Overcurrent protection-relay testing with Real-Time Digital Simulator Hardware

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Abstract. In this paper, the authors present an overcurrent protection-relay testing procedure by a applying special simulation hardware for a real-time power-system digital simulation (RTDS). The RTDS simulator enables real-time calculation of the electromagnetic phenomena with the calculation time step of even 50 µs. The hardware enables import and export of many signals from the simulator to an external actual power-system equipment and therefore the so-called closed-loop testing. In this way, it is possible to have an insight both into the equipment behaviour and also into the impact of this equipment on the power-system operation. Testing of a very simple definite-time protection function by using the ABB protection relay REF 630 is described and the obtained test results are shown proving a remarkable usefulness of the RTDS simulator for determination of the actual power-system equipment behaviour at various power-system states.

Keywords: real-time power-system digital simulation, real-time electromagnetic-phenomena calculation, overcurrent protection relay, closed-loop power-system equipment testing.

1 INTRODUCTION

Power system operators as well as power-system protection- and control-equipment manufacturers are forced to thoroughly test their equipment before it is put in operation. There are many different types of tools available for such testing and consequently also different approaches.

The era of digitalization and technological progress has brought much advancement in power-system simulators, especially those enabling electromagnetic transients analysis. Analogue simulators have been replaced by digital ones. Nowadays, there are many different software tools available in the market offering power-system dynamic simulations. They all take advantage of the standard numerical calculation techniques known for decades. One of the most commonly used such technique is modelling of reactive elements with a controlled current source and ohmic resistance connected in parallel [1]. Using this technique simplifies the procedure of bus admittance formation and consequently also the calculation of the dynamic phenomena by using algebraic equations instead of the differential ones. Simulations are performed sequentially with the time increment ΔT. Setting of ΔT determines the calculation time requirement as well as the point of interest of the dynamic-phenomena frequency range. The simulations are not performed in real-time which has been one of the past major obstacles in equipment testing. For the purpose of the so-called "classic" simulations, the relay operation is modelled with a certain logical structure. However, this kind of approach is acceptable only in cases when enough data about the relay is available. It should be noted that it is not the relay modelling "know-how" that is a problem, but rather obtaining the necessary data about the relay itself, as the structure and operation of such equipment is usually kept secret by the manufacturer. Consequently, operation of a particular relay in a power-system environment (including signal distortions) can only be tested with real-time simulations. In this way, different events are simulated in a power-system model and the obtained signals are introduced to the actual device which does not detect the difference between the real-time simulation and the actual power-system environment. Of course, in a real power system a three-phase short-circuit test at the 400 kV level cannot be performed.

By developing parallel processing techniques, phenomena lasting a few milliseconds can be calculated in a time shorter than or equal to a millisecond by using specialized equipment. The main problem to be solved is how to reach the values of ΔT to be small enough to be able to model the dynamic phenomena in a higher frequency range and at the same time to strongly increase the number of the required mathematical operations in the same time frame.

The Real-Time Digital Simulator (RTDS), manufactured by the Canadian company RTDS Technologies, is one of the simulators with which the real-time power-system electromagnetic phenomena can be calculated. The calculation time steps ΔT are about 50 μs and for modelling power electronics elements, such as thyristor converters, even as low as 1.5 μs [2]. The special hardware makes it possible also to import and export signals to external devices which is particularly important for closed-loop testing of external equipment with a power-system model. In this way, the RTDS user can analyse the external device itself as well as its impact on the rest of the power system [3, 4]. So, the model within the RTDS simulator can be considered as a replacement of a real power system.

RTDS represents the state-of-the-art in the power system simulation area and the first such simulator used in Slovenia. The first experiences in using such equipment were obtained by attending a few weeks lasting training courses held at Siemens AG Erlangen and at University of Manitoba, Canada. The main goal of this paper is to present the state-of-the-art simulation equipment and to make a short presentation of the RTDS simulator as well as its use in an actual power-system equipment-testing procedure.

