A Real-time Dynamic Simulation Tool for Transmission and Distribution Power Systems

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***Abstract*— e*PHASOR*sim tool offers real-time dynamic simulations for transmission and distribution power systems. Applications such as contingency studies, testing control devices, operator training, and SCADA system tests are examples for employing this tool. This paper describes the hardware and software architecture of the e*PHASOR*sim and its development. The accuracy of the tool has been evaluated in comparison to other commercial, but non-real-time, simulation packages for both transmission and distribution systems. Its real-time performance has been tested with a time-step of 10ms on a real-time simulator for large-scale power systems in the order of 20000 buses, 5000 generators, and over 9000 control devices.**

***Index Terms*-- Large-scale systems, power system simulation, power system dynamics, real-time simulation, time domain analysis**

I. Introduction

In transmission level networks, an unplanned power outage, abnormal frequency oscillations, or mal-operations in utilities can lead the system to collapse and black out. These types of events are considered costly in several aspects, such as possible damages to the industry and system restoration expenses, and may carry substantial political and social impacts. In this context, the dynamic simulation (and specifically transient stability analysis) for transmission-level power networks have considerable importance [1]. There are several commercial software packages, such as PSS/E, EUROSTAG, DIgSILENT, and PSAF that are widely used to perform these types of studies in offline mode [2].

The distribution power systems were traditionally considered as passive networks that only involved end-users and loads. The simple topology of these systems, utilization of low-voltage cables and overhead lines, passive loads and connection to strong power grid made it unnecessary to perform time-domain dynamic simulations for these networks. Therefore, most efforts in the area of distribution-system-simulation tools have focused on load flow programs, short-circuit and fault calculations, and harmonic analysis [3][4].

However, integration of several types of small and medium energy resources within distribution systems has transformed their nature from passive to active. Currently, a large number of wind turbines, micro-turbine generators, and photovoltaic panels are connected to distribution networks. The massive penetration of small but geographically dispersed generators (DG) has changed the dynamics of distribution networks. A disturbance in a distribution system within the context of large DG penetration can no longer be considered an insignificant local event. For example, a disturbance in the transmission system can lead to the tripping of the DG units in the distribution system, and in return the disconnection of DG units increases the chance of subsequent load-shedding due to lack of generation. Therefore, the overall stability of power systems is affected by both the transmission and distribution networks.

The objective of this paper is to report on recent advancements in development of the e*PHASOR*sim tool to perform real-time dynamic and transient-stability simulations in power systems. This tool and its application has been introduced in [5] for balanced transmission-level networks, where the positive sequence modeling of the system is enough for analyzing transient-stability phenomena. This paper will present the new features of the e*PHASOR*sim for the modeling of three-phase and unbalanced distribution-level power systems, and also the significant optimizations in the performance of the solver.

The paper is organized as follows. In Section II the architecture of the e*PHASOR*sim from software and hardware points of view will be described. The existing library for both transmission and distribution systems is presented in Section III. The user interface and input/output features are explained in Sections IV and V. Experimental real-time simulation results on several test cases, accuracy validation, performance evaluation, and a discussion of the results are shown in Section VI. Concluding remarks are presented in Section VII.

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II. SOFTWARE AND HARDWARE ARCHITECTURE

A. e*PHASOR*sim *Solver*

To simulate the dynamic behavior of the power systems it should first be mathematically described by a set of differential-algebraic equations (DAEs) as follows [6]:

$$\dot{x}(t) = f(x,V) \quad (1)$$

$$YV = I(x,V) \quad (2)$$

$$x(t_0) = x_0 \quad (3)$$

where x is the vector of state variables, V and I are the vector of bus voltages and currents, Y is the nodal admittance matrix of the network, and x_0 is the initial values of state variables. Each component in the system (except the controllers) is represented in the network's Y matrix by its primitive admittance matrix (Y_p). The size of Y_p depends on type of system modeling and type of the element. In transmission systems Y_p is 1x1 for loads, machines, transformers, and 2x2 for transmission lines. However, in the 3-phase distribution system Y_p is 3x3 for loads, voltage source, and it is 6x6 for transformers and lines. For dynamic simulation, the power system is modeled in the main frequency phasor domain, and the dynamics of the system only depend on rotating machines and control devices such as excitation systems, power system stabilizers, turbines and governors. Therefore, a simulation time-step in the order of few milliseconds to half of a cycle is sufficient. Equation (1) describes the dynamic behaviour of the system, while equation (2) describes the network constraints on (1).

