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DOI: 10.1109/IESES.2018.8349934

Publisher version: https://ieeexplore.ieee.org/document/8349934

Distributed Real-Time Co-Simulation as a Service

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***Abstract*—The increase of faster dynamics in power systems has led to growing interest in new simulation solutions, especially in the field of hardware-in-the-loop and real-time simulation. Due to the size of power systems, detailed simulation of the faster dynamics is only feasible for a section of the system, whereas the rest is usually modeled as an infinite power bus. The aim of this work is to present a solution which would allow the representation of a significant portion of the dynamics that are usually not captured by the infinite power bus approach and enable the joint simulation among multiple simulation laboratories to share this dynamic model of the network beyond the boundaries of the detailed simulation. Furthermore, the presented architecture should allow the virtualization of each of these laboratories in cases where this coarse model of the neighboring grid sections is sufficient. First distributed simulation examples show the current status of our implementation of the architecture presented here.**

I. Introduction

The current evolution of the grid characterized by a higher penetration of renewable energy sources is significantly changing the main dynamics of the power system. This change is reflected in two main aspects:

- Higher volatility of the generation input
- Faster dynamics due to reduction of the mechanical inertia connected to the system

This process has attracted a growing interest in the development of new simulation solutions and in particular a significant development of the concepts of real-time simulation and hardware-in-the-loop (HIL). These technologies are widely used both in the analysis and in the development of advanced automation solutions intended to overcome the new challenges that power system dynamics are facing [1]. The lack of knowledge about the behavior of a power grid widely based on power electronics devices is asking for new simulation analysis able to give insight at different levels of details: from the slow dynamics of interaction of the large system scenarios to the complex non-linear interactions of switching devices at local level. On the other hand, it is becoming more and more clear that the computational complexity is such that the problem can not be solved by a single laboratory. Furthermore, availability of data on electrical infrastructure is also sometimes not easy to share among scientists. This scenario is calling for the development of a new architecture of real-time simulation that could support integration of knowledge among different players in the creation of large and meaningful scenarios [2]. The work proposed in this paper fits exactly in this direction of research, providing a platform which facilitates the joint research on large scale power systems.

II. The Vision

Main goal of the work described in this paper is the creation of a network of laboratories sharing knowledge and creating large scenarios of interaction to tackle the appropriate level of complexity. The idea is that to achieve such goals two components are necessary:

- A programmable system to support data interchange among laboratories set-up in real-time
- A simulation platform that is able to model only the dynamics that are compatible with the bandwidth of the interface.

Experimental results show that, with the current internet infrastructure, it is feasible to reach round-trip times within some milliseconds within distances in the order of hundred kilometers [3]. Such performance is in line with the main dynamics present at transmission level typically in the order of few hertz. Coherently, it would be interesting to have available a real-time simulation with a resolution in the range of milliseconds. It should be clarified that while operating at this time step does not allow the representation of every possible dynamic interaction among different sections of a network, on the other hand it provides a much more significant representation than what is possible within a single lab. In effect, currently, given the computational limits of whatever simulation platform, each laboratory needs to set a boundary condition to the analysis which is typically described in terms of infinite power bus. The architecture and the combination of tools proposed in the paper allows the substitution of such ideal hypothesis with an interaction model able to capture a significant portion of the dynamic interaction.

One step further is the virtualization of the laboratory in the cloud. Given that it is not reasonable that all the laboratories will be permanently connected, it is important to define a process that supports the substitution of the laboratory with its virtual representation. Each institution could run its own real-time simulation either in the cloud or locally in their facilities depending on their current activity while still contributing to the overall network. This approach has two benefits:

- Other participants always have some kind of power system representation available which they can connect to
- Each participant can move his simulation from the cloud to his local simulation environment to connect hardware at any time without coordination of other participants.

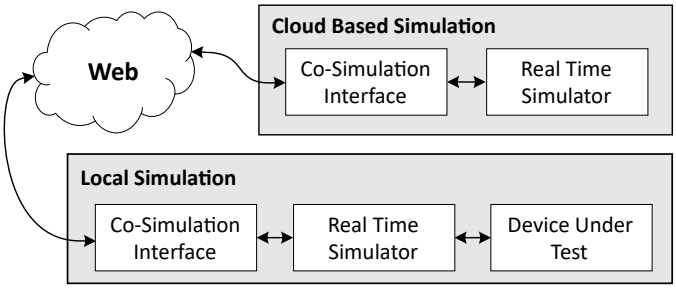

Fig. 1. Co-simulation as a service concept.

Today's availability of cloud computing resources and the free software, which was employed for this study, can form the basis for an always running real-time simulation collaboratively operated by the research community. Open protocols and the free software presented in this paper are key ingredients for this idea.

Other research disciplines already collaboratively operate such test beds. Examples are the Decentralized Network 42 (DN42), which builds a virtual overlay network on top of the real Internet [4]. Operated by individuals and researchers, this network is used for training purposes and experimentation. Annual *Battle the Mesh* events are hosted by a community built around the development of open source mesh network stacks [5].

III. Key Components of the Architecture

A. Geographically Distributed Real-Time Simulation

Geographically distributed real-time simulation as special case of distributed simulation has the advantage of being able to share computational load among several processing units. However, it is required to synchronize the simulators involved in the simulation. While distributed simulation does not specify the type of network connection between the simulators, geographically distributed simulation excludes high speed network interconnection, such as InfiniBand, since the connection can only be established through the Internet. Section III-B will further elaborate the challenges of this approach.

Apart from increasing the overall computational power of the simulator, there are more advantages of distributed real-time simulation [6], [7]. The following list summarizes the most important ones:

- Hardware and software in different simulation sites can be shared to facilitate remote software-in-the-loop (SIL) and (power-)hardware-in-the-loop (PHIL)
- Knowledge exchange is facilitated and encouraged since several research groups may work on the same case study without the need to move personnel and equipment
- Confidential data does not need to be shared as each laboratory can be responsible for simulating its own part of the model locally, solely exchanging interface variables with other interconnected systems, imitating the real world where regional or national power grids are interconnected through tie-lines
- Several algorithms to control, manage, or regulate systems can be tested in laboratories where no realistic models of the environment (e.g. power grid model) are available

B. Modelling of the Appropriate Resolution

As explained in Section III-A, the simulators are connected through the Internet. This results in a typical round-trip time (RTT) between two simulators in the range of milliseconds. If electromagnetic transient (EMT) values are exchanged among the simulators, a simulation time step of $10\,\mathrm{ms}$ ($50\,\mu\mathrm{Hz}$ AC) or smaller is required according to the sampling theorem. Besides, the typical simulation time step of EMT simulators is $50\,\mu\mathrm{s}$. Therefore, the relation between simulation time step and data exchange time step is very large and a lot of samples have to be sent at once.

The solution proposed [7] overcomes the problem of data size by compressing the information through an EMT-Phasor-Interface. This requires extraction of the phasor information and may alter simulation data. Such a data resolution calls for an appropriate simulation solver able to operate on the same time-scale and working directly in the phasor domain.

An alternative solution to data compression could be the simulation with static phasors. However, this approach would only cover simulations at fixed system frequency.

IV. VILLASnode Gateway

Communication between real-time solver instances is realized by a dedicated gateway called VILLASnode. VILLASnode is part of the VILLASframework, a toolkit for distributed real-time simulation which is released as open source software under the GLPv3 license [8]. The gateway is a software component which runs on a real-time optimized Linux machine which also executes the DPsim solver (see section V).

Responsibilities between the solver and the gateway are clearly separated. This modular approach allows to use the components in combination as well as with other software. The gateway supports a variety of pluggable transports like UDP/IP, ZeroMQ, nanomsg, IEC61850 Sampled Values & GOOSE as well as interfaces to commercial digital real-time simulators, like OPAL-RT and RTDS.

