Powerful Advanced N-Level Digital Architecture
for models of electrified vehicles and their components

Research Innovation Action

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all types of electrified vehicles and components

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Written By	Fei Gao (UBFC) Eduard-Edis Raclaru (SISW)	2020-12-27 2021-02-19
Checked by	Walter Lhomme (ULille) Gabriel-Mihai Sîrbu (RTR)	2021-03-04 2021-02-25
Approved by	Cristir Irimia (WP4 leader) Alain Bouscayrol (coordinator)	 2021-04-12
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Publishable Executive Summary

Air pollutant emissions from transport are one of Europe's main concerns in controlling the air quality. Emission regulations are in place as part of the EU framework for light-duty and heavy-duty road vehicles. As part of the Horizon 2020 initiative of the European Commission, project PANDA addresses new technological developments to accelerate vehicle electrification which helps protect the environment and reduce the air pollution. The current report belongs to Work Package (WP) 4 of the PANDA project related to electrified vehicle virtual testing. As the result of task 4.4 of WP 4, the current report addresses the system level simulation of fuel-cell electric vehicles.

Technical advancements in fuel-cell based electric vehicles offer an alternative to road vehicles for reducing air pollution. New research and development on fuel-cell vehicles relies on system level simulations to test new vehicle technologies, architectures, and control. Also, system level simulations represent an integrated step in the virtual development of fuel-cell vehicles that helps optimize system design and reduces the costs and time through identifying design flaws early in the development process. In task 4.4, a framework that allows for running fuel-cell vehicle simulations is provided though prebuilt and reconfigurable models of fuel-cell vehicles.

In the PANDA project, the model organization is based on the EMR (Energetic Macroscopic Representation) methodology. Using this representation, models for fuel-cell electric vehicles are developed at the component level and integrated into system level complete vehicle simulations. The purpose of this report is to present the validation of fuel-cell vehicle (FCV) models and to prove the performance of the methodology proposed by using reconfigurable multi-level models.

One of the advantages of the proposed methodology is the flexibility of the simulations, in which components or subsystems models can be replaced with other components or subsystems models, of possibly different complexity, in a seamless manner such that the transition from one type of simulation to another is made easily. In this way, by quickly replacing a subsystem model and adjusting some model parameters, we can perform, through simulation, both subsystem performance tests and global performance tests. In this report, besides the validation of the global vehicle performances, we test the flexibility of the simulation architecture when models are changed.

To prove the accuracy of the models developed, simulation results of the global traction system for the FCV are compared with measured data from a real vehicle. Mobypost is the vehicle that was chosen to perform the tests which were carried on the daily postal delivery track from La Poste by UBFC. Simulations are done using Matlab-Simulink© software and Simcenter Amesim© software provided by the partner SISW. A complete vehicle model of the Mobypost is provided by UBFC by modelling each of the vehicle components using the EMR formalism and integrating them into the complete system model. Validation of the complete vehicle model was done by UBFC, SISW and ULille. The flexibility of the FCV simulations using EMR is tested by replacing the current battery model with other multi-level battery models built by VUB. Thus, the accuracy and efficiency of different simulations was proven, and the model organisation capability was demonstrated.

The comparison between simulated and measured results was done to evaluate the models regarding simulation results precision and time of computation, to ensure a necessary level of quality both for virtual but also real testing.

Contributions:

No	*Who*	*Description*	*Date*
1	F. Gao (UBFC)	Report creation and outline	2020-12-27
2	F. Gao (UBFC)	Section 1, 2, 3	2021-01-18
3	E. Raclaru (SISW), C. Husar (SISW)	Section 4	2021-02-19
	E. Raclaru (SISW), C. Husar (SISW), J. Jaguemont (VUB)	Section 4.2	2021-02-19
4	F. Gao (UBFC), E. Raclaru (SISW), C. Husar (SISW)	Section 5	2021-02-19
5	F. Gao (UBFC), E. Raclaru (SISW), C. Husar (SISW)	Update and conclusions	2021-03-25
6	F. Gao (UBFC), E. Raclaru (SISW), C. Husar (SISW), W. Lhomme (ULille)	Finalization	2021-03-25

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4.1 Simulation and validation of the FCV model

The FCV model is also implemented in Simcenter Amesim© to be made available for virtual testing. The validation of the model is done on the driving cycle of the test scenario shown in Figure 2, which is collected based on the daily postal delivery track from *La Poste.* The Simcenter Amesim© simulation of the Mobypost FCV model is organized in the EMR. Figure 19 shows the Simcenter Amesim© implementation of the model. The EMR library for Simcenter Amesim© [PANDA D4.1] has been used to implement the EMR diagram of the Mobypost test vehicle in Simcenter Amesim©. The simulation in Simcenter Amesim© is done with a 1ms fixed time-step solver for the driving cycle from 0 to 10800s (3 hours).

