HARDWARE-IN-THE-LOOP SIMULATION OF A DISTRIBUTION NETWORK WITH AN ON-LOAD TAP CHANGER CONTROLLED BY AN INTELLIGENT ELECTRONIC DEVICE VIA DIGITAL COMMUNICATION

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Abstract: This paper deals with hardware-in-the-loop simulation of the distribution network, which is equipped with the on-load tap changer on the HV / MV transformer. This tap changer in the simulation is controlled from a real physical external device - the multi-functional intelligent electronic device REX 640 from ABB. This device receives and processes the sampled measured values of voltages and currents. Based on these values, an instruction to switch the transformer tap is then given back into the simulation. All communication between the simulator and the external device is provided using the IEC 61850 industrial communication protocol. The paper summarizes both the benefits of hardware-in-the-loop simulations and the possibilities of using intelligent electronic devices and data communication in distribution systems.

Keywords: HIL simulation, Real-time simulator, IED, Voltage regulation, SMV, GOOSE

1 INTRODUCTION

The way they operate distribution networks is changing. Increasing distributed generation sources, which leads primarily to change the direction of power flow. Therefore, there is an effort to create complex control systems with advanced digital communication, which will help eliminate the negative effects of these sources and will turn them into positives (for example, smart management of these resources).

The increasing complexity of control systems leads to the need to use methods of testing their functionality, which are more sophisticated. One option is real-time simulator (RTS) testing. The RTS is a device that is able to perform EMT (Electromagnetic Transient) simulations in real time. Analog and digital input and output peripherals can also be connected to the simulator. Through these peripherals, it is possible to connect an external device and integrate it into the simulation. Therefore, RTS calculates the network states and sends the results to the external device via the output peripherals. The device responds to these results and sends feedback via input peripherals back to the simulator, which reacts again to these stimuli. In this case, it is a HIL (Hardware-in-the-loop) simulation. For example, the source [1] deals with these simulations.

The paper describes a real-time simulation of a simple HV / MV substation and one section of MV overhead lines. An intelligent electronic device (IED) is connected to the simulator via digital communication. The voltage regulation function is set in the IED. This function controls the on-load tap changer (OLTC) of the HV / MV transformer. A similar test, but with a simpler communication structure and without RTS, is discussed, for example, in article [2].

2 DESCRIPTION OF THE SIMULATION

The simulation was designed in RSCAD in the draft module. The scheme of the simulated network is shown in Figure 1. The network is supplied from an ideal voltage source at a voltage level of 110 kV. A three-winding transformer with a nominal apparent power of 25 MVA with OLTC on the primary side, provides the transformation from HV to MV. The transformer has ± 8 taps, each with a value of 2% of the nominal voltage. Taps can be switched within the simulation, both manually and externally (green arrow), using IEC 61850 GOOSE (Generic Objected Oriented Substation Event). The tertiary winding is delta-connected and is loaded with a fixed value of active power of 1 MW. The secondary winding of the transformer is connected to the AlFe 110/22 type overhead line in a side-by-side arrangement, which is 20 km long. The line was modelled in the RSCAD program in the Tline module, based on the physical parameters of the line. These parameters were taken from sources [3] and [4]. The resulting value of the series impedance is $\overline{Z}_k = (R_k + jX_k) = (0.257 + j0.340)\ \Omega\cdot\mathrm{km}^{-1}$. A load is connected at the end of this line. The voltage (blue arrow) and current (red arrow) measurements are located on the secondary side of the transformer and are routed to a module that provides communication according to IEC 61850 SMV (Sampled Measured Values).

