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メタデータ	言語: 出版者: 琉球大学理工学部 公開日: 2013-09-20 キーワード (Ja): キーワード (En): 作成者: Miyagi, Hayao, Taniguchi, Tsuneo, 宮城, 隼夫, 谷口, 経雄 メールアドレス: 所属:
URL	http://hdl.handle.net/20.500.12000/27616

Transient Stability Studies including the Effects of Load Characteristics

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Summary

The transient stability of a power system is investigated including the effects of load characteristics, through the direct method of Lyapunov. The Lyapunov function is used to understand the stability of the system quantitatively. The composite behaviors of the system loads are expressed in terms of applied voltage. Furthermore, their desirable model for computer stability program is studied.

List of principal symbols

M = unit inertial constant, s
P_E = electrical−power output, p. u.
P_M = mechanical−power input, p. u.
E = voltage behind transient reactance, p. u.
E_l = load voltage, p. u.
X_g = transient reactance of the generator, p. u.
X_t = transformer reactance, p. u.
δ = rotor angle with respect to a synchronously rotating reference, rad.
δ_0 = value of δ at the prefault stable−equilibrium point.
$\omega = d\delta/dt$

Subscripts A and B denote generator A and B respectively. Dot over a symbol denotes vector.

1. Introduction

The direct method of Lyapunov has been applied by various authors to the power system transient stability problem. In several papers, the effects of control system such as automatic voltage regulator[1] or governor[2)~5)] are taken into account. However, there are very few reports which discuss the effects of system loads. Load behaviors may directly influence on the system stability. In this paper, Lyapunov function is used to estimate quantitatively the stability of the power system, including the effects of load characteristics.

Received : October 30, 1978

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In stability studies, power system loads consisting of individual devices are generally represented by their composite characteristics. These characteristics are expressed as functions of applied voltage only. In order to obtain a voltage–power relationship, two approaches have been employed. One is to use a voltage dependent polynominal, taking the form $P_l=K(a_0+a_1E_l^1+a_2E_l^2)$. The other approach is to state $P_l=KE_l^n$, where n might vary between 0 and 3. Since the effect of reactive power is a second order effect and is not significant for the usual range of voltage variations encountered in stability analysis[6] (i.e. 80%~110%), it is treated as a constant impedance load in order to decrease the laborious computations.

2. Load representation

Consider the system as shown in Fig.1. Two equivalent generators furnish the power to the system load. The system is simply represented as Fig.2. Expressing the active and reactive components of load as functions of load bus voltage, it results in :

$$P_l=K(a_0+a_1E_l^1+a_2E_l^2) \tag{1}$$

or

$$P_l=KE_l^n \tag{2}$$

and

$$Q_l=KE_l^2 \tag{3}$$

where, K, a_0, a_1, a_2 and n are constants.

Since the load admittance is used in the analysis, it must be computed using load bus voltage. Relationships between load admittance and load bus voltage are given in Table 1.