The validation procedure consists of a comparison between system signals measured from the real vehicle and from the virtual vehicle in simulations. The real vehicle signals are measured when performing, on track, the test scenario shown in Figure 2. The virtual vehicle signals are obtained through simulation in Simcenter Amesim© on the same test scenario. The results of the validation will be shown through plots where (when it is the case) in solid red line we indicate measured variables from the real test, while with dashed blue lines we indicate simulated variables from simulation in Simcenter Amesim©.

In simulation, we can reproduce the vehicle velocity by simulating the vehicle longitudinal dynamics, given the imposed vehicle velocity reference in Figure 20 . A detailed plot of the results but on a smaller time window is shown at the bottom of Figure 20. Longitudinal tracking of an imposed vehicle velocity profile is demonstrated. Vehicle velocity controller can be tested, and its performances evaluated with the built simulation. The results in Figure 20 show accurate predictability power of the developed models, though the small differences between measured and simulated vehicle velocity.

Given the imposed vehicle velocity profile, using our model, we can predict the required e-drive rotor angular velocities for both the in-wheel motors. A comparison of the measured and simulated rotor angular velocities is shown in Figure 21.The small differences between the two signals indicate good predictability and thus model validation for the rotor angular velocities.

The total power delivered to the two motors from the Energy Storage System is measured at the DC-link side. A comparison between measured and simulated DC-link Power, made in Figure 22, shows accurate prediction of the real e-drive power request, made by our model. In indicates the e-drive's ability to predict the request of power necessary for traction over the desired vehicle velocity profile. The results in Figure 22 validate the prediction of the DC-link power prediction. The energy is computed from the power through integration and it is plotted in Figure 23. The error between measurement and simulation, in energy delivered to the e-drive, at the end of the driving cycle 10800 s, is expressed as

$$\frac{E_{dc-bus,meas} - E_{dc-bus,sim}}{E_{dc-bus,meas}} 100\% = 2.04\ \% \qquad (33)$$

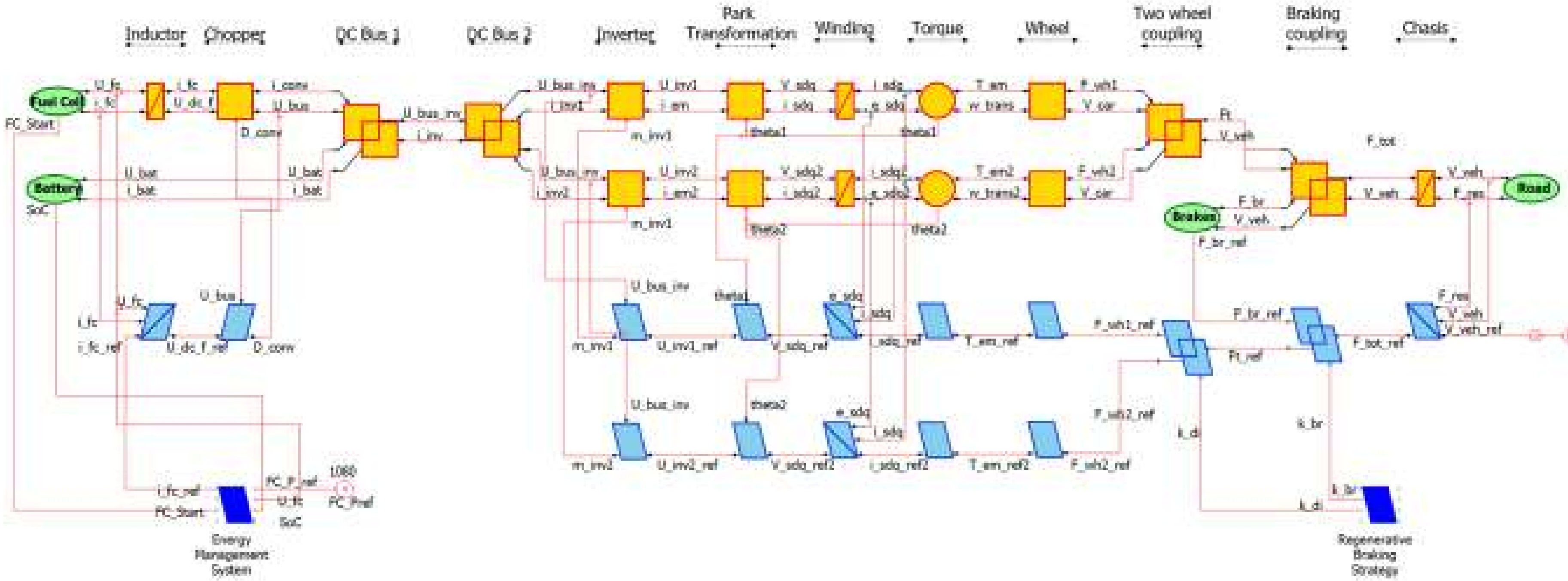


Figure 19 Simcenter Amesim implementation of Mobypost EMR model.