2 REAL-TIME DIGITAL SIMULATOR

There are many different manufacturers of the RTDS hardware in the world, among which RTDS Technologies [5] is one of the leading ones in manufacturing high-quality modular simulators with exceptional characteristics and references from all around the world. The RTDS simulators are constructed from units called "Racks". Each "Rack" consists of maximally six processor cards (Giga Processor Card – GPC or a newer version of the PB5processor cards) and at least one GTWIF card (Giga Transceiver Workstation InterFace card). The latter is required to communicate between the personal computer (PC) and the simulator carried out via TCP/IP communication (Ethernet). Real time simulation is considered acceptable only if the simulation time step is small enough. The RTDS simulator enables ΔT = 50 μs which fulfills this condition (for the so-called »Small-time-step modelling« a time step of as little as 1.5 μs can be provided). However, at the calculation speed of this range a PC cannot update graphs and other monitoring tools in real time with all the data available in the RTDS simulator. Therefore, monitoring of variables is possible only on demand in the RSCAD/RunTime module described in section 2.2.

The RTDS simulator used at the Faculty of Electrical Engineering, University of Ljubljana, consists of one "Rack" with two GPC cards (each of them having two processors) and one GTWIF card. Besides the described hardware, a vital part of the simulator is also the RSCAD software installed on a PC. It is the only tool for communication between the user and the simulator. Connection between the PC and the RTDS simulator can be either direct or via a computer network when multiple users share the same simulator. More information regarding the RSCAD software is written in sections 2.1 and 2.2.

2.1 RSCAD/Draft module

The RSCAD software consists of several modules needed for setting up a real-time simulation. One of those modules is RSCAD/Draft, which enables the user to create a power system model in a user-friendly graphic interface. The RSCAD/Draft module consists of a drawing plane and a library of commonly used power system and control elements.

For each of the inserted elements the user can change its parameters as well as manually determine the GPC processor on which the calculation will be performed. After the power-system model has been finished, a "compile" process has to be provoked in order for create a computer code suitable for the simulator itself. In case of any mistakes or errors in the modelling stage, the compile process cannot be completed. The reasons for this might be unreasonable data for the network and control elements as well as inconsistency of the inserted data and available simulator hardware.

2.2 RSCAD/RunTime module

The RSCAD/RunTime module enables a direct communication between the RTDS simulator and a PC with the installed RSCAD software. In the first step, the user has to select the monitored variables and the controlled elements, which will be used for setting different events in the power-system model (e.g. short circuit, switching, etc.). Next, the compiled model is loaded on the simulator and real-time simulation begins.

2.3 Export of signals from the RTDS simulator

Monitoring the RTDS power-system model parameters in a time domain is possible in different ways. The first possibility is to monitor the variable via the plot function in the RSCAD/RunTime module. The second possibility is to monitor the electric signal corresponding to any variable via an external oscilloscope. For this task it is possible to use the GT Analogue Output card – GTAO, GT Digital Output card – GTDO or interface pins on the front of each GPC processor cards (Figure 1a). Especially the latter is intended for oscilloscope monitoring, as the other output cards (GTAO and GTDO) are capable of producing a

high-resolution signal, required especially for the connection between the RTDS simulator and external protection and control devices.
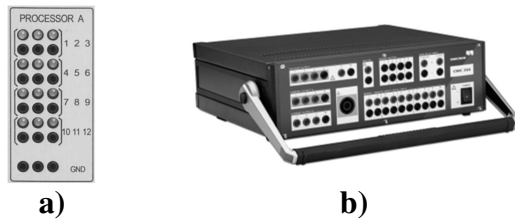

