# The Overview of a Digital Power System Simulator for Large Power System Analysis

**Tae-Kyun Kim*, Yong-Hak Kim*, Jeong-Hoon Shin* and Jin-Boo Choo***

**Abstract** - This paper deals with the development and testing of a large-scale, realtime digital power system simulator for the Korean Electric Power Corporation. The KEPS Simulation Center is located at KEPCO's research center (KEPRI) in Taejon, South Korea and has been operated since September 2001.

The KEPS Simulation Center includes a wide range of off line power system simulation and analysis tools, as well as an advanced realtime digital simulator for the study of large scale AC and DC system performance.

Because the application scope of the KEPS realtime simulator is broad and because the network models being considered are significantly larger and more complex than in traditional realtime simulator applications, many developments and tests have been required during the course of the project. In this paper, the authors describe some of these developments and present results from various benchmark tests that have been performed.

**Keywords**: realtime simulation, non-realtime simulation, electromagnetic transient, stability, power system analysis.

## 1. Introduction

In the next several years, the Korean power system is expected to continue to experience widespread growth and expansion. Such growth will without doubt include the application of advanced power system technologies and techniques such as Ultra High Voltage (UHV) transmission, FACTS, HVDC and tie-line interconnection to neighboring and distant networks. To fully understand and exploit advantage of such techniques, the Korea Electric Power Research Institute (KEPRI) has undertaken a project that will see the development and installation of a large-scale power system simulation and study facility [1].

KEPCO is expecting to use the realtime aspects of the KEPS simulation facility to perform detailed digital simulation studies of electro-magnetic/electro-mechanical transient phenomena as well as dynamic phenomena in the power network. Interactions between equipment like protective relays, controllers, and power electronic devices will be studied in detail. KEPCO will test and investigate the performance and correct operation of protection systems, regulators, stability control devices, and various advanced FACTS systems.

The KEPS facility is also expected to serve as a training and education center for power system researchers and students as well as KEPRI & KEPCO engineers and operators.

## 2. Power System Analysis Tools

A number of analytical tools are available for the study of generation, transmission, and distribution systems. With the exception of the traditional analogue transient network analyzer (TNA), most tools are based on digital computer simulation techniques. The most suitable tool(s) for any one application depend on the specific goal(s) of that particular study.

Although the actual number of simulation tools available for study of power systems is large, most can be grouped into one of a few general categories.

### 2.1. Loadflow Programs

*Loadflow* (or power flow) programs are used to study the steady state operating conditions of an existing or proposed power system. Such studies address the power system under balanced three-phase operating conditions. No negative or zero sequence phenomena (or parameters) are considered.

The basic purpose of the loadflow simulation is to determine whether the proposed system operating conditions are within the capabilities of the installed equipment. Under acceptable system operating conditions, all generators must operate within their real and reactive power limits, all bus voltages must remain within specified limits, and all equipment loading must be within acceptable limits.

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* Power System Analysis Group, Korea Electric Power Research Institute(KEPRI), Taejon, Korea (tkkim@kepri.re.kr, jhshin@kepri.re.kr, jbc@kepri.re.kr).

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Typically, the loadflow study includes a large network model (several thousand buses is common). Many simulation cases representing a wide range of operating conditions are examined.

## 2.2 Stability Programs

*Stability* programs are used to determine whether a network will remain in synchronism following a significant disturbance.

Power system stability, by definition, is the measure of a network's ability to return to an acceptable steady state operating condition following a disturbance.

Network instability can occur in one of two general forms: (i) a steady increase in machine rotor angle due to lack of synchronizing torque, or (ii) machine rotor oscillation of increasing magnitude due to insufficient damping torque.

Depending on the type and magnitude of the disturbance being studied, the stability problem can be classified as either transient or dynamic.

Transient stability simulation is the most common method for studying long term electromechanical behavior of power systems. The transient simulation result is used to determine whether a network will return to acceptable operating conditions following the occurrence of major disturbances such as transmission system faults, loss of generation, sudden change of load, transmission line switching, and so forth.

