Calibrating a VSC-HVDC Model for Dynamic Simulations using RaPId and EMTP Simulation Data

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***Abstract*— High Voltage Direct Current (HVDC) interconnections have seen an increased rate of deployment, in particular to exploit distant renewable energy sources. In order to design and understand their behavior, including their effect on the overall network, different computer tools are used for modeling and simulation of the HVDC model. This approach results in several challenges in modeling and simulation consistency, particularly for HVDC systems. To address some of these issues the standardized modeling language Modelica is used in this paper to model a VSC (Voltage Source Converter) HVDC and its high-level controllers, for phasor-time domain studies. The use of Modelica-tools that support the FMI standard for model exchange allows to utilize the model in different environments. In this work, the FMI standard is used to import the VSC-HVDC model into the RaPId toolbox environment, allowing to calibrate the VSC-HVDC phasor time-domain model against reference waveform generated from its corresponding EMTP-RV model. Model calibration is carried out through different parameter identification methodologies investigated in the paper. The calibration approach and the RaPId Toolbox used to implement it can be of broader interest for researchers involved in power system model validation, particularly those working with field measurements.**

***Index terms* – EMTP, HVDC, System Identification, Modelica.**

I. INTRODUCTION

A. *Motivation*

High Voltage Direct Current (HVDC) transmission systems have received renewed attention in the last decade due to their applications for long distance power transmission, particularly for off-shore wind interconnections [1]. Two main converter technologies for HVDC are the Line-Commutated Converter (LCC) and Voltage Source Converter (VSC), which are used for different applications in power systems [2]. VSC-based HVDC systems provide certain advantages w.r.t. LCC, including independent control of active and reactive power, and others [3]. An overview of different VSC topologies are reported in [4] and includes conventional two-level, multi-level diode-clamped, floating capacitor multi-level converters, among others.

Recently, the Modular Multilevel Converter (MMC) technology has been adopted because of its advantages w.r.t. other multilevel converter topologies for HVDC applications [5]. With the adoption of different types of HVDC technologies, modeling and simulation of these devices has become of crucial importance for different network studies, and, of particular interest in the context of this work, for Dynamic Security Assessment (DSA). An overview of VSC-HVDC models for "transient simulations" is given in [6]. One of the iTesla project Transmission System Operators (TSOs) had available an HVDC-VSC model that is used for Electro-Magnetic Transient (EMT) simulations, implemented using EMTP-RV [7]. This model can only be used in the EMTP-RV software, however, the DSA approach carried out using the iTesla toolbox [8] requires phasor time-domain models that can be used by different simulation engines (e.g. Eurostag, PSS/E, OpenModelica and/or Dymola for Modelica models). Hence, the development of a VSC-HVDC model available for phasor time-domain simulation using a Modelica-compliant simulation engine was necessary for the iTesla Toolbox internal simulation, data management, and model exchange needs. Modelica [9], is an object oriented equation-based standardized language suitable for modelling "multi-engineering" cyber-physical systems. Among its many advantages, it is worth to mention that it has a large standardized library of component models from different domains (e.g. electrical, mechanical, thermal, fluid etc) and it supports acausal modelling. In addition, several Modelica-standard-compliant tools also support the Functional Mock-UP Interface (FMI) [10] standard for model exchange and co-simulation that has been accepted by a broad user community, and it is being used for a great number of applications [11]. Due to these and several other unique advantages, the iTesla project [12] choose Modelica as the main modeling language to represent power system dynamic models.

B. *Previous Work*

There are already two implementations of VSC-HVDC models using Modelica in [13] and [14] however, these have not been validated against a high bandwidth model (EMT type model). In addition, these specify the inner control, phase lock loop (PLL) and modulation strategy that might be unnecessary for large scale stability studies as such detailed representation leads to an increase in computational requirements and simulation execution time.

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C. *Paper Contribuitions*

This paper presents the calibration of a Modelica VSC-HVDC model with respect to a reference EMTP-RV model. While previous work [15] has considered the identification of simplified VSC models represented with equivalent open loop transfer functions, this work differs in that it provides methods to calibrate the controllers' parameters by minimizing the error of the full non-linear model response while utilizing real or synthetic time-series data.

The article describes how the developed Modelica model has gone through a Software-to-Software (SW-to-SW) validation against EMTP-RV, and can be used for phasor time-domain simulations. To assure that the Modelica model can represent adequately the same behaviour as the EMTP-RV model when used to model an actual VSC-HVDC link, it needs to be parameterized adequately. Hence, this paper also presents methods for parameter identification of the high level controllers of the implemented model using the RaPId toolbox [16].

