Development of an instantaneous and phasor analysis combined type real-time digital power system simulator

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***Abstract* – This paper describes the outline and verification results of an instantaneous and phasor analysis combined type real-time digital power system simulator. This simulator enables real-time calculation for large-scale power systems, using instantaneous analysis for detailed part of the system and phasor analysis for the rest to reduce calculation load. This may also reduce instantaneous analysis modeling errors because network reduction is no longer necessary.**

Keywords – real-time digital power system simulator, instantaneous analysis, phasor analysis, combined analysis.

I. INTRODUCTION

Large-scale power system simulators for transient analysis and equipment testing are coming to be significant for sophisticated power systems. In the case of digital simulations for power systems, instantaneous values or RMS (Root Mean Square) values are used. Instantaneous values are used for simulations of electromagnetic and electromechanical phenomena. The calculations are carried out with short time-steps such as 50 microseconds, requiring many powerful processors to analyze large-scale power systems in real-time [1]. On the other hand, RMS values are used in phasor analysis. It is used for long-term stability studies with larger time-steps so that it can easily realize large-scale power system analyses.

Authors have developed the real-time digital simulator which combines instantaneous and phasor analysis to simulate both transient and dynamic phenomena in bulk power system. The advantages of the proposed simulator are expected to decrease uncertainty caused by network reduction, to ease incorporating detailed modeling, such as load characteristics and complicated generator control systems, and to enable simulation of HVDC system interfaced with other simulators, such as RTDS [2].

Authors are now developing the combined instantaneous and phasor analysis program. This paper describes the combined analysis real-time power system simulations.

II. SIMULATOR CONFIGURATION

The simulator has been developed on a parallel computer, SGI ORIGIN2000 (32 CPUs). It consists of INS program (instantaneous analysis program), RMS program (phasor analysis program), control analysis program, sequence program, output processing and Graphical User Interface (GUI). They are processed in parallel, respectively. The configuration of the processing units is shown in Fig.1.

Each program, such as sequence, output and GUI, occupies one CPU. INS program, RMS program, and Control analysis program use several processors required for real-time processing.

Each processing unit uses its own time-steps. For example, INS program; 50 microseconds, RMS program; 1 millisecond. Processors synchronously exchange analysis data and results at each processing time step among them.

III. PROCESSING OUTLINE

This chapter shows the outline of each processing unit.

A. INS program

The instantaneous analysis program uses the Bergeron method [3]. By this method, since one power system can be separated into several partial power systems at distributed-parameter lines, real-time simulation is achieved to calculate the transient phenomena of these partial power systems in parallel.

The time step is typically 50 microseconds, and it is equipped with electric models, such as generators, AC and DC lines (Π model and distributed-parameter line model), transformers, constant impedance elements, breakers and switches.

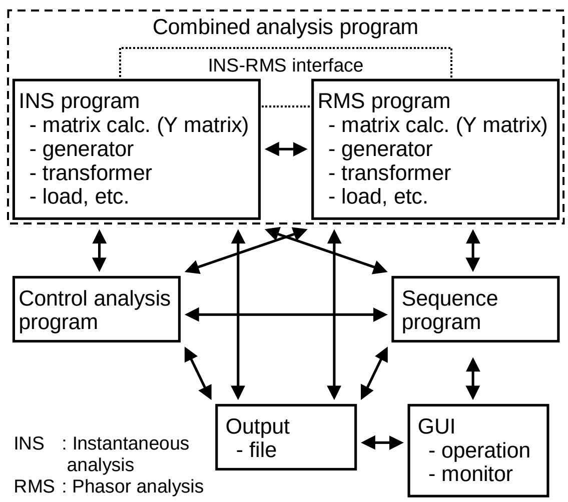


Fig. 1 Configuration of the developed real-time simulator

B. RMS program

This program uses per-unit values and simulates three phase AC power systems by phasor analysis. It uses load flow program results as initial conditions, and executes series of simulations. Generators and machines are expressed in differential equations, and state variables are acquired by numerical integration for every time step. Transmission lines, transformers, and loads are expressed in algebraic equations, and state variables are acquired by iterative calculations to have convergence, such as Newton-Raphson method, for every time step.

