REVERSE ACTION OF ON-LOAD TAP-CHANGER TRANSFORMER

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ABSTRACT

In this paper expression is derived that shows the condition for instability of on-load tap-changer (OLTC) transformer controlling the voltage of an impedance load. Use of sensitivity and eigenvalue analysis to predict voltage collapse is discussed.

INTRODUCTION

Due to the interconnection of large power systems and the increase of EHV transmission lines for large amount of power transmission, reactive power losses in power systems have greatly increased.

This results in reducing the system voltage. Besides this, high load demands and transmission losses may cause the system voltage to drop below the nominal value. Control devices such as on-load tap-changer transformers, shunt capacitors, synchronous condensors and static var compensators can be adjusted or switched on to restore the system voltage. However, the control devices do not always operate as expected. Under some adverse operating conditions, control devices may aggravate the low voltage profile, causing voltage collapse.

In Power Systems it is a common practice to control the magnitude of voltage at buses which are connected to large amount of loads using on-load tap changer transformers. However, in a highly stressed (highly loaded) power system, it has been observed that raising the turns ratio in order to increase the bus voltage results in a decrease of voltage at the bus. This de-stabilizing effect is called reverse action of on-load tap-changer and is one of the mechanisms responsible for voltage collapse of power systems.

In [1], Sekine et al examined reverse action of on-load tap changer transformers for both static and dynamic loads. For the former case, they used resistive load R connected to a constant voltage source through a reactance and an on-load tap-changer transformer. The turn ratio n of the on-load tap changer transformer is assumed to vary stepwise.

They concluded that for resistive load reverse action occurs if the value of n is such that n^2x is greater than the load resistor R, where x is the sum of the reactance of the transmission line and the ideal transformer.

For dynamic simulation of reverse action of tap changer transformer, they used induction motor as load with slip dynamics. They concluded that reverse action caused by the tap changer occurs when the initial operating point lies in the lower part of the PV curve. They also claimed that, in actual power systems, the operating point is able to lie in the lower voltage region (lower part of the PV curve) only during transient period.

They also showed that if the operating point lies in the higher voltage region near the critical point of voltage collapse, reverse action occurs if the tap position is stepwise raised from 1.0 to 1.24. However, if the tap- position is gradually raised, reverse action does not occur even if the tap position exceeds 1.24.

In [2], C. C. Liu et al derived the condition for instability for an impedance load fed from a constant voltage source via a reactance and on load tap changer transformer. For big system, they assumed that the resistances of transmission lines are negligible and that the bus angle difference between two buses of each line is small. Based on these assumptions, they represented the power system by the de-coupled load flow equation. Generators are modeled by constant voltage sources. For loads they assumed that the reactive power demand is a function of the secondary voltage of the on-load tap changer transformer. The dynamics of the on-load tap changers is assumed to be governed by a first-order differential equation. To analyze the steady state stability of the power system, they suggested that the equations be linearized around an operating point and eigenvalue analysis be used.

The authors have used the singular perturbation theory to study and classify possible voltage instability mechanisms.

The power system has been divided into slow and fast subsystems by taking into account the dynamic responses of the power system constituent factors. It has been suggested in these studies that the stability of slow and fast dynamics should be treated separately and that the stability region should be determined as the intersection of the slow and fast stability regions.

In [3], Yorino et al applied the singular perturbation theory to analyze the performance of OLTC transformer. They classified analysis of OLTC in the slow subsystem where the fast dynamic variables, such as generators and loads are treated as static algebraic equations. To perform the analysis using the singular perturbation theory, they made the following assumptions:

1. Only tap-changer dynamics are considered as slow dynamics, while the other slow dynamics such as load frequency characteristics are neglected.

2. As static characteristics of the generating units, a constant terminal voltage within a limited var generation is assumed. Further the following type of load characteristics are used:

$$P_i = P_{oi} V_i^{\alpha}, \quad Q_i = Q_{oi} V_i^{\beta},$$

where α and β are constants.

