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Valles, Jose M.; Gonzalez-Longatt, Francisco; Angeles-Camacho, Cesar; Rueda, Jose Luis; Riquelme-Dominguez, Jose Miguel

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A Simple Validation of ePHASORSIM's User-Defined Model of a Virtual Synchronous Machine Suitable for Real-time Simulations

Jose M. Valles
Instituto de Ingeniería
Universidad Nacional Autónoma de México
Mexico City, Mexico
JVallesC@iingen.unam.mx

Francisco Gonzalez-Longatt
Centre for Renewable Energy Systems
Technology (CREST)
Loughborough University
Loughborough, United Kingdom
fglongatt@fglongatt.org

Cesar Angeles-Camacho
Instituto de Ingeniería
Universidad Nacional Autónoma de México
Mexico City, Mexico
CAngelesC@iingen.unam.mx

Jose Luis Rueda
Department of Electrical Sustainable
Energy
Technical University Delft
Delft, Netherlands
J.L.RuedaTorres@tudelft.nl

Jose Miguel Riquelme-Dominguez
Escuela Técnica Superior de Ingenieros
Industriales
Universidad Politécnica de Madrid
Madrid, Spain
jm.riquelme@upm.es

Abstract—This paper presents a simple validation of ePHASORSIM's user-defined model of a Virtual Synchronous Machine (VSM) suitable for real-time simulations. The validation consists of a software-to-software comparison of the real-time simulator ePHASORSIM against the offline transient simulation tool PowerFactory. The comparison evaluates the models in the native library and user-defined models imported to ePHASORSIM. These user-defined models are coded in a Modelica environment and imported as a functional mock-up unit (FMU) model—the dynamic model of a voltage source converter operating as a VSM was implemented to test this functionality. A modified version of the IEEE 39-bus New England system was used for testing and validation. The time series from each (software) transient simulation were compared using the percentage error and the mean percentage error (MPE); the results demonstrate the suitability of the proposed approach.

Keywords—Real Time, Power system dynamics, Simulation, Virtual Synchronous Machine, VSM, Modelica, PowerFactory, ePHASORSIM.

I. INTRODUCTION

Electric power systems are increasingly incorporating renewable energy sources (RES) in an effort to reduce greenhouse emissions [1]. However, RES does not come without issues. Solar and wind power generation is influenced by environmental factors, making them highly variable and highly unpredictable. This negatively affects the power system [2]. Using power electronic converters (PECs) to connect RES to the grid also brings some issues [3]. The reason is that PEC's dynamics are faster than the electro-mechanical dynamics of the synchronous generators while also lacking inertial response [4], [5]. The paradigm shift has prompted operators and researchers to explore alternatives to the traditional analysis and simulation of power systems [6]. One tendency is using real-time simulators in power system studies [4], [7]. The reason is that real-time simulators enable engineers to test complex devices and applications in real-time [5], thus enabling faster development and adoption of innovative technologies and algorithms [8]. There are several real-time simulation hardware and software providers [6]. However, the more dominant in the market are Typhoon HIL

[9], [10], RTDS [11], and OPAL-RT [12]. The manufacturer OPAL-RT, established in 1997 in Canada, offers a combination of hardware and software specifically designed for real-time simulations. One software offer is ePHASORSIM, which is software for an electro-mechanical transient simulation tool that is able to run offline simulations and real-time simulations on RT-LAB-enabled simulators. The ePHASORSIM simulation tool is equipped with a native library of dynamic models, including many of the typical power system components, but also enables the development of user-defined models using the Modelica [13] language, specifically, OpenModelica [14] or Dymola [15] environments can be used. The capability of creating user-defined models makes ePHASORSIM an attractive option for studying electro-mechanical dynamics in large power systems with increased penetration of PECs.

This paper presents a simple validation process of the implementation in ePHASORSIM's of the user-defined model representing a Virtual Synchronous Machine (VSM) suitable for real-time simulations. The validation process is straightforward; the performance of the implemented VSM model in ePHASORSIM is compared with a very well-known power system analysis software, which already includes the VSM model, DIGSILENT PowerFactory [16].