In order to realize combined analysis (instantaneous and phasor analysis), this program uses 1 millisecond time step. It also uses the BBDF (Bordered Block Diagonal Form) method to divide admittance matrix [4]. Each of the divided matrix is assigned to different CPU and calculated in parallel to achieve real-time simulation.

C. Control analysis program

This program expresses all control systems with differential equations and algebraic equations, and uses the fourth order Runge-Kutta method as the integration technique. Since time constants of the power system control systems are larger than time steps of instantaneous and phasor analysis program, this program is separated from other programs and calculated in parallel. It uses larger time step to obtain real-time simulation.

D. INS and RMS Combined analysis program

This is the program which combines INS and RMS program. At the combined point of INS and RMS analysis network, a common branch is given to both analysis, and they exchange the voltage, current, and phase angle data each other (Fig.2).

In the INS program, common branches are modeled in the distributed-parameter line. Since RMS program's time step is larger than INS program, INS program cannot acquire the latest results from RMS program for every time step. Therefore, INS program uses the predicted values sought from the past RMS data.

In the RMS program, common branches are modeled in the surge impedance and the equivalent current source, and the propagation time is expressed as the phase angle difference.

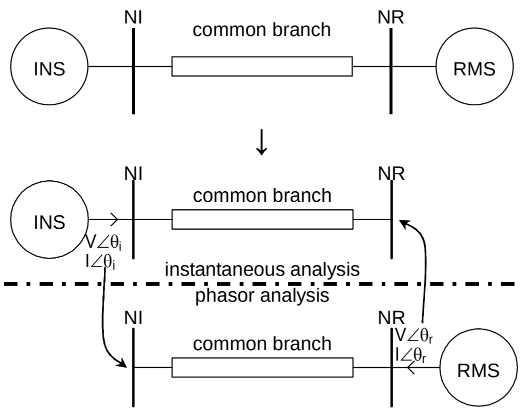


Fig. 2 Data exchange at INS-RMS combined point

D.1 Data communications

(a) RMS to INS communication

INS program receives the latest voltage, current and phase angle from RMS program. The communication diagram between RMS and INS program is shown in Fig.3. Data communication is performed for every RMS program time step, and previous time step data are transferred to INS program from RMS program. Since RMS program time step is longer than INS program, INS program predicts current values from past data. The prediction method is written in subsection D.2.

(b) INS to RMS communication

RMS program receives the latest voltage, current and phase angle from INS program. Data communication is performed for every RMS program time step, as shown in Fig.3. Since INS program time step is sufficiently smaller than RMS program time step, RMS program doesn't need prediction.

D.2 Data prediction

Prediction values, which are used in INS program, are sought from the past two data by calculating a weighted average value. In this way, the data become more continuous.

The prediction formulas are as follows.

$$|V|_{(0)} = (1-\alpha)|V|_{(-2)} + \alpha|V|_{(-1)}$$
$$\theta_{V(0)} = (1-\alpha)\theta_{V(-2)} + \alpha\theta_{V(-1)}$$
$$\left.\begin{aligned} V_a &= |V|_{(0)}\cos(\omega t + \theta_{V(0)}) \\ V_b &= |V|_{(0)}\cos(\omega t + \theta_{V(0)} - \tfrac{2}{3}\pi) \\ V_c &= |V|_{(0)}\cos(\omega t + \theta_{V(0)} + \tfrac{2}{3}\pi) \end{aligned}\right\}$$

The numbers in parenthesis express relative time step from the present time. $|V|_{(0)}$ expresses absolute value of the current voltage. $\theta_{V(-2)}$ represents the voltage phase angle of two previous RMS data. α is the ratio of the present time to one RMS program time step. For example, α = T1/T0 in Fig.4.

