Maximum permissible loading of a power system within voltage stability limits using Thevenin parameters

Prof. D.K.Rai[1] Dr. H.K Verma[2] Dr.L.S.Titare[3]

*Dept. of Electrical &Elex.Engg.ShriVaishnav[SM] Institute of Tech.&science,Indore(M.P.)-India
**Dept. of Electrical &Elex.Engg.SHRI G. S. I. T. S.,Indore(M.P.)-India
***Dept. Electrical Engineering, GEC Jabalpur, (M.P)India

ABSTRACT :

Estimating the proximity of power system to voltage collapse in real time still faces difficulties. Beside the data management and computational issues, any central-control method is subject to the reliability of long-distance data communications. On-line determination of the maximum permissible loading of a power system is essential for operating the system with an adequate security margin. A very simple and straightforward method of determining the maximum permissible loading and voltage stability margin of a power system using information about the current operating point is proposed. The method simply requires some locally measurable quantities, such as bus voltage magnitude, and active and reactive components of load power. The measured data are carefully processed to estimate the maximum permissible loading and voltage stability margin of a system.

Key words:voltage stability,Voltage stabilitymargin ,Bus voltage magnitude and active and reactive components of load power.

I. INTRODUCTION

Power companies are facing a major challenge in the maintaining of quality and security of power supply due to ever-increasing interconnections and loading in large power system networks. Economic constraint has forced the utilities to operate generators and transmission systems very near to maximum loadability point. One of the major problems that may be associated with such a stressed system is voltage instability or collapse and that causes a steady-state security problem. To operate a power system with an adequate security margin, it is essential to estimate the maximum permissible loading of the system using information about the current operating point. The maximum loading of a system is not a fixed quantity but depends on various factors, such as network topology,availability of reactive power reserves and their locations etc. this paper deals with maximum permissible loading of a power system using some locally measurable quantities.

When the loading of a power system approaches the maximum power or voltage collapse point, the voltage magnitude of a particular bus (or area) decreases rapidly. However, thevoltage magnitude itself may not be a good index for determining the imminence of voltage collapse[1]. The voltage magnitude decreases because of inadequate local reactive power support to meet local demand and losses. Importing large amounts of reactive power from remote buses (or areas) may further deteriorate the voltage collapse. Determining the maximum permissible loading, within the voltage stability limit,is becoming a very important issue in power system operation and planning studies. The conventional P-V or V-Q curve is usally used as a tool for assessing voltage stability and hence for finding the maximum loading at the verge of voltage collapse[2,3].these curve are generated from the results of repetitive load flow simulations and thus involve a significant amount of computations. References[4,5] determined the maximum loading of a particular bus in a power system by assuming that the load of other buses remains constant. Such an assumption is not very realistic. Also, the equivalent system used to estimate the maximum loading of the bus may not faithfully represent the original system over the entire operating range: several other methods, such as bifurcation theory[6],energy methods[7],A few studies[8] have used static voltage stability limit for evaluating reliability indices.

theEigen value (or singular value) method[9], the multiple load flow solutions method[11], etc have been reported in the literature for assessing the voltage stability or for determining the maximum permissible loading of a system. All the methods described above require a considerable amount of calculations and thus cannot be candidates for on-line application.

Reference[12] proposed a simple method for determining the voltage stability margin of a power system using some local measurements. The method used the complex voltage and current of a particular load bus to determine the relative strength or weakness of the transmission network connected to that bus. The measured voltage and current can also be used to design a digital relay for preventing voltage collapse by load shedding. Reference[13] first evaluated the system states with the help of forecasting- aided state estimator. The voltage stability of the system is then assessed through an extrapolation technique based on tangent vector behavior.Reference[14] first estimate the voltage stability margin with the help of Thevenin and load admittance andobtained maximum permissible loading of power system using some locally measurable quantities.

The metod described in this article is quite simple and does not require off-line simulation and training. Based on local measurement (voltage, active and reactive power it produces an estimation of the strength/weakness of the transmission system connected to the bus.