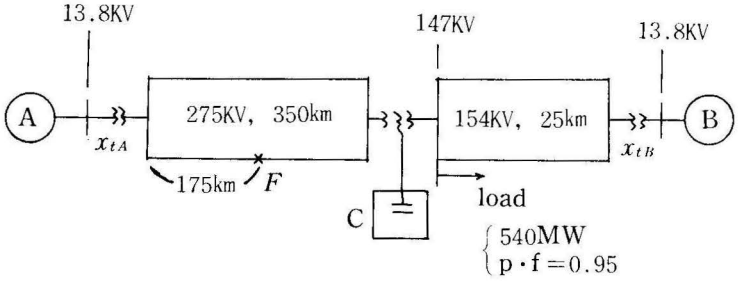

Fig. 1 Sample system

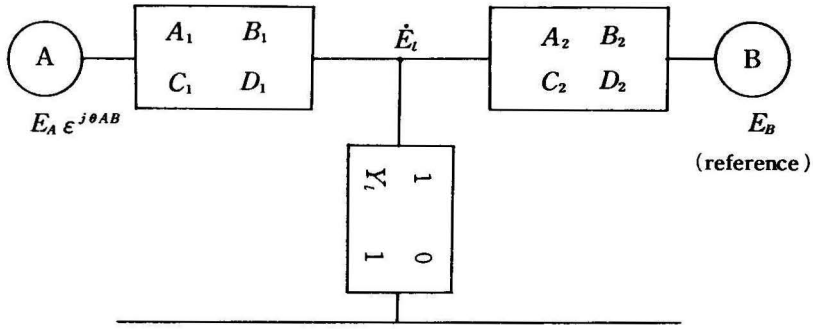

Fig. 2 Equivalent circuit

Table 1

case	load characteristic	admittance	relationship
1	constant impedance $P_l = K E_l^2$	$Y_l = K$	$\dot{E}_l = \dfrac{\dot{B}_2 E_A \varepsilon^{j\theta AB} + \dot{B}_1 E_B}{\dot{A}_1 \dot{B}_2 + \dot{B}_1 \dot{D}_2 + K\dot{B}_1 \dot{B}_2}$
2	constant current $P_l = K E_l$	$Y_l = K / E_l$	$\dot{E}_l = \dfrac{\dot{B}_2 E_A \varepsilon^{j\theta AB} + \dot{B}_1 E_B}{\dot{A}_1 \dot{B}_2 + \dot{B}_1 \dot{D}_2 + K\dot{B}_1 \dot{B}_2 / E_l}$
3	constant power $P_l = K$	$Y_l = K / E_l^2$	$\dot{E}_l = \dfrac{\dot{B}_2 E_A \varepsilon^{j\theta AB} + \dot{B}_1 E_B}{\dot{A}_1 \dot{B}_2 + \dot{B}_1 \dot{D}_2 + K\dot{B}_1 \dot{B}_2 / E_l^2}$
4	composite characteristic constant impedance a_1 % constant current a_2 % constant power a_3 % $P_l = K(a_3 + a_2 E_l + a_1 E_l^2)$	$Y_l = K\left(a_1 + \dfrac{a_2}{E_l} + \dfrac{a_3}{E_l^2}\right)$	$\dot{E}_l = \dfrac{\dot{B}_2 E_A \varepsilon^{j\theta AB} + \dot{B}_1 E_B}{\dot{A}_1 \dot{B}_2 + \dot{B}_1 \dot{D}_2 + K\dot{B}_1 \dot{B}_2\left(a_1 + \dfrac{a_2}{E_l} + \dfrac{a_3}{E_l^2}\right)}$
5	exponent characteristic $P_l = K E_l^n$	$Y_l = K E_l^{n-2}$	$\dot{E}_l = \dfrac{\dot{B}_2 E_A \varepsilon^{j\theta AB} + \dot{B}_1 E_B}{\dot{A}_1 \dot{B}_2 + \dot{B}_1 \dot{D}_2 + K\dot{B}_1 \dot{B}_2 E_l^{n-2}}$

3. Stability analysis

Neglecting the effects of damping, the swing equations for generator A and B are

$$\frac{d^2\theta_A}{dt^2} = \frac{\omega_0}{M_A}\left(P_{MA} - P_{EA}\right), \tag{4}$$

$$\frac{d^2\theta_B}{dt^2} = \frac{\omega_0}{M_B}\left(P_{MB} - P_{EB}\right). \tag{5}$$

Using eqn. (4) and (5), we obtain

$$\frac{d^2\theta_{AB}}{dt^2} = P_{MAB} - P_{EAB}\,, \tag{6}$$

where

$$\theta_{AB}=\theta_A-\theta_B\ ,$$

$$P_{MAB}=\omega_0\left(\frac{P_{MA}}{M_A}-\frac{P_{MB}}{M_B}\right)\ ,\qquad P_{EAB}=\omega_0\left(\frac{P_{EA}}{M_A}-\frac{P_{EB}}{M_B}\right)\ .$$

The Lyapunov function is constructed as

$$V=\frac{1}{2}\left(\frac{d\theta_{AB}}{dt}\right)^2+\int_{\theta ABO}^{\theta AB}(P_{EAB}-P_{MAB})\,d\theta_{AB}\ . \tag{7}$$

Since the load admittance varies according to the applied voltage, quantity of the admittance may be changed at each step of calculation.

