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voltage stability estimation,
Thevenin equivalent

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VOLTAGE STABILITY ESTIMATION OF RECEIVING NODE USING APPROXIMATE MODEL

The paper presents approximate model for determining the voltage stability margin. In the first part, Thevenin model and equations describing this model e.g. stability limit are presented. Influence of load and system impedance changes on variations of node voltage are shown. Second part consist description of approximate model determination methods. For the analysis, the 14-bus IEEE model have been chosen. Basing on this model the impact of configuration changes on the Thevenin parameters of considered receiving nodes have been analysed. At the end, the possibilities of use of approximate model for determining the voltage stability margin are described.

1. INTRODUCTION

Today electricity is treated as a commodity and like any commodity should meet defined quality requirements. Required parameters are described in European Standard EN 50160 [1]. One of the parameters is the voltage level. To ensure acceptable value of the voltage in some power system nodes voltage regulation should be installed. This regulation affects voltage level and also other parameters of power system node, e.g. voltage stability conditions. Ensuring appropriate quality of energy and power system safety in the same time may be difficult. For the recipient the most important is quality and for power system operator safety. Additional difficulty results from slow changes of power system characteristic from centralized to distribute. Serious problem may be wind generation which cannot be precisely predicted in long term. Increasing energy generation using distributed generation (DG) connected to distribution networks may cause voltage stability problems [2]. In such networks, the problem is also voltage

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regulation processes and a large number of its activations. This may be caused by changes of direction of the power flow [3].

To ensure appropriate level of voltage and stability margin, these values should to be considered simultaneously. This can be done by global and local control systems. In literature examples of global systems like Wide Area Control System [4] and their implementation [5] can be found. Methods of approximate value of voltage stability margin determination using local measurements are also described. Both approaches global and local possess the advantages and disadvantages, but development of new control and measurements techniques like PMU (Phasor Measurement Unit) increase a number of advantages of local solutions. The main advantages are: greater reliability, lower installation costs and easier integration of control processes with protection devices. This integration will allow adapting protection algorithms and responding more quickly when adverse condition occurs. The development of local automation is a part of the Smart Grid idea.

2. LOCAL MODELS OF RECEIVING NODE

2.1. THEVENIN EQUIVALENT

Steady state of power system, seen from considered node, can be represented by Thevenin equivalent. Assuming the symmetry of generations and loads of power system, such model can be reduced only to positive-sequence components. Such simplifications are also used to value of short–circuit currents calculation [6]. Thevenin equivalent consist of ideal voltage source E and system impedance Z_S (Fig. 1).

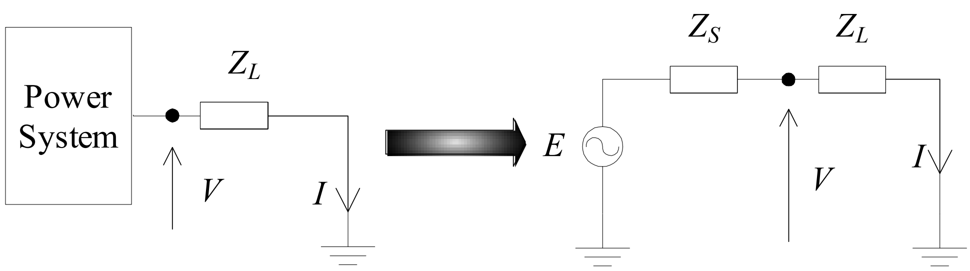

Fig. 1. Power system representation as Thevenin equivalent

Node voltage and apparent power of presented Thevenin model (Fig. 1) can be defined by the following equations [7]:

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

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

where: V – voltage of node, S – apparent power, $W = Z_S/Z_L$, Z_S – system impedance, Z_L – load impedance, $\beta = \varphi_S - \varphi_L$, φ_S and φ_L – system and load impedance phase angle.

Based on equations that describe model from Fig. 1 value of maximum power transfer (voltage stability limit) can be calculated. Stability limit occurs when the absolute values of system Z_S and load Z_L impedance are equal [8]:

$$|Z_L| = |Z_S|. \tag{3}$$

By transforming formula (1), voltage stability margin calculation equation can be obtained:

$$\Delta W = 1 - \frac{|Z_S|}{|Z_L|}. \tag{4}$$

Factor W can be considered as a load of node ratio. The range of factor W changes from 0 (for idle node) to 1 (voltage stability limit).

