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REVERSE ACTION OF ON-LOAD TAP CHANGER IN ASSOCIATION WITH VOLTAGE COLLAPSE

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ABSTRACT

This paper discusses the reverse action that the secondary voltage of a transformer is pulled down when the tap position of on-load tap changer is raised to increase the secondary voltage. A dynamic model of an induction motor is adopted as a load model simulating this kind of reverse action during voltage collapse. The transient mechanisms of the reverse action are analyzed by using P-V curves.

Key Words: Voltage Collapse, Reverse Action, Tap Changer, Dynamic Response Characteristics of Load, P-V curve

INTRODUCTION

The secondary voltage of a transformer is usually maintained at a level higher than its lower bound by the automatic on-load tap changer even if the voltage of primary transmission system drops. However, if the load demand becomes excessively heavy, the secondary voltage may become unstable. The instability of tap changer is caused by the fact that the tap changer tries to keep the secondary voltage constant resulting in keeping the load demand constant, in worse cases, increasing it. In studying such effects of tap changer, no dynamics of load have so far been taken into considerations[1],[2],[3].

In recent studies on voltage collapse, a strong attention has been paid to the dynamic characteristics of load which have great effects on the voltage collapse[4],[5],[6]. The feasibility of emergency controls against the voltage collapse is pointed out in the author's previous paper[6] where a dynamic induction motor load model is used.

This paper discusses a reverse action of tap changer. More precisely speaking, the phenomenon is that raising the position of on-load tap changer for raising the secondary voltage causes the drop of the secondary voltage. The dynamic characteristics of load are taken into account in this study.

STATIC ANALYSIS OF REVERSE ACTION

The possibility of a reverse action of tap changer can easily be learned from the calculation using a simple model system as shown in Fig. 1. The secondary voltage of the transformer is given by

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$$|V_2| = \frac{R}{\sqrt{R^2+(n^2x)^2}}\, nE \tag{1}$$

which gives

$$\frac{\partial|V_2|}{\partial n} = \frac{R(R+n^2x)(R-n^2x)}{\{R^2+(n^2x)^2\}^{\frac{3}{2}}}E \tag{2}$$

where

$$\frac{\partial|V_2|}{\partial n} < 0 \qquad \text{if} \qquad R < n^2x \quad . \tag{3}$$

The above equation shows that the secondary voltage drops if the tap position n is raised aiming at raising the secondary voltage. It should be noted that the critical condition ($R=n^2x$) for the occurrence of reverse action coincides with the power matching condition under which the power consumed by resistive load R is maximized. In other words, the power matching condition is nothing but the voltage collapse condition. This fact suggests that the reverse action of tap changer is closely related to the voltage collapse.

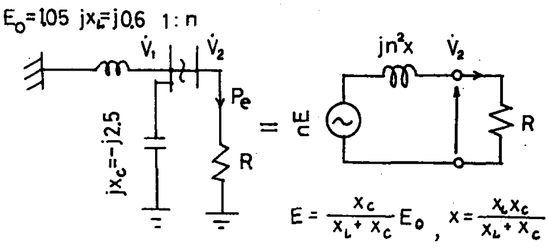


Fig. 1 Simple model of transmission system with resistive load

DYNAMIC SIMULATION OF REVERSE ACTION

Load model

There are two types of dynamic load models. One represents slow transient phenomena caused by the operations of tap changers or the operations of control equipment[4]. The other represents fast transient phenomena caused by the dynamics of electric motors[5],[6]. In this paper, the fast transient phenomena of voltage collapse are treated and an induction motor model is adopted. This is because the induction motor is the most typical dynamic element among the loads which have the constant power characteristics. Its dynamic response is described by differential equations easily.

Tap changer model

An ideal transformer with off nominal turn ratio connected to an inductance is adopted as a model of tap changer. The turn ratio 'n' is assumed to be increased stepwise.

Procedure of dynamic simulation

Dynamics of generators and transmission lines is ignored for simplification. Fig. 2 shows the simulation model. An induction motor is assumed to be connected to an infinite bus through a transmission line and tap changer. Interconnected power systems taking into account dynamics of generators and control equipment are also under consideration and the authors may discuss the results at the next chance.

