European Research Infrastructure supporting Smart Grid Systems Technology Development, Validation and Roll Out

Technical Report TA User Project

DEF-HIL

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Table of contents

1 General Information of the User Project 4

1.1 Research Motivation 4

1.2 Objectives and Scope 4

1.3 Pictures 5

2 State-of-the-Art/State-of-Technology 6

3 Results and Conclusions 7

3.1 Executive Summary 7

3.2 Overview of Hardware-in-the-Loop Systems 7

3.3 Definitions 10

3.4 Letter Symbols 15

4 Open Issues and Suggestions for Improvements 18

5 Dissemination Planning 18

6 References 18

7 Annex 19

7.1 List of Figures 19

7.2 List of Tables 19

1 General Information of the User Project

This section includes a brief motivation for undergoing research on the proposed topic. In what follows, objectives and scope of the research project is formulated respectively. Finally, pictures of the user group are highlighted as general information of the user project DEF-HIL. The locations for working have been selected as Kassel, Germany with Fraunhofer IEE and Vienna, Austria with AIT Austrian Institute of Technology.

1.1 Research Motivation

HIL systems provide a wide area of potential scenario investigations, but the applicable experimental possibilities are related and limited to the used HIL setup. HIL system can be used for system studies including hardware components or small-scale power systems, or component studies including power system operations. Different use cases demand specific conditions of the real-time simulation and/or hardware.
Questions will be addressed during the project like, the simulation time scale, simulation mode requirements (EMT/Phasor), interface components (in SW/HW), required laboratory adaption system (power/signal amplification), potential hardware devices/systems, etc. A general description structure should be an outcome to unify HIL setup and experiment explanation in a general way.

1.2 Objectives and Scope

The benefits of use of HIL technologies (Controller-/Power-HIL) for power system is shown related to the rise of RI putting effort into the development of such systems.
Until now, no ‘out-of-the-box’ systems providing full hardware and software access exist. Most RIs need to invent and develop their own HIL system related to following list:
- Available budget and personal resources
- Laboratory space
- Power and voltage level
- System or component testing

All those points are similar for each HIL developer and due to need of designing and building HIL systems out of individual components, various HIL systems with different benefits and disadvantages are present nowadays.
According to the general HIL requirements, various components, common or individual obstacles of the use of HIL systems, a unify description and definition of HIL is essential for future purposes.
The scope of the proposed research is to analyze several different HIL systems in different laboratory environment, performing test under different test cases and identify similarities and differences.
The proposed bilateral exchange between two key experts in the design and conception of HIL systems is needed to perform several investigations of different setups to analyze potential components of HIL systems.
Therefore, a key expert exchange is planned, meaning, one person from Fraunhofer IEE will stay for two weeks at AIT, and later two weeks one person from AIT will stay at IEE.

1.3 Pictures

Figure 1: Pictures of the working group related to the DEF-HIL project in Vienna (AIT).

Figure 2: Picture of the working group related to the DEF-HIL project in Kassel (Fraunhofer IEE).

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

The enhancement of functional capabilities of Smart Grid technologies is challenging the nowadays studies, testing and validation methods. Currently, the capabilities of testing infrastructures and simulation tools are limited in terms of achieving fully scalable as well as complex testing and analysis. New power system architectures with new control concepts are topics of ongoing research. Various studies focus on cell based networks or even small island grids, which are controlled, decentralized via e.g. microgrid controllers.

With the advancement of real-time computation, power system testing solutions have increased significantly. Solutions as simulation-only, co-simulation, controller and power hardware-in-the-loop and pure hardware testing enhance tomorrows' testing chain (see Figure 1).
Compared to simulations-only studies of a developed controller in a holistic approach (integrating power system models, components, cyber-physical systems, grid protection schemes, etc.), the advantage of the testing chain proposed in this project consists in adding flexibility and realism to the test scenarios by, for example, replacing simulation models with real hardware. Furthermore, co-simulation platforms integrate controller schemes, weather data and real online measurements data into the real-time simulation environment providing the possibility to perform investigations that are more realistic.