In the e*PHASOR*sim tool, the Modified Euler integration method with one iteration of prediction and one of correction at each time-step has been used [7]. The coalesced data pattern and contiguous memory allocation have been taken into account carefully to utilize the CPU's cache line and memory bandwidth as efficiently as possible. Moreover, sparse matrix methods have been exploited to factorize and solve the network nodal equations.

B. Real-time Simulator

The software architecture of e*PHASOR*sim tool is developed based on OPAL-RT's e*MEGA*sim platform. The e*MEGA*sim is a PC-based simulator comprised of two groups of computers known as *target* nodes, and *hosts*. Target nodes are the computational cores that carry out the simulation and each of them is powered by the modern high-performance distributed supercomputer technology found in off-the-shelf Intel or AMD multi-core processors. The host is a computer used to develop, design, and evaluate a model in offline mode. The host computer also provides the interface between the user and the target nodes. High-speed communication links connect multiple targets to each other, as well as hosts and targets. External hardware can also be connected to the simulator via FPGA-based (Field-Programmable Gate Array) analog/digital inputs/outputs. The CPUs in a given target communicate with each other through shared memory, as well as on-chip cache memory.

The targets are also capable of eXtreme High Performance (XHP) mode execution, in which one core is dedicated entirely to run real-time operating system tasks and schedulers, while other cores perform the computations without any intervention form the operating system. Running a model in the XHP mode ensures that the simulation is in real-time with jitter less than 1 to 2 microseconds; otherwise the simulator reports the number of overruns where the computation could not fit in the assigned fixed time-step [8].

III. BUILT-IN MODELS LIBRARY

The e*PHASOR*sim tool is based on C++ templates that make its library extensible. Its architecture is flexible both to register a new type of model to existing library and to build and add a new item to the present tool. Therefore, if the user wishes to model a component that does not exist in the library, the new component can be integrated to the solver by defining specific interfacing functions and modules.

A. e*PHASOR*sim *Transmission System Library*

The library for transmission systems is based on single-phase models using the positive sequence parameter only. The transmission system library contains the following models:

- Synchronous generator: There are two built-in models for synchronous generators: (1) the so-called *classical* model that only models the mechanical behavior of machine, and (2) the 6th order *detailed* model.
- Load (balanced): The controllable constant impedance, constant current, and constant power loads are modeled based on their active and reactive power at initial voltage value.
- Excitation system: based on IEEE Type AC4 excitation system.
- Power system stabilizer (PSS): a speed sensitive stabilizer.
- Turbine and governor: The model is based on the time constants of a high pressure turbine along with the re-heater and governor.
- Transformer: A two-winding transformer with a controllable tap position is modeled.
- Transmission line (symmetric): The PI model is used for transmission lines.

B. e*PHASOR*sim *Distribution System Library*

The distribution system components in e*PHASOR*sim tool are developed based on multiphase and unbalanced models. Therefore, it can provide a phase-based simulation for both unbalanced systems as well as asymmetric events. The transmission system library contains the following models:

- Voltage sources: The parameters are based either on three-phase and single-phase short circuit levels, or on its zero and positive sequence impedances.

- Load (unbalanced): The constant impedance, constant current, constant power, and complex ZIP load are modeled. Each load can have its own profile to vary during simulation.
- Shunt devices: Capacitor banks can be modeled with these components.
- Transformer: Three-phase transformer with various types of winding configurations and variable tap-position is modeled [9].
- Line (asymmetric): the model is either based on sequence network parameters or based on predefined configuration types. It encompasses both cables and lines.
- Current injector: used to externally set the injected current at a specific bus in Eq. (2).

IV. Inputs and Data Import

A. Data Entry

The e*PHASOR*sim is built as a MATLAB/SIMULINK S-function. However, the main user interface is designed based on the Excel workbook in which all the components, their required parameters and initial values are defined. The use of an Excel spreadsheet makes it practical to create large-scale systems (in the range of 20,000 buses), validate the parameters, and modify or change values with ease.

