Scientific Papers of the
Institute of Electrical Power Engineering of
Wrocław University of Technology

PRESENT PROBLEMS OF POWER SYSTEM CONTROL

No 2

Wrocław 2012

local voltage stability, reactive power compensation,
load shedding, transformer tap control

Bartosz BRUSIŁOWICZ*, Janusz SZAFRAN*

VOLTAGE AND LOCAL STABILITY MARGIN REGULATION OF THE RECEIVING NODE

Regulation methods of the receiving node voltage has been analyzed in the paper. There has been used Thevenin equivalent to develop, simulate and analyze these methods. The paper presents also an on-line method of Thevenin model parameters updating using local phasor measurements. Based on this model influence of the voltage regulation on the local stability margin of the receiving node has been analyzed. Three methods of voltage regulation: transformer tap changing, compensation of reactive power and under voltage load shedding have been examined.

1. INTRODUCTION

A lot of occurrences in power system can influence voltage level and local stability margin at the receiving node. The most significant are power system configuration and node load changes. Incorrect reaction of power system control in such cases can lead to disturbance or even blackout; therefore it is important to take intelligent actions to maintain voltage and simultaneously stability margin at the acceptable level. To study the safety of node there may be used a simplified Thevenin equivalent model. Parameters of this model can be calculated and updated using local measurements, so it is possible to apply the model in substation automation. Voltage level and stability margin depend on parameters of Thevenin model seen from receiving node as well as on the parameters and type of load. The node voltage and stability margin can be maintained by use of: transformer tap changer, reactive power compensation and in extreme cases load shedding. In the paper the influence of the above mentioned methods of voltage control on local stability margin for different types of load is analyzed and simulated.

---

* Institute of Electrical Power Engineering, Wrocław University of Technology, Wrocław Poland.

2. THEVENIN EQUIVALENT

To analyze power flow in the power system there is used a model containing complete information about the current system configuration and its parameters. Assuming the symmetry of loads and generators, the model can be considered as a single-phase one. For analysis of influence of voltage regulation on local stability margin simplified Thevenin model may be used (Fig. 1).

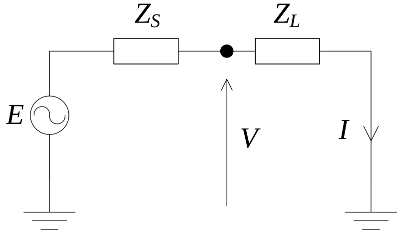

Fig. 1. Simplified Thevenin equivalent

Thevenin equivalent consists of: ideal voltage source E, series system impedance Z_S and load model Z_L. This circuit may be defined by following formulas:

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

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

where: V – node voltage, S – load apparent power, E – ideal source voltage, Z_S - series system impedance, $W=Z_S/Z_L$, $\beta=\varphi_S-\varphi_L$, φ_S and φ_L – system and load impedance phase angles, respectively.

In the Thevenin model values of parameters E, Z_S and Z_L can fluctuate. Impedance Z_S corresponds to actual power system configuration. Actions that change value of this impedance are the inclusions and exclusions of power system components like power lines and transformers. Changes are significant especially when connections occur close to the considered node. Value of Z_S is not directly measurable. However method described below to calculate and update of value of this impedance can be used. Considering the voltage changes it is assumed that the node is connected to strong power system and changes of voltage source E are insignificant. So, constant value of E can be assumed. Changes of load impedance Z_L cause changes of received apparent power and value of actual node voltage. Decrease of voltage provokes voltage regulation actions. Tap changer regulation change not only value of load but also the load impedance seen at the high voltage terminals of the transformer. Frequently it causes decrease of the local stability margin. Conditions are different with compensation of reactive power, which increase voltage level and the stability margin. In extreme case of voltage decrease load shedding ought to be initialized. To determine actual stability margin Z_S value should be calculated and load impedance Z_L should be measured.

