Identification of Correlative Transmission Lines for Stability Prediction

Yoon-Sung Cho, Gilsoo Jang, Sae-Hyuk Kwon and Yanchun Wang

Abstract - Power system stability is correlated with system structure, disturbances and operating conditions, and power flows on transmission lines are closely related with those conditions. This paper proposes a methodology to identify correlative power flows for power system transient and small-signal stability prediction. In transient stability sense, the Critical Clearing Time is used to select some dominant contingencies, and Transient Stability Prediction index is proposed for the quantitative comparison. For small-signal stability discusses a methodology to identify crucial transmission lines for stability prediction by introducing a sensitivity factor based on eigenvalue sensitivity technique. On-line monitoring of the selected lines enables to predict system stability in real-time. Also, a procedure to make a priority list of monitored transmission lines is proposed. The procedure is applied to a test system, and it shows capabilities of the proposed method.
Keywords - Transient stability, Small-signal stability, TSP, CCT, Eigenvalue, Sensitivity

1. Introduction

Electric power systems have become more complex and the operating characteristics of many power networks around the world have been changing considerably. It makes an increasing need for on-line stability monitoring. Recent research works deal with the analysis of electromechanical characteristics of synchronous generators to a certain fault as well as stability estimation for on-line stability control [1][2]. Power system stability is correlated with system structure, disturbances and operating conditions, and power flows on transmission lines are closely related with those conditions. If correlated transmission line flows can be identified, monitoring of the lines with Energy Measurement System enables system stability to be enhanced.

This paper proposes a methodology to identify correlative power flows for power system transient and small-signal stability prediction. In transient stability sense, the Critical Clearing Time (CCT) is used to select some dominant contingencies, and TSP (Transient Stability Prediction) index is proposed for the quantitative comparison. The proposed procedure is applies a 3-generator 9-bus system. [3] For small-signal stability prediction purpose, eigenvalue sensitivity with respect to power flows is used to make the priority list [4]. The proposed procedure is applied to a simple two-area system. [5] A procedure incorporating above two approaches is proposed to identify crucial transmission lines for the system stability in this paper. The proposed procedure is applies a 6-generator 20-bus test system [6], simulation results show capabilities of the proposed method.

This work was supported by the Electrical Engineering & Science Research Institute.

Manuscript received: Oct. 31, 2001 accepted: Nov. 30, 2001.

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2. Identification of correlative transmission lines

An algorithm to identify correlative transmission lines for on-line stability diagnosis is proposed in this paper. The procedure is described in Fig. 1.

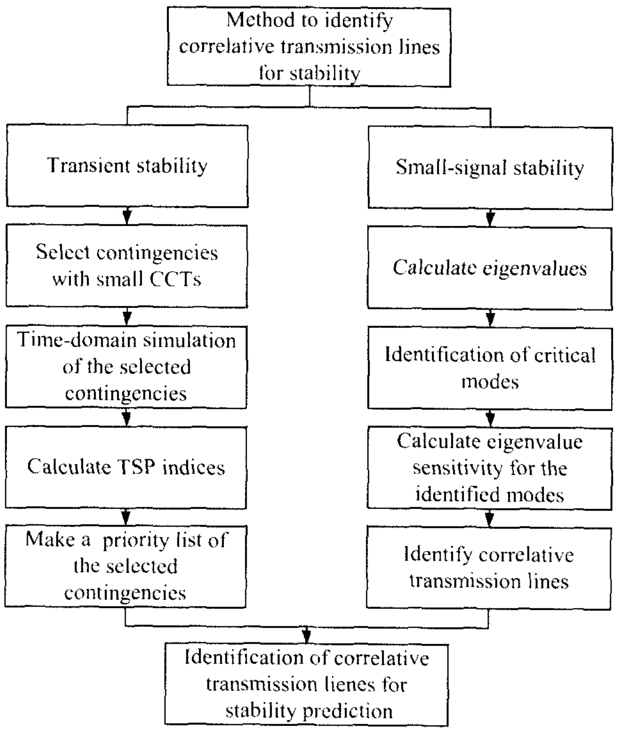

Fig. 1 Identification procedure

Each step will be described in the following sections in detail.

