Model-In-The-Loop Real-Time Simulation in Phasor Domain

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Abstract— The ePHASORsim tool offers real-time phasor domain simulations for large-scale power systems. Applications include contingency studies, testing control devices, operator training, and SCADA system tests. This paper describes a new application of this tool for Model-In-the-Loop simulations. Two test experiments are shown in this paper to demonstrate the accuracy and advantages of utilizing ePHASORsim for this purpose. The Matlab SimPowerSystems toolbox is used to validate the results.

Keywords— Model-in-the-loop simulation; phasor simulation; power system simulation; power system dynamics

I. INTRODUCTION

Simulation tools and modeling techniques are necessary for the design and analysis of modern power systems. However, the fast evolution of new technologies, such as renewable energies, and their interconnection with power grids, makes it challenging to have a simulation tool that can be used for modeling all the new component developments. One criterion in the assessment of a simulation tool is how comprehensive is its library of models. Other criteria, depending on the application, are the simulation performance and accuracy, quality of its user interface, and the scalability of the tool.

The variety of existing models for the power system industry is extensive. These models can be classified into two major groups: (a) power system components, such as transformers and synchronous machines, and (b) controllers, such as voltage regulators and power system stabilizers. Even though several models are defined in standards such as the IEEE, creating a rich library of models remains a challenge in the development of a simulation tool. It may take a considerable amount of time to develop and validate a new model that is compatible with an existing software architecture. Conversely, not all of these various types of models are required for every user. It is not uncommon to encounter a real power system component or controller that is not documented or supported by the simulation tool. Therefore, a key capability of a simulation tool is how easy it is to extend its library to adopt new models.

The concept of “user-defined-model” is a well-adopted feature in many commercial simulation tools that partially addresses the requirement of having an extensive library. However, in some simulation tools, this useful feature is limited only to the implementation of controller components of the power system, such as excitation systems and turbine governors. Also, in some tools, the development of user-defined models is such a complicated process that the user cannot develop power system components such as machines without having an extensive knowledge with the internal design of the simulation tool. Moreover, there is always the concern that the simulation performance will be reduced if there are many user-defined models in the simulated system.

Real-time hardware-in-the-loop (HIL) simulation is an appreciated technology to test and validate new components before installing them in the field [1]. In HIL simulation, the power system is running in a real-time environment whose fidelity provides a realistic set-up to test and prototype the final application of a new component. The design iteration is slow at this point. The concept of model-in-the-loop (MIL) simulation ranks one level before HIL simulation. In this type of simulation the model of the new component is developed and connected to the simulation tool. Therefore, the development iterations are fast since the detailed modeling issues can instantly be implemented and tested with the system [2].

The goal of this paper is to report on applications of a real-time-phasor-domain simulator to perform model-in-the-loop simulations. The paper is organized as follows. In Section II the overview of the simulation tool from software and hardware points-of-view will be described. The application of the tool for model-in-the-loop simulation is presented in Section III. Experimental simulation results are shown in Section IV. The future work and concluding remarks are presented in Section V and VI.

II. PHASOR-DOMAIN SIMULATOR

Real-time simulation for electromagnetic transient (EMT) studies in power systems has been well established. The fundamental principles of most real-time simulations are based on the mathematics of EMT-type analysis. This includes the hardware/power/model-in-the-loop simulations. Nevertheless, power system experts have further realized the need for real-time-phasor-domain simulation, beyond EMT-domain simulation. This type of tool can be used to perform dynamic security assessments and test the functionality of hardware such as global control devices (special protection and control systems) in large-scale power systems. Furthermore, it can be used for training purposes in academic
laboratories, or as a tool for operator training in energy management centers.

The ePHASORsim from OPAL-RT Technologies Inc. is a simulation environment for both transmission and distribution, balanced and unbalanced power systems [3]. The mathematical background of ePHASORsim is based on a set of differential-algebraic equations (DAEs) as follows [4]:

\[
\begin{align*}
\dot{x}(t) &= f(x, V) \quad (1) \\
YY &= I(x, V) \quad (2) \\
x(t_0) &= x_0 \quad (3)
\end{align*}
\]

where \( x \) is the vector of state variables, \( V \) and \( I \) are the vectors of bus voltages and injected currents, \( Y \) is the nodal admittance matrix of the network, and \( x_0 \) is the vector of initial values of state variables. The core of solver is built as a MATLAB/SIMULINK S-function and its library of models are coded in C++. The built-in library includes major and common components that are used for this type of simulation in power systems, such as synchronous machines and their controllers, different type of loads, transformers with on-load tap changers, among others.

