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Observing Chaotic Oscillations Induced by under Load Tap Changer in Power Systems

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Abstract: Power transfer margins are studied with Under Load Tap Changing (ULTC) transformers based on both static and dynamic analysis. The P-V Curve, Q-V Curve, have been widely used to analyze power system behaviors under varying loading conditions. Voltage stability analysis and loadability analysis are examples of the application of these curves in power system analysis. Voltage stability of a power system is related to load characteristics and voltage control devices such as (ULTC) transformers .The regulation of a sample power system's voltage has adopted automatic ULTC operation in order to maintain a constant voltage level. Dynamic behaviors of major power system components, i.e., different loads, ULTC and mechanically switched shunt capacitor *et al.*, are thoroughly examined by a small yet typical equivalent system. In this paper, the effects of distribution ULTCs are investigated by both static and dynamic analysis. In dynamic analysis, both the ULTC and the load are considered as dynamic devices. The load is modeled as a generic dynamic load model. The ULTC is modeled as continuous dynamic model. Time constants of loads and ULTCs are key factors that affect voltage stability. The effects on system behavior of tap dynamics modeling are illustrated. This study discusses effect of the Under Load Tap Changing transformers (ULTCs) on voltage stability and identifying critical ULTCs to avoid possibilities of voltage instability conditions. This research is intended to decide with simulations results as a first step before tackling under real load case. It is intended as an aid for power systems engineers to get acquainted with the dynamics of voltage collapse for the tap changer. Because of it's simplicity, a detailed mathematical model can easily be derived.

Key words: Power loads, load characteristic, ULTC, voltage stability, voltage collapse, limit cycle

INTRODUCTION

The voltage stability problem has become a major concern in operating and planning today's power system as a result of heavier loading conditions, without sufficient transmission and/or generation enhancements Voltage stability problems normally occur in heavily stressed systems. While the disturbance leading to Voltage collapse may be initiated by a variety of causes, the underlying problem is an inherent weakness in the power system. The factors contributing to Voltage collapse are the generator reactive power voltage control limits, load characteristics, characteristics of reactive compensation devices and the action of the voltage control devices such as (ULTCs) (Thukaram *et al.*, 2004).

The under load tap changer (ULTC) an important voltage regulation device automatically adjusts its turns ratio in order to keep the load side voltage within an acceptable range. The time constants of ULTCs are usually between 20s and 100s and therefore can be considered to be a slow dynamic device. In transient stability analysis, the dynamics of the ULTC can be neglected and its turn's ratio assumed to be constant. However, a mid-term voltage instability incident leading toward voltage collapse is often a slow, gradual process (Dong *et al.*, 2004). ULTCs have been shown to play an important role in long term voltage collapse, since they aim to keep load voltages and therefore the load power constant even though transmission system voltages may be reduced. Considerable effort has been given to voltage collapse are closely linked to dynamic interaction between dynamics of voltage collapse are closely linked to dynamic interaction between the ULTCs and loads. It led to significant progress in the area of dynamic load modeling (Larsson, 2000). The increase of power demand at a higher rate than the expansion of generation and transmission facilities has resulted in power systems functioning closer to their operational and physical limits. In heavily loaded systems, voltage profile in the transmission systems is often maintained by generator

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reactive power injection or by adjusting the tap ratio of load tap changing transformers (Roman, 2006). Many papers analyze tap changer behavior at distribution points, where the interaction between the load and the system characteristics can lead to voltage collapse (Vu, 1992; Venkatasubramanian, 2000; Popovic, 1996). Zhu (2000) and Vournas (2002) use static analysis to show the ULTC's effect on the increase of maximum power transfer and its impact on system stability.

It is well known that the operation of the ULTC has a significant influence on mid-term voltage instability (Dong *et al*., 2004). In (Van Cutsem, 1998), a stability region around the equilibrium point is constructed. In (Vu, 1992), the mechanisms of voltage collapse have been studied by considering a dynamic load characteristic as well as ULTC dynamics. In both references (Vu, 1992; Van Cutsem, 199), the voltage V at the load bus is considered as a state variable in the load model. Voltage stability of a power system is related to load characteristics and voltage control devices such as ULTC transformers.