II. BACKGROUND

Consider an N-bus power system characterized by the admittance matrix Y. The i, j element Y_{ij} of Y is given by

$$Y_{ij} = -y_{ij}, i \neq j \quad (1)$$

$$Y_{ii} = \sum_j y_{ij} + y_{ig} \quad (2)$$

Where y_{ij} is the admittance of the line between buses i and j , and y_{ig} is the ground admittance of bus i. The real and imaginary parts of each element Y_{ij} of Y are denoted by G_{ij} and B_{ij}, respectively, so that $Y_{ij} = G_{ij} + jB_{ij}$.We denote the total active power generation and the total active load at bus i by P_x^g and P_x^l, respectively, and their reactive power counterparts by Q_x^g and Q_x^l. The load terms P_x^l and Q_x^l are assumed to be fixed. The net power injections at bus i in terms of the load and generation are

$$P_i = P_i^g - P_i^l \quad (3)$$

$$Q_i = Q_i^g - Q_i^l \quad (4)$$

Figure 1 shows a load bus and the rest of the system treated as a Thevenin equivalent. The load bus k having a load of $\mathbf{S_k}$ (=P_k+jQ_k), connected to a general power system as shown in fig,1(a)

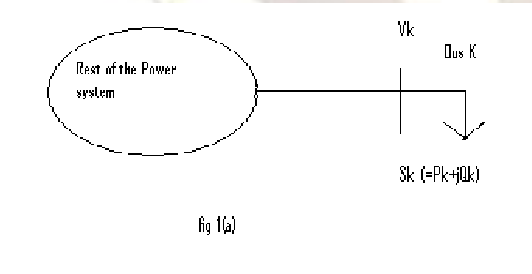

Fig. 1(a) representation of load bus k in ageneral power system

The rest of the power system in fig. 1(a) may consist of any number of generators, transmission line and loads. When this part of the system is represented by its Thevenin equivalent, the system of fig. 1(a) becomes simply a 2-bus system as shown in fig. 1(b). the procedure of finding the parameters of the Thevenin equivalent(E_{th} and Z_{th}) through on-line measurement of bus voltage magnitude, for various load condition, is described in section 3. For various load condition, the load impedance Z_L of fig. 1(b) can be written as:

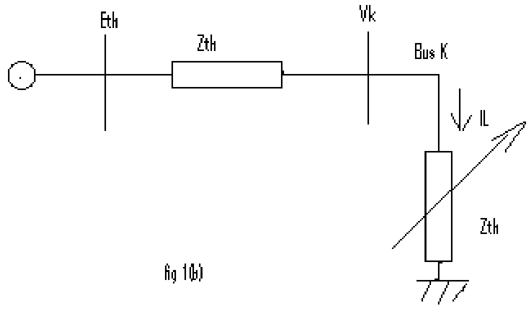

Fig. 1(b) Thevenin equivalent 2-bus system

$$\mathbf{Z_L} = \mathbf{V_k}^2/\mathbf{S_k}^* \quad (5)$$

Here V_k,is the voltage magnitude of bus k. in term of Thevenin parameters and load impedance, the magnitude of load apparent power can be expressed as:

$$S_k = E_{th}^2 Z_L/(Z_{th}^2+Z_L^2+2Z_{th}Z_L\cos(\beta-\theta)) \quad (6)$$

Where

$\mathbf{Z_{th}}$=$Z_{th}\angle\beta$= (R_{th} + jX_{th})
$\mathbf{Z_L}$ = $Z_L \angle\theta$=(R_L + jX_L)
$\mathbf{E_{th}}$ = $E_{th} \angle\delta$= (E_{thr}+ jE_{thm})
$\mathbf{S_k}$ = $S_k \angle\theta$= (P_k + jQ_k)

For a given load power factor (or cosθ), the condition of the maximum load apparent power can be written as:

$$\partial S_k/ \partial Z_L = 0 \quad (7)$$

The solution of (7) provides the following criterion:

$$Z_L = Z_{th} \quad (8)$$

Thus, when the magnitude of load impedance becomes the same as the magnitude of the Thevenin impedance, the system reaches the maximum power point or the critical point at which the voltage collapse occurs. The maximum or critical load apparent power of bus k (S_k^{cr}) can be obtained by substituting(8) in to (6) and is given by:

$$S_k^{cr} = E_{th}^2/(2Z_{th}(1+\cos(\beta-\theta)) \quad (9)$$

Eqn.(9) indicate that the maximum loading depends on the Thevenin parameters. However, these parameters are, in general, not constant, but depend on the system operating point.

III. PROPOSED METHODOLOGY

Thevenin-parameter are the main factors that dictate the maximum loading of a load bus. However, a single set of parameters may not faithfully represent the rest of the system of fig.1(a) for the entire operating range,especially for a system with a finite reactive power reserve. Thus it is necessary to regularly update the thevenin parameters as the system load or operating point changes.