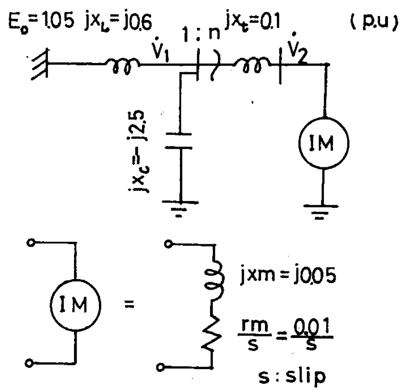


Fig. 2 Model system with induction motor and tap changer

Basic equations used in this dynamic simulations are as follows.

load flow equations

F1(k) : $$Pe_k+\{\sum_{j=1}^{N}(G_{kj}e_j-B_{kj}f_j)e_k+\sum_{j=1}^{N}(G_{kj}f_j+B_{kj}e_j)f_k\}=0$$

F2(k) : $$Qe_k+\{\sum_{j=1}^{N}(G_{kj}e_j-B_{kj}f_j)f_k-\sum_{j=1}^{N}(G_{kj}f_j+B_{kj}e_j)e_k\}=0$$

where

G_{kj}, B_{kj} : conductance and susceptance between nodes k and j

e_k, f_k : real and imaginary components of node voltage k

Pe_k, Qe_k : active and reactive powers injected to node k

induction motor

F3(k) : $$Pe_k-\frac{rm_k/s_k}{(rm_k/s_k)^2+xm^2}(e_k^2+f_k^2)=0$$

F4(k) : $$Qe_k-\frac{xm_k}{(rm_k/s_k)^2+xm_k^2}(e_k^2+f_k^2)=0$$

where

rm_k, xm_k : resistance and reactance of the equivalent circuit of induction motor k

s_k : slip of induction motor k

In the steady-state condition, the electric power injected into the induction motor is equal to the mechanical load. This relationship is described as follows.

F5(k) : $$Pe_k(1-s_k)-Pm_k=0$$

The dynamic equation of the induction motor can be derived from an equation of motion. This differential equation is described as a function of slip as follows.

F6(k) : $$\frac{ds_k}{dt}=\frac{1}{I_k\omega_s^2}\left(\frac{Pm_k}{1-s_k}-Pe_k\right)$$

where

I_k : moment of inertia of induction motor k

$\omega_s=2\pi f_s$, f_s :frequency of the power system

The flowchart of the dynamic simulation is shown in Fig. 3.