The main focus of these studies which mainly relate to voltage stability questions has been of understanding of the complex dynamic nature of voltage collapse to which ULTC dynamics significantly contributes This study investigates the ULTC's effect on dynamic loads and attempts to underscore some of the discrepancies with static analysis results. Voltage instability in a system leads to a loss of post-disturbance equilibrium. Extending the power transfer capability helps to make the system re-enter a reasonable post-disturbance operating condition. We use static analysis to show the ULTC's effect on the increase of maximum power transfer and its impact on system stability. However, voltage stability is a dynamic phenomenon and analysis based on static modeling is not sufficient and usually leads to erroneous results. In the third section of this paper, the effect of the ULTC on dynamic analysis is theoretically studied for a simple test system. This paper further explores the oscillatory behavior of power supply systems with emphasis on illustrating interactions between ULTC and load dynamics. These oscillatory behavior curves serve their purpose well on the conservative side in predicting several system limits such as voltage stability limit or loadability limit. Load models are known to have profound impacts on power system behaviors.

Static voltage stability analysis:
Static load model:
Voltage-sensitive loads can be modeled as:

$$P = P_0 \left(\frac{V}{V_0}\right)^{\alpha} \tag{1}$$

$$Q = Q_0 \left(\frac{V}{V_0}\right)^{\beta} \tag{2}$$

Where P_0 is the real power at V_0, Q_0 is the reactive power at V_0, V is the bus voltage magnitude, α is the voltage sensitivity exponent of the real power, β is the voltage sensitivity exponent of the reactive power. If $\alpha = 0$, $\beta = 0$, then the load model essentially represents a constant power type load; if $\alpha = 1$, $\beta = 1$, the load model becomes a constant current type and if $\alpha = 2$, $\beta = 2$, then it becomes a constant impedance type load. An ULTC can automatically adjust and keep the load-side bus voltage constant given that enough buck or boost taps exist (Van Cutsem, 1998).

Two bus sample system: A simple two bus example system considering static analysis is shown in Fig. 1. Where X = 0.5 p.u and B_l= 0.01 p.u are reactance and shunt capacity of transmission line, respectively. The load power demand is $P_d + jQ_d$. For the sake of simplicity but without loss of generality, the resistance of the transmission line is neglected; i.e.V_1 and V_2 are voltage values of generator and load bus, respectively.

Active and reactive power values fed from buses using load flow equations are given Eq. 3-5

$$\delta = \delta_1 - \delta_2,\ \zeta = 1 - \frac{XB_l}{2},\ \xi = 1 - \frac{XB_l}{4},$$

$$P_G = \frac{B_l \xi X + \zeta^2}{a^2 X_t \zeta + X} a V_1 V_2 \sin\delta \tag{3}$$

$$P_G = \frac{1}{a^2 X_t \zeta + X} a V_1 V_2 \sin\delta \tag{4}$$

$$Q_L = \frac{a V_1 V_2 \cos\delta - V_2^2 a^2 \zeta}{a^2 X_t \zeta + X} \tag{5}$$

Where a and X_t= 0.1 p.u are tap rate and leakage reactance of ULTC, respectively. Figure 2 shows the extended maximum power transfer (knee points on the PV curves) by the increased tap ratio settings. All three curves, showing voltage at bus 2 versus power transfer, are with unity power factor load at bus 2. Based on the above analysis, one can conclude that if the improvement of the power transfer capability due to ULTC operation is more than the increase in the load, then there exists an equilibrium point and the system can maintain stability. This phenomenon has potentially beneficial effects on static voltage stability of the system.