2.1 Transient stability

CCT is a good index to evalutate transient stability in power system. It is defined as the time for which a fault can last without losing synchronism. Power transfers in transmission lines at CCT can determine if generators will lose synchronism, and an index is proposed based on this assumption. The proposed index is Transient Stability Prediction (TSP) index, which is the summation of normalized power variation rate. Transmission lines which are sensitive to faults can be determined by comparing indices.

$$TSP = \sum_{t=t_0}^{t_1} \frac{|P_2 - P_1| / |P_1|}{\Delta t} \quad (1)$$

t_0 = fault initiating time
t_1 = fault clearing time
P_1 = power flow
P_2 = power flow at the next time-step

The comparison of TSP indices has a meaning at same fault case since the indices are dependent on the fault. The fault cases used in this paper are selected using contingency studies. Each step is as follows:

① Calculate CCTs for the all buses. CCT is calculated by the gap criterion after time-domain simulation.
② Select contingencies with small CCTs.
③ Calculate TSP indices of the selected cases.
④ Make a priority list of the selected contingencies

The above procedure is implemented as an automatic calculation module in a time domain power system simulation program, PSS/E. Hence, the proposed algorithm can be performed automatically whenever system configuration changes. The priority list of the transmission lines is provided as a result of this procedure.

2.1.1 Test Results

The proposed method is applied to a WSCC 9 bus system which has 3 generators and 9 buses. PSS/E is used for nonlinear time simulation program. The time-step used is 0.0083 sec (0.5 cycle). The fault at bus is considered in this study. CCTs are calculated by the developed module, and some critical ones are given here.

- CCT of bus #4 = 0.3320 sec
- CCT of bus #7 = 0.1826 sec
- CCT of bus #9 = 0.2075 sec

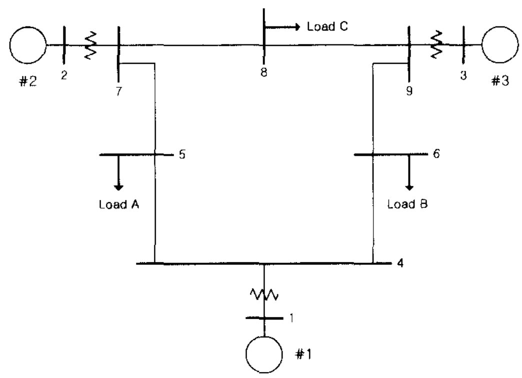

Fig. 2 WSCC 9 bus system

Table 1 Priority list w.r.t. transient stability

From	To	Bus #4	Bus #7	Bus #9
4	5		aaa	aaaa
4	6		a	aa
7	5	aaaa		aaa
7	8	a		a
9	6	aa	aa	
9	8	aaa	aaaa	

*a is priority indices of correlative out-of-step system

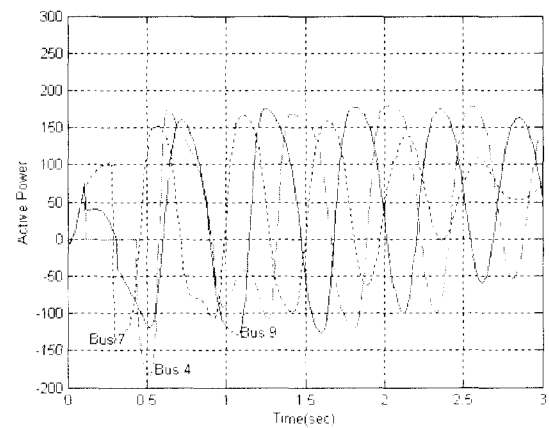

Fig. 3 Active power between buses #4 and 5 (before CCT)

