Effect of On-load Tap Changer on Voltage Stability of Power Systems with Nonlinear Load

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***Abstract*— In this paper we analyze the effect of tap changing of the on-load tap changer (OLTC) on the voltage stability via the calculation of the maximum power transmission and singular induced bifurcation. It is shown that the maximum reactive power increases when the ratio of OLTC increases and the possibility of voltage collapse will be decrease under the same load command. We also get some results on the voltage stability of the power system with OLTC from a singular induced bifurcation point of view. Finally, noting that the voltage instability is directly affected by the load characteristics, we discuss the effect of OLTC on the voltage instability under different static load models.**

***Index Terms*— on-load tap changer, power system, voltage stability, maximum power transmission, singular induced bifurcation.**

I. Introduction

Power industry plays a more and more important role in modern society and economics. The objective of the large power system is to economically generate and to distribute power to its customers through transmission and distribution networks with standard quality and as free as possible of disturbances, oscillations, etc. How to keep the stability and security of the power system is the most important problem in power industry.

Generally, the stability problem of power systems can be classified as two classes: angle stability and voltage stability[1][2]. Due to the tendency of increasing of load demand on the power network with long transmission lines, voltage stability has been of more important. The on-load tap changer (OLTC) has a significant influence on voltage stability[3]-[5]. Zhe et al[5] discussed how the maximum power transfer limit was affected by on-load tap changers. Kang et al[6] proposed a technique for on-line automatic condition assessment of OLTC via a self-organising map. In [7], Hong et al investigated the control sequence for improving voltage stability in power systems. The controllers include transformers (step-up, EHV and on-load-tap-changer (OLTC)), generators, and shunt capacitors. Rivas et al analyzed the vibration and fault detection of power systems with OLTC via the wavelet method[8][9].

In this paper, we analyze the effect of OLTC on the voltage stability via the calculation of the maximum power transmission. It is shown that the maximum reactive power increases when the ratio of OLTC increases and the possibility of voltage collapse decreases under the same load command. We also get some results on the voltage stability of the power system with OLTC from a singular induced bifurcation point of view. Finally, noting that the voltage instability is directly affected by load characteristics, we discuss the effect of OLTC on the voltage instability under different static load models.

The rest of the paper is organized as follows. In section 2 we provide a nonlinear differential algebraic system model for the power system with OLTC and nonlinear load. In Section 3 we discuss the effect of OLTC on the voltage stability via a maximum power transmission point of view. In Section 4, we propose some result on the voltage stability via the calculation of singular induced bifurcation. In section 5, we discuss the voltage stability conditions with different type of load characteristics. Section 6 summarizes the results and draws the conclusion.

II. Dynamic Model of Power Systems with OLTC and Nonlinear Load

Consider a power system consists of a generator, a transmission line, an OLTC and a nonlinear static load, as shown in Fig. 1.

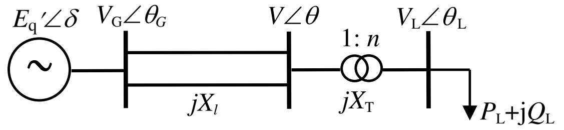

Fig. 1: the configuration of a power system with OLTC and Nonlinear Load

Suppose the OLTC is lossless, the system can be equivalently expressed as Fig. 2.

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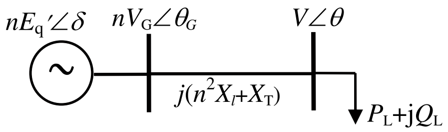

Fig. 2: the simplified configuration of the power system

The dynamic of the generator can be written as

$$\dot{E}_q' = -\frac{x_d}{T_{d0}'x_d'}E_q' + \frac{x_d - x_d'}{T_{d0}x_d'}V_G\cos(\delta_G - \delta) + \frac{1}{T_{d0}'}E_{fd}, \quad (1)$$

The regulation dynamic of the excitation can be expressed as

$$\dot{E}_{fd} = \frac{1}{T}\big(- E_{fd} + E_{fd0} - K(V_G - V_{ref})\big), \quad (2)$$

The power flow equation of the system is

$$0 = \frac{E_q'V_G}{x_d'}\sin(\theta_G - \delta) + \frac{nV_GV}{X}\sin(\theta_G - \theta), \quad (3)$$

$$\begin{aligned} 0 = &\frac{1}{x_d'}\big(V_G^2 - V_GE_q'\cos(\theta_G - \delta)\big) \\ &+\frac{1}{X}\big(n^2V_G^2 - nV_GV\cos(\theta_G - \theta)\big), \end{aligned} \quad (4)$$

$$0 = \frac{1}{X}nV_GV\sin(\theta - \theta_G) + P, \quad (5)$$

$$0 = \frac{1}{X}\big(V^2 - nV_GV\cos(\theta - \theta_G)\big) + Q, \quad (6)$$

where δ is the power angle of the generator; E_q' is the q-axis internal transient voltage of the generator; E_{fd} is the voltage of the field circuit of the generator; V_G is the voltage of the generator terminal bus; x_d' is the d-axis transient reactance of the generator; x_d is the d-axis reactance; T_{d0}' is the d-axis transient open-circuit time constant.