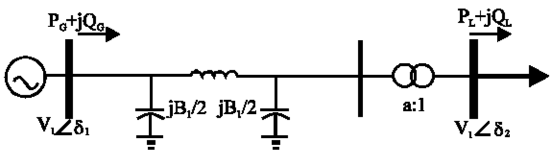

Fig. 1: A simple two bus example system

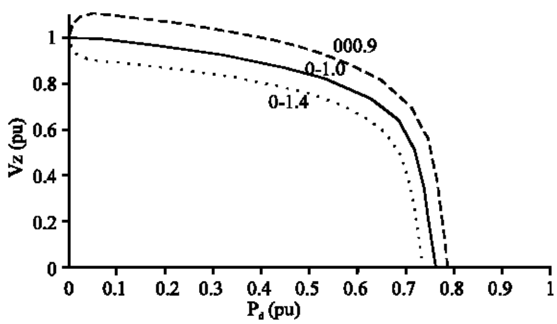

Fig. 2: PV curves with ULTC of bus 2

The effect of shunt capacity B_1: Here, the effects of voltage stability of various B_1 values stated in Eq. (4) are examined. In order to this analysis, the best suitable method is to obtain PV curves. In this analysis, tap rate and initial condition of ULTC are taken as 1.0 and 0.01 p.u., respectively. In PV curves pictured in Fig. 3, with discrete and points curves are to belong to values of 0.009 p.u. and 0,011 p.u. of B_1, respectively. Increasing of B_1 has affected to improve of voltage stability as positive direction.

Dynamic analysis: The ULTC is beneficial in extending the power transfer capability and thus increasing the static stability margin. However, the margin obtained by the static method is rather optimistic. In general, the voltage stability problem involves complex dynamic phenomena. A common situation that is often encountered is that the system can collapse after a disturbance even if a post disturbance equilibrium point exists. In such cases, detailed dynamic models need to be used to analyze system stability.

Power system model: The simple two bus system of show in Fig. 1. The p.u dynamic equations that represent this system, using a basic dynamic generator model, a frequency and voltage dependent dynamic model for the load, are given by

$$\dot{\omega} = \frac{1}{M}(P_M - P_G - D_G\omega) \tag{6}$$

$$\dot{\delta} = \omega \tag{7}$$

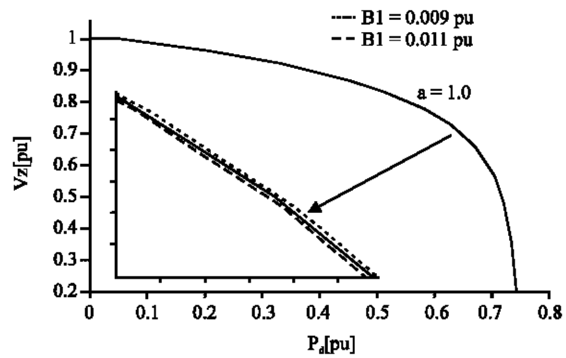

Fig. 3: Curves with ULTC in different B_1 values

$$\dot{V}_2 = \frac{1}{\tau}(Q_L - Q_D) \tag{8}$$

where δ is the generator rotor angle, ω the generator angular speed, M the generator inertia constant, P_M the mechanical power of prime mover, D_G the generator damping, τ the voltage time constant of the dynamic-load and V_2 the bus voltage of the dynamic-load. The load power demand is $P_d + jQ_d$. $P_M = P_d$ (Canizares, 1995). Furthermore, it is assumed that the load, in steady-state conditions, has a constant power factor, i.e., $Q_d = kP_d$, where k is a given constant. The active power demand P_d of the dynamic load is the parameter that can be varied, All other system parameters are as follows; M= 0.9 s, D_G= 0.1, k = 0.3 and τ = 2 s.

Generic dynamic load model: The typical load-voltage response characteristics can be modeled by a generic dynamic load model proposed in Fig. 4.