The stability is evaluated by a index ξ as

$$\xi=1-\frac{V}{V_c} \tag{8}$$

where, V_c is the critical value of V and is obtained by substituting the equilibrium point of the system into V.

The procedure for determining the critical reclosing time is shown in flow chart in Fig.3. The followings are the main steps :

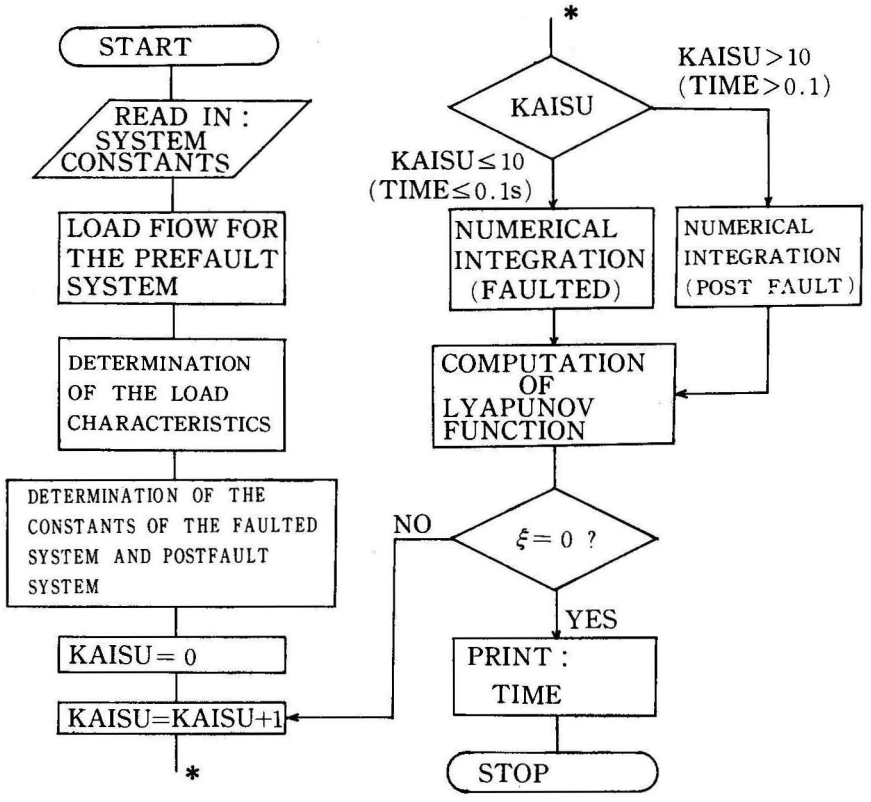

Fig. 3 Flow chart

Step 1 Load flow for the prefault system
Step 2 Determination of the load characteristic
Step 3 Determination of the constants of the faulted system and postfault system
Step 4 Forward step−by−step integration (swing curves) to find the critical reclosing time ($\xi = 0$)

4. Numerical example

The following numerical examples are presented to investigate the effect of load on stability of the power system. A symmetrical three phase fault to ground is assumed at point F in Fig.1. The faulted line is disconnected after 0.1 second and is reclosed sucsequent to time t_0. The critical reclosing time $\tau_c (=0.1+t_0)$ is determined by using the stability index ξ. The system constants[8] are listed in Table 2.

