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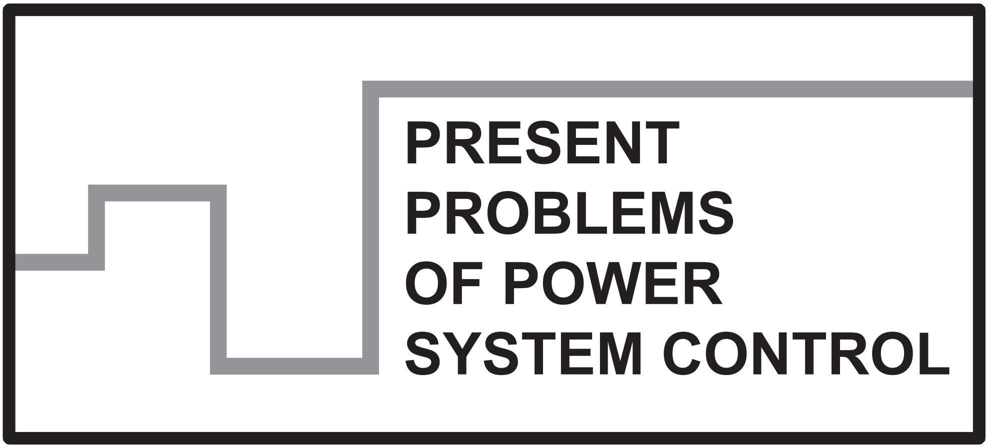

# PRESENT PROBLEMS OF POWER SYSTEM CONTROL

## 4

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*voltage stability,*
*transformer tap changer*

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# INFLUENCE OF TRANSFORMER TAP CHANGER OPERATION ON VOLTAGE STABILITY

The paper concerns influence of transformer tap changer regulation on secondary voltage level and voltage stability margin of receiving node. At the beginning there are presented general information about voltage stability and tap changer. Voltage value of secondary terminals of transformer can be regulated using tap changer. This regulation also affects the calculation of Thevenin equivalent parameters seen from the secondary terminals. Changes of equivalent parameters cause a change of voltage stability conditions. Simulation studies of this influence for various types of load have been done. Selected simulation results are presented in the paper. At the end there are placed conclusions from the performed studies.

## 1. INTRODUCTION

Electricity delivered to customers should have appropriate quality. Required parameters are defined in European Standard EN 50160 [1]. One of the power quality parameters is the voltage value. The voltage variations can be caused by normal operation of power system – changes of power system configuration or parameters of loads. The power system can be designed to maintain the value of voltage in acceptable limits despite of these changes. However, randomly situations where these limits are exceeded can occur. To ensure constant voltage level, some of power system nodes should have a voltage control systems. This regulation, what is obvious, also affects other parameters of the operating point of power system node. The most commonly used methods of voltage adjustment are: voltage tap changer, reactive power compensation and undervoltage load shedding. This paper refers only to analysis of the influence of transformer tap changer operation on voltage level and voltage stability.

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Voltage stability is defined by IEEE in the following way: “*Voltage stability is the ability of a system to maintain voltage so that when load admittance is increased load power will increase and so that both power and voltage are controllable*” [2].

Margin of this stability can be determined using a full model of the power system and the power flow calculations. Voltage characteristics of loads can be added for such model. For each node stability margin can be calculated basing on changes of parameters caused by voltage variations e.g. $\mathrm{d}\Delta Q/\mathrm{d}V$ [3, 4].

To study voltage stability of selected power system receiving node, it is more convenient to use a simplified Thevenin equivalent model. In this model part of power system seen from the node may be replaced by ideal voltage source $E$ and system impedance $Z_S$ (Fig. 1).

