Enabling large-scaled MMC EMT-RMS co-simulation by data exchange in the loop (DXiL)

Xiong Xiao, Soham Choudhury, Martin Coumont, Jutta Hanson
Department of Electrical Power Supply with Integration of Renewable Energy (E5)
Technical University of Darmstadt
Landgraf-Georg-Straße 4, Darmstadt, Germany
Phone: +49 (0) 6151/16-24657
Fax: +49 (0) 6151/16-24665
Email: xiong.xiao@e5.tu-darmstadt.de
URL: https://www.e5.tu-darmstadt.de

Keywords

≪HVDC≫, ≪co-simulation≫, ≪MATLAB/Simulink≫, ≪electromagnetic-transients≫, ≪phasor simulation≫.

Abstract

This paper presents a comprehensive co-simulation method of electro-magnetic (EMT) and electromechanical (RMS) dynamic models in MATLAB/Simulink to investigate transient stability in large scale hybrid AC/DC grids. The modeling of modular multilevel converter (MMC) as well as co-simulation of EMT-RMS programs in MATLAB/Simulink is first described. For further reducing the unnecessary data exchange time between EMT and RMS programs, data exchange in the loop interaction method is introduced. With this method, the frequent data exchange through MATLAB workspace is avoided, and the co-simulation is thus accelerated significantly.

Introduction

Electro-magnetic transient (EMT) simulation and electro-mechanical transient (RMS) simulation are two main modeling and simulation tools for dynamic studies of power systems. EMT models use differential equations for describing the electro-magnetic transient processes and are suitable for simulating a relative small power grid. However, they are not suitable for studying large-scale systems because of huge calculation expense. In the contrast, RMS models, also called positive sequence models or transient simulation models, are implemented in the phasor-frame without considering any harmonics. They are suitable for investigating large-scale power system dynamics, such as rotor-angle stability of large AC grids. e As more and more HVDC grids with modular multilevel converters (MMC) are coming into application in the future transmission grids, it is necessary to investigate dynamic stability for large-scale hybrid AC/DC transmission grids, which calls for suitable dynamic models not only for AC grids, but also for DC grids and MMC. In standard power system simulation softwares such as MATLAB/Simulink and DIgSILENT/PowerFactory, there are already well developed RMS models for AC grids, and they have been proven accurately and rapidly since years. Even though MMC RMS models have been developed in recent years, such as [1]-[6], they are still not able to replace EMT models in some cases, such as long-term dc-voltage drops [2].

Co-simulation of EMT-type programs and RMS-type programs are another opportunity for simulating hybrid AC/DC power systems, in cases when MMC RMS models do not have identical results as EMT models. In such simulations, the AC system is simulated in RMS-type programs, while the DC grid is simulated in EMT-type programs. As in [7], an EMT-type averaged converter model is combined with a RMS-type AC grid model. Researches about interfacing techniques between the EMT-and RMS-type programs have been also carried out in [8]-[10].

MATLAB/Simulink provides both EMT-and RMS-type simulation environments, nevertheless, there are few literature about implementation the co-simulation into MATLAB/Simulink. A hybrid EMT-RMS simulation method for MATLAB/Simulink for studying distribution grids is developed in [11], where the standard voltage source converter (VSC) model in Simulink-library is used for the EMT part. However, there are still no standard models for MMC in MATLAB/Simulink. Based on the method of [11], this paper provides a MATLAB/Simulink-based EMT-RMS hybrid modeling method for simulating large-scale hybrid AC/DC transmission grids. Moreover, date exchange in the loop (DXiL) method is introduced for accelerating the co-simulation.

Principle for Co-simulating EMT and RMS models

As is mentioned in the introduction, AC and DC systems are respectively simulated in RMS- and EMT-type programs, it is necessary to define the interface of both types for each HVDC converter. This section explains the generic co-simulation principle adopted in this paper, including equivalent circuits of RMS and EMT model in each other, interaction protocol and the time interpolation method. It is worth noting that the co-simulation principle is applicable to all simulation softwares, not only MATLAB/Simulink.

Selecting interface bus

The point of common coupling (PCC) is selected as the interface bus, where the currents, voltages as well as power can be measured in both EMT and RMS models.

Subsystem equivalent circuits

As EMT and RMS models are simulated with quite different types of solver, it is necessary to define the equivalent models of them in each other, enabling them independently to be solved.