a) **b)**

Figure 1. a) GPC processor card interface pins, b) OMICRON CMC 356 device

As an example we performed a short simulation during which we put into operation an additional transmission line parallel to an already operating one. Then we monitored the phase A current in the connecting line both via the RSCAD/RunTime module (upper graph - Figure 2) and via interface pins on the front of the GPC processor card by using an oscilloscope (lower graph - Figure 2). As mentioned above, compared to GTAO, the interface pins on the processor cards are capable of producing signals with a relatively low dynamic tracking [2], which can be clearly seen from comparing the two graphs in Figure 2. At this point it has to be noted that there is a difference between the two graphs despite the oscilloscope sampling frequency of 40 MHz. Therefore, it can be concluded that for exporting signals to the external equipment, GTAO is a better alternative.
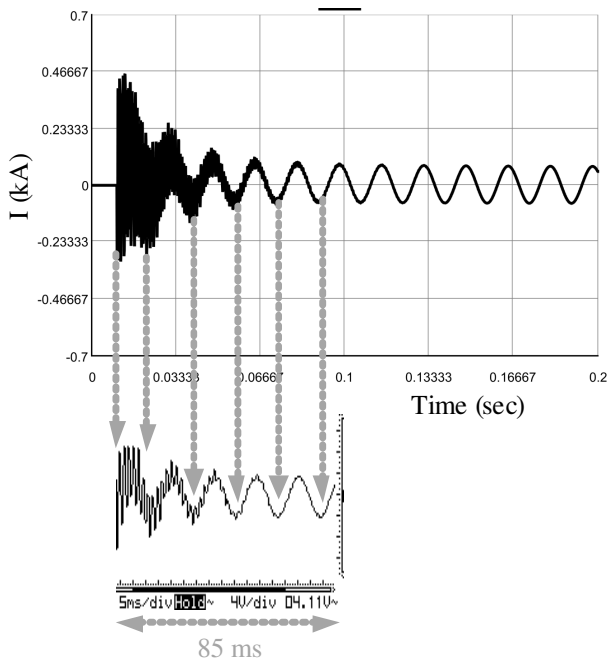

Figure 2. Comparison of the phase A current in a connecting power line parallel to the already operating power line - RSCAD/RunTime module graph (upper) and oscilloscope graph (lower).

The maximum range of the voltage on the GTAO pins is ±10 V, where the maximum current cannot exceed 25 mA. Following this information, in order to export the current signal from the RTDS simulator, the current amplifier is used. We used the CMC 356 device manufactured by the company OMICRON (Figure 2b – [6]) with the help of experts from Elektro Ljubljana (electric-power distribution utility).

Usually, the CMC 356 device is used as a standalone relay testing equipment, as it is capable of producing a practically random current and voltage signal. In our case, CMC 356 was controlled so as to act as a converter and amplifier from the voltage signal (from RTDS) to the current source (required by the relay). The advantage of testing the relay with the RTDS simulator instead of the CMC device is in the simulating circumstances, which are much closer to real situations in which the relay will operate in reality. This includes harmonic distortions, frequency deviations, etc.

Conversion from the voltage signal (RTDS output) to the current was made by applying CMEngine library, which enables implementing practically any programme code desired [7] for controlling the CMC devices. The mean function used in our case is called "multimeter". The function is intended for measuring and determination of input signals, e.g. the peak and rms values of harmonic signals, phase delays, frequencies, etc. within the measuring interval. At the same time, we used CMC generating functions to copy the measuring signals properties into the current signals, which were sent to the CMC 356 output pins. Crucial at this procedure is that CMC 356 operates as an independent converter-interface device.

By combining the CMC 356 and the RTDS simulator we created a testing system which calculates real-time dynamics of a power system and presents the current power-system situation to a protection device. When conditions require tripping, the protection device generates a tripping signal which is sent back to the RTDS simulator, which causes disconnection of a corresponding circuit-breaker model.

2.4 Import of signals to the RTDS simulator

Possibility of importing external signals to the RTDS simulator is one of its special features, which enables the so-called Closed-Loop Testing. At such simulations, a part of a power-system model is replaced by an actual equipment, which is looped with the simulator. Import of external signals is possible via three channels: GT Analogue Input Card – GTAI, GT Digital Input Card – GTDI and GT Front Panel Interface – GTFPI. The latter is intended mostly for importing tripping signals from protection relays (Figure 3).
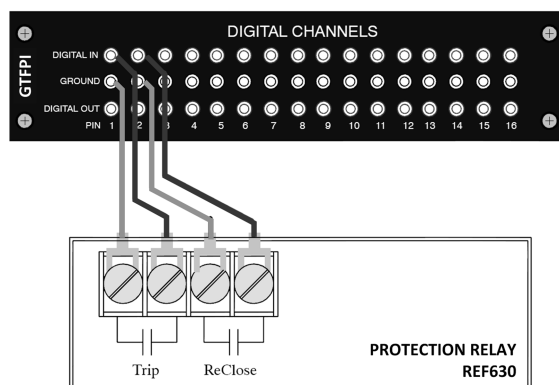
Figure 3. Protection relay REF630 and GTFPI connection