Dynamic stability simulation (sometimes referred to as small-signal stability) is used to evaluate the ability of the network to maintain synchronism under small disturbances. Dynamic simulation is really a simple extension of the loadflow solution in which a slightly more complex representation of machines can be included. Since the disturbances considered in dynamic simulation studies are small, a linearized set of equations can be applied during the solution. As in the case of loadflow simulation, typical studies might include thousands of buses and hundreds of generators.

## 2.3 Electromagnetic Transient Simulation Studies

*Electromagnetic transient* simulation studies are concerned with fast transients on power systems. Network and component models include more detailed representation than in loadflow or stability simulation.

Electromagnetic transient simulation is based on concepts introduced by H. Dommel in his 1969 publication [2]. According to the Dommel algorithm, all passive components within the network can be converted to an equivalent resistor in parallel with a current source. The equivalent resistance value is time invariant (unless switching occurs) and depends on the component type and its parameters. The current injection, on the other hand, is time- and history-dependent and must be updated each time a new system state is produced.

Most of the electromagnetic transient simulation programs apply the trapezoidal rule of integration. Trapezoidal integration is both numerically stable and accurate enough for practical purposes.

Unlike loadflow and stability, electromagnetic transient simulation includes unbalanced system representation. Fast transients, such as those caused by switching or even lightning phenomena, can be studied. The chosen simulation time step (□t) will directly affect the fastest transient that can be accurately represented. Smaller time steps allow representation of higher frequency phenomena. However, as the time step is decreased, the computer time required to complete the required calculations increases. Typical electromagnetic transient simulations are performed using a time step of about 50 usec.

Electromagnetic transient simulation programs like EMTP and EMTDC are used to study system and equipment behavior over a very short period of time. In addition, because of the complexity of the solution algorithm, these programs generally deal with a reduced version of the original power system. Various reduction and equivalencing techniques exist that allow the user to retain important characteristics of the original system in the simulation model.

## 2.4 Realtime Simulation

*Realtime* simulation can be performed using either analogue or digital technology. Most analogue simulators are actually hybrid in that they are comprised of both analogue and digital components. The analogue/hybrid simulator represents a natural extension of the traditional analogue TNA, which has been applied in power system studies over the past several decades. Although analogue simulator studies have been widely applied by both equipment manufacturers and utilities, it is well known and well understood that several limitations and approximations are inherent in such studies. Perhaps the most significant difficulty with the analogue TNA relates to excessive damping.

The analogue TNA is essentially a scaled down replica of the actual power system. The simulator consists of various discrete analogue components that are connected together in a way that matches the actual network. Since the actual system includes various linear and non-linear components operating under high voltage and high current conditions, a scaled down model should accurately represent the response of these components at low voltage and current conditions, which is significant since the properties of the actual component don't necessarily scale linearly. For example, a transformer model on the simulator will contain a significantly higher resistance to inductance ratio than the actual unit. Special electronic components have been used to compensate for excessive losses; however, the application of such techniques is difficult and can lead to erroneous results and even instability if applied incorrectly.

The main advantage of the TNA is its ability to operate in realtime and hence its usefulness in testing physical equipment. Because of complexity in system set-up and calibration, analogue TNAs normally include a relatively limited network model. Portions of the network that are considered distant from the main area of study are either ignored or represented as equivalents.

During the past decade, several important advances have been made in digital computer hardware and in solution algorithms for the power industry. Perhaps the most significant evidence of this relates to the introduction of a fully digital realtime power system simulator [3]. Realtimedigital simulation essentially combines the modeling accuracy and flexibility of computer based simulation programs with the realtime operating aspects of the TNA.

## 3. The Keps Simulator

At the core of KEPS simulation facility is the Real Time Digital Simulator (RTDS®). The hardware architecture of the RTDS is based on parallel processing. A large number of digital signal processors (DSPs) participate in the simulation of the network solution as well as the individual power and control system components connected within the network. Each DSP is assigned specific computing tasks based on the topology of the network defined by the user. Timing and operation of all DSPs is synchronized to a single master time step clock that ensures accurate coordination of both computation and data exchange (data transfer).