The Hardware-in-the-Loop-based testing method is the next development step after the pure simulative testing approach and enables the testing of the physical controller hardware in a configuration called controller hardware-in-the-loop (CHIL).
The basic controller model developed in the framework of the European Horizon 2020 project ERIGrid (GA No. 654113) is depicted in Figure 2 and integrates controller in the defined control level. It can be seen that the basic controller model integrates different controller levels (D1-D5) and communication interfaces (L1-L4). For instances a network cell controller (D3) controls level D4, i.e. the distributed energy resource (DER) controller, and not the DER unit directly. The D4 level is, in current practice, not considered in simulation studies and CHIL testing, but essential for seamless operation.
Power hardware-in-the-loop (PHIL) setups enable testing according to the basic controller model concept described above, by including the controller levels D4 and D5. This testing method provides developers a flexible method of performing hardware and software adaptions in an early development phase.
Until now, contrary to other technologies, HIL methods for power system studies do not have a common standard. Many research infrastructures (RI) dealing with initial obstacles in the use and conception of HIL testing systems. Therefore, to provide a common methodology and to push global HIL development and research, a standardized description of HIL systems, components and procedures are essential for research and industry.

3 Results and Conclusions

3.1 Executive Summary

The document contains relevant lists of definitions, acronyms, and abbreviations and is structured in the following way. An overview related to hardware-in-the-loop (HIL) simulation is given, which is presenting a generalized scheme of HIL applications. In the following section, the hierarchical relations in HIL-simulation-based systems are defined and preliminary formulations are elaborated. In the following section, definitions are enumerated and the following categories are utilized for description—i.e., term, abbreviation, description, and remarks. The following section presents a generalized draft structure for a possible nomenclature and terminology. The topics have been structured as follows. Letter Symbols—including categories such as variables and constants, functions, operators, sets, matrix pattern indicators, subscript indicators, superscript indicators, and accents. Next, a collection of proposed abbreviations and definitions of the topic of real-time simulation and real-time simulation machines is given.

3.2 Overview of Hardware-in-the-Loop Systems

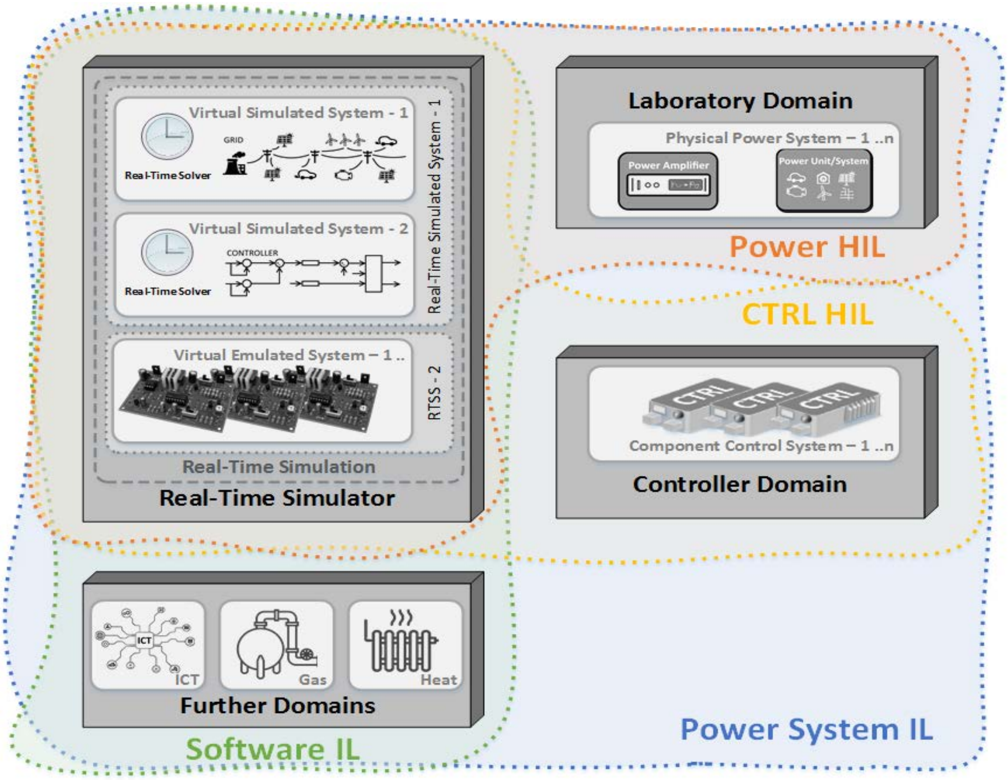

Figure 3: General Scheme of different Hardware-in-the-Loop Applications

Legend:
Software-in-the-Loop/Co-Simulation
Controller Hardware-in-the-Loop
Power Hardware-in-the-Loop
Power System in-the-Loop