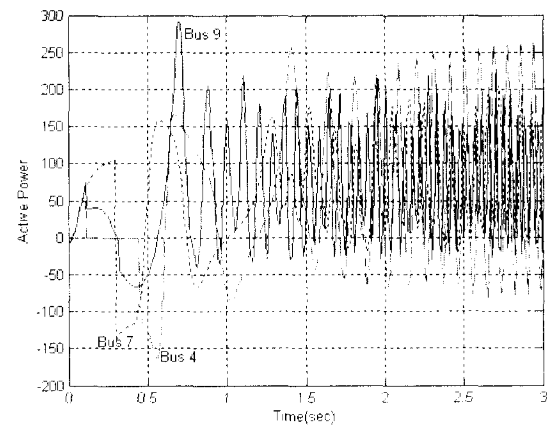

Fig. 4 Active power between buses #4 and 5 (at CCT)

Table 1 shows TSP indices of transmission lines, and the priority list is proposed based on the indices. The results say that lines between buses 4 and 5, buses 7 and 5, and buses 9 and 8 are related to the faults which are not on their buses. Time domain simulation of those contingencies are performed to verify identification method, and Fig. 3, 4, 5, and 6 show the line flow between buses #4 and #5 has more significant variations due to fault clearing time than other ones.

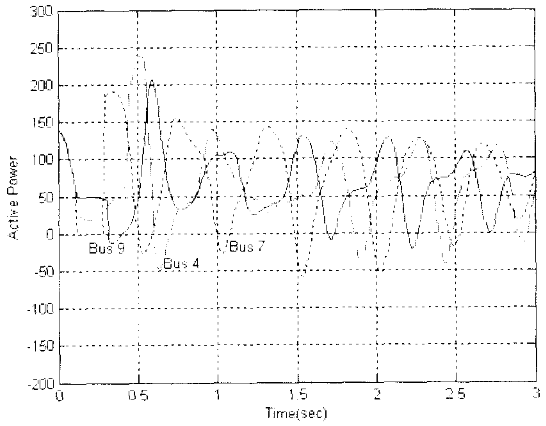

Fig. 5 Active power between buses #7 and 8 (before CCT)

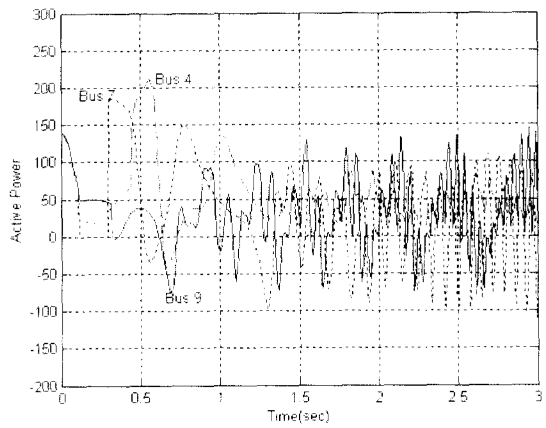

Fig. 6 Active power between buses #7 and 8 (at CCT)

2.2 Small-signal stability

The identification method in terms of small-signal stability is based on eigenvalue sensitivities with respect to power flows of T/Ls.

2.2.1 Eigenvalue sensitivity

System dynamics are represented as equation (2).

$$\dot{x} = Ax \tag{2}$$

Equation (3) shows the solution of equation (2).

$$\begin{aligned} x_i(t) &= \sum_{j=1}^{N} u_{ij} y_{j0} e^{\lambda_i t} \\ &= \sum_{j=1}^{N} u_{ij} \sum_{k=1}^{N} y_{jk} X_{k0} e^{\lambda_i t} \\ &= \sum_{j=1}^{N} \sigma_{ij} e^{\lambda_i t} \end{aligned} \tag{3}$$

Eigenvalue sensitivity with respect to line power flow, P_{ab}, is given in equation (4).

$$\frac{\partial \lambda_i}{\partial P_{ab}} = \frac{v_i^T \frac{\partial A}{\partial P_{ab}} u_i}{v_i^T u_i} \tag{4}$$

where,

$$\frac{\partial A}{\partial P_{ab}} = \frac{\partial A}{\partial x_i} \cdot \frac{\partial x_i}{\partial P_{Gj}} \cdot \frac{\partial P_{Gj}}{\partial P_{ab}} \tag{5}$$

v_i = left eigenvector
u_i = right eigenvector.

