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A NEW METHOD OF THE STABILITY MARGIN DETERMINATION OF A RECEIVING NODE

The paper concerns the problem of local voltage instability of the power system receiving node. There were presented bases of analysis of stability margin determination using Thevenin equivalent model. Basing on Thevenin model new method of stability margin calculation was developed. The method has been described in the article. Contrary to well known methods, presented algorithm does not use a derivates of measured parameters. The algorithm uses only the measured values of steady working points. The last part of paper contains an analysis of potential errors.

1. INTRODUCTION

It is well known that in the analysis of work and control of power system there are important two pairs of values: active power–frequency *P–f* and reactive power–voltage *Q–V* [1]. The first of these pairs is global. The frequency of the entire power system should be constant. This corresponds to the balance of generated and received active power. It is different with the voltage and reactive power. In some of the power system nodes voltage can be close to the nominal value and in others differ quite significantly. Therefore voltage is the local parameter and can be controlled, changed and stabilized according to the requirements. This task must be realized in on-line mode to ensure suitable quality of energy. The reasons of voltage changes are normal operation of power system where configuration changes and temporary, daily and seasonal load changes occur. The system can be designed to maintain the value of voltage in acceptable limits despite of load changes. However, randomly situations and system configuration changes where these limits are exceeded (most of decrease of voltage to low value) can occur. In such situation there is a need to use different voltage control

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methods. The simplest but the most severe for customer is undervoltage load shedding. In the nodes where such situations occur regularly, voltage regulation using the transformer tap changer (under load) should be performed. When the tap changer is used, problem of stability margin decreases along with the voltage increase occurs. This may cause tap changer blocking in some positions. This shows, that analysis of node working point requires, beyond the voltage measuring and undervoltage criterion formulating, stability margin studies. Moreover, similar case can occur when reactive power compensation is used. Using this method of voltage regulation can lead to a situation when changing the load impedance argument causes the possibility of local instability even when the node voltage is close to the nominal value. This might mean that undervoltage load shedding should be performed despite of voltage near or even greater than the nominal. This also shows that it is not only reasonable to measure the voltage, as it is done in most cases, but also there is a need to calculate the stability margin.

Paper presents a new method of local stability margin calculation. In literature a lot of stability margin determination methods can be found [2–5], including work of the authors [6]. Most of these methods use derivatives of voltage or apparent power against the load impedance changes. Ensuring adequate accuracy is possible for linear load impedances. The non-linear models require appropriate adjustments. Presented method does not use these derivatives. Therefore, the method may be freely used for any load model, assuming that parameters of steady working point are used.

2. THE RECEIVING NODE AND ITS THEVENIN EQUIVALENT

Figure 1 shows scheme of Thevenin equivalent calculation. Because of using offline modelling in suitable digital environment it is possible to determine all values of parameters of Thevenin model. The parameters are real and imaginary parts of voltage, current and impedance: E, Z_S, Z_L, V, I or their amplitudes and angles. According to the initial power system model, parameters of Thevenin equivalent are calculated as follows [1, 2, 4, 7]: ideal voltage source E parameters are calculated basing on voltage phasor measured at idle node, parameters of series impedance Z_S are determined by short-circuit all voltage sources and calculating impedance seen from considerate node.

Unfortunately, according to the protection devices operating or processes of power system configuration switching, values of E and Z_S are changing. These parameters do not physically exist; they are only parameters of section of power system virtual model. In the node directly measurable are current I and voltage V (Fig. 1) and derived values e.g. load impedance Z_L. Other parameters, including value of ideal voltage source E and series system impedance Z_S, which affect the stability of the power system, must be calculated indirectly in on-line mode and updated in the measurement process. It may be noted that, range of changes of E and Z_S can be determined in off-line mode according to the switching processes that may occur.

