# 과도 안정도 해석을 위한 다기 계통 2축 모델을 이용한 확장 비반복 알고리즘

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# Extended Noniterative Algorithm Using Multi-machine Two-Axis Model for Transient Stability Analysis

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**Abstract** - The Conventional time-domain simulation of transient stability requires iterative calculation procedures to consider the saliency of generator. Recently, a non-iterative algorithm has successfully developed to take into account the generator saliency exactly with the use of $E_q'$-model. This study proposes an extended non-iterative algorithm by adopting the two-axis generator model. Given internal voltages and rotor angles of the generators, network voltages and generator currents can be directly calculated by solving a linear algebraic equation, which enables us to reduce the computation time remarkably.
Key Words : Power-system Transient Stability, Two-Axis Model, Dynamic Load Modeling, Non-iterative Algorithm, On-Line Application, Sparsity-oriented Programming.

## 1. Introduction

Recently, more interests have been focused on the fast transient stability simulation in order to establish the countermeasures against the possible contingencies. Most of the conventional algorithms adopt the iterative computation procedures to take into account the saliency effects of generators, which consume most of the computation time. Dandeno and Kundur[1] presented a non-iterative technique by eliminating the generator saliency with the use of the 'dummy' rotor circuits. Moon et al. presented a new approach to analyze the polarized linear networks with two reactance components[2,3]. This approach provides us with a new non-iterative technique for the transient stability simulation with the consideration of the generator saliency. On the basis of this new technique, Moon et al. presented the SRNI (Saliency-Reflected Non-Iterative) algorithm using the sparsity-oriented programming technique[3]. This algorithm is developed with the use of $E_q'$-model for the generators, and thus has some limitation in taking into account the detailed characteristics of the generator.

In this study, a non-iterative algorithm of the transient stability simulation has been successfully developed by extending the SRNI algorithm for the application to two-axis modeling cases. The sparsity-oriented programming technique is adopted to take advantage of the sparsity of the network matrix.

The extended algorithm has been tested for 145-bus Ontario Hydro system with 50 generators. The test results are compared in accuracy and in computation time with those obtained by the SRNI algorithm and the commercial program package CYME.

## 2. System Representation with Two-Axis Model

In this study, the generators are represented by the two-axis model. For each generator, the state equations are given by

$$T_{do}' \frac{dE_q'}{dt} = -E_q' - (X_d - X_d')I_d + E_{fd} \quad (1.a)$$

$$T_{qo}' \frac{dE_d'}{dt} = -E_d' + (X_q - X_q')I_d \quad (1.b)$$

$$\frac{d\delta}{dt} = \omega - \omega_s \quad (1.c)$$

$$\frac{2H}{\omega_s}\frac{d\omega}{dt} = P_M - E_d'I_d - E_q'I_q - (X_q' - X_d')I_dI_q - T_{FW} \quad (1.d)$$

In transient stability analysis, two difficult problems are usually encountered. One is dealing with the generator saliency and the other is the treatment of the nonlinearity of the loads. However, Moon et al.[2,3] pointed out that the circuit with generator saliency is also a linear network with polarity and thus the polarized linear network can be analyzed without any iterative procedure by solving a set of linear equations.

In order to remove the nonlinearity of the load, we can introduce a dynamic current source model as follows:

$$T_{Li}\dot{I}_{Li} = -\mathbf{I}_{Li} + [P_{Li}(V_i) - jQ_{Li}(V_i)]/\mathbf{V}_i^* \quad (2)$$

$$\text{with} \quad V_i = |\mathbf{V}_i|$$

Here it is noted that the above equation has the steady state current.

$$I_{Li} = [P_{Li}(V_i) - jQ_{Li}(V_i)]/V_i^* \quad (3)$$

Consequently, the load model represented by (2) always satisfies the steady state power condition. If the time constant $T_{Li}$ is sufficiently small, then the current source model has almost negligible errors compared with the ideal load model. As a matter of fact, almost all the bus loads in power systems have the non-negligible time constant and they are usually assumed to be constant impedance loads during the transient period after a large disturbance. In order to take a compromise between the ideal and the practical models, this study adopts an assumption that the time constant is equal to the integration time step, i.e. the current in (2) can be updated with a simple formula as follows[4]:

$$I_i(t_{k+1}) = [P_{Li}(V_i(t_k)) - jQ_{Li}(V_i(t_k))]/V_i^*(t_k) \qquad (4)$$

With the use of the above dynamic current source model for all loads, the power system can be represented by the following polarized linear network. This system can be analyzed by solving a set of linear equations without any iteration procedure[2].