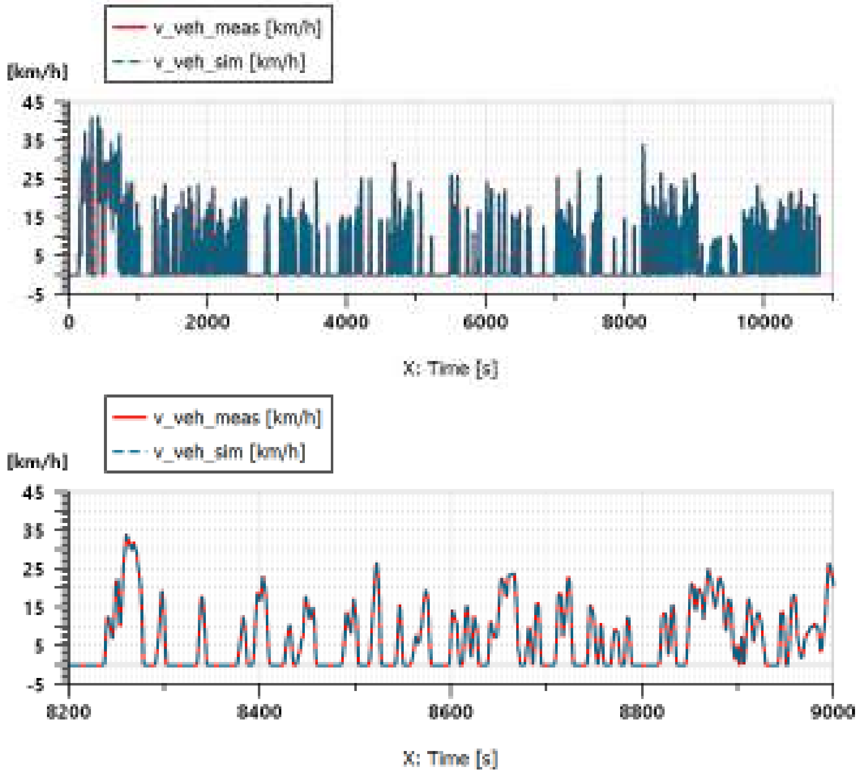


Figure 20 Vehicle speed.

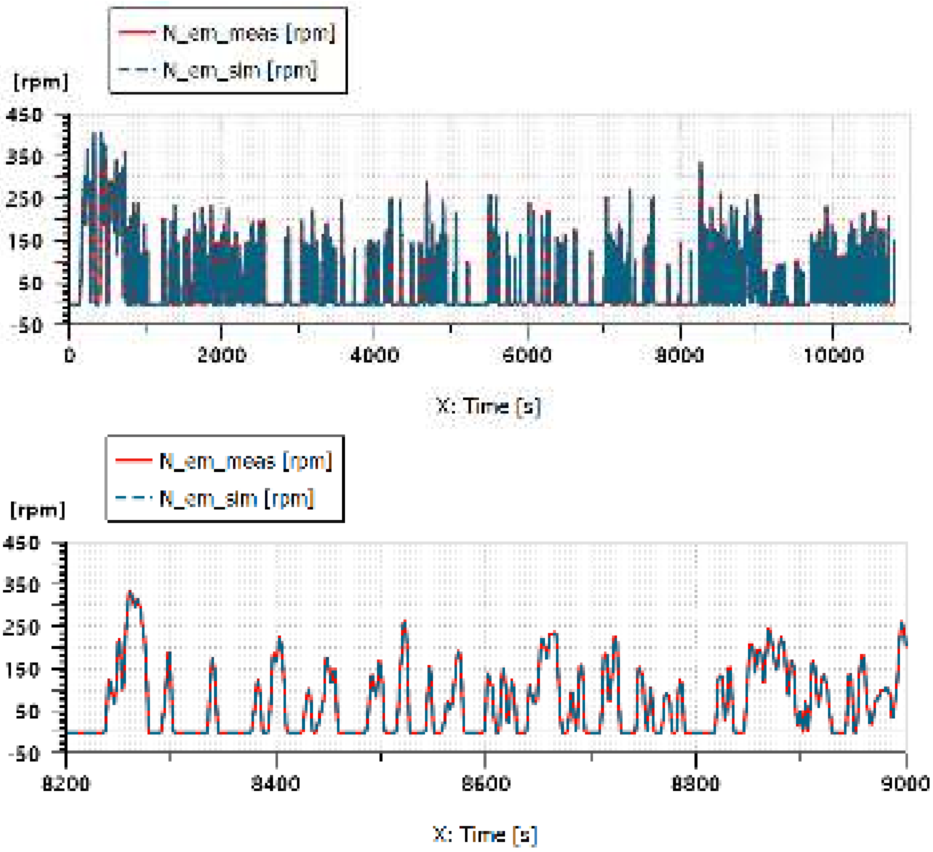


Figure 21 E-drive motor rotating speed.

