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***Abstract*— This paper is a step forward in the effort to create an appropriate open-access library of benchmark test systems for offline and real-time simulations. The library will consist of 13 test systems for steady-state and dynamic power system analysis considering different relevant features (topology, control mode and element details). In this scientific paper, the authors selected one of the test systems, the 5-bus test transmission system, in meshed topology. Details of its implementation using several power system analysis platforms for offline and online/real-time simulation. Offline steady-state performance results are presented using PowerWorld, DIgSILENT PowerFactory and IPSA. Plots of the main electromechanical variables of the time-domain response considering a generator outage are presented using offline simulations from PowerFactory and real-time simulation ePHASORSIM. Simulation results show very minimal discrepancies between the results considering different platforms.**

Keywords—Benchmark test system, modelling, offline simulation, real-time simulation, simulation, test system,

I. INTRODUCTION

The long road of transitioning from traditional power systems to net zero requires a massive change in several aspects of the design and operation of the electricity infrastructure[1], [2]. Consequently, the appropriate, reliable design, planning, and operation of power systems start with the proper tools and models to simulate the electrical power systems. Traditionally, the power industry has used the so-called "Benchmark Test Systems" for many years to evaluate and compare the performance of different power system analysis methods, algorithms, and software tools on a common platform [3], [4].

At the beginning of the power system software development era, the benchmarks were very well documented for specific scenarios or configurations of a power system, also known as test cases [5], [6]. Many famous test systems used nowadays in the context of power system stability were developed in the 1960s and 1970s and presented in early research papers, technical reports, etc. Two of the most famous benchmark test systems in the power system transient stability analysis are included in the classical books, the P.M. Anderson [7] test system and the New England 10 generator power system [8]. Later, the power system analysis software developer and the scientific community d recognised the importance and the need to standardise the benchmark models as a mechanism to create well-documented test cases that can be thrust used to evaluate and compare the performance of different power system analysis methods, algorithms, and software tools on a common platform. Two central standardisation tendencies on the benchmark test system came from the United States of America (USA) and Europe in the form of the IEEE and CIGRE benchmarks.

Several committees and task forces of the IEEE have developed a set of benchmark models that can be used in several power system studies ranging from planning, small signal stability [9], voltage stability [10], [11], state estimation [12],[13], reliability [14], control, etc. In Europe, the International Council on Large Electric Systems (CIGRE) has developed several benchmark systems, including AC and/or DC power systems [15], integration of renewable and distributed energy resources[16], etc.

A recent and well-documented review of the most frequently used standardised test systems is presented in [17]; the authors presented the analysis of approximately 2,500 IEEE journal papers between 1986 and early 2019. Many institutions and individual researchers have put a lot of effort into implementing benchmark test systems in various power systems analysis software.

The IEEE Power System Dynamic Performance Committee, through the IEEE PES Task Force on Benchmark Systems for Stability Controls, made available the benchmark systems for small-signal stability analysis and control on the website [18] considering power system analysis software such as PacDyn, PSS/E, MATLAB, Dsat, ANAREDE, ANATEM, etc. Also, Test Systems for Voltage Stability Analysis and Security Assessment are available in [19], and several implementations use popular power systems software such as RAMSES, PSS/E, ANATEM, and DIgSILENT PowerFactory.

The authors in [20] presented three IEEE Test Systems [21], [22], [23] implemented using the MATLAB/Simulink-based toolbox called SimpowerSystems; the files are openly available at MATLAB-Central file exchange. Another initiative of the open-access database of implemented benchmark test systems includes SimBench [24], fglongatt.org [25], and BetterGrids.org [26].

The massive integration of low-carbon technologies requires appropriate simulation tools to ensure reliable design, planning, and operation. A cutting-edge and effective technique for testing and validating electric power systems

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and low-carbon technologies is the real-time hardware-in-the-loop (HIL) simulation. Although real-time simulator manufacturers like OPAL-RT [27], RDTS [28], Typhoon HIL [29] and others offer built-in test systems, more effort is required to offer a broad set of benchmark systems that allow the industry and researcher to ensure a secure net-zero energy system. The authors in [30] introduce a benchmark system for HIL testing incorporating DER into the real-time simulation environment based on the CIGRE LV network with the DER benchmark system [16].