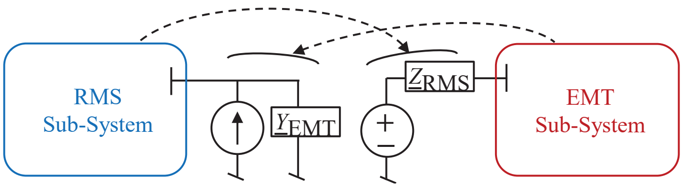


Fig. 1: EMT and RMS subsystem equivalent models [9].

Figure 1 shows the boundary condition of a converter consisting of EMT and RMS parts, including the Norton equivalent circuit of the EMT subsystem in the RMS model, as well as the Thevenin equivalent circuit of the RMS subsystem in the EMT model.

-Thevenin equivalent circuit of the RMS subsystem in the EMT model

The phasor voltage $\underline{V}_{\mathrm{PCC}}$ and current $\underline{I}_{\mathrm{PCC}}$, as well as the AC grid equivalent impedance $\underline{Z}^{\mathrm{eq}}_{\mathrm{RMS}}$ are measured at the PCC. In this way, the Thevenin equivalent voltage source of the RMS subsystem in the EMT model can be calculated as

$$\underline{V}^{\mathrm{eq}}_{\mathrm{RMS}} = \underline{V}_{\mathrm{PCC}} + \underline{I}_{\mathrm{PCC}} \cdot \underline{Z}^{\mathrm{eq}}_{\mathrm{RMS}}. \tag{1}$$

-Norton equivalent circuit of the EMT subsystem in the RMS model

The three-phase complex power is computed as

$$P + \mathrm{j}Q = \frac{1}{2}(\underline{V}_{\mathrm{a}} \cdot \underline{I}^{*}_{\mathrm{a}} + \underline{V}_{\mathrm{b}} \cdot \underline{I}^{*}_{\mathrm{b}} + \underline{V}_{\mathrm{c}} \cdot \underline{I}^{*}_{\mathrm{c}}), \tag{2}$$

where $\underline{V}_{\mathrm{a,b,c}}$ and $\underline{I}_{\mathrm{a,b,c}}$ are three-phase voltage and current phasor signals, respectively. The complex power $P + \mathrm{j}Q$ is provided by the EMT system, and the voltages $\underline{V}_{\mathrm{a,b,c}}$ are measured locally in the RMS system. As this work concentrates only on symmetric situations, it is adopted that all three-phase voltages and currents are symmetric, so that the power is equal in each phase, namely

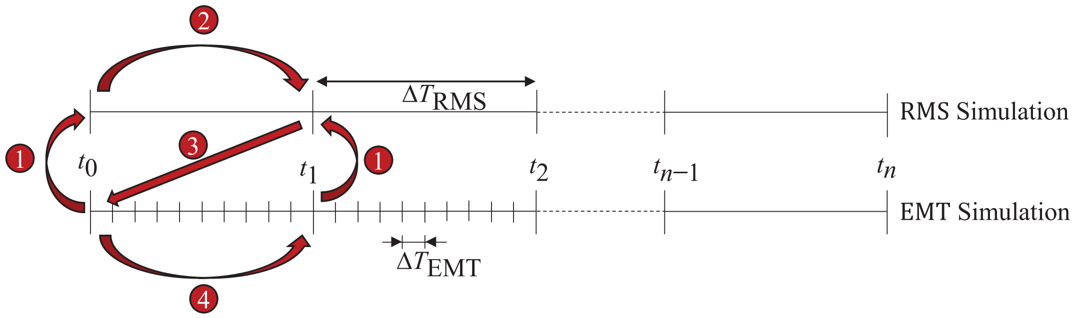
$$\underline{V}_{\mathrm{a}} \cdot \underline{I}_{\mathrm{a}}^{*} = \underline{V}_{\mathrm{b}} \cdot \underline{I}_{\mathrm{b}}^{*} = \underline{V}_{\mathrm{c}} \cdot \underline{I}_{\mathrm{c}}^{*}. \tag{3}$$

