ASPECTS OF REAL-TIME DIGITAL SIMULATIONS OF ELECTRICAL NETWORKS

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ABSTRACT

The paper is focusing on the overview of the real-time digital simulations of electrical networks. The target is to show the main challenges of real-time simulations of transmission networks, industrial networks and switching devices. Complexity of such networks is often much greater than what a single processor simulator is capable to compute in a real-time, therefore simplifications and special simulation approaches are often introduced. These special modeling approaches are analyzed in view of transmission line modeling, network partitioning and accuracy of high frequency switching devices.

INTRODUCTION

The digital simulations of electrical networks are nowadays the only practical and flexible tool for network operation analyses. Complexity of the networks increases the processing time for calculations of the EMT simulations while the advanced computational methods decrease the time needed for individual simulation. The increase of computational power of modern personal computers has drastically improved digital simulations in view of computational speed. EMT programs are in general able to simulate unlimited size of electrical networks but as the size and complexity increases the calculation duration of a single time-step (Δt) simulation increases. Depending on the accuracy and the size of the simulated network 1 second of simulation is normally calculated in a period that is in range of ten, hundreds or even more times greater than the simulated second.

Introducing the real-time (RT) digital simulations demands a careful approach on the building of the simulation case. The goal of the real-time simulation is to perform a single Δt of the simulation in a time that is equal to Δt. The simulations are often calculated even in a shorter period leaving some additional time for other processes of the RT simulators as are DA conversions to analog output ports or others.

Limited calculation periods of the RT simulators decrease the flexibility to simulate complex electrical networks. With increased complexity the need for computational power increases. Multiple parallel computing processing cores are therefore engaged to deal with large simulated systems [1]-[2].

The RT simulations play important role also in development or prototyping of the network connected devices [3]. Often, the control devices are introduced into the simulation loop (Hardware-in-the-loop HIL) to control the simulated devices (Fig. 1a).

The use of Power-Hardware-in-the-loop (PHIL) has also become a common practice to test the entire hardware of the device under test, which is connected to the RT-controlled voltage source representing the simulated network (Fig. 1b) [4]. In such cases the voltage sources often suffer from higher delays or nonlinear characteristics which deteriorate accuracy or stability of the simulated system.

Accuracy of acquisition of analog and digital signals is beside the processing power demand and delays of the exchanged signal between processing cores one of the most common issues that influence accuracy and stability of the simulated system.

The HIL simulations are becoming more and more attractive for prototyping of modern switching devices (e.g. Active filters, PV inverters, etc) where the controller is used as the hardware under test retrieving the measured electrical signal from the simulator and passing control and firing pulses to the simulator. The experiences are showing that the main issue of simulating such devices is in acquisition of the high frequency switching pulses where a slight error of the acquired pulse width could lead to dramatic deterioration of the simulation results. The detailed study of such case is presented in the paper.

RT SIMULATIONS OF TRANSMISSION NETWORKS

Real-time simulations of transmission networks are utilized whenever there is a need to introduce certain real controlling hardware device (e.g. protection relay, controller, etc.) into the simulation. Analyses are generally focused into transient as well as into steady state behavior therefore a high precision needs to be considered with mathematical modeling of all devices used in the simulation.

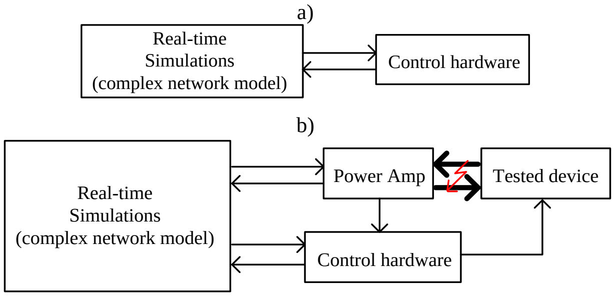

Fig. 1: Scheme of the a) control hardware in the loop (HIL) and b) power and control devices in the loop (PHIL)

To analyze the transients, the most crucial points of simulation are the models transmission lines [5], [6] that can be modeled in several ways as:

- PI section models,
- Travelling wave models (Bergeron's, frequency dependant - FD or wide-band - WB).