This paper is a step forward in the effort to create an appropriate open-access library of benchmark test systems for offline and real-time simulations. The authors propose a set of eleven simple test systems with full details of topology, parameters, and associated control schemes, making them suitable for understanding in a simple way some of the most elementary phenomena that can be found in traditional power system analysis. The initial set of test systems was proposed by Prof F. Gonzalez-Longatt in 2007 [31] to evaluate the performance of load flow implementations and, later, transient stability analysis. It provides a portfolio of 13 test systems considering different relevant features to power systems analysis studies (e.g., topologies such as radial, mesh, and loop). In this scientific paper, the authors selected one of the test systems and details of its implementation using several power system analysis platforms for offline and online/real-time simulation; those details are shown in Section II. The main contribution of this scientific paper is an open-access, multi-platform benchmark test system, which is well-documented, validated and openly available to the scientific community at https://github.com/fglongatt.

II. Implementations

The document titled "FGL TEST CASES: LOAD FLOW Network Data" [31] 13 test systems proposed by Prof Gonzalez-Longatt in 2007; the initial set was developed to tested for manual calculations for academic purposes, teaching but also to test power flow solution algorithms, so they were extensively documented. In 2015, the test systems were enhanced with models and data to perform offline time domain simulations for power system stability and control analysis. This paper is a step forward to offering the scientific community an open-access library of benchmark test systems for offline and real-time simulations. Due to the limited space available, the authors decided to show details of the implementation (this section) and validation process (next section) of one test system (following subsection).

A. *Test Systems 5-bus test system -Mesh*

Fig. 1 shows the proposed test system; it represents a simplified single-voltage level mesh transmission system considering three synchronous generators (G1 as reference). Two loads are assumed lumped; the transmission lines are modelled considering only the series impedance, and generators G3 and G5 are deemed to operate to a constant voltage mode (no reactive limits included in this case but included in other test systems of the library).

B. *Steady-State Model*

1) Offline implementation: Steady-State performance

The authors have implemented the proposed test system for offline simulation using three well-known commercial power system analysis software: PowerWorld, IPSA and DIgSILENT PowerFactory. PowerWorld software was made commercially available in 1996; it is a very user-friendly program with enhanced graphic display and calculation features. In this paper, PowerWorld was included as it directly allows the use of per unit values as input data at the time that offer the user access to the numerical values of the admittance matrix; this feature makes it attractive to be used in the classroom for results validations. IPSA is another commercial power system analysis software that allows the introduction of per-unit values directly, making it simple to implement academic test systems. On the other hand, DIgSILENT PowerFactory is a utility-oriented power system analysis commercial software, and it requires the use of real values (e.g., Ohms/km series resistance in transmission lines), so the authors have tabulated those values to simplify the implementation.

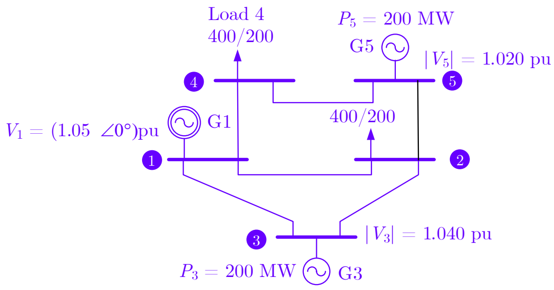

Fig. 1. Single line diagram of -bus test system -Mesh: *Test System*.

The positive sequence model of the test system shown in Fig. 1 has been implemented using the three commercial software; the comparison of the numerical results of the steady state performance (power flow) is presented in Section II.

2) Real-time implementation: Dynamic performance

In this paper, the authors have selected OPAL-RT as a real-time simulation hardware platform using the software ePHASORSIM for time-domain phasor-based simulations. The real-time simulation framework implementation must be carefully developed to allow a fair comparison between the simulation results. Therefore, the authors have carefully selected the device models: a standard load, a PI-line model, and the operation modes: PQ, PV, and slack/reference operation mode. The power system analysis software uses the lumped parameter PI model for representing transmission lines, but there are differences in the input parameters. The traditional offline time-domain simulation software models the load as constant power for power flow analysis, and then they are converted into constant impedance for positive sequence time-domain simulations (RMS-based). The load models have been appropriately transformed into constant impedance for using ePHASORSIM.

