21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE-117

CAGRE 2015

Applications of a Real Time Simulator for Electric Utilities

P. FORSYTH
RTDS Technologies Inc.
Canada

R. KUFFEL
RTDS Technologies Inc.
Canada

C. PETERS
RTDS Technologies Inc.
Canada

SUMMARY

Real time power system simulators are widely used in the electric power industry by utilities, equipment manufacturers and research organizations. The simulators are used to study the power systems themselves as well as for the development and testing of new equipment to be installed in power systems. In particular, electric power utilities have used these systems for closed-loop testing and training on control and protection for HVDC, FACTS, generators, transmission lines, transformers, etc. These simulators provide continuous, hard real time, ElectroMagnetic Transient (EMT) simulation results. EMT simulation is necessary to provide the instantaneous value results needed to test real protection and control equipment. Over the years, the hardware and software of these simulators has undergone many improvements since they were first being introduced commercially in the early 1990's. The improvements have increased their performance and widened their scope of application. The paper focuses on the applications of real time digital simulators at electrical utilities.

KEYWORDS

RTDS®, HVDC, FACTS, PMU, WAMPAC, IEC 61850, Closed-Loop Testing

paf@rtds.com

1.0 - INTRODUCTION

Real time power system simulators are now widely used in the electric power industry by utilities, equipment manufacturers and research organizations. The simulators are used to study the power systems themselves as well as for the development and testing of new equipment to be installed in power systems. This paper specifically describes several applications of real time simulators at electric power utilities.

Simulation has played an important role in developing power systems into the modern, complex networks we have today. Before digital simulation was developed, analogue simulators were used to study electrical power systems and test physical protection and control equipment. Analogue simulators were composed of scaled down models of power system components (e.g. machines, transmission lines, loads, etc.) and inherently operated in real time. Although analogue simulators were important tools, particularly in the development and testing of HVDC and FACTS controls, they did have several drawbacks. The limited size and complexity of the network representation as well as the high initial and operating costs were among the biggest drawbacks.

In the late 1960's, an electromagnetic transient simulation algorithm was developed by Dr. Hermann Dommel [1]. The algorithm applied the trapezoidal rule of integration to convert differential equations into linear algebraic equations that were easily be solved by a computer. Dr. Dommel's technique was used in a number of non-real-time simulation programs such as EMTP, ATP and PSCAD.

The trapezoidal rule of integration solve the equations at discrete points in time, not continuously. The time between the discrete points is known as the simulation timestep and is denoted as Δt. Typically in power system simulations, a timestep in the order of 50 microseconds (μs) is applied to capture dynamics in the range from 0 Hz to approximately 3 kHz. However, modern power electronic systems sometimes utilize switching frequencies in the order of kilohertz. When these higher switching frequencies are used in a network model, the simulation timestep must be reduced below 5 μs to accurately represent the system dynamics.

Non-real-time, or "off-line", simulation programs have progressed considerably in the decades following the publishing of Dr. Dommel's paper and are now widely adopted, particularly for insulation coordination and over voltage studies as well as for the study of power electronic schemes (e.g. HVDC and FACTS). However, off-line simulations programs are not able to connect to physical equipment. They can only be used for pure modeling simulations as they cannot interact with the outside world.

It wasn't until the late 1980's that computer technology and modeling techniques were developed that made it possible to perform digital simulations in real time. The goal of real time digital simulation was to combine flexibility and accuracy of digital simulation with the ability of analogue simulators to test physical protection and control devices. In 1989, the Manitoba HVDC Research Centre was the first to successfully run a purely digital simulation in real time and eventually led to the development of the Real Time Digital Simulator (RTDS®).

A digital simulation is considered to operate in "real time" when the results for each timestep are calculated, and the necessary communication with external physical equipment is completed, within a real world time less than or equal to the simulation timestep. Furthermore, the exchange of data with the external physical equipment must occur at equidistant points measured in real world time (i.e. once per timestep) throughout the entire simulation.

Real time digital simulators are now widely used by electrical utilities around the world. It is important for utilities to have a tool to study their networks and different strategies for their protection and control systems. Descriptions of how some utilities apply real time digital simulators are included below.

2.0 - INPUT / OUTPUT

The key advantage provided by real time simulators, compared to off-line simulation programs, is their ability to connect to and test external equipment. In each timestep, the real time simulator will provide information (i.e. output) to the device under test and it will also read information (i.e. input) from the device under test. This is referred to as closed-loop operation. Conventional input and output is done using both analogue and binary data exchange.

