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Tap changing transformer role in voltage stability enhancement

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Abstract

It was long known that tap-changing transformers can affect voltage stability of power systems. Evaluation of these effects are provided in this paper. Influence of tap-changing transformer on maximum transmitted power and nodes critical voltages, from the point of view of voltage stability, are clarified. Wide range of tap-changing are used in this clarification and stability margins excursions are explored.

Keywords: Maximum transmitted power; Nodes critical power; Tap-changing; Voltage stability

1. Introduction

Nearly all distribution substations are provided with transformers with tap-changers facilities . It was long believed that transformers with tap-changers can eliminate or minimize effectively voltage instabilities of power systems. Several studies were devoted to explore the stabilization effects of such transformers in voltage stability domain [1–8]. Some of these studies were interested in proposing new models for such tapped-changing transformers [4–6]. Others were interested in their effects on voltage stability [7–10].

This study concerns their effects on steady-state voltage stability margins [9]. The limitations of depending solely on these transformers to improve voltage stability of stressed power systems are put into evidence. Contribution of such transformers to maximum transmitted powers with their corresponding critical voltages are highlighted [10]. That study showed a limited effects of these tapped transformers on voltage stabilization aspects of power systems.

2. Model of transformer with tap-changer

A transformer with off nominal turn ratios can be represented by its impedance, or admittance, connected in series with an ideal autotransformer as shown in Fig. 1a. An equivalent π circuit can be obtained from this representation to be used in load flow studies and voltage stability, and the elements of the equivalent π circuit, can be treated in the same manner as line elements. The parameters of the equivalent π circuit are shown in Fig. 1b).

The off-nominal tap-ratio (‘t’ $= 1/a$) is the percent deviation over or under the nominal unity value. It usually ranges between 0.8 and 1.2. The three π branches elements are y_{pq}, $[(1-a)/a]$, y_{pq}, $[(a-1)/a^2)]y_{pq}$, or ty_{pq}, $t[(t-1)]y_{pq}$, and $(1-t)y_{pq}$. Where ($t = 1/a$), and a is the turns ratio of the ideal equivalent auto transformer shown in Fig. 1a.

At normal transformer tapping, the ratio ‘a’ tends to unite and the transformer model turns to its series admittance y_{pq}, i.e. the two shunt elements vanish completely.

3. Steady state voltage stability criteria

Having known the operating conditions of any system, the system is proposed to be reduced to its Thevenen’s equivalent using the technique presented in Ref. [9]. The system then to be represented by an equivalent Thevenen’s emf E, Thevenen’s impedance Z, load node voltage V, and load powers P and Q. Improvement technique of Ref. [11] is then applied. In the dE/dV

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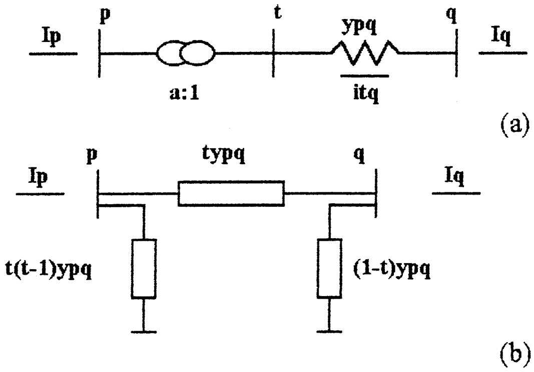

Fig. 1. Tapped-changing transformer representations. (a) Equivalent circuit; (b) equivalent π circuit with parameters.

criterion [9], a factor K_c is to be calculated. Voltage stability holds when the factor K_c exceeds zero. $K_c = 0$ indicates critical voltage instability.

When investigating the conditions required for voltage instability by the dZ/dV criterion [9] another factor K_z may be calculated. $K_z < 0$ indicates node voltage stability, while $K_z = 0$ indicates critically voltage stability. $K_z > 0$ announces state of voltage instability. In the L indicator technique, an indicator called L is to be calculated. $L = 1$ indicates state of node critical voltage stability. $L > 1$ is the indication of load node voltage instability. In order to keep the node voltage stable, L should be less than unity. Formula of these factors and indicators are given in Refs. [9–11] for a two nodes systems, which represents any large power system.

