Maximum permissible loading and Static voltage stability limit of a power system using V-I polynomial

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Abstract:
P-V or Q-V curve are commonly used to determine the maximum permissible load or static voltage stability limit of a power system. Voltage versus current relation approximation is presented as a tool to assessThe voltage stability limit.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 current data at present operating point. The measured data are carefully processed to estimate the maximum permissible loading and voltage stability margin of a system. The proposed method is tested on IEEE 6-bus and 14-bus system

Keywords: voltagestability, Voltagestabilitymargin, Bus voltage magnitude and load current.

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.
Most long AC transmission lines operate below the surge impedance loading and well under the thermal rating of the lines. 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, the voltage magnitude itself may not be a good index for determining the imminence of voltage collapse[1].The potential threat of a heavily loaded line or system is voltage instability or collapse. Thus, a priori knowledge of the voltage stability limit at various operating condition is essential to operate the system with an adequate safety margin.

There are two different approaches to analyzing the voltage stability problem of a power system; static and dynamic. In the static approach, the voltage stability problem is analyzed through steady state models and techniques [2,3]. It provides the ability of the transmission network to support a specified load demand. The result of such studies indicates the difference between current operating point and voltage collapse point. On the other hand, the dynamic approach tries to reveal the voltage collapse mechanism, i.e. why and how the voltage collapse occurs. Determination of the steady state voltage stability limit is essential in power system operation and planning studies. The result of such studies may be used to develop a control action, such as load shedding, toavoid voltage collapse [4,5].Such result can also be used for screening purposes to identify the critical cases that require further detail of dynamic analysis [6].

Usually, P-V or Q-V curves are used as a tool to assess the static voltage stability limit of a power system [2,7]These curve are generated from the result of repetitive power flow simulation of various load condition. The critical load at the verge of voltage collapse is then determined from the 'knee' point of the curve. It is noted that P-V and Q-V curve are highly non-linear around the knee point, and in fact the slope of the curve changes sign at the knee point.When the system load approaches the critical value, the power flow Jacobian becomes almost singular. Reference [8] used the minimum eigenvalue of the jacobian as an index to determine the distance between the present operating point and the voltage collapse point.
Reference [9] proposed a simple method of determining the voltage stability margin(VSM) of a power system using some local measurements. The measured data are used to obtain the thevenin equivalent of the system. The locally measured data and the concept of

Theveninequivalent are also used in [10,12] to find various voltage stability indices.

References [13] use the V-I characteristic as a tool to assess the static voltage stability limit of a power system.

This paper proposes a simple method of estimating the value of critical load at the edge of voltage collaps using the V-I relation approximation. The proposed method is tested on the IEEE 6-bus and 14-bus to calculate the static voltage stability limit and Maximum permissible loading for various system condition.

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

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

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

The load impedance Z_L and load current I_l of fig 1(b) can be expressed as :

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

$$\mathbf{I_L = (P_k - jQ_k)/ V_k^*} \quad (6)$$

$$I_L = (P_k - jQ_k)/ V_k \quad (7)$$

This section describes the basis of using V-I relation approximation as a tool to assess the static voltage stability limit and maximum permissible loading of a power system. First, consider a general power system with a local load bus or voltage uncontrolled bus as shown in fig.1a. the rest of the system in fig.1a can be represented by its thevenin equivalent, and such an equivalent of the system is shown in fig.1b. the load of the local bus is considered as $\bar{S} = S\angle\theta = P + jQ$ and is represented by a shunt impedance $\bar{Z} = Z\angle\theta$ in the equivalent system. The load voltage, current and power can be varied by changing the load impedance. A typical variation of load voltage magnitude against the load current magnitude, obtained by varying Z at a constant angle θ, is shown in fig.2 and is called the V-I characteristic of the bus.