In this paper, the gateway provides two interfaces for exchanging simulation data between the solver and over the Internet as depicted in Figure 2

A. Shared-memory Interface

A shared memory interface is used to exchange simulation data between one or more processes on a single compute node. In this paper, a shared memory region is used to exchange

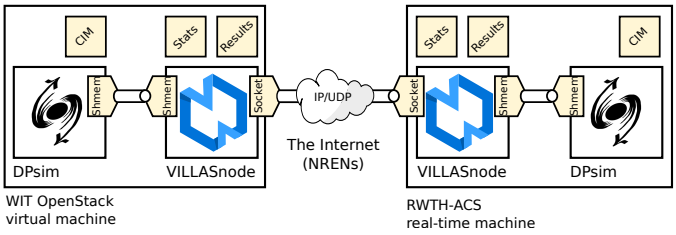

Fig. 2. Co-simulation architecture.

simulation data between the real-time phasor solver DPsim and the gateway.

The interface consists of two simple lock-free single-producer single-consumer (SPSC) queues for bidirectional communication between the processes. Shared-memory has been chosen over other inter-process communcation methods as it requires operating system (OS) support only for the initial setup. During a running simulation the OS remains in the background and does not disturb the execution of the solver. This is a key requirement for executing the solver in real time.

The shared memory interface has also been used for the first simulation case described in section VIII-B.

B. Network Interface

The communication between multiple gateways is realized by UDP/IP packets which are exchanged over the public Internet and the national research and education networks (NREN). Additional meta data such as time stamps and sequence numbers which is being exchanged is used to monitor the current quality of the connection and drop invalid or reordered packets.

By using Linux's NetEm queueing discipline, real network communication characteristics such as latency, packet loss and reordering can be emulated. This feature is utilized to anticipate the results of the distributed co-simulation. As part of the traffic control (TC) subsystem, NetEm is a special queuing discipline which is tightly integrated into Linux networking stack [9], [10] and allows good emulation of real communication characteristics in real-time.

V. DPsim - Dynamic Phasor Real-Time Simulator

As described in Section III-B, the exchange of time-domain or EMT values among simulators imposes strong requirements on the sampling rate. Therefore, previous work already introduced dynamic phasors as a means of exchanging data in the frequency domain rather than the time domain [3]. The difficulty lies in the extraction of the dynamic phasors from the time domain signal for every simulation step. Here, the DPsim simulator offers an alternative. Instead of simulating the entire system in EMT, the simulation operates on dynamic phasors. This method avoids the conversion from the time domain to the frequency domain and improves the possible sampling rate with regard to Shannon's sampling theorem. Simulation results which demonstrate this advantage of dynamic phasors compared to EMT are presented in [11].

The dynamic phasor approach is combined with modified nodal analysis and resistive companion method. Therefore, the majority of network components is represented by the network admittance matrix whereas more complicated models such as synchronous generators are solved separately and interfaced through, for example, a Norton equivalent model [12].

VI. Scheduling and Synchronization

A completely synchronized execution of both solvers over the Internet is not possible for two reasons:

- First, the communication latency of about 15 ms between the two sites exceeds the simulation time step of 1 ms.
- Secondly, the unreliable nature and the inherent jitter makes it impossible to provide any guarantees.

Therefore, all solvers are started synchronously in reference to a global point in time which was agreed upon before. During the execution of the co-simulation, every solver proceeds in real-time with its own time step without synchronization to its peers. The interface quantities described in section VIII are exchanged at periodical intervals which can, but do not have to, be equal to the simulation time step. This scheme allows multiple rates to be used for participating simulators as well as the interface itself.

To guarantee a synchronized start of the simulation as well as to avoid them drifting apart, all simulators must be synchronized to a global clock. This synchronization source is most conveniently provided by the global positioning system (GPS) and distributed by existing time synchronization protocols such as the network time protocol (NTP) or the precision time protocol (PTP/IEEE-1588).

VII. Network Measurements

Figure 3 shows the geographical location of routing hops used in the pan-European laboratory infrastructure which has been used to conduct the following simulations. The black line

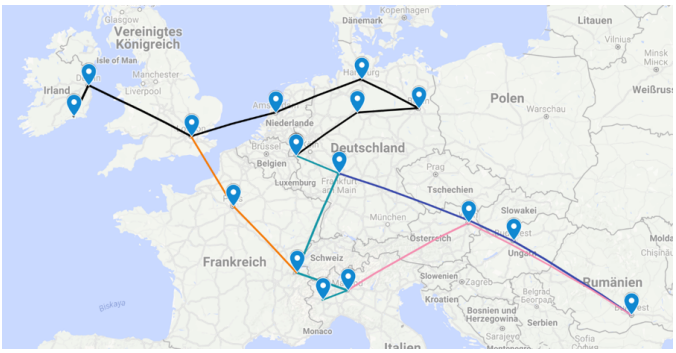

Fig. 3. Network connection of Pan-European Laboratory infrastructure.

in this map shows the communication link between Waterford Institute of Technology (WIT) in Ireland and RWTH Aachen University (RWTH) in Germany. In total, the connection is comprised of 15 routers/hops. Figure 4 shows the distribution of round-trip time as well as the geographical distance across those hops. The average RTT measured between RWTH and

WIT is 47.7 ms and was between 50 ms and 60 ms during the execution of the test simulations described in Section VIII.

These results show that the geographical distance between the sites is the main contributor of the RTT. The RTT is

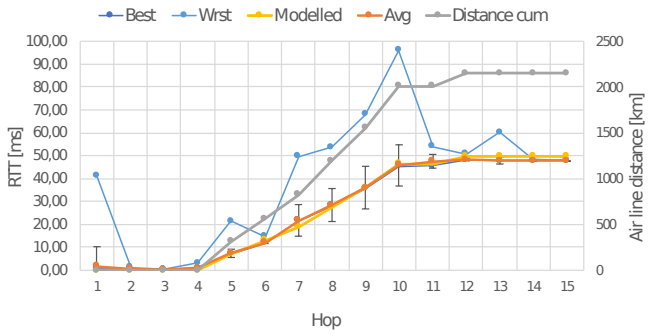

Fig. 4. RTT over communication hops.

only one, but important, metric for evaluating the quality of a connection for real-time simulation. Another metric of interest is the maximum packet rate, which we can use to exchange simulation samples while keeping the packet loss below a certain threshold. For this test, VILLASnode is used to generate sample streams at different packet rates and number of values.

Figure 5 shows the cumulative distribution of the RTT between RWTH and WIT in dependency to the sending rate. Not shown in this figure is the loss and reordering of packets, which gets significant with higher rates. At higher rates, the connection is susceptible to third party network traffic which causes loss and reordering.

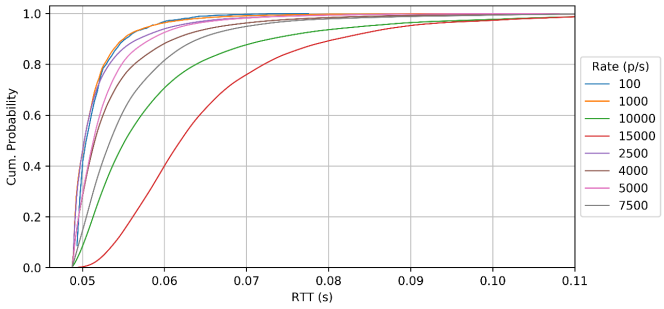

Fig. 5. Cumulative probability of RTT.

VIII. Co-simulation Example

The RTT delay measurements described before, allow an estimation of the dynamics that are able to propagate through the laboratory interface. However, real-time simulation test cases provide us with more details on the expected dynamic interaction between the distributed simulation laboratories since also the simulators themselves introduce latency.