They pointed out that because the load rate of change is comparable to the response of the tap-changers in actual situations, instability could occur if the movement of tap-changers fails to follow the moving equilibrium point which can escape from its stability regions resulting in voltage collapse.

Using constant load characteristics and the systems PV curves, they showed that at light load, the operating point lies on the upper portion of the PV curve and the voltage increases as the tap-ratio is increased. On the other hand, at heavy load, the operating point moves to the lower part of the PV curve and the voltage decreases when the tap-ratio is increased.

Single Machine Impedance Load

In Fig.1 an impedance load Z_L is supplied by a generator modeled as a constant voltage source E_S through a transmission line with impedance Z_T and an on-load tap changer. The on-load tap changer is used to regulate the magnitude of the load voltage V_L.

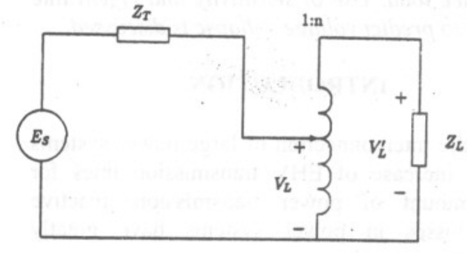

Figure 1

The load voltage V_L referred to the source side is given by

$$V_L = E_S - \frac{E_S Z_T}{Z_T + Z_L / n^2}$$

$$= E_S - \frac{E_S Z_T n^2}{n^2 Z_T + Z_L}$$

The load voltage referred to the load side is V_L' and is given by

$$V_L' = n\left(E_S - \frac{E_S Z_T n^2}{n^2 Z_T + Z_L}\right)$$

$$= nE_S - \frac{E_S Z_T n^3}{n^2 Z_T + Z_L}$$

The rate of change of load voltage with respect to the tap-ratio n is given by

$$\frac{\partial V_L'}{\partial n} = E_S - \frac{[(n^2 Z_T + Z_L)(3n^2 E_S Z_T) - E_S Z_T n^3 (2nZ_T)]}{(n^2 Z_T + Z_L)^2}$$

$$\frac{\partial V_L'}{\partial n} = \frac{E_S Z_L^2 - n^2 E_S Z_T Z_L}{(n^2 Z_T + Z_L)^2}$$

For reverse action to be observed, i.e. for load voltage to decrease as the tap-ratio n is increased $\partial V' / \partial n$ should be less than zero.

$$\frac{E_S Z_L^2 - n^2 E_s Z_T Z_L}{(n^2 Z_T + Z_L^2)^2} < 0$$

i.e.

$$E_S Z_L^2 - n^2 E_S Z_T Z_L < 0$$

For E_S and Z_L positive,

$$Z_L - n^2 Z_T < 0,$$

$$or,$$

$$Z_L < n^2 Z_T$$

Thus, for impedance load reverse action of on-load tap-changer takes place only if the load impedance is less than the impedance of the system referred to the load side. This is shown in Fig. 2, where load voltage vs reactive power is shown for different value of tap-ratio n. In Fig. , 2, $Z_T = j0.6\Omega$ and V_L is observed for $Z_L = j0.9\Omega$. V_L is in the upper part of $Q - V$ curve for n=1.0, 1.1, and 1.2, but is in the lower part of $Q - V$ curve for n= 1.3, 1.4 and 1.5. Reverse action is seen as n is changed from 1.2 to 1.3.

From the figure it is seen that reverse action takes place only in the lower part of the $P - V\ (Q - V)$ curve. Thus for impedance load, normal operation is observed on the upper part of the $P - V\,(Q - V)$ curve and no-reverse action takes place.

In Fig. 1, suppose the load voltage is lower than the specified value and the tap-ratio n is increased to raise the load voltage. For $\Delta n > 0$, the load voltage can be restored to the specified value if and only if $\Delta V_L' > 0$. But for $\Delta n > 0$, if $\Delta V_L' < 0$, then the load voltage will further be reduced and as a result voltage instability will occur.