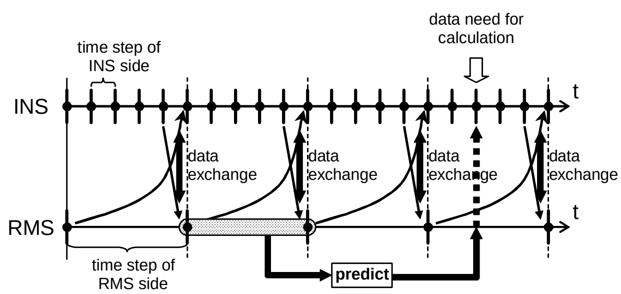


Fig. 3 Communication between INS and RMS

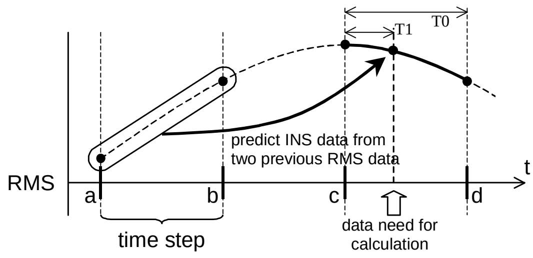


Fig. 4 Prediction method of RMS data

E. Sequence program

This program manages control sequence, such as circuit breaker operation and generator power setting. It uses one CPU exclusively, and data communication is executed with other CPUs for every RMS program time step.

When power system conditions are changed, such as line-to-ground fault, this program calculates new admittance matrix for RMS and INS program dynamically. Also, a user can create control sequence to arbitrary timing.

F. Output

This program saves the analysis results, which are calculated on other CPUs. In order to avoid the interruption of real-time simulation caused by file operations, this program uses one CPU exclusively and is executed in parallel with other CPUs.

When this program receives the output instructions from the sequence program, output CPU stores the results data obtained by the analysis program, and saves the results to files. Output intervals can be individually set up for every analysis program (RMS, INS, and control).

G. GUI(Graphical User Interface)

This program interfaces a user with analysis. It also uses one CPU exclusively, and is executed asynchronously with other CPUs. A user can operate and monitor the simulation models through the GUI.

If a user gives sequence instructions to GUI, they are sent to the sequence CPU. To display the current status of the power system, GUI asynchronously refers to required data from output CPU. GUI example is shown in Fig.5.

IV. REAL-TIME SYNCHRONIZATION

Concept of real-time synchronous processing is explained in Fig.6.

In INS program, partial power systems are assigned for some CPUs, and data transfer among them is performed for every INS program time step. Also data transfer among the partial power system analysis CPUs and the control system analysis CPUs is performed for every control system time step. RMS program performs data transfer similarly.

In combined analysis, data transfer between INS and RMS program is also performed for every RMS program time step.

In order to assure the real-time operation, the programs

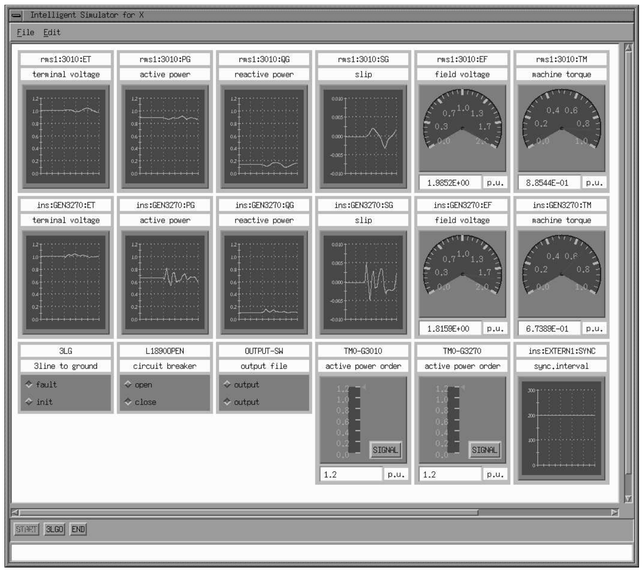


Fig. 5 Example of real-time simulation panel (GUI)