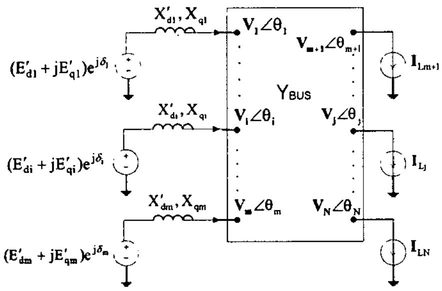



Fig. 1. Polarized Linear System

## 3. Extended Noniterative Algorithm

### 3.1 System Equations

The system equations are given by the generator-referenced terminal voltage equations and the network equations.

The generator terminal voltage equations are given by

$$(E'_{qi} - jE'_{di}) = V_i e^{j(\theta_i - \delta_i)} + R_{si}(I_{qi} - jI_{di}) + X'_{di}I_{di} + jX'_{qi}I_{qi} \qquad (5)$$

By multiplying both sides of (5) by $e^{j\delta_i}$ the generator terminal equations can be rewritten as

$$\mathbf{E}'_{Gi} = \mathbf{V}_i + R_{si}\mathbf{I}_{Gi} + jX'_{di}\mathbf{I}_{Di} + jX'_{qi}\mathbf{I}_{Qi} \qquad (6)$$

where

$$\mathbf{E}'_{Gi} = (E'_{di} + jE'_{qi})e^{j(\delta_i - \pi/2)} \qquad (7.a)$$

$$\mathbf{I}_{Gi} = I_{qi}e^{j\delta_i}, \mathbf{I}_{Di} = I_{di}e^{j(\delta_i - \pi/2)} \qquad (7.b)$$

$$\mathbf{I}_{Gi} = \mathbf{I}_{Di} + \mathbf{I}_{Qi} \qquad (7.c)$$

By using the partitioned bus admittance matrix, the network equation is given by

$$\begin{bmatrix} \mathbf{I}_G \\ -\mathbf{I}_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} \mathbf{V}_G \\ \mathbf{V}_L \end{bmatrix} \qquad (8)$$

with $\mathbf{V}_G = [\mathbf{V}_1, \Lambda, \mathbf{V}_m]^T$
$\mathbf{V}_L = [\mathbf{V}_{m+1}, \Lambda, \mathbf{V}_N]^T$

$Y_{GG}, Y_{GL}, Y_{LG}, Y_{LL}$: Partitioned matrices of $Y_{BUS}$

With introduction of real variables $K_{Di}$ and $K_{Qi}$, we can assume that

$$\mathbf{I}_{Di} = -jK_{Di}\mathbf{E}'_{Qi} \qquad (9.a)$$

$$\mathbf{I}_{Qi} = K_{Qi}\mathbf{E}'_{Qi} \qquad (9.b)$$

where

$$\mathbf{E}'_{Qi} = E'_{qi}e^{j\delta_i} \qquad (9.c)$$

The above equations are the basic equations to be considered in the transient simulation.

In the time simulation, we have two major problems; one is to calculate the initial conditions of generators, and the other is to calculate the network bus voltages after the generator state update.

### 3.2 Update of the Network Bus Voltages

In the transient stability simulation, it is the most time consuming process to calculate the network bus voltages for the updated generator internal voltages and the updated load currents. Here, we will consider the update of network bus voltages by assuming that all of $E_{Qi}'$, $E_{Di}'$ and $I_{Li}$ are known at the time $t = t_k$ for all generators and loads.

By using (6) and (9), we can rewrite (8) in the following matrix form:

$$\begin{aligned} &A\mathbf{K}_D + B\mathbf{K}_Q - Y_{GL}\mathbf{V}_L = Y_{GG}\mathbf{E}'_G \\ &C\mathbf{K}_D + D\mathbf{K}_Q - Y_{LL}\mathbf{V}_L = -(\mathbf{I}_L + Y_{LG}\mathbf{E}'_G) \end{aligned} \qquad (10)$$

$$\begin{aligned} &A = -j(I + Y_{GG}(R_S + jX'_d))D_{EQ} \\ &B = (I + Y_{GG}(R_S + jX'_d))D_{EQ} \\ &C = jY_{SG}(R_S + jX'_d))D_{EQ} \\ &D = -Y_{SG}(R_S + jX'_d))D_{EQ} \\ &\text{with } D'_{EQ} = \mathrm{diag}(\mathbf{E}'_{Q1}, \Lambda, \mathbf{E}'_{Qm}) \end{aligned} \qquad (11)$$

$R_S, X'_d, X'_q$ : Diagonal matrices

The derivation of the above equation can be found in [3]. Here, it is noted that the matrices A, B, C, D keep the sparsity of $Y_{BUS}$.