Thus, the three-phase currents in the Norton equivalent circuit are derived as

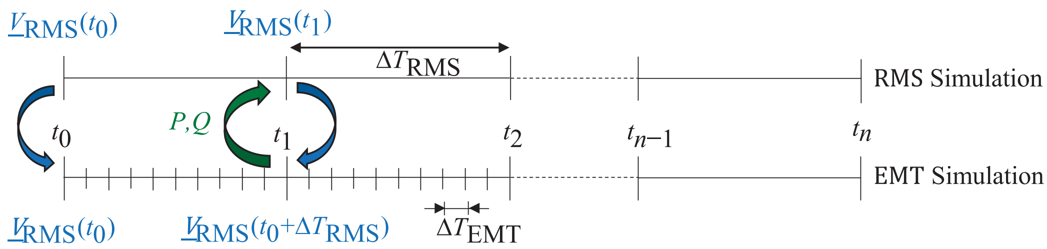
$$\underline{I}_i = \frac{2}{3}\left(\frac{P+\mathrm{j}Q}{\underline{V}_i}\right)^{*}, \quad i = \mathrm{a,b,c}. \tag{4}$$

Interaction protocol

The interaction protocol between EMT and RMS subsystems can be parallel or serial. In this work, series protocol is adopted for its accuracy, which is shown in Figure 2(a).



(a) Series interaction protocol [11].



(b) Data exchange between EMT and RMS models.

Fig. 2: Interaction protocol of EMT-RMS co-simulation.

The series interaction protocol is explained as follows:

- At the very beginning of the co-simulation t_0, both EMT and RMS models are initialized according to power flow calculation results.
- Step 1: At the beginning of the i-th co-simulation cycle, the active power P and reactive power Q in the EMT subsystem, derived from currents and voltages measured at PCC, are transferred into the RMS subsystem.
- Step 2: Divided by the measured voltages, P and Q are converted into currents, and the Norton equivalent circuit in the RMS model is updated according to (4). The RMS program runs for one step ΔT_{RMS} till t_i.
- Step 3: The starting and end value of RMS equivalent voltage throughout the time step ΔT_{RMS}, $\underline{V}_{\mathrm{RMS}}^{\mathrm{eq}}(t_{i-1})$ and $\underline{V}_{\mathrm{RMS}}^{\mathrm{eq}}(t_i)$, are transferred to the EMT subsystem.
- Step 4: With $\underline{V}_{\mathrm{RMS}}^{\mathrm{eq}}(t_{i-1})$ and $\underline{V}_{\mathrm{RMS}}^{\mathrm{eq}}(t_i)$ as start and end value, the momentary value of RMS subsystem equivalent voltage V_{RMS} can be derived through the interpolation method in [9]. The EMT model is simulated for a RMS time step ΔT_{RMS} till t_i with the time step ΔT_{EMT}.

- Step 1-4 are repeated until the end of co-simulation.

Co-simulation in MATLAB/Simulink

The EMT and RMS parts are modeled first separately in two Simulink files, whose data exchange is carried out through the MATLAB workspace, just like in [11]. Standard models in the library of „Simscape/Electrical/Specialized Power Systems" are adopted for modeling the AC system, whereas the MMC is user defined as it is not available in the Simulink model library.

As there are hundreds of sub-modules (SM) in each phase of the MMC, it is difficult to model all of them exactly. Moreover, for investigating the dynamic behavior of a power grid in system-level, it is not necessary to consider the inner states of each SM. Thus, the averaged value modeling method for MMC in [12] is adopted, which is shown in Figure 3. Assuming that in each arm, the arm voltage is always

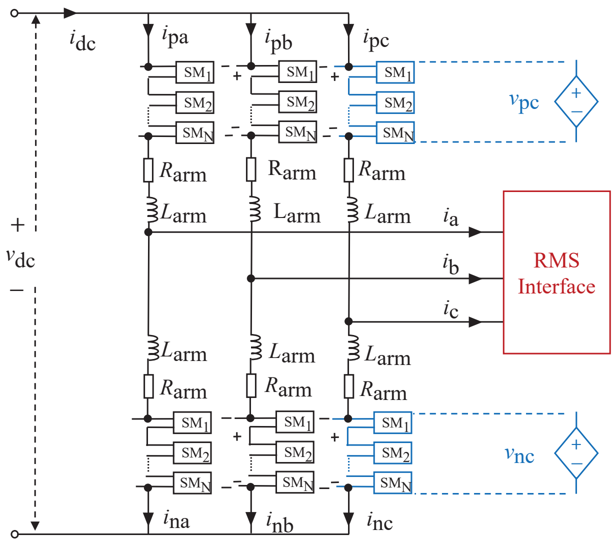


Fig. 3: Averaged value model of modular multilevel converter.

equally distributed to inserted SMs, all SM voltages in each arm are considered as an equivalent voltage source, so that

$$v_{pi} = \sum_{j=1}^{N} v_{SM}^{pj}, \quad i = a, b, c \tag{5}$$

and

$$v_{ni} = \sum_{j=1}^{N} v_{SM}^{nj}, \quad i = a, b, c, \tag{6}$$

where v_{pi} and v_{ni} are respectively equivalent voltages of upper and lower arm in each phase; v_{SM}^{pj} and v_{SM}^{nj} are sub-module voltages. As the transformer is modeled in RMS subsystem, the MMC in Figure 3 is directly connected to the RMS interface, where the three-phase voltages and currents are measured and an equivalent RMS AC grid is established.