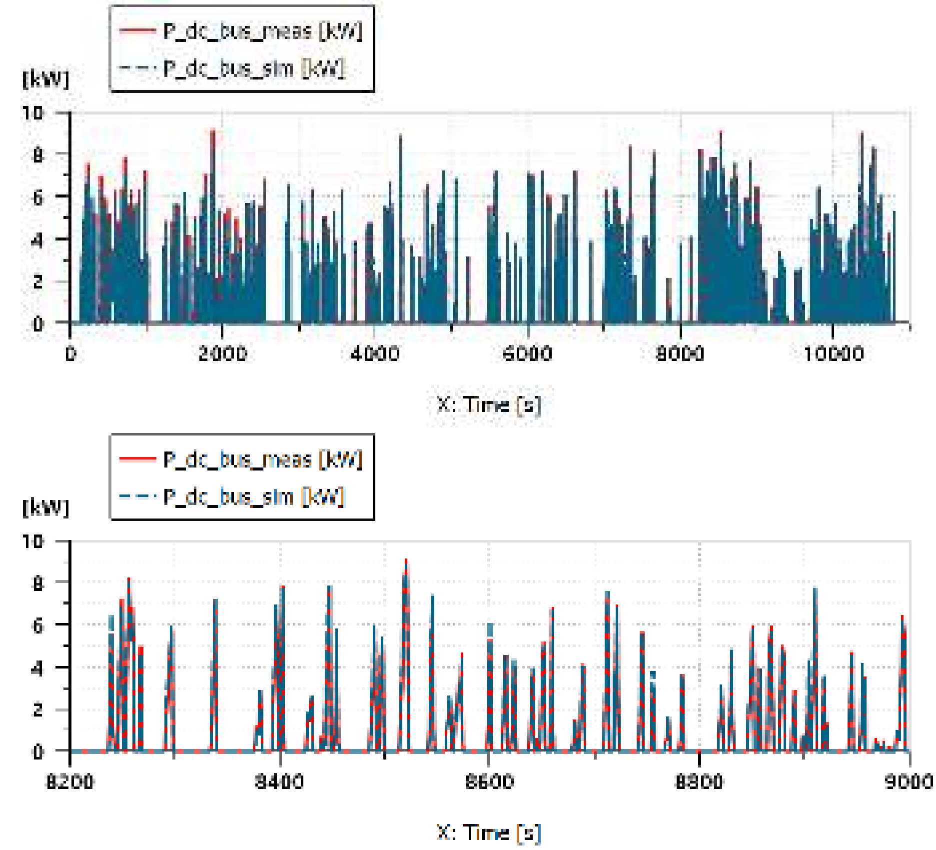


Figure 22 Total power consumptions of two e-drives measured in the DC side.

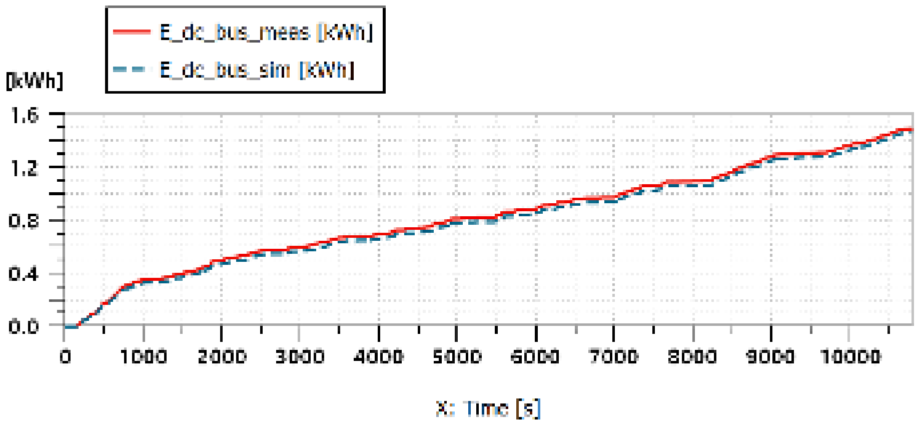


Figure 23 DC Bus Energy transferred measured and simulated.

The error result is due to model uncertainty, the simplified model of the e-drive, to the simple constant e-drive efficiency and simplified road conditions in terms of weather, slopes, traffic and wheel friction.

The power requested by the e-drive for traction is supplied by the Energy Storage System made of the Battery and the Fuel Cell stack. Our model can be used to predict the battery state-of-charge (SoC) as well as fuel-cell tank state-of-charge. The model can be used for virtually testing the Energy Management System before the real testing. The results in Figure 24 and Figure 25 show satisfactory prediction power of our model. Errors occur due to unmodeled complex phenomena (e.g. in battery and fuel cell), unmodeled effects of modules such as auxiliary consumers, simple vehicle dynamics model such as no complex tire-road interaction. Another factor influencing the prediction is the use of constant efficiency models instead of more complex losses model. However, such complex models are not well suited for system-level simulations. On top of that, the simulation test is over a long period of time which makes the error accumulation more noticeable and the computation time long for complex models. Even with our system-level simulation, the prediction of battery SoC and fuel-cell tank SoC, over long simulation tests, are accurate enough to be used for system-level virtual testing Equations (24).