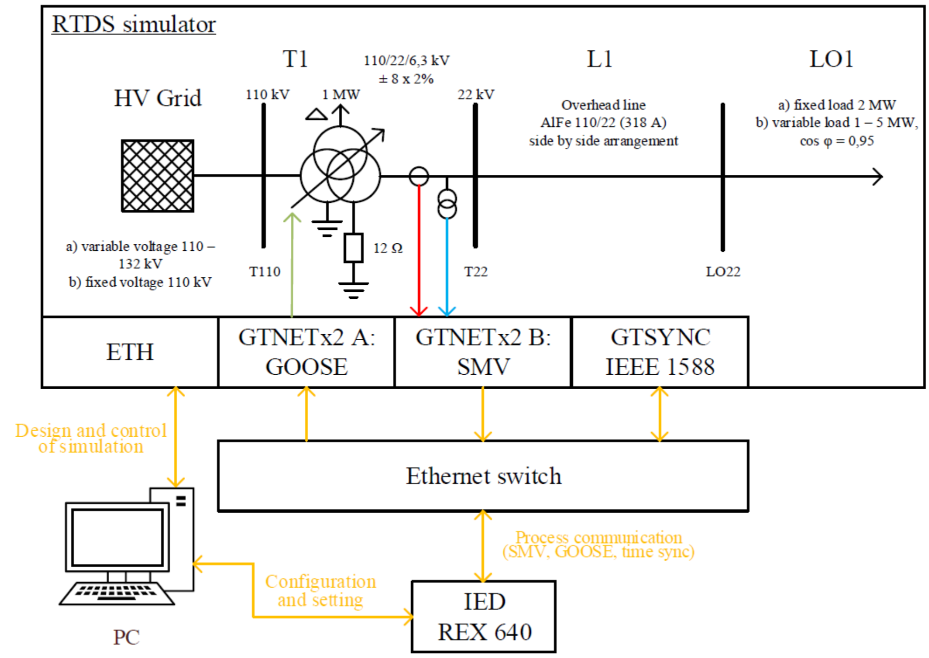

Figure 1: Simulated network diagram

The external connection is also shown in Fig.1. A computer (PC) is connected to the Ethernet interface of the simulator, through which the simulation was designed and which is used to parameterize and run the simulation. There are also Ethernet ports on the simulator of the GTNETx2 network card, which has two modules for communication via the IEC 61850 protocol. Another port has a GTSYNC card for time synchronization according to IEEE 1588. All these ports are connected to one switch, to which the IED REX 640 is also connected. the synchronization source is the internal clock of the IED.

2.1 SETTING AND PARAMETERIZATION OF THE IED

The nominal value of the voltage U_n was set to 22 kV (L-L, RMS), i.e. to the same value as the nominal voltage of the system. The rated current I_n has been set to 300 A with respect to the maximum value of the overhead line load (318 A) to the value of the next lower rated value.

The OL5ATCC function block was used for voltage regulation. According to the manual for the IED [5], the function works so that if the average measured RMS value of all three phases U_{meas} for the time delay t_1 exceeds the range of the set voltage band U_{band} and does not fall below the hysteresis value, the tap is switched. The hysteresis value is 10% of the U_{band} value and is located at the lower and upper limits within the U_{band} range. The U_{band} range is symmetrical according to the set value U_{band_center}. This centre value is therefore the required voltage value. According to [5], it is recommended to set the U_{band} range to a value around twice the step of one tap, but never below this value. For simulation purposes, this value was chosen as twice the step of one tap. If the voltage exceeds the limit by a larger value and it would not be sufficient to switch only one tap, the timer t_2 is activated instead of the timer t_1. Timer t_1 is set to 1 s, timer t_2 to 2 s. In practice, these values are set to a significantly larger value. According to [5], the recommended value for t_1 is 60 s and for t_2 30 s. The low set value of the timers is chosen to speed up the performed tests.

In the settings, it is also possible to compensate the voltage drop on the line. This function is called LDC (Line Drop Compensation). If the LDC function is switched on, it is necessary to set the percentage values of the voltage drop on the resistance of the line U_r and on the reactance of the line U_x. These values are calculated according to equations (1 and 2), which are taken from [5].

$$U_r = \frac{\sqrt{3} \cdot I_n \cdot R}{U_n} \cdot 100 \text{ , } U_x = \frac{\sqrt{3} \cdot I_n \cdot X}{U_n} \cdot 100 \qquad (1, 2)$$

3 SIMULATION RESULTS

Two tests were performed as part of the simulations. In test a), the load LO1 was set to a constant value and the voltage at the source changes. Test b) consisted of verifying the LDC function. Here, the voltage of the source remained at the nominal value and the value of the load at the end of the overhead line changes. The measurement in test b) remains at the same place as in test a), but now the IED calculates the voltage on the load based on the measured current and the set line impedance.