4. Studied system

The six-bus Ward–Hale test system is used as a test system. It was used in Ref. [9] for the same purpose. The system consists of two generators, six nodes, five lines and two transformers with tap-changers. The system is shown in Fig. 2. Its data appear in Ref. [10]. Node 5 is selected to be a variable load node, its base case powers are $P = 0.3$ p.u., $Q = 0.18$ p.u.

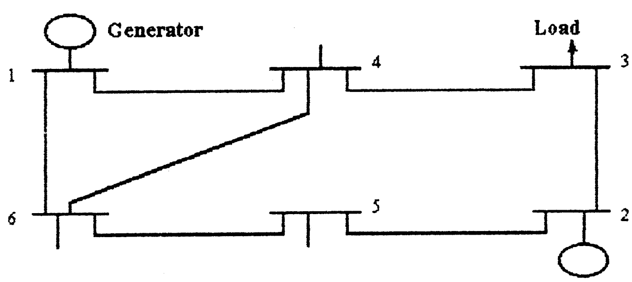

Fig. 2. Six bus Ward–Hale test system.

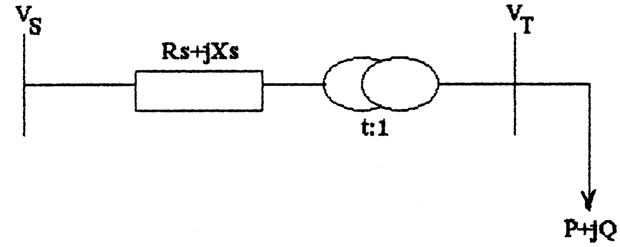

Fig. 3. Thevenin's equivalent system.

5. Interrelation between loads power and tap-changing ratio at different load voltages

In order to study the relation between load powers at different load voltages, when connected to tap-changing transformer, the system of Fig. 3 is used. Two cases are considered. Constant power load and constant reactive power load. Using the simplified voltage drop relation, the system equations are:

$$\Delta V = \left|\frac{V_S}{t}\right| - |V_T| = \frac{((X_S + X_t)/t^2)Q + (R_S/t^2)P}{V_T} \tag{1}$$

$$V_T^2 t^2 - V_T V_S t + R_S P + (X_S + X_t)Q = 0 \tag{2}$$

From these equations, 't' can be calculated as:

$$t_1 = (V_S V_T + ((V_S V_T)^2 - 4V_T^2(R_S P + (X_S + X_t)Q))^{1/2}) / 2V_T^2 \tag{3}$$

$$t_2 = (V_S V_T - ((V_S V_T)^2 - 4V_T^2(R_S P + (X_S + X_t)Q))^{1/2}) / 2V_T^2 \tag{4}$$

Using Eqs. (3) and (4), the off nominal tap ratio of tap-changing transformer with load powers can be plotted at different load voltages and loading conditions.

6. Results and discussions

6.1. Tap-changing effects on degree of voltage stability

The Ward–Hale 6-bus system is used as a test system to illustrate the of tap changing transformer on steady state voltage stability.

When there is no control, i.e. tap-changer not being utilized, the results of load flow and the three different

Table 1
The results of load flow nodes loads voltages and different criteria without control of voltage stability

Bus number	V in p.u	L Ind.	dE/dV K_c	dZ/dV K_z
3	$0.8966\angle -14.6$	0.379	3.92	−0.034
4	$0.9075\angle -10.7$	0.240	4.88	−0.039
5	$0.7367\angle -14.5$	0.53	1.35	−0.033
6	$0.8376\angle -13.3$	0.292	3.68	−0.057

Table 2
The results of load flow voltage at node #5 and different criteria with various tap changer transformer