Similar as in case of the output cards used for controlling the power electronic devices (e.g. HVDC and FACTS technology with thyristor firing) the GTDI card is used instead of GTFPI. Also, small time step modelling elements are used due to the required smaller time step which can be as low as 1.4 – 2.5 µs.

3 POWER-SYSTEM TESTING MODEL

A schematic overview of a power-system testing model used in this paper is shown in Figure 4. The model comprises two synchronous generators, four transmission power lines and two load busses. The currents monitored by an external overcurrent relay are obtained by a current transformer. The relay can disconnect both circuit breakers, BR_1 and BR_2, and by doing so protect the L2 power line. In a steady state, the rms value of the phase A current equals 111.1 A, which in turn corresponds to 0.913 A on the current-transformer secondary winding, of course, considering the transformer ratio 120:1 and the transformer load. The GTAO card ratio was determined as 5V → 10A, which means that in case of a 10A current of the current-transformer secondary winding, the voltage on the GTAO pins would be 5V. Therefore, in a steady state, the peak value of the voltage signal on the GTAO card is 0.65V.

After internally triggering the 3-phase short circuit on bus 1 (via the RSCAD/RunTime module), the maximum peak value of the phase A short-circuit current is approximately 15A, which corresponds to 7.5V on GTAO. A permanent value of the short-circuit current is approximately 5A, which corresponds to 2.5V on the GTAO card.

4 PROTECTION-RELAY TESTING

A schematic overview of our testing set-up is presented in Figure 5. Within the RTDS simulator, a power-system model was created with the output signals corresponding to three single-phase currents from the current-transformer secondary winding I_A, I_B and I_C. By

determining the GTAO ratio, the output from the RTDS simulator is in the form of three voltage signals V_{IA}, V_{IB} and V_{IC}. The CMC 356 device converts and amplifies these voltage signals and produces currents I_A, I_B and I_C, which correspond to those in the model. These currents are fed to the relay and when tripping conditions are fulfilled, the relay produces a trip signal. The trip signal is led back to the RTDS simulator via FPI and in this way affects the state of the BR_1 and BR_2 circuit-breaker models.
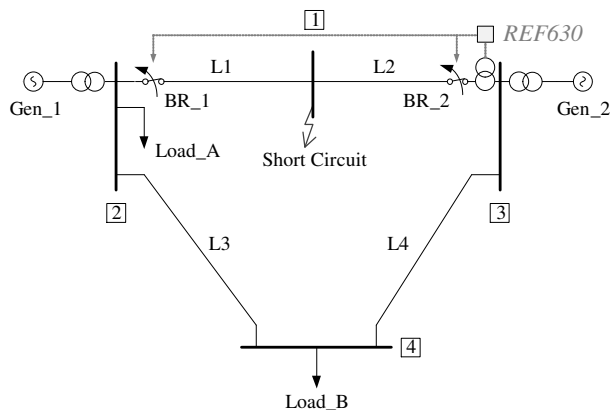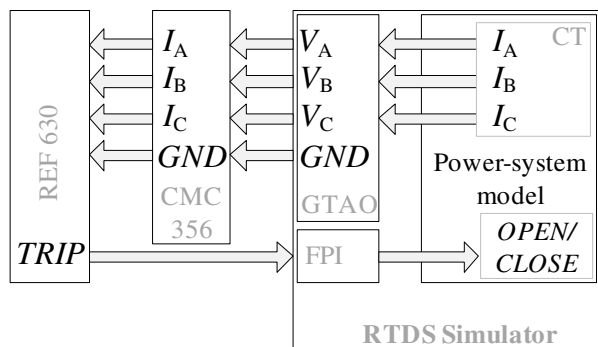