Value of node voltage depends on factor W and angles of system φ_S and load impedances φ_L (2). Assuming certain changes of these parameters, curves presenting voltage variations can be plotted (Fig. 2). Ratio W, as noted above, varies between 0 and 1 and β between 50° and 130°.

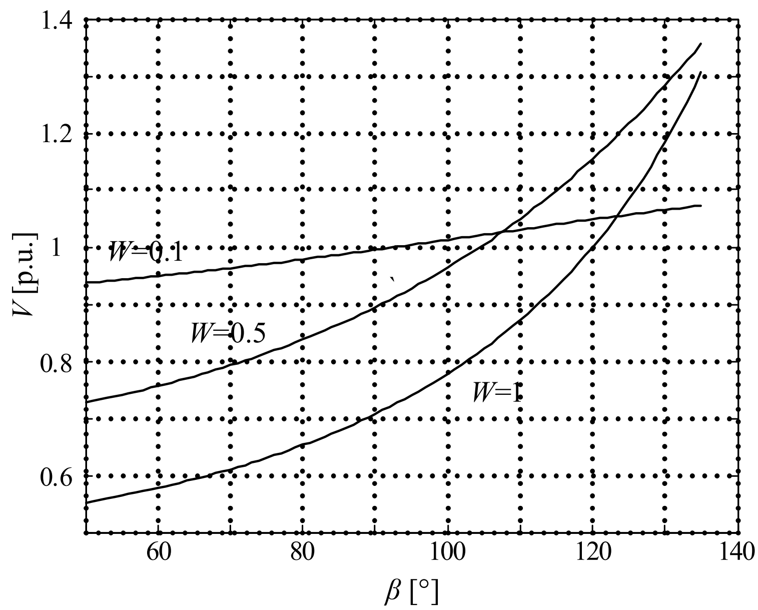

Fig. 2. Variations of voltage depending on W and angle β changes

For one value of angle β, voltage can have different values depending on factor W (Fig. 2). However, one value of voltage can correspond to several levels of W depending on angle β. Basing only on voltage measurements, voltage stability margin of the node cannot be exactly determined. To calculate accurate stability conditions, attaching measurements of other parameters is needed.

Basing on formula (4) and parameters of system and load impedances, distance from operation point of power system node to stability limit can be calculated. Parameters of load impedance Z_L can be measured with high accuracy basing on local measurements. The problem is determination of system impedance Z_S parameters. This value cannot be measured with direct methods.

2.2. THEVENIN CIRCUIT CALCULATION

The simplest way to determine Thevenin model is to calculate parameters using full model of power system. Such model should contain information about whole configuration of power system including parameters of generators and lines. The full models used for power flow calculations represent components of power system as positive-sequence representations. To determine Thevenin equivalent one of the power system nodes should be chosen. Voltage source E is equal to voltage occurring in the idle node. Impedance Z_S is the impedance seen from considered node when all voltage sources are grounded.

Power system configuration and parameters of loads (magnitude and angle) are continuously changed during normal operation. Both of these variations affect the parameters of Thevenin equivalent. Changes of loads can be measured in real time. However, to determine stability conditions according to these changes remaining parameters of Thevenin model should be also updated. These model parameter changes are not measurable directly. Voltage source E and system impedance Z_S are not physical elements. They are virtual equivalents of power system steady state seen from considered node.

2.3. UPDATING OF THEVENIN CIRCUIT PARAMETERS

Thevenin model updating using full power system model requires collecting and analysing a large amount of information about configuration and loads. This method is unsuitable to implementation in automation installed in receiving node, because global information is not available. Better idea is to use local information and measurements or derived from close environment of the node.

One of the methods of voltage stability determination using local measurements has been described in literature [8]. To calculate the Thevenin parameters, local voltage and current measurements are used. Using Kirchhoff's law, Thevenin circuit (Fig. 1) can be described by the following formula:

$$\overline{E} = \overline{V} + \overline{Z}_S \overline{I} . \quad (5)$$

Measurable values in the node are voltage V and current I orthogonal components. Unknown are components of serial impedance R_S, X_S and voltage source E_r, E_i. Formula (5) is insufficient to calculate this parameters because there are four unknown values. Two additional independent equations can be obtained by substituting the known parameters obtained for different time. It is important that all calculated parameters should not change between measurements in specific time.