Which model is to be used is a question of the simulated system and simulation time-step. The PI section models are generally not recommended for use since they tend to express lower accuracy within some frequency regions. Therefore, use of the frequency dependent (FD or WB), the travelling wave model is preferable solution although it is limited by the simulation time-step which defines the minimum length of the transmission line. For example, simulation that computes network solution in 50 µs can adequately represent at least 15 km of the transmission line model. Shorter lines can be therefore modeled with the FD model only if the simulation time is shorter. However, using PI section for modeling of short, balanced lines can be considered as quite accurate approach.

One of the advantages of the FD model is its ability to split the simulated power network into multiple partitions that can be simulated in parallel on different processing units. The unavoidable delay of the exchanged signal can be attributed to the expected delay of the signal transmission between the both ends of the travelling wave model. The PI section transmission line model on the other hand does not offer theoretical time delay of the signals therefore it is not usable for network partitioning [7].

The Fig. 2 shows the most basic mathematical representation of the travelling wave model of the transmission line, the Bergeron's model.

Such circuit can be used for partitioning of the simulated network between different processing units or to use it as an artificial coupling link between the RT simulator and PHIL.

Generally, the RT simulators are using one processing unit per calculation of individual network section while the electrical machines (synchronous machines, transformers and others) are calculated on separate processing cores. It depends on the RT simulator, but the results of the individual core can be exchanged once or multiple times during one simulation time Δt to improve the simulation accuracy.

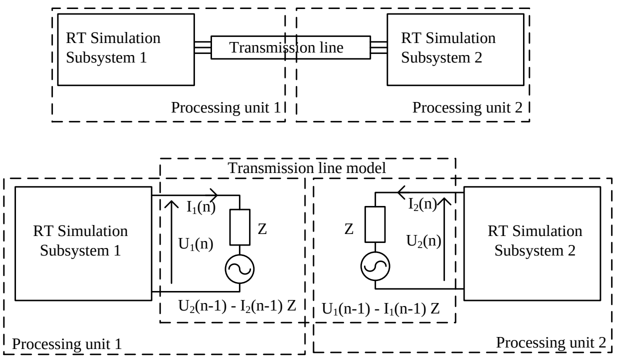

Fig. 2: Representation of the Bergeron's model of the travelling wave

RT SIMULATION OF INDUSTRIAL NETWORKS

The industrial networks are in comparison to the transmission networks composed of higher number of electrical machines, shorter cable connections which results in higher number of electrical nodes. Limitations of the RT simulator (e.g. number of nodes) often require use of parallel processing units and the interface line for exchanging the electrical signal in the coupling point. As it was already mentioned, to accurately represent the delay of the exchanged signals between the processing units, the travelling wave model of the coupling line can be used. Still, there is more unlikely to find such cable in the industrial network that would suit the model of the 15 km of the coupling line. As far as the simulation allows the simulation time-step could be further decreased in order to shorten the length of the coupling cable to reach more accurate model of the entire network.

However, there might still be a case when there is no possibility to avoid unrealistic length of the coupling cable. In this case, the main concern is focused on the frequency response of the network or devices connected through the artificial coupling line.

Coupling travelling wave model

Using the simple lossless Bergeron's model of the travelling wave, the travel time of wave propagation on an electrical line can be given as:

$$\Delta t = (LC)^{0.5} \quad (1)$$

where:

Δt is wave travel time,

L is series inductance of the model,

C is shunt capacitance of the model.

It can be clearly seen that the travel time Δt is a function of the product of the line inductance and the capacitance. Both can be arbitrarily chosen to influence the overall performance of the network as low as possible. In the simulation section it will be shown how the different combinations of line impedances influence the frequency characteristics of the simulated network and what the negative consequences are.

RT SIMULATIONS OF LOADS

While the passive loads (RLC based) are calculated within the main network solution processing unit, the other machines (induction, synchronous machines, transformers, switching devices) are computed on the parallel units to achieve reasonably low simulation time-step. The 50 µs is fairly acceptable time-step for simulations of machines with slow dynamics while in order to simulate modern switching devices and to reach the desired level of accuracy much lower simulation time-step needs to be introduced.