Tap a	V in p.u. at bus 5	L Ind.	dE/dV K_c	dZ/dV K_z
0.25	$1.189\angle -18.4$	0.6	0.3	−0.01
0.4	$1.007\angle -17.8$	0.53	1.27	−0.029
0.5	$1.002\angle -16.5$	0.480	1.38	−0.032
0.6	$0.9987\angle -15.0$	0.475	1.50	−0.043
0.7	$0.9659\angle -13.4$	0.450	1.545	−0.047
0.8	$0.8538\angle -13.8$	0.457	1.53	−0.0459
0.85	$0.8239\angle -13.9$	0.480	1.49	−0.0418
0.9	$0.7950\angle -14.1$	0.496	1.46	−0.0380
0.95	$0.7646\angle -14.3$	0.512	1.41	−0.0370
1.0	$0.7367\angle -14.5$	0.530	1.35	−0.0330
1.05	$0.7070\angle -14.9$	0.550	1.28	−0.0320
1.1	$0.6790\angle -15.3$	0.575	1.20	−0.0310
1.15	$0.6517\angle -15.7$	0.602	1.12	−0.0299
1.2	$0.6240\angle -16.3$	0.634	1.03	−0.0279
1.3	$0.5692\angle -17.7$	0.714	0.799	−0.0226
1.4	$0.5091\angle -19.87$	0.838	0.49	−0.014
1.45	$0.4653\angle -21.56$	0.957	0.239	−0.0007
1.5	$0.4419\angle -23.1$	1.03	−0.03	0.002

criteria at each bus are given in Table 1. Here, the voltage of bus 5 is the lowest one and the different three criteria are near to stability limit.

In order to improve the voltage at bus 5, tap-changing transformer is used for the voltage stability enhancement purposes. It is assumed that a tap changer transformer is connected at bus 5 through the transmission line from bus 5 to bus 6 and its off nominal tap ratio is varied from $a = 0.25$ up to appearance of voltage instability by steps of 0.05. The results are given in Table 2. This table shows that at certain off nominal tap changer value, voltage instability can occur, other ratios can improve voltage instability.

At off-nominal tap ratio of 0.79 in the studied system, voltage stability is at its maximum state. Below or over this value, degree of voltage stability will decrease and can go to a state of instability at $a = 1.5$ or at a near 0.2, which are both not used in practice ($0.8 < a < 12$). Fig. 4, shows the variation of the off-nominal tap ratios dE/dV criterion

6.2. Off nominal tap ratio/power voltage response with constant reactive power loads

First of all, the source equivalent voltage is kept constant at 1.004 p.u, the load reactive power is assumed to be kept constant at $Q = 0.18$ p.u.

The link resistance and reactance are taken as 0.08126 and $(X_S + X_t) = 0.3 + 0.3125$ p.u., respectively. Fig. 5 shows the load powers corresponding to load voltages between $V_T = 0.8$ and $V_T = 1.2$ p.u. at different off nominal tap ratios between 0 and 1.2. The figure shows that at lower load voltages, the transformer off-nominal tap-ratio should be more than 0.75 for

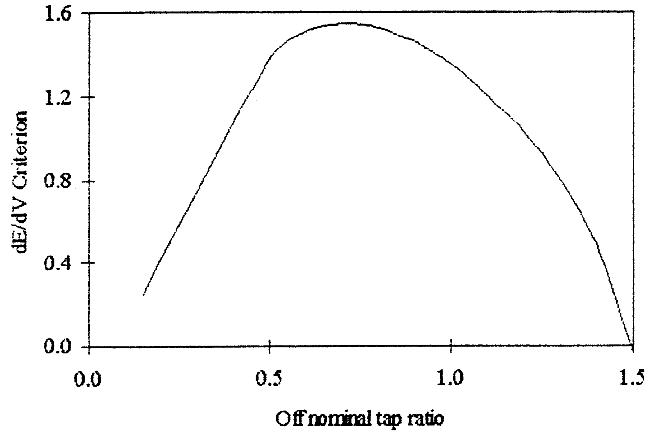

Fig. 4. The variation of off nominal tap ratio's with dE/dV criterion.

stable voltage operations. This value will be 0.5 p.u. for higher voltage cases. Moreover, the maximum allowable load power is the same for all load voltage levels. The figure reveals that lower off nominal tap ratio's are not preferable from voltage stability point of view and the transformer tapping variations do not affect the maximum transmitted power.