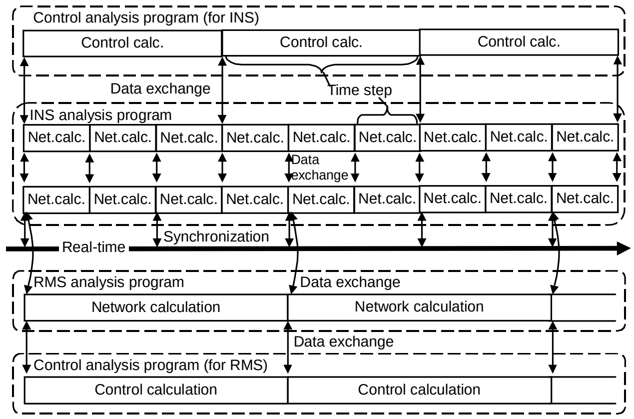


Fig.6 Synchronization with real-time

are required to synchronize with real time clock. In this analysis system, one CPU in INS program manages real-time operation. Real-time simulation of the whole analysis system is assured by synchronizing with this CPU.

V. COMBINED ANALYSIS SIMULATION RESULTS

In order to verify the developed simulator, simulation tests were carried out. Also, off-line simulations were performed by EMTP [3] and the Y-method [5], which is a phasor analysis program widely used in Japan, to compare with the combined simulator results. The Institute of Electrical Engineers in Japan (IEEJ) Power System Model [5] is used as simulation data.

A. one-point connection

First, one-point connection model is verified by using IEEJ WEST10 power system model, which is shown in Fig.7. This model has 10 generators and G10 is the largest generator. The power system frequency is 60Hz, all transmission line has two circuits, and all loads have constant current characteristic originally.

In the combined analysis, the load characteristic is changed into constant impedance and the central branch is set as common branch, which is 100 kilometers long.

The left hand side of the Fig.7, which includes generator G1, is set as the INS analysis, and the right hand side as RMS analysis. Moreover, the time step is set to 1 millisecond for the Y-method, in accordance with the RMS program.

At the fault point in Fig.7, three-phase fault occurs at 2 second, and the fault continues for about 70 milliseconds until the fault transmission line is opened.

The simulation results are shown in Fig.8. Fig.8 (a), (b) show the active power of generators, which are expressed as INS and RMS model, and they are compared with the Y-method results. Fig.8 (c), (d) show three phase voltage at the fault point, which are the results of the combined simulator and EMTP, respectively.

As shown in Fig.8, power system dynamic characteristics of the combined simulation well coincide with the Y-method results. Moreover, the accuracy of this combined simulator during transient phenomena is also confirmed.

In order to evaluate the influence of RMS program time step, it is changed to 5 milliseconds, and the results are compared with 1 millisecond and Y-method result (Fig.9).

Since RMS program exchanges the results with INS program, it is equivalent that 60Hz transient phenomena, which comes from the direct current component in INS program, is superimposed on RMS analysis. In this case, RMS program time steps is equivalent to sampling time. For this reason, longer time step results in larger error.

However, as shown in Fig.9, the influence on power system dynamic characteristics is negligible.

B. two-point connections

In order to verify two-point connections and load characteristics, IEEJ WEST30 power system model is used. This network has 30 generators, all loads have constant current characteristics, and the power system frequency is 60 Hz. The network is divided into three subsystems, and one of the subsystem, which is shown in Fig.10 shaded area, is modeled in INS program. Also the load characteristics are set as constant impedance in INS program and constant current in RMS program. Common Branches are about 80 (RMS1 – INS) and 55 (RMS2 – INS) kilometers long. In the Y-method analysis, the load characteristics are set to two types;