Developments of described method are algorithms that use level of operating point parameters changes caused by load variations. This variations cause node voltage and current changes and consequently apparent, active and reactive power changes. In the literature can be found algorithms using for example: derivative of the node voltage against load admittance $\mathrm{d}V/dY$ [9] or derivative of apparent power against voltage of node $\mathrm{d}S/\mathrm{d}V$ [10]. In the paper [9] have been additionally described use of $\mathrm{d}V/\mathrm{d}Y$ method to block transformer tap changer and to determine the need to load shedding start.

Methods using the local measurements have acceptable accuracy if certain conditions are fulfilled. One is change of the load impedance. It is needed to measure the parameters of working point of two time moments. This may result in a lack of dangerous conditions identification in the case of system configuration change while there is no change of load parameters. Other approach that uses local measurements and information from close environment of node is use of Thevenin approximate model.

2.4. APPROXIMATE THEVENIN MODEL

Approximate Thevenin model can be created basing on separated area of power system full model. In such model analysis of Thevenin parameters changes caused by variations of configuration can be performed. To study this approximate model, IEEE 14-node test model have been used (Fig. 3). The IEEE model has been implemented in ATP-EMTP software.

The IEEE model can be divided into two areas. One with the generators (Area 1) and second with loads only – distribution system (Area 2). Both parts are connected by two important links between nodes 5–6 and 4–9. For analysis nodes 10–14 have been chosen. These nodes are located farthest from generators (considering the electrical distance) and their parameters are most susceptible to changes of configuration. In tables 1–5, changes of Thevenin parameters caused by exclusion of particular line are presented. The greatest impact on the parameters has exclusion of the line directly connected to considered node and disconnection of one of connection between Area 1 and Area 2 (Fig. 3).

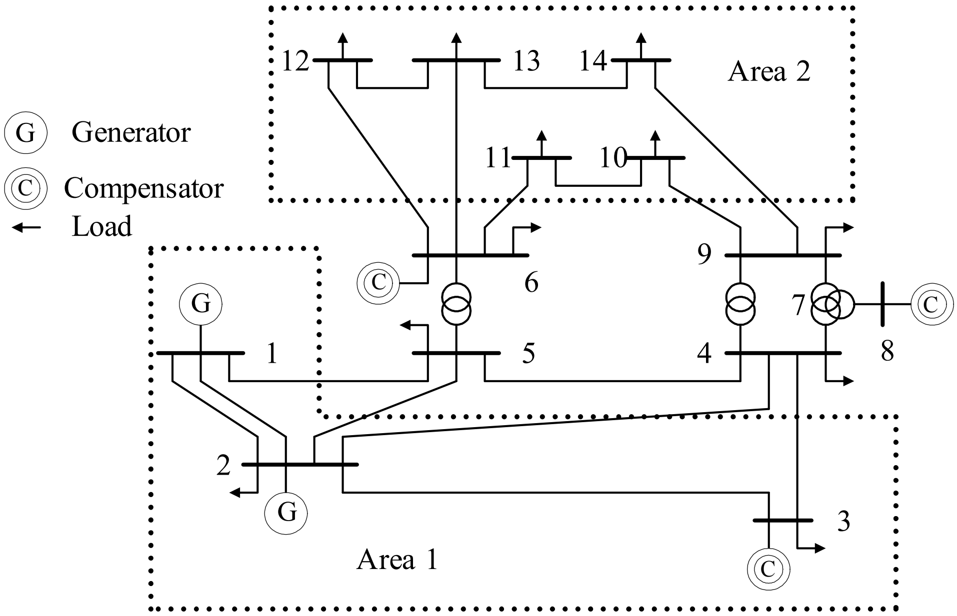

Fig. 3. IEEE 14-node test model

Table 1. Node 10 Thevenin parameter changes

Node 10						
	Full conf.	Excluded line				
		L10–11	L9–10	L6–11	L5–6	L4–9
Z_S [p.u.]	0.296	0.349	0.668	0.346	0.360	0.502
φ_S [°]	68.3	69.6	65.4	69.2	65.9	61.3
E [p.u.]	1.02	1.02	1.03	1.01	1.00	0.91
φ_E [°]	–12.1	–12.1	–12.2	–12.4	–16.6	–18.1