A. Circuit Model

To validate the estimation of the delay and demonstrate the functionality of the interface between VILLASnode and DPsim, we present the simulation results for a simple circuit as depicted in Figure 6. The circuit consists of an AC voltage

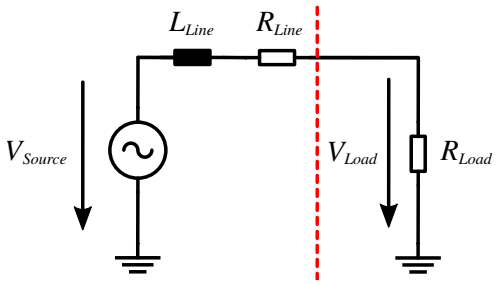

Fig. 6. Circuit model for distributed simulation.

source of $V_{Source} = 10\,\text{kV}$ peak voltage with a resistance of $R_{Source} = 1\,\Omega$, an RX-series element of $R_{Line} = 1\,\Omega$ and $L_{Line} = 1\,\text{H}$ and a load resistance of $R_{Source} = 10\,\Omega$. Internally, the voltage source is transformed to its Norton equivalent.

For a first test simulation, the circuit depicted in Figure 6 is split into two parts, indicated by the red line, and each part is simulated in a different location. The two locations that we consider are our institute, RWTH, and WIT. The source and line model are simulated in RWTH on a dedicated Linux workstation while the load resistance is simulated in the WIT OpenStack installation.

The depicted circuit is simulated for four different cases. First, both parts are simulated within one instance of DPsim. This case serves as reference for the three co-simulation cases. Secondly, the circuit is simulated using two separate instances of DPsim running on one computer that are interconnected via VILLASnode in the most optimal way. Then, the co-simulation is executed including a network latency emulation between two DPsim instances running on the same machine. Finally, one DPsim instance is running on a machine in RWTH while the other DPsim instance is executed in WIT.

The simulation time step is 1 ms in all cases. In comparison to EMT based simulation, this time step is relatively large and allows us to exchange interface quantities without down sampling. EMT simulations with 50 µs time step would require a decimation to reduce the amount of data. At $t = 1\,\text{s}$, the load resistance is changed from $10\,\Omega$ to $8\,\Omega$. This change is an ideal step, which would not appear like this in a real setup. Still, it is an interesting test case because the step introduces very high frequencies and, therefore, presents the worst-case scenario for the distributed co-simulation and dynamic phasor approach since only the fundamental phasor is used.

The ideal transformer model (ITM) [13] which is shown in Figure 7 interconnects the two network solutions where t_D describes the latency introduced by the interface. The ITM is introduced as follows: The external voltage source is used in the left part of the circuit whereas the external current source is integrated into the right side. The voltage and current values which are exchanged between the two simulations are the complex voltage and current values split into real and imaginary part.

It should be noted that the bandwidth of the signal passing through the interface can be increased by considering also the phasors of higher harmonics. Therefore, fast electromagnetic phenomena in one section of the network could be seen in the remote section of the network. Still, the bandwidth of a control loop which is across the co-simulation interface is restricted by the delay t_D of the interface.

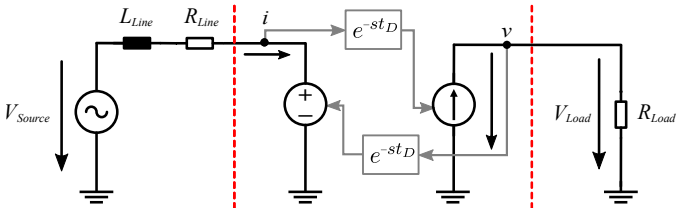

Fig. 7. Separated circuit with ITM and communication delay.

B. Local Co-Simulation Separated

For the co-simulation case where both DPsim instances are coupled in an optimal way, the communication delay is rather small but already visible. The delay between the monolithic reference simulation and the co-simulation is about 3 ms as can be seen in Figure 8. Since there is no communication network in between the two DPsim instances, this delay is only introduced by the software interface. DPsim is interfaced to VILLASnode through a shared memory segment and the two VILLASnodes instances, one for each DPsim instance, are exchanging data through a UDP connection.

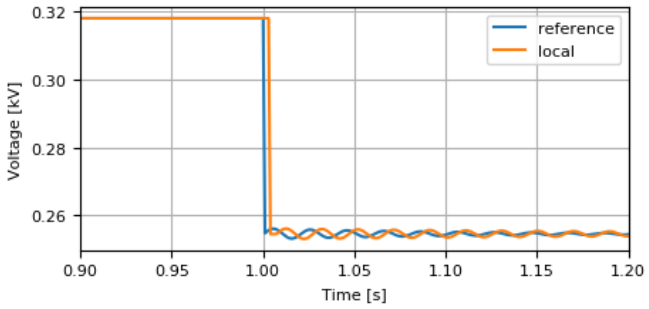

Fig. 8. Comparison of integrated reference simulation and local co-simulation.

C. Local Co-Simulation with Emulated Network Latency

In this case, the communication delay is emulated using the NetEm feature of VILLASnode. The properties of the artificial delay for sending data are set to 30 ms ± 1 ms, normal distributed for each VILLASnode. This results in an emulated RTT of about 60 ms which is close to the measured RTT in Section IV-B. Therefore, the delay in simulation should be comparable to the distributed case. As can be observed in Figure 9, the resulting delay in the simulation is about 32 ms.

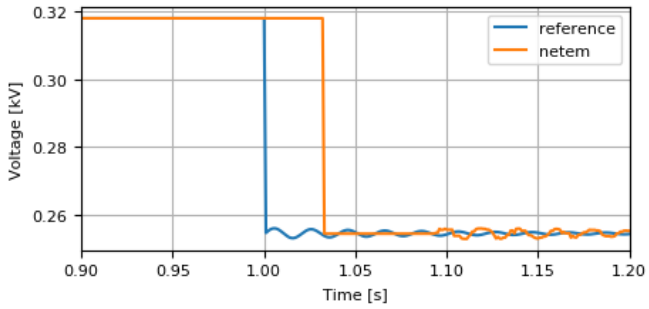

Fig. 9. Comparison of integrated reference simulation and local co-simulation with emulated network latency.

D. Distributed

As depicted in Figure 10, the distributed simulation between RWTH and WIT features a delay of about 33 ms. Hence, the measurement of the delay as in Section IV-B and the simulation including emulated delay as presented in Section VIII-C allow a very good prediction of the behavior of the distributed simulation.

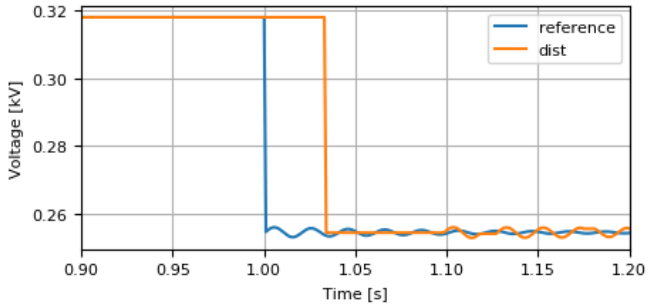

Fig. 10. Comparison of integrated reference simulation and distributed co-simulation among RWTH and WIT.

IX. Simulation of Slow Dynamics

The previous simulations are intended to show how the communication latency affects the distributed simulation in the extreme case. The main purpose of the proposed simulation solution is the investigation of slower dynamics. Slow dynamics can be represented by dynamic phasors very accurately as shown in Figure 11. Here, the voltage source is changing its frequency by −1 Hz over 200 ms. Figure 11 shows the EMT reference simulation which is simulated with a simulation time step of 50 µs and the absolute value as well as the shifted version of the dynamic phasor values are simulated with a time step of 1 ms. The shifted version is the result of the complex phasor signal shifted by 50 Hz in the frequency domain. It can be seen that the dynamic phasor values are following the transient very well even though the simulation time step is much larger. In this case, the simulation is integrated and not interfaced through VILLASnode. This is an example of the dynamics that we want to be able to propagate between distributed simulators in the future.