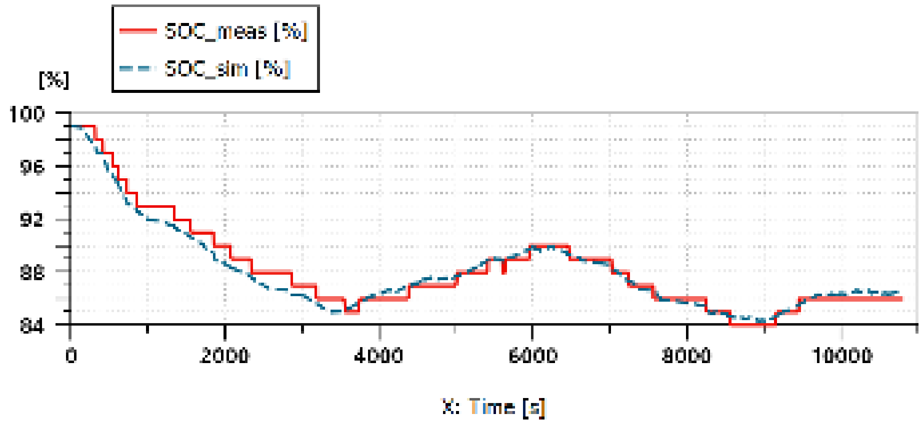


Figure 24 Battery SOC.

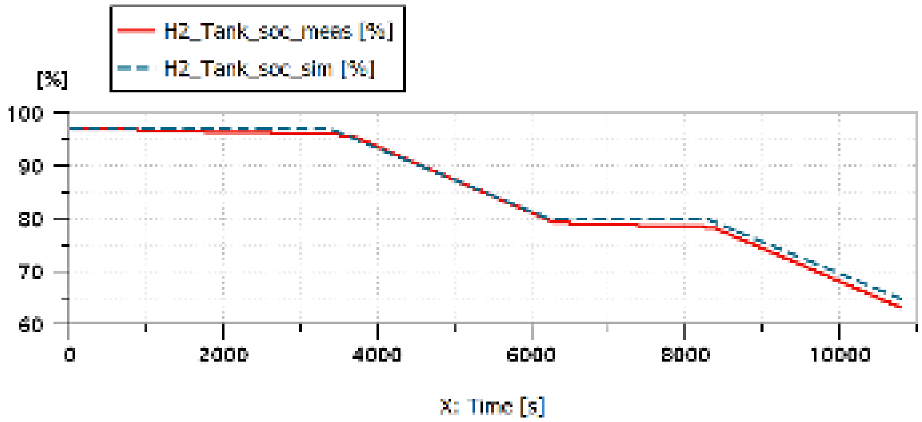


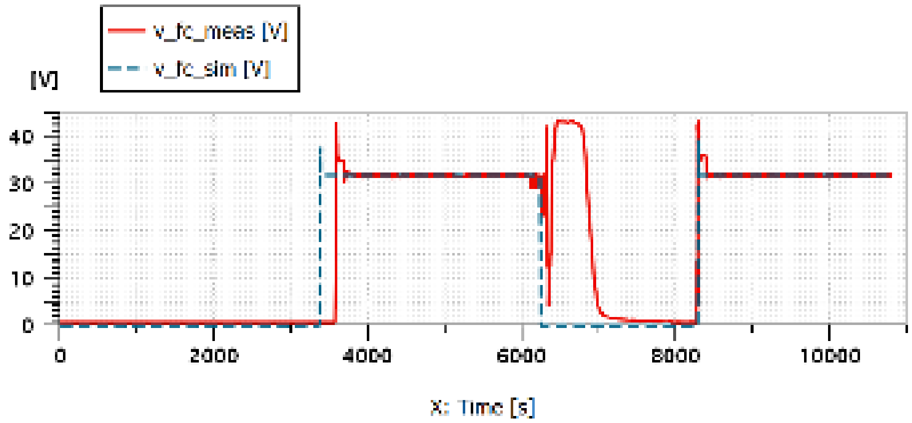
Figure 25 H2 tank SOC.

For both the fuel-cell stack and the battery, the error in SOC at the end of the cycle (t=10800 s) is given by the difference between the SOC measured and SOC simulated.