The terminology “*Hardware-in-the-Loop*” contains several different application-oriented setups depending on several different investigations that the user desires to plan. Fig. 1 demonstrates a general scheme of current applications using Hardware-in-the-Loop. Since Hardware-in-the-Loop setups contain several specific elements, it is necessary to form a generic description of their dependencies and relations.

A. Relations linked on Real-Time Simulations

DefA Several Real-Time Simulation Machines combined are still called Real-Time Simulation Machine

DefA.1 A Real-Time Simulation Machine is solely digitally running Real-Time Simulations.

DefA.2 A Real-Time Simulation contains at least one or more Real-Time Simulated System(s).

DefA.3 A Real-Time Simulated System can be either a numerical/digital environment or the physical/analog environment.

DefA.3a A Virtually Emulated System contains physical (analog) elements and is inherently Real-Time Constraint. All Virtually Emulated Systems form on a Real-Time Simulated System.

DefA.3b A Virtually Simulated System contains numerical/digital equations/models and is Real-Time Constraint of it is executed by a Real-Time Solver. All Virtually Simulated Systems form on a Real-Time Simulated System.

B. Wording and relations of associated domains

DefB.1 A Power Unit or a whole Power System is called Physical Power System.

DefB.1b The Physical Power System(s) are part of the laboratory domain. Additional elements (e.g., Power Interface, connection cables, power flow signals, measurement probes) necessary for performing Hardware-in-the-Loop experiments are included in the Laboratory domain.

DefB.2 A Controller (de/centralized controller, protection devices, etc.) is called Controlled Component System.

DefB.2b The Controlled Component System(s) are part of the Controller domain. Additional elements (e.g., Controller Interface, signal amplifier, cables, and measurement probes) necessary for performing Hardware-in-the-Loop experiments are included in the Controller domain.

DefB.3 A communication unit or whole system is part of the information and communications technology (ICT) domain

DefB.4 A heat-related unit or the whole system is part of the Heat domain

DefB.5 A gas-related unit or the whole system is part of the Gas domain

C. Relations linked to Hardware-in-the-Loop

DefC.1 A combination of several Real-Time Simulation Machines/Targets (either hard/continuously or soft/discretely) is named a Software-in-the-Loop environment (or Co-Simulation).

DefC.2 An interaction between one or more Real-Time Simulation Machines and one or more Hardware Domains (e.g., laboratory and/or controller domain) is called Hardware-in-the-Loop.

DefC.3 An interaction between one or more Real-Time Simulation Machines and the Laboratory Domain is called Power Hardware-in-the-Loop.

DefC.3a A Laboratory Domain contains one or more power units or systems (power interface included) that are called Physical Power System.

DefC.4 An interaction between one or more Real-Time Simulation Machines and the Controller Domain is called Controller Hardware-in-the-Loop.

DefC.4a A Controller Domain contains one or more controller/protection devices (signal amplifier included) that are called Controlled Component System.

DefC.5 A combination of several additional physical domains (e.g., laboratory, ICT, heat, gas) is called Power System in-the-Loop.