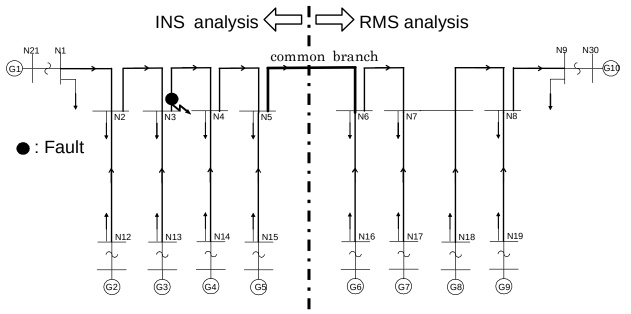
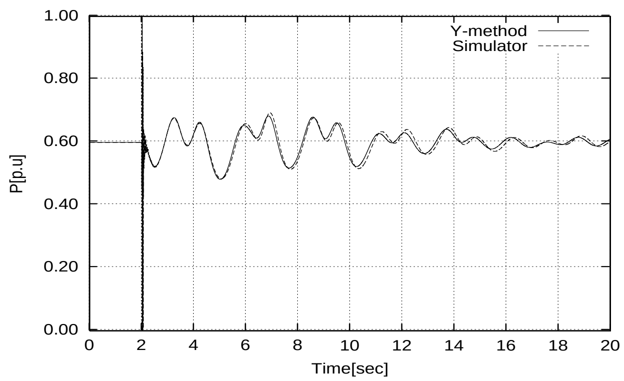
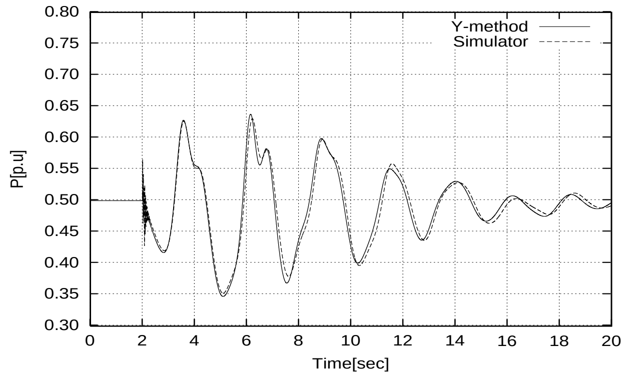


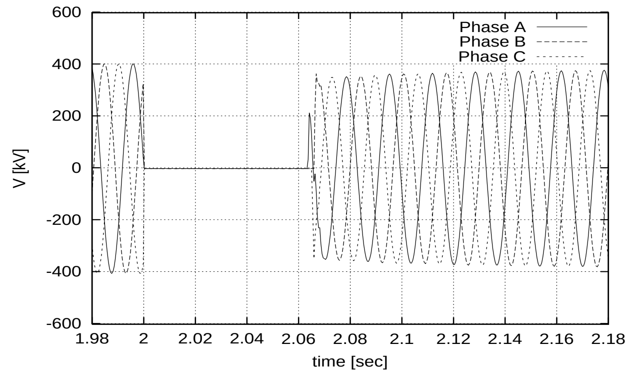
Fig. 7 IEEJ WEST10 Power System



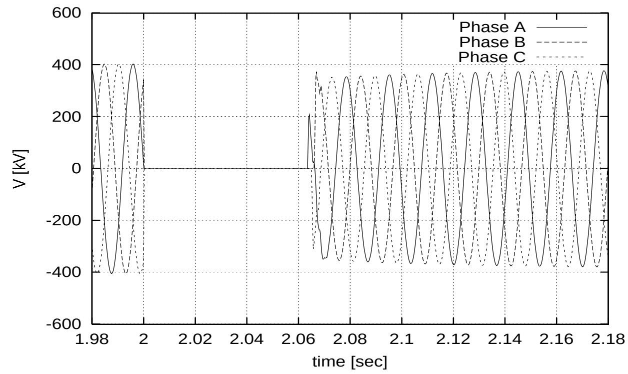
(a) Generator G4 Active Power (INS network side)



(b) Generator G7 Active Power(RMS network side)



(c) Fault point three phase voltage (Simulator result)



(d) Fault point three phase voltage (EMTP result)

