Power System Analysis Using the Real Time Digital Simulator

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Abstract: This paper will describe the findings and developments associated with an ongoing R&D project at the Korean Electric Power Corporation's research institute, KEPRI, in which a power system simulation center is being designed and installed. The so-called KEPCO Enhanced Power System Simulator (KEPS) will include both off line (i.e. non-real time) and on line (real time) simulation capabilities and will be used by KEPRI to study various aspects of the growing power network in Korea. A Real Time Digital simulator based on the well known RTDS^{TM} hardware and software architecture will form the core of the KEPS system. A number of developments and enhancements have been made to the fundamental simulation technology in order to meet some of the special requirements defined in the KEPS project.

The authors will also provide a brief summary of various simulation and analysis tools including those used for steady state simulation, dynamic simulation, transient simulation, electro-magnetic transients simulation and real time simulation. A comparison of simulation results from the KEPS real time digital simulator with other well accepted programs will be given in order to illustrate the accuracy and the application scope of KEPS.

Keywords: Real Time Simulation, Non Real Time Simulation, Dynamic, Transient, Electromagnetic Transient, KEPS, Power System Analysis.

I. INTRODUCTION

It is expected that over the next several years the Korean power system will experience continued growth and expansion. In anticipation of the challenges presented by rapid network expansion and in order to ensure a full understanding of the existing and future network configuration(s), KEPCO has undertaken the task of establishing an advanced simulation and study facility. When completed, the facility will include a host of simulation programs as well as the real time digital simulator.

KEPCO is expecting to use the real time 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.

It is also expected that the KEPS facility will serve as a training and education center for KEPRI engineers and operators.

II. POWER SYSTEM ANALYSIS TOOLS

A large 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) all other commonly used tools are based on digital computer simulation techniques. The most suitable tool(s) for any study will depend on the specific goal(s) of that study.

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

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 proposed system operating conditions are within the capabilities of 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.

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.

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) 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, the stability problem can be classified as either transient or dynamic.

Transient stability simulation is the most common method to study long term electromechanical behavior of power systems.

It is the transient simulation result which 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, etc.

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.

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

Electromagnetic transient simulation is based on concepts introduced by H. Dommel in his 1969 publication [1]. 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 (except if 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 effect 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 in the order of 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 which allow the user to retain important characteristics of original system in the simulation model.

Real time 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. This is not trivial 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 not applied correctly.

The main advantage of the TNA is its ability to operate in real time and hence its usefulness in testing physical equipment. Because of complexity in system set-up and calibration, analogue TNA's 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 real time power system simulator [2]. The RTDS^{TM} simulator was developed in Canada by the Manitoba HVDC Research Centre and introduced for commercial application in 1993. Since its introduction, the RTDS has gained widespread acceptance throughout the power industry and is now being used for a broad range of studies.

The RTDS simulator represents a very powerful tool for the power systems engineer since it combines the real time benefits of the analogue TNA with the accuracy and flexibility of software based simulation programs.

The remainder of this paper will address some of the more important aspects of the KEPS simulation facility. Special emphasis will be placed on Real Time Digital Simulation (RTDS) and how it can be used to complement other study tools. In addition, a comparison will be made between RTDS Simulator results and results from other simulation tools. Through such a comparison the authors intend to show that the applicability of the RTDS extends well beyond that of traditional real time simulators.

III. THE RTDS SIMULATOR

The RTDS simulator is based on a combination of advanced Digital Signal Processor (DSP) technology and specialized power system simulation software. The fundamental concept of the RTDS is to accelerate the computation of the electromagnetic transient solution to the point of continuos real time operation and response.

At the core of KEPS simulation facility will be the RTDS real time digital simulator[3]. The hardware architecture of the RTDS is based on parallel processing. A large number of processors 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 computational tasks based on the topology of the network defined by the user. Timing and operation of all DSP's is synchronized to a single master timestep clock that ensures accurate coordination of both computation and data exchange (data transfer).

For the KEPS project, more than one thousand high speed digital signal processors (DSP's) will be included in the RTDS hardware architecture. The Analogue Devices AD21062 DSP has been utilized in so-called triple processor Cards (3PC).

Fig. 1 illustrates three different versions of the RTDS hardware. The KEPS simulator racks (26 in total) are mounted in 13 full size cubicles.

The software used by the RTDS simulator can be grouped into three basic categories, namely:

- High Level Graphical Interface
- RTDS Compiler & Linker
- Power & Control System Component Models

The high level software is based on the PSCAD™ Graphical User Interface, originally developed for application with the EMTDC program [4]. It is through this software that the operator defines power system models and runs simulation cases.