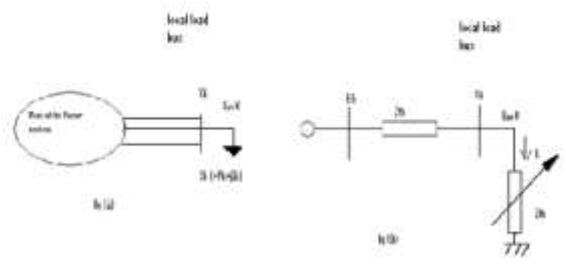

Fig. 1 representation of load bus in ageneral power system
A .Schematic diagram.
B .Thevenin equivalent

The complex load of the bus can be written as

$$\bar{S} = S\angle\theta = \bar{V}\bar{I}^* \quad (8)$$

However, the magnitude of load apparent power S is the product of load voltage and current magnitudes. Thus :

$$S = VI \quad (9)$$

Consider the system is operating at point x on the V-I characteristic of fig.2. thus, the magnitude of load apparent power S_y at point y is given by :

$$S_y = V_y I_y \quad (10)$$

Here, V_y and $I_y$are the load voltage magnitude and current magnitude, respectively, at point y. equation (10) suggests that the magnitude of load apparent power can also be represented by the shaded rectangular area a-b-y-c-a(see fig.2).when the load impedance change, the operating point y and load apparent power(or shaded area) are also changed. One of the objectives of this paper is to find the maximum load apparent power(or simply the critical)

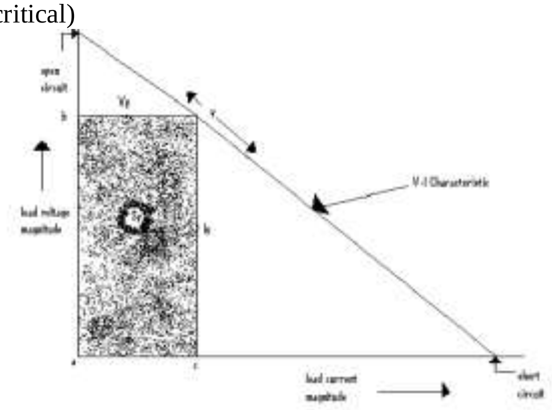

Fig. 2 V-I characteristic of the local load bus of fig.1b

At which the voltage collapse occurs. Graphically, the value of the critical load can be determined by sliding the operating point y along the V-I characteristic until the shaded area become the maximum.

From the above discussion, it is clear that the determination of critical load requires only the V-I relation and its characteristic of the bus. It may be mentioned here that the V-I characteristic depends on the thevenin parameters (E_{th} and Z_{th}in fig.1b) but that the value of these parameters are not directly used in finding the maximum shaded area. In fact in a real power system the V-I characteristic of any load bus can directly be generated from load measurements of voltage and current magnitude. Thus the knowledge of thevenin parameters is not required at all to establish the V-I characteristic. However the value of critical load depends on various factor in the rest of the system, such as network configuration, amount and location of reactive power reserves etc. however, all these factors usually modify the V-I characteristic.

III. Voltage stability margins and the maximum permissible loading

For a given operating condition the VSM_s of a load bus k in a general power system can be defined as:

$$(VSM_S)_k=(S_k^{cr} – S_k^o) / S_k^{cr} \quad (11)$$

Here S_k^{cr} is the critical load of bus k estimated at the present load of the bus S_k^o .the procedure of estimating the critical load, at the present operating point, through the V-I polynomial is described in the following.

Consider that the V-I relation of the bus, around the present operating point, can be represented by the following m^{th} order polynomial:

$$V = f(I) = a_0 + a_1I + a_2I^2 + \ldots \ldots + a_mI^m \quad (12)$$

The magnitude of load apparent power S of the bus is the product of voltage and current magnitudes and is given by :

$$S = VI = f_1(I)$$
$$= a_0I + a_1I^2 + a_2I^3 + \ldots \ldots + a_mI^{m+1} \quad (13)$$

As noted earlier, the value of the maximum load can be determined by sliding the operating point along the V-I characteristic until the shaded area (similar to fig. 2) becomes maximum. Alternatively, the condition of the maximum load can be written as:

$$\frac{\partial S}{\partial I}= 0$$

Or,

$$a_0 + 2a_1I + 3a_2I^2 + \ldots \ldots + (m+1)a_mI^m=0 \quad (14)$$

the feasible solution of (14) provides the value of current at the maximum load point and is called the critical current I^{cr} . thus, the value of the maximum or critical load S^{cr} can be obtained by substituting I^{cr} in (13):

$$S^{cr}= f_1(I^{cr}) \quad (15)$$

The above techniques of finding the VSM and critical load can also be applied to other load buses of the system.