Table 2 System constants

device	constants
154 KV transmission line 25km	$z_1 = 0.0166 + j0.1070$ (p.u.) $y_1 = j0.0087$ (p.u.)
275 KV transmission line 350km	$z_2 = (0.1776 + j1.5946) \times 10^{-3}$/km (p.u.) $y_2 = j1.0293 \times 10^{-3}$/km (p.u.)
generator and transformer A	$X_{gA} = 0.2017$ (p.u.) $M_A = 14.4$s $E_A = 1.2319$ (p.u.) $X_{tA} = 0.0756$
generator and transformer B	$X_{gB} = 0.1042$ (p.u.) $M_B = 18.816$s $E_B = 1.0891$ (p.u.) $X_{tB} = 0.0722$ (p.u.)
three winding transformer (substation) see appendix I	$X_{t13} = 0.0058$ (p.u.) $X_{t12} = 0.0377$ (p.u.)
load	$Y_l = 2.7 + j0.5226$ (p.u.)

Table 3 $P_l = K(a_0 + a_1 E_l^1 + a_2 E_l^2)$

case	a_0	a_1	a_2	V_c	load characteristic
1			1.0	46.07	constant impedance
2		0.5	0.5	34.80	50% constant impedance 50% constant current
3 [7]	0.32		0.68	28.67	pure residential−commercial load
4	0.1	0.6	0.3	27.82	composite load
5		1.0		25.29	constant current
6	0.5		0.5	21.32	50% constant impedance 50% constant power

Table 4 $P_l = K E_l^n$

case	n	V_c	load characteristic
7 [7]	1.367	33.15	pure residential−commercial load
8 [7]	0.353	12.77	pure agricultural load
9 [7]	0.266	11.37	pure industrial load

Tables 3 and 4 give the critical values of Lyapunov function for the various load characteristics. The amount of V_c may indicate the margin of stability.

Fig. 4 shows time(t)−stability index(ξ) curves for the various load characteristics. In the faulted system, these characteristics are all treated as a constant impedance one. As shown in the figure, constant power loads are always detrimental to stability. Constant impedance characteristic(i.e. static loads consisting of heating and lighting equipment) gives good results to the power system stability. Such loads may have a damping effect on voltage oscillations.

In case of involving a constant power characteristic, load voltage often falls below 50 percent of the base voltage at the moment when fault occurs. The absence of a network solution has been experienced when using the Newton−Raphson method at low voltages. Such fact arises from the imperfection of the load model. Existence of suitable model would require substantially more field testing and analysis.

The comparison of the polynominal representation of the load with the exponent representation is given in Fig. 5. In this figure, both $t-\xi$ curves are about the pure residential−commercial load. Polynominal one gives conservative results in transient stability analysis. Therefore, this representation may be acceptable from a security view point.