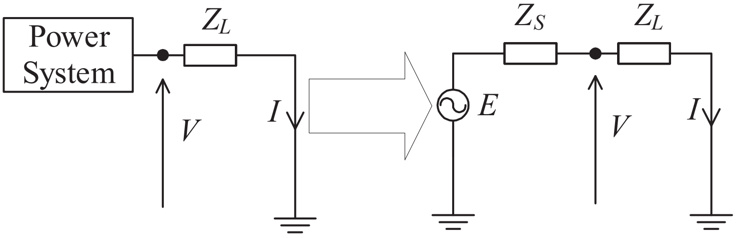

Fig. 1. Thevenin model

Parameters of stable operating point of presented Thevenin circuit are defined by the following equations [5]:

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

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

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

Voltage stability limit occurs at the point of maximum power transfer [6]. In this point, the equation (3) is true. Thus, to calculate voltage stability margin it is more practical to use equation (4).

$$\left|\overline{Z}_S\right| = \left|\overline{Z}_L\right|, \tag{3}$$

$$\Delta W = 1 - W = 1 - \frac{\left|\overline{Z}_S\right|}{\left|\overline{Z}_L\right|}. \tag{4}$$

Value of load impedance is greater than system impedance, so *W* parameter is changing from 0 to 1. The power system receiving node is stable if value of *W* is lower than 1.

In the literature various methods of *W* parameter calculation can be found. These methods often use only locally available measurements of voltage and current. For example *W* parameter can be calculated using: equations of Thevenin model [6], derivatives of apparent load power against the node voltage d*S*/d*V* [7] or node voltage against load admittance d*V*/d*Y* [8].

## 2. TRANSFORMER TAP CHANGER

To regulate the secondary voltage level separated coils of winding are connected to the tap changer at one of the transformer site, usually at the primary. Operation of the tap changer modifies the total number of active coils of primary winding. For a fixed number of coils at secondary winding, this action causes change of transformer voltage ratio.

Types of tap changers are divided into: De-Energized Tap Changer (DETC) and Load Tap Changer (LTC) [9]. DETC regulators are used in systems where need of voltage level changing occurs relatively rare. If the voltage value changes often LTC systems are used.

For Thevenin model (Fig. 1) voltage regulation using transformer tap changer can be added (Fig. 2a). In this model, the winding and core losses are omitted. Level of secondary voltage depends on the position of tap changer *g* according to equation (5)

$$g = \frac{V_L}{V_1}. \tag{5}$$

To eliminate the tap changer from presented model, Thevenin parameters to various windings of transformer can be calculated. The system impedance $Z_S$ and voltage source $E$ can be converted to the secondary winding according to the formula (6). Figure 2b shows Thevenin model with calculated parameters.

$$Z_S{}' = Z_S * g^2 \qquad E' = E * g \tag{6}$$

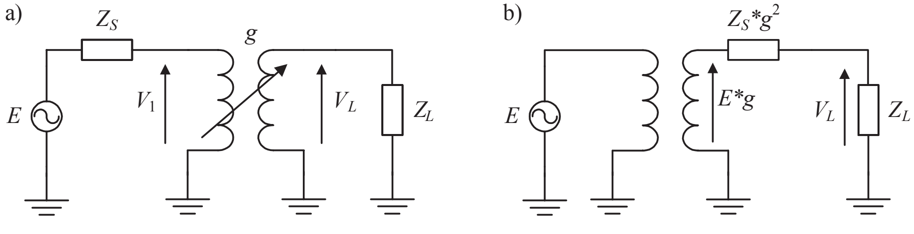

Fig. 2. Thevenin model with tap changer

Taking into account transformer ratio $g$ in voltage equation (1), secondary voltage can be described by following formula:

$$V_L = \frac{Eg}{\sqrt{1 + \left(Wg^2\right)^2 + 2Wg^2 \cos\beta}}. \tag{7}$$

From equations (5) and (7) primary voltage can be calculated in the following way:

$$V_1 = \frac{V_L}{g} = \frac{E}{\sqrt{1 + \left(Wg^2\right)^2 + 2Wg^2 \cos\beta}}. \tag{8}$$

Above presented equations show that the change of tap changer position affects primary and secondary transformer voltage. When $g$ parameter increases, secondary voltage raises and primary voltage decreases. Figure 3 shows an example of this relation. Curves have been plotted for following parameters: $E = 1$, $W = 0.3$, $\varphi_{ZS} = 85°$, $\varphi_{ZL} = 15°$. Derivatives of primary and secondary voltages against transformer ratio $g$ and sum of these derivatives are shown in Figure 3b.