Definition A: Real-Time Simulations

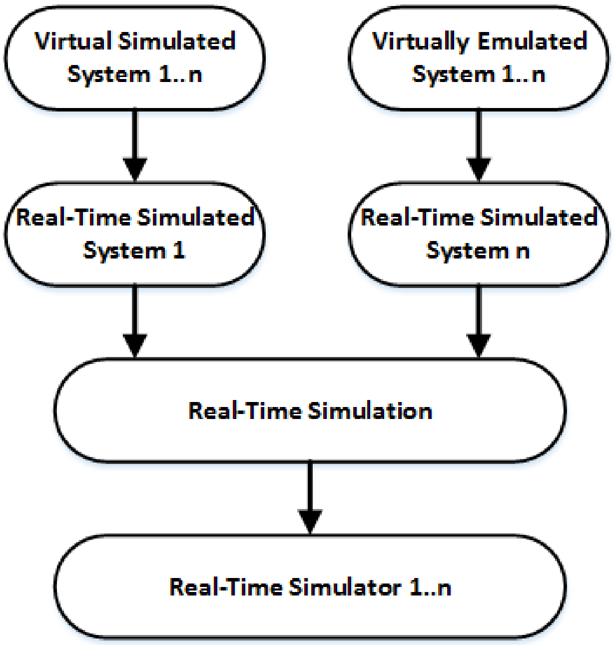

Figure 4: Hierarchical Relation of Real-Time Simulations

Definition B.1: Laboratory Domain

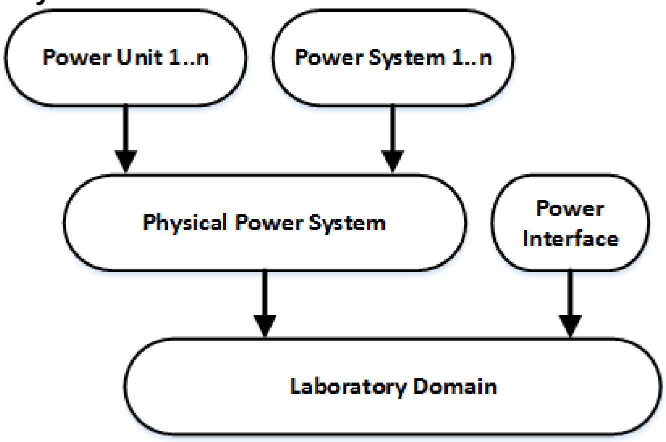

Figure 5: Hierarchical Relation of a Laboratory Domain

Definition B.2: Controller Domain

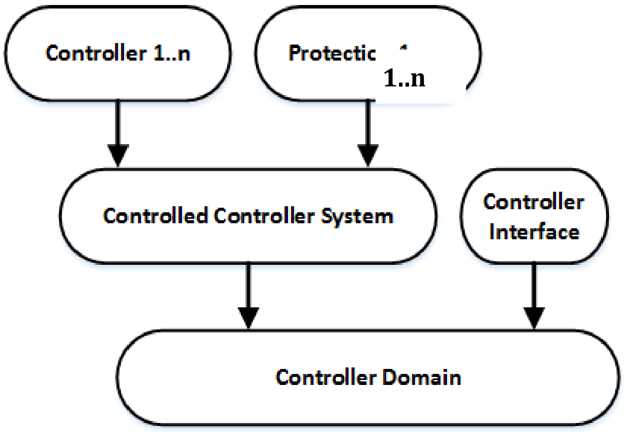

Figure 6: Hierarchical Relation of a Controller Domain

3.3 Definitions

Table 1: Definitions related to real-time HIL simulation systems

Term	Abb.	Description	Remarks
Simulation	-	Simulation is the process of imitating the operation of a real-world systems. A model that behaves or operates like a given system when provided a set of controlled inputs	Source: [1]
Emulation	-	Emulation is the process of imitating the behavior of one or several hardware pieces with another hardware piece (Real-Time Simulator). A model that accepts the same inputs and produces the same outputs as a given system	In terms of Hardware Emulation [1]
Real-Time	RT	Real-Time in terms of simulation means that continuous calculation and the execution of numerical model equations are exactly performed at the same time as a wall clock.	
(Digital) Real-Time Simulation	RTS	A simulation which is solely digitally executed in a real-time way on a Real-Time Simulation Machine.	Current another naming of the RTS: - Digital RTS - DRTS
Real-Time Simulated System	RTSS	An RTSS is a simulated system/model, which is executed on a Real-Time Simulation Machine. The RTSS can be regarded as either numerical model equations or as analog elements emulation of a power system; one Real-Time Simulation contains at least one system simulated in a real-time fashion.	THE RTSS for digital, numerical execution is called VSS. - Current naming of RTSS: - ROS /Rest of System
Real-Time Simulation Machine	RTSM	An RTSM is a physical computational system, which is able to solely digitally perform the execution of numerical model equations in a real time.	Current another naming of the RTSM: - Digital RTS - Real-Time Target/Machine
Hardware-In-the-Loop	HIL	A test setup that combines a real-time simulated system with a physical hardware component or system, where interfaces with physical and simulated systems enabling closed loop interactions.	HIL requires a virtual domain (see VSS) connected to any additional domain (e.g., CCS, PPS, MMS, …)
Software-In-the-Loop	SIL	A test setup that combines at least two different software tools executed on one or more computational systems. Co-Simulation is meant by Software-in-the-loop (SIL)	It does not require real-time capability and can be performed in a discrete event-based manner
Controller Hardware-In-the-Loop	CHIL	A hardware-in-the-loop setup where the sensors and actuators of a physical controller are interfaced with a real-time simulation.	