The validation involves three steps. During the first step, only the native library, consisting of machines and controllers, is validated. The second step uses the previously validated system to compare the performance of user-defined models. The third step evaluates the results of the ePHASORSIM's simulator when multiple user-defined models are used in the same system. To achieve this, the very well-known IEEE 39-bus New England test system is used to validate the VSM model and synchronous generators are replaced with a voltage source converter (VSC) enabled with the VSM control model [17]–[19]. The VSM controller model has attracted so much attention as a grid-forming method to enable PECs to mimic the dynamic behaviour of a synchronous generator (as much as the PEC can). One of the ideas behind the use of PowerFactory is that the model of a PEC enabled with VSM control is already available, included in the PowerFactory global library as a general template. Hence, the authors

decided to replicate the same model using the OpenModelica environment and then imported it to ePHASORSIM to compare the results. It is easy to say and hard to do, as the modelling implementations are radically different. DIGSILENT PowerFactory uses DIGSILENT Simulation Language (proprietary language), and Modelica requires state model representation (the full detailed implementation of the VSM is presented in [20]). If readers are interested in learning more about these modelling languages, they can refer to [21], [22]. This paper is organised in the following manner. Section II describes the basics of the power systems components models and the differences in input data between the simulation software (ePHASORSIM and PowerFactory). Section III describes the VSM model, Section IV introduces the test system used for the validation process based on numerical simulations, explains the evaluation metrics, and shows the results obtained from validation. Finally, Section V presents the general conclusions.

II. SYSTEM MODELLING

To produce a fair comparison of the performance between both software (ePHASORSIM and PowerFactory), the exact system representation, data, and models must be used. This section briefly describes the models used for system representation and the dynamic models used to represent the generator and its controllers. Minor discrepancies exist between the input data of the models used in each software. These discrepancies will also be addressed. Users should be aware of how the input data is required to adapt the data they are using accordingly and avoid mistakes.

A. Network Model

Lines: The PI line model is used to represent transmission lines. However, there are differences in how each software requires parameter inputs—both models transformers use a positive sequence two-winding transformer. The input data of the winding resistance and reactance of the transformer are presented per unit system.

Loads: Power loads can be input into PowerFactory using a constant power model for power flow calculations and can be transformed to constant impedance for time-domain simulations. In the case of ePHASORSIM, a constant power load is not converted to constant impedance before a transient simulation. To resolve this issue, one can use a constant impedance load model before running a power flow calculation. The input data for the load is in either MW or MVar at a voltage of 1.00 pu. To achieve this, the load should be transformed from operational voltage to 1.00 pu using the following relationship:

$$P_{new} = \left(\frac{V_{new}}{V_{old}} \right)^2 P_{old} \quad (3)$$

where P_{new} is the load power at the voltage V_{new} , in this case, $V_{new} = 1.00$ p.u., and P_{old} is the load power at the voltage V_{old} , in this case, V_{old} is the result from the power flow calculation using the constant power load at value P_{old} . The user should run a power flow calculation with a constant power load model and then use the results to convert the load to a voltage of 1.00 p.u.

B. Generator models

The generator model used to represent the generator in transient simulations is named the Standard Model in PowerFactory. The model used is the round-rotor synchronous

machine (SM), which is referred to as Model 2.2 in [23]. In contrast, ePHASORSIM uses the GENROU machine model, which is equivalent to Model 2.2. Under the simplification, the sub-transient reactances are equal, e.g., $X''_d = X''_q$.

C. Control models

The SM is equipped with an AVR, which is modelled as an EX-ST1 [24]. For a more detailed description of this model and other exciter models, the reader can refer to the IEEE std 1110-2019 [24], [25]. The governor is modelled as a TGOV1 [26], which is a simple steam turbine-governor. For a more detailed description of turbine-governor modelling, please refer to the technical report PES-TR1 [27].

III. VIRTUAL SYNCHRONOUS MACHINE CONTROLLER MODEL

This section explains the model used in this paper for the VSM control technique. The implemented model is based on the Grid-Forming Converter Templates created, validated, and included in the software DIGSILENT PowerFactory. The model used in this paper was implemented using the OpenModelica [14] environment and exported as an FMU model before being imported into the ePHASORSIM simulator. The model includes the following elements: a VSC, a virtual impedance (VI), a virtual voltage source, a VSM control, and voltage control. A high-level overview of the model implemented is presented in Fig. 1. The VSM control is shown in circuit form (on the left-hand side), and the VSC is depicted as a controllable voltage source (on the right-hand side).

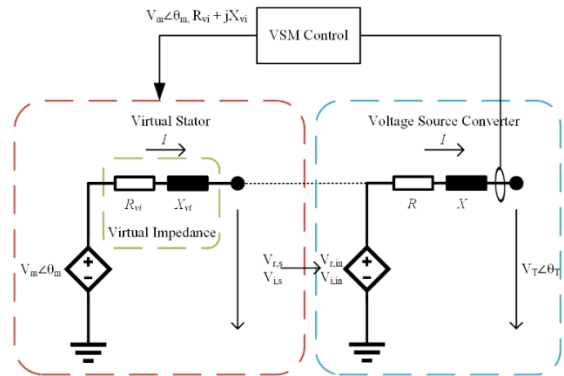


Fig. 1. Circuit representation of the implemented VSM model using OpenModelica.