For the KEPS project, nearly one thousand high-speed DSPs are included in the RTDS hardware architecture. The Analog Devices AD21062 DSP has been utilized in triple processor cards (3PC) used by the RTDS. Fig. 1 includes a view of the KEPS simulator hardware. In total, 26 racks of hardware mounted in 13 cubicles are used for the KEPS realtime simulator.

Operation and control of the KEPS realtime simulator is accomplished through user friendly graphical interface software, PSCAD® [4]. A number of developments were carried out to improve the applicability of PSCAD to realtime simulation of *large-scale power systems*. Fig. 2 illustrates visualization modules.

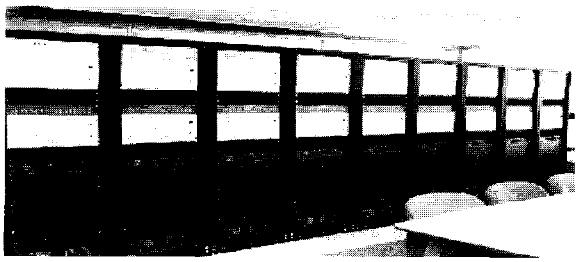

**Fig. 1** KEPS Hardware

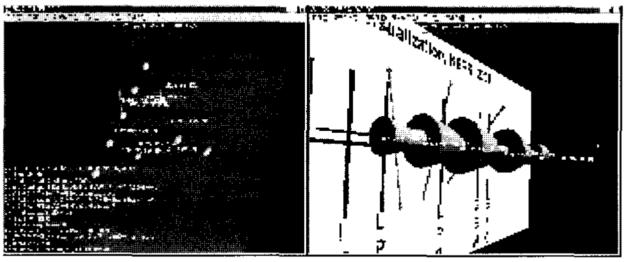

**Fig. 2** KEPS Software

Fig. 3 illustrates the basic layout of the KEPS RTDS simulator in Korea. Although the simulator can be operated as one large unit, its modular design also makes it possible to run several smaller simulators simultaneously, so that several studies can be carried out in parallel. Figure 3 shows that the KEPS final installation takes advantage of the inherent modularity and that separate study areas have been provided for protection development and testing, HVDC development and testing, SVC development and testing, FACTS development and testing, and for power system development and analysis. With this approach, KEPRI is able to take full advantage of the realtime simulator in all planned areas of application.

## 4. The Keps Realtime Network Model

The power system configuration upon which the size, of the realtime KEPS simulator (i.e., number of processors) has been based is a dynamically reduced equivalent of the expected Korean power system in 2010. The portion of the system with voltages of 154 kV and above has been considered in the specified largest equivalent system (LES) model. For the LES, at least the following components are included.

- 30 Generators and controllers
- 30 Generator Transformers
- 15 Step Down Power Transformers
- 6 Lumped Passive Loads
- 66 Dynamic and Other Load Models
- 8 Voltage Sources
- 24 Three-Phase Circuit Breakers
- 17 PI Model Lines (short lines)
- 11 Single Circuit Lines
- 92 Twin Circuit Lines
- 1 Triple Circuit Line
- 1 Quadruple Circuit Line
- 124 Buses
- Multiple Movable Fault Branches

