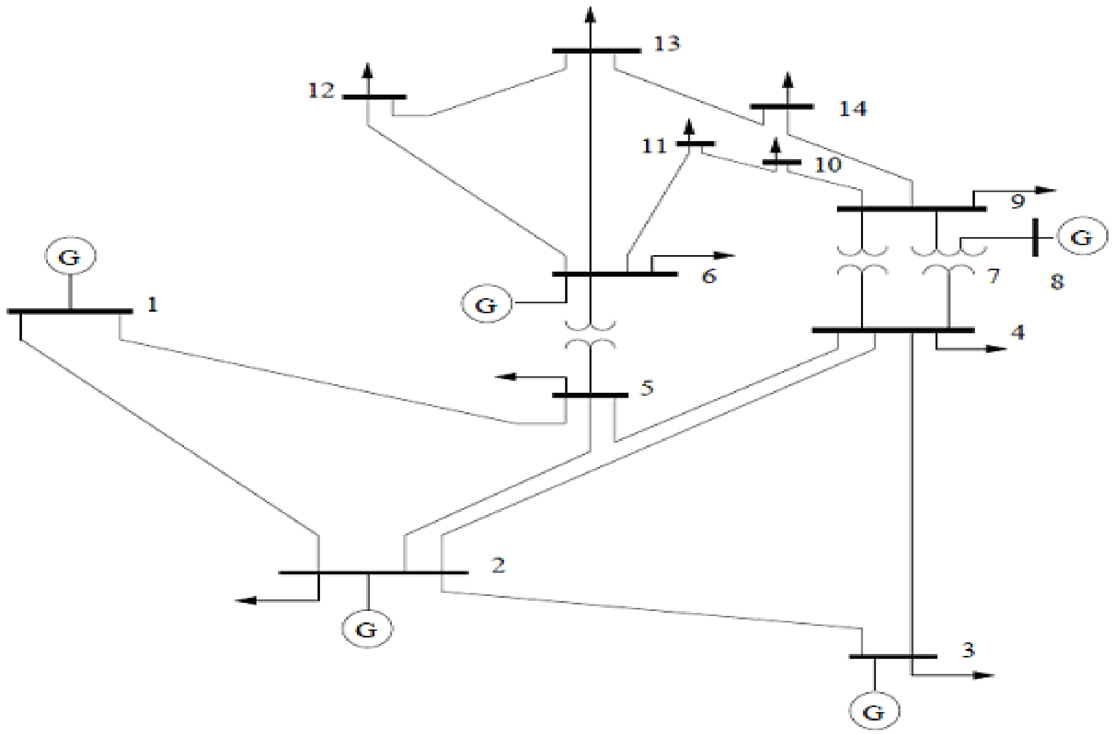

Figure 4. Single line diagram of the modified IEEE 14-bus system.

Table 5. Operating conditions of the modified IEEE 14-bus system.

Bus no	V(pu)	Loads	
		P(pu)	Q(pu)
1	1.06	-	-
2	1.045	-0.3038	-0.178
3	1.09	-1.32	-0.266
4		-0.669	-0.056
5		-0.106	-0.022
6	1.07	-0.157	-0.105
7		0.0	0.0
8	1.09	0.0	0.0
9		-0.413	-0.232
10		-0.126	-0.081
11		-0.049	-0.025
12		-0.085	-0.022
13		-0.2	-0.086
14		-0.208	-0.07

Table 6. Results of 6-bus power system

Bus		V(pu)	δ (deg)	P(pu)
4	NR	0.55	-29.2	3.12
	SA	0.53	-27.1	3.14
	TS	0.54	-30.0	3.12
5	NR	0.55	-32.4	2.81
	SA	0.54	-31.6	2.83
	TS	0.54	-33.2	2.82
6	NR	0.55	-53.3	3.40
	SA	0.55	-53.0	3.43
	TS	0.57	-49.5	3.39

RESULTS

The critical values obtained with NR, SA, TS are shown in Tables 6 and 7. This study states that intuitive SA and TS algorithm methods are alternative and easy method in the estimations of critical value. This is shown in Tables 6 - 7, 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 and TS algorithm, the critical value for required bus is reached directly. SA and TS algorithms 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

Table 7. Results of IEEE 14-bus power system.

Bus		V (pu)	δ (deg)	P (pu)
4	NR	0.69	-68	7.40
	SA	0.68	-63	7.38
	TS	0.66	-61	7.43
5	NR	0.72	-51	6.20
	SA	0.71	-54	6.18
	TS	0.69	-56	6.17
9	NR	0.61	-54	2.55
	SA	0.62	-55	2.58
	TS	0.65	-55	2.51
10	NR	0.59	-47	1.64
	SA	0.57	-49	1.63
	TS	0.59	-52	1.62
11	NR	0.57	-61	1.83
	SA	0.59	-55	1.86
	TS	0.60	-63	1.81
12	NR	0.57	-73	1.81
	SA	0.56	-71	1.80
	TS	0.56	-71	1.79
13	NR	0.63	-71	2.66
	SA	0.65	-68	2.69
	TS	0.64	-66	2.64
14	NR	0.59	-48	1.31
	SA	0.57	-47	1.32
	TS	0.56	-51	1.35

are easier way of defining voltage stability border values. Tables 6 and 7 show the voltage stability critical values obtained 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 and TS algorithms which can directly reach the voltage stability limit values are alternative solution methods to problems.

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