Elektrotechnik & Informationstechnik (2014) 131/8: 378–385. DOI 10.1007/s00502-014-0231-z

DERri Common Reference Model for Distributed Energy Resources—modeling scheme, reference implementations and validation of results

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One main issue in current research activities regarding power distribution networks is the grid operation with a high penetration of Distributed Energy Resources (DER), particularly renewable sources from wind, solar or biomass, characterized by intermittent and only partially predictable production. In fact, in order to keep power quality and grid stability in presence of great amount of variable production from renewable sources, a large effort is necessary to control the distributed power generators and/or the energy demand (i.e., loads and storages).

The exchange and reuse of DER dynamic simulation models between different users is very complicated today. In fact, heterogeneous models are used for representing component models, which are normally described for a particular simulation environment, contain different levels of details and are difficult to compare.

In order to improve sharing of simulation models the project partners of the European DERri project have developed a standardized modeling schema and exchange format called Common Reference Model (CRM). This approach and specification is suited to study the DER-grid interactions, in dynamic conditions, under various simulation scenarios and time horizons.

Within this work, rules and procedures for modeling DER components in simulation environments in an implementation independent representation based on the CRM specification are proposed. In addition, some reference implementations are presented which are validated by comparing simulation results in different platforms.

Keywords: simulation; real-time simulation; portability; exchangeability; data model; Smart Grids; Common Reference Model; Distributed Energy Resources

Published online November 7, 2014
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1. Introduction and motivation

One main issue in current research activities regarding power distribution networks is the grid operation with a high penetration of Distributed Energy Resources (DER), particularly Renewable Energy Sources (RES) from wind, solar or biomass, characterized by intermittent and only partially predictable production. In fact, in order to keep power quality and grid stability in presence of great amount of variable production from renewable sources, a large effort is necessary to control the distributed power generators and/or the energy demand (i.e., loads and storages).

Dynamic simulations play an important in studying new grid control strategies and improving control strategies used in DER components [1]. They allow a better understanding of the behavior of each DER device interfaced to the power grid and the complex interactions among different DERs as well as other components (e.g., loads, storages, regulators) connected to the same grid.

During the past years advanced validation and testing methods are in the focus of various research groups. A promising approach is related to real-time simulation and Hardware-in-the-Loop (HIL) experiments. Especially, the so-called Power-Hardware-in-the-Loop (PHIL) method has a big potential to become a powerful validation technology for evaluating and testing the integration of DER devices into active power distribution networks in a near real-world scenario [2, 9]. In order to perform PHIL-related tests a powerful Real-time Simulation System (RTS) together with a power interface for the amplification of low-power signals (i.e., typically in the range of a few volts or amperes) to the power level of the DER components (e.g., 230 V/400 V for low-voltage grids) and proper measurement equipment is necessary. While a big focus is on the improvements of the RTS and the used PHIL algorithms, the modeling of DER components in real-time environments is still an open research issue [3].

In the European DERri project [4, 5] an approach for harmonizing the modeling of DER components—the so-called Common Reference Model (CRM)—has been introduced. The CRM contains a set of modeling rules for real-time HIL simulations and experiments. In parallel, this common model provides an exchange format for models of DER devices [6–8]. The purpose of the CRM specification is to describe DER models in a representation independent from sim-

Paper submitted for the CIGRE Session 2014, SC C6, Paris, France, August 24–29, 2014.

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ulation environments, languages and tools, so it is simpler to facilitate the exchange and sharing among different users. This allows an easier exchange and reuse of the DER models between the DERri partners or other users.

The main goal of this contribution is to discuss the usage of the CRM specification for modeling DER components applied in real-time simulations and HIL experiments. A focus of this publication is on the reference implementation and validation of selected DER models. It is a continuation of the ideas presented in [7].

The rest of this paper is organized as follows: Sect. 2 gives a brief overview of the CRM specification and its main elements. It provides a categorization according to the type of the DER components as well as on the different simulation objectives. A reference scheme for the collection of power grid interfaced DER devices and its CRM models are presented in Sect. 3 whereas some selected reference implementations are discussed in Sect. 4. Finally, this paper is concluded with the main findings in Sect. 5.