2.1. THEVENIN MODEL ON-LINE ACTUALIZATION

Changes in power system configuration affect the fluctuation of Thevenin model parameters. It is continuously changing due to operations carried out in the system, such as switching or disabling the components that take place during normal operation and failures. To use model in substation automation it is necessary to make on-line actualization of value of parameters according to changes occurring in power system. Value of Z_L impedance is easily measurable. However calculations of E and Z_S are required. Method described in paper [1] can be used. Assuming that only parameters of load Z_L are changing (E, Z_S – const.) derivatives of voltage V against W parameter dV/dW and apparent power S against W factor dS/dW from equations (1) and (2) can be calculated, respectively. Dividing obtained derivatives yields:

$$\frac{dS}{dV} = -\frac{S}{V}\,\frac{1 - W^2\left(1 + 2\dfrac{d\cos\beta}{dW}\right)}{W\left[\cos\beta + W\left(1 + \dfrac{d\cos\beta}{dW}\right)\right]} \tag{3}$$

In case of when value of factor W is positive and contained between 0 and 1 (1 is stability limit), the value of this derivative is negative. Consequence of increase of load is increase of apparent power and decrease of node voltage. Equation (3) allows to calculate value of W factor according to:

$$W = \frac{-b\cos\beta - \sqrt{b^2\cos^2\beta - 4a\left[b(1+c) - a(1+2c)\right]}}{2\left[b(1+c) - a(1+2c)\right]} \tag{4}$$

where: a=S/V, b=dS/dV, c=dcosβ/dW.

Determining series system impedance Z_S value by calculating W from previous formula and dividing by measured Z_L value can be done. It is assumed that the Z_S, E_S and φ_S are constant between each measurement or these variations are so small that cause negligible errors in estimated values. Changes of received apparent power S and node voltage V must be caused only by load impedance changes. This term is easy to meet because changes of load impedance are much more often than changes in system configurations.

2.2. LOCAL STABILITY LIMIT

Determined parameters of Thevenin model can be used to calculate local stability margin. By using of the Thevenin model there can be proved that the maximum power transfer and also the limit of stability of receiving node occur when the following equation is true [5]:

$$\overline{V} = \left(\overline{E} - \overline{V}\right)^{*} \tag{5}$$

From equation (5) the impedance condition can be determined. The stability limit occurs when load impedance and series system impedance are equal:

$$\left|\overline{Z}_{L}\right| = \left|\overline{Z}_{S}\right| \tag{6}$$

For easy implementation the voltage stability margin should be restricted. Therefore, the local voltage stability margin ΔW can be described as:

$$\Delta W = 1 - \frac{\left|Z_S\right|}{\left|Z_L\right|} = 1 - W \tag{7}$$

The voltage margin indicator ΔW takes values from 0 (stability limit) to 1 (idle node).

3. VOLTAGE CONTROL OF THE RECEIVING NODE

Parameters of working point of receiving node vary according to changes in power system and changes of load. This causes changes of received active and reactive power, value of voltage and stability margin. Work at insufficient stability margin can lead to instability. In those conditions appropriate value of voltage should be maintain and demanded power should be delivered. All of this should be done in conditions of stable work of receiving node with secure value of stability margin. Voltage and stability margin regulation processes are connected to each other. Therefore they must be considered simultaneously. Furthermore, there is a need of identifying of voltage regulation influence on voltage stability margin. There will be considered three regulation possibilities: transformer tap changing, reactive power compensation and load shedding.

3.1. TRANSFORMER TAP CHANGING

Regulation of transformer tap should maintain voltage close to nominal according to power system configuration and node load changes. In situation when measured voltage is too high tap changer position should be decreased and when it is too low this position should be increased (Fig. 2). Those operations have impact on voltage stability margin what causes some limitations e.g. blocking of transformer tap changer [3, 4].