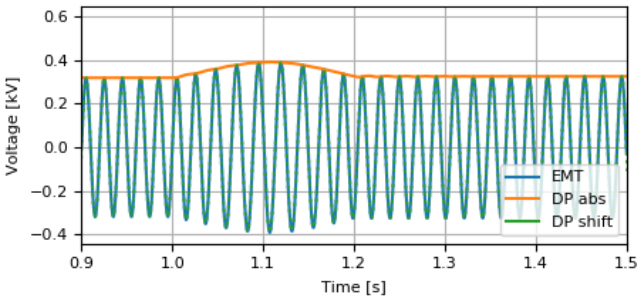

Fig. 11. Frequency change simulated for dynamic phasors and EMT.

X. Conclusion

Initial test cases have shown that DPsim and the VILLASnode gateway can be used to conduct simple geographically distributed simulations in real time over the Internet. Besides, it can be seen that the latency caused by VILLASnode is very small compared to the latency expected from the network connection with the co-simulation partner WIT.

It is presented that the communication network measurements and the simulation test cases are coherent. The comparison with the network connectivity measurement in Section IV-B shows that predictions of the delay in the simulation can be very accurate based on the network measurements.

Furthermore, the simulation highlights an important condition for the validity of co-simulation results. The dynamics of variables which are propagated between the simulators should not be faster than the communication delay or otherwise the results will differ from the integrated simulation results. This is exactly why dynamic phasors can be an important tool to support distributed real-time simulation. They allow the mapping of high frequencies to lower frequencies which decreases the impact of the communication delay. Hence, the dynamic behavior of the grid model beyond the detailed simulation in one laboratory can be improved as stated in Section I.

XI. Outlook

Upcoming tests must validate these results using larger networks including multiple sources and detailed models, such as synchronous generators.

The transition of frequency changes as shown in [11] should be investigated. If fast events are of interest, the simulation could be extended to include dynamic phasors of higher harmonics as well. However, for system frequency control investigations, as conducted in the Horizon 2020 project RESERVE the fundamental phasor is the most important one [14]. In the frame of RESERVE, the presented components are developed as part of a pan-European real-time simulation infrastructure for the validation of innovative approaches to system level automation based on innovative ancillary service provision.

In the simulation case described here, no data processing is applied to the exchanged values. In the future, current simulation values at the interface could be extrapolated from previous values. This could further improve the correct propagation of fast dynamics through the co-simulation interface.

The achievable data exchange rates discussed in section IV-B are dependent on the current conditions of the communication medium. Future work could investigate adaptive methods to determine the optimal sending rate and its effects on the simulation fidelity. The real-time protocol (RTP) commonly used for streaming of audio / video content is a good candidate and can be used as the basis to develop a new variant of that protocol for exchanging simulation data.

XII. Acknowledgment

This project has received funding from the European Unions Horizon 2020 Framework Programme for Research and Innovation under grant agreement no 727481.

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SoftwareX 10 (2019) 100253

Contents lists available at ScienceDirect

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DPsim—A dynamic phasor real-time simulator for power systems

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ARTICLE INFO

Article history:
Received 17 December 2018
Received in revised form 12 April 2019
Accepted 21 May 2019

Keywords:
Real-time simulation
Dynamic phasors
Co-simulation

ABSTRACT

DPsim is a real-time capable solver for power systems that operates in the dynamic phasor and electromagnetic transient (EMT) domain. This solver primarily targets co-simulation applications and large-scale scenarios since dynamic phasors do not require sampling rates as high as EMT simulations do. Due to the frequency shift introduced by the dynamic phasor approach, the sampling rate and rate of data exchange between simulators can be reduced. DPsim supports the Common Information Model (CIM) format for the description of electrical network topology, component parameters and power flow data and it is closely integrated with the VILLASframework to support a wide range of interfaces for co-simulation. Simulation examples demonstrate the accuracy of DPsim and its real-time performance for increasing system sizes.

Code metadata

Current code version	v1.0.0
Permanent link to code/repository used for this code version	https://github.com/ElsevierSoftwareX/SOFTX_2018_244
Legal Code License	GPLv3
Code versioning system used	git
Software code languages, tools, and services used	C++, python
Compilation requirements, operating environments & dependencies	DPsim can be compiled for Linux, OSX and Windows. The main dependencies are: gcc, Eigen, Python, CIM++, VILLASnode, Sundials. A Dockerfile with all dependencies is included in the repository.
If available Link to developer documentation/manual	https://fein-aachen.org/projects/dpsim/
Support email for questions	mmirz@eonerc.rwth-aachen.de

Software metadata

Current software version	v1.0.0
Permanent link to executables of this version	https://hub.docker.com/r/rwthacs/dpsim
Legal Software License	GPLv3
Computing platforms/Operating Systems	Linux docker container
Installation requirements & dependencies	Only a docker installation is required.
If available, link to user manual	https://fein-aachen.org/projects/dpsim/
Support email for questions	mmirz@eonerc.rwth-aachen.de

1. Motivation and significance

DPsim introduces the dynamic phasor (DP) approach to real-time power system simulation. The motivation is to remove the requirement of proportionality between the simulation time step

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https://doi.org/10.1016/j.softx.2019.100253

and the highest frequency of simulated signals. Especially for power electronics and geographically distributed real-time simulation, this is an interesting feature. Currently, the focus of DPsim is more on the application in distributed real-time co-simulation than power electronics. The idea is that the larger the simulation step, the smaller the impact of the communication delay between simulators, which are geographically distributed.

Distributed real-time co-simulation is motivated by large system simulations requiring more simulation capacity than is locally available and by the possibility of Hardware-In-the-Loop (HIL) testing with hardware under test and simulators at different locations. Using dynamic phasors for this application is a fairly recent development although the dynamic phasor, or the envelope function concept, is well known and was introduced in power electronics analysis in [1] as a generalized state space averaging method.

The authors of [2] have developed a distributed real-time simulation laboratory by applying a communication platform as a simulator-to-simulator interface in order to enable remote and online monitoring of interconnected transmission and distribution systems. Each simulator carries out simulations in time domain, while the variables exchanged at the interconnected nodes, i.e. decoupling point, are in the form of time-varying Fourier coefficients. The electromagnetic transient (EMT) values cannot be exchanged at every simulation step due to the communication delay. This delay may be directly incorporated into the physical power system model using traveling wave transmission line models [3]. However, electromagnetic waves travel about 15 km in 50 μs, a time which equals the typical step time in real-time EMT power system simulation. This means that a communication delay in the range of milliseconds would have to be compensated with a line length of several hundred kilometers which may require large and unrealistic changes to the original system model. Therefore, this method is suited for applications on local simulation clusters where the delay is only few simulation steps, but not for internet-distributed simulation, where the expected delay is often tens of milliseconds. In the latter case, the insertion of a transmission line model with the required parameters into the model would have a severe impact on the behavior of the system. Without compensation, the communication delay might cause large errors and even instability of the simulation as shown in [4] for a delay of more than 30 ms.

Starting from the concept presented in [2], we propose interfaces and system-wide simulation state variables based on dynamic phasors. This approach has two benefits explained in [5], which presents a comparison of DP and EMT simulations conducted in DPsim. First, it takes advantage of the computational efficiency of dynamic phasors in scenarios that involve bandpass signals with large center frequencies, as in the case of switching power electronics. Secondly, it increases the simulation time step thus reducing the difference between the local simulation time step size and the round trip time between simulators.

The approach employed in [2] requires the extraction of phasor information from the EMT signals. Therefore, the transparency of the interface is not guaranteed since the interface algorithm may alter the exchanged signals. This extraction step is eliminated by using dynamic phasors as state variables. Because of these features, DPsim is now part of the distributed real-time co-simulation platform described in [6], which is also the base for the experiment described in [2]. A first example of distributed real-time co-simulation using DPsim is presented in [7]. This example shows the impact of the latency in geographical distributed simulation on the results and how the latency can be modeled a priori to running actual simulations.