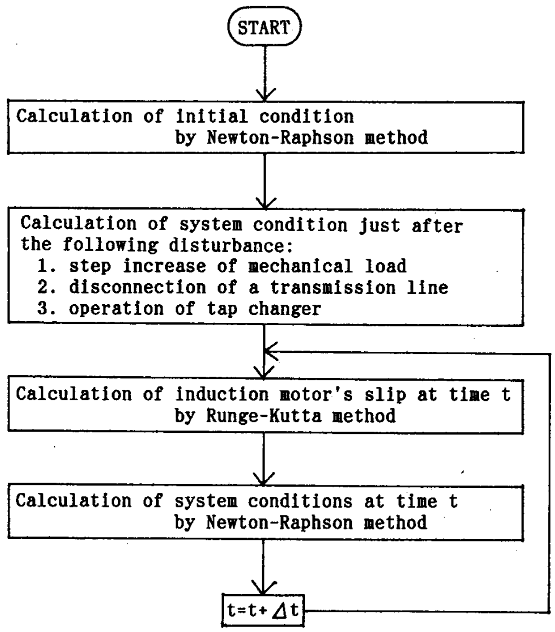


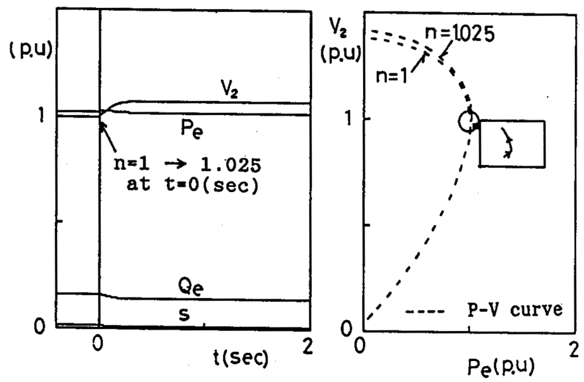
Fig. 3 Flowchart of dynamic simulation

REVERSE ACTION IN CASE OF SINGLE-INDUCTION MOTOR MODEL

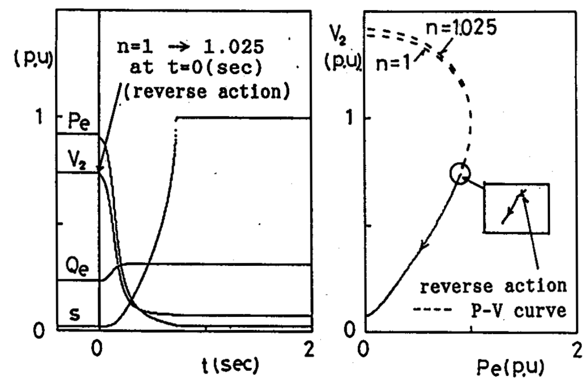
Numerical examples of dynamic simulation

First, consider a single induction motor model as shown in Fig. 2. The transient phenomena for the operating points in the higher voltage region and the lower voltage region of P-V nose curve are shown in Fig. 4 respectively. In actual power systems, the operating point is able to lie in the lower voltage region only during transient period. It is learned that the reverse action caused by the tap changer occurs when the initial operating point lies in the lower voltage region.

Fig. 5 shows the reverse action in the case where the initial operating point lies in the higher voltage region near the critical point of voltage collapse. In this case, if the tap position is stepwisely raised from 1.0 to 1.24, the reverse action occurs. If the tap position is raised gradually, however, the reverse action does not occur even if the tap position exceeds 1.24.

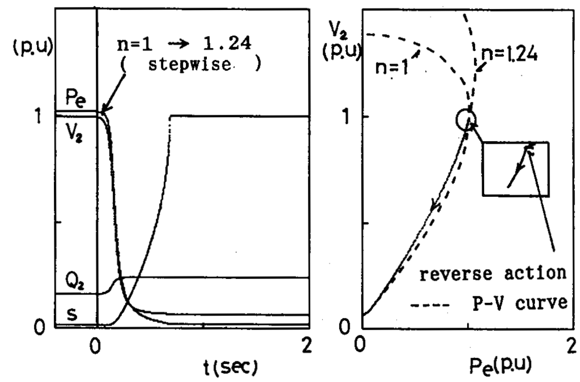


(a) starting from the higher voltage region
(mechanical load:Pm=1.005(p.u))

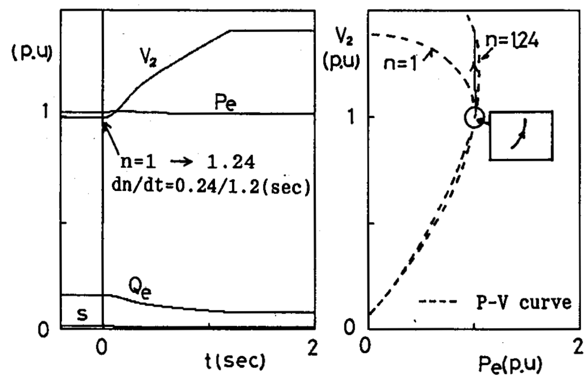


(b) starting from the lower voltage region
(mechanical load:Pm=0.9(p.u))

