

Real time simulation based development and testing of modern power systems

J. ZAKONJŠEK
EnLAB JSCC, Russian Federation
P. FORSYTH, C. PETERS
RTDS Technologies Ltd., Canada
janez-zakonjsek@ennlab.ru

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1 INTRODUCTION

Different factors influence increasing complexity of modern power systems. Economical and environmental aspects prevent their growth compared to what has been a standard practice in the past. Under this consideration the introduction of different new technologies is a must, starting with controlled power electronic devices within the AC network as well as DC systems and introduction of other FACTS elements. All these help generally increasing system stability, however without their reliable operation the power system may become naturally unstable.

Environmental concerns have introduced non-conventional power sources, like wind and photovoltaic generation to our existing and new power systems. These elements influence to a great extent the operation of existing power systems on distribution as well as on transmission level.

- Distribution systems are facing so called distributed generation, which has a strong influence not only to their operation but also to their secondary systems (i.e. protection, automation and control)
- Big wind farms (on and off-shore) together with powerful photovoltaic installations require the reshaping of complete existing AC systems, in some cases incorporating the introduction of parallel DC links. Furthermore, DC grids are now being seriously discussed, which so far has not been a practice anywhere in the world.

All these changes in primary power systems require also new, more complex approach in the corresponding secondary systems. This relates to relay protection as well as system automation and control in normal and emergent operating conditions. Requirements on their security and dependability are becoming more demanding, the operating (response) times will need to be shorter and the presence of emergent conditions determined much faster than ever before.

The goals and requirements stated above require the development and testing of novel systems not yet in operation. In addition, supervision of their operation and analysis of performance during different system events requires fast working methods. One of the extremely important elements in all this work is short amount of time available to explore new solutions because of tough economic conditions as well as quickly arising needs of existing power systems.

One method of securing the fastest possible development and testing activity for securing the same time high quality of work performed is the use of a so called Real Time Digital Simulation.

In the paper we describe the basic needs and characteristics of state of the art real time digital simulation methods, used in conventional way for testing and development of different relay protection devices, generator control systems, classical elements of power electronics as well as digital simulation for state of the art VSC and MMC (Multi Module Converters) and their development. The complete approach to development and testing of SIPS (System Integrity protection Schemes) based

on PMU information and systems based on complete IEC 61850 International Substation Communication Standard will also be presented.

2 SOME HISTORY ON POWER SYSTEM MODELLING

We do not make any mistake if we consider that Thomas Alva Edison built up in his laboratories at Menlo Park kind of a model for his first bigger electric power system, today known as New York City's Pearl Street Station (1882). The development went later on, as known, in the direction of AC power systems and as they grew up also their models got bigger and more complex, leading in fact the complete power system development. Electromechanical models have been in use for a very long time and even today they serve excellently their purpose.

Definitely the biggest (and still working in very good shape) electromechanical power system simulator in the world we can find today in St. Petersburg, Russia, a "Scientific and Technical Center of Unified Power System", more known as "NIIPT". It has been established already in 1945 as a "High Voltage Direct Current Power Transmission Research Institute". This institute and the model there have decidedly contributed to fast development of former Soviet Union HVDC system and UHV (750kV and 1150kV) AC systems, and they continue their work even in modern Russian Federation.

Introduction of electronic (static) technologies and first computers influenced also the development of power system models. A very interesting example was this way an analog electronic power system simulator, developed at late seventies of last century by ASEA Relays (today ABB) in Sweden. The model itself was built by analog electronic components, and its operation, configuration, settings and data collection were controlled by five computers and four specialized operators. Its operation was based on Clarke components, which also made it unique of its sort worldwide. Here it was also possible to meet strong current and voltage amplifiers, providing to tested relays realistic system voltages and currents up to 280A.

2.1 Digital solution for simulation of electromagnetic transients

Already in 1969 published Hermann W. Dommel his famous paper on Digital Computer Solution of Electromagnetic Transients in Single-and Multiphase Networks [1]. This has been definitely a revolutionary step in (real time and non-real time) digital (computerized) simulation of electromagnetic transients in power systems, providing possibilities to move from electromechanical and static models to digital and at the same time increase the frequency range of different events to be observed within power system.