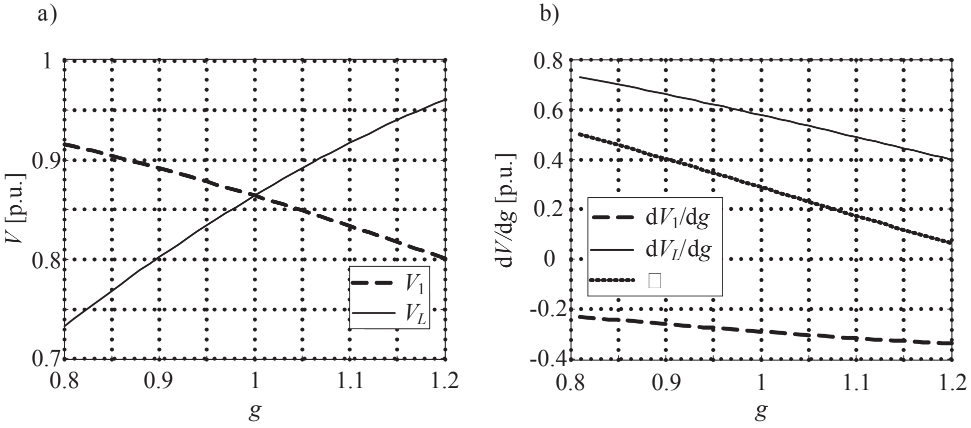

Fig. 3. Changes of primary and secondary voltage a) and derivatives b) for $W = 0.3$, $\beta = 70°$

The derivative of the voltage against $g$ ratio can be used as a criterion for tap changer operation blocking. The blocking should be performed when the changing tap changer does not provide desired effect. Such criterion has been described in literature [8]. The tap changer should be blocked when the derivatives of voltages are equal. Therefore, tap changer operation is allowed when the condition (9) is true. When this condition is not fulfilled, $g$ ratio changing causes a greater decrease of primary voltage than increase of the secondary voltage. In such case, it is reasonable to block the tap changer.

$$\frac{dV_L}{dg}+\frac{dV_1}{dg}>0 \tag{9}$$

## 3. SIMULATION RESULTS

Simulations of influence of tap changer operation on primary and secondary voltage changes have been performed. The following parameters of Thevenin model have been assumed: $E = 1$ $|Z_S| = 1$ $\varphi_{ZS} = 85°$. Load angle $\varphi_{ZL}$, as in the previous case, has been 15°, so $\beta$ angle has amounted 70°. Simulations have been performed for different values of the load impedance. The $W$ parameter has taken following values: $W = 0{,}1$; 0,3; 0,5 and 0,7. Figures 4–7 show changes of the primary and secondary voltage and derivatives of these changes.

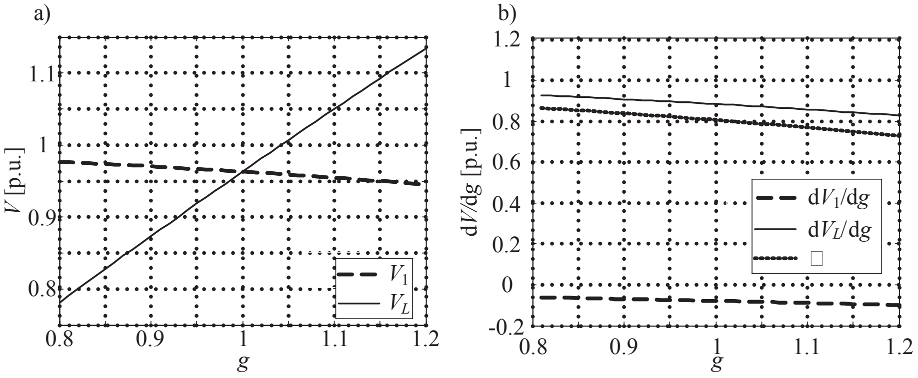

Fig. 4. Changes of primary and secondary voltage a) and derivatives b) for $W = 0.1$, $\beta = 70°$