Fig. 4 transient phenomena by raising tap position

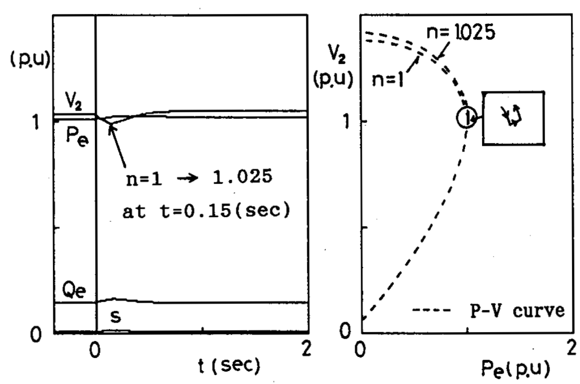


(a) stepwise raising operation of tap position

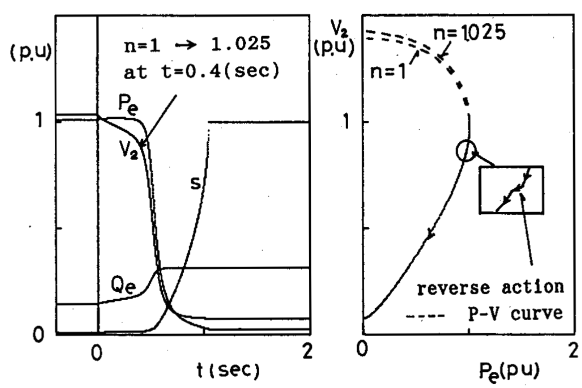


(b) slow raising operation of tap position
(dn/dt=0.24/1.2(sec))

Fig. 5 Reverse action under heavy load condition
(mechanical load:Pm=1.005)



(a) raising operation of tap position
above the critical point of reverse action



(b) raising operation of tap position
below the critical point of reverse action

Fig. 6 Reverse action during voltage collapse
(first disturbance:Pm=1 → 1.01 at t=0(sec))

Fig. 6 shows the results from the cases where the tap position of on-load tap changer is raised during the voltage collapse after the step increase of load. If the operating point moves downward along the P-V curve in the higher voltage region, the node voltage tends to increase to a lesser extent with the increase of tap position n. If the operating point moves further downward passing through the critical point of the reverse action, the node voltage begins to decrease with the increase of tap position. This is the reverse action of tap changer.

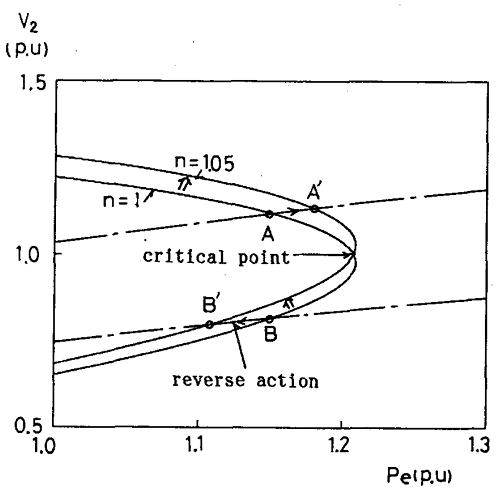
Explanation by P-V curves

To study the reverse action by dynamic simulation method, the P-V curves with different tap positions are drawn in Fig. 7. The model system shown in Fig. 1 is used. It is found that two P-V curves in Fig. 7 cross each other. This fact can be explained as follows. The secondary voltage of the transformer in Fig.1 is a function of tap position n or

$$|V_2| = \sqrt{\frac{E^2 \pm \sqrt{E^4 - 4x^2Pe^2}}{2}}\, n \qquad (4)$$

Presence of double sign gives the possibility that two P-V curves with a little different tap positions may cross each other at a point between the tips of P-V curves for low tap position and for high tap position as shown in Fig. 7.

In the static analysis as represented by Eq. (1), the impedance of load is considered invariant. Under this condition, the operating point is fixed on the characteristic curve of the constant impedance load. If the operating point lies above the point of intersection in Fig.7, it jumps upward(A → A') when the tap position is raised. On the other hand, if the operating point lies below the point of intersection, it jumps downward(B → B') resulting in the reverse action. The critical point of the reverse action is the point of intersection in Fig.7. This fact coincides with the results of theoretical analysis given by Eq. (3).