Since the development of RT simulators tends toward optimization of the processing effort and increasing of the

accuracy the use of different simulation time-step domain has been adopted (small and large time-step). The number of the consecutive small-time steps within one large time-step has to be the integer value to accurately represent the time-instant when the signals are exchanged, normally once every large time-step.
The exchange of signals between the processors calculating small and large time-step domain is again realized by introducing artificial travelling wave line. The one is often incorporated into the model of the transformer (e.g. Active filter connected to the grid through transformer) where the transformer inductance is used as real series impedance of the Bergeron's model while the shunt capacitors are artificially added.
The next significant concern of the RT simulations is modeling of switching devices. The switching elements (tyristors, GTO, IGBT, etc.) are modeled in a different ways. Use of ideal switches has been introduces by some RT simulators. Each combination of switching state is defining new network solution G-matrices and therefore involving high amount of processing/memory effort. An adopted solution was also modeling of the ON switching state as an inductor and the OFF switching state as a series connected capacitor and resistor [7]. Such model is suitable in view of minimizing number of G-matrixes and of the length of the required time-step but it tends to express higher amount of artificial losses in case of higher switching frequency.
Beside the accuracy of the models of switching devices the most influence to the simulation accuracy has the acquisition of high frequency switching signals. Although the sampling accuracy of digital switching pulses is normally relatively high, it depends on the topology of the device how a small error of the sampled pulse reflects the simulation accuracy. The simulation case follows.
Modeling the high frequency (>10 kHz) switching PWM devices has shown the need for compensation of the error produced by inaccurate firing pulse duration. Nowadays, the RT simulators are reaching sampling frequencies of digital firing pulses up to 50 MHz. Although only one pulse status (on or off) can be considered within one simulation time-step the high number of analyzed digital samples allows compensation of the partially misused signals [8].

SIMULATIONS

The following simulations are showing different cases where the described issues of RT simulations are pinpointed.

Simulation of transmission networks

As mentioned, modeling and simulation of transmission networks are showing the most crucial point in representation of network line models for observing transients while the relatively high calculation time-step Δt does not influences drastically, even in case when there is a need to exchange the signals between the

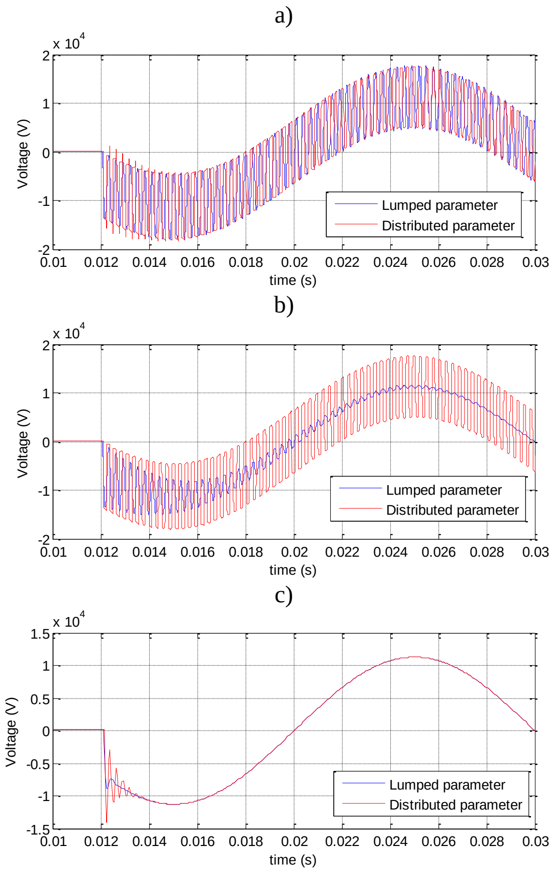

Fig 3: Line energization – Impact of different simulation time-steps to the simulation accuracy using two models of transmission line: a) continuous time b) discrete simulation time (Δt = 2µs) c) discrete simulation time (Δt = 50µs)

processing units. The simulations of transmission networks show the case with two different models of a transmission line – a travelling wave model and lumped PI model. The figure is showing phase-voltage response at the end of the line during the line energization. Simulation is performed using different simulation time-steps.
The results in Fig. 3 show that despite of use of the precise models of the network line the simulation time-step in range of 50 µs still expresses relatively high error of the simulations. The main issues of the RT simulations are therefore the deviation of lumped parameter model from the exact or distributed parameter transmission line model and the deviation of simulation results of different transmission line models in case with lower simulation time-step.