In this model, x is the state variable. $P_t(V)$ and $P_s(V)$ are the transient and steady-state load characteristics respectively and can be expressed as,

$$P_t = V^{\alpha_t} \text{ or } P_t = c_2V^2 + c_1V + c_0 \tag{9}$$

$$P_s = P_0V^{\alpha_s} \text{ or } P_s = P_0(d_2V^2 + d_1V + d_0) \tag{10}$$

Where V is the per-unit magnitude of the voltage imposed on the load. It can be seen that, at steady-state, state variable x of the model is constant. The input to the integration block, $e = P_s - P_d$ must be zero and, as a result, the model output is determined by the steady-state characteristics $P_s = P_d$. For any sudden voltage change, x maintains its predisturbance value initially. Because the integration block cannot change its output instantaneously. The transient output is then determined

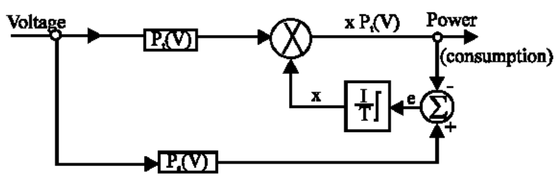

Fig. 4: A generic dynamic load model

by the transient characteristics $P_d = xP_t$. The mismatch between the model output and the steady-state load demand is the error signal e. This signal is fed back to the integration block that gradually changes the state variable x. This process continues until a new steady-state (e = 0) is reached. Analytical expressions of the load model including real (P_d) and reactive (Q_d) power dynamics are,

$$T_p \frac{dx}{dt} = P_s(V) - P_d, P_d = xP_t(V) \tag{11}$$

$$T_q \frac{dy}{dt} = Q_s(V) - Q_d, Q_d = yP_t(V) \tag{12}$$

$$P_t(V) = V^{\alpha_t}, P_s(V) = P_0 V^{\alpha_s};$$

$$Q_t(V) = Q^{\beta_t}, Q_s(V) = Q_0 V^{\beta_s}$$

Typical load parameters are α_t = 0.72~1.30, β_t = 2.96~4.38 for residential load; α_t = 0.99~1.51, βt = 3.15~3.95 for commercial load and α_t = 0.18, β_t = 6.0 for industrial load. The steady-state load parameters and load time constant depend strongly on the voltage level at which the load is aggregated. Since the downstream ULTC's play a very important role. To authors knowledge, no data has been fully documented and α_s = 0, β_s = 0 are commonly used (Xu and Marisour, 1994).

Continuous ULTC model: The continuous ULTC model is based on the assumption of a continuously changing tap a (t), which can take all real values between a^{min} and a^{max}. Usually the effect of the dead band is neglected in a continuous ULTC model, so that the following differential equation results,

$$\dot{a} = \frac{1}{T_C}(V_2 - V_2^0) \qquad a^{min} \leq a \leq a^{max} \tag{13}$$

Where V^0_2 is the reference voltage and T_c is the time constant and taken 120 s as simulation time. The ULTC is modeled as an integral controller using Eq. (13).

Simulations: In the Fig. 1, that load bus has dynamic load is admitted. Generic dynamic load is used as load model. It is analyzed though being three type loads as residential, commercial and industrial load. Typical parameters commercial and industrial load. Typical parameters

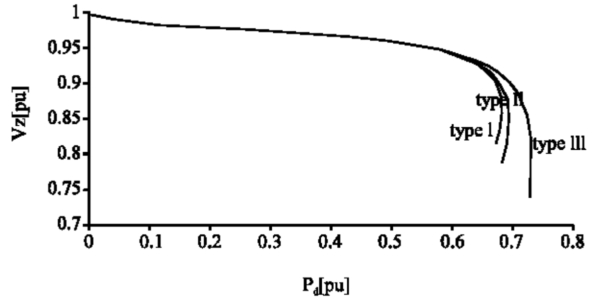

Fig. 5: PV curves for different load types

in order to each load are chosen as following; αt = 0.75, βt = 3.0 for residential load (Type I), αt = 1.25, βt = 3.75 for commercial load (Type II) and αt = 0.18, βt = 6.0 for industriaload (Type III). α_s and β_s are taken as zero for all loads.