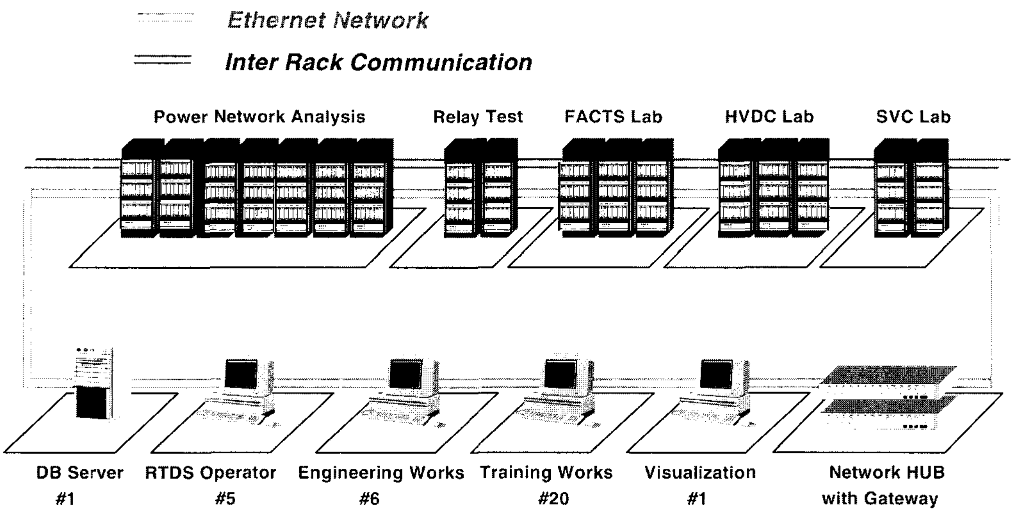

**Fig. 3** Final KEPS Configuration

In addition to the LES, KEPRI will set up a large number of smaller networks to study behavior of numerous devices under various network and operating conditions. Additional components to be represented on the realtime simulator of KEPS include the following.

- HVDC Converters and Controllers
- SVC Systems and Controllers
- Measurement Transducers
- Induction Machines
- TCSC and Controllers
- STATCOM/UPFC and Controllers
- Power Plant Models
- Protective Relay Models

## 5. Rtds Result Comparison

Because the KEPS realtime digital simulator solves the electromagnetic transient equations on a continuous basis, it is better suited to study a wider range of phenomena than other traditional study tools. In fact, the RTDS can accurately represent the system under fast transient conditions (like emtp), interfaced realtime test conditions (like TNA), transient conditions (like stability simulation), and steady state conditions (like loadflow simulation).

Throughout the KEPS project, the authors have been investigating the extent to which the RTDS simulator can be used within the planned simulation center. As part of this investigation, a number of studies have been performed and the results compared with other well known and well accepted programs. In fact, as part of the validation work, RTDS simulator results were compared with non-realtime electromagnetic transients programs, realtime analogue/hybrid TNA, transient/dynamic stability programs, loadflow programs.

In general, RTDS results for each of these types of simulations gave an extremely good match when compared to results obtained from the more traditional programs/tools. The following casestudies show how well the real time simulator was able to match results from other programs/tools.

***Casestudy 1***: *SSR Benchmark Validation*

One of the benchmark cases considered for validation of RTDS results was the published IEEE Benchmark for Sub-Synchronous Resonance [5]. For this case, a comparison with the widely used non-realtime simulation program EMTDC [4] provided the results shown in Figure 4.

As can be seen from the plots, the RTDS and EMTDC results match nearly exactly. A comparison against published results also gives a close match.

***Casestudy 2***: *Generator Unit and Controller Validation*

Since KEPCO engineers often use the PSS/E simulation program and since much of the KEPCO network is already available on PSS/E, equivalent models for generator controls were implemented in the RTDS during the KEPS project. More than 24 exciter, governor, and turbine models were developed and tested. In addition, several power system stabilizer models were considered.

All RTDS based controllers were initially implemented using the KEPS control system modeling software and tested against PSS/E simulation cases. Once proven to have the correct response, the controllers were collapsed into individual models to make them compatible with conversion