Analogue output can be used to represent, for example, voltages and currents from the simulation model. The simulation model is digital, so digital to analogue (d/a) converters are used to create low level signals (typically in the range of +/- 10 V) proportional to the actual power system values. If it is necessary for the device under test to measure secondary level values typically provided by instrument transformers (i.e. CT's and PT's), the d/a converters can be used to drive voltage and current amplifiers. The amplifier output is connected to the device under test to provide the same signal input that would be experienced in an actual power system.

Analogue to digital (a/d) converters can also be used to bring analogue information, for example a regulation signal, back into the simulation model from the device under test. Once the signal is converted and available inside the digital simulation, it can be viewed with other simulation signals for monitoring and/or applied as input to control a simulation model.

Binary outputs are normally provided in the form of voltage signals (e.g. 0 V represents the off-state and 24 V represents the on-state) or through dry contacts. Often binary outputs are used to represent status signals from the simulation model (e.g. breaker status). If the status signal changes during a simulation, the voltage of the binary output changes.

Binary inputs are also normally provided by voltage signals. Binary input are typically used to bring trip and reclose signals or firing pulses for power electronics into the simulation model.

In addition to the conventional input and output described above, it is also desirable for real time simulators to communicate using high level protocols like IEC 61850, DNP, C37.118, etc. More discussion regarding these advanced capabilities is provided below.

3.0 - CLOSED-LOOP TESTING

To be effective as a testing tool, a real time simulator must be able to subject the device under test to any type of operation it might see in service. This ranges from regular steady state operation, to emergency operation, to fault conditions rarely seen. During all tests, the device(s) connected to the simulator must sense output from the simulator and provide the corresponding feedback (i.e. the device under test must be connected in the loop with the simulation). Therefore when a real time simulator is used to test a device, it is referred to as closed-loop testing.

A great advantage of digital simulator is that the model can be precisely controlled. If for example the inception angle of the fault should be 90°, it can be provided reliably and it is easily repeatable. The control and repeatability of the testing is a tremendous asset for understanding and investigating the behaviour of a device.

The models implemented in the simulator are created not only to represent healthy operation, but also to represent faulted conditions. For example, faults on a transmission line or within a transformer must be possible. It must be possible to switch in or out breakers at any time. The mechanical dynamics of machines must be represented. With all these possible operating conditions, closed-loop testing with a real time simulator provides the most advance means available to test a device before it is deployed in an actual grid.

4.0 - HVDC

4.1 Education and Investigation

HVDC has been used in electrical power systems for decades and it is becoming increasingly prevalent. However many utilities have no experience with HVDC and do not know how it will operate in their network. When a utility is planning to introduce HVDC into their network, a real time simulator is a good tool to help educate personnel on the fundamentals and operation of DC schemes. Even using a modest size simulator, a utility can model the HVDC scheme in detail and study the operation and effects of the control system design. They can also learn about the effects of the HVDC scheme on the AC network. The knowledge learned through the use of a simulator can be feed back into the specification for the scheme itself as well as used for bid evaluations.

All manufacturers of HVDC schemes use real time simulators for factory testing of the protection and control systems before they are installed on-site. It is standard practice for utility personnel to be present during the factory acceptance tests. When the utility personnel have working experience and knowledge of real time simulation beforehand, they can be much more effective in contributing to and evaluating the witness tests. This in turn leads to smoother project development and greater confidence in deployment of the scheme.

4.2 Replica Schemes

Many utilities have adopted the practice of specifying that a replica scheme must be provided as part of the HVDC project. A replica scheme is a set of replica controls (a duplicate of controls installed on-site minus redundancy and other secondary elements) and a real time simulator to represent the HVDC scheme.

The replica controls must have the same physical core and function as the protection and control installed on-site. The Human-Machine Interface (HMI) for the replica controls must also offer the same functionality as that installed onsite.

The real time simulator provided with the replica scheme must represent the HVDC scheme in full detail as well as the AC network equivalent(s). As a minimum, the AC network equivalent will be infinite buses with variable network impedances to allow the short circuit ratio to be adjusted. Such a minimal representation will allow the operation and behavior of the HVDC scheme to be studied. If a more complex (i.e. larger) AC network equivalent is specified, the operation of the HVDC scheme and the interaction between the AC and DC systems can be investigated.