It is very well-known that the synchronous machine model (SM) is a very complex issue when comparing numerical results of the dynamic performance of power systems models. The dynamic model for the SM used in DIgSILENT PowerFactory is known as the "Standard Model". The rotor d-axis is represented by two rotor loops, one representing the excitation winding and the other representing the $1d$-damper winding. A machine model with a round rotor is employed, which utilises the $1q$ and $2q$-damper windings. This model is referred to as Model 2.2 in the IEEE Guide for Synchronous Generators [32].

The real-time simulation software, ePHASORSIM, uses the so-called GENROU model for modelling the SM; that model is equivalent to Model 2.2 in [32], considering the subtransient reactances xd'' and xq'' have the same value. To model the generation controls, the EXST1 and TGOV1 are used for the exciter and governor, respectively. These models are selected because they are well documented in the literature, are simple to implement, and are included in both PowerFactory and ePHASORSIM. Block diagrams and documentation for the dynamic models previously mentioned can be found at [33], [34]. Additional considerations of modelling and simulation include:

- ePHASORSIM requires the electromechanical constants of the SM to be presented as open-loop time constants for the subtransient and transient time constants.
- The rotational inertia constant *(H)* must be defined in ePHASORSIM rated to the MVA base of the SM.
- PowerFactory allows the users to take into consideration the effect of speed variation on the Standard Machine Model. The software ePHASORSIM does not have this option, so in PowerFactory, the user must select to neglect this calculation.
- It is recommended to select the option to perform an *'Exact conversion of Time Constans'* in PowerFactory.
- When running time domain simulations in PowerFactory, it is recommended to use the speed deviation based on the rated speed of each machine.

III. Simulation Results

A. Results of Steady-State

Fig. 2 to 5 shows the numerical results of the power flow using three power system analysis software: PowerWorld version 23, DIgSILENT PowerFactory 2023 SP4 and IPSA version 2.10.1, respectively. The authors made an effort to configure the software considering the same setting. However, each power system analysis software has different stopping criteria: PowerWorld (MVA convergence tolerance -inner loop options, maximum number of iterations), PowerFactory (maximum acceptable load flow error, maximum number of iterations), IPSA (convergence and maximum iterations) Comparing the numerical results, there are minor differences in terms of voltage magnitude and phase angle, and the more significant differences are found on the reactive power.

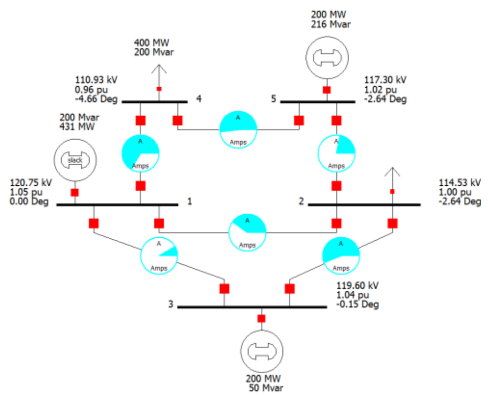

Fig. 1. Load flow simulation results: PowerWorld.

B. Results of Dynamic

The dynamic performance of the test system is analysed considering a sudden disconnection of the G3 at $t = 0.5$s, and the total simulation is run for 10s. This simulation aims to evaluate the network's general stability and the response of the controls when a sudden generator disconnection occurs. The same simulation is performed in both software. The results of the offline time-domain simulation conducted in PowerFactory are presented in Fig 4-7. Fig. 4 and 5 show the response of the speed (in per unit) and rotor angle (degrees) with reference to G1 of the SMs, respectively. Fig. 6 and 7 show the response of the active and reactive power (top in MW and bottom in MVAr) and the per unit bus voltages of all busbars, respectively.