Usually, the open-circuit and short-circuit test data are used to estimate the thevenin parameters of an external network. Conducting these tests in a real power system is unrealistic. However any two tests data, at

Different operating points, can be used to achieve the same goal. Reference[10] proposed a method for estimating the thevenin parameters using the complex bus voltage and load current at two different load condition. Reference[12] modified the method and obtained the thevenin parameters from the bus busvoltagemagnitudeV_k and the corresponding active $P_k$and reactive Q_k components of load power. in a power system operation, all these quantities can easily be measured on-line for any bus in the system. When the load voltage $\mathbf{V_k}$offig.1(b) is considered as a reference, the load current $\mathbf{I_L}$can be expressed as:

$$\mathbf{I_L = (P_k - jQ_k)/ V_k^*} \qquad (10)$$
$$I_L = (P_k - jQ_k)/ V_k \qquad (11)$$

The voltage equation of fig.1(b) can be written as:

$$\mathbf{E_{th} = V_k + Z_{th} I_L}$$

Or

$$(E_{thr}+jE_{thm})=(V_k+j0)+(R_{th}+jX_{th}) *((P_k/V_k)-j(Q_k/V_k)) \qquad (12)$$

The complex(12) can be transformed into the following two real equation:

$$V_k E_{thr}+0.E_{thm} - P_k R_{th} - Q_k X_{th} = V_k^2 \qquad (13)$$
$$0.E_{thr}+V_k E_{thm}+Q_k R_{th} - PkXth=0 \qquad (14)$$

The above pair of equations consists of four real unkowns (E_{thr},E_{thm},R_{th} and Xth) and thus another pair or set of equations. Similar to (13) and (14) at a different load condition, is required to determine the unknowns or thevenin parameters. Consider that V_{k1} and V_{k2} are the bus voltage magnitudes for load conditions $S_{k1}(=P_{k1}+jQ_{k1})$ and $S_{k2}(=P_{k2}+jQ_{k2})$ respectively. Using the above information,(13) and (14) can be rewritten in the following matrix form:

$$\begin{matrix} Vk1 & 0 & -Pk1 & -Qk1 \\ 0 & Vk1 & Qk1 & -Pk1 \\ Vk2 & 0 & -Pk2 & -Qk2 \\ 0 & Vk2 & Qk2 & -Pk2 \end{matrix} * \begin{matrix} Ethr \\ Ethm \\ Rth \\ Xth \end{matrix} = \begin{matrix} Vk12 \\ 0 \\ Vk22 \\ 0 \end{matrix} \qquad (15)$$

Or

$$\mathbf{AX} = \mathbf{B} \qquad (16)$$

The thevenin parameters of fig.1(b) can now be determined from (15) and it involves the measurement of load voltage magnitude at two different load condition. In power system operation, the measured data (V_k,P_k, and Q_k) may have some errors or noises and that might lead to inaccurate estimation of thevenin parameters can be obtained by using more than two set of data extracted from past load conditions and applying the least- square curve fitting technique.

IV. Voltage stability margins and the maximum permissible loading

The system reaches the maximum load point when the condition:

$$Z_L = Z_{th} \quad \text{or} \quad Y_L = Y_{th} \qquad (17)$$

Is satisfied. Thus, the voltage stability boundary can be defined by a circle with a radius of thevenin impedance Z_{th}as shown in fig 2. For normal operation, the load impedance Z_L lies outside the circle.

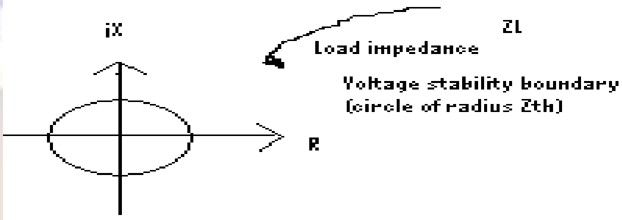

Fig. 2 Graphical representation of voltage stability boundary

Maximum power transfer is reached (Voltage instability) when the load impedance of the load bus hit the thevenin circle .for a given load impedance Z_L The difference between Z_L and Z_{th} can be considered as a safety margin. Thus the voltage stability margin in terms of impedance may be defined as:

$$VSM_Z = (Z_L - Z_{th}) / Z_L \qquad (18)$$

The voltage stability margin(VSM) defined by (18) is a noninutuitve quantity, and it is better to express the margin in terms of load apparent power (VSM_s), such a margin may be defined as:

$$VSM_S = (S_k^{cr} - S_k) / S_k^{cr} \qquad (19)$$

Note that both VSM_Z and VSM_S are normalized quantities and their values decrease as the load is increased. At the voltage collapse point, both the margin reduce to zero and the corresponding load is considered as the maximum permissible loading. Consider that the system reaches the voltage collapse point when the current load of bus k is increased by a factor of r_k. in other word, r_k is the ratio of critical load to curret load:

$$r_k = S_k^{cr}/S_k \qquad (20)$$

The critical or maximum permissible loading of bus k(S_k^{cr}) estimated at current load of S_k, is:

$$S_k^{cr} = r_k S_k \qquad (21)$$

The above techniques of finding the voltage stability margins and the maximum permissible loading can be applied to any load bus in the system. The load bus that has the lowest value of VSM may be considered as the weakest bus in the system and is vulnerable to voltage collapse. When the load of a power system increases uniformly, it is expected that the voltage collapse would first occurs at the weakest bus of the system. With this in mind, the maximum permissible loading of the system (S_{sys}^{cr}) at the critical point or voltage collapse point can be expressed as:

$$S_{sys}^{cr} = r' S_{sys} \qquad (22)$$

Where r' is the value of load multiplier factor of the weakest bus of the system found from(20) at a current system load of S_{sys}.

V. RESULTS

TABLE.1 Load flow solution for 6-bus test system under base load 100 MVA case condition.

Bus no.	Load impedance (pu)	Thevenin Impedance (pu)	Voltage Stability Margin In term of Z(pu)	Voltage Stability Margin In term of S(pu)	Critical Loading of system (pu)	Maximum permissible loading of system (pu)
1	2.2222	0.0860	0.9613	0.8568	3.1417	0.9690
2	1.9907	0.1496	0.9248	0.7426	1.9515	1.0817
3	3.4177	0.3689	0.8921	0.6485	0.8324	0.6301
4	13.7490	0.9695	0.9295	0.7539	0.2955	0.1566
5	6.3112	0.7588	0.8798	0.6337	0.4326	0.3412
6	3.9349	0.6378	0.8379	0.5356	0.5472	0.5472

TABLE-2 Load flow solution for 14-bus test ystem under base load of 100 MVA case condition

Bus no.	Load impedance (pu)	Thevenin Impedance (pu)	Voltage Stability Margin In term of Z(pu)	Voltage Stability Margin In term of S(pu)	Critical Loading of system (pu)	Maximum permissible loading of system (pu)
1	0.5972	0.0232	0.9611	0.8561	11.6334	2.2294
2	2.0312	0.1549	0.9237	0.7419	1.9078	0.6554
3	2.2624	0.2426	0.8928	0.6533	1.2747	0.5884
4	3.2377	0.6831	0.7890	0.4276	0.5381	0.4101
5	0.0000	1.0500	0.0000	1.0000	0.4762	0.0000
6	1.8911	0.3844	0.7967	0.4384	0.9416	0.7039
7	45.3901	1.0941	0.9759	0.0000	0.0000	0.0293
8	10.4301	0.9783	0.9062	0.7074	0.3278	0.1277
9	1.7506	0.5860	0.6652	0.2489	0.7605	0.7605
10	11.1053	1.0464	0.9058	0.7660	0.3847	0.1199
11	28.5217	1.1005	0.9614	0.9114	0.3954	0.0467
12	7.0874	0.9800	0.8617	0.5780	0.3343	0.1878
13	4.6812	0.9183	0.8038	0.4596	0.3953	0.2844
14	17.2408	1.1259	0.9347	0.8531	0.3949	0.0772

VI. CONCLUSION

This paper proposes a very simple and straightforward method for estimating the maximum permissible loading and voltage stability margins(VSMs) of a power system using some measurable quantities. Tracking stability margins has always been a challenging problem because of nonlinearity. The value of the maximum loading of a power system is not a fixed quantity and depends on various factors. However, the proposed method determine the correct value of maximum loading from given bus voltage magnitude and active and reactive components of load power.

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Mr. Dev Kumar Raireceived the B.E. .degree (with Hon's) andM.E.(Digital Technique and Instrumentation) Degree with in Electrical engineering in 2004 and 2010 bothfrom Rajiv Gandhi Technical University, Bhopal, Madhyapradesh, India.