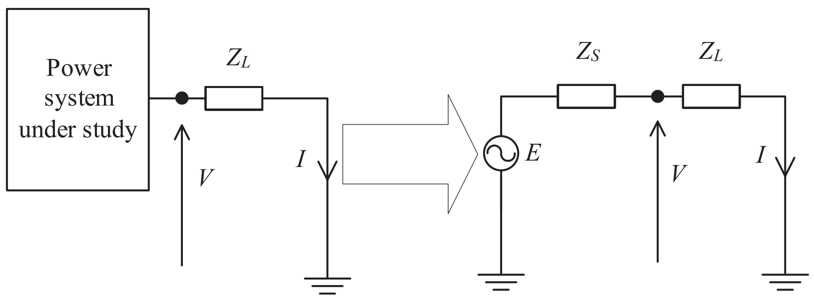

Fig. 1. Thevenin model calculation scheme

Determination of those indirect parameters can be made basing on two fundamental values that can be described by the following equations [3]:

$$V = \frac{E}{\sqrt{1 + W^2 + 2W\cos\beta}}, \tag{1}$$

$$S = \frac{E^2 W}{Z_S(1 + W^2 + 2W\cos\beta)}. \tag{2}$$

where: $W = Z_S/Z_L = Z_S{*}Y_L$ and $\beta = \varphi_S - \varphi_L$.

Common curve that corresponds to equations (1) and (2) changes its shape according to the variations of parameters e.g., Z_S and β. Also the load curve can have different shapes because the active and reactive power characteristics may depend on various factors. In general it can be written that both parameters $W = f(V)$ and $\beta = f(V)$ depend on the voltage

It can be calculated that the maximum of receiving power occurs when $W = 1$ that is when series and load impedance are equal $Z_S = Z_L$ [4]. On the other hand it can be noticed in equation (2) that when impedance Z_S is larger the value of maximum received power is lower.

Therefore, with the increase of system impedance Z_S or decrease of load impedance Z_L value of W increases. This causes the node voltage drop. When the constant impedance load model is used, changes of node voltage results in received power change and when constant power load model is used, there is only the voltage change and the received power remains constant. It can be noted that the decrease of voltage in this model is much higher because the value of W is greater. This is caused by increase of system impedance Z_S as well as the decrease of load impedance Z_L (or increase of load admittance Y_L) with change of node voltage.

Equations (1) and (2) are valid in steady-state either for the constant impedance load model (not depending on the voltage) and constant power load model or any other load model.

As Figure 2 shows, for impedance Z_S change occurrence identification following condition can be used:

$$\frac{\Delta S}{\Delta V} \geq 0 . \tag{3}$$

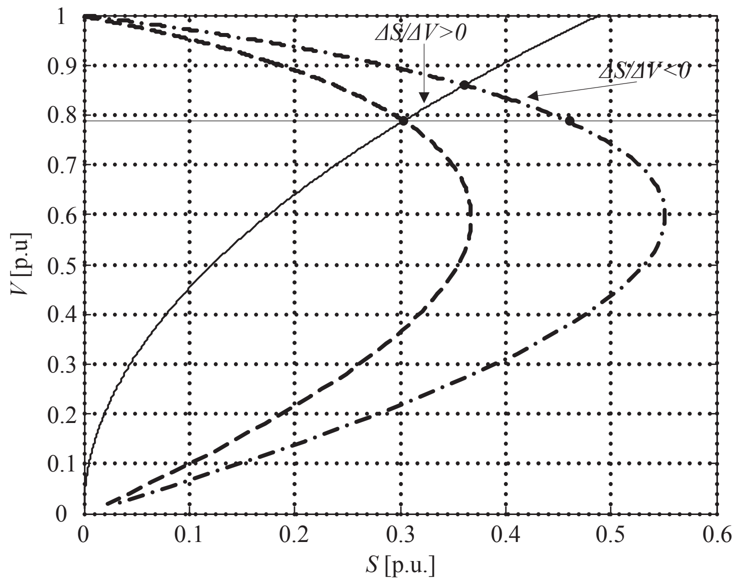

Fig. 2. Nose curves for different value of impedance Z_S and load curve

This condition can indicate the need of starting the procedure of calculating the new value of impedance Z_S and voltage measuring for the changed value of load impedance Z_L and/or β. The value of angle needed for the calculation can be taken as the average value $0,5(\varphi_{S\max} + \varphi_{S\min})$. Changes of this argument are not large, and extreme values can be obtained from off-line simulation studies of considered power system section.