The basic idea of Dommel's algorithm is ideal for computerized calculation:

1. Convert the user defined power system to equivalent network consisting only of current sources and resistors (see Figure 1)
2. Formulate conductance matrix for equivalent network (Figure 1)

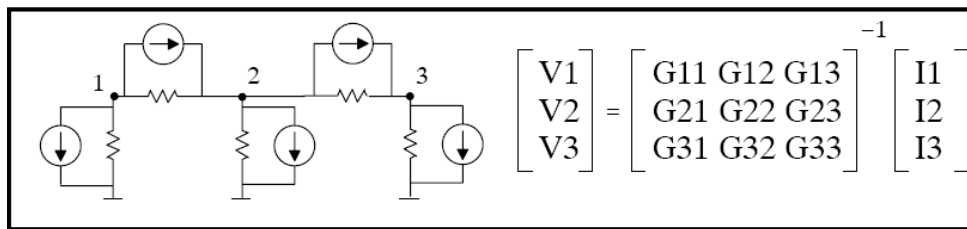


Figure 1: Equivalent network consisting of only current sources and resistors with corresponding conductance matrix

3. Using data from previous time step (or initial conditions for the 1st time step), compute new values for currents [I]
4. Solve for voltages [V] using new values of [I]
5. Calculate branch currents with new values of [V] and [I]
6. Repeat steps from 3 to 5

Important in this respect is a dimension of chosen time step. It should be much shorter than the cycle of maximum frequency expected within the simulated transient process.

3 REAL TIME SIMULATION

Time required for the complete calculation process depends on different factors as: the dimension of power system to be simulated, the characteristics of the transients to be studied, number of observation points and finally also very much on the capacity of computer(s) used. Two possibilities generally exist:

- Calculation time of each time step is longer than the simulated process takes in nature, so that complete simulation can take many seconds or even minutes. This kind of simulation is performed off line and is called non-real time or off-line simulation. The results are usually saved in files (e.g. Comtrade) and presented graphically in form of time diagrams for further studies.
- Calculation time is equal or even shorter than each time step in simulated process, so that the result of each time step is available on line in real time, as the process would be running in nature on real power system. The result can as well be saved in files and observed later on in graphic form or replayed by different means, but the greatest advantage of real time simulation is a possibility to connect in closed loop also different hardware and study its performance like it would be installed directly in real power system. Such kind of simulation is called Closed Loop Real Time Digital Simulation (CSRTDS) and many times we hear also expression Hardware in the Loop (HIL) Simulation. One of very important requirements for this kind of simulation is that the time steps are strictly controlled and all the time securely within the specified limits, otherwise it is impossible to trust the results obtained.

Each method has its pros and cons. Non-real time simulations do not require computers with extremely high capacity, saved files can later on be replayed to the tested equipment through different intermediate hardware (e.g. current and voltage amplifiers when we discuss protection testing). The disadvantage is that it is not possible to study direct response of the simulated system on certain actions performed by tested equipment during specific event. On the other hand off-line simulations make it possible to study extremely fast transients, which cannot be simulated today (due to required extremely short time steps) even with best computers available.

Figure 2 shows typical example of equipment used and required connections for real time testing of protective relays. Such testing has also been one of the first practical applications of hardware in the loop real time testing.