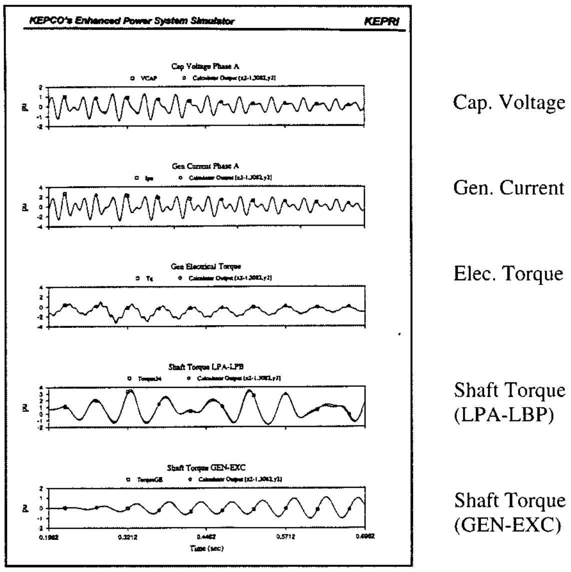

**Fig. 4** SSR Benchmark Comparison

software developed for KEPS. The conversion software allows KEPRI to directly port PSS/e files to the PSCAD/Draft program for use with the KEPS RTDS realtime simulator. This conversion software was also one of the deliverables for the KEPS project.

Fig. 5 shows a comparison between PSS/E and RTDS results for a simulation including a generator, exciter, and power system stabilizer. During the simulation, a 0.2 sec, three-phase fault was applied on the generator high voltage bus. The specific generator controllers were chosen from the list of available PSS/e models. In this case the generator includes an IEEE Type 2A exciter, a GAST governor model, and an IEE2ST power system stabilizer model. Both the response from the RTDS simulator and from PSS/E program are shown in the figure. As with all other cases, very good correlation is seen.

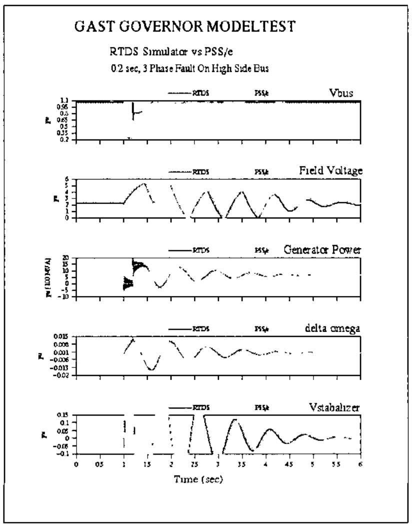

**Fig. 5** PSS/E vs RTDS Generator Response

A number of observations were made during detailed testing and comparison. One of the more interesting points relates to generator representation and response. Generator representation in the RTDS includes the effect of stator transients on speed deviation whereas PSS/E ignores this effect. The difference in response can be seen in some of the observed results. In general, the PSS/E gives a more optimistic response. This effect is well explained in Section 5.1 of Kundur's textbook *Power System Stability and Control* [6].

*Casestudy 3*: *Large-Scale Simulation Validation*

As part of the final validation and acceptance test procedure, a number of large-scale simulation cases have been studied, and comparisons between the KEPS RTDS and the PSS/e program have been made. Large-scale test cases included in the final validation procedure are based on KEPCO's actual power system.

Several reduced network models were prepared by KEPRI for comparison purposes. Different regions within the KEPCO network were considered to gauge both the applicability (and limitations) as well as the accuracy of the RTDS simulator when used for simulation studies of large, complex networks. The results presented below are from the LES system described in Section IV. A large number of individual test cases were run and quantitative comparisons were made between RTDS and PSS/e. The overall comparison includes monitoring of all bus voltages as well as real and reactive power flows at generators and load points and on transmission lines. The acceptance criteria for the KPES project require a very close match between PSS/e and RTDS results for various steady state, dynamic, and transient conditions. Whenever differences were noted between PSS/e and RTDS results, detailed analysis was carried out to determine and explain the cause of such differences.