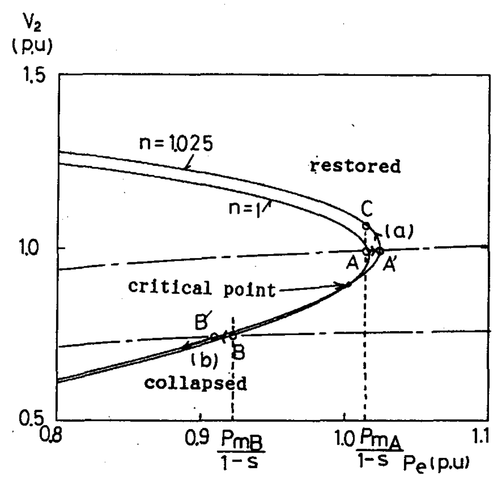


—·— load characteristic curve

Fig. 7 Explanation of reverse action by P-V curves in case of resistive load in Fig. 1

Next, let's take into account the dynamic characteristics of load by using a single induction motor model as shown in Fig. 2. In this case, the point of intersection lies a little below the tips of both P-V curves as shown in Fig. 8.

The slip of the induction motor is kept invariant owing to the inertial mass and the constant impedance jumping phenomenon takes place. If the operating point lies above the point of intersection, it jumps upward(A→A') and reaches a stable point(A'→C). This is because the active power injected to the induction motor exceeds the mechanical power resulting in the acceleration of the induction motor. On the contrary, if the operating point lies below the point of intersection, the direction is downward(B→B') and the node voltage collapses. This is because the active power injected to the induction motor is insufficient for the mechanical load resulting in the deceleration of the induction motor. Therefore, the node voltage is usually pulled down unless the initial operating point lies above the crossing point.



—·— load characteristic curve

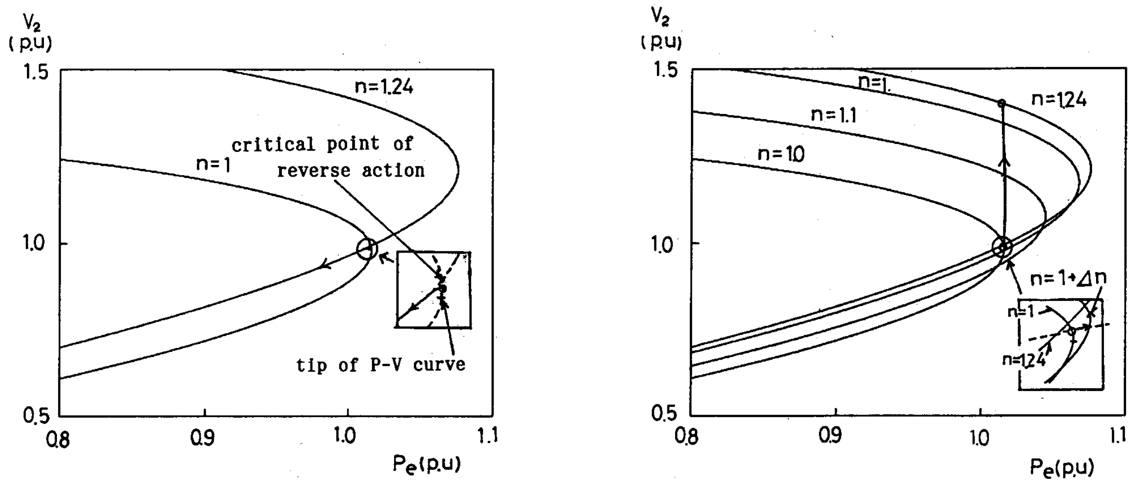
(a) normal action(case (a) in Fig. 4)
(b) reverse action(case (b) in Fig. 4)

Fig. 8 Explanation of reverse action by P-V curves in case of induction motor load

Even though the initial operating point lies on the upper portion of the P-V curve, the reverse action may occur. An example of such case is shown in Fig. 9-(a). In this analysis, the tap position is changed so quickly that the load can be treated as the constant impedance load. On the other hand, if the tap position is changed so slowly that the load behaves as a constant power load, the reverse action does not occur as shown in Fig. 9-(b). The above two examples demonstrate the importance of the load dynamics.

