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Locally Distributed Real-time Co-simulation Infrastructure for Scalable System Simulation (LD-RTCosim)

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List of Abbreviations

CO	Project Coordinator
CPU	Central Processing Unit
DER	Distributed Energy Resources
DRTS	Digital Real-Time Simulator
DTLM	Distributed Transmission Line Model
EC	European Commission
EMT	Electro-Magnetic Transient
EMTP	Electro-Magnetic Transient Program
HIL	Hardware-In-the-Loop
IA	Interface Algorithm
ITM	Ideal Transformer Method
LA	Lab Access
PHIL	Power Hardware-In-the-Loop
PSUT	Power System Under Test
SFP	Small Form Pluggable
UG	User Group
UP	User Project

Executive Summary

Power system analysis requires real-time simulation via Digital Real-Time Simulator (DRTS) to reproduce the complex behaviour of transmission and distribution grids with high diffusion of Distributed Energy Resources (DER) with the aim of enhancing the process of energy system integration~\cite{europeancommission_communication_2020}. These systems not only permit solving power system network by means of nodal analysis but also accelerate the study and development of power system equipment by means of Hardware-In-the-Loop (HIL) and Power Hardware-In-the-Loop (PHIL) application. To this extent, different DRTS commercial solutions (e.g., OPAL-RT and RTDS Technologies) have been proposed to accelerate the required computation for highly intensive tasks, such as Electro-Magnetic Transient (EMT) analysis~\cite{babikir2021acompensated}. However, the real-time simulation of innovative smart grids calls for huge computation capabilities, mostly to coordinate complex systems for large-scale scenarios.

Different works in the literature already implemented parallel computing strategies to solve EMT analysis of scalable Power System Under Test (PSUT). For instance, the MATLAB Simulink Simscape library~\cite{simscape} allows splitting a power system by using the propagation delay of a transmission line to absorb the inherent delay required to avoid direct feedthrough. Classic power systems present many transmission lines long enough to decouple points in the network, allowing parallel computation on multiple cores of a Central Processing Unit (CPU)~\cite{dufour2015testing}. The same concept is applied in ARTEMiS library~\cite{artemis} to split a power system on different cores of OPAL-RT Technologies DRTS, enhancing their real-time scalability~\cite{faruque2015realtime}. However, the computational capability of a single DRTS is limited and cannot overcome the problem of analysing large smart grid scenarios.

Thus, the scientific community proposed to interconnect different DRTS racks by means of communication protocols (e.g., Ethernet) to join their computational capabilities in a unique distributed digital real-time power system co-simulation environment~\cite{arjen2017cyberphysical}. Communication latencies, synchronization, and time regulation are the main issues in these interconnections, where the time step duration reach tens of microseconds. So, to accomplish this target is necessary to develop new technologies that allow DRTS systems to be connected without compromising simulation performance, particularly in terms of the accuracy of the dynamic simulation. Most of the proposed solutions in the literature are inspired by the PHIL application and its stability and accuracy intrinsic issues~\cite{zhiwang2020ascheme}. For instance, the time delay compensation method presented in~\cite{guillo2021characterization}. However, this strategy restricts the analysis to slower dynamics than EMT ones. Other works are inspired by the Interface Algorithm (IA) proposed for PHIL real-time simulation. The most suitable IA for these interconnections is the Ideal Transformer Method (ITM)~\cite{barbierato2023sj}. However, the effect of the latency experienced by the signal exchanged (i.e. voltages and currents) still generates a noticeable non-linear effect, affecting the accuracy of the real-time co-simulation solution. As a matter of fact, none of the previous solutions permits linking with flexibility different DRTS together maintaining the accuracy of a monolithic simulation.

In this LD-RT-Cosim project, we developed a digital real-time power system co-simulation implementing a Distributed Transmission Line Model (DTLM) as an adapter to split and extend the scalability of a PSUT with respect to a monolithic digital real-time simulation. The DTLM is applicable to transmission lines with a minimum length determined by the characteristic propagation

velocity v of the line. The co-simulation setup is accomplished by interconnecting two DRTS by means of an optical fiber link between their Small Form Pluggable (SFP) ports, exploiting the Aurora 8B/10B protocol. Aurora, in a nutshell, ensures the minimum communication latency among the available protocols on commercial DRTS. The proposed solution absorbs the communication latency experienced during the data exchange management of the co-simulation setup in the propagation time of the travelling wave of the DTLM. Because the communication latency is typically a multiple of the time step duration T_s depending on the commercial DRTS setup [\cite{barbierato2023sj}](#), the proposed DTLM allows for the setting of a variable communication latency attribute based on the laboratory configuration. To avoid complex time regulation and synchronisation schemes, the co-simulation setup has been tested over a laboratory setup with a single DRTS by employing an optical fiber echo link among two SFP ports of an OPAL-RT OP5700. The proposed solution has been tested over a simple PSUT with the aim of demonstrating the stability and accuracy of the co-simulated experimental result, resulting in identical performances with respect to a monolithic simulation.

