Functional Mock-up Interface Based Parallel Multistep Approach with Signal Correction for Electromagnetic Transients Simulations

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***Abstract*—This letter presents the latest improvements of a previously proposed parallel and multistep approach based on the Functional Mock-up Interface standard for the simulation of electromagnetic transients (EMTs). The improved approach extends the capacity of the original parallel asynchronous mode into accommodating the use of different time-steps in different decoupled subsystems. It also introduces a signal correction procedure using linear extrapolation in multistep simulations, greatly enhancing simulation flexibility, efficiency and accuracy. Numerical examples are provided to demonstrate the computational advantages of the improved approach.**

***Index Terms*—FMI, electromagnetic transients, parallel simulation, multistep simulation.**

I. Introduction

With the ever-growing popularity of Electromagnetic Transient (EMT) simulation tools [1]-[3] among utility engineers, the computing time reduction has become crucially important due to the constraint from numerical integration time-step as well as high accuracy models. In the meantime, state-of-the-art developments in HVDC systems and wind generation [4] have created more and more challenging cases for the studies of modern-day power systems, which also prompted computing time reduction to become a hot research topic.

Many techniques proposed over the years to improve computation speed in EMT-type solvers fall into two categories, which are *parallel* and *multistep* approaches (see references in [5]). Despite certain numerical advantages, the implementation of many of these techniques is limited by either the network decoupling interface, level of user intervention, or flexibility.

This letter proposes new developments that further enhance the performance of a previously proposed co-simulation-based parallel and multistep approach using the Functional Mock-up Interface (FMI) standard [6] for EMT simulations with complex control systems [5]. In the improved approach, the computation capacity of the original parallel asynchronous mode is extended into accommodating the use of different time-steps in different subsystems decoupled in memory, greatly improving simulation flexibility and efficiency. Furthermore, a signal correction procedure based on linear extrapolation is introduced to achieve higher accuracy in a multistep simulation environment. Test cases studied in this letter demonstrate that the newly developed features have markedly upgraded the previously proposed approach [5] in terms of flexibility, efficiency and accuracy.

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II. Improvements on an FMI-Based Parallel and Multistep Approach

A. Parallel Multistep Asynchronous Mode

The synchronization scheme between master and slaves in the improved parallel multistep asynchronous mode is divided into three scenarios based on the comparison of master and slave time-steps, as are presented in Fig. 1, Fig. 2, andFig. 3. The definitions of the terms in these figures can be found in [5].

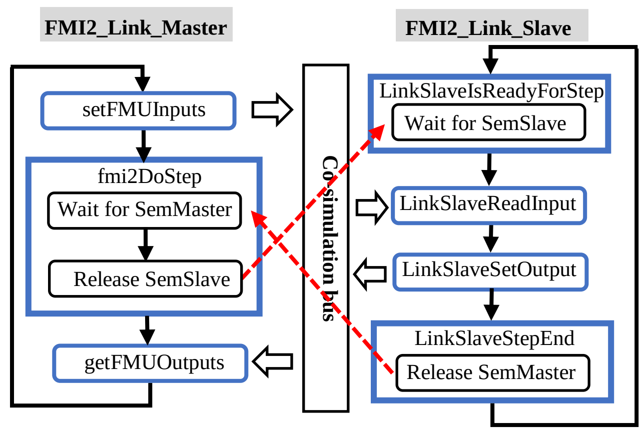

Fig. 1. First synchronization scenario ($\Delta t_{master} = \Delta t_{slave}$) between master and slave in the parallel multistep asynchronous mode.