Power Hardware-In-the-Loop	PHIL	A hardware-in-the-loop setup, where at least one of the bi-directional interfaces of a setup exchanges power with real, physical power hardware.	
Phasor Power Hardware-In-the-Loop	PPHIL	An approach (which is not addressing very fast analysis) where the simulation is performed by use of Phasor signals. A conversion to sinusoidal signal is required.	The current naming of PPHIL: - QsPHIL / Quasi-static PHIL
Power System In-the-Loop	PSIL	A hardware-in-the-loop setup where more than two domains interface each other in order to perform holistic experiments, e.g., a connection between the VSS, CCS, and PPS.	
Interface Algorithm	IA	An interface algorithm in the context of HIL is a method of linking a Real-Time Simulation Machine to a Hardware System (eg. Physical Power System, Controlled Controller System, …). The IA can contain software and hardware elements.	
Power Interface	PI	A Power Interface is required for PHIL tests and contains parts of Real-Time Simulated System and the laboratory domain (e.g., Interface Algorithm, Power Amplifier)	
Power Amplifier	PA	Power amplifiers receive reference signals that reflect voltages and/or currents of simulated subsystems. The amplifier transforms the reference signals to voltages and/or currents at its power terminals to interact with the EUT.	
Controller Signal Interface	CSI	A Controller Signal Interface is required for CHIL test and contains parts of the Real-Time Simulated System and the controller domain (e.g., simulation adaption, signal amplifier)	
Domain		An area of knowledge or activity characterized by a set of concepts and terminology understood by practitioners in that area—Source: IEC 62559 [2] (from ISO/IEC 19501:2005)	In a system configuration, domains represent a categorization of the connections between systems; a domain can be divided into sub-domains; domains interface with other domains via components.
Sub-domain		An internal domain that is a part of a primary domain with more particular common concepts and terminology.	
System Under Test	SUT	A (specific) system configuration that includes all relevant properties, interactions, and behaviors (for the closed-loop system with input/output and electrical	Part of Test Case's specifications.

		coupling), that are required for evaluating an object under investigation (OUI) as specified by the test criteria.	
Domain Under Investigation	DUI	A DUI identifies the relevant domains of test parameters and connectivity.	Part of Test Case's specifications.
Function(s) Under Test	FUT	The functions relevant to the operation of the system under test, as referenced by use cases.	The reference would typically be to a use case document; a preliminary identification of functions by function names and placement in a UC-GSC is typically acceptable in a Test Case.
Function(s) Under Investigation	FUI	A referenced specification of a function, which is realized (operationalized) by the object under investigation.	The FUL is a subset of the FuT.
Object(s) Under Investigation	OUI	An object/component(s) that is to be characterized, verified or validated by a test.	
Component		A constituent part of a system that cannot be divided into smaller parts without losing its particular function for the purpose of investigation.	(Based on IEC 60050 (151) [3], replacing "device" with "system"). In a system configuration, components cannot further be divided; connections are established between components.
Design of Experiments	DEE	A systematic method to determine the relationship between factors affecting a process and the output of that process.	Methodology applicable to the design and the evaluation of experiments. Refers to a mathematical framework. Related terms: (controllable, uncontrollable) Input Parameter, Output Parameter, Target Metric, Test System.
Scenario		A compilation of a System Configuration, use cases, and holistic test cases in a shared context.	
System Configuration	SC	An assembly of (sub-)systems, components, connections, domains, and attributes. Several forms of system configuration are distinguished.	System configuration or Systems configuration are used interchangeably. As a descriptive method, it provides a standardized way of representing systems that can be also multi-domain; related terms: Do-