From (5) and (6), we have

$$V_G^2 = \frac{1}{n^2V^2}\big((XP)^2 + (XQ + V^2)^2\big) \quad (7)$$

So (3) and (4) can be simplified as

$$0 = \frac{1}{X'}nE_q'V\sin(\theta - \delta) + P, \quad (8)$$

$$0 = \frac{1}{X'}\big(V^2 - nE_q'V\cos(\theta - \delta)\big) + Q, \quad (9)$$

thus we have

$$E_q'^2 = \frac{1}{n^2V^2}\big((X'P)^2 + (X'Q + V^2)^2\big), \quad (10)$$

$$\begin{aligned} E_q'V_G\cos(\theta_G - \delta) = &\frac{1}{n^2XV^2}(X + n^2x'd)\big((XP)^2 \\ &+(XQ + V^2)^2\big) - \frac{x_d'(XQ + V^2)}{X}, \end{aligned} \quad (11)$$

where $X = n^2X_L + X_T$, $X' = X + n^2x_d'$, x_L is the reactance of the transmission line and x_T is the reactance of the transformers.

According to (7)-(11), the dynamic of the power system can be written as

$$\begin{aligned} \dot{E}_q' = &\frac{1}{T_{d0}'}\Big\{ - \frac{x_d}{x_d'}E_q' + \frac{x_d - x_d'}{x_d'E_q'}\Big[\frac{1}{n^2XV^2}(X + n^2x_d') \\ &\big((XP)^2 + (XQ + V^2)^2\big) - \frac{x_d'(XQ + V^2)}{X}\Big] + E_{fd}\Big\}, \end{aligned} \quad (12)$$

$$\begin{aligned} \dot{E}_{fd} = &\frac{1}{T}\Big[- K\big(\frac{\sqrt{(XP)^2 + (XQ + V^2)^2}}{nV} - V_{ref}\big) \\ &-E_{fd} + E_{fd0}\Big], \end{aligned} \quad (13)$$

$$0 = n^2E_q'^2V^2 - (X'P)^2 - (X'Q + V^2)^2, \quad (14)$$

Above equations do not contain the phase angle and are suitable for the stability analysis.

III. Effect of OLTC on the Maximum Power Transmission of Power System

In this section, we analyze the voltage stability affected by OLTC under different loads from a maximum power transmission aspect.

Rewrite the equation as

$$\Big(\frac{nV_GV}{X}\Big)^2 = P^2 + (Q + \frac{V^2}{X})^2, \quad (15)$$

and we have

$$Q = \sqrt{\Big(\frac{nV_GV}{X}\Big)^2 - P^2} - \frac{V^2}{X}, \quad (16)$$

From above equation, we have the following simulation result:

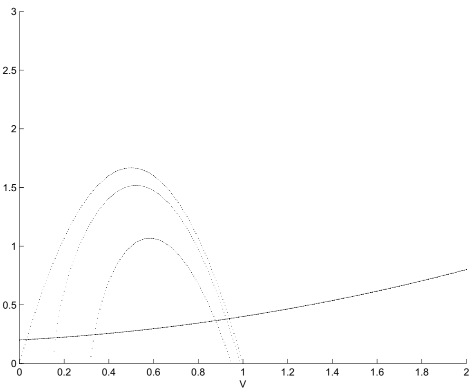

Fig. 3: the QV curve when n=1

From Fig. 3 and Fig. 4 we can see that the maximum reactive power increases when the ratio of OLTC increases. So the possibility of voltage collapse will decrease under the same load command.