Although the purpose of model-in-the-loop simulation is more focused on developing controller models to work with the model of the power plant, this paper reports the latest advancements in ePHASORsim to develop, integrate, and test the power system components along with their controllers. The motivation for this effort is to model the impact of DC system and their controllers in the phasor-domain simulation.

### III. PROPOSED Technique

In ePHASORsim, power system components inject current via an external source into an individual bus of the power system. The current flow can be positive-sequence-balanced, or three-phase-unbalanced. This injection is directly added to the vector \( f(x, V) \) in (2). Therefore, any component that has a Norton equivalent can be linked with ePHASORsim solver via a controlled current source and internal impedance.

Fig. 1 illustrates the current injection concept for a voltage-source-converter (VSC). Most DC components, such as FACTS devices and HVDC transmission lines, are connected to the AC grid via inverters and rectifiers which normally have an embedded transformer. In Fig. 1.a, \( V_{ac} \) is a function of \( V_{dc} \), modulating amplitude (\( m \)) and firing angle (\( \alpha \)). The injected current into the AC grid is also a function of \( V_{ac} \), the voltage of the grid-side winding of the transformer (\( V_{gs} \)), and \( Z_T \) (transformer impedance). The equivalent model of a VSC is shown in Fig 1.b, where the injected current \( I_{inj} \) establishes the connection between the VSC and the AC grid. Examples of DC sources include photovoltaic cells (PV), fuel cells, battery storage, and capacitors in FACTS devices. With this formulation, the user can develop DC-side components and their required control scheme, and then the unit can be placed in a closed-loop system where the AC grid is modeled in ePHASORsim.

### IV. SIMULATION Results

This section presents two test cases that demonstrate model-in-the-loop simulation with ePHASORsim. In both cases, the new components do not exist in the simulation tool library; they are built using the Matlab’s SimPowerSystems (SPS) toolbox [5]. The components’ responses during both the steady and the dynamic states of the system are analyzed. After validating the simulation results against the phasor-mode simulation of SimPowerSystems, the newly-developed components are ready to be scripted and integrated into the built-in library of ePHASORsim; this effort, however, is not presented in the paper.

#### A. Static Synchronous Compensator (STATCOM)

The STATCOM is a shunt-connected FACTS device used to regulate the voltage of an AC bus by absorbing or generating reactive power. It consists of three parts: DC source, voltage-source-converter (VSC), and controller. The SPS toolbox includes the STATCOM unit and its controller developed for Phasor type simulation. This model is integrated with ePHASORsim by using the technique explained in the previous section.

The topology of the AC grid in this experiment is depicted in Fig. 2. It consists of two 500 kV equivalent networks that are connected by two 300 km transmission lines. The STATCOM is located at the junction point of these lines, i.e. Bus 2, and it models a three-level PWM, with a DC link nominal voltage of 40 kV and an equivalent capacitance of 375 \( \mu F \). On the AC side, its total equivalent impedance is 0.22 pu on 100 MVA. This impedance represents the transformer’s leakage reactance and the phase reactor of the bridge of an actual PWM STATCOM [1].

As illustrated in Fig 2, the entire grid, excluding the STATCOM, is implemented in the ePHASORsim environment, and the STATCOM block is connected externally to Bus 2. The block “Communication link” refers to the voltage and current exchanges as discussed in the previous section.
The steady state and dynamic response of the simulation are compared with the Phasor mode simulation of SimPowerSystems toolbox. Two test scenarios are presented here:

1) **Response to control signals**
The reference voltage of the STATCOM’s controller is initially set to 1 p.u., and subsequently lowered at \( t = 0.5 \) s to 0.97 p.u., raised at \( t = 0.7 \) s to 1.03 p.u., and changed back to 1 p.u. at \( t = 1 \) s. The controller operation mode is voltage regulation at the AC connected bus. Fig. 3 depicts how the voltage at Bus 2 follows the references voltage in both SimPowerSystems and the ePHASORsim-based model-in-the-loop simulations (indicated as SPS and MIL, respectively). Fig. 4 shows the current flow at transmission line. The maximum discrepancy of voltage magnitude between the MIL tool and the SPS simulation was found to be 0.4%, using the error-measure defined in (4):

\[
\varepsilon = \max\left(\frac{V_{\text{MIL}} - V_{\text{SPS}}}{V_{\text{SPS}}}\right) \quad (4)
\]