Figures 2 and 3 show the PSCAD windows used for circuit definition / parameter entry and simulator control / operation respectively.

The PSCAD/Draft program allows the user to build up the power and control systems from one or more libraries of predefined component icons.

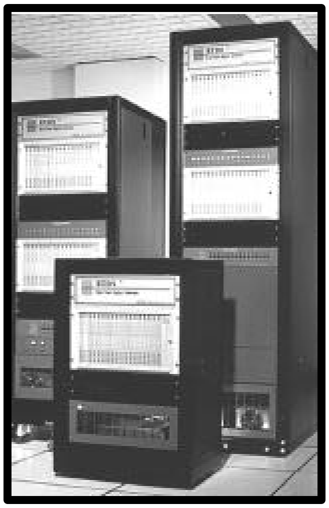

Fig. 1. RTDS Hardware Configurations

The PSCAD/RunTime module acts as an operating console and provides a facility for on line monitoring and data acquisition.

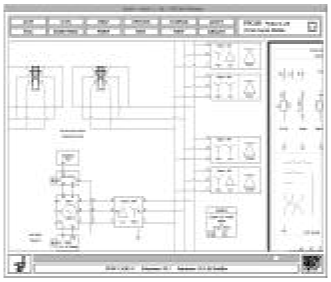

Fig. 2. PSCAD/Draft Software

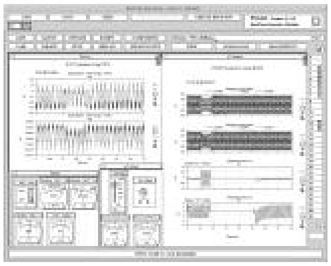

Fig. 3. PSCAD/RunTime Software

IV. THE KEPS NETWORK MODEL

The simulated power system upon which the size of the KEPS simulator has been based is a dynamically reduced equivalent of the expected Korean power system in the year 2010. The portion of the system with voltages above 154 kV has been considered in the network model. For the Largest Equivalenced System at least the following components will be included:

- 30 Generators c/w AVR & Gov/Turbine
- 30 Generator Transformers
- 15 Step Down Power Transformers
- 6 Lumped Passive Loads
- 66 Dynamic & 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

In addition to the Largest Equivalenced System model, KEPRI will set up a large number of smaller networks in order to study behavior of various devices under various network and operating conditions. Additional components to be represented on the real time simulator include:

- HVDC Converters and Controllers
- SVC Systems and Controllers
- Measurement Transducers
- Induction Machines
- Series Compensation with MOV

?? TCSC and Controllers
?? STATCOM and Controllers
?? UPFC and Controllers
?? Protective Relay Models
?? Power Plant Models

In its final configuration, the KEPS RTDS simulator will be set up in such a way that a number of real time (and non real time) studies can be carried out simultaneously. If required, all RTDS processors can be used together to form one large simulation model, however if several smaller studies are to be carried out, the RTDS processors can be shared and used simultaneously by multiple users.

V. RTDS RESULT COMPARISON

Since the RTDS is used to solve the electromagnetic transient equations on a continuous basis, it is well suited to study a wider range of phenomena than any other study tools. In fact, it is asserted that the RTDS can accurately represent the system under fast transient conditions (like emtp), under interfaced real time test conditions (like the TNA), under transient conditions (like stability simulation) and under steady state conditions (like loadflow simulation). With this point in mind, KEPCO has been investigating the extent to which the RTDS simulator can be used within the KEPS simulation center. As part of this investigation a number of RTDS cases have been run and the results compared with other well known and trusted programs. In the following section the authors will present a sample of results obtained from RTDS validation cases

Study Case 1:
Comparing RTDS with an off-line EMTP program

The example considered here illustrates the ability of the RTDS to accurately perform simulations involving electromagnetic transient simulations.

The selected test circuit represents an actual portion of KEPCO's power system. The Cheju Island AC system includes both 154 kV transmission and 66 kV distribution level equipment. Included in the circuit model are:

?? 31 three phase buses
?? 6 full generator models (c/w detailed controls)
?? 1 equivalent source model
?? 10 transformer models
?? 15 three phase line models
?? 4 twin circuit line models
?? various circuit breakers and fault branches

A number of steady state and transient operating conditions were observed and compared. The plots in Fig. 4 represent system conditions before during and after a temporary single line to ground fault at a selected bus in the system. The upper traces are the actual 3 phase bus voltages at the bus in question while the lower traces represent the faulted bus voltage in per unit. Extremely good correlation can be seen between the RTDS results and the off line EMTP type simulation for this complex case.