II. VSC MODELS

The reference model from EMTP-RV represents a multilevel VSC-HVDC system and is used to model different interconnections [7]. In EMTP-RV there are two types of MMC stations: Monopole and Bi-pole configuration with ground return. The MMC station can be represented using four kinds of models: (a) Full detailed model, (b) Detailed equivalent model, (c) Switching function of arm model, and (d) Average-value model (AVM). In the AVM, the MMC station is modeled using controlled voltage and current sources however, the switching of the IGBTs including diodes are not physically represented. The full description of the model's behavior is documented in [7]. An equivalent AVM model of the VSC converter was implemented in Modelica using the reference model EMTP-RV, and its associated controllers. The AC-side of the converter is a current injector and the DC-side is a current source, shown in Fig. 1. All the high-level controls are the same as the high level controls as in EMTP-RV, which were re-implemented in Modelica. The inputs of the high level controls (HLCs) in Modelica are Vdc, P, Q, Uac measured on the DC or AC side of the physical model. The outputs of the HLCs in Modelica are named Irorder, Iiorder (IPORDER and IQORDER respectively in EMTP-RV). These are the currents injected into the AC side of the grid. Lower level controllers, or inner controllers, are not of interest in the context of this work as the models are to be used in large power network simulations. The VSC model works with the iTesla Power System library for Modelica [16].

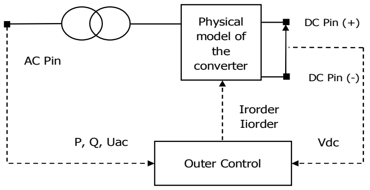

Figure 1: Schematic of the Modelica implementation of the VSC converter.

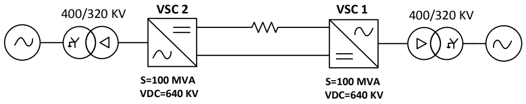

Figure 2: VSC-HVDC Test system.

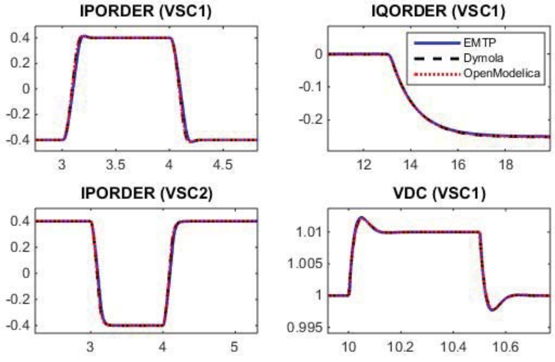

Figure 3: SW-to-SW validation results
x-axis: time (sec.), y-axis: controller output

III. SOFTWARE-TO-SOFTWARE VALIDATION

Software-to-Software model validation has been carried out by comparing simulation results from EMTP-RV, OpenModelica and Dymola.

A. *VSC-HVDC Link: EMTP-RV and Modelica Test Systems*

The VSC-HVDC test system implemented in EMTP-RV and in Modelica is shown in Fig. 2. The equivalent sources at both VSC connections points are with a short circuit power of 10 GVA. The DC cable equivalent resistance is 1Ω. Converter 1 (VSC1) controls the DC voltage and Converter 2 (VSC2) controls the active power, while 40 MW active power is transferred from VSC2 to VSC1.

B. *Software-to-software validation*

To test all the controllers in both converters (VSC1 and VSC2), different step perturbations were applied in the controller's reference and simulated in EMTP-RV and in two Modelica tools, as shown in Fig. 3.

IV. PARAMETER IDENTIFICATION USING RAPID

Two methods to calibrate the controllers' parameters using the RaPId toolbox are presented next. Of particular interest for parameter identification of the VSC-HVDC was the estimation of the parameters for the high level (or upper level) controls of the VSC-HVDC model: active power (P), reactive power (Q), and DC voltage (VDC) controllers.

A. *Parameters of the EMTP-RV model*

Within the EMTP-RV model, the integral and proportional gains of each of the HLCs are automatically calculated within a sub-routine that takes as input the desired settling time defined by the user in the model configuration window. The values of the gain parameters computed by EMTP-RV are shown in TABLE I. Note that the procedure to determine these parameter is tool-specific and not a general applicable methodology, hence it might not be suited for other simulation environments or applications. Furthermore, note that as the VSC-HVDC reference model has been implemented within EMTP-RV, the validity of this model is directly linked to the fidelity of the parameterization used in EMTP-RV, which may need to be varied in order to use the model's parametrization in different simulation environment and types of studies.