6.3. Off nominal tap ratio/reactive power voltage response with constant power load

The same above system data are used except the load power is assumed fixed at $P = 0.3$ p.u. and the load reactive power is allowed to change.

Once more, off nominal tap ratios less than 0.45 will lead to unstable operations of the power system. The maximum allowable (critical) reactive power is the same for all cases, as shown in Fig. 6. Transformer tapping does not affect this value. The range of the off nominal tap ratios is more wider than that with constant reactive power case, for the same voltage levels.

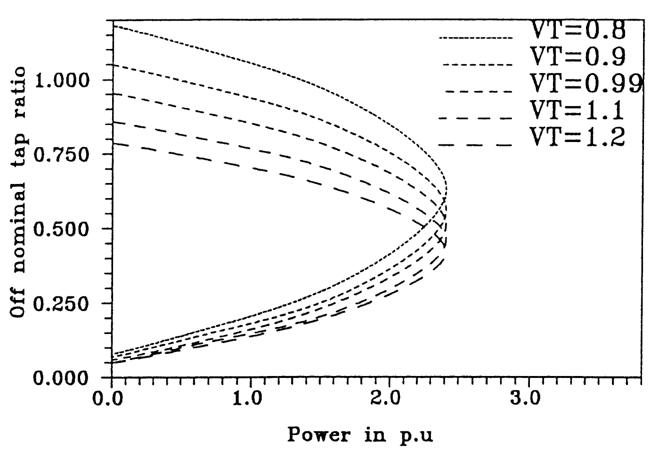

Fig. 5. Off nominal tap ratio/load power at different load terminal voltage.

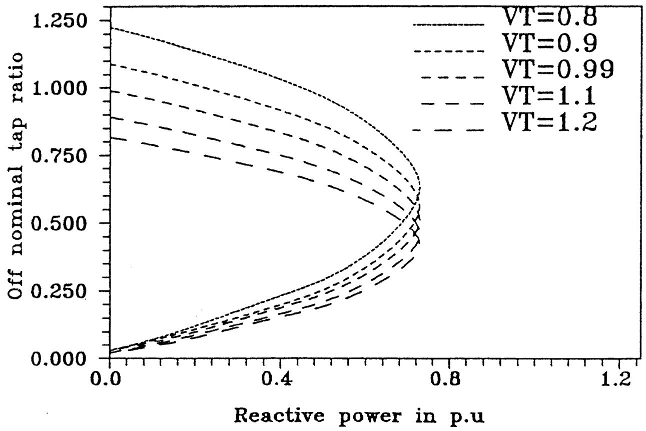

Fig. 6. Off nominal tap ratio/load reactive power at different load terminal voltage.

From Figs. 5 and 6, corresponding to $P_{\max}$, the two values of (t) are coincident. Then the value under the roots must vanish, i.e. the term under the root of Eqs. (3) and (4) becomes zero. Therefore, the values of taps ($t_{1,2}$) are thus the first part of Eqs. (3) and (4), i.e.:

$$B^2 - 4AC = 0 \tag{5}$$

$$B^2 = 4AC$$

$$(-V_S V_T)^2 = 4(V_T^2)(R_S P + (X_S + X_t)Q)$$

$$V_S^2 = 4(R_S P + (X_S + X_t)Q)$$

Therefore the maximum load power is independent of V_T.

7. Conclusions

(a) Any transformer provided by an automatic tap-changer may affect the system voltage stability. Very low values or very high values (outside the practical range 0.8–1.2) can turn the system voltage to be unstable. Within the practical range the system voltage is usually stable when the system voltage is originally stable, but with different stability degrees and with different margins of stabilities.

(b) Presence of tap-changing transformers only does not improve voltage stability significantly. Slight variations are detected within practical ranges.

(c) Tap-changing transformer at the load terminals does not change its maximum power value, slightly affects its critical voltage value.

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