2. Common Reference Model for Distributed Energy Resources

2.1 User defined model vs. common/standard model

Today's practice is to apply user defined DER models in power system related simulation studies since such component models are only partly available in commercial but also in free/open source simulators [7]. Normally, each simulation environment offers its library of elementary simulation blocks and in front of new needs/requirements the user can build a new model using such elementary blocks and freely combining them to model DER components. This leads to different representations of DER components in power system simulators and makes the exchange between different users and simulators more difficult. A standardized way of DER model representation is therefore required (Fig. 1).

User defined model

- Described by a network of simulation blocks
- Define the connections between the blocks
- Documentation of each block
- Define the parameters/coefficients of the blocks

Common (standard) model

- Same model used for many DERs
- Model components always connected the same way
- Always use the same parameter definition
- Well documented in the public domain

Fig. 1. User defined vs. common/standardized DER models

2.2 Main elements of the Common Reference Model

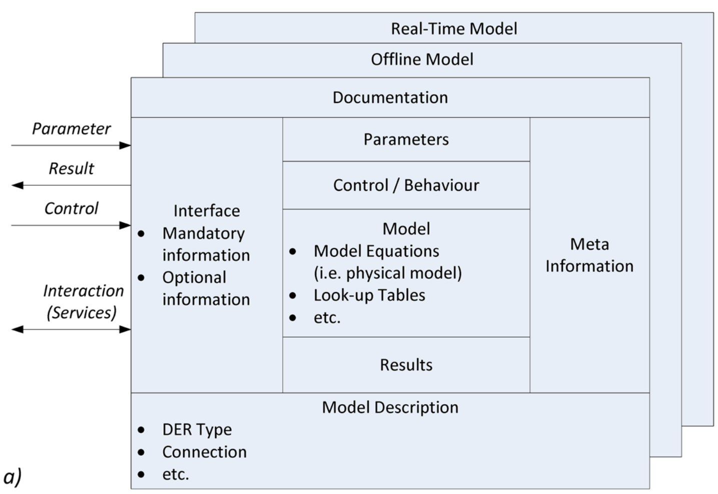
As stated above a standardized way and exchange format for DER components used in power system analysis, incl. real-time simulation and HIL experiments, would be necessary to allow a much simpler exchange of model data between the partners and other research groups.

In order to overcome this limitation the DERri consortium has therefore proposed the so-called Common Reference Model (CRM) for DER devices with the goal to improve the portability and exchangeability of DER models for different simulation experiments, especially for real-time simulations and HIL experiments [6–8]. Figure 2 provides an overview of the CRM idea and its main elements.

2.3 Categorization of DER simulation models

Due to the different nature and usage of DER components, as well as different simulation cases a categorization is suggested. Therefore, the DERs simulation models will be classified using the following two main categories: (i) the first related to the DER equipment represented by the model (i.e., DER type), and (ii) the second related to the goals and objectives of the simulations and also the time horizon of models (i.e., simulation type/objective). In general, three main simulation types can be specified. The categorization used in this work is based upon the magnitude of significant dynamic time constants of the modeled device and on the simulation time scale (i.e., the simulated time span), even though the subdivision is not sharp-cut (i.e., different simulation types can have overlapping significant time constants). Each simulation type can be further subdivided into "sub-types" in function of the phenomena of interest for the simulation. Again, the subdivision is based upon the time constants of the represented phenomena and some overlaps exist between subcategories. For the scope of this work only the three main presented categories will be used:

- *Fast transients*: The fast transients simulations are characterized by maximum time constants in the order of milliseconds. These simulations are used to analyze internal behavior of DERs in response to grid events or network transient behavior due to fault



a)

Element Name	*Element Description*
Interface	Interface for the interaction with other models and systems
Parameters	Model parameters and definitions
Control/Behaviour	Description of the model behaviour
Model	Description of the model equations (depend on the simulation objectives)
Results	Description of model results for evaluation of the reference implementation
Model Description	Description of the scope of the model
Meta Information	Provision of model meta information
Documentation	Model documentation

b)

Fig. 2. Overview of the Common Reference Model for DER devices [7]: (a) overview, (b) elements

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or other electromagnetics phenomena. For this reason this simulation type can be also referred as "electromagnetic simulation". Typical simulation time constants range from microseconds (μs) to few seconds (s).