Simulation of industrial networks

Simulation of the industrial network emphasizes the influence of the "sometimes unavoidable" network splitting among two processing units. It is shown how different artificial link impedances influence the impedance characteristics which can in industrial networks cause severe resonance conditions. In the case shown below, the harmonic filters HFs (e.g. used with SVC) are simulated on a different processing unit than the rest of the network. The coupling cable between the HFs and the main feeder feeding other loads is in reality relatively short (100m). In simulations it is necessary to use the artificial impedance with minimum length of the travelling wave model that meets the condition (1).

There are two major possibilities what type of the link to use; the one with low series inductance and high phase-to-ground capacitance (cable type) or vice-versa (overhead line type). Simple simulations of the HFs connected over an artificial coupling line (Fig. 4) are showing that the line drastically influences the simulated system. The series impedance changes the frequency characteristic of HFs seen from the feeder (secondary side of transformer) (Fig. 5).

The main difference between the overhead line and the cable is that the cable has much larger ground capacitance and lower inductance, therefore the capacitance dominates. In case of coupling with the overhead line, the capacitance is very small and therefore the length of the linking line needs to be much longer to meet the (1). The minimum length of the cable and overhead line are 6 km and 11 km respectively. The influence of the overhead line to the impedance conditions is much more drastic in the low harmonic range. The series resonance point of the lowest tuned harmonic filter (95 Hz) is causing that the impedance at 50 Hz has increased; therefore higher fundamental current is drawn from the filters. The result can be seen in Fig. 6. It is obvious that such coupling line is not appropriate to be used as a coupling line for RT simulations.

The cable line, on the other hand, doesn't change the impedance characteristics drastically in the low frequency range (especially in case of high capacitance and low inductance) but it generates additional resonances in the region above 1 kHz. This new resonances could eventually lead to some unwanted behavior in case of harmonically distorted current loads causing problematic voltage distortions.

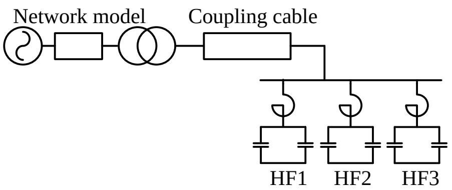

Fig. 4: Simulation scheme of industrial network with harmonic filter banks and artificial coupling cable

Network	Transformer	Coupling line	Harmonic filters
U_n 110 kV S_k 1300 MVA	U_n 110/20 kV S_n 60 MVA u_k 11%	Cable: L_1 2.52 mH C_1 1.2 µF Overhead line: L_1 12.25mH C_1 0.22 µF	Q_n 20 Mvar f_{rH1} 95 Hz f_{rH2} 145 Hz f_{rH3} 195 Hz

Table 1: Simulation parameters of the industrial network

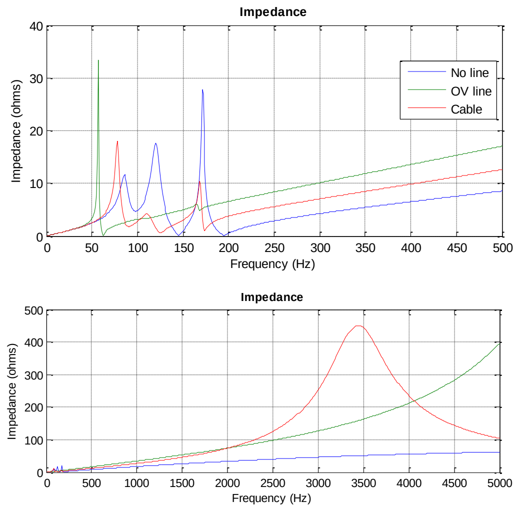

Fig 5: Frequency characteristic of the simulated system with different artificial coupling lines

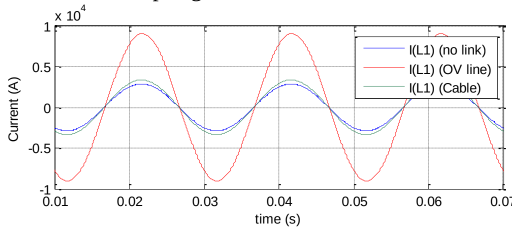

Fig 6: Steady state current at the coupling impedance

Simulations of switching devices

The following case is showing the weaknesses of RT simulations of the high frequency switching devices. As it was already explained, high frequency devices are generally simulated in the small time-step domains to assure certain simulation accuracy. The first issue is the coupling connection of such domain to the large-time step domain which demands additional coupling impedance, a transmission line with travel time at least 1 Δt to assure stable connection.