1 Lab-Access User Project Information

1.1 Overview

TODO: “This section should include: title, acronym, host infrastructure, access period, user group members; use the same information as in the corresponding Lab Access User Project Proposal. This section should not be divided into subsections.”

1.2 Research Motivation, Objectives, and Scope

TODO: “This section should briefly outline the research motivation, the corresponding objectives, and the scope of the Lab Access User Project. This section should not be divided into subsections.”

1.3 Structure of the Document

This document is organised as follows: Section 2 briefly outlines the state-of-the-art/state-of-technology that provides the basis of the realised Lab Access (LA) User Project (UP). Section 3 briefly outlines the performed experiments whereas Section 4 summarises the results and conclusions. Potential open issues and suggestions for improvements are discussed in Section 5. Finally, additional information is provided in the Appendix A. Document Guidelines, Appendix B. Heading, and Appendix C. Heading.

2 State-of-the-Art/State-of-Technology

In this section, the theoretical formulation of the Electro Magnetic Transient Program (EMTP) is presented for the sake of self-consistency and clarity of the manuscript.

In [\[dommel1969dpl\]](#), the lossless distributed LC line is characterised by two values for a single-phase line: *i*) the surge impedance $Z_c = \sqrt{L'/C'}$, and *ii*) the wave propagation speed $v = 1/\sqrt{L'C'}$ where L' and C' are the per-unit length inductance and capacitance respectively. Figure [\[fig:linemodel\]](#) show the equivalent impedance circuit of a single-phase line. For a lossless line (i.e. $R' = 0$), the quantity $e + Z_c i$, where e is the voltage of the line and i is the current of the line of one subsystem, must arrive unchanged at the other subsystem after a transport delay τ .

$$\tau = \frac{d}{v}$$

where d is the length of the line and v is the propagation speed. The model equations for a lossless line are:

$$\begin{aligned} e_r(t) - Z_c i_r(t) &= e_s(t - \tau) - Z_c i_s(t - \tau) \\ e_s(t) - Z_c i_s(t) &= e_r(t - \tau) - Z_c i_r(t - \tau) \end{aligned}$$

knowing that:

$$\begin{aligned} i_s(t) &= \frac{e_s(t)}{Z} - I_{sh}(t) \\ i_r(t) &= \frac{e_r(t)}{Z} - I_{rh}(t) \end{aligned}$$

in a lossless line, the two current sources I_{sh} and I_{rh} are computed as:

$$\begin{aligned} I_{sh}(t) &= \frac{2}{Z_c} e_r(t - \tau) - I_{rh}(t - \tau) \\ I_{rh}(t) &= \frac{2}{Z_c} e_s(t - \tau) - I_{sh}(t - \tau) \end{aligned}$$

When losses are taken into account, new equations for I_{sh} and I_{rh} are obtained by lumping $R/4$ at both ends of the line and $R/2$ in the middle of the line where R is the total resistance of the line:

$$R = R' d$$

where R' is the characteristic resistance per unit length. The current sources I_{sh} and I_{rh} are then computed as follows:

$$\begin{aligned} I_{sh}(t) &= \left(\frac{1+h}{2}\right) \left(\frac{1+h}{Z} e_s(t - \tau) - h I_{rh}(t - \tau)\right) + \left(\frac{1-h}{2}\right) \left(\frac{1+h}{Z} e_r(t - \tau) - h I_{sh}(t - \tau)\right) \\ I_{rh}(t) &= \left(\frac{1+h}{2}\right) \left(\frac{1+h}{Z} e_r(t - \tau) - h I_{sh}(t - \tau)\right) + \left(\frac{1-h}{2}\right) \left(\frac{1+h}{Z} e_s(t - \tau) - h I_{rh}(t - \tau)\right) \end{aligned}$$

where:

$$Z = Z_c + \frac{R}{4}$$

$$h = \frac{Z_c - \frac{R}{4}}{Z_c + \frac{R}{4}}$$

$$Z_c = \sqrt{\frac{L'}{C'}}$$

$$v = \frac{1}{\sqrt{L' C'}}$$

$$\tau = d\sqrt{L' C'}$$

L' and C' are the inductance and capacitance per unit length of the line, R is the total resistance of the line, and d is the line length. For a lossless line, $R = 0$, $h = 1$, and $Z = Z_c$.