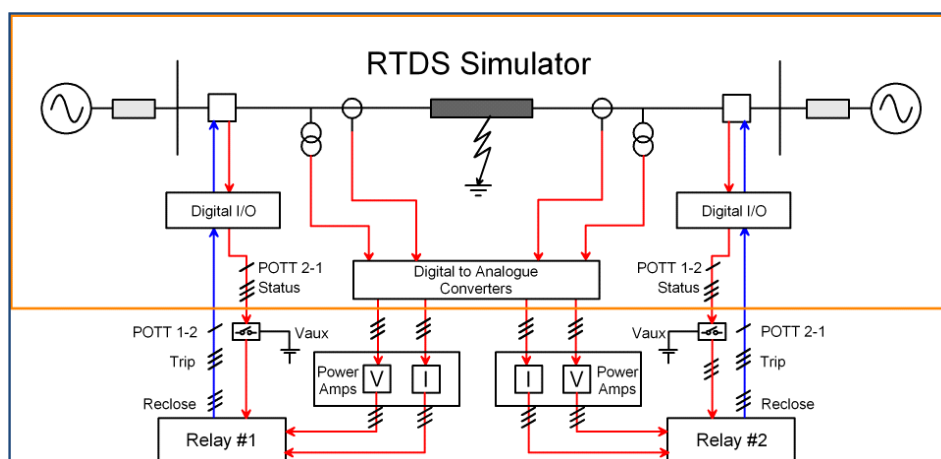


Figure 2: Closed loop real time digital testing of protection relays in power system

Results of numerical simulation are used as inputs to high precision Digital to Analog Converters (observed currents and voltages) and digital outputs (breaker positions, communication commands and similar). Converted values of currents and voltages are then amplified in Power Amplifiers, so that relays under test receive on their analog inputs the same quantities as they would

appear in real substation (e.g. 100V AC ph-ph and up to 250A AC). Relays under test will react on certain simulated events and through binary inputs send different information back to the simulator (e.g. tripping command to CBs), which changes in real time the system conditions and continues the simulation under new conditions. Selected time step is for such cases typically around $50\mu\text{s}$ (400 calculations per cycle at 50Hz rated frequency).

4 MODERN APPLICATIONS OF CLOSED LOOP REAL TIME DIGITAL SIMULATIONS

4.1 Relay protection and automation

Relay protection devices have been the first “user” of CLRTDS. Today it is practically impossible to imagine implementation of modern protection and control IEDs within complex network configurations without testing them and optimizing their settings and configurations without the help of CLRTDS. Typical example of such case is a double circuit power line presented in **Figure 3**.

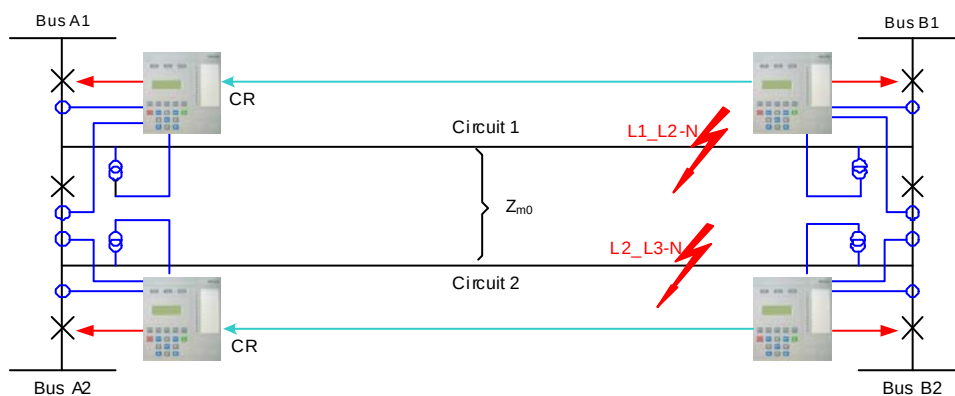


Figure 3: Double circuit parallel operating line with complex faults, multi-pole tripping and adaptive autoreclosing

The requirements on modern line protection are very high. It is supposed to trip the faulty phases and keep the complete line in operation as long as two different phases of a double circuit, parallel operating line are still healthy (so called multi-phase tripping). Autoreclosing shall be adaptive on per phase basis. All this requires thorough studies, simulations of different fault conditions (internal and external) and fine tuning of protection settings. It is quite possible that not only the protective relays will be tested, but the complete relay panels at each line end. They will after that be installed on site and put in operation.