In the i-th co-simulation cycle, the RMS simulation is first executed for a time step before it is paused, voltage result $\underline{V}_{RMS}(t_i)$ is logged to the workspace after ΔT_{RMS}. The interface voltage in EMT simulation $\underline{V}_{EMT}(t_{i-1})$ is interpolated in the workspace and updated in the EMT Simulink file. Executing EMT simulation for ΔT_{RMS}, power data $P(t_i)$ and $Q(t_i)$ are transferred to the RMS file through MATLAB workspace. In the above-mentioned steps, **set_param** handle is used for updating parameters from workspace, pausing and stepwise running EMT and RMS programs.

Different from normal Simulink blocks, the impedance block representing $\underline{Z}_{\text{RMS}}$ in Figure 1 can not be updated when the simulation is running. That means, the impedance value can not be changed with **set_param** handle, as long as the Simulation is running.

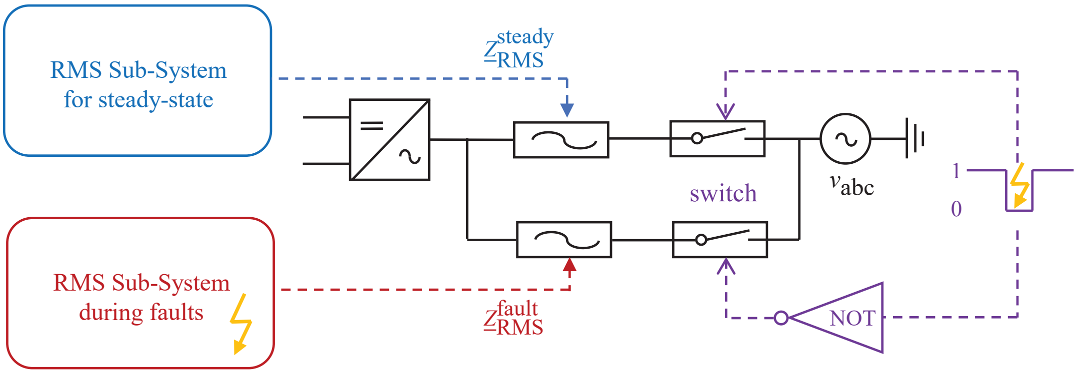


Fig. 4: Update impedance value in EMT model during co-simulation.

To overcome this problem, a back-up fault impedance block is introduced for representing the equivalent AC grid impedance during faults. As is shown in Figure 4, the value of the fault impedance is measured off-line in the RMS system before running the co-simulation. The fault impedance block is bypassed in steady-state and comes into service only if a fault takes place.

Simulation acceleration through data exchange in the loop (DXiL)

It can be seen from Figure 5 that in the *i*-th co-simulation cycle, there is extra time cost for pausing on program and starting the other, saving data to the workspace and importing data from it. The longer the co-simulation is carried out, the more such extra time expanse must be paid.

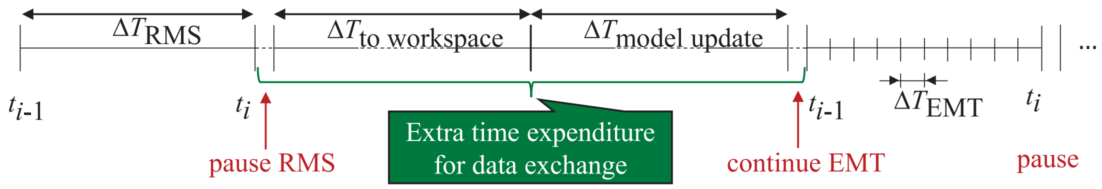


Fig. 5: Pausing time and time for data exchange for co-simulation.