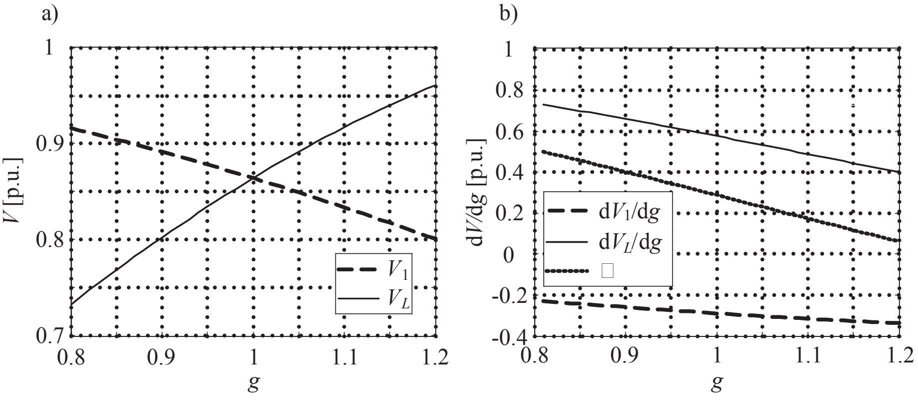

Fig. 5. Changes of primary and secondary voltage a) and derivatives b) for $W = 0.3$, $\beta = 70°$

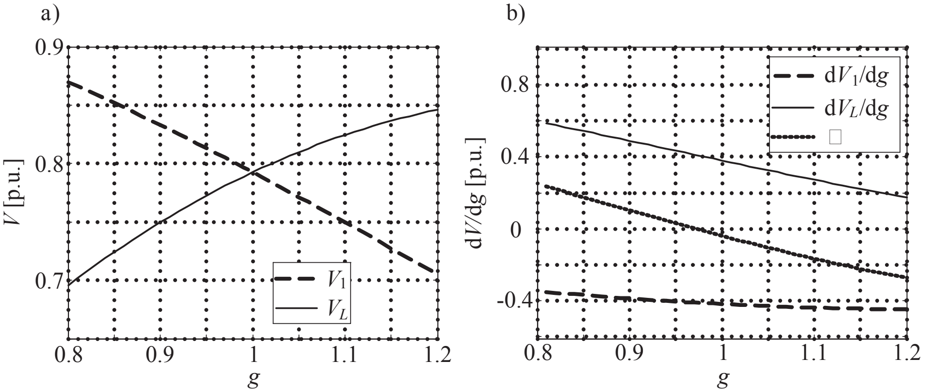

Fig. 6. Changes of primary and secondary voltage a) and derivatives b) for $W = 0.5$, $\beta = 70°$

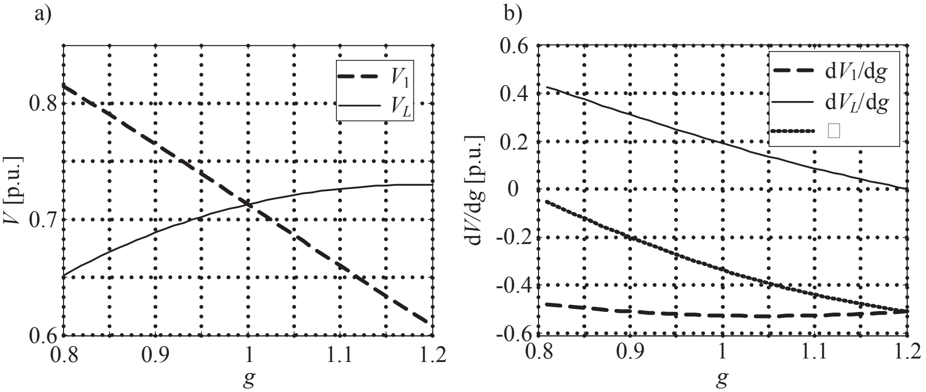

Fig. 7. Changes of primary and secondary voltage a) and derivatives b) for $W = 0.7$, $\beta = 70°$