4.2.1 During commissioning

If a replica scheme was specified with a project, the utility will be assured that any difficulties encountered during commissioning can be investigated on a real time simulator even though the controls have been delivered to site (i.e. the replica scheme will be available). Unforeseen network conditions can be studied and/or modifications to the protection and control can be tested on the simulator without risk to network operation.

4.2.2 After commissioning

After the HVDC scheme is installed it is inevitable that there will be changes to the AC network. The effect of the changes can immediately be studied using the replica scheme. In some circumstances, modification of the HVDC protection and control will be desirable or even necessary. If a replica scheme is available, modifications can easily be made on the replica controls and tested before they are implemented on the real scheme.

4.2.3 Training

Experience has shown that HVDC schemes are in operation for many years, even decades. As a result, new personnel must be trained on the operation and performance of these schemes. If a replica scheme was provided with the original project, new personnel can be trained using the replica. They can learn to operate the scheme just like the actual HVDC installation and they can investigate changes in operation and settings without any risk to network.

4.3 LCC, VSC and MMC

Until the last decade, all HVDC schemes were constructed using Line Commutated Converters (LCC) based on thyristors or previously on mercury arc valves. More recently some schemes are constructed using Voltage Source Converters (VSC) based on IGBT's. A few different VSC topologies have been implemented. Schemes with 2- and 3-level converters using Pulse Width Modulation (PWM) switching as well as Multi-Module Converter (MMC) based schemes are in operation.

Real time digital simulators have been used to test protection and control for LCC-based schemes for over 20 years. In modern schemes, LCC-based valves are constructed with a large number of series connected thyristors. However when testing the behaviour and performance of the protection and control, it is acceptable to assume that all thyristors of a converter arm turn on or off at the same instant in time. Therefore each converter arm can be modelled as one device or switch. When considering the interface of the control to the real time simulator, only six firing pulses (i.e. one per arm) must be input to the simulator per converter.

VSC-based valves are more challenging to represent using a real time simulator. Like LCC-based valves, 2- and 3-level valves are constructed with a large number of series connected devices and they can also be assumed to turn on or off at the same instant. In terms of I/O, only a relatively small number of firing pulses are required (6 or 12) along with one capacitor voltage. However 2- and 3-level valves typically use PWM switching in the range of 1-2 kHz which requires a simulation timestep in the range of 5 μs or less. This presents two problems:

1. More hardware resources (i.e. computing power) and possibly different modeling techniques are required to achieve the smaller timestep in a real time simulation.
2. It is not practical to model a larger AC equivalent using such a small simulation timestep.

Techniques have been developed and implemented for the RTDS Simulator to deal with both of these problems [2].

MMC-based valves present some different challenges for real time simulation. The arm of an MMC-based valve is made up of a number of series connected submodules. Each submodule will contain either two or four IGBT / back diode pairs respectively for half- and full-bridge configurations as well as a capacitor. The submodules can all be controlled independently. That means the controls will provide firing pulses to the simulator for each submodule and the simulator must send the capacitor voltage for each submodule back to the controls. Since there are often several hundred submodules in each MMC-based valve arm, the I/O requirements are massive. The only practical approach to connect the firing pulse controls of an MMC-based scheme to a real time simulator is a direct digital communication link rather than conventional analogue and binary I/O. Conventional I/O can also be used, but the bulk of the data will be transferred through optical fibre using high speed serial communication [3].

5.0 - FACTS

Utilities are also purchasing replica schemes for FACTS devices and all of the points made above for HVDC also apply to FACTS installations. To date, replica schemes have been provided with SVC, TCSC and STATCOM projects.

6.0 - EXCITER CONTROL TESTING

Utilities have also used real time simulators to test and tune exciter controls [4]. There are very detailed and accurate models of synchronous machines available for real time simulators that allow full access to the field winding [5]. As such, a controlled rectifier can be modelled at the field terminals and connected to an external exciter control. Standard tuning actions and commissioning tests, such as step changes in the set point, can be applied to test the response with a particular machine (i.e. exact machine parameters for the particular site will be used in the simulation model). The machine can easily be run at off nominal speed to test V/Hz functions or under extreme conditions to test the full range of operation. It should be noted that the tests and tuning conducted using the real time simulator do not require the use of energy (e.g. fuel) for the prime mover. As a minimum, the cost to commission the exciter on-site will be reduced through time and energy savings.