In contrast to this, changes of load impedance argument, the second component of β angle can be significant, especially when load model is highly non-linear or when the node voltage regulation is performed. However, even large changes of load impedance argument do not have a significant impact on the stability margin estimation results because they are directly measurable in considered node, as well as other needed parameters obtained based on the measurements of currents and voltages.

3. A NEW METHOD OF STABILITY MARGIN ASSESMENT

Taking into account the assumptions presented in previous paragraph and assuming that the stability margin identification based on changes of node voltage is carried out when these changes are caused by load impedance module or argument changes, the following equation for two steady working points can be obtained:

$$V_1 = \frac{E}{\sqrt{1 + W_1^2 + 2W_1 \cos\beta_1}}\,, \tag{4}$$

$$V_2 = \frac{E}{\sqrt{1 + W_2^2 + 2W_2 \cos\beta_2}}\,, \tag{5}$$

where: $W_1 = Z_S{*}Y_{L1}$, $W_2 = Z_S{*}Y_{L2}$, $\beta_1 = \varphi_S - \varphi_{L1}$, $\beta_2 = \varphi_S - \varphi_{L2}$, $E =$ const.

After squaring both sides of equations (4) and (5), dividing and transforming the quadratic equation is obtained:

$$aZ_S^2 + bZ_S + c = 0\,. \tag{6}$$

This has the following solution:

$$Z_{S1,2} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}\,, \tag{7}$$

where: $a = Y_{L2}{}^2(g^2h - 1)$, $b = 2Y_{L2}[gh\cos\beta_1 - \cos\beta_2]$, $c = h - 1$ and $g = Y_{L1}/Y_{L2}$, $h = (V_1/V_2)^2$.

Basing on the calculated value of system impedance Z_S and measured impedance Z_L stability margin can be determined. Limit of local stability occurs when:

$$Z_S Y_L = 1\,. \tag{8}$$

So stability margin is equal to:

$$\Delta_{stab} = 1 - Z_S Y_L\,. \tag{9}$$

4. ANALYSIS OF ERRORS COMING FROM UNMEASURABLE VALUES

In presented method of stability margin determination unknown value of voltage source E is simplified. The only unknown parameter is β angle (or cosine of this angle $\cos\beta$) – equations (4) and (5). However, considering the derivation of equation (4) and (5) it can be noticed that, due to possibility of load impedance argument φ_L measuring, the only unknown is actual value of system impedance argument φ_S. Range of system impedance Z_S changes in equivalent Thevenin model can be estimated on the basis of off-line studies of power system model according to the particular connections – especially close power lines. It can be expected that the difference of maximum and minimum values of the argument generally does not exceed ten to twenty degrees. Assuming an average value obtained from off-line studies, errors of stability margin estimation basing on the average value and the expected changes can be calculated as follows:

$$\arg Z_S = 0{,}5\left[\varphi_{S\max} + \varphi_{S\min}\right] + \Delta\varphi_S\,, \tag{10}$$

where

$$\Delta \arg Z_S = 0{,}5\left[\varphi_{S\max} - \varphi_{S\min}\right]. \tag{11}$$

Arising errors can be considered basing on the Figure 3. This figure shows curve of the value of V/E as a function of the β angle (in range 0°–140°) for various values of W (0,1; 0,5; 1) or alternatively various stability margin Δ_{stab} (0,9; 0,5; 0) (equation (9)). Obviously, the minimum values of voltage occur for the smallest voltage stability margin and these values are growing with the increase of β angle. The observed increase of steepness of the V/E curve indicates also that in the area of larger value of β there will be greater sensitivity to errors in the β angle determination.