PV curves attained each load type are shown in Fig. 5. It can be observed that the system has led toward unstable at P_d = 0.6 p.u. As from this point, the curves obviously have bifurcated. That parameter β_t is bigger with respect to other load types are delayed collapse time. This result with respect to being stable state again at heavy loading conditions of post disturbance of system is very important. The simulations obtained the relation to this results are shown in Fig. 6 (a, b). In this stable system having to P_o = 0.6 p.u and Q_o = 0.2 p.u values, the load at t = 500 s is supposed to increase P_o = 0.7 p.u as disturbance effect. The same ratio increasing is also validity the reactive power. The disturbance effect has been applied to each three load types are shown to return to initial operation point at t = 750 s. The post disturbance, the voltage of load bus has begun to step down. Thus, according to Eq. (12), Q_s (V)-yQ^{β}_t is bigger than the zero. This difference is bigger at Type I having the smallest β_t parameters. Thus, deficit of reactive power of load bus is getting more increasing. In case of this increasing has trigger to collapse, so the collapse time of Type I have accelerated. After the disturbance is cleaned, in order to being a stable state of the system that the difference $Q_s(V)$ and yQ^{β}_t has converged to zero has required. It is said that Type III having more big β_t value is being to stable state more fast with respect to the other load types. In order to each three load types, the state space trajectories for Type II and Type III are stable, for also Type I is unstable (Fig. 6a). The state space trajectory for state t= 0s are shown in Fg. 6b. Since the load voltage is below from V^0_2, the transformers begin to step down its tap ratio.

The effect of T_c: The stability analysis in order to two different values of T_c parameter in ULTC model given Eq. (13) is arranged and plotted to phase portraits as shown in Fig. 7a-c, also the curves attained from changing voltage and angle as shown in Fig. 7b and d. The system

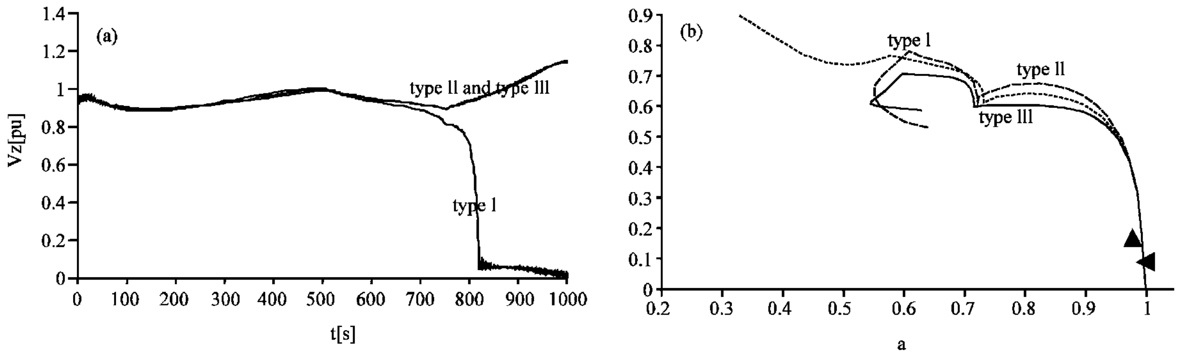

Fig. 6: In during disturbance and post disturbance of each load types (a) The change of between voltage and time, (b) The state space trajectory