When the tap-ratio n is increased from n_1 to n_2 such that $n_2 - n_1 > 0$, the change in the load voltage $\Delta V_L'$ depends on two factors:

1. For a fixed source side load voltage V_L, the load voltage V_L' tends to increase for $\Delta n > 0$.
2. For $\Delta n > 0$, the load impedance referred to the source side of the on-load tap changer decreases, and this increases the source side current I_L. This in turn increases the voltage drop on the transmission line impedance thereby decreasing the load voltage on the source side of the on-load tap changer. Thus this lowers the load voltage V_L'.

From these two factors, it is seen that reverse action of on-load tap changer occurs when the second factor dominates the first one.

For constant power load on the single machine system reverse action has not been observed on the upper part of the $P - V$ curve. In a large power system, (a 39 bus, 10 machine system shown in Figure 3 was considered by the author) reverse action is observed in the upper part of the $P - V$ curve.

Reverse action in large power system is observed when the system is highly stressed.

A transformer is introduced between Bus 21 and Bus 22 and the load at bus 21 is increased (to 8.45 times the nominal value) till the system is highly stressed. Reverse action occurred when n is increased from 1.33 to 1.34 thereby decreasing the voltage at Bus 21 from 0.7916 to 0.7914. Increasing n, the tap-ratio, beyond 1.34 results in further decrease in the magnitude of the voltage at Bus 21.

The value of n at which reverse action takes place depends on the stress at which the system is subjected to and the particular bus at which the tap-ratio is increased. Reverse action was observed at Bus 8 at a lower value of n (i.e. between 1.2 and 1.3). Similarly a transformer was introduced between Bus 15 and Bus 16 and the load at bus 15 was increased to 6.7 times the base load. Reverse action is observed as n is changed from 1.25 to 1.26. With the tap-ratio between Bus 15 and Bus 16 equal to 1.28, reverse action on Bus 21 is observed when the tap-ratio n between Bus 21 and Bus 22 is equal to 1.13.

Sensitivity and Eigenvalue Analysis

Consider the following system of equations:

$$f(\theta, V_L, V_G, n) = P_L - P_G \quad (1)$$

$$g(\theta, V_L, V_G, n) = Q_L - Q_G \quad (2)$$

where, V_L and V_G are the magnitude of voltages at the load and generator buses, respectively, θ angle of the voltages at the buses, n transformer tap-ratio, P_L, Q_L active and reactive power load at the load (PQ) buses and P_G, Q_G active and reactive power generated at the generator (PV) buses.

For constant active and reactive power load P_L and Q_L and constant generator terminal voltage V_G,

$$\frac{\partial f}{\partial \theta}\Delta\theta + \frac{\partial f}{\partial V_L}\Delta V_L + \frac{\partial f}{\partial n}\Delta n = -\Delta P_G \quad (3)$$

$$\frac{\partial g}{\partial \theta}\Delta\theta + \frac{\partial g}{\partial V_L}\Delta V_L + \frac{\partial g}{\partial n}\Delta n = -\Delta Q_G \quad (4)$$

In normal load flow equations, the generated power at the generator (PV) buses are specified and hence are constant. In equation (3), $\Delta P_G \neq 0$ only for the swing bus. ΔQ_G may be different from zero for all generator buses. However, equation (1) is not written for the swing bus and equation (2) is not written for all PV buses in the loadflow equations.