A. Voltage Source Converter Model

The VSC is modelled as a controllable voltage source in series with an impedance. The voltages $V_{r,in}$ and $V_{i,in}$ are the real and imaginary inputs of the positive sequence voltage reference. The resistance R_{VSC} and reactance X_{VSC} of the impedance Z_{VSC} are calculated as follows:

$$Z_{VSC} = \frac{u_k}{100} \quad (4)$$

$$R_{VSC} = \frac{P_{cu}}{1000} \quad (5)$$

$$X_{VSC} = \sqrt{(Z_{VSC})^2 - (R_{VSC})^2} \quad (6)$$

where u_k is the short circuit impedance in %, and P_{cu} are the copper losses in kW. The circuit equations are expressed on real and imaginary terms. The terminal voltage $|V_T| \angle \theta_T$ can be transformed to its real and imaginary v_r and v_i using

trigonometric expressions. The VSC current $I = i_r + ji$ is calculated as:

$$i_r = \frac{pv_r + qv_i}{|V_T|^2} \quad (7)$$

$$i_i = \frac{pv_i - qv_r}{|V_T|^2} \quad (8)$$

where, p and q are the active and reactive power generated by the VSC (these powers can be negative for power absorption). The real and imaginary part of the voltage drop, $\Delta v_{r,in}$ and $\Delta v_{i,in}$, over the impedance Z_{VSC} can be calculated using the following algebraic equations:

$$\Delta v_{r,in} = R_{VSC}i_r - X_{VSC}i_i \quad (9)$$

$$\Delta v_{i,in} = R_{VSC}i_i + X_{VSC}i_r \quad (10)$$

B. Virtual Synchronous Machine Control Model

The VSM control is used to emulate an inertial response and to provide primary frequency control. The block diagram for the VSM control is shown in Fig. 2.

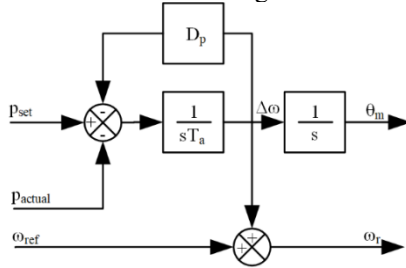


Fig. 2. Block diagram depicting the specific implementation of the VSM control.

From Fig. 2, the gain T_a represents the time constant of the VSM, p_{set} is the active power setpoint, p_{actual} is the active power output of the VSM, ω_{ref} is the speed set point, ω is the speed of the VSM, D_p is the damping coefficient, and θ_m is the angle of the voltage source behind the virtual impedance. This control emulates the electro-mechanical behaviour of a synchronous generator by using the swing equation. The model does not include a frequency droop to emulate a governor response. However, the damping term D_p can be tuned to be used for primary frequency regulation by setting it to the inverse of the frequency droop.

C. Voltage Control

This control acts on the virtual voltage V_m , in a similar fashion to an exciter in a SM. In Fig. 3, the model is presented in block diagram form. The voltage control is a proportional controller with a gain K_v and lag blocks with time constants T_r for the voltage measurement and T_{lpf} for the controller. These lags represent delays in the measurements and control action, respectively.

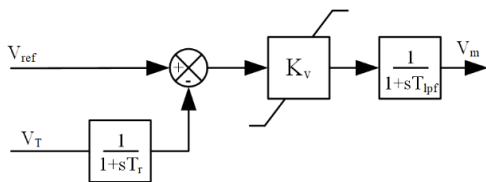


Fig. 3. Block diagram representing the voltage control implemented in this paper.

D. Virtual Stator or Virtual Impedance Model

The voltage magnitude V_m and the VSM angle θ_m are the magnitude and angle for the virtual voltage source behind the virtual impedance (VI). These two components can be thought of as a virtual stator. Since this virtual stator must follow Kirchhoff's current laws, the virtual voltage source injects current equal to the current flowing through the VSC. Thus, the voltage drop across the virtual impedance can be calculated as:

$$\Delta v_{r,vi} = R_{vi}i_r - X_{vi}i_i \quad (11)$$

$$\Delta v_{i,vi} = R_{vi}i_i + X_{vi}i_r \quad (12)$$

where R_{vi} and X_{vi} are the virtual resistance and reactance in pu, and $\Delta v_{r,vi}$ and $\Delta v_{i,vi}$ are the real and imaginary parts of the virtual voltage drops over the VI. Since the values R_{vi} and X_{vi} do not represent a physical element, a VI control [19] can be used to adjust them. These values are modified in proportion to the absolute value of the current.