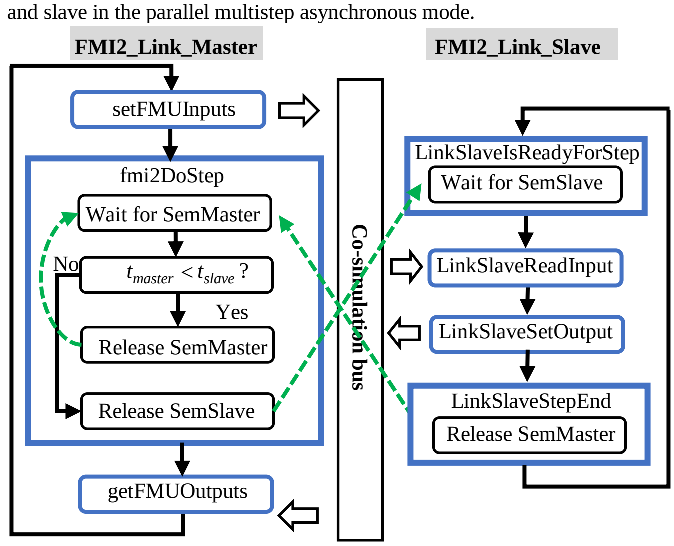

Fig. 2. Second synchronization scenario ($\Delta t_{master} < \Delta t_{slave}$) between master and slave in the parallel multistep asynchronous mode.

The first scenario (Fig. 1) in which $\Delta t_{master} = \Delta t_{slave}$ was already implemented in [5].

In the second scenario where $\Delta t_{master} < \Delta t_{slave}$ (Fig. 2), after waiting for the slave to release SemMaster, the master keeps releasing SemMaster to itself if it lags behind the slave to catch up with the latter, and it releases SemSlave to the slave once it catches up such that both can execute their subsequent calculations simultaneously.

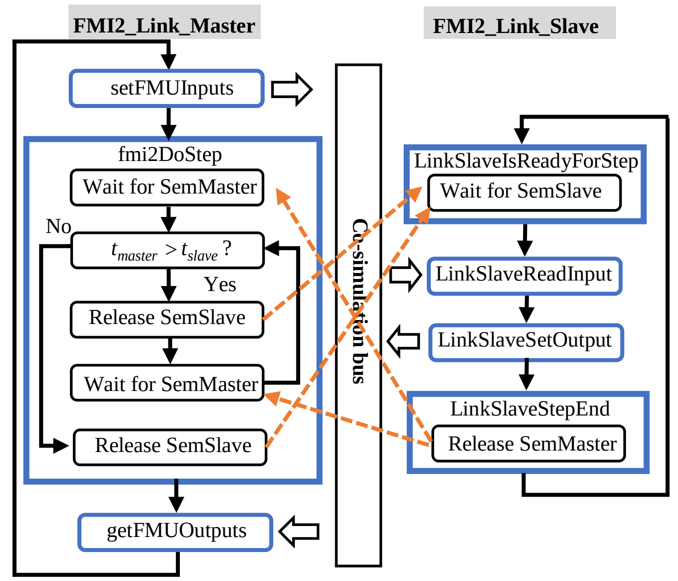

Fig. 3. Third synchronization scenario ($\Delta t_{master} > \Delta t_{slave}$) between master and slave in the parallel multistep asynchronous mode.

If $\Delta t_{master} > \Delta t_{slave}$ (third scenario), the master keeps releasing SemSlave to the slave for it to catch up if it lags behind. Once the slave catches up, the master releases SemSlave once more and both continue their subsequent calculations in parallel. Such an improved synchronization mechanism allows multiple time-steps to be employed in the parallel asynchronous mode, considerably enhancing simulation flexibility with the use of single or multiple time-steps in both co-simulation modes.

B. Linear Extrapolation-Based Signal Correction

The proposed linear extrapolation-based correction procedure is implemented for floating-point type signals in the pre-built function *getFMUOutputs* (see Fig. 1Fig. 2, andFig. 3) whose main functionality is to read data exported from the slave.

Vector $\mathbf{y}_{slave}$ of size n (number of floating-point type signals) represents floating-point type outputs from the slave at $t=T$, and an extrapolation vector $\mathbf{y}_{extrapol}$ of size $2n$ is used to sequentially store floating-point type slave outputs at $t=T-\Delta t_{slave}$ and $t=T-2\Delta t_{slave}$,

$$\mathbf{y}_{extrapol} = [\overbrace{\mathbf{y}_{slave,T-\Delta t_{slave}}}^{n}, \overbrace{\mathbf{y}_{slave,T-2\Delta t_{slave}}}^{n}] \tag{1}$$