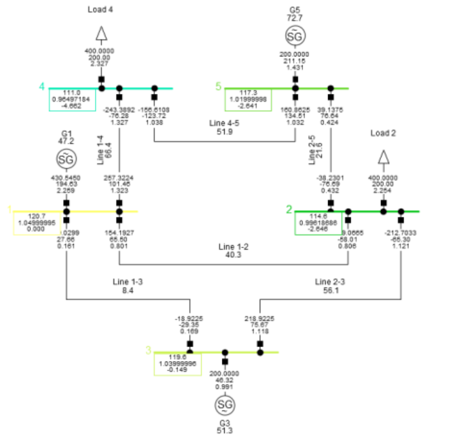

Fig. 2. Load flow simulation results: DIgSILENT PowerFactory

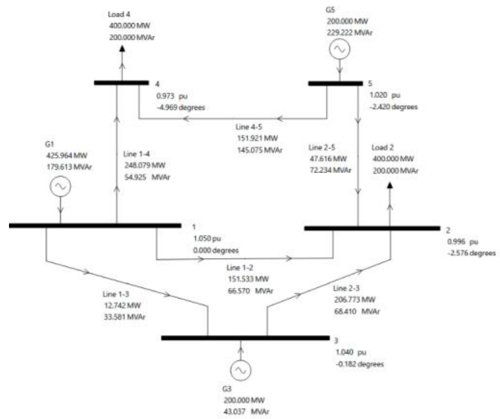

Fig. 3. Load flow simulation results: IPSA.

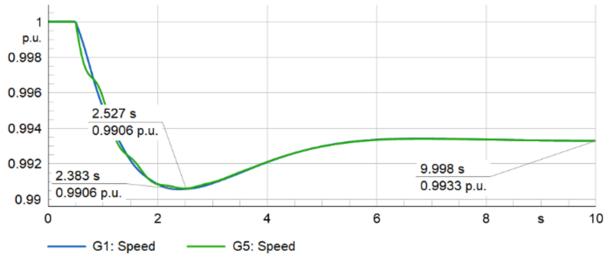

Fig. 4. Offline time-domain simulation, PowerFactory: Speed of G1 and G5.

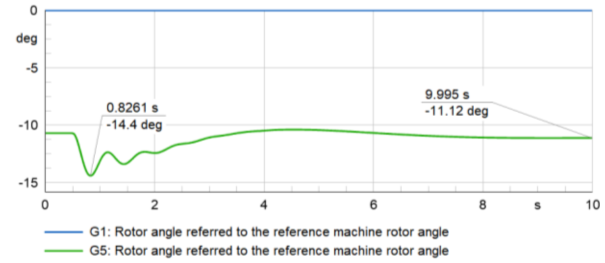

Fig. 5. Offline time-domain simulation, PowerFactory: Rotor angle referenced to G1.

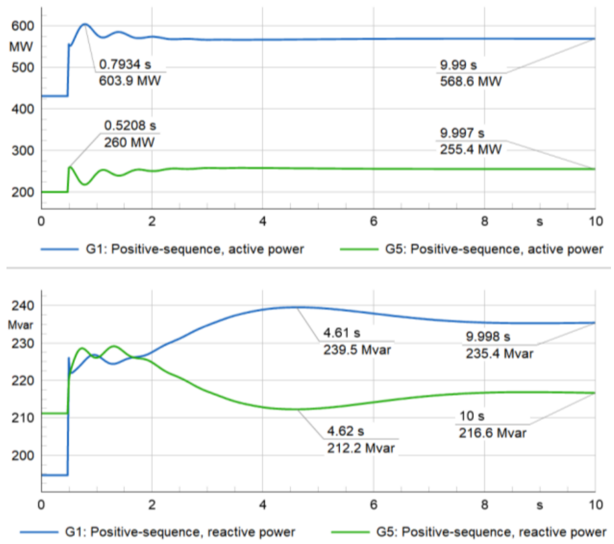

Fig. 6. Offline time-domain simulation: PowerFactory: Generated active (top) and reactive (bottom) power of G1 and G5.

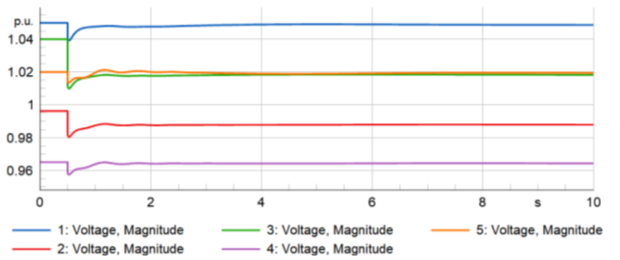

Fig. 7. Offline time-domain simulation: PowerFactory: Voltages at the busbars (per unit).