One method for accelerating the co-simulation is to increase the RMS time step ΔT_{RMS} and reduce the cycle number. In some cases, ΔT_{RMS} can be reduced to 10-20 ms, just like in [11], where AC transmission grids are represented as voltage sources, instead of generators and loads. However, for simulating other AC grids with generators whose elements have relative tiny time constants, ΔT_{RMS} can not be as long as 10 ms, but maximum 1-2 ms.

Another thought is to avoid data exchange through the MATLAB workspace, which is the main contribution of this work. The main idea is to put both RMS and EMT models in one Simulink file and run them in rotation. Instead of extra programming, the „enabled subsystem" block can already realize rotational running different systems.

Enabled subsystem in MATLAB/Simulink

An example is shown in Figure 6, where a three-phase signal is generated in a enabled subsystem block. The subsystem is deactivated from 0.1 s to 0.2 s. It can be seen that the state variables in the subsystem are kept unchanged, when the subsystem is deactivated. This character can be applied to EMT-RMS co-simulation in one Simulink file.

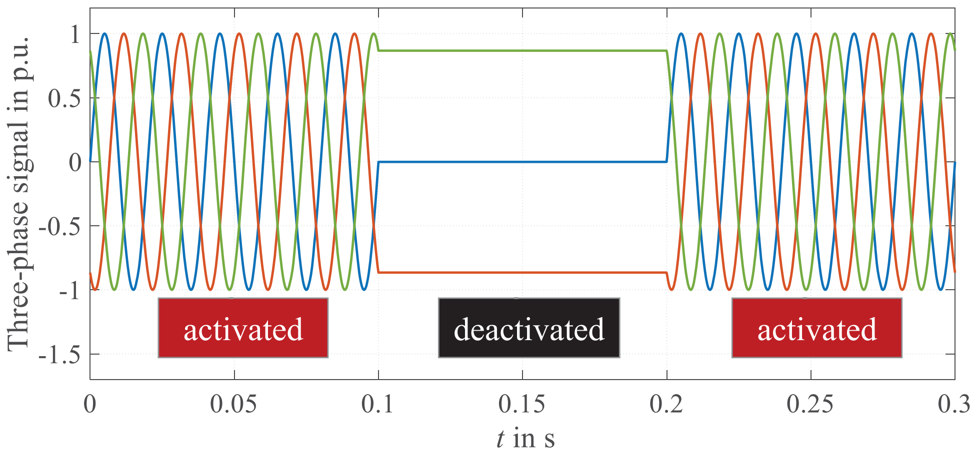


Fig. 6: Rotational simulation with enabled subsystem block.

Hybrid EMT-RMS model in MATLAB/Simulink

As is shown in Figure 7, the EMT and RMS models are now put in two enabled subsystem blocks in one Simulink file. The subsystem is activated under a pulse signal **1** and deactivated under a signal **0**. At

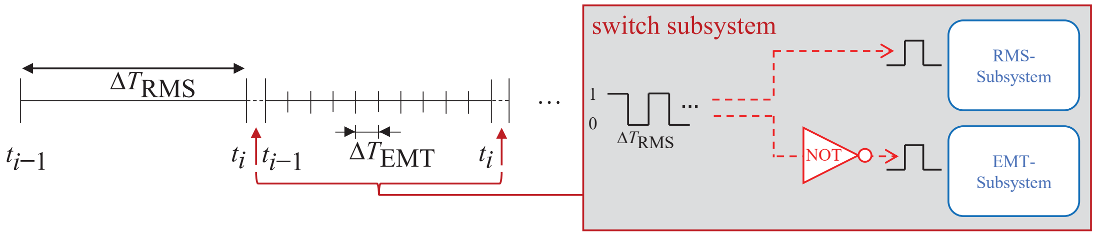


Fig. 7: Hybrid EMT-RMS model in different enabled subsystems.

the beginning of the i-th co-simulation cycle, a pulse signal **1** is generated to activate RMS subsystem, whereas EMT subsystem is deactivated under the inverse signal **0**. The pulse signal is overturned as long as the RMS simulation is finished, and the simulation mode is switched to EMT. In this way, the two subsystems are alternatively activated and deactivated in every co-simulation cycle, enabling EMT and RMS simulations to be executed rationally.