The presented plots show that the lean of curves depends on the $W$ parameter. For small values of $W$ (Fig. 4) regulation of secondary voltage $V_L$ does not change significantly the primary voltage $V_1$. Secondary voltage derivative $dV_L/dg$ is positive and primary voltage derivative $dV_1/dg$ is negative. In the operational range $g = 0.8{:}1.2$ sum of these derivatives will be greater than zero. So the condition (9) is true. Also, for $W = 0.3$ in the operational range sum of derivatives does not reach zero. Approaching to the end of range, the sum is close to zero. However, the tap changer should not be blocked. For $W = 0.5$ sum of voltages derivatives reaches zero for $g = 0.97$. When tap changer is in neutral position $g=1$ and such load occurs, any increase of the secondary voltage results in a large decreasing of primary voltage so the regulation is not effective. When $W = 0.7$ regulation of voltage is not effective over the operational range.

Different rates of changes of derivatives for various values of $W$ parameter are caused by the increase of voltage and apparent power. Therefore, the operating point is moved both upwards and in the direction of maximum power transfer. These contingencies for various values of *W* parameter are shown in Fig. 8. The solid line is the curve plotted for $g = 1$. Dashed lines indicate the transformer ratio changes to $g = 0.8$ and $g = 1.2$. Load characteristics are marked by dotted lines. Fig. 8 shows that for rising initial *W* parameter, increase rate of secondary voltage caused by tap changer operation is getting smaller and increase rate of apparent power is growing.

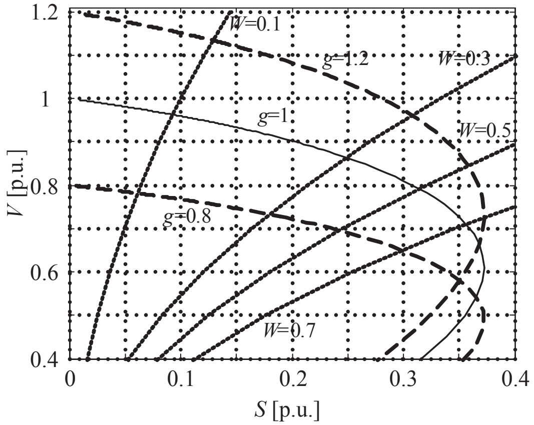

Fig. 8. Nose curves and load characteristics

It is obvious that changes of $V_1$ and $V_L$ voltages also depend on the angle of the load impedance. For angles close to zero or negative (capacitive load) the initial voltage drop is smaller and regulation brings greater effect. Figure 9 shows sum of derivatives for $W = 0.4$ and three values of the load impedance angle. In the tap changer operational range blocking should be performed only for angle amounting $\varphi_{ZL} = 15°$.

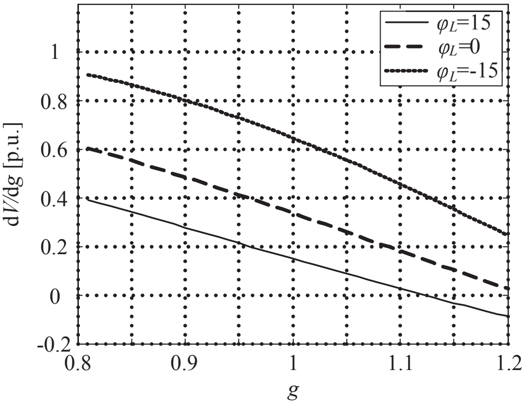

Fig. 9. Sum of derivatives for various load angles

Assuming that the limit of voltage stability occurs when $W = 1$ and that the change of tap changer position affects calculation of system impedance $Z_S$, equation (10) can be written. Equation (10) can be transformed to formula (11). This formula can be used to calculate limit tap changer position for which the circuit reaches the limit of stability. Changes of $g_{lim}$ according to value of $W$ variations are shown in Fig. 10.