A similar reverse action may occur in the transient process of the voltage collapse as shown in Fig. 10.

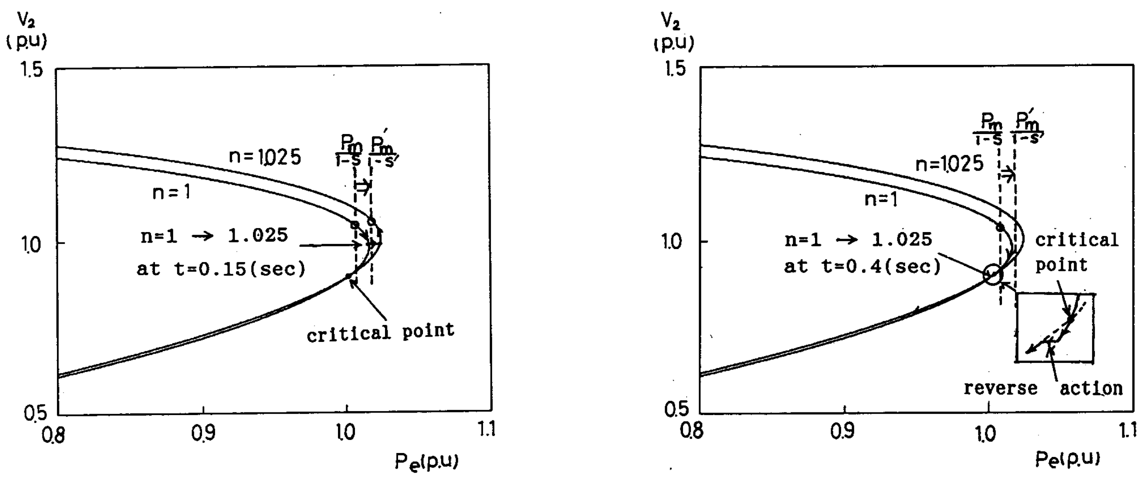
The above dynamic simulations show that there exists the dangers of the reverse action when tap changers are operated under the heavy load condition.



(a) stepwise raising operation of tap position
(case (a) in Fig. 5)

(b) slow raising operation of tap position
(case (b) in Fig. 5)

Fig. 9 Explanation of reverse action under heavy load condition



(a) normal action: the operating point has not reach the point of intersection.
(case (a) in Fig. 6)

(b) reverse action: the operating point has passed through the point of intersection
(case (b) in Fig. 6)

Fig. 10 Explanation of reverse action by P-V curves during voltage collapse

LOCAL VOLTAGE COLLAPSE IN DOUBLE-INDUCTION MOTOR SYSTEM

Numerical analysis by dynamic simulation

As discussed in the author's previous paper[6], all the node voltages in a multi-load power system do not simultaneously collapse. In this chapter, the reverse action of on-loaded tap changer is analyzed in a multi-load power system.

Two cases are simulated by using the double-induction motor model as shown in Fig. 11. One is the case where the induction motor connected to the secondary bus is heavily loaded. The other is the case where the induction motor connected to the primary bus is heavily loaded. The disturbance is given by opening one circuit of the double circuit transmission line between the infinite bus and the transformer. When the secondary voltage of the transformer collapses first, say in case (a), the reverse action of tap changer may occur as shown in Fig. 12-(a). On the other hand, when the primary voltage of the transformer collapses first, say in case (b), the reverse action does not occur as shown in Fig. 12-(b). These results show that the reverse action of the tap changer occurs only at the node whose voltage locally collapses earlier than at the other nodes.