$$\begin{aligned} &\mathbf{A}_R\mathbf{K}_D + \mathbf{B}_R\mathbf{K}_Q - \mathbf{G}_{GL}\mathbf{V}_{LR} + \mathbf{B}_{GL}\mathbf{V}_{LI} = \mathrm{Re}[Y_{GG}\mathbf{E}'_G] \\ &\mathbf{A}_I\mathbf{K}_D + \mathbf{B}_I\mathbf{K}_Q - \mathbf{B}_{GL}\mathbf{V}_{LR} + \mathbf{G}_{GL}\mathbf{V}_{LI} = \mathrm{Im}[Y_{GG}\mathbf{E}'_G] \\ &\mathbf{C}_R\mathbf{K}_D + \mathbf{D}_R\mathbf{K}_Q - \mathbf{G}_{LL}\mathbf{V}_{LR} + \mathbf{B}_{LL}\mathbf{V}_{LI} = \mathrm{Re}[-\mathbf{I}_L - Y_{LG}\mathbf{E}'_G] \\ &\mathbf{C}_I\mathbf{K}_D + \mathbf{D}_I\mathbf{K}_Q - \mathbf{B}_{LL}\mathbf{V}_{LR} + \mathbf{G}_{LL}\mathbf{V}_{LI} = \mathrm{Im}[-\mathbf{I}_L - Y_{LG}\mathbf{E}'_G] \end{aligned} \qquad (12)$$

where $V_{LR} = \mathrm{Re}[V_L]$ and $V_{LI} = \mathrm{Im}[V_L]$

$Y_\alpha = G_\alpha + jB_\alpha \quad \alpha = \mathrm{GL}$ or $\mathrm{LL}$

<u>Notations</u> : The real and imaginary part of the matrices are denoted in the manner of $A_R$,$A_I$ and so on.

## 4. Time Simulation Results

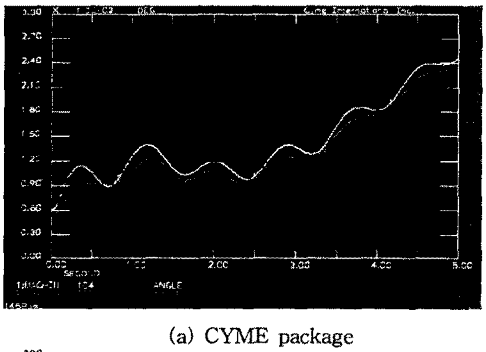
The proposed algorithm was applied to the OH 50-generator system. The test was conducted for two generator models, i.e. 1-axis and 2-axis models. For the comparison with the conventional iterative methods, the time simulation was also performed by using the CYME package(VER 1996), which use the fast-decoupled Newton-Raphson method for solving the nonlinear power flow equations.

The time simulation was performed for 5 sec simulation periods with time interval 0.01 sec for the contingency of three-phase fault at t = 0. In this test, the specified fault was always cleared at 0.1 sec. Since the test was intended to prove the applicability of the proposed algorithm to the two-axis generator model, all governor and exciter effects were neglected. The numerical results are given with the comparison of the execution time with that of the CYME packages.

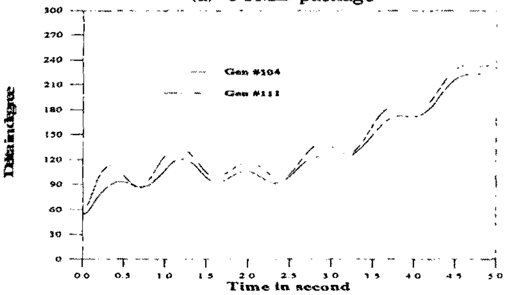
### OH50-Generator System

The proposed method was tested with OH 50-generator system. A three phase at Bus 7 was selected as a contingency case in concern and the fault duration was assumed to be 0.1 sec. The rotor angle plots for generators at Bus 104 and Bus 111 are given in Fig. 2. Figure 2 (a) and (b) show the results by the both methods respectively. The simulation results in the case of 1-axis generator model can be found in Reference [3].

These plots show that the simulation results obtained by both methods are exactly same.



(a) CYME package




(b) Proposed Algorithm

Fig. 2 Plot of Generator Angles of OH 50-Generator System by the Proposed Algorithm

Table 1 lists the comparison of simulation time for OH 50-generator test system, which shows the proposed method reduces the computation time drastically. From this results, the computation speed of proposed algorithm almost competes for the on-line application.

Table 1. Comparison of Computation Time for 5sec. ( OH 50-generator test system)

| Model \ Method | The CYME package | Proposed Algorithm |
|---|---|---|
| 1-Axis Model | 65.00 sec | 4.50 sec |
| 2-Axis Model | 84.00 sec | 4.73 sec |

## 5. Conclusion

This paper presents an extended noniterative algorithm to apply to the power system with the 2-axis generator model. The SRNI algorithm is extended to be adaptable to the two-axis generator model with slight modification related to the transient q-axis reactances and the generator internal voltages. It provides the remarkable reduction of calculation time by avoiding the time consuming iterations.

In this paper, it has been shown that the noniterative algorithm can be well applied to 2-axis generator model with the test results to the OH 50-generator systems.

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