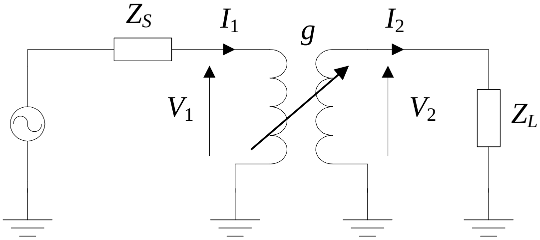

Fig. 2. Transformer with tap changer diagram

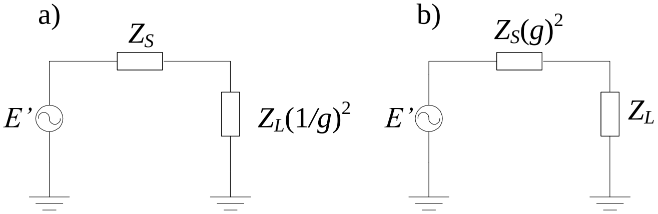

Fig. 3. Impedances calculated for each transformer windings

In Figures 3a and 3b there are presented impedances calculated to the primary and secondary winding of transformer. Voltage regulation (using tap changer), changes not only value of voltage but also stability margin of node. This is because when ratio g is bigger than nominal value g_n load impedance calculated to primary winding of transformer decreases. It causes decrease of stability margin:

$$\Delta W = 1 - \frac{|Z_S| g^2}{|Z_L|} = 1 - W g^2 \tag{8}$$

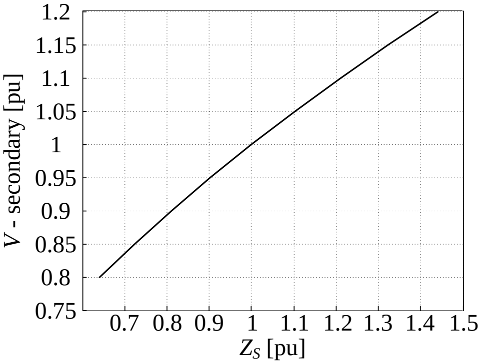

Fig. 4. The voltage and Z_S impedance of g ratio dependence

Figure 4 shows plot of the voltage against series impedance Z_S of g ratio dependence. The voltage at secondary winding of transformer depends on transform ratio g and series impedance Z_S depends on square of g ratio. Therefore, decrease of stability margin goes faster than the increase of value of voltage. As a consequence of increase of series system impedance stability margin ΔW=1-W decrease. That is why sometimes there is a necessity of blocking of transformer tap changer [3, 4].

3.2. REACTIVE POWER COMPENSATION

Other way of voltage control (that also causes decrease of power transmission losses) is compensation of reactive power in receiving node. Possible realization scheme is shown in Fig. 5. It can assumed that impedance Z_L has resistive-inductive character and source of capacitive reactive power is impedance Z_C. Vector plot corresponding to circuit from Fig. 5 is shown in Fig. 6. Figure 6a shows full compensation, 6b under compensation and 6c over compensation of reactive power. Compensation cause decreasing of the amplitude of current. In consequence equivalent load impedance increases and impedance angle decreases (to zero for full compensation), both of them cause increase of voltage.

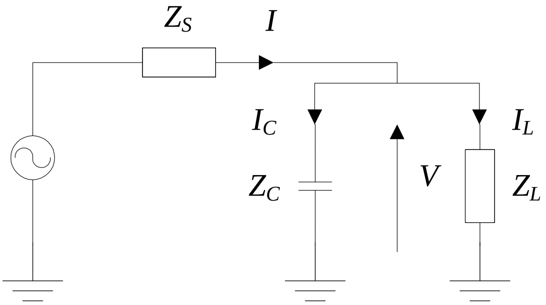

Fig. 5. Reactive power compensation scheme

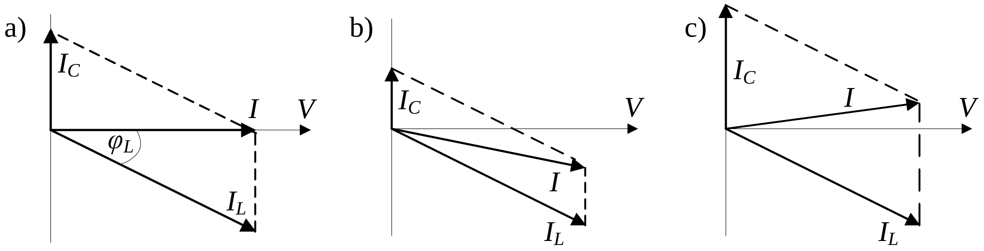

Fig. 6. Vector plot of reactive power compensation a) full compensation, b) under compensation, c)over compensation