7.0 - PROTECTIVE RELAY TESTING

Real time simulators provide the most comprehensive means available for testing protective relays. Closed-loop testing offers several important advantages compared to open-loop (i.e. COMTRADE playback) testing. Firstly, since closed-loop testing must be and is conducted in real-time, less time is needed to perform a sequence of tests compared to using COMTRADE playback which typically requires scenarios to first be simulated with off-line programs. Secondly, real-time operation allows multiple protection devices to interact with the simulated network at the same time. Therefore it is the only means to fully test and see the interaction of multiple relays (e.g. double-ended twin circuit line protection involves the interaction of four relays).

When conducting closed-loop protective relay testing, or for that matter any closed-loop testing, the real time digital simulator acts as the power system. As described above, the simulator provides low-level analogue outputs (e.g. +/- 10 V) to amplifiers that are connected to the device under test. The low-level signals are proportional to the instantaneous value of the signal being represented (e.g. voltage, current, etc). Voltage and current amplifiers convert the simulator's analogue outputs to the secondary values normally seen by the relays in service (typical nominal values are 115 Vrms ph-ph and 1 Arms or 5 Arms). The simulator also has output contacts so that breaker status can be provided to the relays at auxiliary/station level voltage. Since all of the standard inputs are provided to the relays, they behave as if installed in the actual network. If a simulated fault is applied in the protection zone, the relay should trip. To close the test loop, the relay output contacts are connected to the simulator to provide various signals such as trip, reclose, etc. Both single-phase and three-phase tripping schemes can be tested.

Since the power system is being simulated, various faults, including evolving and cross country faults, can easily be applied using controlled and repeatable network conditions to evaluate the performance of the protection [6].

7.1 Automated testing

Real time simulators will normally offer a facility to create automated test sequences. For example, scripts can be created for the simulator using a combination of special simulator commands and C programming. Nested loops allow very extensive and adaptive testing with thousands of cases to be conducted and documented automatically [7].

7.2 IEC 61850

Utilities are using real-time simulators to test and gain experience with IEC 61850. The simulators can be configured to publish and subscribe to GOOSE messages (i.e. IEC 61850-8-1) as well as sampled values (i.e. IEC 61850-9-2. Therefore the IEC 61850 communication can be used instead of conventional dry contact binary signals and/or analogue input from instrument transformers [8][9].

8.0 - WIDE AREA MEASUREMENT, PROTECTION AND CONTROL

In recent years, many utilities have installed Wide Area Measurement Systems (WAMS) based on Phasor Measurement Units (PMU's). Therefore, PMU models based on IEEE C37.118 have also been developed for real time digital simulators. By representing a large number of PMU's, an extensive Wide Area Measurement System (WAMS) can be modeled and the capabilities tested using simulators [10].

The power industry has also been investigating and developing Wide Area Measurement Protection And Control (WAMPAC) schemes. These schemes are typically very powerful and can have a devastating effect on the network if they respond incorrectly. Therefore, it is critical to test them thoroughly and under widely varying network conditions before they can be put in active service. A real time simulator is the idea tool to develop and test WAMPAC schemes [11].

WAMPAC schemes typically use a number of utility data services. That means in order to interact with WAMPAC schemes, a real time simulator must be able to provide synchrophasor data streams according to IEEE C37.118, publish and subscribe to IEC 61850 GOOSE messages and communicate using SCADA protocols like DNP3 or IEC 60870 all at one time [12].

9.0 - NETWORK SECURITY ASSESSMENT

Large-scale real time simulations can also be valuable to a utility by providing a more detailed representation of the network behavior than standard transient stability simulations. Among other things, real time electromagnetic transient simulations provide a much better frequency response (DC to ~3 kHz), more detailed representations of power electronic installations (as opposed to nominal frequency approximations), real time feedback, and the ability to interconnect with physical devices.

By including detailed models of the protection and control as part of the simulation studies, a more complete representation of the network behavior is provided. With more complete models and accurate representations, even black start scenarios can be studied.

Several utilities have implemented large scale real time simulators that model their high voltage transmission networks. The purpose of these simulators is to allow critical protection and control equipment to be tested in a realistic environment, but without risking the operation of the actual network. For example, the real time simulator laboratory at China Southern Grid (CSG) was identified as one of their key tools to ensure the security and reliability of their network [13].