- *Slow dynamics*: The slow dynamics simulations are characterized by minimum time constants in the order of seconds. These simulations are used to analyze network transients due to change in set points of generators taking into account their dynamics or to analyze operation of grid control and energy management algorithms. This simulation type can be also referred as "electromechanical simulation". Typical simulation time constants range from seconds (s) to tens of minutes (min).
- *Quasi-dynamic*: Typically, power flow simulations are performed with static models. Also phenomena characterized by very long time constants, such as load profile and power production changes, can be simulated by a succession of power flow simulations, one for each working point. The term quasi-dynamic is referred to this last simulation type. Typical simulation time constants range from tens of seconds to days.

3. CRM modeling scheme for DERs

The goal of this work is to enhance the possibility of exchanging and sharing DER dynamic simulation models descriptions. Starting from existing user defined models used by the DERri project partners a set of CRM simulation models for DERs interfaced to the power grid with inverters has been defined. These common models follow a categorization criteria based on time horizon of simulations and on simulation goals as mentioned above. In fact, the dynamic phenomena that the models should reproduce depend not only on the time scale of interest but also on the purpose of the simulation and expected use of simulation results (i.e., simulation objectives transient, slow dynamics and quasi-dynamic).

Table 1. Categorization of CRMs according to different simulation objectives

Simulation type	Time scale (order of)	Proposed DER CRM
Fast transients	100 μs–100/1000 ms	FT
Slow dynamics	100 ms–1 s	*SD*-1s
	1 s–1 min	*SD*-1m
	1 s–1 hour	*SD*-1h
Quasi-dynamic	10 s–1 day	QD

For transient and quasi-dynamic simulations the level of details of the model to use is mainly due to the nature and the goals of the simulation for this only one time scale is proposed for each of these simulation types. In slow dynamic simulations the model complexity is indeed driven also by the simulation time horizon and then three different time scales are suggested for this simulation type. Table 1 provides an overview of the used categorization which corresponds to the definition of a total of five CRMs associated with simulation type and time scale.

In the following sections the description of each CRM defined in Table 1 is resumed using a reference block scheme for each of them.

3.1 Fast transients CRM (FT)

For fast transients simulation the CRM have to be detailed and specialized also depending on modeled DER type. Figure 3 and Table 2 shows the defined CRM.

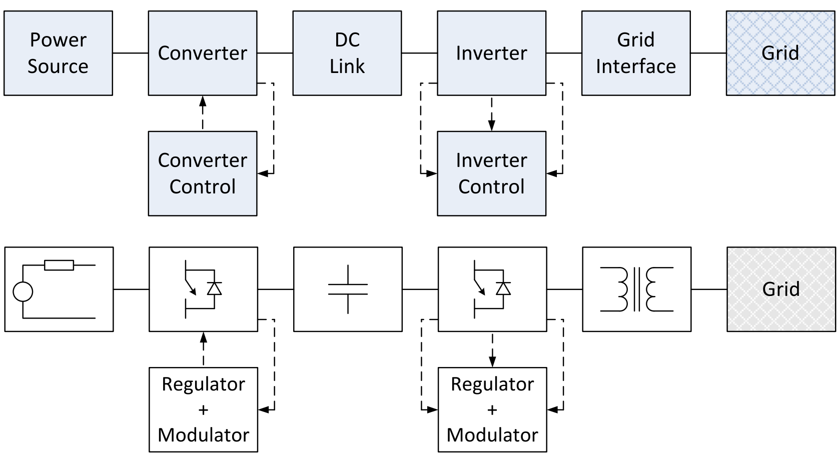

Fig. 3. Block scheme for fast transients CRM

Table 2. Elements of the fast transients CRM

Element	Model and parameters
Power Source	Thevenin or Norton Equivalent Circuit, specifying equivalent impedance's value
Converter	Switching model of the converter with its filter
Converter Control	Regulator (typology & control algorithm) and its parameters, modulation technique
DC Link	Capacitor
Inverter	Switching model of the inverter with its filter
Inverter Control	Regulator (typology & control algorithm) and its parameters, modulation technique
Grid Interface	Transformer physical model, specifying its parameters
Grid	Line & load equivalent, specifying their parameters, grid protections