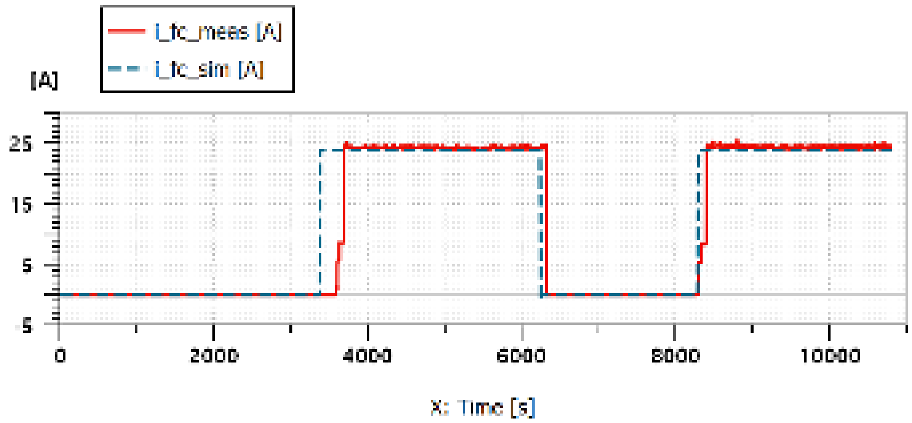
$$\begin{cases} errSOC_{bat} = \ |SOC_{bat,meas} - SOC_{bat,sim}| = 0.74\ \% \\ errSOC_{fc} = |\ SOC_{fc,meas} - SOC_{fc,sim}| = 1.6\ \% \end{cases} \tag{26}$$

The measure of the error is influenced by the unprecise measurement of the battery SOC in Figure 24.

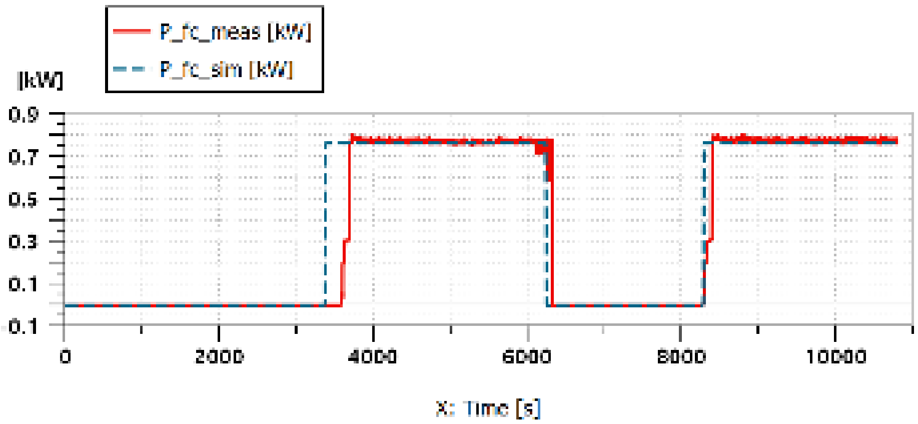
Using our model, we can evaluate the electrical behaviour of the fuel-cell and its contribution to electrical energy supply for traction. Figure 26 compares the measured and simulated electrical variables current, voltage and power delivered. Steady-state results show good predictions made by our model.



(a) Fuel cell voltage



(b) Fuel cell current



(c) Fuel cell output power

Figure 26 Fuel cell output voltage, current, power

The mean error normalized by the current measured value, for the fuel-cell current and voltage, in the steady-state interval [4000,5000] seconds, are small

$$\begin{cases} err(i_{fc}) = \dfrac{|i_{fc,meas} - i_{fc,sim}|}{i_{fc,meas}} 100\% = 1.21\% \\ err(v_{fc}) = \dfrac{|v_{fc,meas} - v_{fc,sim}|}{v_{fc,meas}} 100\% = 0.7\% \end{cases} \tag{34}$$

Some noticeable differences are seen during the start-up and shutdown phases, which depend on the battery SOC. Thus, the small errors due to SOC prediction lead to a delayed activation or deactivation of the fuel-cell stack. Even with the delayed start-up and shutdown times, the model is validated as it is accurate enough to be used for system-level virtual testing.

The battery model is used in vehicle simulation to predict the electrical behaviour of the battery. The measured and simulated battery power in Figure 27 shows accurate predictions made by the model. As such, an accurate evaluation of energy supply can be made with the virtual model. The difference, between measurement and simulation, in energy supplied by the battery is expressed as

$$\frac{E_{bat,meas} - E_{bat,sim}}{E_{bat,meas}} 100\% = 4.45\% \quad (35)$$

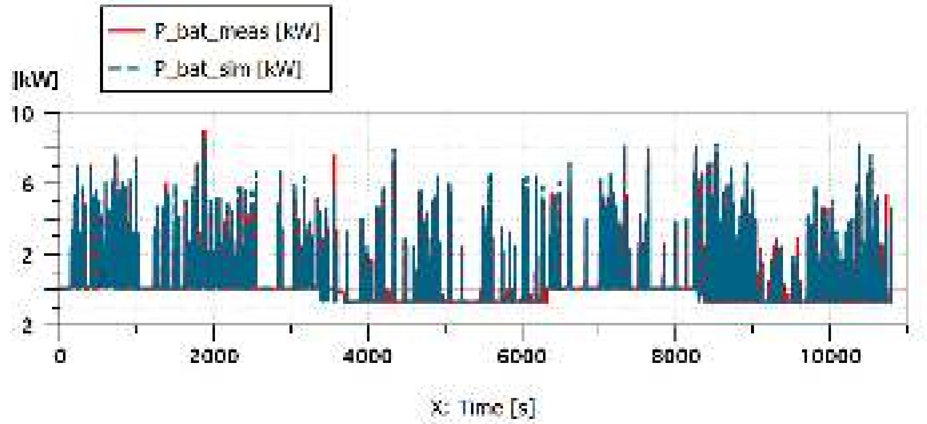


Figure 27 Battery output power.