3.1 TEST A)

Simulation results a) are shown in Figure 2. The time from the beginning of the simulation in seconds is plotted on the common x-axis. The first part of the figure shows the set voltage value on the primary side of the transformer u_{T110}. The voltage is plotted in per units, where the reference value is the nominal value of the voltage U_{nHV} = 110 kV. At the beginning of the simulation, this voltage is at the nominal value. At time 1 s, the voltage begins to rise to a peak of $1.05U_{nHV}$, which occurs at time 11 s. Then the voltage drops sharply back to the nominal value. In the second part of the figure, the voltage on the secondary side of the transformer is plotted. This voltage is also in per units. The reference value is the nominal voltage U_{nMV} = 22 kV. In this part of the graph, both the voltage from the simulation u_{T22} (black curve) and the voltage u_{T22_GOOSE} (red curve), which measures the IED and sends its value back to the simulator using GOOSE messages. When comparing these two waveforms, it can be seen that they are similar.

The voltage profile of the u_{T22_GOOSSE} is stepped, which is because the IED sends the measured value only every 500 ms. This value is sent in FLOAT32 format and is a period value. This value is calculated directly within the OL5ATCC function block and is used to check whether the function calculates the value correctly. Another way to send values from the IED is using SV, but the network card of the simulator does not allow receiving and sending data in SV format at the same time within one module. However, for data received in SV format, it would not be possible to verify the correctness of the calculation of the average three-phase RMS value.

At the beginning of the simulation, it can be seen that while the voltage on the primary side of the transformer is nominal, the voltage on the secondary side is below the nominal value. This difference is due to the voltage drop at the transformer. The voltage u_{T22} shows the correct function of the voltage regulation. When this voltage is above the value of one tap, i.e. above $1.02U_{nMV}$ (U_{band_center} + $0.5U_{band}$), for 1 s (time set by timer t_1), the tap is switched downwards. This fact is also evident from the third part of the graph, where the binary signals received from the IED via GOOSE are plotted. The *G_TIMER* signal indicates an active timer and the *G_DOWN* and *G_UP* signals are commands to decrease / increase the tap. In the last part of the figure, the actual tap position is plotted, which is in the basic position at the beginning of the simulation. It can be seen from the diagram that after the sixth second of the simulation the timer is activated, then after the seventh second the signal from the IED *G_DOWN* decreases the tap. The timer is reactivated before the 11th second, but before it can finish, the voltage drops sharply. The timer is then activated again, but now counts down the time until the tap increases, which occurs after the 12th second.

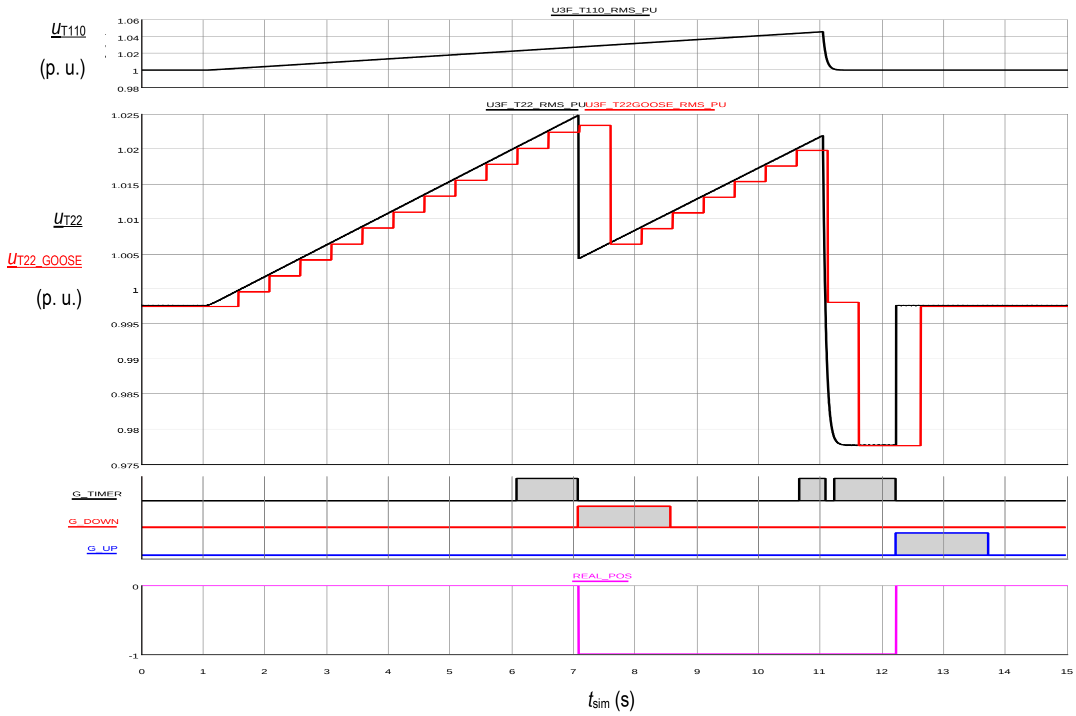

Figure 2: Results of simulation a)