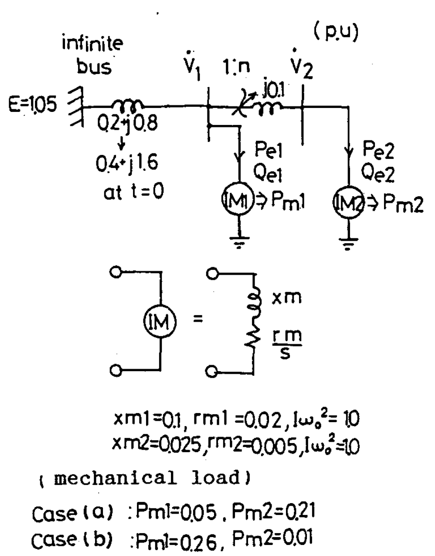


Fig. 11 Double induction motor model with tap changer

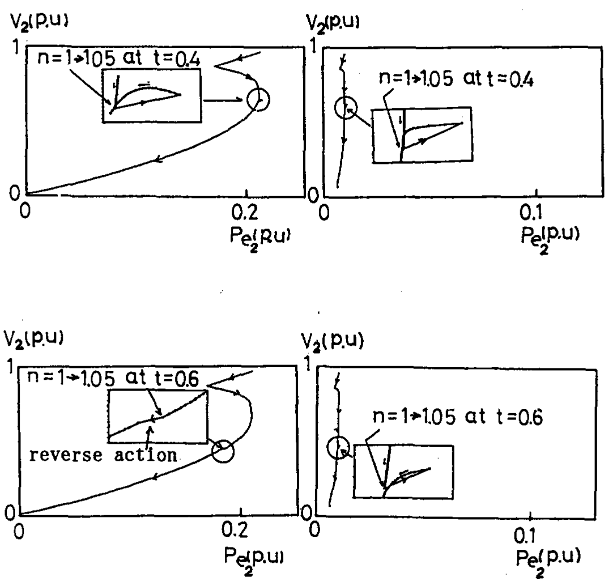
Explanation by transient P-V curves

The phenomena mentioned above can also be explained by the use of P-V curves as in the single-induction motor model. The P-V curves called "transient P-V curves" is introduced at every node in order to indicate how close the present operating is to the critical point of reverse action.

Two operating points before and after raising the tap position can be obtained assuming that the loads are of constant impedance type in the instant of the disturbance. Two "transient" P-V curves of a given node can be drawn from the above two operating points obtained from equations F1,F2,F3,F4 by changing slip s of the specified node and keeping slips of the remaining nodes constant. Fig. 13 shows the transient P-V curves with different tap positions. If the operating point lies above the point of intersection between two P-V curves, it jumps towards the higher direction by the raising operation of tap changer. On the other hand, if the operating point lies under the point of intersection, it jumps towards the lower direction.

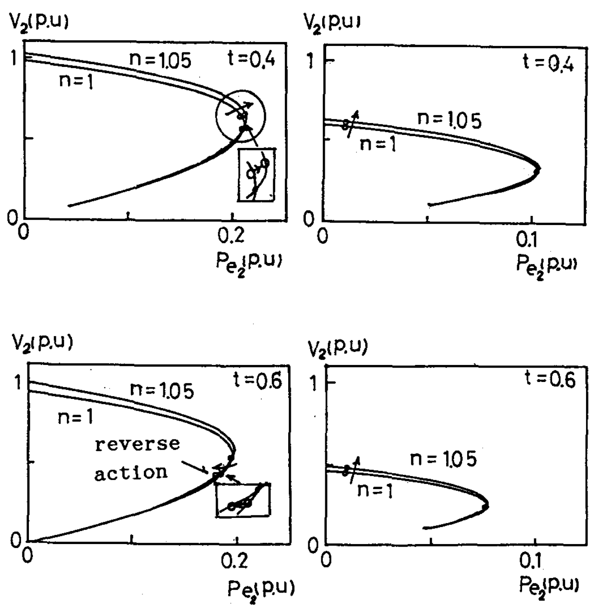
As shown in Fig. 13(b) where the primary voltage of the transformer is collapsed first, the operating point at the secondary bus always lies above the point of intersection and far from the tip of P-V curve. No reverse action occurs. On the other hand, in case (a) where the secondary voltage of the transformer collapses first, the reverse action can occur by raising the tap position if the operating point passes through the point of intersection.