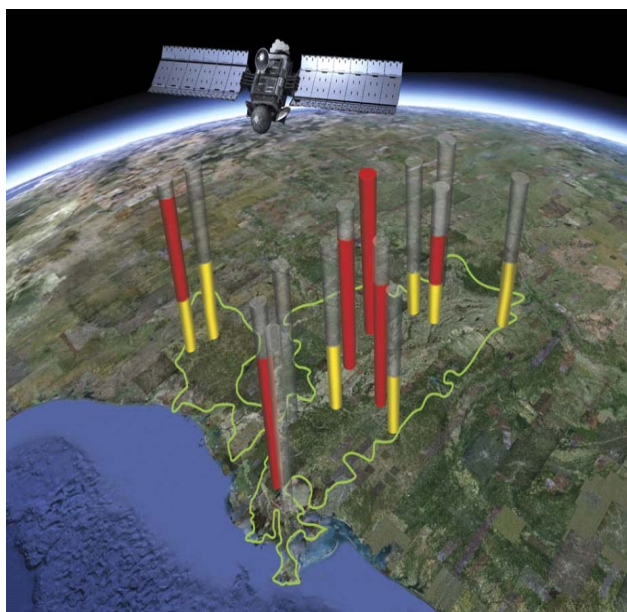
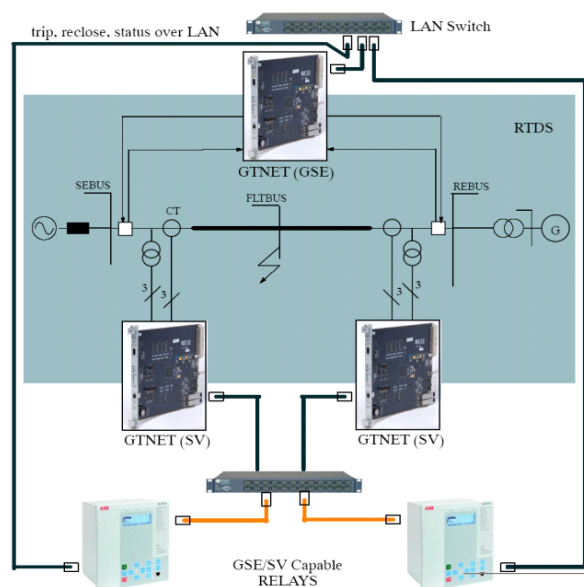


Figure 4: Protection testing according to IEC61850

Figure 5: Investigation of Wide Area system performance

Development of power system protection and automation took within last decade strong steps and many changes are still in front of us. IEC 61850 Communication Networks and Systems for Power Utility Automation standard is definitely bringing a lot of changes in complete design of secondary systems and this way also related simulations. Figure 4 presents a testing configuration, corresponding completely to conventional one presented in Figure 2. Binary I/O units are replaced by special modules providing GOOSE communication and analog outputs together with current and voltage amplifiers are replaced by corresponding modules providing sampled values of currents and voltages in observed points. It is self understanding that all these protocols used for simulation must strictly correspond to testing procedures proposed by the standard.

There are a number of companies worldwide which have determined their own certification requirements and procedures for different types of protection devices. A big part of tests which any potential product (regardless its producer) has to pass is performed on standardized system models by means of CLRTDS. In addition to this also so called Project Oriented Tests are performed for specific projects, especially when applied to EHV and UHV systems.

4.2 System Integrity Protection Schemes (SIPS)

Synchrophasors in power system (see Figure 5) are today used not only for Wide Area Monitoring purposes. More and more utilities are moving towards SIPS, based on synchro-phasors, and obtained from wide areas of power system. Modern CLRTDSs are used to model big systems and provide in real time values from their different points directly to the connected data concentrators. The developers are this way able to on line test their system stability control and emergency control algorithms. Integration of different software available for synchrophasors today with system simulation facilities enables the user to:

- ✓ Visualize and analyze signals for validation
- ✓ Test performance under simulated scenarios through analysis and visualization of results
- ✓ Assess grid performance in terms of key power systems metrics, including phase angle differences, power grid stress, inter-area and local oscillations, voltage sensitivities and frequency response

There are usually two possibilities to obtain synchro-phasors from the simulator itself. The first one is to physically connect PMUs through current and voltage amplifiers to different points of observed power system (similar as protective relays presented in Figure 2) or through a special interface cards providing phasor values according to IEEE C37.118 Standard.