Using (11), the critical load S_k^{cr} of bus k in terms of $(VSM_s)_k$and present load S_k^o of the bus can be expressed as:

$$S_k^{cr} =S_k^o/(1-(VSM_S)_k) \quad (16)$$

In general, when the system load increases uniformly and approaches the critical value, the voltage instability first occurs at the weakest bus, but does not occur at all bus of the system. The bus which has the lowest value of VSM may be considered as the weakest bus and is vulnerable to voltage collapse. Thus, analogous to (16), the system critical load S_{sys}^{cr} for uniformly increased load condition can be considered as:

$$S_{sys}^{cr} = S_{sys}^o/(1-r') \quad (17)$$

Where $r' = \min (VSM_S)_k$; $k \in \Phi$

Here, Φ is a set of all load buses of the system, and S_{sys}^o is the present system load at which the VSM of various buses are evaluated.

Determination of the critical load, and hence the VSM, by the above method requires knowledge of the coefficients a's of the V-I polynomial for various load buses. These coefficients can easily be determined from the voltage and current data at some known operating point. In power system planning, the above data can be found from the result of power flow studies. However in power system operation, these data can easily be obtained from local measurements. Once a few sets of data are known, the least squares curve fitting technique[16] can be applied to obtain the polynomial that represents the V-I characteristics. Then equation (12) can be written in the following matrix form.

$$\begin{bmatrix} 1 & I_1 & \ldots & \ldots & I_1{}^m \\ 1 & I_2 & \ldots & \ldots & I_2{}^m \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ 1 & I_k & \ldots & \ldots & I_k{}^m \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ . \\ . \\ a_m \end{bmatrix} = \begin{bmatrix} V_1 \\ V_2 \\ . \\ . \\ V_k \end{bmatrix} \Rightarrow \mathbf{AX=B} \quad (18)$$

The coefficients of the polynomial(or Vector **X)** can be found from the following normalized equation that minimizes the measurement errors or noise[16].

Once the coefficients of the polynomial are known, the critical load and VSM can easily be determined.

IV. RESULTS

TABLE.1 Load flow solution for 6-bus, 7-Line test system under base load 100 MVA case condition.

Bus no.	Load impedance (pu)	apparent power (pu)	Voltage Stability Margin In term of S(pu)	Critical Loading of system (pu)	Maximum permissible loading of system (pu)
1	2.2222	0.4500	0.5500	1	48.6440
2	1.9907	0.5023	0.4977	1	54.2983
3	3.4177	0.2926	0.7074	1	31.6277
4	13.7490	0.0727	0.9273	1	7.8620
5	6.3112	0.1584	0.8416	1	17.1274
6	3.9349	0.2541	0.7459	1	27.4707

From the table 1 it is cleared that the voltage stability margin is highest for bus 4 and maximum permissible loading in term of weakest bus 2(where VSM is low) is highest for bus 2.

TABLE-2 Load flow solution for 14-bus,20 Line test ystem under base load of 100 MVA case condition

Bus no.	Load impedance (pu)	apparent power (pu)	Voltage Stability Margin In term of S(pu)	Critical Loading of system (pu)	Maximum permissible loading of system (pu)
1	0.5972	1.6746	0.6746	1	2.8042
2	2.0312	0.4923	0.5077	1	0.8242
3	2.2624	0.4420	0.5580	1	0.7402
4	3.2377	0.3080	0.6920	1	0.4904
5	0.0000	0.0000	1.0000	1	0.0000
6	1.8911	0.5288	0.4712	1	0.8834
7	45.3901	0.0220	0.9760	1	0.0401
8	10.4301	0.0959	0.9008	1	0.1661
9	1.7506	0.5713	0.4302	1	0.9542
10	11.1053	0.0900	0.9100	1	0.1508
11	28.5217	0.0350	0.9650	1	0.0586
12	7.0874	0.1411	0.8590	1	0.2362
13	4.6812	0.2136	0.7867	1	0.3572
14	17.2408	0.0580	0.9420	1	0.0971

From the table 2 it is cleared that the voltage stability margin is highest for bus 5 and maximum permissible loading in term of weakest bus 9(where VSM is low) is highest for bus 1.

V. CONCLUSION

This paper proposes a very simple and straightforward method for estimating the maximum permissible loadingvoltage stability margins(VSMs), and static voltage stability limit of a power system using V-I polynomial. 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 current of power system.

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