Table 2. Node 11 Thevenin parameter changes

Node 11						
	Full conf.	Excluded line				
		L6–11	L10–11	L9–10	L5–6	L4–9
Z_S [p.u.]	0.329	0.519	0.494	0.475	0.473	0.435
φ_S [°]	66.7	66.4	67.1	65.6	60.9	63.7
E [p.u.]	1.02	0.99	1.03	1.00	0.97	0.92
φ_E [°]	–12.51	–13.12	–11.95	–13.03	–19.43	–17.04

Table 3. Node 12 Thevenin parameter changes

Node 12							
	Full conf.	Excluded line					
		L6–12	L12–13	L5–6	L6–13	L13–14	L4–9
Z_S [p.u.]	0.405	0.597	0.519	0.653	0.423	0.437	0.455
φ_S [°]	63.1	52.6	65.3	55.7	63.1	64.8	63.5
E [p.u.]	1.02	1.01	1.03	0.96	1.01	1.03	0.96
φ_E [°]	–12.27	–12.7	–11.78	–20.92	–12.78	–11.77	–15.56

Table 4. Node 13 Thevenin parameter changes

Node 13								
	Full conf.	Excluded line						
		L6–13	L12–13	L13–14	L9–14	L5–6	L4–9	L6–12
Z_S [p.u.]	0.335	0.484	0.350	0.394	0.381	0.570	0.397	0.347
φ_S [°]	66.9	60.0	66.9	68.0	66.1	59.0	66.4	66.5
E [p.u.]	1.04	1.01	1.04	1.05	1.03	0.99	0.97	1.03
φ_E [°]	–11.39	–12.12	–11.35	–10.56	–11.92	–19.22	–14.65	–11.55

Table 5. Node 14 Thevenin parameter changes

Node 14							
	Full conf.	Excluded line					
		L13–14	L9–14	L5–6	L4–9	L12–13	L6–13
Z_S [p.u.]	0.381	0.519	0.717	0.483	0.538	0.385	0.416
φ_S [°]	65.5	65.7	62.9	62.6	62.5	65.5	63.6
E [p.u.]	1.03	1.02	1.03	0.99	0.93	1.02	1.01
φ_E [°]	–11.62	–11.41	–11.95	–16.94	–16.4	–11.61	–12.09

Based on full power system model presented studies can be made for every node of power system. Obtained information can be used to calculate voltage stability margin in two ways. It is possible to assign specific values of Thevenin parameters to configuration of close environment of the considered node. To limit amount of information, the exclusions that have the greatest impact on Thevenin parameters can be chosen. Information from breakers and switches are used to update Thevenin model (Fig. 4). Basing on such approximate model and local measurements of load, voltage stability margin calculation is possible. Verification of correctness of this model can be made by comparison of measured voltage and calculated using model. If these values are close it can be assumed that parameters of model are selected correctly and voltage stability is calculated with a small error.