Total impedance after compensation can be calculated from:

$$\overline{Z}_Z = \frac{\overline{Z_L} \cdot \overline{Z}_C}{\overline{Z_L} + \overline{Z}_C} = \frac{\left(R + j\omega L\right)\dfrac{1}{j\omega C}}{R + j\omega L + \dfrac{1}{j\omega C}} \tag{9}$$

$$\left|\overline{Z}_Z\right| = \frac{\left|Z_L\right|}{\sqrt{\left(1 - \omega RC \cdot tg\varphi_L\right)^2 + \left(\omega RC\right)^2}} \tag{10}$$

$$\arg\left(\overline{Z}_Z\right) = \varphi_L - arctg\left(\frac{\omega RC}{1 - \omega RC \cdot tg\varphi_L}\right) \tag{11}$$

Denominator of equation (10) is less than one what ensures load impedance module increases and load angle decreases. It reduces power transmission losses and increases value of node voltage. From equation (10) condition of full compensation can be calculated. When full compensation occurs, argument of equivalent load impedance equals zero. After simple modifications the following condition is obtained:

$$\omega RC = \frac{tg\varphi_L}{1 + tg^2\varphi_L} \tag{12}$$

Equations (9, 10, 11) can be used to calculate required value of capacitance for given parameters of circuit. Instead of this there can be designed voltage regulation system. The system could keep value of voltage in specified range. Block diagram of concept of such system is shown in Figure 7. Regulation of Z_C impedance can be realized using power electronics.

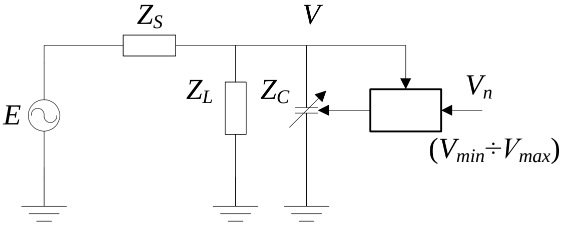

Fig. 7. Voltage regulation diagram

According to the diagram presented in Fig. 7 voltage control simulation tests were realized for two types of load: constant impedance and constant power [2]. Tests include monitoring of received power, voltage and stability margin changes. In simulation there were assumed constant angle of load (tgφ=0.4) and load impedance decreased and increased two and three times. Plot 8 and 10 show changes of node parameters without compensation for constant impedance and constant power models. As an effect of load impedance changes active and reactive power increased and voltage decreased. For constant power model changes have larger values than for constant impedance model.