Extrapolation on $\mathbf{y}_{slave}$ is performed if the master keeps advancing and reading in the same data at $t=T$ as at $t=T-\Delta t_{slave}$ ($\mathbf{y}_{slave}=\mathbf{y}_{extrapol}[1:n]$) while the slave, having a larger time-step, remains idle (see Fig. 17 in [5]). Otherwise, only the contents of $\mathbf{y}_{extrapol}$ are updated as the slave has advanced one step in time, no extrapolation is hence needed,

$$\mathbf{y}_{extrapol}[n+1:2n] = \mathbf{y}_{extrapol}[1:n] \tag{2}$$

$$\mathbf{y}_{extrapol}[1:n] = \mathbf{y}_{slave} \tag{3}$$

III. Numerical Examples

The improvements presented in this letter have been validated in terms of accuracy and simulation efficiency on a practical system benchmark using different scenarios as shown in Table 1. In this table the Original Case provides the reference waveforms from the single-core benchmarks without co-simulation. In all cases, a multiphase unbalanced load-flow solution is performed to initialize the time-domain solution where a fault condition is simulated. A numerical integration time-step of 5 µs is used in the electrical network for all shown examples.

TABLE 1 Test Case Co-simulation Mode Scenarios

	Co-simulation mode	WP control Δt (µs)
Original Case	N/A	5
Scenario 1	Asynchronous	5
Scenario 2	Asynchronous	50
Scenario 3	Asynchronous	100
Scenario 4	Synchronous	50
Scenario 5	Synchronous	100

A. Accuracy Validation

This test validates the accuracy of the newly developed features, using the test benchmark presented in Fig. 4, which is a network consisting of 3 wind park (WP) feeders connected to a collector grid and an equivalent network represented by a Thevenin equivalent. The detailed model [4] whose control system contains 2235 blocks, is used for all wind generators. The detailed WP control systems are modeled in FMI slaves.

The results with four wind generators (two in F1, one in F2 and F3 each) for Scenarios 3 and 5 are selected and presented below, in which both scenarios (asynchronous and synchronous) with and without signal correction (SC) are compared with the Original Case. The simulation interval is 10 s for all cases and a three-phase fault of 0.15 s occurs at $t=5s$. The average active power from the three feeders and the phase-a voltage at the 34.5 kV bus, are presented in Fig. 5 and Fig. 6 with clear observation in amplified intervals.

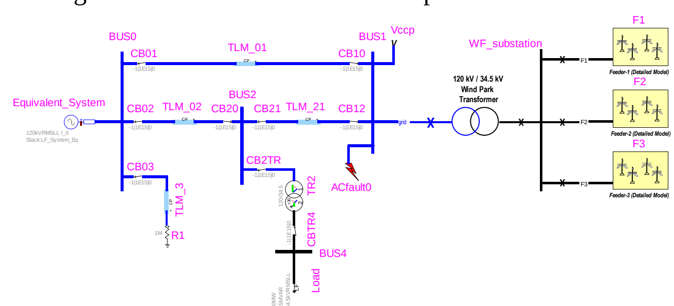

Fig. 4. Test benchmark.

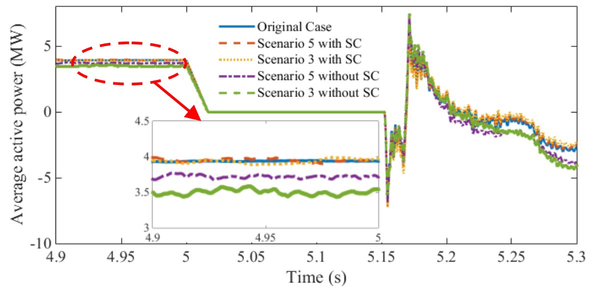

Fig. 5. Average active power from wind park feeder.