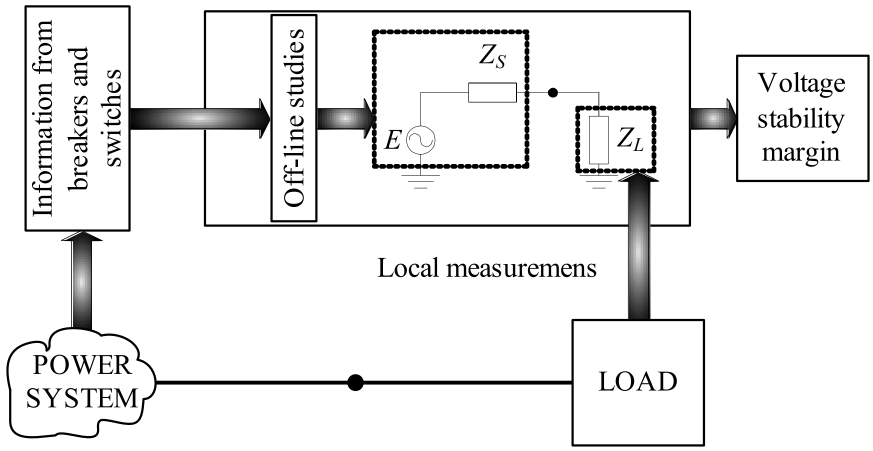

Fig. 4. Approximate model updating

Other use of determined Thevenin parameters is to calculate average value. Such value should be calculated using parameters of states that are not easily identifiable. At node 10 the most dangerous states are: exclusions of the directly connected lines (L9–10, L10–11) and break one of connection between two areas (L4–9). Information about exclusions of direct lines is always available at node. Braking of connection between areas has a major influence on Thevenin parameter changes of all considered nodes. Therefore, information about this occurrence is important and should be forwarded to those nodes. Average values calculated for receiving nodes are presented in Table 6.

Table 6. Average from selected values of Thevenin parameter changes

Avarage from selected values					
	Node				
	10	11	12	13	14
Z_S [p.u.]	0.334	0.428	0.430	0.365	0.416
φ_S [°]	67.8	64.2	63.63	66.47	64.29
E [p.u.]	1.01	0.98	1.01	1.02	1.01
φ_E [°]	–13.7	–15.5	–13.10	–12.38	–13.07

3. SIMULATION RESULTS

According to analysis presented in Chapter 2 it can be seen that variation of system parameters of Thevenin model are small when switching elements "electrically" far distant from considered receiving node are performed. In contrary, these parameters change substantially when switched are elements "electrically close" to given node, mainly connected to this node. These changes can reach over 100 percent comparing to standard configuration. Important is that these switches can be identified locally in the receiving node. This analysis lead to the conclusion that the problem of estimation of system parameters of Thevenin model could be realised in two ways:

1. When exclusion of elements electrically far distant occurs, an average values of parameters for all configurations (single elements switching) are assumed.
2. When elements electrically close are switched off, given disconnected element is identified and adequate for this situation system parameters obtained from simulation are chosen. These parameters are used to estimate voltage stability margin directly using measured load parameters.

Node 10 of IEEE model has been chosen to perform simulations. This node was selected because during changes of configuration Thevenin parameters have changed the most. Value of system impedance Z_S has changed by about 125%. Two cases have been tested to calculate variations of voltage stability margin. Constant value is assumed average value (Table 6). In the first case correct parameters correspond to full configuration and in second to the most dangerous from among unidentified (exclusion of line L5–6). The simulations have been performed for two power factors tgφ = 0.4 (Figs. 5, 6) and tgφ = –0.2 (Figs. 7, 8). The stability margin values correspond to current configuration have been plotted by line number 1. Assumed average value is switched element plotted by line number 2.