2.2.2 Generator models

Generators are modeled by the classical model[3] in this approach, and state equations of the model are as follows.

$$\begin{aligned} M_i \dot{\omega}_i &= P_{mi} - \sum_{j=1}^{N} [C_{ij} \cos(\delta_i - \delta_j) + D_{ij} \sin(\delta_i - \delta_j)] \\ C_{ij} &= E_i E_j B_{ij} \\ D_{ij} &= E_i E_j G_{ij} \end{aligned} \tag{6}$$

System equation is developed using equation (6), and it is given in equation (7).

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & U \\ A & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{7}$$

U = The identity matrix
x_1 = The n-1 vector of the angle changes δ_Δ
x_2 = The n-1 vector of the speed changes $d\delta_\Delta / dt$

2.2.3 Relation of line active power and rotor angle

Electrical power of i-th generator is given in equation (8)

$$P_{ei} = \sum_{j=1}^{N} V_i V_j |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{8}$$

Equation (9) shows $\partial X_i / \partial P_{Gj}$ which is required to calculate eigenvalue sensitivity.

$$\begin{bmatrix} \Delta P_{e1} \\ \vdots \\ \Delta P_{e(n-1)} \end{bmatrix} = \begin{bmatrix} \sum_{j=1,i\neq j}^{N} F_{1j} & \cdots & -F_{1(n-1)} \\ \vdots & \ddots & \vdots \\ -F_{(n-1)1} & \cdots & \sum_{j=1,i\neq j}^{N} F_{ij} \end{bmatrix} \begin{bmatrix} \Delta x_1 \\ \vdots \\ \Delta x_{(n-1)} \end{bmatrix} \quad (9)$$

$$F_{ij} = D_{ij}\cos(\delta_i - \delta_j) - C_{ij}\sin(\delta_i - \delta_j)$$

2.2.4 Relation of generator active power and line active power

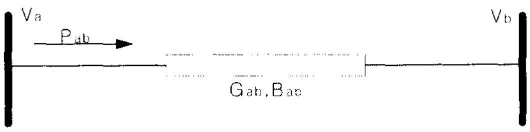

Fig. 7 Active power between two buses

The active power between two buses can be represented with the line admittance, $G_{ab}+jB_{ab}$. $\partial P_{Gi}/\partial P_{ab}$ is obtained by substituting P_{ab} into equation (9), since P_{ab} can be represented with respect to generator rotor angles.

2.2.5 Correlative lines identification procedure

① Identification of critical modes:
- Calculate eigenvalues from system matrix
- Select less damped modes with low frequencies

② Calculate eigenvalue sensitivity w.r.t. line active power for the identified modes

③ Identify correlative transmission lines

2.2.6 Numerical Results

The proposed method is applied to a simple two-area system which has 4 generators and 9 buses.

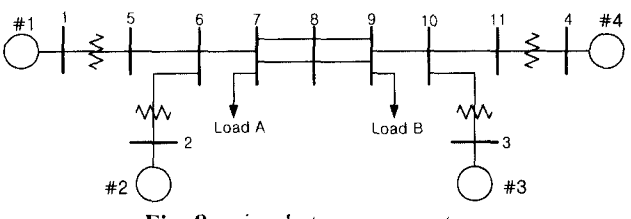

Fig. 8 a simple two-area system

Damping of the modes isn't represented since classical model is used for the generator modeling for the derivation of the eigenvalue sensitivity w.r.t. line flow. Table 2 shows the modes of a simple two-area system, and table 3 shows $\partial\lambda/\partial P_{ab}$ of the modes.

Table 2 Modes of a two-area system

	$\lambda_{1,2}$	$\lambda_{3,4}$	$\lambda_{5,6}$
200MW	±j3.05377	±j8.87407	±j8.94562
300MW	±j2.83321	±j8.90799	±j8.97002
400MW	±j2.35730	±j8.95629	±j9.00335

Table 3 Eigenvalue sensitivity of bus #7 and 8

	$\partial\lambda_{1,2}/\partial P_{ab}$	$\partial\lambda_{3,4}/\partial P_{ab}$	$\partial\lambda_{5,6}/\partial P_{ab}$
200MW	$\mp$ j0.16105	$\pm$ j0.03263	$\pm$ j0.03195
300MW	$\pm$ j0.36540	$\pm$ j0.08670	$\pm$ j0.02006
400MW	$\pm$ j0.95970	$\pm$ j0.21240	$\pm$ j0.02122

The eigenvalues have different variations from line flows respectively. Therefore, it is possible to determine correlated lines with the sensitivity values.