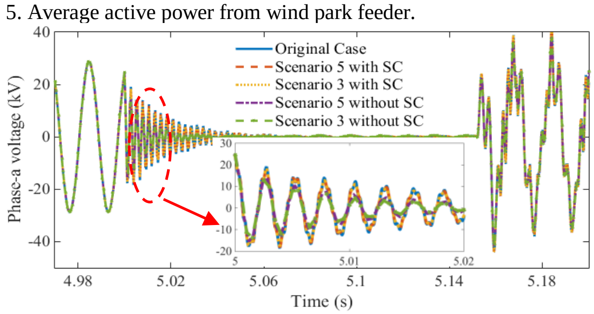

Fig. 6. Phase-a voltage at the 34.5 kV bus.

Firstly, it is observed that the newly implemented parallel multistep asynchronous mode (Scenario 3) offers comparable accuracy with the previously developed sequential multistep synchronous mode (Scenario 5), demonstrating that this new feature does not affect accuracy. Secondly, the accuracy of both modes can be greatly improved with the implementation of SC compared with the Original Case.

B. Computation Time Gains

The tests performed in this section demonstrate the numerical performance advantages of the improved approach with parallel multistep asynchronous mode on the same test benchmark shown in Fig. 4. A 24-core PC with Intel (R) Xeon (R) E5-2650 v4 processors is used. The tests include the Original Case and 5 co-simulation scenarios (Table 1). The simulation interval is 2 s for all cases. It is noted that different numbers of wind generators (slaves) are used in the three feeders to test the performance and scalability of the proposed method.

The solution time speedup in comparison to the Original Case with respect to the number of slaves is shown in Fig. 7. It is observed that substantial solution time speedup can be obtained in all scenarios, but the parallel multistep asynchronous mode (Scenarios 2 and 3) renders the highest speedup that was not observed in the scenarios of the previously developed approach (Scenarios 1, 4, and 5) [5], confirming that the newly developed parallel multistep asynchronous mode further enhances simulation efficiency.

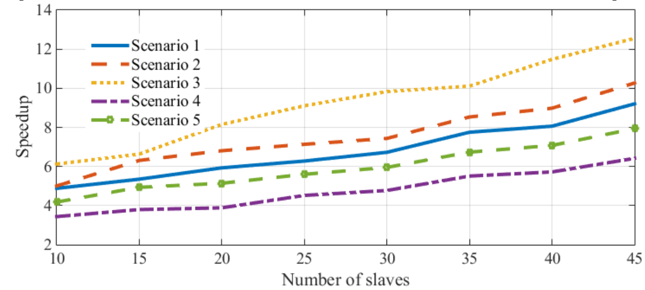

Fig. 7. Solution time speedup with respect to the number of slaves.

CONCLUSION

This letter presented latest improvements for a previously proposed FMI-based parallel and multistep approach for EMT simulations using a new parallel multistep asynchronous mode and a linear extrapolation-based signal correction procedure. The newest features have been proven via different tests to further enhance efficiency and accuracy in power system EMT simulations with computationally expensive control systems.

REFERENCES

[1] J. Mahseredjian, S. Dennetière, L. Dubé, B. Khodabakhchian, and L. Gérin-Lajoie, "On a new approach for the simulation of transients in power systems," *Electric power systems research*, vol. 77, no. 11, pp: 1514-1520, 2007.

[2] A. Ametani, "Numerical Analysis of Power System Transients and Dynamics", IET (The Institution of Engineering and Technology), 2015.

[3] J. Mahseredjian, V. Dinavahi, and J.A. Martinez "Simulation Tools for Electromagnetic Transients in Power Systems: Overview and Challenges," *IEEE Trans. on Power Delivery*, vol. 24, issue 3, pp. 1657-1669, July 2009.

[4] U. Karaagac, J. Mahseredjian, L. Cai, and H. Saad, "Offshore Wind Farm Modeling Accuracy and Efficiency in MMC-Based Multi-Terminal HVDC Connection," *IEEE Trans. on Power Delivery*, vol. 32, no. 2, pp. 617-627, April 2017.

[5] M. Cai, H. Gras, J. Mahseredjian, E. Rutovic, and A. El-Akoum, "Functional Mock-up Interface-Based Approach for Parallel and Multistep Simulation of Electromagnetic Transients," *IEEE Trans. on Power Delivery* (Early Access).

[6] Modelica Association Project "FMI", "FMI for Model Exchange and Co-Simulation - Version 2.0," 2014.