If the current is larger than the predefined limit ($|I| \geq I_{lim}$), then:

$$Z_{vi} = (k_{pr}R_{vi} + jk_{px}X_{vi})(|I| - I_{lim}) + R_{vi} + jX_{vi} \quad (13)$$

where k_{pr} and k_{px} are proportional factors for the virtual resistance and virtual reactance, respectively.

If the current is smaller than the predefined limit ($I < I_{lim}$), then:

$$Z_{vi} = R_{vi} + jX_{vi} \quad (14)$$

IV. VALIDATION USING NUMERICAL SIMULATIONS

In this section, a comparison between the numerical results of dynamic simulation results in both software is assessed to validate the ePHASORSIM's user-defined model of VSM. The goal is to determine what is the percentage error between the two software considering the rotors' speed time series.

A. IEEE 39-bus New England Test System

A modified version of the very well-known IEEE 39-bus New England System data was utilised for the simulations in this paper. Generator G1 is assumed to work as constant power. This test system is provided as an example both on PowerFactory and ePHASORSIM. The data was changed so that it had the same grid and dynamic model representation. There are some discrepancies between the input data from PowerFactory and ePHASORSIM. PowerFactory allows the user to create a system diagram, which automatically makes a database that can later be browsed and edited using a data manager. In ePHASORSIM, the user must use a specific data format, Microsoft Excel ".xls".

B. Evaluation Metrics

This section provides a brief explanation of the evaluation metrics used. The percentage of the error (ε) is the absolute error divided by the reference value, multiplied by 100%, as shown below:

$$\varepsilon [\%] = \frac{|y-x|}{y} 100\% \quad (15)$$

where y is the reference value, and x is the value to be compared. The Mean Percentage Error (MPE) is the average of the percentage of errors on the time series as defined below:

$$MPE [\%] = \frac{100\%}{n} \sum_{i=1}^n \frac{|y_i - x_i|}{y_i} \quad (16)$$

where n is the number of results or observations in the time series.

C. BASE CASE: System operating only with SM

The base case considers only SM, and the error between the time series of the rotor speed of all generators considering the two software is analysed. The simulation event is the disconnection of generator G3 at the time $t = 1.0$ s. This event will cause the frequency to decline, which will then be stabilised by the actions of the controls, mainly the governor's response. Fig. 4 shows a graph of the step-by-step per cent of the error (ε) for both time series of the SM speeds.

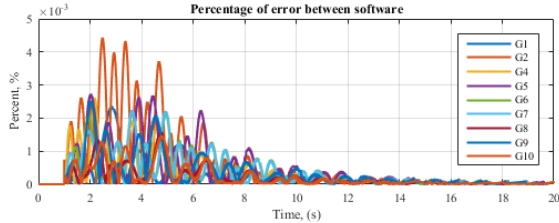


Fig. 4. Percentage of error (ε) for generator speeds between software.

The figure above shows that the percentage of error between rotors speed obtained from both software is very small ($<4.4 \times 10^{-3}\%$ at G2 -orange line at Fig. 4). The discrepancies tend to be significant in the first seconds after the disturbance, it is when the generators are oscillating. Since most of the error occurs during the first few seconds after a disturbance, one can take a window of time and calculate the mean per cent of error in that time window. In this case, a time window of 10.0s from the start of the disturbance is considered.

The mean percentage of error for generator G2 in this time window is $MPE = 1.1 \times 10^{-3}\%$. The MPE for all generators for this time window is $MPE = 0.617 \times 10^{-3}\%$. A smaller or larger time window could be considered. However, since the error before the disturbance is zero, and the error at the end of the simulation tends to zero, the MPE will be smaller considering a time window that includes those instances. In Fig. 5, a point-to-point comparison between the speeds of generator G2 is presented. Here, one can visually compare the evolution of generator G2 speeds after the disturbance. In Powerfactory, the frequency nadir is $f = 0.9956$ p.u., while on ePHASORSIM, the frequency nadir is $f = 0.9955$ p.u. This represents a percentage error for the nadirs, $\varepsilon = 2.74 \times 10^{-3}\%$. The settling frequency for generator 2 is $f = 0.9963$ pu, in both software.