In phasor time-domain simulations, to represent actual physical equipment, the Modelica model's parameters need to be appropriately set in order to match the model's response to a measured response (field data). Because currently there are no measurements available in order to calibrate the model, the authors use EMTP-RV simulations as "synthetic measurements" as an input for two different model calibration approach presented in the next section.

B. *Overview of RaPId's workflow*

Using the RaPId toolbox [16], parameters can be identified for any Modelica model by generating FMI standard-compliant Flexible Mockup Unit (FMU). As illustrated in Fig. 4, RaPId takes the FMU with the system model and measurement data as input, and then simulates the model using a set of initial 'guess' parameters. Then the adequacy of the parameters is assessed by evaluating an objective function, that quantitatively appraises error criteria between the simulation results and measurement data. This process continues sequentially until the optimization method finds a set of parameters satisfying the error criteria or when the maximum number of simulations is reached. The initial parameter values and bounds can be set by the user.

1) *Proposed Identification Procedures*

Two different approaches for parameter identification using RaPId were considered. The first approach calibrates each controller individually (and sequentially), while the second approach calibrates all controllers simultaneously. Before generating an FMU for calibration using RaPId, start 'initial guess' values were provided to the Modelica model. Observe that these start values are different from those used in EMTP-RV. In addition, for comparison purposes, uncalibrated 'test values' for the parameters are used to compare the model response to that of calibrated models. The parameter settings used in RaPId are given in TABLE II.

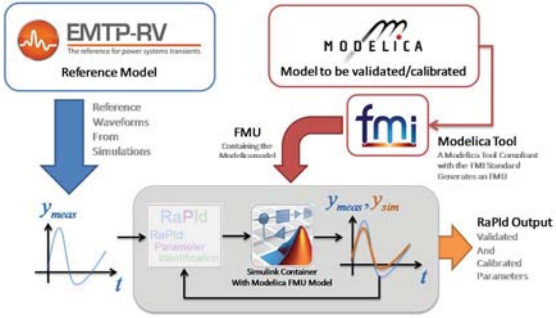

Figure 4: Workflow of the RaPId toolbox.

2) *Identification of individual controller parameters*

In the individual calibration approach, each of the control's (P, Q and VDC) gain parameters are identified separately and only the output of each controller is used as the reference waveform and simulation output (i.e. sequentially). The identification process was carried out using thirty *different* simulation experiments. Each experiment consisted in applying a *different perturbation* to the controller's input in the form of ramp and step changes. This requires to configure three different identification setups and for each, to configure the model outputs, as shown in Fig. 5 for the VDC controller.

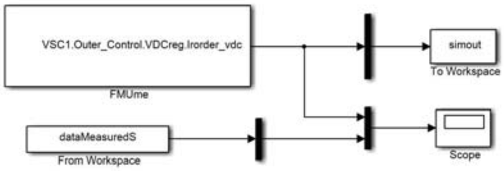

Figure 5: Simulink container used for parameter identification in RaPId.

TABLE I. GAIN VALUES OF CONTROLLERS

Control loops	Parameter in EMTP	
	Name	Value
Active power	Pctrl_Ki	30
	Pctrl_Kp	0
DC voltage	VdcCtrl_Kp	24
	VdcCtrl_Ki	734.7
Reactive power	Qctrl_Ki	30
	Qctrl_Kp	0

TABLE II. PARAMETER SETTINGS

Parameters Identified	Min value	Max value	Settings Start value	Modelica Test Value
Pctrl_Ki (VSC2)	5	50	25	5
Pctrl_Kp (VSC2)	0	10	5	0
Qctrl_Ki (VSC1)	10	50	25	10
Qctrl_Kp (VSC1)	0	10	5	0
VdcCtrl_Kp (VSC1)	10	40	20	10
VdcCtrl_Ki (VSC1)	550	950	750	300

3) *Simultaneous identification of all parameters*

In the simultaneous calibration approach, all the controllers' parameters are estimated simultaneously. This requires only one setup (similar to Fig. 5), with all controllers' 'measurements' and simulation outputs being compared simultaneously. The identification process was carried with different ramp and step perturbations.

4) *Identification results*

A statistical analysis of the identification results for experiments was carried out. Histograms for the parameters estimated using the individual identification approach are shown in Fig. 6. The mean (μ), standard deviation (σ), variance (σ^2) and confidence interval (95%) of all the parameters identified with both the individual and the simultaneous identification procedure are summarized in Table III. Using the lower and upper bound values of the estimated confidence intervals, simulations were carried out again by applying different perturbations, as shown in Fig. 7. The figure also shows the simulation results obtained when using 'test values' (see TABLE II). In addition to these statistical results, the quantitative assessment of the simulation results shown in Fig. 7 was carried out using the Root Mean Square Error (RMSE), errors are shown in Table IV.