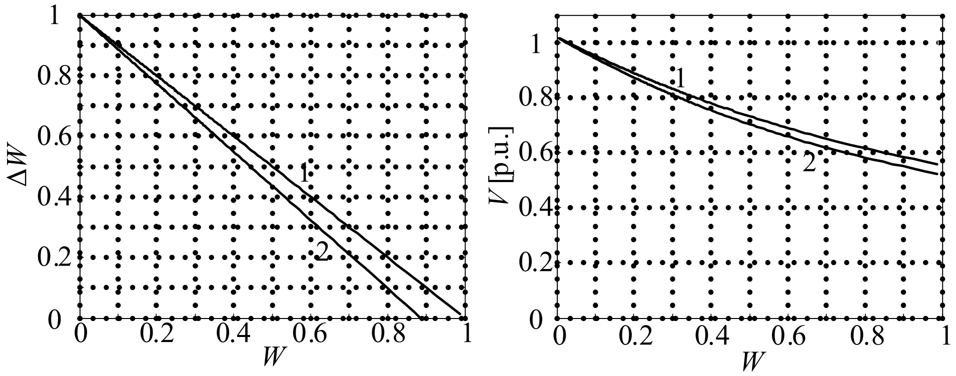

Fig. 5. Changes of stability margin and voltage tgφ = 0.4 – full configuration

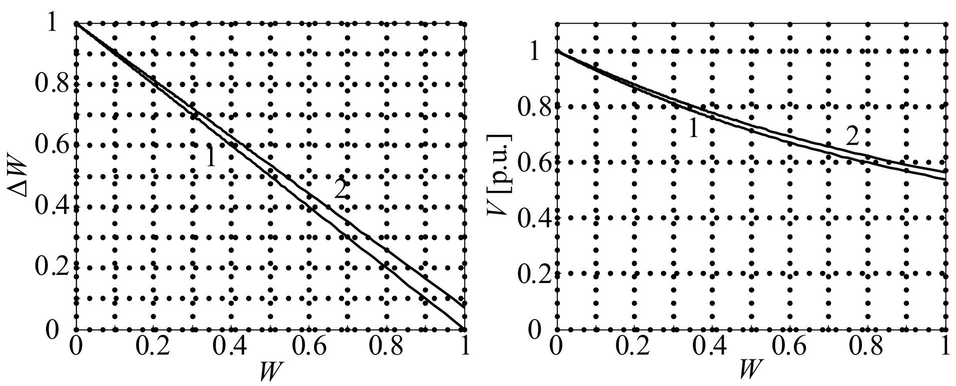

Fig. 6. Changes of stability margin and voltage tgφ = 0.4 – excluded line L5–6

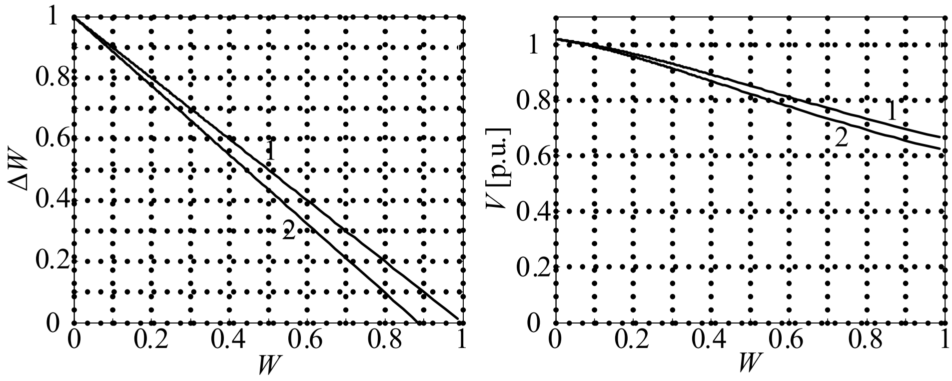

Fig. 7. Changes of stability margin and voltage tgφ = –0.2 – full configuration

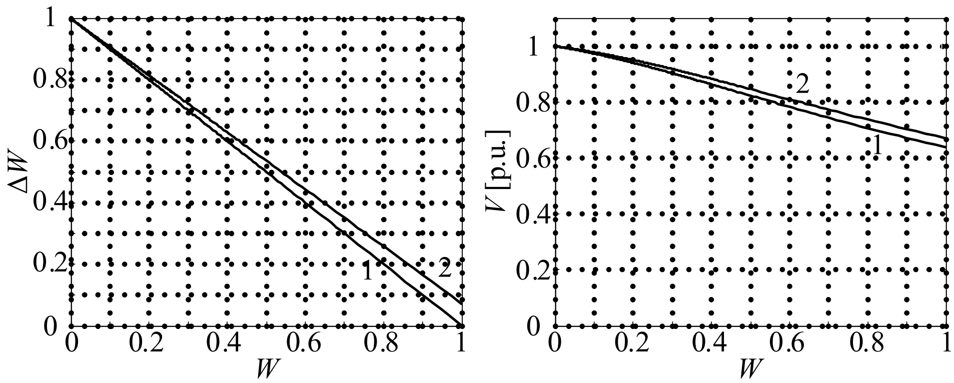

Fig. 8. Changes of stability margin and voltage tgφ = –0.2 – excluded line L5–6

System impedance Z_S for full configuration is less than average value of this parameter. Therefore, calculated stability margin is also less than exact. This is the safe case. The reverse event occurs when the exact value is correspond to exclusion of line L5-6. Calculated stability margin is higher, but we can estimate the error of calculation. In both cases, the difference grow as operating point approach to the stability limit. The values of voltage calculated using approximate model possess similar errors as stability margin estimation.