Fig. 8 WEST10 simulation results

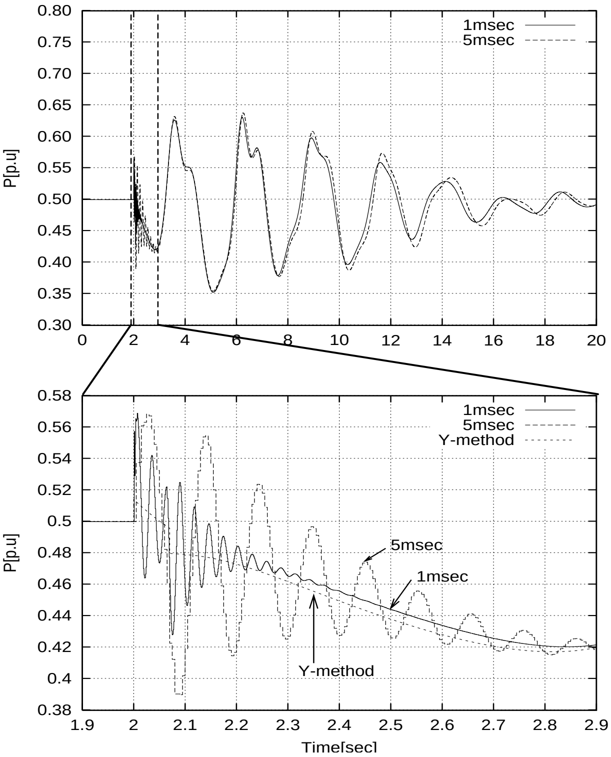


Fig.9 Influence of time step (Generator G7 Active Power)

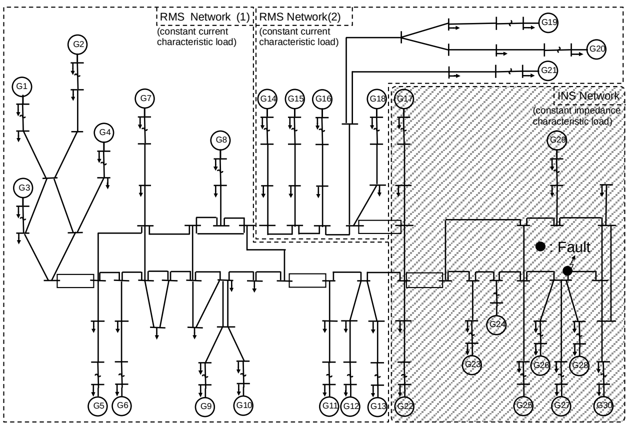


Fig. 10 IEEJ WEST30 power system

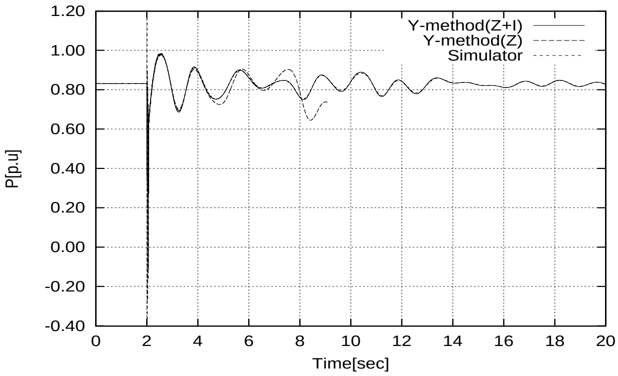
(1) All loads have constant impedance characteristics (Z).

(2) Loads of RMS network 1 and 2 have constant current characteristics and INS network loads have constant impedance characteristics (Z+I).

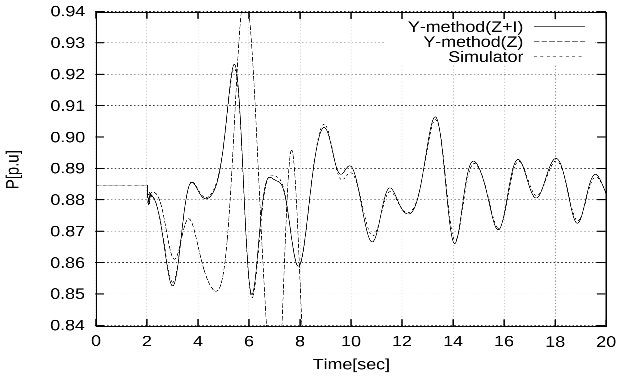
At the fault point in Fig.10, three-phase fault (1 line) occurs at 2 second, and the fault continues for about 70 milliseconds until the fault line is opened.

The simulation results are shown in Fig.11. Each figure shows the active power of the generators in each subsystem. The combined simulator results are superimposed with the Y-method results.