Besides, there are other relevant open-source initiatives in the field of power system simulation to be mentioned. In particular the Modelica community is very active in adapting Modelica environments for large scale power system cases [8,9] and providing comprehensive libraries of models [10,11]. These initiatives aim to enable large scale, fast simulation of power systems using open-source components but the focus is slightly different compared to the work presented here. The primary objective of DPsim is to assure a deterministic time step in terms of simulated and computation time to provide real-time capability required for Hardware-in-the-Loop (HIL) experiments. This is why in DPsim higher order solver methods are avoided and the system is split into subsystems, which are solved separately. The aforementioned related work does not seem to rely on such compromises since a deterministic time step is not required. While Modelica allows a convenient definition of physical models, DPsim does not intend to provide a solution in this regard. The idea is rather to extend the set of available models in DPsim by generating C-code from Modelica models to represent components connected to the network. These can be linked to DPsim and solved by the ODE solver that was integrated into DPsim for this purpose.

Another related work which is not open-source but also DP based is described in [12]. Similarly to DPsim, the authors have developed a simulator based on the DP approach. However, the focus does not seem to be fast simulation or real-time simulation since the simulator was developed in Python and there are no measures described in order to speed up the simulation. Furthermore, the validation is focusing on the correctness of the simulation rather than simulation speed.

2. Software description

The main theoretical building blocks of DPsim are the dynamic phasor concept and the modified nodal analysis (MNA). Dynamic phasors [13] have various names in scientific literature. Depending on the field and application, they are known as generalized averaging method [1], shifted frequency analysis [14], equivalent envelope [15,16] or baseband signal [17]. Here, the term dynamic phasors is selected because it is widely known in the power system community. The basic idea of dynamic phasors is to approximate a time domain signal x with a Fourier series representation as shown in (1)

$$x(\tau) = \sum_k X_k(t) e^{jk w_s(\tau)} \tag{1}$$

where $\tau \in (t - T, t]$. The kth coefficient is determined by

$$X_k(t) = \langle x \rangle_k(t) = \frac{1}{T} \int_{t-T}^{t} x(\tau) e^{-jk w_s(\tau)} d\tau \tag{2}$$

where ω_s is the fundamental system frequency and $k\omega_s$ are its harmonics.

MNA is used for the representation of the network as a linear equation system, whereas complex components, such as electrical machines, connected to the network are treated by a separate ODE solver. Depending on the simulation scenario, the admittance matrices of the required network topologies can be preprocessed, i.e. factorized, before simulation start to guarantee a deterministic simulation time step.

The simulation kernel of DPsim is extended with interfaces to support different use cases such as circuit or system simulation, batch simulation, co-simulation and HIL testing. DPsim supports the Common Information Model (CIM) [18] as native input for the description of electrical network topologies, component parameters and load flow data, which is used for initialization. Users can interact with the simulation kernel via Python bindings, which can be used to script the execution, schedule events, change parameters and retrieve results. Python scripts have been proven an easy and flexible way to codify the complete workflow of a

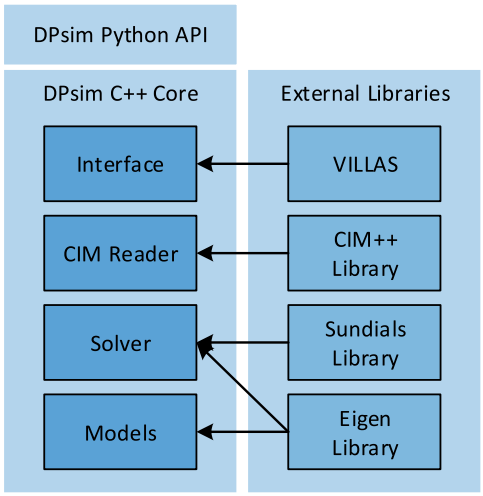

Fig. 1. Overview of DPsim's main components and dependencies on external libraries.

simulation from modeling to analysis and plotting, for example in Jupyter notebooks using Numpy and Matplotlib. Furthermore, DPsim supports co-simulation and interfaces to a variety of communication protocols of commercial hardware via the integration of DPsim with the *VILLASframework* [19], that enables large-scale co-simulations and HIL experiments.

2.1. Software architecture

2.1.1. Module structure

The DPsim simulation kernel and its component models are implemented in the C++ programming language. The availability of good compilers and highly optimized software libraries, such as *Eigen* [20], *Sundials* [21] and *VILLASnode*, which is part of the VILLASframework, for C++ were key factors for this decision.

The core of DPsim consists of models and solvers as depicted in Fig. 1. Interfaces to other software, hardware or data are supported through external libraries. Grid data in CIM standard format is imported using the *CIM++* library [22]. Communication with other software, e.g. real-time simulators, control and monitoring software, as well as hardware is provided by the VILLASframework. For linear algebra operations, DPsim uses the Eigen library. The MNA solver of DPsim uses the Eigen LU factorization and *Eigen::Dense/Sparse::Matrix* are the standard data types for all matrix variables. The Sundials solver package is included in DPsim to provide more complex ODE solvers for components connected to the network.

Compilation from source code requires a Git, a C++11 compiler and CMake 3.6. Tested compilers are Clang, GCC, MSVC and Intel's ICC. As a base operating system Ubuntu 18.04 LTS or Fedora 29 are recommended. For real-time execution a Linux 4.9 kernel with the *PREEMPT_RT* patch-set is recommended.

2.1.2. Class hierarchy

Simulation is the main interface class for users to control the simulation state. The attributes of a *Simulation* instance hold all the information that specifies one simulation scenario in DPsim. The *Simulation* holds references to the solvers, interfaces and the power system model information. This hierarchy is presented in Fig. 2. The complete class hierarchy diagram can be found in the developer's documentation of DPsim [23]. All solvers inherit from *Solver*, e.g. *MNASolver* and *ODESolver*, and all interfaces from *Interface*, e.g. for VILLASnode. All component models, power system, signal etc., derive from the class *IdentifiedObject*. The main

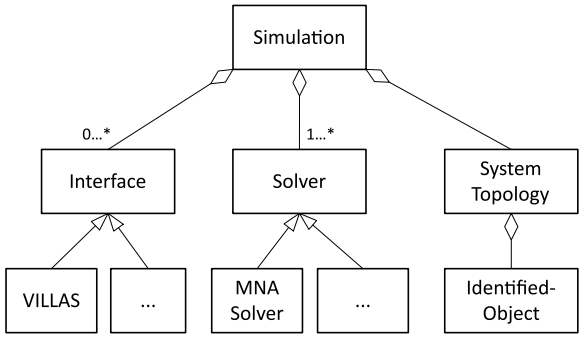

Fig. 2. Diagram of the main classes of DPsim.

attribute of this class is a unique identifier, which is equivalent to the *mRID* in CIM.

2.1.3. Parallelization

In order to utilize the multiple processor cores of modern computer systems and speed up the simulation, the computation of one time step is split up into multiple tasks. These tasks are defined by the various parts of the simulation (like instances of *Solver* and *Interface*). An internal scheduler creates a task graph by analyzing which variables are modified and used by the tasks. This task graph is a directed acyclic graph with nodes representing tasks and edges representing data dependencies. The scheduler uses this graph to distribute the tasks onto multiple threads such that these dependencies are upheld. DPsim implements different scheduling algorithms for this purpose, the simplest of which being level scheduling as used in [24]. This algorithm divides the tasks into ordered levels such that each task only depends on tasks in a previous level. To simulate a time step, these levels are then executed in order by distributing all tasks of one level evenly among the available threads.