TABLE III. PARAMETER IDENTIFICATION RESULTS

	KIVDC		KPVDC		KIP		KPP		KIQ		KPQ	
	II	SI	II	SI	II	SI	II	SI	II	SI	II	SI
Mean	892.09	834.19	26.77	26.66	31.49	31.53	0.004	0	29.52	29.32	0.032	0.263
Std dev.	9.6029	37.501	0.139	0.083	0.026	0.072	0.007	0	1.55	0.082	0.051	0.046
Variance	92.216	1406.4	0.019	0.007	6.7626e-04	0.005	5.6513e-05	0	2.41	0.006	0.002	0.002
CI (95%)	888.51 895.68	794.83 873.54	26.72 26.82	26.58 26.75	31.48 31.50	31.45 31.60	0.001 0.007	0	28.94 30.10	29.23 29.40	0.013 0.051	0.21 0.31

II: Individual Identification, SI: Simultaneous Identification

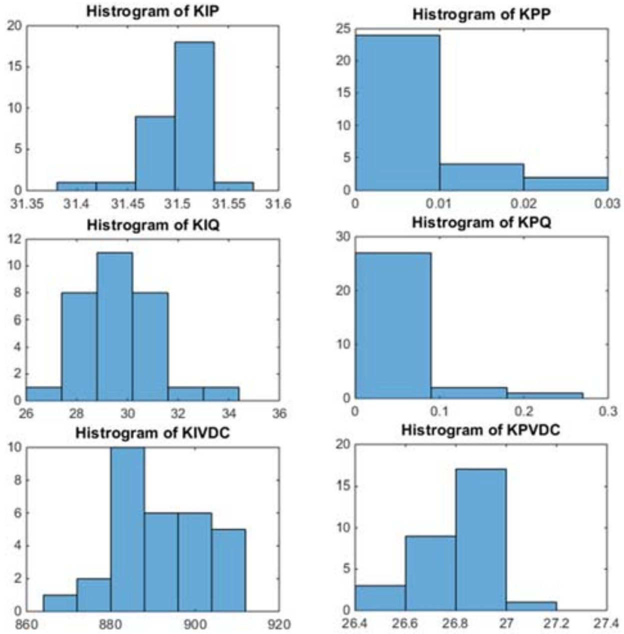

Figure 6: Histogram for the estimated parameters – individual controller calibration (x-axis: parameter value, y-axis: number of occurrences).

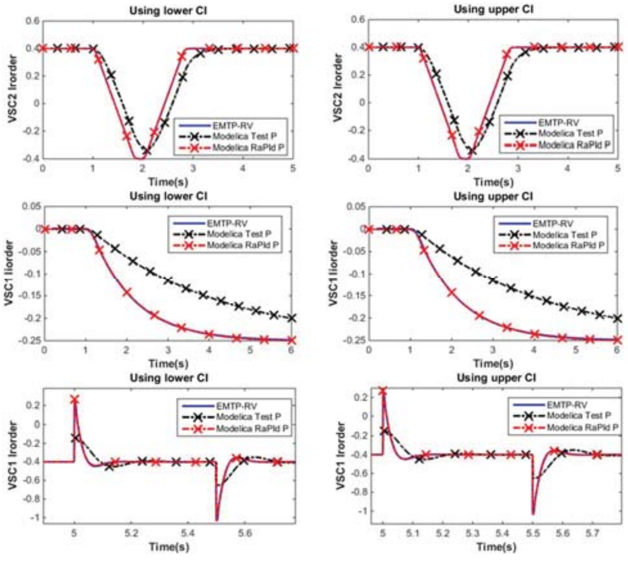

Figure 7:Simulation results using the parameter values at 95% confidence interval bounds and test values**.** Blue traces ('synthetic measurements from EMTP-RV), red traces (simulation using the parameters from the CI bounds), black traces ('test value' – uncalibrated).

TABLE IV. QUANTITATIVE ASSESSMENT (RMSE)

Variable	Upper CI		Lower CI		EMTP-RV value	Test value
	II	SI	II	SI		
Irorder (VSC2)	1.8302e-04	1.8283e-04	1.8514e-04	1.8954e-04	9.3324e-04	0.0813
Iiorder (VSC1)	0.0017	0.0011	0.0015	0.0011	0.0016	0.0687
Irorder (VSC1)	0.0049	0.0050	0.0049	0.0049	0.0059	0.0252

Both identification processes resulted in very similar statistical values, i.e. mean, standard deviation and confidence intervals except for the integral gain parameter of the VDC regulator.