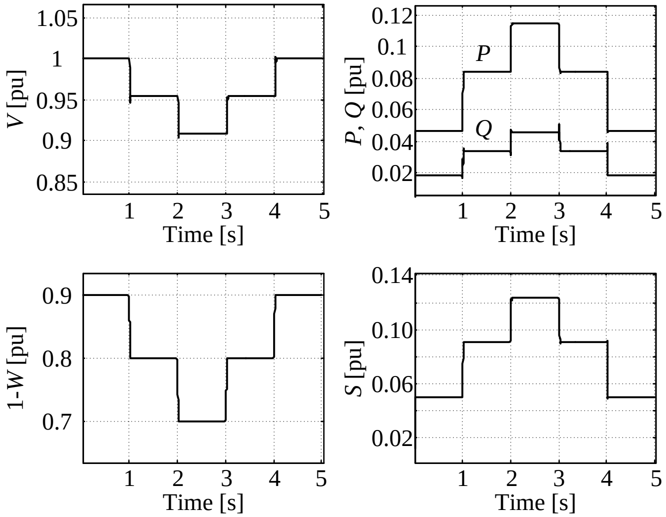

Fig. 8. Plots for constant impedance load model without compensation

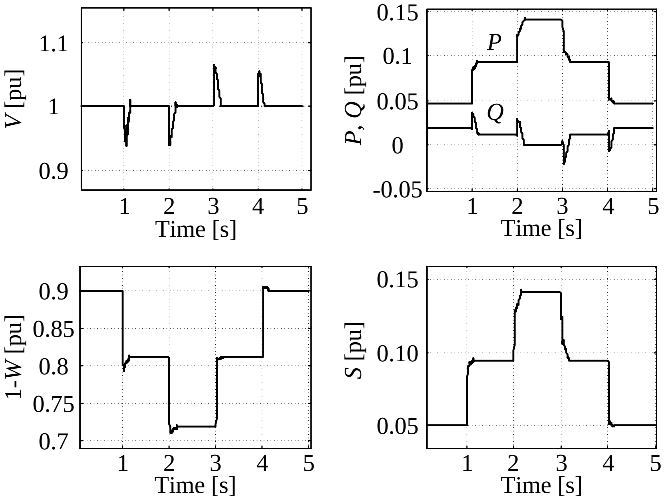

Fig. 9. Plots for constant impedance load model with compensation

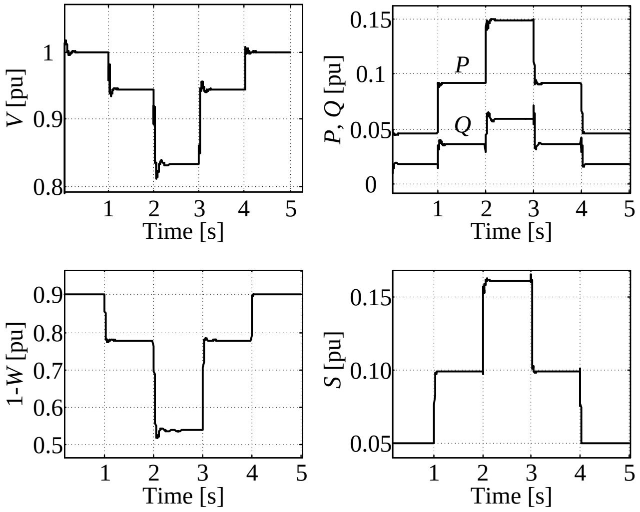

Fig. 10. Plots for constant power load model without compensation

When voltage of the node goes down the voltage control system starts its operation. Effect of this operation is reactive power decrease (compensation) and keeping node voltage at nominal level V=1. Regulation of voltage also enlarges local stability margin. It is caused by changes of angle and module of equivalent load impedance.