Dealing with simulation time

Theoretically, EMT and RMS systems should be simulated parallel at the same time. However, they have to be executed alternatively in order, when they are put in one Simulink file. Thus, the recorded time in Simulink is twice as the simulation time. Following remedies are taken for dealing with this problem:

- The total simulation time is doubled.
- The duration of all events in the grid, such as shout circuits, is doubled.
- For interpolating voltages in the EMT subsystem according to [9], „Clock" block is used to get the actual simulation time. In the DXiL co-simulation mode, however, the recorded simulation time should be halved, before it is used for voltage interpolation.
- All data are saved in form of „structure with time" after the co-simulation. The time in such structures should be halved before plotting the simulation results.

Case study and simulation results

Test bench and case

The test bench is shown in Figure 8. The AC system is represented as a voltage source in series with

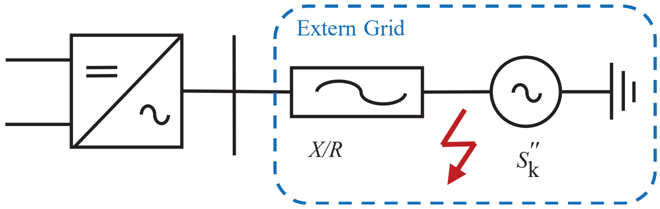
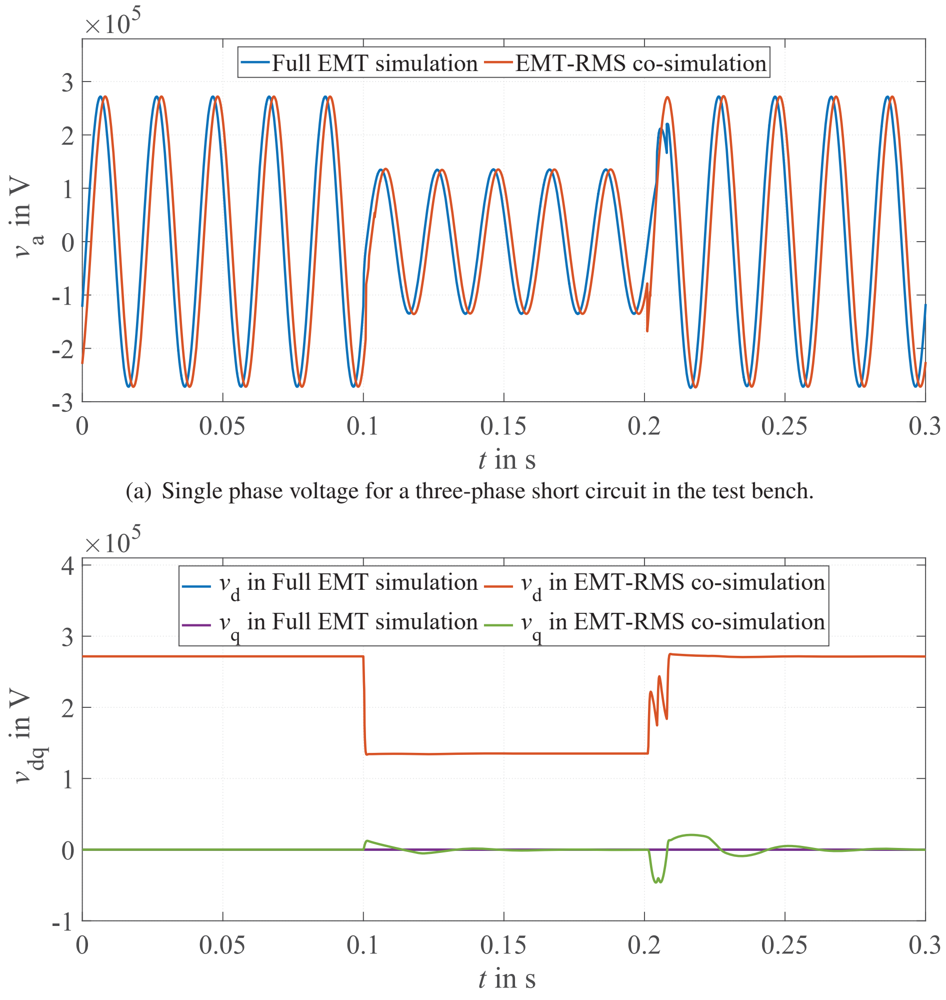


Fig. 8: Test bench.

an impedance. The short circuit ratio (SCR) as well as the X/R ratio are both 10. The co-simulation is executed for 0.3 s. A three-phase AC voltage drop to 50% is simulated at the PCC from 0.1 s to 0.2 s, representing a symmetrical AC fault somewhere in the AC network.