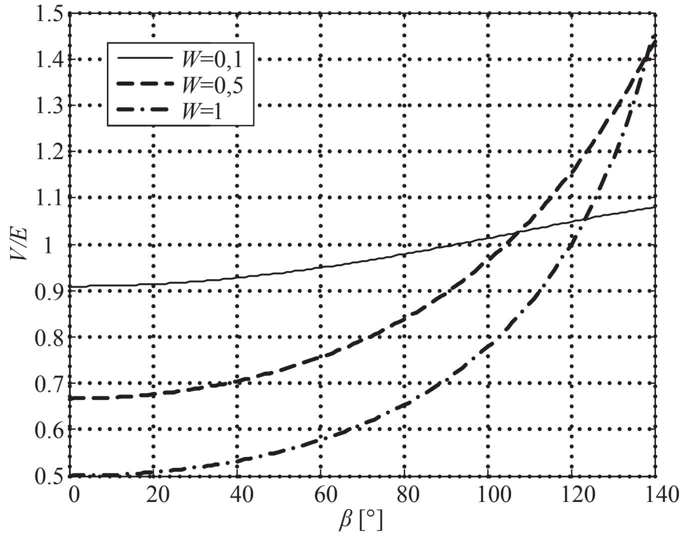

Fig. 3. Value of V/E as a function of β curve for different value of W

Details of these errors which confirm previous considerations are shown in Figure 4. This Figure shows curves of errors as a function of β angle for different W values. For a given value of W and β angle, errors obtained by inaccurate estimation of the β were calculated. Changes of β angle have amounted ±5°. It can be seen that errors rise when β parameter increases. It is obvious because the steepness of voltage changes (Fig. 3) rises with increasing β. The specific curves are plotted for different values of W. The lowest errors are for W = 0.1 and the largest for W = 1 which is the voltage stability limit.

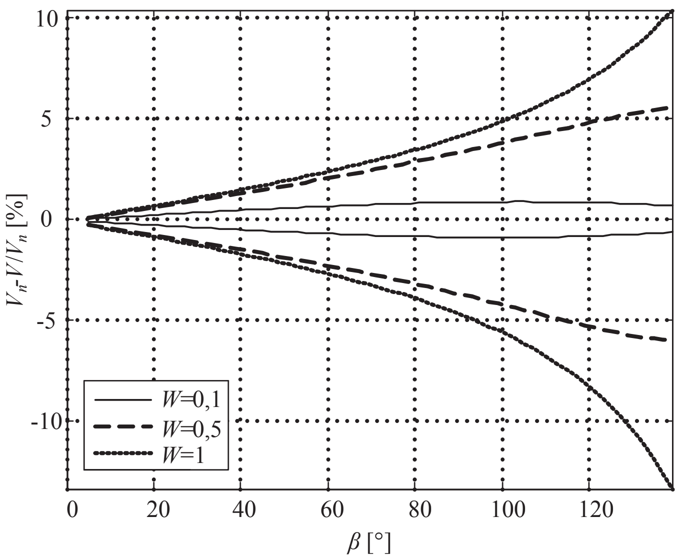

Fig. 4. Value of $V_n - V/V_n$ error for +/–5° β deviation as a function of β for different value of W

Figure 3 also shows that the large changes of β value, according to the non-linear load model or using of reactive power compensation, can cause changes of critical value of voltage of stability limit in a wide range. In this range values of voltage may differ significantly from the nominal value but also these differences can be very small. This means that the application of the voltage stabilization or undervoltage load shedding requires consideration of current voltage stability margin or/and load impedance angle calculation. Such extend of information can greatly improved quality and reliability of the decisions about the undervoltage load shedding.

5. CONCLUSIONS

1. The paper presents a simple method of voltage stability margin assessment of the receiving node based on the Thevenin model equivalent. The method uses locally measurable parameters of stable working point in two different moments of time.

2. Discussed algorithm ensures good accuracy of stability margin estimation and can be used for any non-linear load impedance model. The method is insensitive to small deviations of impedances arguments β. For standard values of the β angle relative voltage measurements differ by a few percent when the angle deviations amount ±5°. It is worth noting that the source of errors is an unknown argument of system impedance which changes slightly.
3. Undervoltage load shedding should be used when the node voltage decrease below an acceptable value and there is no voltage control or range of this regulation is exceeded.
4. Using reactive power compensation to regulate or stabilize node voltage can cause closing of voltage value to the nominal even when the node working point is near or at the local stability limit. Therefore, for load shedding additional criteria, beyond undervoltage, should be use. These criteria can be: value of voltage and/or stability margin or value of voltage and/or difference of arguments of series and load impedance. It is also possible to use the hierarchy of this criteria or assign them specific weights.

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