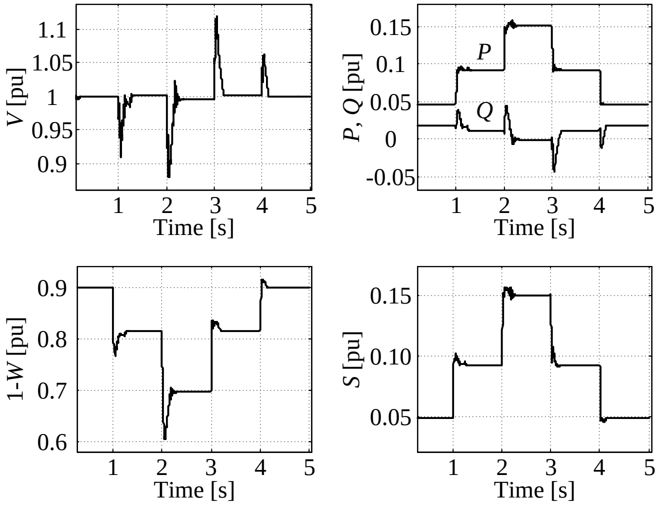

Fig. 11. Plots for constant power load model with compensation

3.3. UNDERVOLTAGE LOAD SHEDDING

In extreme case of voltage decrease (that cannot be regulated by tap changer and reactive power compensation undervoltage) load shedding can be rescued. Possibilities of the shedding are related to the social and business conditions but it is also important to study what effect will be achieved by disconnecting different types of loads. Two examples of the load shedding are shown in Figs. 12 and 13. In the first case (Figs. 12a, 13a) two constant impedances model with the same value but different angle are connected to the node. Plots 12a and 13a show result of disconnection one of them. Curve I presents exclusion of load with tgφ=0.4 and curve II load with tgφ=0. In the second set (Fig. 12b, 13b) there are two loads with the same value and angle but different types. One of them is constant power (III – disconnection of the model) and the second one constant impedance model (IV – disconnection of the model). Test consists three parts: 0-1s normal operation state, 1-2s state after doubling system impedance, 2-3s state after switching off one of two loads. Test with constant impedance models (Figs. 12a, 12b) shows that disconnection of one of them caused great voltage and small stability margin changes. In the second test (Figs. 12b, 13b) with mixed type of load it is important to decide which load should be disconnected. When constant power load is disconnected changes of voltage and stability margin are about two times larger than when constant impedance model is disconnected.

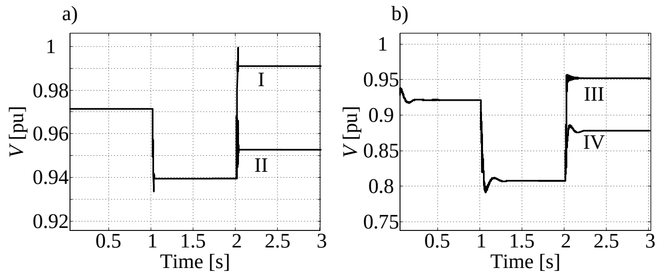

Fig. 12. Voltage plots of load shedding of constant impedance models (I-tgφ=0.4, II-tgφ=0) (a) and constant power – III and constant impedance - IV models (b)

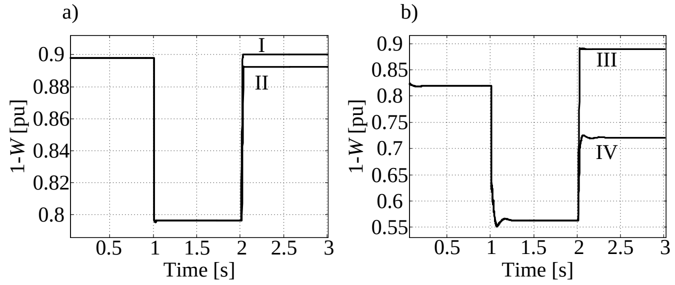

Fig. 13. Stability margin plots of load shedding of constant impedance models (I-tgφ=0.4, II-tgφ=0) (a) and constant power – III and constant impedance - IV models (b)

4. CONCLUSIONS

Local measurements obtained at receiving node of the power system can be used to control its voltage level and stability margin. This can be done by using Thevenin model. Also update of the model parameters can be made by using local measurements.

Simulation tests show that voltage regulation system by reactive power compensation has advantageous properties. It brings dual effect: voltage stabilisation and increase of local stability margin.

Illustrative examples show that algorithms of load shedding may be intelligently applied with load portioning to achieve the best possible stability and economic effects. Intelligent load shedding and voltage and stability margin control can be part of Smart Grid technology.

ACKNOWLEDGMENT

The paper was realized in framework N N511 472439 project sponsored by the Polish Ministry of Science and Higher Education.

REFERENCES

[1] BRUSIŁOWICZ B., REBIZANT W., SZAFRAN J., *A new method of voltage stability margin estimation based on local measurements,* APAP 2011 Conference, Beijing, No 1790, pp. 2443-2447.

[2] MACHOWSKI J., BIALEK W. J., BUMBY R. J., *Power system dynamics and stability*, John Wiley & Sons 1997.

[3] WISZNIEWSKI A., REBIZANT W., KLIMEK A., *Distributed stability control using intelligent voltage margin relay,* Proceedings of the CIGRE Canada Conference on Power System, Vancouver, paper 131, 17-19 October 2010.

[4] WISZNIEWSKI A., REBIZANT W., KLIMEK A., *Intelligent voltage difference control maintaining the voltage stability limit*, Proceedings of the 43th CIGRE Session, Paris, France, paper B5_107_2010 August 2010.

[5] VU K., BEGOVIC M. M., NOVOSEL D., SAHA M. M., *Use of local measurements to estimate voltage stability margin*, Power System, IEEE Transactions on, vol. 14, pp. 1029-1035, Aug. 1999.