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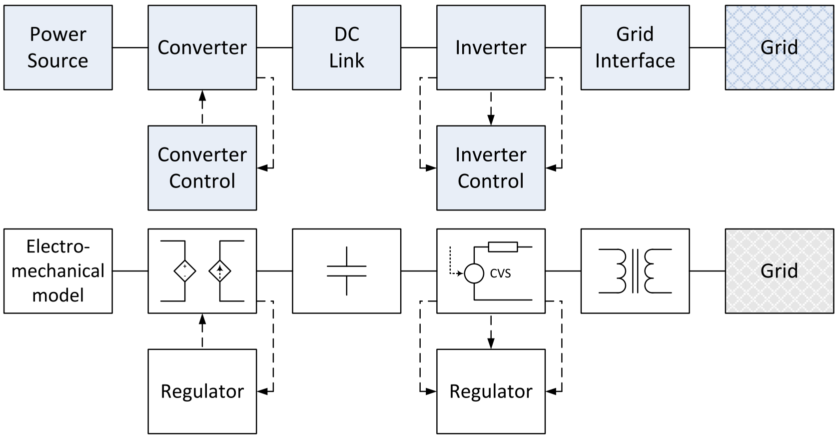

Fig. 4. Block scheme for slow dynamics CRM (t < seconds)

Table 3. Slow dynamics CRM (t < seconds)

Element	Model and parameters
Power Source	Electro-mechanical model, specifying its parameters
Converter	Average model of the converter with its filter
Converter Control	Regulator (typology & control algorithm) and its parameters
DC Link	Capacitor
Inverter	Controlled voltage source, with series reactance
Inverter Control	Regulator (typology & control algorithm) and its parameters
Grid Interface	Transformer physical model, specifying its parameters
Grid	Line & load equivalent, specifying their parameters

3.2 Slow dynamics CRM (SD)

For slow dynamics CRMs different block schemes were defined depending mainly on the simulation time horizon. It may be observed that this sub-classification of time scale is not rigid. As general remark, a model useful for representation of short time constants phenomena may also be used for longer time constants.

As shown in the following schemes the problem is that the smaller the time constants result usually in a higher model complexity. The more appropriate CRM scheme for a simulation goal has to be chosen taking into account also model complexity and computational burden for the simulator. For dynamics below one second time constant the CRM have to be detailed and specialized also depending on the modeled DER type. For slowest dynamics simulations the CRM may be generalized and also considered independent of the specific power source (PV array, wind generator, etc.).

- *CRM SD-1s*: Time scale from hundreds ms to seconds (Fig. 4, Table 3).
- *CRM SD-1m*: Time scale from seconds to minutes (Fig. 5, Table 4).
- *CRM SD-1h*: Time scale from minutes to hours (Fig. 6. Table 5).

3.3 Quasi-dynamic CRM (QD)

For quasi-dynamics simulations the CRM may be generalized and considered independent of the specific power source (PV array, wind generator, storage devices, etc.) as shown in Fig. 7 and Table 6. Due to its computational efficiency [10] the approach enables detailed modeling of the grid with all of its nodes.

4. Reference implementations and validation of results

The main goal in definition of CRMs was to obtain dynamic models of DERs which are open and independent from the software environment that will be used to perform simulations. The availability of a CRM for a specific DER allows different users to easily exchange and compare their models improving the reusability of already tested models. In order to validate the CRM specification as well as to setup a CRM model library reference implementations have been made. In the following sections the applied working method as well as some selected implementations in specific simulation languages is discussed and the results are compared.

4.1 Working method

In order to validate CRMs for a DER device the model is applied in real simulation test cases. The validation procedure is described in the following steps:

1. The appropriate CRM is selected depending on the simulation type and the time horizon of the simulation to be performed and the DER model is described in this open format. Also other components involved in the simulation test case are described in this format.
2. Starting from this open model description for DERs in a simulation test case, the models for the power grid and the involved devices are implemented in different simulation environments.
3. At this point it is verified that all CRMs contain all the necessary information to build the model in the selected simulation environment.
4. A set of common simulation outputs for the test case is then established and the simulation is run using different simulation software.
5. The simulation outputs obtained from the different environments are compared.