To further optimize the simulation performance for large networks when using multiple processors, a decoupling transmission line model can be introduced. In this model a transmission line is represented using equivalent current sources and resistances at the line ends that are not topologically connected as described in [25, ch. 6.2]. Instead, the ends are indirectly connected by updating the values of the sources based on the values on the other end only after a delay τ, which depends on the line's parameters. As subsystems that are connected using this line model are not connected in a strict topological sense, they can be solved independently and in parallel. This significantly reduces the computational effort to simulate large systems.

2.2. Software functionalities

DPsim supports both dynamic phasor and EMT simulation. Furthermore, DPsim is optimized for real-time simulation but it is also possible to run the same simulation scenario offline meaning that the simulation is executed as fast as possible. These different simulation modes are compatible with the user and simulation interface which are covered in the following.

2.2.1. User interface

Network models can be directly defined in the C++ code. This technique is complemented by a CIM importer, which allows the user to directly load network models from CIM-XML files. This proves to be an adequate form to describe network topology and component parameters, which are required by the solver. This CIM importer relieves the user from defining the model in plain C++ code. However, CIM-XML is not suitable for

the definition of more complex simulation scenarios with time varying parameters or topology changes caused by contingencies in the system (e.g. breaker events or faults). Therefore, DPsim features Python bindings to most parts of the C++ programming interface. A scripting language like Python is used to define scenarios by leveraging the flexibility of a general purpose imperative language. This allows the user to write a single Python script to:

- Describe the network topology and parameters
- Load a network from CIM data and optionally extend it
- Define a simulation scenario with events or parameter changes
- Execute the simulation and analyze or plot the simulation results

2.2.2. Simulation interface

Interfacing the simulation kernel is desirable for multiple reasons:

- Real-time exchange of simulation signals for co-simulation or HIL testing
- User interface for online monitoring and control of the simulation
- Logging of simulation results for offline analysis
- Import of time series data, for example load and production profiles

For commercial simulation tools these interfaces are a major selling point as new protocols and standards and DAQ cards are introduced continuously. Their implementation and maintenance is time consuming and seemingly never ending. By design, DPsim tries to avoid this pitfall by leaving the implementation of interfaces, data formats and protocols to a separate project. VILLASnode, a component of the VILLASframework project, handles input/output as well as translation between different protocols. DPsim focuses on solving the system model and provides only a single type of interface, shared memory, to the VILLASnode gateway. Interfaces to external systems, databases, files or the web interface are then handled by the wide range of supported interfaces of the VILLASnode gateway, which in this case acts as a proxy between the shared-memory interface to DPsim and the outside world. Responsibilities are clearly separated. This allows the development of new interfaces without having to modify the simulation kernel itself.

In addition, DPsim can use the VILLASnode interfaces for co-simulation with other simulators or remote DPsim instances. In such a scenario, DPsim is usually coupled using an Ideal Transformer Model (ITM). Fig. 3 shows a decoupled model, which exchanges voltages in one and current signals in the opposite direction to control respective sources. For a phasor simulation, the exchanged signals are complex-valued attributes which are passed via the shared-memory interface to VILLASnode which further sends them to a remote simulator using one of VILLAS' supported protocols (e.g. MQTT, UDP, ZeroMQ, …). For geographically distributed simulations, VILLASnode can implement interface algorithms to compensate for the inherent communication latencies when executed in real-time over a high latency connection such as the internet. Alternatively, the implementation of a Discrete Fourier Transform (DFT) in VILLASnode allows for a coupling of the phasor-based DPsim with other EMT-based simulation tools like OPAL-RT or RTDS.

DPsim exchanges simulation data with the VILLASnode gateway via a shared-memory region. The execution of DPsim and VILLASnode as independent processes is crucial in real-time simulation scenarios as the main simulation kernel must not be interrupted by background activities such as data logging to a possibly blocking database.

Furthermore, DPsim has its own simple logging module to write results to CSV files for archival and post processing. This method is easy to setup and convenient for small simulations where post processing and analysis of simulation results is done in MATLAB or Python. In the long term, the internal CSV logging functionality is planned to be incorporated into VILLASnode and enhanced by the support of additional data formats like HDF5 as used by MATLAB.

3. Implementation and empirical results

To complement the previous overview of DPsim's architecture, the next subsection explains implementation specifics affecting the real-time performance of DPsim. The real-time performance of DPsim is demonstrated in the following subsection. The remaining two subsections demonstrate the correctness of the solution computed by DPsim against Matlab Simulink. The first simulation validates only the network solution, which is computed by the MNA solver. The second simulation features a combination of the MNA solver for the network solution and an ODE solver for the numerical integration of the synchronous generator equations.

3.1. Implementation details

Only a compiled language like C++ with minimal runtime overhead is suitable for the implementation since DPsim is targeting simulation time steps in the range of milliseconds to microseconds on off the shelf computing hardware. Great care was taken to avoid memory allocation during the actual simulation. Whenever possible, DPsim utilizes low order integration methods and avoids iterative solver strategies to minimize computation time. That is why the network part is handled by the MNA solver specifically developed for DPsim.

DPsim is compatible with Windows, macOS and Linux operating systems. Eventually, the operating system configuration can have a large impact on the real-time performance. To guarantee real-time execution, DPsim leverages several Linux real-time features such as the real-time capable *SCHED_FIFO* scheduler, real-time signals, the *timerfd* interface, or control groups (*cgroups*). Many of these features are nowadays incorporated in the standard Linux kernel but have their origin in the *PREEMPT_RT* patch-set. The patch-set is slowly integrated into the mainline kernel but still exists and can be applied to further improve the real-time performance by enabling preemption of critical sections such as interrupt handlers. The capability to preempt critical sections in the operating system kernel reduces the overall system latency and therefore helps to ensure strict deadlines at each time-step interval.

Real-time execution on Windows or macOS is not supported. Best real-time performance was achieved on a recent Intel x86_64 multi-core machine with optimized BIOS settings to avoid interruptions of the system by the System Management Mode (SMM). To do so, DPsim execution threads are isolated from remaining system processes using Linux's *cgroup* feature. This reduces the impact of background jobs in the system on the real-time performance.

As a good start for real-time optimizations, we recommend Redhat's Real-time Guide [26] with its *tuned* tool and the *realtime* profile. An updated list of optimization options can be found in the DPsim documentation [23].

To control the time step, DPsim is using *timerfd* interface in Linux environments. The *timerfd* interface allows for the configuration repetitive interval and one-off timers. It uses blocking file descriptors to suspend the execution of the simulation loop until the beginning of the next interval. This approach is more

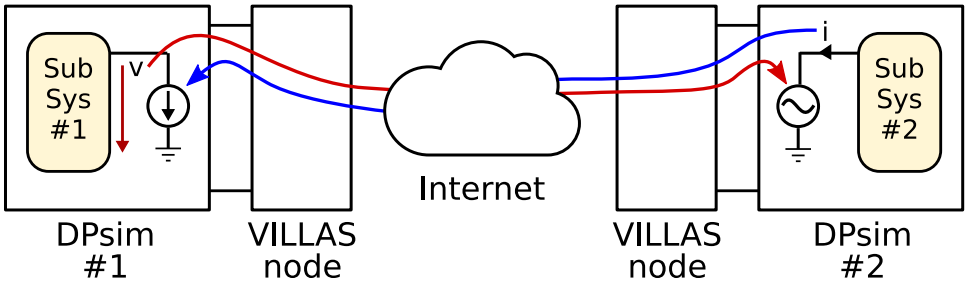

Fig. 3. VILLASnode as a gateway for distributed co-simulation with DPsim.

efficient than the use of the more common *timer* interface, which relies on signals. At the same time, *timerfd* is more accurate as calls to *sleep* or *nanosleep* as they suffer of a lingering drift to non-equidistant execution intervals. The *timerfd* is also used to schedule the synchronized start of distributed simulations as described in the introduction.