It is seen that the reverse action of tap changer may occur at the node whose voltage collapses locally at first. When the secondary voltage is pulled down by raising the tap position during the voltage collapse, the operation of reducing tap position or locking the tap changer may be required to reduce the demand of load.



(a) Secondary Voltage collapse case (b) Primary voltage collapse case

Fig. 12 P-V trajectory of voltage collapse in double-induction motor model system (tap position is raised at t=0.4(sec) or 0.6(sec))



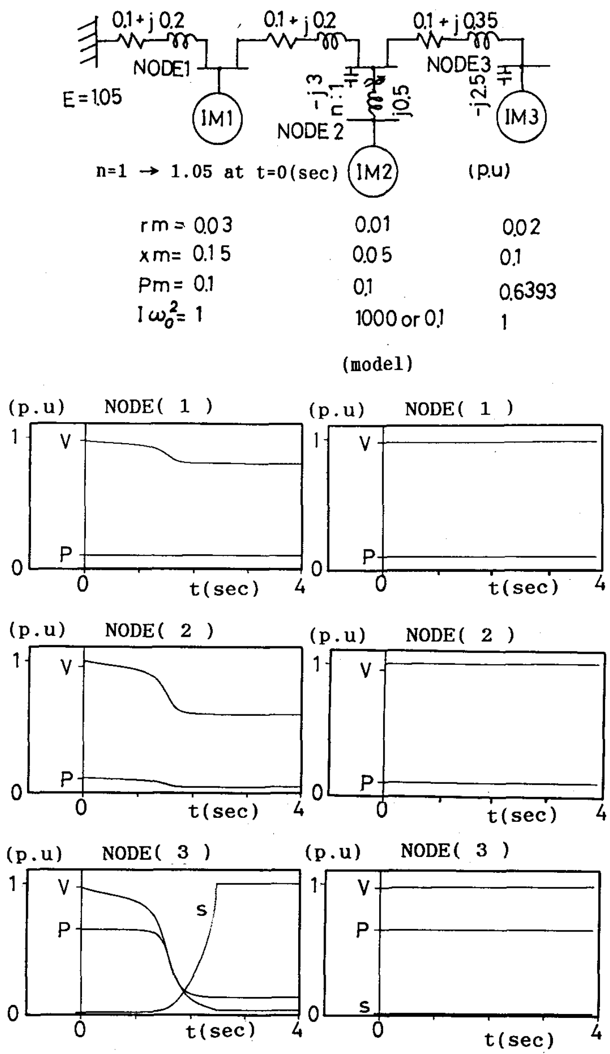
(a) Secondary Voltage collapse case (b) Primary voltage collapse case

Fig. 13 Explanation of reverse action by transient P-V curves

INDUCED VOLTAGE SHOCK AND CASCADED VOLTAGE COLLAPSE

Concerning the dangerous action caused by the tap changers, there is another problem. This is the problem of voltage shock on the primary bus of a transformer, or more precisely, the drop of the primary bus voltage caused by raising the tap position to boost the secondary voltage. Fig. 14 shows that the voltage shock caused by raising the tap position of node 2 induces the local voltage collapse at node 3 which is heavily loaded. Two cases are simulated. In case (a), the inertial mass of node 2 is so large that the load impedance can be regarded as being invariant. In case (b), the inertial mass is so small that the load can be regarded as being of constant power type. The operating point at node 3 is near the tip of the P-V curve.

In case (a), the voltage at node 3 collapses. On the contrary, in case (b), the voltages never collapse. These results show that the load characteristics have a great effect on the phenomena of voltage collapse.



(a) constant impedance load (b) constant power load
(numerical examples)

Fig. 14 Voltage collapse caused by induced voltage shock

CONCLUSION

Occurrence possibility of reverse action of on-load tap changer has been demonstrated theoretically by using very simple models. The transient phenomena of the reverse action are also analyzed by dynamic digital simulation and their mechanisms are examined by the use of P-V curves. It is made clear that reverse action caused by on-load tap changers may deteriorate the operating condition in a heavily loaded power system where the cascaded voltage collapse may occur.

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