			main, Component and System, Connectivity, Constraints, and Attributes.
Test Case	TC	A test case is a set of conditions under which a test can determine whether or how well a system, component or one of its aspects is working given its expected function.	
Holistic Testing		A process and methodology for the testing of a system or component (regarded as a distinct object) within its functional context. This context, or the environment, is the encompassing and surrounding systems and subsystems stretching across domains such as electric power and ICT.	
Interface		1. A shared boundary between two functional units, defined by various characteristics pertaining to the functions, physical signal exchanges, and other characteristics. 2. A hardware or software component that connects two or more other components for the purpose of passing information from one to the other.	Source: 1. ISO/IEC 2382-1:1993 [4], 2. (ISO-IEC-IEEE 24765.2010) [5]
Virtually Simulated System	VSS	A VSS represents a separate area that is simulated or calculated on a virtual machine (e.g., RTS). Several VSS can be combined (e.g., to power system LV/MV, control algorithms, etc.)	
Virtually Emulated System	VES	A VES represents a separate area that is emulated on a machine (e.g., an RTS). Several VESs can be combined in order to form a bigger system (e.g., a power system, power electronic converter, etc.)	
Physical Power System	PPS	A PPS represents the whole domain, where power flow exchange occurs. It contains the power amplifier, as well as power system components. An HIL which is including the RTS and the PPS is called PHIL.	
Component Control System	CCS	A CCS represents the whole domain, where low-level signals are exchanged. It contains the signals amplifier, as well as controller and protection devices. An HIL which is the RTS and the CCS is called CHIL.	
Multi-Signal System	MSS	An MSS represents the whole domain (where the signal exchange between components occurs) which is not part of either the CCS or the PPS. It contains offline data (e.g., databases, Profile da-	

		ta, etc.) and online data (e.g., PMU, smart metering, weather data, etc.)	
Protocol Controlled System	PCS	A PCS represents the whole domain, where digital signals are exchanged. It contains interfaces between different parts, e.g., grid operation, virtual power plants, central control solution, etc. by making use of protocol signals (e.g., IEC61850 [6], EtherCAT, C37.118, etc.)	
Rest-of-System	ROS	Depending on the main OUI of the HIL test, which needs to be defined in the Test Specification, the Rest-of-System contains all other systems that are needed to perform the test is call Rest-of-System. This can be either the Hardware System under Test or the Software System under Test and can include additional domains.	The ROS is a flexible term that needs to be definied in the Test Spezification, since it does not suit only to the simulated system (like in general) but can also represent other domains.

3.4 Letter Symbols

a) Variables and Constants

$\boldsymbol{A}$	system matrix
A	coefficient
a	counter
$\boldsymbol{B}$	linear system vector
B	coefficient
b	coefficient
BW	bandwidth
$\boldsymbol{C}$	system matrix
C	capacitance
C'	capacitance per unit length
c	coefficient
$\cos\varphi$	power factor
D	denominator polynomial
d	polynomial degree
f	frequency
f_c	cut-off frequency
G	electric conductance
I	instantaneous current
I_A	current on the hardware side
I_D	current on the software side
L	inductance
M	number of MIMO systems
$\boldsymbol{N}$	network matrix
n	counter
P	active power
Q	reactive power
R	resistance
R_1	software resistance
R_2	hardware resistance
R'	resistance per unit length
$\boldsymbol{S}$	linear system matrix
S	apparent power
$\boldsymbol{T}_D$	time delay transfer matrix
$\boldsymbol{T}_C$	current measurement transfer matrix
$\boldsymbol{T}_V$	voltage measurement transfer matrix
T_C	current measurement transfer function
T_V	voltage measurement transfer function
t	time

U	instantaneous voltage
U_{A}	voltage on the hardware side
U_{D}	voltage on the software side
U_{S}	reference voltage of ac grid network ***N***
X	reactance
X'	reactance per unit length
x	state variable
y	output variable
$\boldsymbol{Z}$	impedance matrix
$\boldsymbol{Z}_1$	software impedance matrix
$\boldsymbol{Z}_2$	hardware impedance matrix
Z	impedance
Z_1	software impedance
Z_2	hardware impedance
α	coefficient
ε	error
μ	counter
ξ	generic variable
τ_{e}	execution time
τ_{D}	time delay
τ_{S}	sample rate of subsystem
ω	angular frequency
ω_c	cut-off frequency