Thus $\Delta P_G = \Delta Q_G = 0$ in the above equations. Hence,

$$\frac{\partial f}{d\theta}\Delta\theta + \frac{\partial f}{\partial V_L}\Delta V_L = -\frac{\partial f}{\partial n}\Delta n \quad (5)$$

$$\frac{\partial g}{\partial \theta}\Delta\theta + \frac{\partial g}{\partial V_L}\Delta V_L = -\frac{\partial g}{\partial n}\Delta n \quad (6)$$

which in matrix notation becomes

$$\begin{bmatrix} \frac{\partial f}{\partial \theta} & \frac{\partial f}{\partial V_L} \\ \frac{\partial g}{\partial \theta} & \frac{\partial g}{\partial V_L} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V_L \end{bmatrix} = -\begin{bmatrix} \frac{\partial f}{\partial n} \\ \frac{\partial g}{\partial n} \end{bmatrix}\Delta n \quad (7)$$

with the solution

$$\begin{bmatrix} \Delta\theta \\ \Delta V_L \end{bmatrix} = -\begin{bmatrix} \frac{\partial f}{\partial \theta} & \frac{\partial f}{\partial V_L} \\ \frac{\partial g}{\partial \theta} & \frac{\partial g}{\partial V_L} \end{bmatrix}^{-1} \begin{bmatrix} \frac{\partial f}{\partial n} \\ \frac{\partial g}{\partial n} \end{bmatrix}\Delta n \quad (8)$$

so that

$$\begin{bmatrix} H_1 \\ H_2 \end{bmatrix} = -\begin{bmatrix} \frac{\partial f}{\partial \theta} & \frac{\partial f}{\partial V_L} \\ \frac{\partial g}{\partial \theta} & \frac{\partial g}{\partial V_L} \end{bmatrix}^{-1} \begin{bmatrix} \frac{\partial f}{\partial n} \\ \frac{\partial g}{\partial n} \end{bmatrix} \quad (9)$$

where

$$\Delta V_L = H_2 \Delta n \quad \text{and} \quad (10)$$

$$\Delta\theta = H_1 \Delta n \quad (11)$$

The dynamics of the on-load tap-changer is modeled by a first-order differential equation

$$\frac{dn}{dt} = \frac{1}{T}(V_{ref} - V_L) \quad (12)$$

where, n is the turn-ratio of the on-load tap-changer, V_{ref} is the constant voltage at which the load bus is regulated, and T is the time constant. The differential change in $\frac{dn}{dt}$ becomes, given the constancy of V_{ref},

$$\Delta \dot{n} = -\frac{1}{T}\Delta V_L$$

Substituting for ΔV_L gives

$$\Delta \dot{n} = -\frac{1}{T} H_2 \Delta n \quad (13)$$

Hence, if H_2 is positive, the system is stable and if negative it is unstable.

Using the sensitivity matrix H_2, it is possible to predict whether there will be reverse action or not for raising the tap-ratio n at a given on-load tap-changer.

For small value of H_2, the increase in voltage (for negative value of H_2) or the decrease in voltage (for positive value of H_2) might be zero. But however small H_2 is, a decrease in voltage for negative value of H_2 and an increase in voltage for positive value of H_2 is not observed. Hence H_2 is a good way of predicting whether there will be reverse action or not for raising the tap-ratio at a given load bus when the load bus voltage is lower than the specified reference voltage.

System with a Single Tap-changing Transformer

H_2 was calculated for the stressed power system which has on-load tap changer between bus 21 and bus 22. Initially, when the system is not stressed, H_2 is negative for all buses and the voltage at the buses either increased or remained constant when n is increased from the nominal value. But when $n = 1.3$, H_2 is positive for all buses except for bus 21 which is –0.011. And when n is increased to 1.31, the voltage at bus 21 is increased from 0.7915 to 0.7916. The voltage in all the other buses either decreased or remained the same. When $n = 1.33$, H_2 is positive for all the buses and when n is increased to 1.34, the voltage at bus 21 decreased from 0.7916 to 0.7914. All the other bus voltages also decreased.

Similarly, H_2 was calculated for a stressed system, which has on-load tap-changer between bus 15 and bus 16. At $n = 1.2$, H_2 is positive for all the buses except bus 15 which is –0.0711. When n is increased to 1.21, the voltage at bus 15 increased from 0.7260 to 0.7269. All the other bus voltages either decreased or remained the same. For $n = 1.25$, H_2 is positive for all the buses and when n is increased to 1.26, all the bus voltages decreased in magnitude.