3 Executed Tests and Experiments

3.1 Test Plan, Standards, Procedures, and Methodology

TODO: “This section should briefly outline the applied test plan, used standards and procedures as well as the corresponding methodology of the Lab Access User Project. If appropriate, this section can be divided into subsections.”

3.2 Test Set-up(s)

TODO: “This section should include implementation details: equipment and communications involved, control strategy, monitoring aspects, etc. of the Lab Access User Project. If appropriate, this section can be divided into subsections.”

3.3 Data Management and Processing

TODO: “This section should briefly outline the used/applied data management and processing strategy of the Lab Access User Project. If appropriate, this section can be divided into subsections.”

4 Results and Conclusions

4.1 Discussion of Results

TODO: “This section should summarise the achieved results of the Lab Access User Project.”

4.2 Conclusions

TODO: “This section should provide the main conclusions of the Lab Access User Project. Especially, the following points need to be addressed in the conclusions:

- The impact of using the ERIGrid 2.0 Lab Access programme (User Group and hosting organisation benefits, scientific advancements, commercial benefits, etc.).
- Where applicable, describe experiences related to the use of the Holistic Test Description (HTD). Does the HTD help in organising the access (e.g., agreeing test objectives and evaluation criteria).
- Where applicable, describe challenges and solutions specific to multi-lab experiments.
- Where applicable, describe challenges and solutions specific to Hardware-in-the-Loop (HIL) experiments.

”

5 Open Issues and Suggestions for Improvements

TODO: “This section should briefly outline open issues and potential suggestions for improvements of the Lab Access User Project.

- Where applicable, describe potential improvements related to the use of the Holistic Test Description (HTD).
- Where applicable, describe gaps in lab capabilities where things can be improved to enable future access or fulfilling objectives that could not be met in the current project.

If appropriate, this section can be divided into subsections.”

References

- Lamport, L. (1994). LATEX: a document preparation system: user's guide and reference manual. Addison-Wesley.*
- Tan, P.-N., Kumar, V., & Srivastava, J. (2004). Selecting the right objective measure for association analysis. Information Systems, 293-313.*

Appendix A. Document Guidelines

A.1. Report Titles

Reports have a title that is defined in the submitted LA UP proposal. Please stick to the official spelling.

A.2. File Naming

The project will generate many documents (reports) and versions of these reports. It is beneficial to consistently use an agreed file naming format.

ERIGrid2-Report-Lab-Access-User-Project-AccessProjectNumber-AccessProjectAcronym-Status-vn.n.Extension

- Notice the hyphen between the various elements of the file name.
- **ERIGrid2:** Each ERIGrid 2.0 report should be preceded by the project acronym. Notice, there is only one correct spelling of the acronym, i.e., 'ERIGrid 2.0', but for file names 'ERIGrid2' will be used.
- **AccessProjectNumber:** This should be based on the formal LA UP number according to the submission system
- **AccessProjectAcronym:** This should be based on the formal LA UP acronym as stated in the corresponding, submitted proposal.
- **Status:**
 - *draft* = Draft Version – indicates that the drafting of the report is in progress;
 - *final* = Final Version as checked and updated by the User Group (UG) and the hosting institution;
 - *submitted* = submitted version as submitted to the ERIGrid 2.0 Project Coordinator (CO).
- **vn.n:** The version of the report starting from v1.0.
- **Extension:** File extension, e.g., 'docx' for Microsoft Word and 'pdf' for Portable Document Format.

Examples:

- ERIGrid2-Report-Lab-Access-User-Project-116-GRIDPV100-draft-v1.2.docx
- ERIGrid2-Report-Lab-Access-User-Project-116-GRIDPV100-submitted-v1.8.pdf

A.3. Change Log

The Change Log is there to keep track of the changes made to the document. Whenever changes are made to the document, a new version should be created and the changes should be briefly summarised in the Change Log. We anticipate a minimum of three phases of Change Log entries. (1) The researcher responsible for the given report enters the changes as he/she develops the document. (2) The two reviewers register the changes made in

the quality assurance phase. Once the responsible researcher passes the report on to the hosting institution, the status should be changed from 'draft' to 'final'.