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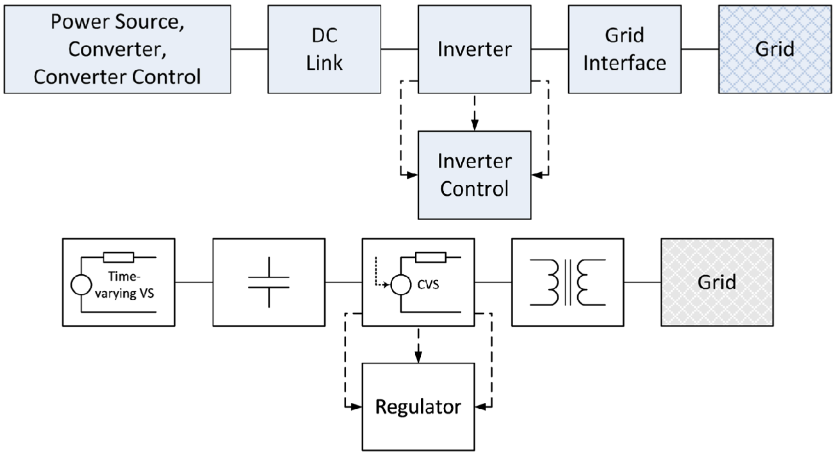

Fig. 5. Block scheme for slow dynamics CRM (seconds < *t* < minutes)

Table 4. Slow dynamics CRM (seconds < *t* < minutes)

Element	Model and parameters
Power Source	Time-varying voltage/current source
Converter	
Converter Control	
DC Link	Capacitor
Inverter	Controlled voltage source, with series reactance
Inverter Control	Regulator (typology & control algorithm) and its parameters
Grid Interface	Transformer physical model, specifying its parameters
Grid	Line & load equivalent, specifying their parameters

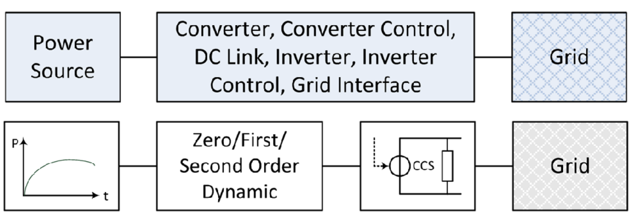

Fig. 6. Block scheme for slow dynamics CRM (minutes < *t* < hours)

Table 5. Slow dynamics CRM (minutes < *t* < hours)

Element	Model and parameters
Power Source	Power production profile
Converter	Controlled current generator (even without dynamics)
Converter Control	
DC Link	
Inverter	
Inverter Control	
Grid Interface	
Grid	Line & load equivalent, specifying their parameters

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6. Finally, it is assessed if the same or similar results are obtained from the reference implementations. If the procedure is successful the tested CRM model is validated as mean to represent the dynamic behavior of DERs in a format independent from simulation environments and tools.

4.2 Implemented test cases

The validation procedure for testing CRM models described previously has been proven in DERri project consortium defining a set of specific CRMs for DERs and simulation test cases and collaborating together with the defined working method. Some partners proposed CRM models and test cases that have been distributed and simulated by other partners in different simulation environments. The following Table 7 resume the work that has been done.

The results of the fast transient simulation test case will be presented in this paper. In Fig. 8 a simplified scheme of the power distribution system with a PV generator is shown where all elements have been modeled using the CRM specification introduced in Sect. 2. Moreover, the DER device (i.e., the PV generator with the inverter system) has been modeled according to the scheme proposed above in Sect. 3.1.

The CRM specification of this test case has then be used as basis to implement the model in two different simulators, ATPDraw and Matlab/Simulink. Figures. 9 and 10 show the results obtained from both simulation environments during a phase fault.