System with Two Tap Changers

When there are more than one on-load transformer tap-changers as is usually the case in a power system, the voltage at any load bus depends on the resultant effect from the individual tap-changers. It is found that, if the row sum of H_2 at a particular bus is negative, the voltage at the bus either increases or remains the same when the turns-ratios of the on-load tap changers are increased in response to a decrease of the magnitudes of the voltages at the load buses below the specified values.

Similarly if the row sum of H_2 is positive, the voltage at the bus either decreases or remains the same.

Thus the row sum of the H matrix enables us to predict an increase or decrease of voltage at a given load bus when the turns ratio of the on-load tap changers are increased.

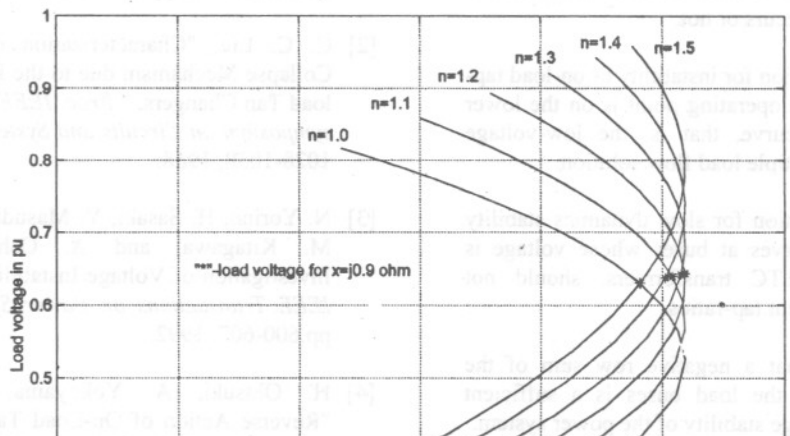

Figure 2

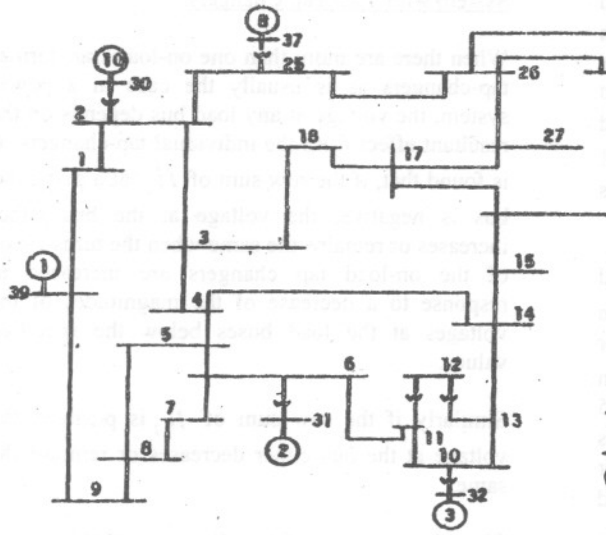

Figure 3.

CONCLUSION

The rate at which the tap position is increased is an important factor in whether reverse action of on-load tap changer occurs or not.

A necessary condition for instability of on-load tap-changer is that the operating point is on the lower part of the PV curve, that is, the low-voltage solution of the multiple load flow solution.

A necessary condition for slow dynamics stability is that the PV curves at buses whose voltage is controlled by OLTC transformers, should not intersect for different tap-ratios.

It is concluded that a negative row sum of the H matrix for all the load buses is a sufficient condition for voltage stability of the power system.

It may not always be possible to control the voltage at a load bus using control devices. On-load tap changer transformers may show reverse action, i.e., reduce the magnitude of the load voltage that was intended to be increased by increasing the transformer tap-ratio. Thus in a stressed power system, the operation of the on-load tap changer may have to be blocked in order to prevent reverse action operation.

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