The analysis of stability conditions of receiving node should consist information about stability margin and also node voltage. These values are close connected. Assumed is often that minimum acceptable voltage value is V = 0.8 [p.u.]. For inductive load (tgφ = 0.4) this value occurs for W = 0.3. For this value stability margin estimation errors are less than 10%. For capacitive load (tgφ = –0.2) voltage value V = 0.8 [p.u.] correspond to W = 0.6. errors of stability margin estimation are about 15–30%.

In the second case when electrically close elements are disconnected (line L9–10 or L4–9) parameters of system model (receiving node 10) changes substantially (see Fig. 3 and Table 1). When disconnection of the line is identified, fix parameters obtained from simulation can be taken. By measuring load parameters voltage stability margin and voltage values can be calculate with proper accuracy. Calculated node voltage and measured voltage can be compared, this will increase the confidence of estimated values when the difference is small.

4. CONCLUSIONS

1. A simplified method of analysis and estimation of voltage stability margin is presented in the paper.
2. Basis of this analysis is model of given part of power system. For all receiving nodes and all possible single switching processes Thevenin equivalents is calculated.
3. Simulations made for one of IEEE model reassured known fact that substantial changes of the system seen from given node are caused by switching the elements close electrically to this node.
4. Switching of elements electrically distant to given node have a small influence on Thevenin model parameters at this node.
5. Considerations and made simulations allowed to assume an average model for far distant switching. This allows to calculate voltage stability margin directly when load parameters were measured.
6. Knowing all parameters of Thevenin model, calculation of voltage and compare it with measured value is possible. Small difference of these voltage can reassure correct assumptions, modelling and calculations.
7. In case of switching electrically close elements to considered node it is possible to locally recognize what happened and substitute parameters known from modelling and simulations. Voltage stability margin can be calculated directly as well as voltage which could be compared with measured value.
8. Generally the approximated method is simpler than known ones and is independent on the type of load.

REFERENCES

[1] EN 50160, *Voltage characteristics of electricity supplied by public electricity networks.*

[2] ARAUJO F.B., PRADA R.B., *Distributed generation: Voltage stability analysis*, [in:] Proc. 2013 IEEE Grenoble PowerTech, 16–20 June 2013, pp. 1–4.

[3] ZOKA Y., YORINO N., WATANABE M., KURUSHIMA T., *An optimal decentralized control for voltage control devices by means of Multiagent System*, [in:] Proc. 18th Power Systems Computation Conference, PSCC 2014, Wrocław, Poland, August 18–22, 2014.

[4] TAYLOR C.W., ERICKSON D.C., MARTIN K.E. et al., *WACS-Wide-Area Stability and Voltage Control System: R & D and Online Demonstration*, [in:] Proc. of the IEEE, Vol. 93, Iss. 5, May 2005, pp. 892–906.

[5] SANGWOOK H., LEE B., KIM S. et al., *Voltage stability monitoring using PMU data in KEPCO system*, [in:] Proc. IEEE PES Transmission and Distribution Conference and Exposition, New Orleans, LA, USA, 19–22 April 2010, pp. 1–5.

[6] IEC 60909-0, *Short-circuit currents in three-phase a.c. systems – part 0: Calculation of currents.*
[7] WISZNIEWSKI A., *New Criteria of Voltage Stability Margin for the Purpose of Load Shedding*, IEEE Transactions on Power Delivery, Vol. 22, Iss. 3, July 2007, pp. 1367–1371.
[8] VU K. BEGOVIC M.M., NOVOSEL D., SAHA M.M., *Use of local measurements to estimate voltage stability margin*, IEEE Transactions on Power Systems, Vol. 14, Iss. 3, 1999, pp. 1029–1035.
[9] WISZNIEWSKI A., REBIZANT W., KLIMEK A., *Intelligent voltage difference control maintaining the voltage stability limit*, [in:] Proc. 43rd CIGRE Session, Paris, France, B5_107_2010, Aug. 2010.
[10] BRUSIŁOWICZ B., REBIZANT W., SZAFRAN J., *A new method of voltage stability margin estimation based on local measurements*, [in:] Proc. of the International Conference on Advanced Power System Automation and Protection APAP 2011, Beijing, China, Vol. 3, 16–20 October 2011, pp. 2443–2447.