The next important aspects are the simulation accuracy and limited accuracy of the firing pulse acquisition which are indicated in the following simulation case representing the operation of the grid connected voltage source converter (VSC) – the active filter. Two models of converters are considered, one with the output filter using large series choke (6.4%) and other using smaller series choke (3%). Both models are tested at high and low accuracy of digital input acquisition and sampling frequency, 1µs and 0.2 µs respectively.

Although 1 Mhz sampling frequency seems to be relatively high for digital signals, it is practically much too low for accurate simulation of switching devices. Maximal latency of 1 µs in respect to the pulse duration of 10 kHz switching device is 1%, which means that the average value of the output switched converter's voltage can vary up to 1% in amplitude. Such voltage variation could lead to much higher current variations due to relatively low coupling series impedance towards the network. The current error is expected to be higher with the model with smaller choke. This fact can be observed in Fig.7 where the current error of the low precision simulation shows much higher unpredictable current ripple caused by the error in switching pulse acquisition. By increasing the accuracy of the acquisition and simulation calculations, the ripple is reduced to similar value for both topologies.

CONCLUSIONS

The paper has been written with the idea to show what the main obstacles when simulating different networks and devices in RT simulators are. In comparison to the classic EMT programs, the RT simulators are designed to operate with relatively high simulation time-step to allow simulations of large-scale networks. To optimize operation, multiple parallel processors are engaged which introduces additional issue with the delayed exchange of signals. The paper describes that the transmission networks are much more appropriate to be partitioned into multiple processing units, while small industrial networks, where the need for partitioning might also persist, tend to express relatively high influence of multi-processor components to the network impedance and therefore to simulation results. On the other hand, network connected voltage source converter has been recognized as one of the most critical components for simulations in view of the size of the simulation time-step and accuracy of digital signal acquisition.

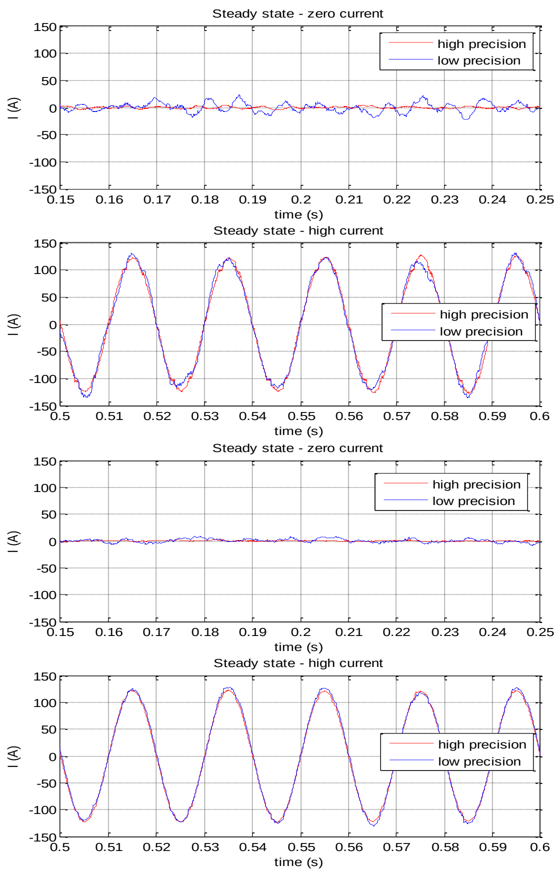

Fig 7: Simulation results with high and low precision simulation and acquisition: VSC with small choke at a) zero and b) rated current and VSC with larger choke at c) zero and d) rated current

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