Figure 4. Power-system testing model

Figure 5. Schematic overview of our testing set-up

4.1 Settings

By combining the RTDS simulator and the CMC device, the actual circumstances in which the relay will operate after implementation are produced. This requires setting the GTAO card ratio as well as the conversion ratio in the CMC device. As mentioned above, GTAO can produce a signal with maximally ±10 V. It is therefore necessary to make sure that the output signal does not exceed the voltage limitation. Moreover, the CMC conversion has to be set in such a way that the currents from CMC correspond exactly to the currents measured on the secondary winding of the current-transformer model. Therefore, the following equation applies:

$$G_{AMP} = \frac{1}{G_{GTAO}} \qquad (1)$$

Where G_{GTAO} represents the GTAO ratio (equal to 0.5 V/A) and G_{AMP} represents CMC conversion following (1) and is therefore equal to 2 A/V. The overcurrent protection function on the REF 630 relay is set so that the tripping signal is produced when the $I_{M1} = 3I_n$ phase current is exceeded (momentary value), where I_n represents the rated single-phase current on the 110 kV L2 power-line model. The tripping signal is generated when this condition lasts for more than $T_{M1} = 20$ ms. The described »definite - time« characteristics is shown in Figure 6.

4.2 Three-phase short circuit

By manually activating the three-phase short circuit via the RSCAD/RunTime module, a fault is applied to the modelled power system. Single-phase currents on the current-transformer secondary winding are depicted in Figure 7. In Figure 8, binary signals relevant for our case are also shown with respect to the time. One has to keep in mind that the time scales of the two graphs are different. Namely, in the case of the binary signals, time $t = 0$ is determined as the time of the fault occurrence. On the other hand, in case of the analogue signals, the time $t = 0$ is determined to the 5 % of the total time scale before the fault occurrence. This value can be freely changed by the user in RSCAD/RunTime.
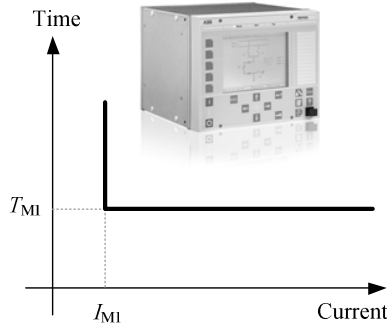

Figure 6. Overcurrent protection setting of the REF630 relay of the ABB manufacture

On the horizontal axis of Figure 8, the time scale from 25 ms before until 250 ms after the fault is presented. The LGFLT variable is a three-bit binary word, where each individual bit represents the state of the fault (short circuit) in each phase. As seen from the figure, at $t = 0$ s, a three-phase short circuit takes place as all the three bits obtain the value of 1 simultaneously. The first bit of the two-bit binary word DIN represents a trip signal by the protection relay controlling all the three phases of the circuit breaker. The second bit of the same word, however, corresponds to a close signal, again produced

by the protection relay for all the three phases. It can be seen from Figure 7 that the circuit breaker disconnects the line at the first phase-current zero crossing. Finally, the third three-bit binary word represents the state of the BR_2 circuit-breaker. The value 1 means that the breaker is closed (conducting the current) and the value 0 that the breaker is opened (not conducting the current).

It can be seen from both graphs that from the moment of the short-circuit occurrence until the final disconnection of the first phase (current zero crossing!) on the L2 line, 0.1846 seconds have passed. The tripping signal was generated 0.13185 seconds after the fault and after that 0.050 seconds passed due to the circuit-breaker operation (set by the user in RSCAD/Draft) and 0.00275 seconds until the first current zero crossing. In the time interval of 0.13185 seconds, mostly three time delays are included:

1. CMC 356 time delay,
2. Overcurrent protection operation delay (set to $T_{M1} = 20$ ms),
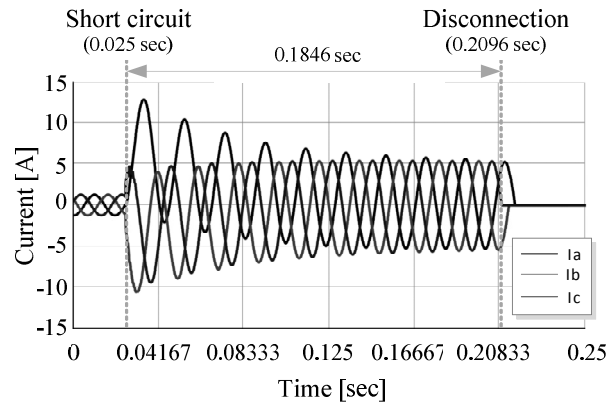3. Overcurrent relay operation delay.