$$W = W_1 * g^2 = 1, \tag{10}$$

$$g_{\text{lim}} = \frac{1}{\sqrt{W_1}}. \tag{11}$$

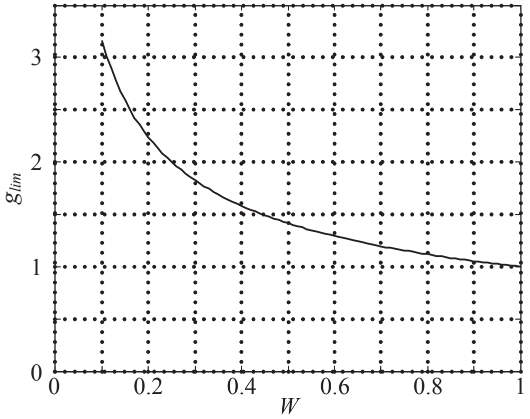

Fig. 10. Changes of $g_{lim}$ according to $W$ variations

It can be seen that the values of $g_{lim}$ are greater than those resulting from quoted criterion based on measurement of voltage derivatives. In the presented example, for $W = 0.5$ blocking tap changer should be performed for $g = 1.125$ (Fig. 6). For this level of $W$ parameter, value of $g_{lim} = 1.4$ (Fig. 10). This confirms the validity of voltages derivatives criterion. However, between the values of $g$ resulting from this criterion and $g_{lim}$ there is an area where the regulation might be performed.

## 4. NONLINEAR LOADS

Previous considerations have been carried out assuming that the load impedance is linear. However, in reality, the value of impedance depends on the voltage level. Example dependences are presented in the IEEE publication [9].

The simplest way of describing nonlinear load model is the exponential equation (12).

$$Z_L = Z_{L0}\left(\frac{V}{V_0}\right)^{\alpha} \tag{12}$$

where: $Z_{L0}$ – rated impedance, $\alpha$ – exponent of voltage characteristic.

Examples of basic models (constant impedance, current and power) are shown in Fig. 11. The Figure shows that changes of voltage and apparent power are different for various load models. It can be concluded that the impact of tap changer regulation depends on $\alpha$ exponent (equation (12)).

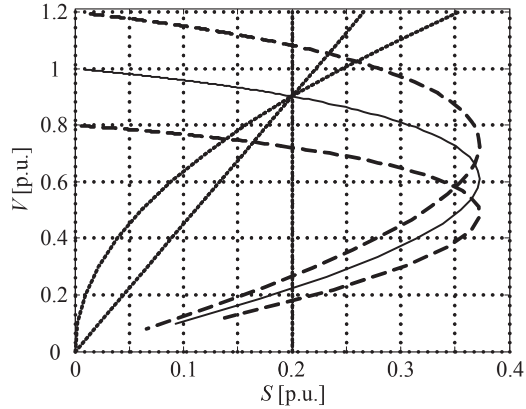

Fig. 11. Nose curves and load characteristics

For the fixed parameters of Thevenin model value of $W$ depends only on the load impedance. In nonlinear model this impedance is changing according to value of secondary voltage. Converting the load impedance on the primary voltage and including dependence on voltage equation (13) can be obtained.

$$W_1 = \frac{Z_S}{Z_L} = \frac{Z_S}{Z_{L0}\frac{(V_1 g_1)^{\alpha}}{g_1^2}} \tag{13}$$

where: $V_1 = V_1/V_0$; $V_0$ – rated voltage.

The $W$ parameter strongly depends on transformer ratio $g$. Equation 13 can be also written for changed value of $g_2$. From both equations, system impedance $Z_S$ can be determined. Comparing and transforming these two equations formula (14) can be calculated. $W_2/W_1$ parameter represents variations of $W$ according to change of $g$ and $\alpha$ exponent of load model.

$$\frac{W_2}{W_1} = \left(\frac{g_2}{g_1}\right)^{2-\alpha} \tag{14}$$

Changing the value of tap changer position $g$, curves corresponding to changes of $W_2/W_1$ parameter for fundamental load models have been plotted. These models have been: $\alpha = 0$ – constant impedance, $\alpha = 1$ – constant current, $\alpha = 2$ – constant power. Obtained curves are shown in Figure 12.