Shared-memory is a common method for inter-process communication (IPC) used on symmetric multi-processing (SMP) machines. It enables user processes to exchange data without the involvement of the OS kernel. Shared-memory IPC allows both processes, the solver and the gateway, to be executed in parallel while streaming their data with minimal latency over a queue in the shared memory region. The queue is implemented as a lock free multiple producer/multiple consumer (MPMC) queue and relies on atomic operations of the processor to facilitate synchronization of the DPsim and VILLASnode processes. The lockfree queue is a thread safe data structure. It is used to pass samples of simulation data between the involved processes. As such *message passing* is used as the main paradigm to avoid data races. During the initialization phase, semaphores are used to avoid race conditions in the setup of the shared-memory regions. The absence of the operating system in the communication is crucial to avoid costly context switches, which have to be avoided in a real-time context. Using the shared-memory interface, the DPsim simulation loop can run uninterrupted in a high priority process. At the same time, VILLASnode gets assigned a lower priority for handling of possibly blocking disk or database accesses. In a hardware-in-the-loop simulation it might be necessary to have hard real-time capable interfaces to the real world. For this purpose, DPsim supports an arbitrary number of shared-memory interfaces at the same time. This allows the user to configure one VILLASnode process with a high priority for the control of PCIe FPGA or DAQ cards, and at the same time another VILLASnode process for low priority logging of simulation data in the background.

3.2. Real-time performance evaluation

DPsim is specifically designed for real-time simulation. To assess the effect of system size on the real-time performance of DPsim, a simple test network was copied multiple times and connected with additional transmission lines. Fig. 4a shows the WSCC 9-bus system, which was used for this purpose. The copies were connected in a ring-like topology using additional transmission lines at the nodes 5, 6, and 8. The average wall clock time needed to simulate one time step was measured for a simulation time period of 0.1 s with a time step of 100 µs. Each measurement was further averaged over ten simulations of the same system. The measurements were performed on a system running Ubuntu 16.04 on an Intel Xeon Silver 4114 processor featuring ten cores clocked at 2.2 GHz. The results are shown in Fig. 4b for two different configurations: For the normal simulation, the additional transmission lines were modeled using the Pi model and only one thread was used. For the parallel simulation, the decoupling transmission line model was used for the additional lines and ten threads were employed. As it can be seen, the use of multiple threads and the special transmission line model greatly reduces the wall clock time necessary for simulating a single time step. Even for 40 copies of the original system (resulting in a system size of 360 nodes), the wall clock time per step stays under the simulation time step of 100 µs, thus allowing for real-time simulation. For a small number of system copies, DPsim supports simulation time steps of about 10 µs, which is a typical time step for commercial EMT simulators. However, it should be noted that such small time steps are not the aim of DPsim since the simulation is conducted in DP and not EMT.

3.3. Validation of the MNA network solver

The next simulation case demonstrates the accuracy of the MNA network solver compared to Simulink results. Both simulators DPsim and Simulink are run with a simulation time step of 100 µs. It can be seen that for such small time steps DP simulations yield the same results as EMT. The larger the time step, the more will the results degrade. It is shown in [5] that the degradation of the results with larger time steps is smaller when using the DP approach compared to EMT.

Fig. 5a shows the simulated circuit, which is composed of one current source of 10 A, two resistors of 1 Ω, an inductor of 1 mH and a capacitor of 1 mF. The voltage source is set to its nonzero peak value at the beginning because it is following a cosine with zero phase shift. Therefore, the system is not starting from steady-state and a transient can be observed. The DPsim dynamic phasor results are transformed to time domain values and compared against Simulink EMT results. As can be seen from Fig. 5b, the results match.

3.4. Validation of the ODE solver for components

The following example compares the results of Simulink and DPsim for a three phase synchronous generator fault. Here, the simulation time step is 50 µs for DPsim and Simulink. As in the previous simulation case, the DP approach would allow for larger time steps than EMT. A comprehensive study investigating this property and featuring synchronous generator models is presented in [27]. Initially, the load is 300 MW and the fault is applied at 0.1 s. The generator parameters are taken from example 3.1 in [28]. As in the previous example, the dynamic phasor results are transformed to time domain values before the comparison. Again, it is visible that the DPsim results match the Simulink results except when the fault is cleared (see Fig. 6). In contrast to DPsim, the fault in Simulink is not immediately cleared but at the next zero-crossing.

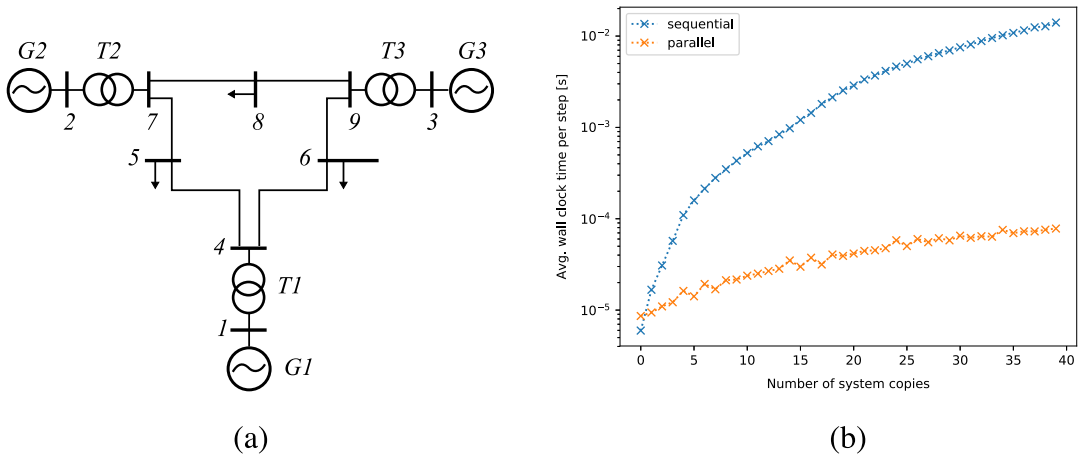

Fig. 4. WSCC 9-bus system (a) and average wall clock time per step (b).

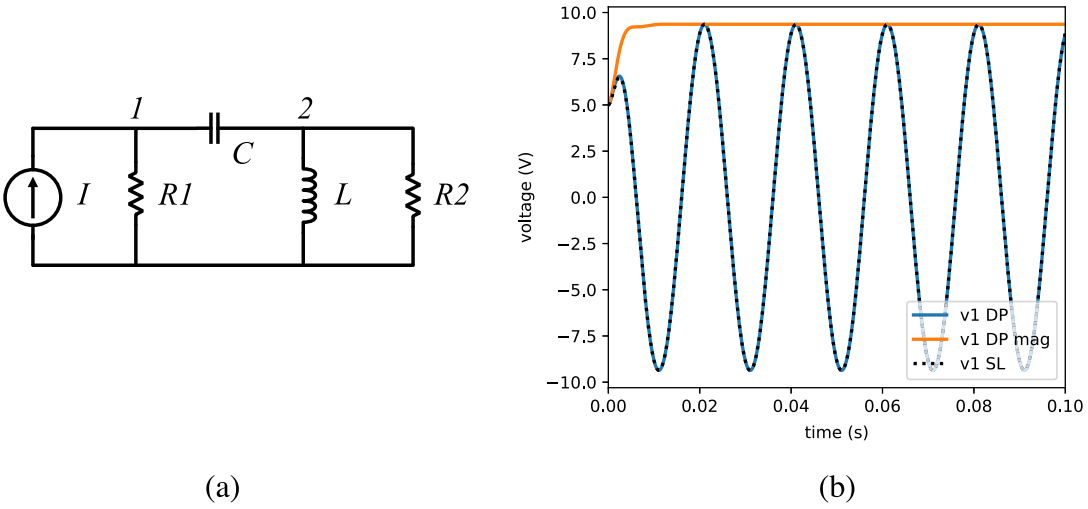

Fig. 5. Example circuit (a) and DPsim dynamic phasor and Simulink EMT simulation results for node 1 (b).