The simulator at CSG models the entire high voltage network, including five HVDC links. Physical replica controls for four of the HVDC links are permanently connected to the simulator and facilitate detection of interaction between the schemes. The highly detailed model ensures an accurate and reliable network representation and allows CSG to confidently and safely explore the operation of their network.

10.0 - CONCLUSIONS

Real time digital power system simulators have undergone significant advancements over the last decade and are now widely used in the power industry. With the advancement and acceptance of the technology, more and more utilities are acquiring real time simulators for closed-loop protection and control system testing as well as for large scale real time simulations. In addition to these traditional applications, new initiatives such as Smart Grid, renewable energy sources and wide area protection and controls will benefit greatly from the use of real time simulators.

BIBLIOGRAPHY

[1] H. W. Dommel, "Digital Computer Solution of Electromagnetic Transients in Single- and Multiphase Networks", *IEEE Trans. On Power Apparatus and Systems*, Vol. PAS-88, No. 4, pp. 388-399, April 1969.

[2] T. Maguire, J. Giesbrecht, “Small Time-Step (<2µSec) VSC Model for the Real Time Digital Simulator”, *In Proc. IPST 2005*, Montreal Canada, June 2005, Paper No. IPST05-168-25c.

[3] T. Maguire, B. Warkentin, Y. Chen, J. Hasler, “Efficient Techniques for Real Time Simulation of MMC Systems”, In proc. IPST 2013, Vancouver, Canada, July 2013, Paper No. IPST13-143.

[4] R. Valiquette, G. Mazur, N. Dhaliwal, X. Jiang, R. Wierckx, “Application of Real Time Digital Simulation for Commissioning Automatic Voltage Regulators for Synchronous Condensers”, In Proc. ICDS '97, Montreal Canada, May 1997, pp. 211-216

[5] A. Dehkordi, et. al., “Development and Validation of a Comprehensive Synchronous Machine Model for a Real-Time Environment”, IEEE Transactions on Energy Conversion, Vol. 25, No. 1, PP. 34-48, March 2010

[6] Frank Plumptre, Stephan Brettschneider, Allen Hiebert, Michael Thompson, Mangapathirao “Venkat” Mynam, “Validation of Out-of-Step Protection With a Real Time Digital Simulator”, Western Protective Relay Conference 2006, Spokane, Washington, October 17 – 19, 2006

[7] Testing a Protection System using the RTDS Batch Mode Facility In Proc. IPST 2001, Rio de Janeiro Brazil, June 2001, pp. 447-452

[8] Yu.I. Morzhin, S.G. Popov, M.V. Vazyulin, Yu.V. Korzhetsky, M.D. Ilyin, “The stages of introduction of the technology of the Digital substation» on UNEG facilities”, Actual Trends in Development of Power System Protection and Automation, Yeketerinurg, Russia, June 2013, paper S.3.1-6

[9] Allison Auld, Joshua Park, Anthony Johnson, Marc Desjardine, and Rudi Wierckx., “RTDS Simulation and Testing of a Remedial Action Scheme at Southern California Edison”, Western Protective Relay Conference 2013, Spokane, Washington

[10] Heng Chen; Bhargava, B.; Habibi-Ashrafi, F.; Park, J.S.; Castaneda, J., "Integration of RTDS with EPG synchrophasor applications for visualization and analysis of simulation scenarios at Southern California Edison," *North American Power Symposium (NAPS) 2012* , pp.1,5, 9-11 Sept. 2012

[11] Hjörtur Jóhannsson, Hugo Morais, Allan Pedersen, Qiuwei Wu, Dean Ouellette “SW-platform for R&D in Applications of Synchrophasors Measurements for Wide-Area Assessment, Control and Visualization in Real-Time”, Cigré US National Committee 2014 Grid of the Future Symposium, October 19 – 24, 2014, Houston, TX

[12] P. Forsyth, D. Ouellette, C. Peters, M. Desjardine, “A Real Time Environment for Closed-Loop Testing of PMU-based WACS Schemes”, Cigre Canada 2013, paper 235, September 2013

[13] Dacai Qi, “DEFENSE SCHEMA AGAINST LARGE DISTURBANCES IN CHINA SOUTHERN POWER GRID”, Electra No. 257, pp. 4-16 , August 2011