2) **Applying fault**
At \( t = 1.4 \) s a three-phase-to-ground fault happens at Bus 1 for a duration of 50 ms. The simulation results obtained for the voltage at Bus 2 and the transmission line current flow measured at Bus 1 are shown in Fig. 3 and Fig. 4. In this case the discrepancy between SPS and MIL simulations is larger than the previous scenario, but it is still in an acceptable range (less than 2%).

**B. Simple Photovoltaic cell (PV)**
A PV unit is an arrangement of parallel strings of series PV cells, as shown in Fig. 5, whose equivalent model can be simplified as a voltage and radiation-dependent current source.
A PV unit is usually connected to a microgrid system via a boost converter and an inverter. Fig. 6 shows the simple model for PV used in this case. The PV is modeled as a current source in parallel with a capacitor and the details of the PV equation related to diode’s voltage-current characteristics are ignored. Then the PV unit is connected to AC grid via a transformer-embedded voltage source converter. The AC grid system has a similar topology to Fig. 2, however, the voltage level and power base are reduced to be able to see the impact of PV unit. In this case, the simulated situation is an increase in the solar radiation with a step function characteristic at \( t = 0.5 \) s. This causes an increase in the input current of PV unit. There is no voltage regulator model, and therefore this increase causes the elevation of the voltage magnitude at Bus 2, where the PV unit is installed. Fig. 7 demonstrates the steady state and dynamic response of MIL and SPS simulations. The relative discrepancies according to (4) is less than 1%.

V. FUTURE WORK

The ongoing research in the area of MIL simulation at OPAL-RT Technologies is aimed at performing software-in-the-loop simulation with ePHASORsim. Then, the user will be able to script the model for the new device in a modern language, like Modelica, and integrate the code with the simulator’s internal solver.

In the mathematical formula presented in (1)-(3) the \( Y \) matrix is explicitly given as part of the Nodal equations, and therefore each component must provide its internal admittance. Most power system component models naturally include an internal admittance, which is incorporated into the admittance matrix \( Y \). This is certainly the case for passive linear components, such as lines and transformers. The presence of non-linear components without a clear impedance element can present a numerical stability challenge, by worsening the conditioning of the admittance matrix \( Y \) if the component impedance is not incorporated. Such situations arise, for instance, when the computational model of the component is developed in Modelica and exported into a Functional Mock-Up Unit [6], where the admittance matrix of the component is not explicitly given.

The solution under investigation in ePHASORsim is as follows:

- Compute the derivative of the current injection with respect to the bus voltage, at steady-state;

During the simulation, the current injection of the component must now comprise its normal value of current injection and an added “compensation term” to account for the current drawn from the grid by the artificially-generated internal admittance of the component.

Such a technique is also used in other simulation packages, such as OpenDSS [7]. From a mathematical standpoint, this process improves the convergence rate of the numerical iterative solution of equation (2), when a fixed-point method is used without the re-computation of the Jacobian of \( I(x, V) \) at each solution step. This method is equivalent to the Very Dishonest Newton method, which is popular for the numerical solution of power systems.
VI. CONCLUSION

This paper presented the application of the ePHASORsim tool to perform the MIL simulation. Although this type of simulation is more for controller devices, this paper showed how to make power system components such as STATCOM and PV and integrate them with the rest of the power system. The demonstrated test cases in this paper are small power grids, while the ePHASORsim has a high performance for power grids in the range of 10,000 buses and more. Thus, the obvious advantage of using ePHASORsim for this type of simulation is the capability to test the response of the new device or a wide area controller, e.g. automatic generation control (AGC), when it is connected with a realistic-size power grid. The ongoing research in this area at OPAL-RT Technologies is aimed at performing the software-in-the-loop simulation with ePHASORsim. Then, the user will be able to script the model for the new device and integrate the code with the internal solver of the simulator.

REFERENCES