Comparing the results of the grid connected PV inverter CRM example implemented in the ATPDraw and the Matlab/Simulink (i.e., SimPowerSystems toolbox) simulation environments, it turned out that both models can be used for the evaluation of the interaction of the inverter with the grid. The main difference is the behavior of the inverter currents during the voltage dip, which in the ATPDraw model rise, while in the Matlab/Simulink model decrease. From theoretical considerations and from the adopted control algorithm, the inverter currents should increase during the voltage dip, in order to maintain constant the DC link voltage. An analysis of the two models shows that, even though every parameter in the two simulation environment has the same value, the DC link voltage behaviors are different, resulting in quite different responses of the PI regulators within the control of the inverter. These differences can be probably related to calculation methods (i.e. solvers), tolerances and other simulator parameters that can differ in either simulation environments or different realizations of base simulation elements. This issue deserves further investigations, which are beyond the scope of this paper.

Table 6. Quasi-dynamics CRM

Element	Model and parameters
Power Source	Power production profile
Load	Power consumption profile
Converter	(P, V) or (P, Q) node, specifying DER's capability
Converter Control	
DC Link	
Inverter	
Inverter Control	
Grid Interface	
Grid	Line equivalent, specifying their parameters

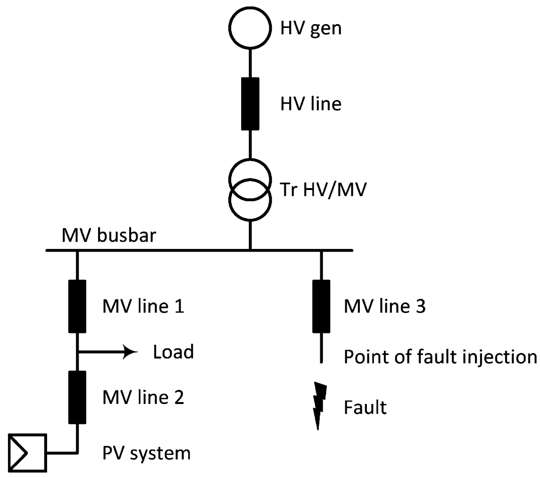

Fig. 8. Simplified scheme of the system simulated in the test case

5. Conclusions

In this paper a modeling approach for the simulation language/tool independent representation of DER components has been presented. The main aim of this work was the improvement of the

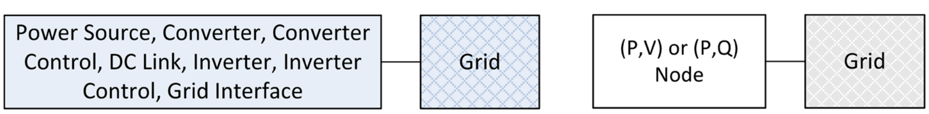

Fig. 7. Block scheme for quasi-dynamics CRM

Table 7. Test case for CRM validation and used simulation tools

Simulation type	Title	Simulation tool
Fast transient	PV generator response to voltage dips	ATP Draw Matlab/Simulink
Slow dynamics	Wind Generators (PMSG)	Matlab/Simulink ATP Draw
	Wind Generators (DFIG)	Matlab/Simulink ATP Draw
Quasi-dynamic	LV distribution network with DG	STATUS DIgSILENT

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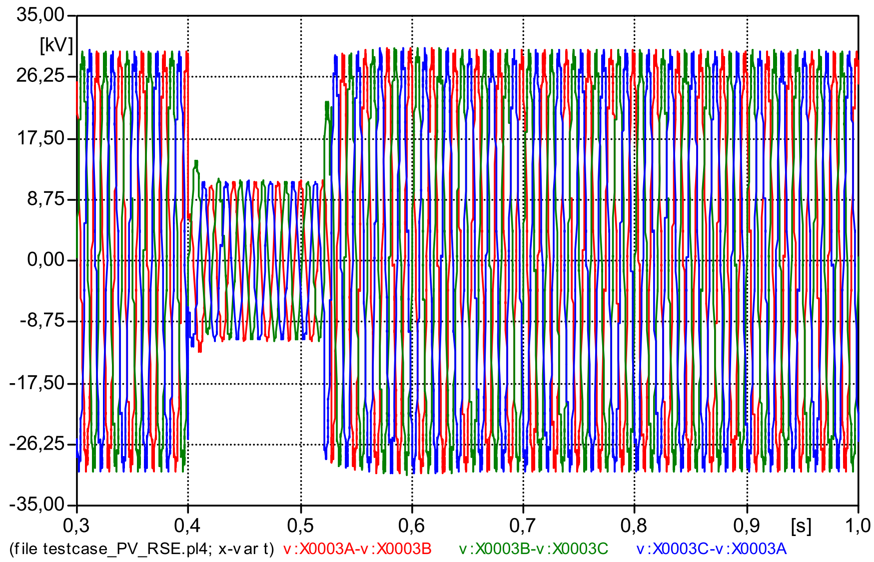