A.4. Document Formatting

A.4.1. Headings

Like in many journals and books, it is a good practice not to use more than 3 levels of headings. If you really need more, then by all means do so, but you may first consider how to structure the document with a maximum of three heading levels.

Use the following capitalisation style for all headings: All terms should be capitalised and do not use a full stop at the end.

A.4.2. Captions and Citations

Use the following for captions and cross referencing:

- 'Table 1' for tables, not 'table 1' or 'Tab. 1', etc.
- 'Figure 1' for figures, not 'figure 1' or 'Fig. 1', etc.
- 'Section 1.1.1' to cross-reference other sections, not 'section 1.1.1' or 'S. 1.1.1', etc.

Do not abbreviate the word 'Equation' to 'eq', 'Eqn', etc.

Table captions should be placed above the table and figure captions should be placed below the figure. The captions should succinctly describe the content of the table or figure.

A.4.3. Tables

Producing informative tables is not easy. Avoid grid lines around each table cells (typical for people with little experience in drafting technical papers). The table below (Table 1) is a good example how tables should look like. Make sure that caption appears on the same page as the table. The table caption is above the table!

The table caption should follow the sentence style layout and end with a full stop. The caption as well as the table should be centred.

Each table must be introduced in the deliverable text. Make sure that cross references to tables are correct before submitting the deliverable.

The same (simplified) table using the Word table feature is shown below (Table 2).

A.4.4. Figures

Good figures/diagrams are even more difficult to produce than tables. Figures should contain legends explaining the symbols in the figure. Avoid surrounding the figure with a box outline. If there are different parts of a figure (e.g., (a), (b), (c)), indicate these clearly. Make sure that the labels within a figure/diagram are spelled consistently within the figure/diagram and are also consistently spelled in the text. Make sure that caption appears on the same page as the figure. The figure caption is below the figure. See an example of a figure and its caption below (Figure 1).

Table 1: Summary of properties of different modelling formalisms. The table below is inserted as graphic.

	Static (s), dynamic (d)	Discrete (d), continuous (c)	Deterministic (d), stochastic (s)	Qualitative (ql), quantitative (qn)	Coarse (c), average (a), fine (f) grained
DG	s		d	ql	c
BYN	s ^a	d,c	s	qn	c
BNN	d	d	d	ql	c
GLN	d	d	d	ql	a
NLDE	d	c	d	qn	a,f
PLDE	d	c	d	ql,qn ^c	a
QDE	d	d	d	ql	a,f
PDE	d	c ^b	d	qn	a,f
SME	d	d	s	qn	f
R	d	d	d	ql	a,f

^aGeneralization to dynamic Boolean networks is possible.

^bSpatial dimension is often discretized.

^cQualitative analysis of models is possible.

Table 2: Summary of properties of different modelling formalisms. The table below is produced using Word table environment.

	Static	Discrete	Deterministic	Qualitative	Coarse
DG	s		d	ql	c
BYN	s	d,c	s	qn	c
BNN	d	d	d	ql	c
GLN	d	c	d	qn	a,f

Each figure must be introduced in the deliverable text. Make sure that cross references to figures are correct before submitting the deliverable.

The figure caption should follow the sentence style layout and end with a full stop. The figure caption as well as the figure should be centred.

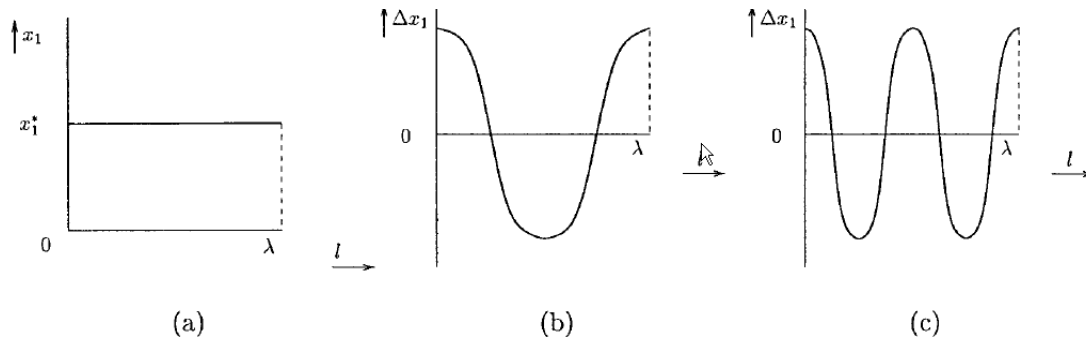


Figure 1: Caption caption caption caption caption caption caption caption caption. (a) Caption caption caption, (b) Caption caption caption, (c) Caption caption caption.