3. Case studies

3.1 Transient stability

The proposed method is applied to a test system which has 6 generators and 20 buses. Some critical ones are given here.

- CCT of bus # 152 = 0.7913 sec
- CCT of bus # 154 = 0.3494 sec
- CCT of bus #3002 = 0.6166 sec

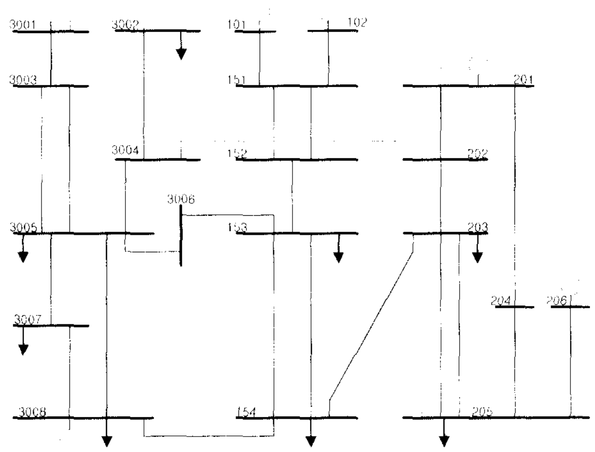

Fig. 9 Test system

Table 4 Priority list w.r.t. transient stability

From	To	Bus 152	Bus 154	Bus 3005
151	101	4277.32	1967.44	975.78
151	102	4277.32	1967.44	975.78
151	152	2808.08	1447.63	641.19
151	201	8386.71	6703.05	7253.62
152	153		953.87	577.75
152	202		17718.46	6037.99
152	3004		9090.21	49902.91
153	154	4926.28	9023.41	586.35
153	3006	12451.01	5918.89	9582.51
154	203	3604.81		475.08
154	205	1951.34		3184.26
154	3008	10303.78		12742.68
201	202	981.72	2729.67	605.33
201	204	3545.88	5666.06	415.88

202	203	4235.21	6312.19	343.93
203	205	4957.12	6565.18	716.72
204	205	3069.72	6079.01	424.75
205	206	3221.23	6192.94	651.88
3001	3002	12722.48	5331.17	9951.33
3001	3003	6490.08	5750.78	7515.23
3002	3004	12722.48	5331.17	9951.33
3003	3005	6464.92	5750.21	
3004	3005	4773.92	1441.57	
3005	3006	10447.11	5744.75	10079.83
3005	3007	3080.24	2021.52	2697.14
3005	3008	5180.26	15673.39	
3007	3008	4651.57	25801.96	5621.25

Table 4 shows TSP indices of transmission lines, and the priority list is proposed based on the indices. The results say that lines between buses 151 and 201, buses 154 and 3008, and buses 3001 and 3002, and buses 3002 and 3004 are related to the faults which are not on their buses. Time domain simulation of those contingencies are performed to verify identification method, and Figures 10, 11, 12, and 13 show the line flow between buses #154 and #3008 has more significant variations due to fault clearing time than other ones.

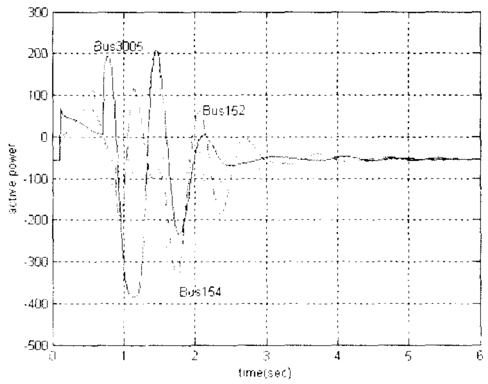

Fig. 10 Active power between buses #154 and 3008 (before CCT)