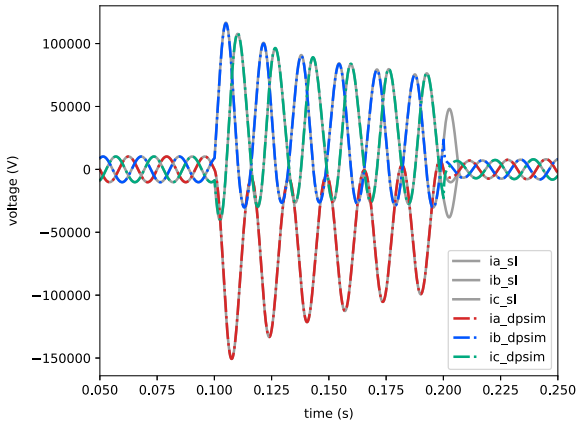

Fig. 6. DPsim dynamic phasor and Simulink EMT results for the synchronous generator three-phase fault example.

4. Illustrative examples

As mentioned in Section 2.2, there are two ways to define a circuit topology for DPsim: coding the topology using Python or C++ or importing it from CIM. The two options are presented by means of two examples: a circuit and a small power system. The first example presented in this section demonstrates the definition utilizing Python while the second example takes advantage of the CIM import function.

4.1. Defining a circuit simulation in python

The circuit of the previous section, Fig. 5, is taken as an example to demonstrate how circuits can be defined using DPsim's Python interface. The topology can be created in Python as depicted by Listing 1.

Listing 1: Python code to define a circuit.

```
# Nodes
gnd = dpsim.dp.Node.GND()
n1 = dpsim.dp.Node('n1')
n2 = dpsim.dp.Node('n2')

# Components
cs = dpsim.dp.ph1.CurrentSource('cs')
cs.I_ref = complex(10,0)
r1 = dpsim.dp.ph1.Resistor('r_1')
r1.R = 1
c1 = dpsim.dp.ph1.Capacitor('c_1')
c1.C = 0.001
l1 = dpsim.dp.ph1.Inductor('l_1')
l1.L = 0.001
r2 = dpsim.dp.ph1.Resistor('r_2')
r2.R = 1
```

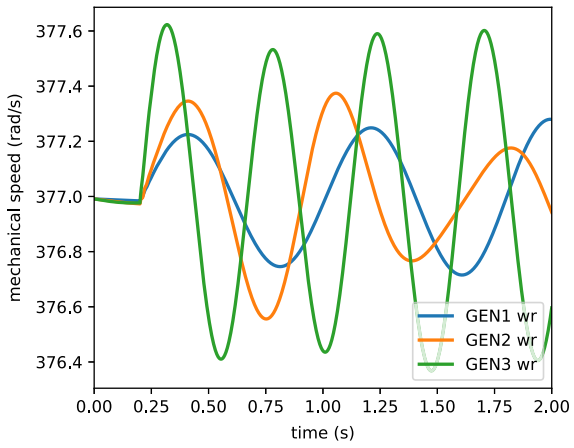

Fig. 7. WSCC 9-bus system mechanical speed simulation results after fault.

```
# Connections
cs.connect([gnd, n1])
r1.connect([n1, gnd])
c1.connect([n1, n2]);
l1.connect([n2, gnd]);
r2.connect([n2, gnd]);

system = dpsim.SystemTopology(50, [gnd, n1, n2], [cs, r1, c1, l1, r2]);
sim = dpsim.Simulation('circuit', system, timestep=0.0001, duration=0.1)
sim.start()
```

First, the nodes and components are declared and parameterized. Then, the connections between components and nodes are set and in the following step all network objects are added to the system topology. Finally, the system topology and parameters such as time step and final time can be used to create a simulation instance, which can be started, stopped and stepped through. Optionally, initial voltages could be assigned to the nodes. Since this is not the case here, the initial voltages are set to zero.

4.2. Simulating a power system defined in CIM

The next example presents the CIM loading functionality, which is used to read the data of the WSCC 9-bus system as displayed in Fig. 4a. The objects defined in the CIM file, e.g. *Terminal*, *TopologicalNode*, *SynchronousMachine*, are mapped to DPsim objects according to the *CIM::Reader* class of DPsim. The system frequency, 60 Hz, is not defined in the CIM file. Therefore, it needs to be specified before loading the CIM file. Furthermore, a fault is applied to node 9 of the imported system. To implement the fault, the system is extended by a switch connected to node 9, which connects the node to ground with a small resistance after 0.2 s. The switching action is created as an object of type *Event* and added to the *Simulation* instance.

Listing 2: Python code to import a topology from CIM.

```
# Read from CIM
 files = glob.glob(' ../../ dpsim/Examples/CIM/WSCC09_RX_Dyn/*.xml')
system = dpsim.load_cim('WSCC9bus', files, frequency=60)

# Get existing nodes
gnd = dpsim.dp.Node.GND()
bus9 = system.nodes['BUS6']

# Add switch
sw = dpsim.dp.ph1.Switch('Switch')
sw.R_open = 1e9
sw.R_closed = 0.1
sw.is_closed = False
sw.connect([ bus9, gnd ])
system.add_component(sw)

sim = dpsim.Simulation('WSCC9bus', system,
timestep=0.0001, duration=2, init_steady_state=True)

sim.add_event(0.2, sw, 'is_closed', True)
sim.start()
```

In Fig. 7, it can be seen how the rotational speed of the generators starts to oscillate after the fault. The oscillation frequency depends on the mechanical inertia and as expected the generator with the largest inertia has the lowest oscillation frequency.

5. Impact

Since DPsim is open source, it can serve as a reference implementation for real-time power system simulators and a common basis for users working with different real-time simulation solutions. Having a common basis facilitates discussions on differences in simulation results of different tools. Besides, DPsim allows for real-time simulation on standard computing hardware, making real-time applications available to a wider range of researchers.

Thanks to its design, DPsim facilitates distributed real-time co-simulation, which promotes collaboration and allows the use of the simulation capacity of geographically distributed laboratories to support large scale scenarios [5]. Distributed real-time co-simulation allows also for better data privacy, enabling cooperation because, in a co-simulation, each entity can keep its data confidential and only exchange boundary variables. This could be interesting for confidential grid data but also black box device models where manufacturers cannot share implementation details.

The dynamic phasor approach is used here in a system level simulation in contrast to component level power electronics applications as in [1]. With an increasing share of power electronics in power systems, this approach supports the investigation of future grids.

DPsim is already used in the EU H2020 research project RESERVE [29] and it was developed as a solution to decrease the difference between communication delay and simulation time step in previous co-simulation projects, e.g. RT-Superlab [2]. DPsim is promoted by the FEIN association that also hosts its code and documentation [23].

6. Conclusions

The presented software project, DPsim, exploits the dynamic phasor approach to overcome the requirement for EMT simulation that the simulation time step needs to be proportional to the highest signal frequency. In doing so, DPsim facilitates distributed real-time simulation and lets users exploit simulation resources in different geographical locations. For this purpose, DPsim is programmed in the C++ language and has its own MNA based network solver. Despite having a C++ core, the DPsim allows for scripting simulations via the python interface and reading grid topologies in the standard CIM format via the CIM++ library. These features are demonstrated in two simulation examples, a circuit and a grid simulation. Likewise, the computational correctness of DPsim and its real-time performance are demonstrated by means of simulation examples. Furthermore, DPsim is tightly integrated with the VILLASframework that offers many interfaces to commercial real-time simulators and hardware.

Declaration of competing interest

We confirm that there are no known conflicts of interest associated with this publication.

Acknowledgments

This work was partly funded by the European Unions Horizon 2020 Framework Programme for Research and Innovation under grant agreement no 727481.

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