3.2 TEST B)

The results of the simulation are evident from Fig.3. The graph is in a similar format as in the previous case. In the first part of the graph, the set load S_{LO1} of the load is plotted.

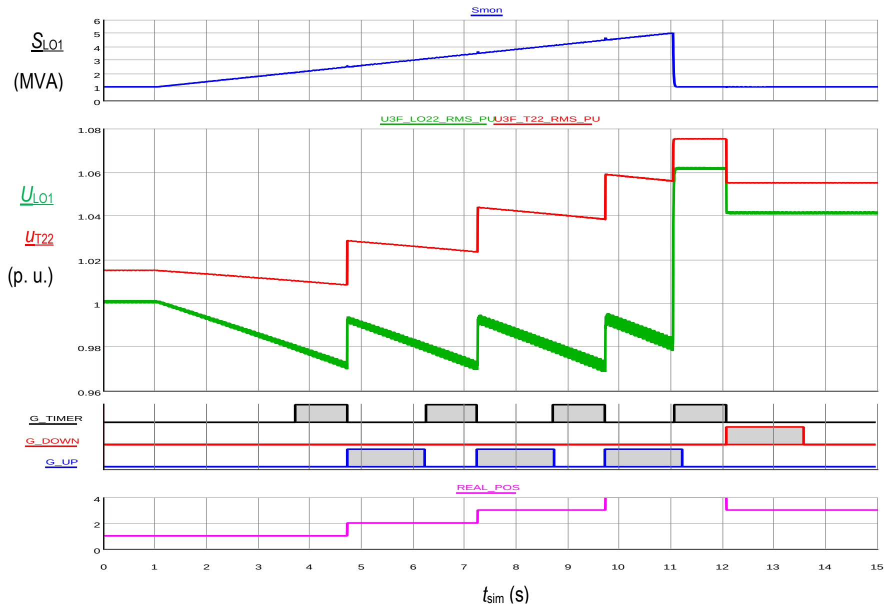

Figure 3: Results of simulation a)

In the second part of the graph, the voltage on the secondary side of the transformer u_{T22} (red curve) and the voltage at the end of the line U_{LO1} (green curve) are plotted. The difference between these curves is due to the voltage drop on the line. As the load increases, so does the difference between these voltages. The third and fourth parts of the graph are in the same format as in test a). It can be seen from the diagram that the default state is now the first tap. As soon as the voltage on the load falls below the value of one tap ($0.98U_{nMV}$), the timer is activated and after time t_1, the tap is changed. Therefore, the controller now does not regulate to the value of the voltage behind the transformer, but to the value of the voltage at the load node. It can be seen from the picture that the tap will increase three times. After a sharp load reduction, the tap will decrease.

4 CONCLUSION

HIL simulations using a real-time simulator are a suitable tool for testing devices for grid control and protection. With the help of a real-time simulator, it is possible to test the devices in almost the same conditions to which they are exposed during real operation. In this experiment, the possibility of using a multifunctional IED for voltage regulation by switching transformer taps using IEC 61850 SMV and GOOSE was successfully verified on a simulated part of the distribution network. This concept, where one universal device is used, instead of several single-purpose ones, will already be the standard. The paper also outlined another possibility to improve voltage quality by using a LDC function, which may help, but which needs to be approached in a reserved manner and based on judgment based on knowledge of the character of the network.

ACKNOWLEDGEMENT

This research work has been carried out in the Centre for Research and Utilization of Renewable Energy (CVVOZE). Author gratefully acknowledge financial support from the Ministry of Education, Youth and Sports of the Czech Republic under BUT specific research programme (project No. FEKT-S-20-6449).

Author gratefully acknowledge financial support from the Technology Agency of the Czech Republic (project No. TK01030094).

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