B. Operation Commands

The power system can be operated in the e*PHASOR*sim tool as it happens in real life. The control commands can be sent to the solver either directly or via Distributed Network Protocol (DNP3) [10]. The DNP3 is crucial for communications between SCADA stations, Remote Terminal Units (RTU), and Intelligent Electronic Devices (IED). Therefore, the e*PHASOR*sim can be used for testing the SCADA systems and operator training. The user can send any single or simultaneous commands such as:

- Apply faults on buses
- Apply faults on lines, with variable fault location
- In-service/Out-of-service commands for loads, capacitor banks, and transmission lines
- Generator outage
- Adjust tap position
- Adjust the reference for controllers
- Change load profile
- Open and reclose breakers

C. Data Import

The e*PHASOR*sim tool also provides a straightforward way to import data from other simulation packages. The key feature is a well-defined ASCII data format for each built-in component and its parameters. Therefore, every user can write a script (e.g. Matlab m-files) to generate or convert the data from the third party simulation package. Right now, for the transmission systems, the tool offers importing from PTI's PSS/e load flow cases (*.raw) and dynamic data files (*.dyr) for a list of components.

V. Outputs and Data Export

A. Measurements

The output of results in the e*PHASOR*sim tool requires the defining of measurement pins at certain locations. The pin location can be as general as a bus, or an internal variable of a block, e.g. d-axis electromagnetic flux in a synchronous machine. All inputs and outputs of blocks can be observed. The measurements for a transmission system are single-phase and for a distribution system are three-phase. Here are some examples:

- Voltage at each bus (RMS and angle)
- Current flow through lines (RMS and angle)
- Rotor angle and frequency of synchronous machine
- Tap-position for transformers

In addition to the power system measurements, there are also options to monitor and report the performance of the simulation in terms of CPU computation and idle time during each time-step, and the number of over-runs (i.e. where the computation tasks cannot terminate by the end of the fixed time-step),

B. Analog and Digital Inputs and Output

In the case of performing hardware-in-the-loop simulations, the e*PHASOR*sim can communicate with external devices such as protection relays and controllers. Utilization of I/O signal conditioning cards makes it possible to have voltage signals in the range of 150V (RMS), and current signals in the range of 2A and 5A as the outputs of the e*PHASOR*sim.

C. Instantaneous Outputs

Although the outputs of the e*PHASOR*sim solver are in the phasor domain (i.e. RMS value and angle), it is still possible to represent them as the sinusoidal waveforms (with no DC offset). The signal generation can be done in a separate CPU core running with a faster time-step (e.g. 50us) in parallel with the e*PHASOR*sim solver which is running with a slower time-step (e.g. 10ms).

The sinusoidal waveform for the voltage measurement can be represented as:

$$v(t) = \sqrt{2}\,V_{rms}\,\sin(2\pi ft + \varphi_V) \qquad (4)$$

where f is the nominal frequency of the power system (i.e. 50 or 60 Hz), and V_{rms} and φ_V are the outputs of the e*PHASOR*sim solver. This feature is useful to interconnect with classical or IEC61850 compatible protection relays

D. Data Export

All the measurements from the e*PHASOR*sim can be recorded as Matlab *.mat files. The records can be obtained either for a given duration length of time or as a one-time snapshot of the system. These files are exported as Excel spreadsheets for further analysis or report purposes.

VI. EXPERIMENTAL RESULTS

A. Accuracy Validataion

Although the e*PHASOR*sim solver is identical for transmission and distribution systems, the accuracy of the solver is evaluated separately with different simulation tools. For transmission systems, PTI's PSS/E is used as the validation tool, while for distribution system CYMEDIST (CYME), SimPowerSystems toolbox (Simulink/Matlab) in discrete and phasor modes, and OpenDSS (EPRI [11]) have been utilized. The maximum discrepancy that is found with the test cases in the RMS values is 0.11% for transmission systems and 0.08% for distribution systems, and for angles, in both systems, is less than 0.1 degree.

B. Performance Evaluation

The performance of the e*PHASOR*sim for real-time simulation has been tested with different types of transmission and distribution systems. For demonstration purposes, TABLE I. lists three transmission power systems with details about the number of components. Figure 1. depicts the simulation configuration for these tests.

In this experiment, the e*PHASOR*sim runs on a computer with the Linux operating system, and with a 3.4GHz Intel CPU. Although the CPU has six cores, the e*PHASOR*sim is designed, for now, to utilize only one CPU core for computation. The test scenario is to begin the simulation from a steady state condition, and then apply several types of disturbances (as listed in Section IV.B) in the network to stress the solver. In TABLE II. the computation time is expressed for "Normal" and "Disturbed" operational conditions. In a "Disturbed" condition, depending on the type of event, the admittance matrix of the system can change. For example, removing a transmission line or adjusting the tap-position will change the admittance matrix, while changing the reference voltage of regulators or excitation system will not have any impact on the admittance matrix. If the disturbance event changes the admittance matrix, then to solve Eq. (2) the LU factors of the Y must be recalculated or modified for the new topology. Depending on the system size, these calculations can be a bottleneck for the real-time performance. As shown in TABLE II. the computation time for three cases in "Normal" operating conditions where the admittance matrix is not changing is well below the fixed time-step (i.e. 10ms). However, in a "Disturbed" condition where the Y matrix is changing there are overruns in Case 3.