Fig. 9. Line to line voltage at the Point of Common Coupling simulated in ATPDraw

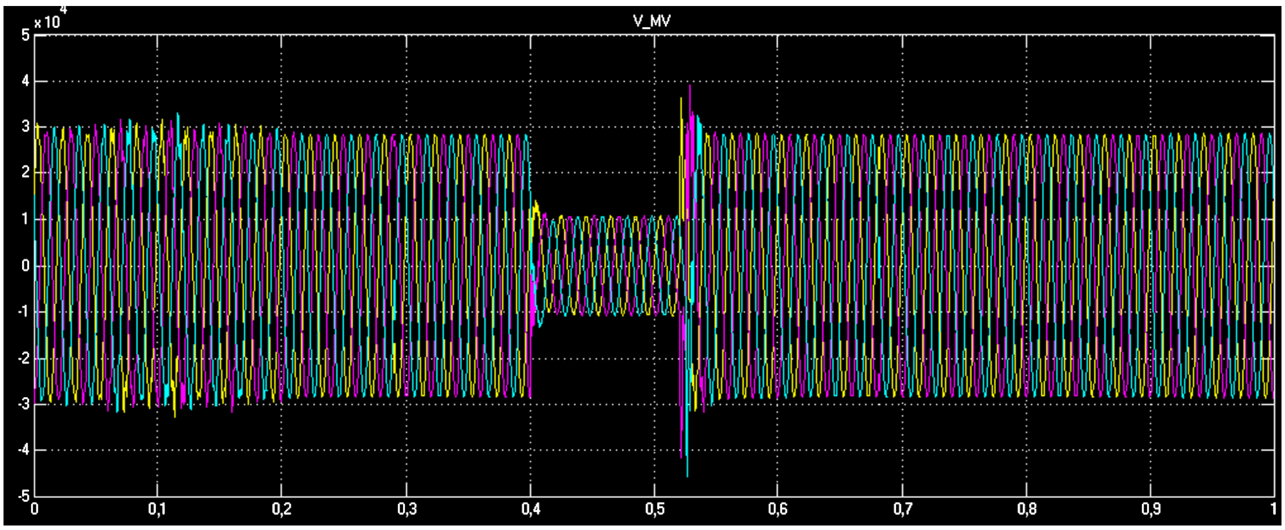

Fig. 10. Line to line voltage at the Point of Common Coupling simulated in Matlab/Simulink

portability and exchangeability of DER model data for simulation experiments, especially in the real-time domain.

The core element of this approach is based on the definition of a Common Reference Model for DER devices. This information technology representation contains an interface definition, the physical/mathematical model for the DER device, as well as model description and meta-information as well as some documentation data. An important aspect of the CRM definition is its implementation/simulation platform independent format and the fact that multiple types of a DER device model for different simulation purposes are possible.

Some reference implementations of selected DER models, supporting different simulation types in different simulation environments, have been made. It turned out that the CRM specification provides a good basis for the definition of common DER models and can be used to derive simulation tools specific implementations.

The comparisons of simulation results for some test cases pointed out that the use of CRMs doesn't always guarantee identical simulation results in different simulation environments due to the fact that the simulators may have different approaches on how the model is calculated. Nevertheless, this simulation-based validation work has shown its usefulness and validates the CRM specification as a very useful tool that enables DER models interchange and facilitates the reuse of already tested models. The implementation of a model in another simulation environment was eased, allowing a massively reduced effort in time for this work.

Acknowledgement

The work leading to this approach received funding from the European Community's Seventh Framework Program (FP7/2007–2013) under grant agreement No. 228449. Further information is available at the website: www.der-ri.net.

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