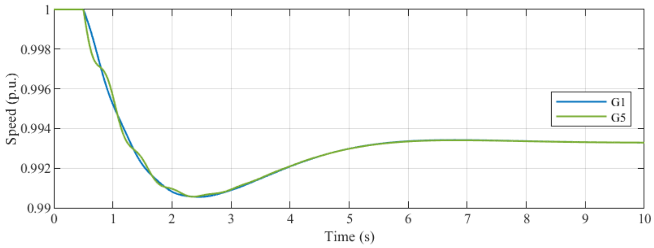

Fig. 8. Real-time time-domain simulation, ePHASORSIM: Speed of G1 and G5.

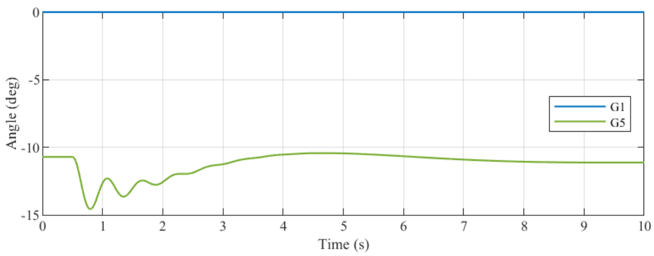

Fig. 9. Real-time time-domain simulation, ePHASORSIM: Speed and rotor angle of G1 and G5.

The real-time simulation results conducted in ePHASORSIM are presented in Fig. 8 to 11. Fig. 8 and 9 show the response of the speed (in per unit) and rotor angle (degrees) with reference to G1 of the SMs, respectively. Fig. 10 and 11 show the response of the active and reactive power (top in MW and bottom in MVAr) and the per unit bus voltages of all busbars, respectively.

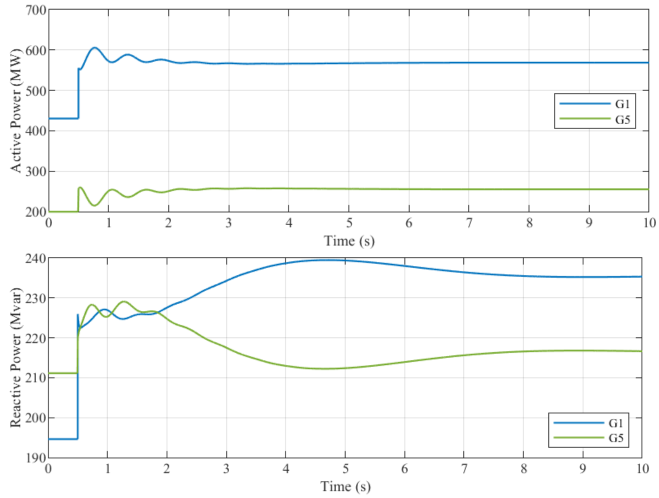

Fig. 10. Real-time time-domain simulation, ePHASORSIM: Generated active (top) and reactive (bottom) power of G1 and G5.

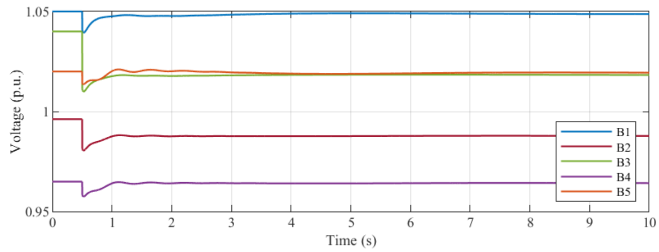

Fig. 11. Real-time time-domain simulation, ePHASORSIM: Voltages at the busbars (per unit).

By a simple inspection of the above-presented plots of all variables, it is clear a very good matching of the dynamic response demonstrates the successful implementation of the test system.

Conclusions

This scientific paper is a step forward in the effort to create an appropriate open-access library of benchmark test systems for offline and real-time simulations. The library consists of 13 test systems; because of space limitations, the authors selected one of the test systems, the 5-bus test transmission system in meshed topology. This paper presented details of its implementation using several power system analysis platforms for offline and online/real-time simulation. Simulation results show very minimal discrepancies between the results considering different platforms. The results presented indicate that the test system can be implemented using a variety of simulation tools, yielding comparable results, which renders it a suitable benchmark.

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