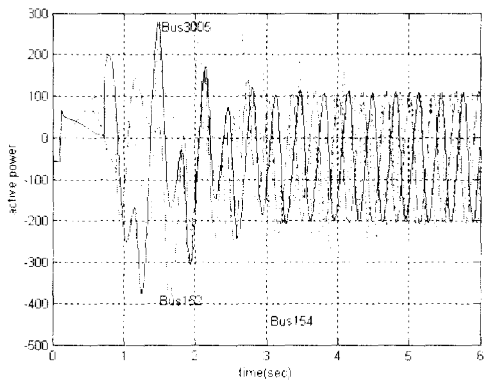

Fig. 11 Active power between buses #154 and 3008 (at CCT)

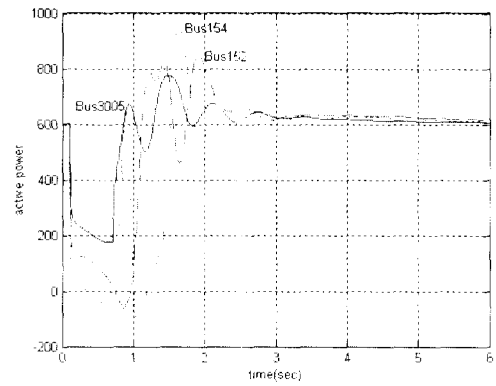

Fig. 12 Active power between buses #204 and 205 (before CCT)

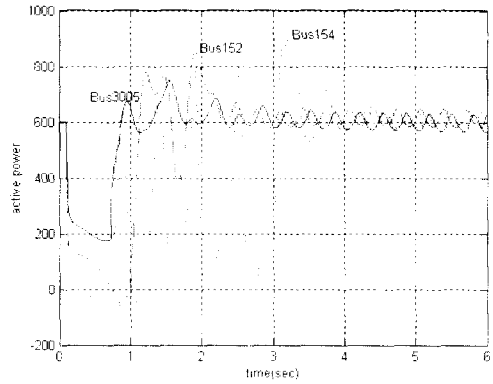

Fig. 13 Active power between buses #204 and 205 (at CCT)

3.2 Small-signal stability

Damping of the modes isn't represented since classical model is used for the generator modeling for the derivation of the eigenvalue sensitivity w.r.t. line flow. Hence, critical modes are selected only by observing the frequencies. Table 5 shows the modes of the test system, and the modes 3 and 4 are identified as the critical modes.

Table 5 Modes of the test system

Eigenvalue		ω[rad/s]	F[Hz]	T[s]
$\lambda_{1,2}$	±j1.645E+02	±1.645E+02	26.19	0.0382
$\lambda_{3,4}$	±j0.348E+02	±0.348E+02	5.535	0.1806
$\lambda_{5,6}$	±j1.274E+02	±1.274E+02	20.27	0.0493
$\lambda_{7,8}$	±j1.089E+02	±1.089E+02	17.33	0.0577
$\lambda_{9,10}$	±j1.089E+02	±1.089E+02	17.96	0.0557

Table 6 Eigenvalue sensitivity of modes 3 & 4

	Bus154~3008	Bus204~205	Bus201~202
$\partial\lambda_{3,4}/\partial P_{ab}$	±j2.103E-06	±j2.498E-07	±j5.576E-07

Table 6 shows $\partial\lambda/\partial P_{ab}$ of the critical modes ($\lambda_{3,4}$), and the eigenvalues have different variations from line flows respectively. Therefore, it is possible to determine correlated lines with the sensitivity values. Sensitivity derivation with detail generator modeling is under way in order to include effects on damping of modes.

4. Conclusion

This paper deals with an identification method for stability monitoring. Transmission lines which are correlated with power system transient and small-signal stability are identified using the proposed method, and time-domain simulation results support the method. Also, the TSP index introduced in this work identified line flows with large variation to large disturbances. Eigenvalue sensitivity with respect to line power flows shows the possibility for the use in identifying crucial transmission lines to the critical modes.

Measurement systems with GPS (Global Positioning System) can be put into the selected transmission lines in order to monitor power flows in real-time, and it could enhance power system stability with proper prediction methods.

Acknowledgment

This work was supported by the Electrical Engineering & Science Research Institute.

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