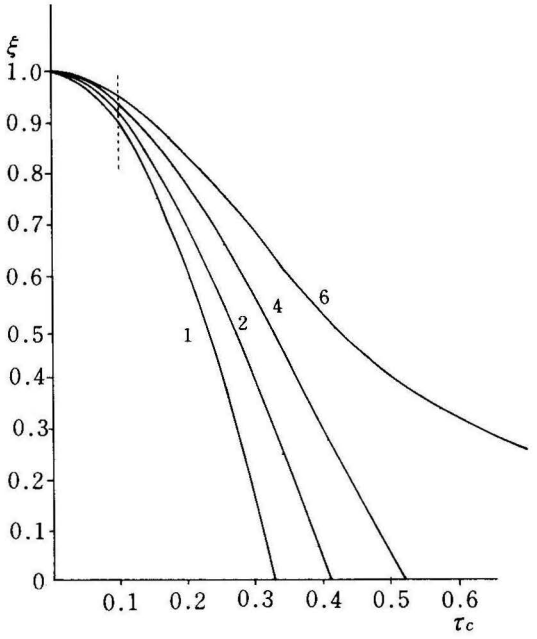

Fig. 4 $\tau_c - \xi$ curves

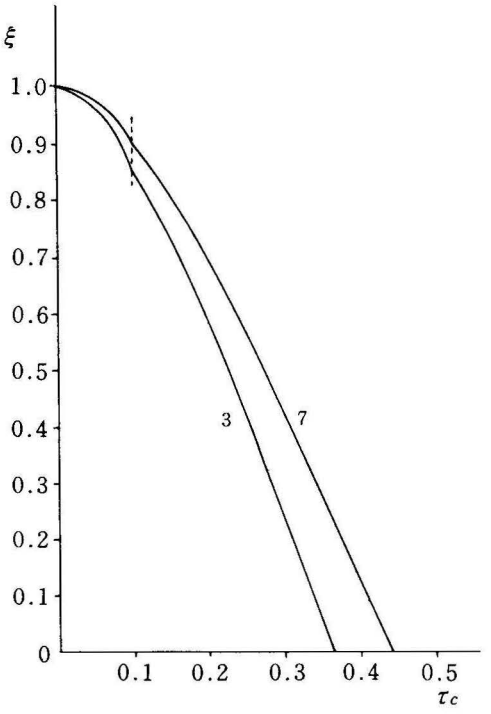

Fig. 5 $\tau_c - \xi$ curves

5. Conclusion

The direct method of Lyapunov has been applied to the transient stability problem of the power system, including the effects of load characteristics. The stability can be grasped quantitatively by using Lyapunov function.

Although the system loads are represented by two voltage−dependent characteristics. more suitable model would be required in the computer stability program. Because of this requirement, further field testing and analysis may be necessary.

Appendix [8]

An equivalent model of typical three winding transformer is given as (a) in Fig. Al, and is equivalent to (b). In general, equivalent secondary−winding impedance is smaller than primary one. Therefore, the transformer may be approximated as (c) in Fig. Al.

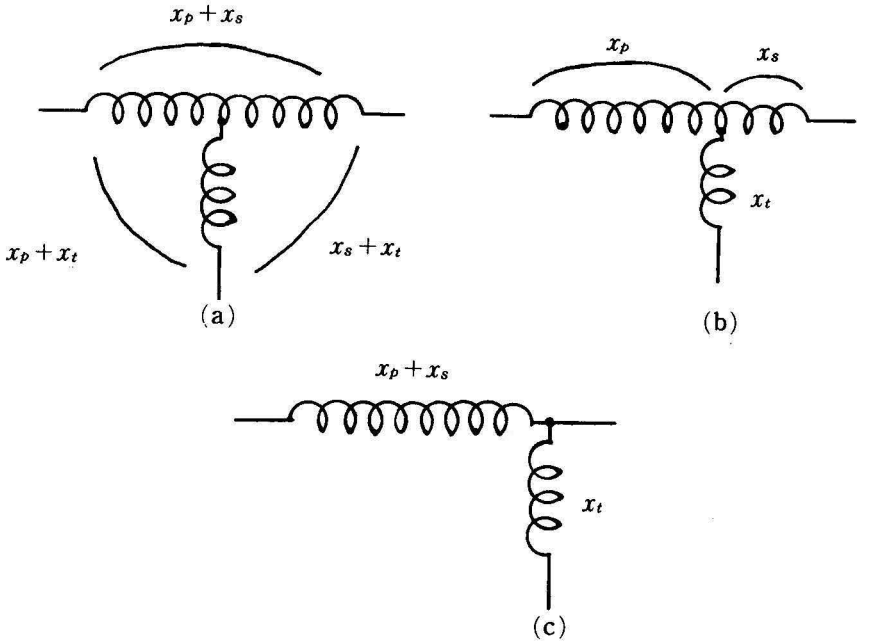

Fig. A1 Approximation of three winding transformer

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