4.3 Development, testing and optimization of classical and most modern control equipment

Testing and parameter optimization of different control equipment in power system by means of CLRTDS is today a standard approach by many utilities worldwide. Figure presents a typical example of static exciter used for control of Rectifier and Field Flash Circuit applied for voltage control of power generator. Similar approach is of course used also for PSS and Governor Control.

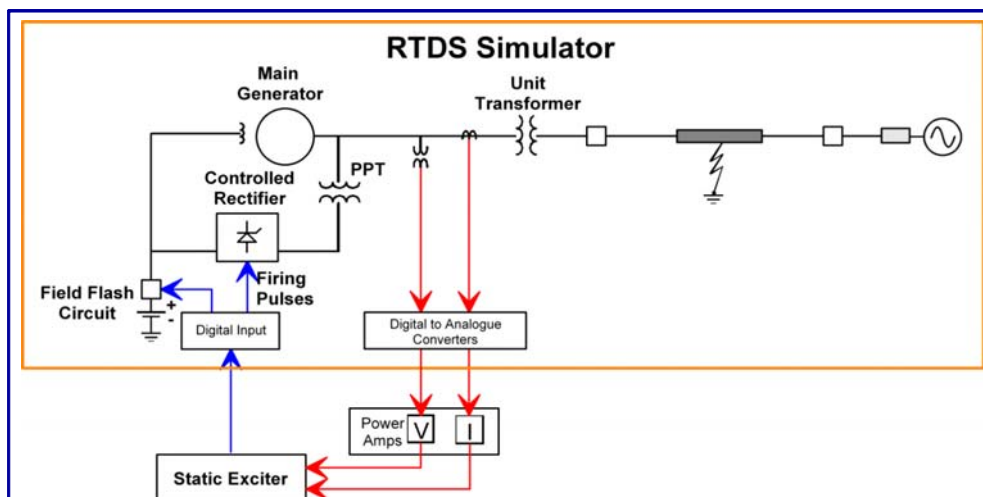


Figure 6: Testing of excitation controller

Similar approach is used also for development and testing of controllers used in Power Electronics applications. Here it is possible to discuss:

- ✓ HVDC (High Voltage Direct Current) installations based either on classic thyristor schemes, using improved firing algorithms either 2, 3 and multi-level VSC based schemes using small time-step sub-networks
- ✓ SVC (Static var Compensators)
- ✓ TCSC (Thyristor Controlled series Compensation)
- ✓ STATCOM with 2, 3 and multi-level VSC based schemes using small time-step sub-networks, etc.

Typical time steps in such applications are in the range of 2-5 μ s.

Special challenges for real time closed loop simulations are in this respect MMC (Modular Multi-level Converters), which are becoming today widely used in HVDC and FACTS applications. Here it is necessary to correctly present over 500 sub-modules per valve or more than 5000 per complete HVDC station. Control of each sub-module must be executed in microsecond (μ s) time-step range. Such modules are used for detailed control development and detailed factory acceptance testing where a physical connection to external firing pulse controls is required. The model must also support various internal faults for in-depth control testing.

4.4 Smart Grid and Distributed Generation

Latest development of power systems differs in great extent from what we have been used on in the past. Renewable energy sources, distributed generation, smart grid in whatsoever sense we consider it are introducing many changes in system operation, protection and control. It is practically impossible to further develop such systems without reliable pre-studies, which definitely need to include in their final stages also real time simulations.

All this requires also additional development work on simulators themselves. Reliable and fast communications are one of the most important building blocks for smart grid and it is mandatory for the real time simulators to provide necessary communication capabilities, including IEC 61850 communication standard on substation level and IEC 60870-5-104 (or 101) or DNP 3 on system level for SCADA purposes as well as IEEE C37.118 for PMU and SIPS purposes.

Correct models of different wind generators, solar energy sources, fuel cells and related power electronic converters are mandatory as well. One should not forget the needs represented by the coming Electrical Vehicles, which requires reliable storage systems and DC/DC converting facilities.