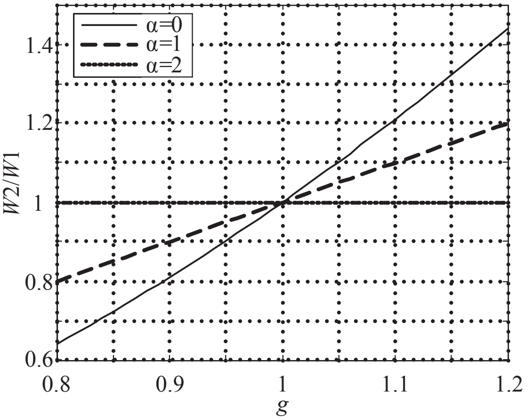

Fig. 12. Chages of $W_2/W_1$ parameter according to $g$ variations

From Figure 12 it can be noticed that increase of $W$ parameter is greater when $\alpha$ exponent is lower. The largest increase is for the constant impedance load and the lowest for constant power model. This contingency is similar to that shown in Figure 11. The greatest increase of load apparent power (getting closer to the stability limit) is for constant impedance model. If the load model is constant power, tap changer operation changes only value of voltage.

To transform load impedance to primary voltage, value of the impedance should be divided by squared transformer ratio $g$. Value of impedance of constant power model depends on squared secondary voltage. This voltage depends on $g$ parameter. Therefore, $W$ parameter is not changed.

Additional tests similar to those in section 3, using constant power model have been made. Formula (12) is nonlinear, so to perform simulations the method of solving nonlinear equations has been chosen. Aitken iterative algorithm has been used [10].

From Figure 13 it can be noticed that rising $g$ parameter causes increase of secondary voltage level with no change of primary voltage. The derivative of primary voltage is zero and derivative of secondary voltage is positive. Therefore, the sum of derivatives will never reach zero. For constant power model, operation of tap changer can be carried out over entire range of regulation regardless of the $W$ parameter and angle of the load.

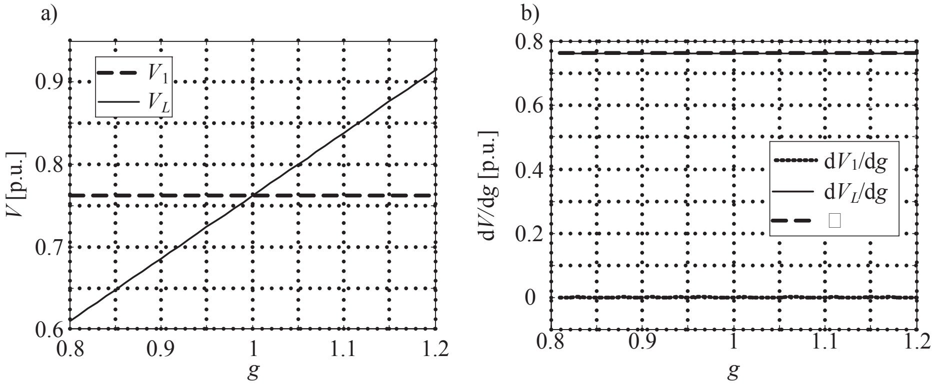

Fig. 13. Changes of primary and secondary voltage (a) and derivatives (b)
for $W = 0.3$, $\beta = 70°$ – constant power model

When voltage regulation using tap changer for constant impedance model is performed the voltage stability conditions are the worst. For this model the apparent power varies with the square of the transformer ratio $g$. Constant power model is the safest because the tap changer operation does not endanger safety of the node.

## 5. CONCLUSIONS

1. It is possible to block tap changer using quoted criterion when increasing secondary voltage level causes a significant decreasing of primary voltage. Blocking point is determined by measuring the derivatives of these voltages according to transformer ratio changes.

2. For each value of $W$ parameter it is possible to calculate the critical transformer ratio. This value corresponds to transformer ratio which will result in loss of voltage stability. In the paper $g_{lim}$ is calculated assuming linear load impedance. For other models, the critical value will be probably greater. Therefore, use of $g_{lim}$ calculated for linear impedance to nonlinear models will result in greater safety margin obtained.

3. Value of $g_{lim}$ parameter is greater than $g$ level arising from the quoted criterion. Between them there is an area where the voltage regulation could be carried out maintaining given stability margin.

4. The effect of tap changer operation depends on load model. The paper describes the dependence of these effects according to value of $\alpha$ exponent.

5. When voltage regulation using tap changer is performed it is required to determine the impact of these actions on value of voltage and voltage stability margin.

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