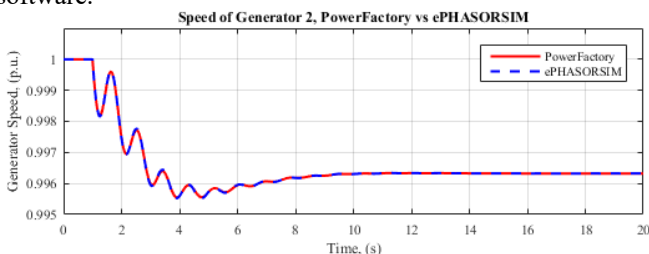


Fig. 5. Point-to-point comparison for the speeds of generator G2.

D. CASE I: Replacing generator G5 with a VSM

This case considers G5, which is connected to bus 34, replaced with a VSM of similar characteristics. The event is the disconnection of generator G3 at the time $t = 1.0$ s. Therefore, only the error between the VSM on both software

will be evaluated. Fig. 6, shows a graph of the step-by-step per cent of the error (ε) for the time series of the VSMs speeds. The maximum error for the simulation is $\varepsilon = 1.3 \times 10^{-3}\%$. Considering a time window of 10s from the start of the disturbance, the $MPE = 0.382 \times 10^{-3}\%$.

In Fig. 7, a point-to-point comparison of the speeds of VSM5 is presented. The visual difference between the two software is minimal; in both cases, the frequency nadir is $f = 0.9957$, which represents a per cent of error $\varepsilon = 0\%$. The settling frequency for the VSM is $f = 0.9963$ p.u. Since the primary frequency droop for the governors is the same in this case study, and since the value of D_p for the VSM is set as an equivalent value, the frequency is set at the same value as the previous case.

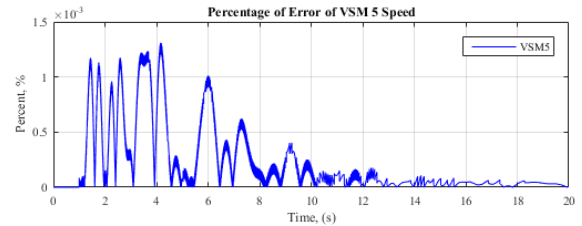


Fig. 6. Percentage of error for VSM5 between software.

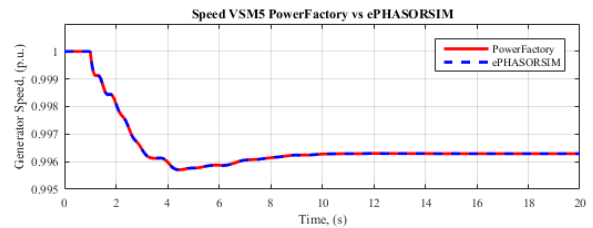


Fig. 7. Point-to-point comparison for the speeds of VSM5.

E. CASE III: System Operating with high penetration of VSMs

This case consists of replacing generators G4-G6 and generators 8-9 with VSMs. The objective is to evaluate the capacity of ePHASORSIM to run with multiple FMUs. The event is the disconnection of generator G3 at the time $t = 1.0$ s. Since the correct functionality of the VSM FMU has already been validated in the previous case, only results from ePHASORSIM will be presented. In Fig. 8, the speeds of the Generators and VSMs are presented. The system response is similar to in the previous cases. The frequency nadir is $f = 0.9960$ pu occurring at Generator G2; this is a small improvement from the previous case. The settling frequency for the system is $f = 0.9962$ p.u., which is a small decrease from the previous case.

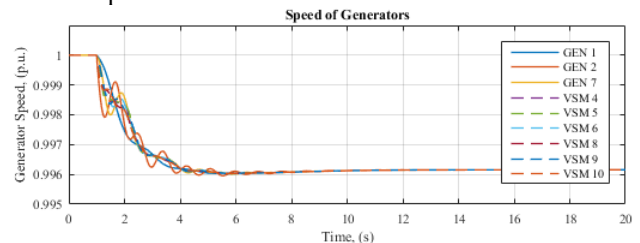


Fig. 8. Plot showing the SM rotor speed and the synthetic rotor speed of the integrated VSMs.

V. CONCLUSIONS

To validate the use of ePHASORSIM as a real-time transient simulator, a comparison of the results between the

two software tools was carried out. This comparison evaluates native models from the software's library as well as user-defined models. The user-defined model in this paper was implemented using OpenModelica, exported to an FMU model, and imported to ePHASORSIM; PowerFactory's VSM model was used as a base. Also, the capability of ePHASORSIM to run a simulation with multiple FMU models was validated.

A simple comparison of metrics was used to calculate the percentage of error and the mean percentage of error between both software. The conclusion from that analysis is that the error between both software is minimal. Hence ePHASORSIM and its user-defined models can be used in transient simulation studies considering real-time simulations.

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