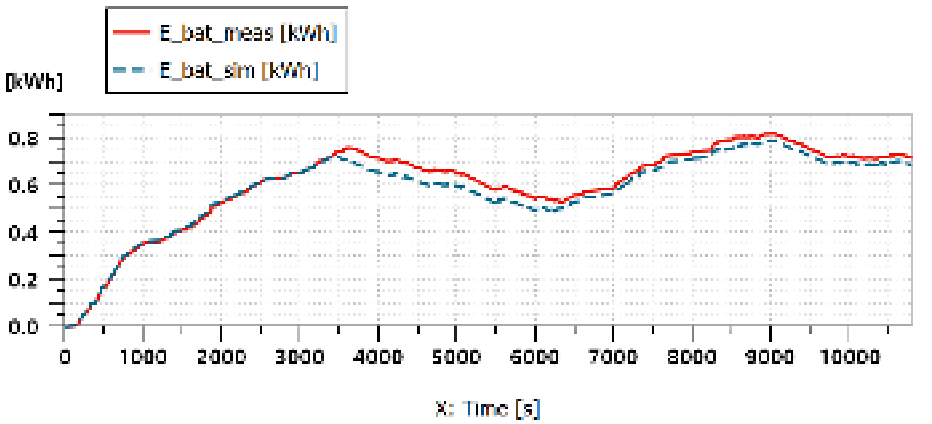


Figure 28 Battery Energy used measured and simulated.

The prediction error for the battery energy is influenced by the difference between measured and simulated E-drive requested energy, and in general by the model uncertainties, especially the uncertainty due to simple constant efficiency factors used.

Using the test scenario based on the daily postal delivery track from La Poste, we have tested and validated the developed FCV model developed in PANDA and implemented in Simcenter Amesim© using the EMR methodology. The system-level simulation involves the simulation of the entire FCV. All the vehicle components are in one simulation interacting with one another, in a holistic manner, to produce accurate simulation results of the complete system-level vehicle behaviour in the given testing scenario.

Once again, most of the errors between simulation and experimental results are within the margin of 2% that is relevant at the system level. Only the battery has an error about 5% that can be explain by 1) a simplified battery model and 2) the possible ageing of the battery. A more accurate battery model with updated parameters from the battery ageing could be a relevant perspective.

The model built is suitable for use in FCV product-lifecycle management. It can be used to virtually test the controllers and the supervisory systems before the real tests. We can thus reduce the costs due to real testing such as using a HIL platform, by solving most of the potential problems in the virtual testing phase using the FCV EMR model in Simcenter Amesim©.

4.2 Multi-level simulation of FCV

System simulations can be done using different complexity models depending on the desired target. We show how FCV simulations with EMR, in Simcenter Amesim©, can be extended to allow for multi-level simulations.

Another battery pack has been added instead of the original one and the vehicle design was tested using simulation in Simcenter Amesim©. We use the same velocity profile as in the last section as reference for the driver. The battery is different from the one used in the previous simulation so the results will be different for the battery predicted variables: current, voltage, state-of-charge. In the context of this section we show that the built model allows for multi-level simulation, by evaluating the system design for the new battery added to our vehicle.

Two level models are used for the battery, one which captures the electrical behaviour only (Figure 35 top, Figure 30) and the other which predicts the electro-thermal behaviour (Figure 35 bottom, Figure 31) [PANDA D2.1].

The first electrical model of a cell is built on the 1st order Thevenin model [PANDA D2.1] (Figure 29) and consists in a voltage source with an ohmic resistance and a parallel RC circuit. Based on the equivalent circuit model, the cell output voltage of the Li-ion cell is the voltage drop resulting from the battery open-circuit voltage (OCV), the battery ohmic resistance (R_0), and battery polarization impedance (R_1C_1 circuit).

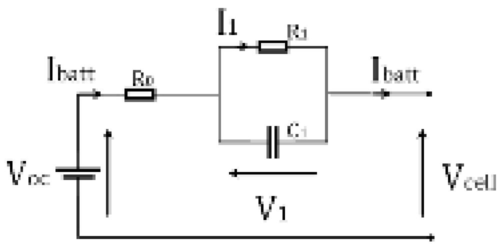


Figure 29 Representation of a 1st order Thévenin model.