4.5 Large Scale Real Time Simulation

Two big power utilities have today installed a so called Large Scale Real Time Digital Simulators (LSRTDS): KEPCO in Korea and South China Grid (SCG) in China. The main advantages of using such LSRTDS are:

- ✓ Efficiency of real time: More scenarios in less time yield more information and better understanding

- ✓ Frequency response from 0-3 kHz with one single tool makes possible observation of operation within full frequency spectrum, which includes also all protection and control aspects
- ✓ Detailed power system control with direct power system interaction can be simulated only or provided with external equipment connected

SCG has identified their LSRTDS as one of four key strategies to ensure security and reliability of their power grid [5]. In addition to well know benefits they identified also an unexpected one. Heavy ice storm caused in 2008 extensive damage to 110kV network. More than 7000 lines have been damaged and millions of customers remained without electric power. The SCG engineers have worked around the clock in order to model the system as it was in a moment and used their simulator to guide the system restoration.

4.6 Black start investigation

Application of LSRTDS identified also the possibility to use it as a help and efficient tool during black start investigation. Connection of real time SCADA information by means of corresponding protocol, realistic protection and control modes provides together with realistic system behavior a reliable feedback to system operators.

4.7 Education and training

As the complexity of power system is increasing it is also expected that the teaching and learning methods on different educational stages will follow the development and provide students with better tools and methods in order to be well prepared for their challenges when starting the work. It is not the same when a teacher speaks about some transient process in power system and provide one or two equations and some pictures or when a student simulate in real time the system and event within, observing also the effect of different measures provided by protection or control equipment. The amount of information accepted and processed within these two cases is completely different. Different universities have already seen such needs and prepared for their students a comprehensive set of lectures with different characteristic cases [6].

Different utilities worldwide have recognized that they need to extensively educate their staff when introducing new technologies within the power system, because they cannot depend thoroughly on each particular vendor. At the same time they need to study and analyze different events during the system operation and possible also change with time some parameters. It is for this reason appearing as a common practice to require with purchase of a complete project also the delivery of real time digital simulator.

4.8 Power Hardware in the Loop (PHIL) testing

All so far presented testing methods belong to a so called Hardware in the Loop (HIL) testing. Here we simulate a power system in connection with external secondary equipment like protective relays, controllers, etc.

On the other hand there is also possible to use a so called Power Hardware in the Loop (PHIL) testing, where a primary (power) device is a subject of tests. This method is not extensively used yet but its popularity is increasing continuously. Several applications have been reported for testing electric machines and motor drives even at the MW range and for industrial purposes.

This method seems to provide a very novel way and possibility for testing different Distributed Energy Resources (DER) devices and systems [4]. Though quite a number of applications have been reported the feasibility of PHIL testing is mainly demonstrated so far, but the usefulness and the added value are scarcely discussed.

5 CONCLUSION

Introduction of different new technologies in modern power systems is today a must, starting with controlled power electronic devices within the AC network as well as DC systems and introduction of other FACTS elements. All these help generally increasing system stability, however without them the power system may become naturally unstable.

All these changes in primary power systems require also new, more complex approach in the corresponding secondary systems. This relates to relay protection as well as system automation and control in normal and emergent operating conditions. Requirements on their security and dependability are becoming more demanding, the operating (response) times will need to be shorter and the presence of emergent conditions determined much faster than ever before.

Closed Loop Real Time digital Simulation is the best method of securing the fastest possible development and testing activity for implementation of new technologies in modern power systems.

The paper presented the basic needs and characteristics of state of the art real time digital simulation methods, used in conventional way for testing and development of different relay protection devices, generator control systems, classical elements of power electronics as well as digital simulation for state of the art VSC and MMC (Multi Module Converters) and their development. The complete approach to development and testing of SIPS based on PMU information and systems based on complete IEC 61850 International Substation Communication Standard have been presented as well.

Introduction of new technologies in modern power systems is an extremely responsible step, which influences not only technical sphere but also socio-economical relations within human society. This requires also extremely high quality of tools used for their testing and development, including CLRTDS. It is well known that the quality of certain simulation can never be better than the quality of the less accurate power system element model used within the complete simulated network. For this reason it is of outmost importance to select the proper tools with good references in many reliably running installations worldwide.

We can expect that with further development of digital computing technologies also real time digital power system models will develop further and the systems modeled will grow in their dimensions.

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