The performance for distribution systems can also be evaluated based on results shown in Table II. The number of buses in Table I represents single phase buses, while in a distribution system each bus is a three-phase component. It means that each bus in distribution system introduces three rows and columns into the admittance matrix. Therefore, the size of largest distribution system that can be simulated in real-time with e*PHASOR*sim is one-third of the largest transmission system in terms of number of buses.

An important observation from the performance test results, as shown in TABLE II. is the linearity of the execution time as a function of the size of the network in the e*PHASOR*sim tool. This observed linear computational complexity is promising for a parallel multi-core based implementation of the e*PHASOR*sim solver.

TABLE I. SIZE OF TEST SYSTEMS

Case Number	Number of Components			
	Bus	Generator	Controller	Other
1	4992	1280	2304	9144
2	9984	2560	4610	18368
3	19968	5120	9216	36820

TABLE II. PERFORMANCE FOR TEST SYSTEMS (TIME-STEP = 0.01S)

Case Number	Computation time (ms)		Real-time Overruns
	Normal	Disturbed	
1	1.62	3.49	NO
2	3.28	7.43	NO
3	6.68	16.61	YES

VII. CONCLUSION

This paper presented the development of the e*PHASOR*sim tool, designed for real-time transient stability simulation of power systems. This tool can be used for dynamic security assessments, contingency studies, functionality tests of hardware such as controllers in large-scale transmission and distribution power systems, as well as for test of SCADA systems, for training purposes in academic laboratories, or for industrial operators.

The performance results showed that networks in the range of 10,000 buses can be simulated in real-time using only one processor core; extrapolation from the observed performance suggests that even 12,000 buses could be successfully simulated in real-time. The ongoing research at OPAL-RT Technologies is aimed at real-time simulation for systems in the size of 100,000 buses, by exploiting parallel processing and high-performance programming techniques. Moreover, adding more built-in components to the library, exporting network data in a third party format are other desirable features. Combining network subsystem simulated in phasor mode with other subsystems simulated with detailed models capable to represent electromagnetic transient phenomena is also considered.

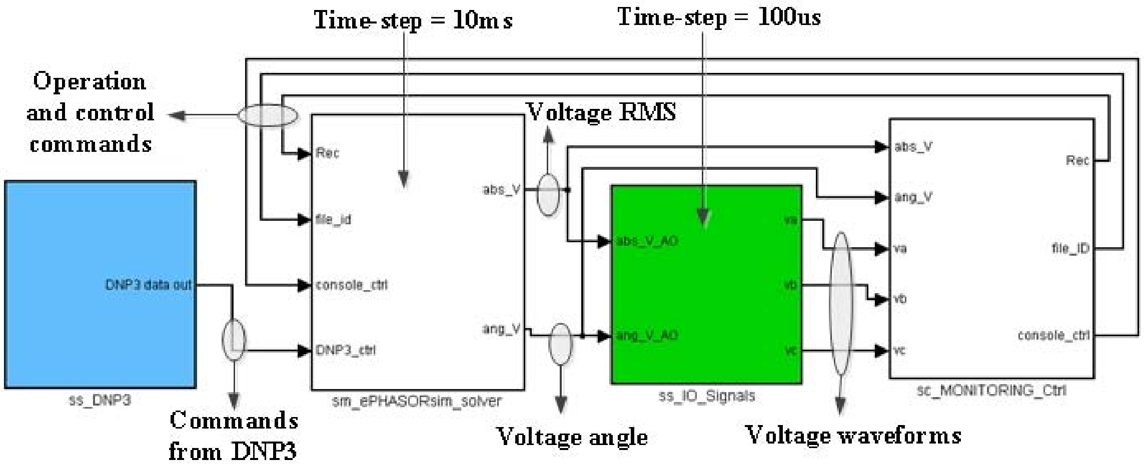

Figure 1. Integration of the e*PHASOR*sim with DNP3 and IOs

VIII. ACKNOWLEDGMENT

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