Figure 7. Single-phase currents on the current-transformer secondary windings with respect to the time
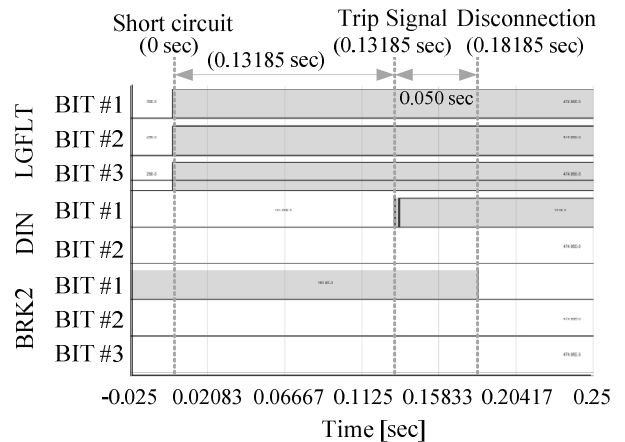

Figure 8. Relevant binary variables with respect to time

Considering the order of the first two time delays, the third one can be neglected. Consequently, the conclusion can be drawn that the CMC 356 device time delay is approximately 112 milliseconds. However, as the test was repeated several times, the average CMC 356 device time delay is even larger and equal to approximately 157 milliseconds. This is the reason why we can state that using the CMC 356 device as a converter and an amplifier is not an optimal solution due to the fact that it brings unacceptable time delays into the whole procedure. Therefore, in future, other alternatives should be found to solve the voltage-to-current conversion from the RTDS signal and amplification problem.

5 CONCLUSION

The main goal of this paper is to present the power-system real-time digital simulator (RTDS) along with its actual use in the area of protection relay closed-loop testing before the protection equipment is implemented in the power system. Such a simulator has been widely accepted worldwide as an indispensable tool for power-system control-equipment testing (e.g. HVDC converter control) for actual circumstances the equipment will be operating in. Namely, in a real power system, such testing cannot be conducted. As an example, let us imagine a controller for a 5000 MW 800 kV HVDC application which has to be tested for a series of different faults at very high voltages.

The RTDS simulator enables actual-equipment closed-loop testing together with a digital model of the rest of the power system. The achievable calculation time step is about 50 μs and if needed it can be lowered down to 1.5 μs (for example for thyristor converters and FACTS devices modelling).

For the purpose of this work we conducted a test of a simple overcurrent "definite time" protection scheme implemented into the ABB REF 630 protection relay. The advantages of testing the equipment with an RTDS simulator are the conditions that can be simulated with RTDS. Namely, all the relevant phenomena such as harmonic distortion, frequency deviation, etc. are included in faults simulated in the RTDS model.

As it turned out during our relay testing, in most of the cases, an additional amplifying equipment has to be used besides the RTDS simulator. As a conversion and amplification tool for the voltage signals produced by the RTDS simulator, a CMC 356 device was used. When using the CMC device, the time delay in the whole procedure was approximately 150 milliseconds. Therefore, in future, another alternative should be found to assure the work in this area to be efficient.

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Rafael Mihalic received his Dipl. Eng., M.Sc. and Dr.Sc. degrees from the Faculty of Electrical Engineering, the University of Ljubljana, Ljubljana, Slovenia, in 1986, 1989 and 1993, respectively. In 1986 he became a Teaching Assistant in the Department of Power Systems and Devices and since 2005 he has been a full professor at the University of Ljubljana. Between 1988 and 1991, he was a member of the Siemens Power Transmission and Distribution Group, Erlangen, Germany. His areas of interest include system analysis and FACTS devices. He is a member of Cigre (Paris, France).