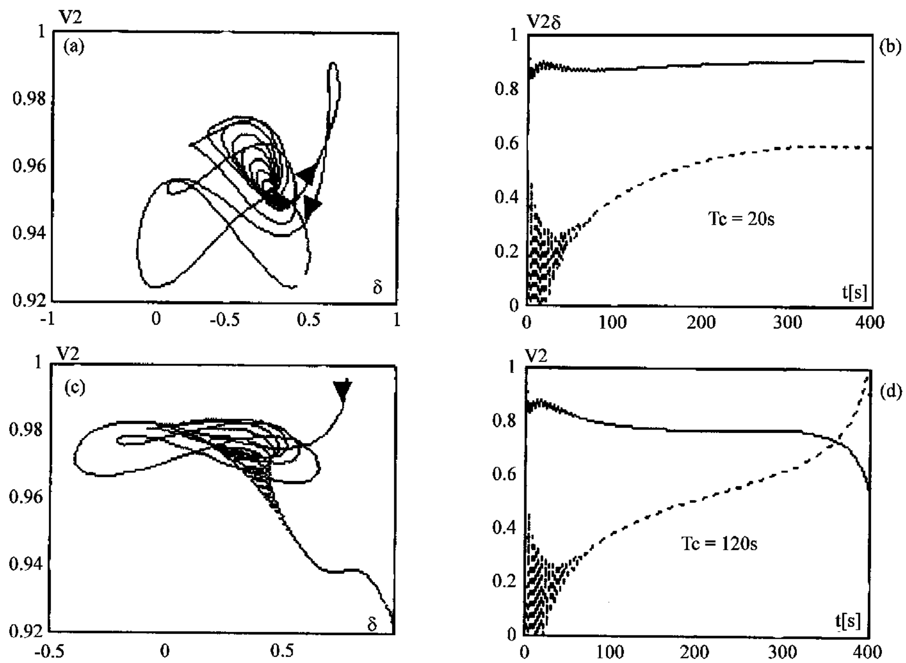

Fig. 7: Phase portraits for Type I (a),(b) Time series and V-δ phase plane for T_c = 20s, respectively, (c),(d) Time series and V-δ phase plane for T_c = 120s, respectively, (V ———, δ ---------)

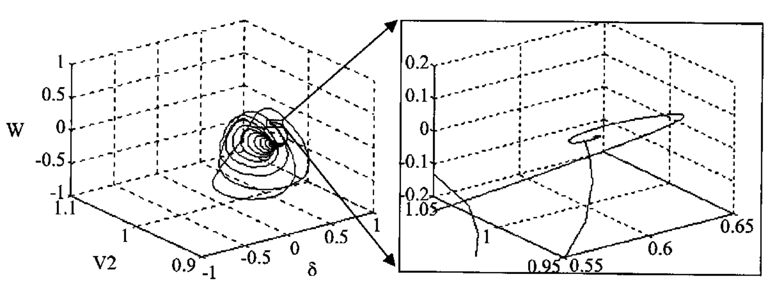

Fig. 8: Stable limit cycle behavior of ULTC after the transient chaos

loaded at a value close to the collapse point is observed to being stable, when the parameter T_c is chosen as at interval 0-20s. If parameter T_c is chosen upper than this interval, the system has been unstable as shown in Fig. 7d.

The system has converged to stable operating point with damped transient oscillation as shown in Fig. 8. When δ_0 is equal to 0.6. After the oscillation damped, while the system is getting to stable state, δ and ω values try to return their initial points. The system has been stable limit cycle, due to tap changer of ULTC.

CONCLUSION

An electrical power system consists of many loads that have different characteristics. Load characteristics are known to have a significant effect voltage dynamics. Voltage stability depends on the details particularly the load characteristics. It is very important have to know characteristics of loads and behaviors in the voltage stability. The energy quality is usually broken down by nonlinear loads. In this study investigated effect different loads those voltage stability behaviors of against voltage changes. In this paper, the results of a static analysis show that ULTCs can increase the power transfer capability and improve the voltage stability. The effects of ULTCs are investigated by both static and dynamic analysis. In respect to power transfer and voltage stability, Increasing shunt capacity of line have given good results (Fig. 3). Thus, in the state being outage one of the parallel lines, the benefit effects of shunt capacitance of the line must also be thought. In dynamic analysis, the load is modeled as a generic dynamic Load model. The ULTC is also modeled as continuous dynamic model. The steady-state load parameters and time constant of load depend strongly on the voltage level at which the load having different parametric values is applying. Since the downstream ULTC's play a very important role. When the time constants and τ increase, P_d has also increased. In the mean while voltage stability margin is also increased. Thus, in the voltage stability studies must be given an importance to time constants of loads and ULTCs. Voltage stability of a power system is related to load characteristics and voltage control devices such as (ULTC) transformers. Voltage collapse period of the post disturbance have shown the difference as depend on parametric values of loads with different characteristic as shown in Fig. 6a. Because the power system with ULTC having loads as Type II and Type III have collapsed immediately. The interferences such as supporting reactive power, tap changing, cleaning the disturbance effect have to been more soon.

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