Co-simulation of EMT-RMS models in separate Simulink-files

The single phase voltage V_a as well as three-phase voltages in the direct-quadrature-zero coordinate $V_{d,q}$ are shown in Figure 9.



(a) Single phase voltage for a three-phase short circuit in the test bench.

(b) Three phase voltage in the direct-quadrature-zero coordinate for a three-phase short circuit in the test bench.

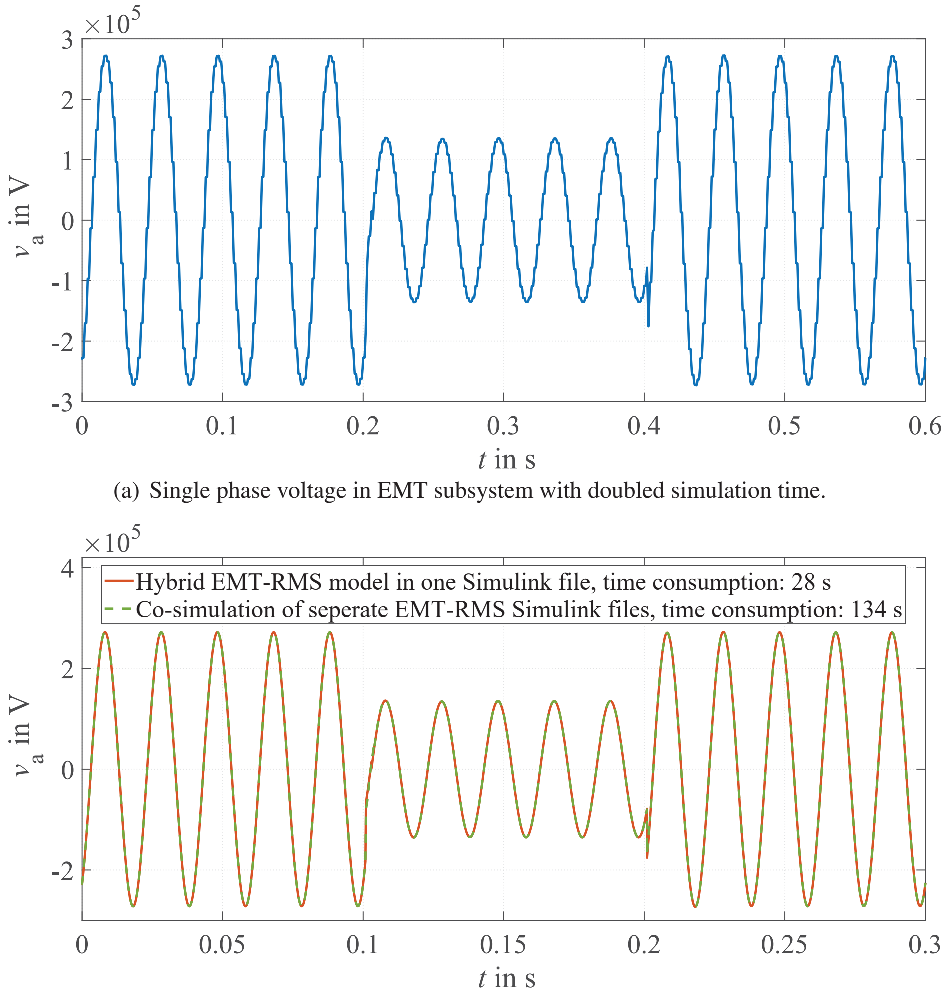
Fig. 9: Simulation results for EMT-RMS co-simulation.

With acceptable errors, the co-simulation can bring out fast the same results as full EMT simulation not only by steady state, but also under transient processes.

However, the co-simulation takes a very long time for 134 seconds, which is regarded as very long for such a small test bench. Even though this co-simulation method can achieve fast the same results as full EMT simulation, it can not be applied for simulating large-scale power systems because of the huge time cost. As is already explained in Figure 5, the long duration is attributed to frequent data exchanges between both sub-modules through MATLAB work space.

Effect of acceleration

The same test bench as well as the same event as above is now studied with the DXiL acceleration method. The simulation results are shown in Figure 10. As is shown in Figure 10(a), the simulation time



(a) Single phase voltage in EMT subsystem with doubled simulation time.

(b) Single phase voltage after dealing with data processing.