A.4.5. Footnotes

This¹ is a footnote.

¹The footnote is at the bottom of the same page where the footnote is cited and the font size is only 9 pt. Footnotes are useful to for including nasty-looking long Web references which would look terrible if used in the main flow of the text.

A.5. Language and Notation

There are a few things we should consider when writing documents in terms of language. The question is not deeply philosophical in the sense of whether one or the other approach is fundamentally correct (or wrong). It is more the case of maintaining a certain level of consistency across the project.

Since British/UK English is the official version of English within the European Commission (EC), we should by default use UK English spelling (and adopt a spell-checker set to UK English). Nevertheless, US spelling is also fine — the main issue to ensure is to be consistent within a given deliverable.

Quotation marks. UK English (unlike US), use single quotation marks ('X') instead of double quotation marks ("X"). At least maintain consistency within a document.

- It is claimed that Y is 'superior' to X.
- 'Good morning, Dave,' greeted HAL.

Do not use quotation marks to indicate emphasis — use italics, bold or underline style instead.

The accepted standard for separating orders of magnitude in large figures is not ', ' or "' (quotation mark) or '.', but a non-breaking (small) space.

- This is inappropriate: 1,000,000 or 1.000.000 or 1'000'000 (very bad!)
- This is good: 1 000 000.

Capitalisation. Use capitalisation according to English grammar rules. If someone is interested, see capitalisation rules:²

Tense. Use past tense when describing activities and tasks (experiments, developments, etc) carried out in the past.

- A test bed was set up to ...
- The evaluation revealed that ...

Use present tense when describing the ideas, design, systems, etc. that exist in the present.

- The system supports the following exchange formats ...
- A key property of the system is its ability to ...

Large numbers. Use explicit format or scientific notation for large numbers

- Use 1 200 000 000, not 1.2bn or 1,200,000,000
- Or use 1.20×10^9 or 1.20×10^9

Small numbers. As usual, unless in tables and similar elements, use one, two, ..., twelve for numbers < 13, and 13, 14, ..., for large numbers.

Numbers and units. Use space to separate figures from units. E.g.,

- 10 GB, not 10GB
- 2.13 s not 2.13s

²<http://andromeda.rutgers.edu/~jlynch/Writing/c.html>, <http://www.grammarbook.com/punctuation/capital.asp>

Bits, bytes and pieces. Use the following terms and abbreviations for bytes (sometimes it is better to use the full term than the abbreviation).

Bits:

kb or Kb	kilobit	10 ³
Mb	megabit	10 ⁶
Gb	gigabit	10 ⁹
Tb	terabit	10 ¹²

Bytes:

kB or KB	kilobyte	10 ³
MB	megabyte	10 ⁶
GB	gigabyte	10 ⁹
TB	terabyte	10 ¹²

Number of decimals. When a number is expressed in the scientific notation, the number of significant digits (or significant figures) is the number of digits needed to express the number to within the uncertainty of calculation. For example, if a quantity is known to be 1.234 ± 0.002 , four figures would be significant³.

Unless there is a good reason, do not use more than three fractional digits or places (the number of digits following the point).

Other issues. Avoid overly long sentences. Certain rules suggest that sentence over approximately 20 words become difficult to understand and should therefore be avoided.

A.6. Formatting Bibliographical References

By default, references should use APA style (as, e.g., used in Google Scholar) and be ordered in alphabetic order. See for example (Tan, Kumar, & Srivastava, 2004), in the list below.

Other styles are also OK, nevertheless the authors should make sure that within a single document the notation to references and their citation should be consistent. In the text, the references should ideally be referred to by the author name and year, e.g., (Lampont, 1994); however, referencing by reference number is also acceptable.

A.7. Associated Outputs

If appropriate, please include a section with details of any datasets, code or other resources being released with this report.

The work described in this report has resulted in the following resources:

Description	URL	Availability
My Dataset 1	http://hdl.handle.net/12345	Public (Apache 2.0)
My Dataset 2	http://hdl.handle.net/54321	Private (consortium only)
My Code	github.com/erigrd2/xxx	Public (GPL3)

³ <http://mathworld.wolfram.com/SignificantDigits.html>

Appendix B. Heading

B.1. Heading

TODO: "Explain the content of the appendix."

B.2. Heading

TODO: "Explain the content of the appendix."

Appendix C. Heading

C.1. Heading

TODO: "Explain the content of the appendix."

C.2. Heading

TODO: "Explain the content of the appendix."

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