Furthermore, solve the following equation

$$\Big(\frac{V^2}{X}\Big)^2 + \Big(2Q - \frac{n^2V_G^2}{X}\Big)\big(\frac{V^2}{X}\big) + \big(P^2 + Q^2\big) = 0. \quad (17)$$

If it has a unique solution, we get the P-Q equation as follows:

$$\Big(2Q - \frac{n^2V_G^2}{X}\Big)^2 - 4\big(P^2 + Q^2\big) = 0. \quad (18)$$

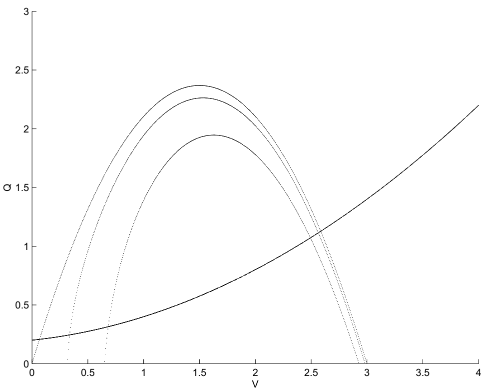

Fig. 4: the QV curve when n=3

or

$$Q = \frac{n^2V_G^2}{4X} - \frac{XP^2}{n^2V_G^2} \tag{19}$$

equivalently. So the maximum of Q is

$$Q_{max} = \frac{n^2V_G^2}{4X} = \frac{n^2V_G^2}{4\big(n^2X_l + X_T\big)}. \tag{20}$$

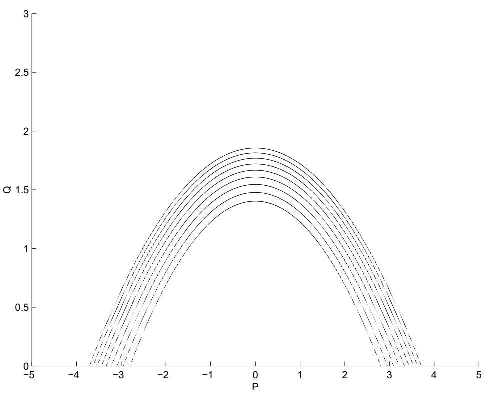

Fig. 5: the QP curve with different tap ratio

Remark 3.1: From equation (16), we have $P \le \frac{V\sqrt{n^2V_G^2 - V^2}}{X} = \frac{V\sqrt{n^2V_G^2 - V^2}}{n^2X_L + X_T}$. So the maximum active power decreases along with the increasing of n.

IV. THE STABILITY ANALYSIS BASED ON THE SINGULAR BIFURCATION

The sufficient condition for the voltage stability is that the voltage at the load bus can be solved from the algebraic equation, that is, the differential algebraic equation of the power system is of index one. If not, the singular induced bifurcation occurs and the system is subject to voltage instability. In this section, we discuss the condition of singular induced bifurcation and get the effect of tap ratio of OLTC on the voltage stability.

First, we assume that the power factor of the load is constant, that is, $P = \eta Q$. Then the algebraic equation (14) can be written as

$$0 = n^2E_q'^2V^2 - (X'\eta Q)^2 - (X'Q + V^2)^2. \tag{21}$$

Let

$$g(E_q', V) = n^2E_q'^2V^2 - (X'\eta Q)^2 - (X'Q + V^2)^2. \tag{22}$$

If there exist a singular induced bifurcation, we have $\frac{\partial g}{\partial V} = 0$, that is, $n^2E_q'^2 = 2(X'Q + V^2)$ and

$$V_s^2 = X'\sqrt{P^2 + Q^2} = X'S = (n^2X_L + X_T + n^2x_d')S, \tag{23}$$

$$E_q'^2 = \frac{1}{n^2}X'(Q+S) = \frac{n^2X_L + X_T + n^2x_d'}{n^2}(Q+S). \tag{24}$$

Noting that for the power systems, the higher voltage usually indicates stable operating point. So if $V^2 > X'S$ or $E_q'^2 > \frac{1}{n^2}X'(Q + S)$, the power system can run safely.

From the inequality condition, we can get the effect of OLTC on the possibility of singular induced bifurcation as follows:

(1) For the load bus, higher tap ratio will increase the critical value of the singular induced bifurcation. Due to the system operates at a higher voltage, the possibility of singular induced bifurcation will increase for the same load condition.

(2) For the internal transient voltage of the generator, we have $\frac{dE_q'^2}{dn} = -\frac{2X_T(Q + S)}{n^3} < 0$, that is, along with the increasing of tap ratio of OLTC, the critical voltage of the singular induced bifurcation of the generator internal voltage will decrease and the possibility of bifurcation will increase.

From above analysis we can see that under the same power transformation, the increasing of tap ratio of OLTC will result higher possibility of singular induced bifurcation and thus has a negative effect on the voltage stability.