Fig. 10: Simulation results with DXiL acceleration for conditions.

is doubled from 0.3 s to 0.6 s, and the fault duration is 0.2 s instead of 0.1 s. Interspaces can be observed in the sinusoidal wave, once the EMT subsystem is deactivated. The processed simulation result is shown in Figure 10(b), where the simulation time and fault duration are reset as 0.3 s and 0.1 s, respectively. The co-simulation with DXiL acceleration method can achieve complete the same results as co-simulation of separate EMT and RMS Simulink files, whereas the simulation duration is reduced from 134 seconds to 28 seconds.

Conclusions

EMT-RMS co-simulation aims at keeping the exact electro-magnetic transient process in DC network and avoiding unnecessary simulation electro-magnetic transient process in AC network, when the transient stability of large-scale hybrid AC/DC power systems is investigated. If the data exchange process brought about by co-simulation takes too much time, however, the original intention of co-simulation is violated. This work has figured out that the EMT and RMS programs are not worth to be paused by data exchange, especially when the RMS time step is set as low to 1-2 ms. With the DXiL interaction method, the data exchange is always going on during simulation running, liberating both EMT and RMS simulations from frequent pausing and restarting throughout the co-simulation.

Acknowledgments

This work was supported by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) under theproject OVANET 2.0 (0350037C).

References

[1] Liu, S., Xu, Z., Hua, W., Tang, G. & Xue, Y. Electromechanical transient modeling of modular multilevel converter based multi-terminal HVDC systems. *IEEE Transactions On Power Systems*. **29**, 72-83 (2013)

[2] Xiao, L., Xu, Z., Xiao, H., Zhang, Z., Wang, G. & Xu, Y. Electro-mechanical transient modeling of MMC based multi-terminal HVDC system with DC faults considered. *International Journal Of Electrical Power & Energy Systems*. **113** pp. 1002-1013 (2019)

[3] Beerten, J., Cole, S. & Belmans, R. Modeling of multi-terminal VSC HVDC systems with distributed DC voltage control. *IEEE Transactions On Power Systems*. **29**, 34-42 (2013)

[4] Longze, K., Lin, Z. & Fangyuan, L. Electromechanical modelling of modular multilevel converter based HVDC system and its application. *2017 IEEE Conference On Energy Internet And Energy System Integration (EI2)*. pp. 1-6 (2017)

[5] Wang, S., Zhao, X., Xue, F., Li, W., Peng, H., Shi, D., Wang, S. & Wang, Z. Electromechanical transient modeling of modular multilevel converter based HVDC network. *2019 IEEE Sustainable Power And Energy Conference (iSPEC)*. pp. 1845-1850 (2019)

[6] Du, W., Tuffner, F., Schneider, K., Lasseter, R., Xie, J., Chen, Z. & Bhattarai, B. Modeling of grid-forming and grid-following inverters for dynamic simulation of large-scale distribution systems. *IEEE Transactions On Power Delivery*. **36**, 2035-2045 (2020)

[7] Meer, A., Gibescu, M., Meijden, M., Kling, W. & Ferreira, J. Advanced hybrid transient stability and EMT simulation for VSC-HVDC systems. *IEEE Transactions On Power Delivery*. **30**, 1057-1066 (2014)

[8] Jalili-Marandi, V., Dinavahi, V., Strunz, K., Martinez, J. & Ramirez, A. Interfacing techniques for transient stability and electromagnetic transient programs IEEE task force on interfacing techniques for simulation tools. *IEEE Transactions On Power Delivery*. **24**, 2385-2395 (2009)

[9] Plumier, F., Aristidou, P., Geuzaine, C. & Van Cutsem, T. Co-simulation of electromagnetic transients and phasor models: A relaxation approach. *IEEE Transactions On Power Delivery*. **31**, 2360-2369 (2016)

[10] Meng, X. & Wang, L. Interfacing an EMT-type modular multilevel converter HVDC model in transient stability simulation. *IET Generation, Transmission & Distribution*. **11**, 3002-3008 (2017)

[11] Athaide, D., Qin, J. & Zou, Y. MATLAB/Simulink-based electromagnetic transient-transient stability hybrid simulation for electric power systems with converter interfaced generation. *2019 IEEE Texas Power And Energy Conference (TPEC)*. pp. 1-6 (2019)

[12] Peralta, J., Saad, H., Dennetière, S., Mahseredjian, J. & Nguefeu, S. Detailed and averaged models for a 401-level MMC–HVDC system. *IEEE Transactions On Power Delivery*. **27**, 1501-1508 (2012)