V. ANALYSIS

The high variance shown in the estimation process of the VDC controller KIVDC parameter (highlighted in grey, Table III) can be interpreted as either an indicator of (i) the poor quality of the parameter estimate (and implicitly the estimation process), *or* (ii) of the modeling adequacy. Hypothesis (i) can be discarded by virtue of the consistent identification results obtain from both procedures for all other parameters and control loops. To be able to prove hypothesis (ii) and determine the source of the high variance in the identification results of KIVDC, the following sensitivity analysis was performed. To analyze the sensitivity of the control loop associated with the KIVDC parameter, a step changes of (1 to 1.019) at the VDC reference were applied in Modelica individually for each value of within the range KIVDC=[550 950]. This is the parameter range specified (see TABLE II) within the bounds used in the previous identification processes.

Figure 8 shows the RMS errors between the EMTP-RV and Modelica responses of the output of the VDC controller vs. KIVDC. The figure shows that the RMS errors are [.0053 0.0036] for KIVDC=[550 950], stagnating at 0.0033 for KIVDC=[780 850]. *This indicates that the variation of* KIVDC *has a negligible impact in the output of the controller.* Figure 9 shows the results of examining this error for a larger range, KIVDC=[250 1500], from where it can be concluded that the parameter KIVDC *has negligible impact in the overall model response*. Hence, *for all practical purposes, it is unnecessary to calibrate this parameter, as the model response is unaffected.*

Given the fact that the integral gain of VDC regulator has a very low sensitivity, the simultaneous identification process gives sufficiently accurate results for all other parameters when comparing the obtained variances to those obtained with the individual identification approach. Note that all the identification results were carried out within specific operation mode, i.e. the controllers do not change parameters during the simulations.

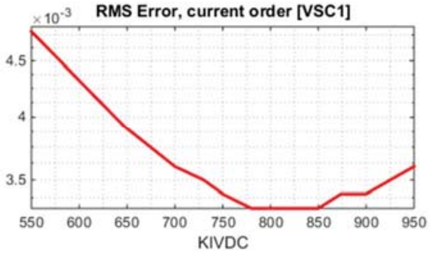

Figure 8: RMS error with KIVDC range [550, 950].

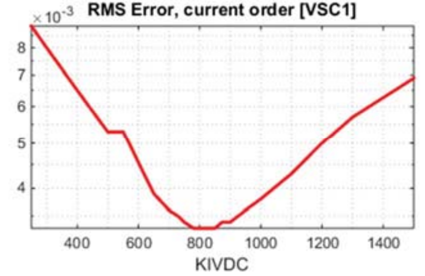

Figure 9: RMS error with KIVDC range [250, 1500].

VI. CONCLUSSIONS

A. Modeling and SW-to-SW Validation

The EMTP-RV and Modelica models of the VSC-HVDC converter give quantitatively similar results when simulating active power, reactive power, DC voltage and short circuit disturbances. From the implementation and SW-to-SW validation of the model presented in this paper, it can be understood that Modelica can be used for model exchange of power electronics-based devices for phasor-time domain simulation. Similarly, to the VSC-HVDC controls, other components (e.g. STATCOMS) also have two control layers (higher or upper-level) and inner (or lower-level) that contain modeling of control functions. While the inner controls (switching logics) can be synthesized without loss of consistency, the upper control levels need to be consistent with their three phase representation used for EMT. The use of Modelica as an exchange language would allow to identify modeling inconsistencies. Currently this approach is not broadly adopted, increase in the complexity of such devices will require a better representation for which today's phasor time-domain representations need to adapt.

B. Measurement based model validation and calibration

This work shows that RaPId is a flexible tool that allows to adopt different calibration approaches in a semi-automated fashion. Both of the proposed individual identification and simultaneous identification procedures provide sufficiently accurate parameter values with relatively low standard deviations (and variance) and confidence intervals.

This method is effective identifying the parameters of controllers that affect the response of the system. In Section V, the sensitivity analysis shows how a controller might have no influence on the model's response. The identification method highlight this fact when analyzing the statistical results from multiple experiments, which means the model might be inadequately modeled or over-parameterized. The over parameterization hypothesis is confirmed through the sensitivity analysis in Section V, which shows that in the VDC control loop the integral gain action has no effect on the model response.

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