In general, the results obtained from PSS/e and RTDS

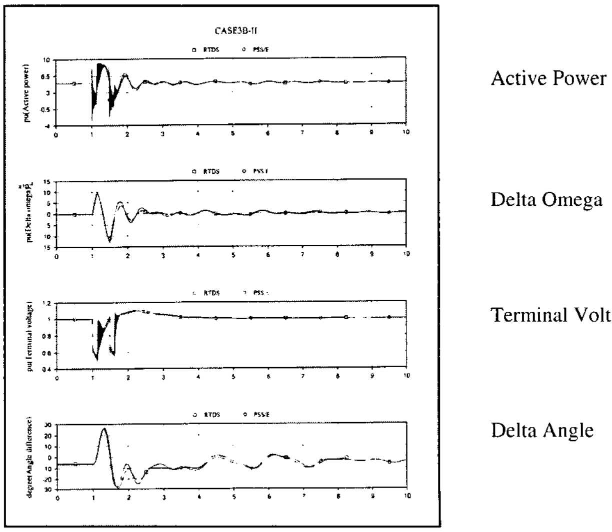

**Fig. 6** Comparison of LES test results

were found to be remarkably close. Criteria for measured bus voltages, for example, is a 0.05% difference between PSS/e and RTDS. All measured voltages were within this required limit.

Fig. 6 shows a result from the LES for one of the operating scenarios defined by KEPRI to validate Power System Dynamics in Transient State. The case considers critical clearing time for temporary system faults. The specific sequence of events for the case shown in Figure 6 is as follows.

- Apply eight cycle three-phase fault at the selected bus
- Temporarily open selected lines to clear the fault
- Re-apply fault after line re-close
- Open lines permanently
- Capture 10 sec. from initial fault for comparison

## 6. Conclusions

KEPCO/KEPRI, along with other industry leaders, have undertaken the development and installation of what is clearly one of the world's most advanced power system simulation and analysis centers. State of the art realtime digital simulation methods along with other well known computer based study tools have been applied in the implementation of KEPS.

Extensive verification of the RTDS simulator has been performed as part of the KEPS project. The purpose of the detailed testing is two-fold: first, to validate the results of the RTDS simulator and secondly, to gauge the applicability and limitations of realtime simulation in the context of an advanced power system simulation center.

Based on observations made by the authors, realtime digital simulation will undoubtedly play an increasingly important role in the development, study, and understanding of power systems.

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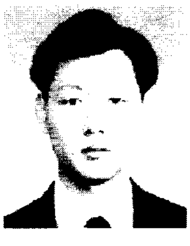
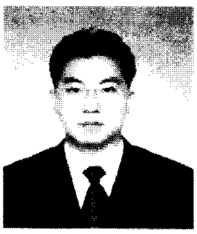


**Tae-Kyun Kim**

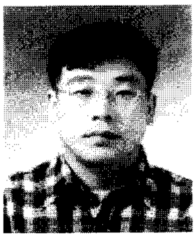
He received the B.S., M.S. and Ph.D. degrees in Electrical Engineering from Hanyang University, Korea, in 1986, 1989, and 1993, respectively. He is a senior member of the technical staff of the Power System Analysis Center of Korea Electric Power Research Institute (KEPRI), a research center of Korea Electric Power Corporation (KEPCO). His interests are power system operation, planning, and analysis. In particlar, he has been working to develop a digital power system simulator and power system stabilizer.



**Jeong-Hoon Shin**

He received the B.S. and M.S. degrees in Electrical Engineering from Kyung-Book National University, Korea, in 1993 and 1995, respectively. He is a senior member of the technical staff of the Power System Analysis Center of Korea Electric Power Research Institute (KEPRI) a research center of Korea Electric Power Corporation (KEPCO). His research interests include analysis, control, and modeling of power systems and the design and tuning of power system stabilizers.

**Jin-Boo Choo**
He received the B.S., M.S., and Ph.D. degrees in Electrical Engineering from Seoul National University, Korea, in 1977, 1987, and 1994, respectively. Currently, he is a center leader in the Power System Analysis Center of the Korea Electric Power Research Institute (KEPRI), a research center of Korea Electric Power Corporation (KEPCO), Korea. He is also a team leader of the National Research Laboratory approved by the Ministry of Science and Technology, Korea. His research interests include power system operation, planning, FACTS, and real-time power system simulation.



**Yong-Hak Kim**
He received the B.S. and M.S. degrees in Electrical Engineering from Chonnam National University, Korea, in 1994 and 1996, respectively. He is a junior member of the technical staff of the Power System Analysis Center of Korea Electric Power Research Institute (KEPRI), a research center of Korea Electric Power Corporation (KEPCO). His research interests include analysis, control, modeling, and operation of power systems.