b) Functions

$\boldsymbol{E}$	error matrix
E	error function
$\boldsymbol{F}_{\mathrm{CL}}$	closed-loop transfer matrix
F_{CL}	closed-loop transfer function
$\boldsymbol{F}_{\mathrm{O}}$	open-loop transfer matrix
F_{O}	open-loop transfer function
Im	imaginary part of
L	Laplace transform
$\max$	maximum of
$\min$	minimum of
Re	real part of
$\boldsymbol{T}$	transfer matrix
T	transfer function

c) Operators

d	differential sign
j	imaginary unit
s	operator variable in the Laplace domain
Δ	sign of difference calculus function
$\forall$	for all
$\in$	is element of

d) Sets

C	set of complex numbers
N	set of natural numbers
R	set of real numbers

e) Matrix Pattern Indicators

F	fill-in element
O	zero element
x	nonzero element

f) Subscript Indicators

A	analog
ac	alternating current
C	capacitor
CA	current-type amplification
D	digital
dc	direct current
DP	damping
den	denominator
dyn	dynamic
F	filter
FB	feedback
FW	feedforward
I	current
id	ideal
init	initial
L	inductor
LC	inductive-capacitive
LP	low pass
L1, L2, L3	phase 1, phase 2, phase 3
lim	limit
MAX	maximum
MIN	minimum

4 Open Issues and Suggestions for Improvements

The work on definitions and related topics in the domain of real-time simulation could be started and the working progress has been successful. However, several issues may be modified, redefined and restructured in the future. The topic itself is very scientific and requires in-depth research on literature, standards, and publications. Therefore, open issues are given per se, as definitions and related items may change or there may be the need to start further works on this.
A follow-up project is already in planning, in which the work on definitions for real-time HIL simulation will be resumed. If funding and time management allows, this follow-up project is targeted for 2019 or eventually for 2020.

5 Dissemination Planning

The work is planned to be published on following conferences:

- IEEE COMPENG, "Workshop on Complexity in Engineering", Oct 10-12, 2018, Florence, Italy
- IRED, "8th International Conference on Integration of Renewable and Distributed Energy Resources", Oct 16-19, 2018, Vienna, Austria

The following publications have been accepted and presented at the conferences:

- 1st Paper and Poster: Title: "Advanced Testing Chain Supporting the Validation of Smart Grid Systems and Technologies" Authors: Brandl, Ron; Strauss-Mincu, Diana; Montoya, Juan, Georg Lauss;
- 2nd Paper: Title: "Power Hardware-in-the-Loop Test Bench for the Integration of Renewable and Distributed Energy Resources", Authors: Brandl, Ron; Strauss-Mincu, Diana; Montoya, Juan, Georg Lauss;

In addition, the work is intended to be distributed to the IEEE WG P2204 team. It is intended for serving as an input for the Chapter Lead in order to establish input on Chapter 3 and other Chapters in the document "*P2004™/D1 Draft Recommended Practice for Hardware-in-the-Loop (HIL) Simulation Based Testing of Electric Power Apparatus and Controls*"

6 References

[1] *IEEE Dictionary*.
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[9] *https://ieeexplore.ieee.org/xpls/dictionary.jsp?stdDict=browse_keyword&pageNumber=1&def_term=hard+real-time&def_id=&stdDictionary_tarid=&stdDictionary_tarn=&stdDictionary_scn=Aerospace+Electronics&nav*=
[10] *http://www.electropedia.org/iev/iev.nsf/display?openform&ievref=351-54-06*
[11] *http://www.electropedia.org/iev/iev.nsf/display?openform&ievref=351-54-09*

7 Annex

7.1 List of Figures

Figure 1: Pictures of the working group related to the DEF-HIL project in Vienna (AIT). 5
Figure 2: Picture of the working group related to the DEF-HIL project in Kassel (Fraunhofer IEE). . 5
Figure 3: General Scheme of different Hardware-in-the-Loop Applications 7
Figure 4: Hierarchical Relation of Real-Time Simulations.. 9
Figure 5: Hierarchical Relation of a Laboratory Domain 9
Figure 6: Hierarchical Relation of a Controller Domain.. 9

7.2 List of Tables

Table 1: Definitions related to real-time HIL simulation systems... 10