V. THE EFFECT OF OLTC ON THE VOLTAGE INSTABILITY UNDER DIFFERENT LOAD MODELS

We have discussed the effect of OLTC on the voltage instability based on the maximum power transmission and singular induced bifurcation. But the condition of voltage instability will directly affected by load characteristics. In this section, we will discuss the effect of OLTC on the voltage instability under different static load models.

A. Constant Power Load

The constant power load consumes constant active power and reactive power, that is, $P = P_0$, $Q = Q_0$. From the algebraic equation, we have

$$\begin{aligned} 0 &= V^4 + 2(X'Q - n^2E_q'^2)V^2 + X'^2(P^2 + Q^2) \\ &= V^4 + 2(X'Q - n^2E_q'^2)V^2 + X'^2S^2, \end{aligned} \tag{25}$$

and so

$$V^2 = \frac{1}{2}\left(n^2E_q'^2 - 2X'Q \pm \sqrt{(2X'Q - n^2E_q'^2)^2 - 4X'^2S^2}\right). \tag{26}$$

Taking into consideration of the higher voltage operating condition, we have

$$V^2 = \frac{1}{2}\left(n^2 E_q'^2 - 2X'Q + \sqrt{(2X'Q - n^2 E_q'^2)^2 - 4X'^2 S^2}\right). \quad (27)$$

If the equation is meaningful, the following inequality must hold

$$E_q'^2 > \frac{2X'(Q+S)}{n^2} = \frac{2(n^2 X_L + X_T + n^2 x_d')(Q+S)}{n^2}. \quad (28)$$

From above inequality, we can see that the internal transient voltage will decrease along with the increasing of the tap ratio. The possibility of voltage collapse will decrease consequently.

B. Constant Current Load

For constant current load, we have $P = bV$ and $Q = aV$, where a and b are reactive and active current respectively. Suppose the active power demand is two times of the reactive power demand, i.e., $b = 2a$, we can get that

$$0 = V^4 + 2(X'aV - n^2 E_q'^2)V^2 + X'^2(4a^2V^2 + a^2V^2), \quad (29)$$

Noting that $V \neq 0$, we have

$$0 = V^2 + 2X'aV - n^2 E_q'^2 + 5a^2 X'^2. \quad (30)$$

The equation has a solution

$$V = -aX' + \sqrt{2(n^2 E_q'^2 - 4a^2 X'^2)} \quad (31)$$

if the following inequality holds

$$\begin{aligned} E_q' > \frac{2aX'}{n^2} &= \frac{2a(n^2 X_L + X_T + n^2 x_d')}{n^2} \\ &= 2a(X_L + x_d') + \frac{2aX_T}{n^2} \end{aligned} \quad (32)$$

From the inequality we can see that the internal transient voltage will decrease along with the increasing of tap ratio. The possibility of voltage collapse will decrease under the higher voltage operating condition.

C. Constant Impedance Load

For constant impedance load, we have $P = GV^2$ and $Q = BV^2$. So

$$0 = V^4 + 2(X'BV^2 - n^2 E_q'^2)V^2 + X'^2 V^4(G^2 + B^2), \quad (33)$$

or

$$0 = (1 + 2X'B + X'Z^2)V^2 - n^2 E_q'^2 \quad (34)$$

equivalently, where $Z^2 = G^2 + B^2$. Solving the equation we get that

$$V = \frac{nE_q'}{\sqrt{1 + 2X'B + X'Z^2}}. \quad (35)$$

So there is no singular induced bifurcation and power system will not to voltage collapse due to the singularity of algebraic equation.

D. Constant Exponential Load

For the constant exponential load, we have $P = aV^\alpha$ and $Q = bV^\beta$. Due to the complexity of the load characteristic, there is no explicit solution of the algebraic equation. Noting that the constant exponential load can be approximately written as

$$\begin{cases} P = P_0 + LV + GV^2, \\ Q = Q_0 + HV + BV^2, \end{cases} \quad (36)$$

the analysis of the voltage instability resulted from the singular induced bifurcation under constant exponential load can be transformed to the combination of constant power load, constant current load and constant impedance load.

VI. Conclusion

In this paper we discuss the effect of OLTC on the voltage stability via the calculation of the maximum power transmission. It is shown that the maximum reactive power increases when the ratio of OLTC increases and the possibility of voltage collapse will be decrease under the same load command. We also get some results on the voltage stability of the power system with OLTC from a singular induced bifurcation point of view. Finally, noticing that the voltage instability will directly affected by load characteristics, we discuss the effect of OLTC on the voltage instability under different static load models. In the further researches, we will analysis the voltage stability of power system with OLTC and dynamic loads.

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