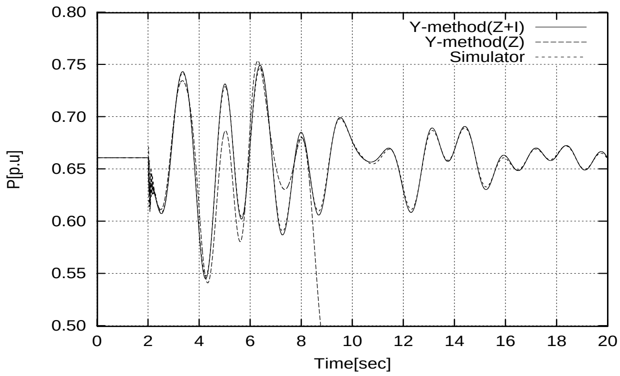
In the Y-method result, when all loads have constant impedance characteristics, the power system is unstable. Some generators (ex; G1, G20) step out, and the analysis stops halfway. As shown in Fig.11, the results of the combined method are well consistent with the Y-method results.



(a) Generator G27 active power (INS network)



(b) Generator G1 active power (RMS network 1)



(c) Generator G20 active power (RMS network 2)

Fig. 11 WEST30 simulation results

As a result, it is also confirmed that the combined simulator has sufficient accuracy when two-point connections and constant current load characteristics are used in the analysis.

C. real- time simulation performance

In order to assure the real-time simulation of the combined analysis program, one INS program CPU manages synchronization with real time. Synchronous interval is the time difference between the previous and current synchronization monitoring time.

Fig.12 shows the synchronous intervals when the simulator is calculating the WEST30 power system. In this case, synchronous interval is set to 200 microseconds, which is four time steps of INS program. Since the combined simulator is completely executed in real-time,

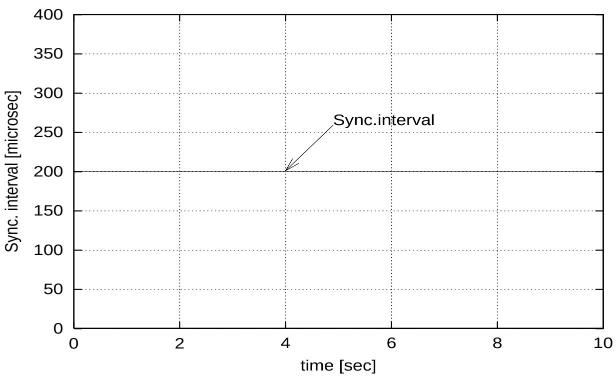


Fig. 12 Synchronization monitoring result

the graph line is fixed to 200 microseconds.

The number of CPUs used for each processing is shown in Table 1. In order to simulate WEST30 power system in real-time, the combined analysis uses 19 CPUs. Therefore it is possible to simulate much larger power systems in real-time by using up to 32 CPUs.

Table 1 Number of CPU used for each transaction

Transaction	CPU
RMS analysis	4
Control analysis for RMS	1
INS analysis	9
Control analysis for INS	2
Output	1
Sequence	1
GUI	1
Total	19

VI. CONCLUSIONS

This paper describes the processing outline of the developed INS and RMS analysis combined type real-time power system simulator, and the verification results by using IEEJ Power System Models.

The combined simulator has enough accuracy to simulate both power system stability and transient phenomena. It is also confirmed that this simulator is able to calculate large-scale power system in real-time.

By using the combined analysis, detailed model of large-scale power system can be used without network reduction. It is also possible to incorporate load characteristics easily in bulk power system simulation by modeling the load in RMS system.

REFERENCES

[1] Hiroto Inabe, “Real-Time Digital Simulation for Power System”, The Journal of The Institute of Electrical Engineers of Japan, Vol.122, No.5, 2002.
[2] “RTDS”, http://www.rtds.com/
[3] H. W. Dommel, “Electromagnetic Transients Program Reference Manual (EMTP Theory Book)”, BPA, 1986.
[4] Hiroto Inabe, et al., “Comparison between the BBDF method and the W-Matrix method for solving sparse network equations on shared memory type of computers”, ICEE2K, 2000.
[5] “Japanese Power System Models”, the technical committee of the Institute of Electrical Engineers in Japan, http://www.pwrs.elec. waseda.ac.jp /powsys /english /index.html