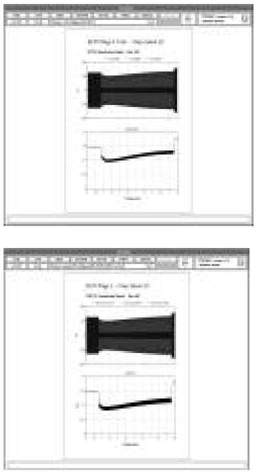

Fig. 4. SLG Fault Comparison for Cheju Island AC System

Study Case 2:
Comparing RTDS generator model response with PSS/E program

Since KEPCO engineers routinely utilize the PSS/E simulation software and since much of the KEPCO network is already modeled using the PSS/E software, equivalent models for generator controls were implemented in the RTDS. As many as 24 exciter, governor and turbine models have been developed and tested. All RTDS based controllers were initially implemented using the control system modeling software and tested against PSS/E benchmark cases. Once proven to have the correct response, the controllers were collapsed into individual models in order to simplify future use and to minimize the achievable simulation time step (i.e. the individual models have greater optimization of executable code than controls system modeling software can achieve).

Fig. 5 shows a comparison between PSS/E and RTDS results for 0.2 sec, 3-phase fault on the generator high voltage bus. The generator includes an IEEE Type 2A exciter, an IEEE standard governor model and an IEE2ST power system

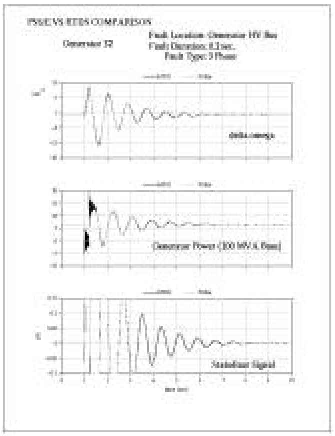

Fig. 5. PSS/E vs RTDS Generator Response Comparison

stabilizer model. Both the response from the RTDS and from PSS/E are shown. Again, very good correlation is seen.

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 while PSS/E ignores this effect. The difference in response can be seen in some of the observed results. In general the PSS/E gives more optimistic response. This effect is weel explained in Kundar's text book "Power System Stability and Control"[5], Section 5.1.

Study Case 3:
Comparing RTDS transient response with PSS/E results for a large scale network

A comparison was made between the PSS/E program and the RTDS simulator for a large scale power system model. The network model used in this test case represents a portion of the KEPCO main power transmission system. Component and parameter data for this case was taken from KEPCO's main data base. Conversion of data from the PSS/E format to a format compatible with RTDS was accomplished using a specially designed conversion program. The conversion program takes information from the standard PSS/E data files and produces a PSCAD/Draft picture in a form ready for direct compiling.

The large scale system model included:
?? 91 three phase buses
?? 14 full generator models (c/w detailed controls)
?? 2 power system stabilizers
?? 3 equivalent source models
?? 103 loads
?? 30 transformers
?? 95 transmission lines (single & twin circuit)
?? various circuit breakers and fault branches

A number of steady state and transient operating conditions were observed and compared. The plots in Fig. 6 represent system conditions before during and after the application of a 0.1 sec, 3-phase fault at a particular bus in the network. The line breakers were also operated in this test case.

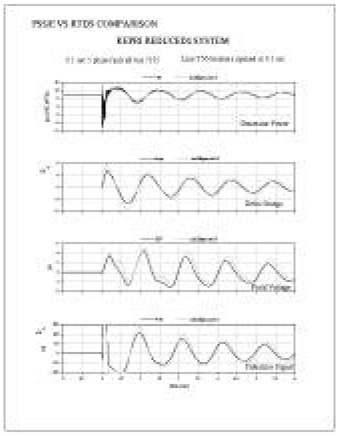

Fig. 6. PSS/E vs RTDS Comparison for Large Scale KEPCO Network Configuration

Results from PSS/E and the RTDS are once again very close. Since the network being considered in this case is indeed very complex, a high level of confidence in the RTDS simulator is gained when results match so closely to the well known and widely used PSS/E program.

VI. CONCLUSIONS

The authors of this paper are currently involved in the development and installation of one of the world's most advanced power system simulation and analysis centers. State of the art digital simulation techniques have been applied in the implementation of KEPS.

In this paper the authors have provided a brief overview of the KEPS project. A relatively new tool, the RTDS real time digital simulator, has been described and its results have been compared with those from more traditional simulation methods. Since the RTDS is based on detailed electromagnetic transients simulation, and since it is capable of continuous operation in steady state and under transient conditions, its scope of application is broader than most other available tools.

VII. REFERENCES

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