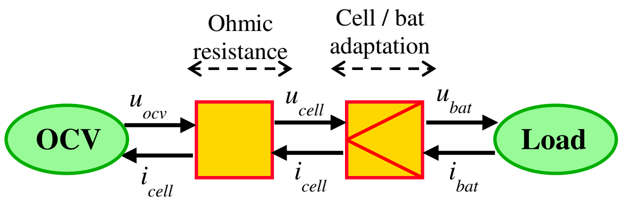


Figure 30 EMR of the first battery model.

The second battery model is an electro-thermal model [German 2020]. The electrical part of the model is the first battery model and was presented previously. Concerning the thermal model, the battery pack is considered as a single thermal component with one temperature point. This means a global heat generation, specific heat capacity and convective coefficient are considered, only the mass is multiplied by the total number of cells, assuming that Joule losses are equally generated from all cells [PANDA D2.1].

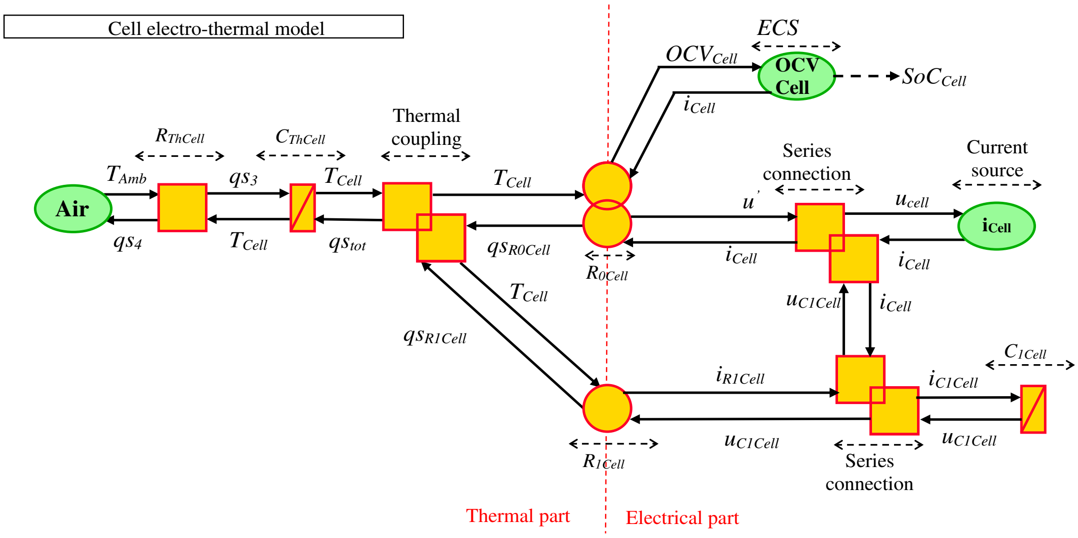


Figure 31 EMR of the dynamical electro-thermal model of a single cell.

The simulation is executed for the same driving cycle as in Figure 2 with the fixed-step solver at a sampling rate of 1 ms. Figure 32 presents the energy measured at the DC bus side when using two different complexity battery models in the FCV configuration of the Mobypost. We want to underline that the battery models are not the original batteries of the Mobypost, these are virtual batteries which are tested. The results indicate that both models have similar performances in predicting the energy consumption over the selected driving cycle. Figure 33 shows the prediction of the battery state-of-charge for the two model levels. The predictions can be evaluated as part of the vehicle functional design process. Again, we see similar performances for the two battery models also for SOC prediction. On top the battery SOC, the thermo-electric battery model can predict also the thermal behaviour. The battery temperature evolution is shown in Figure 34, which can be used for thermal management design.

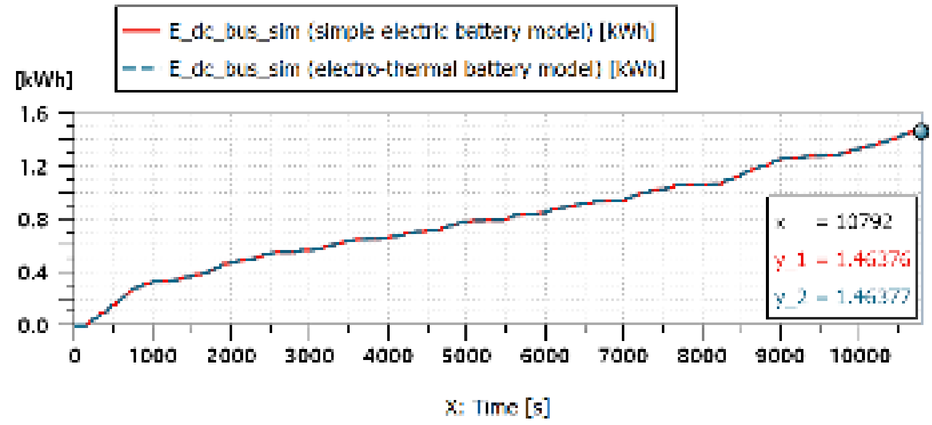


Figure 32 DC bus side Energy provided for multi-level battery FCV.

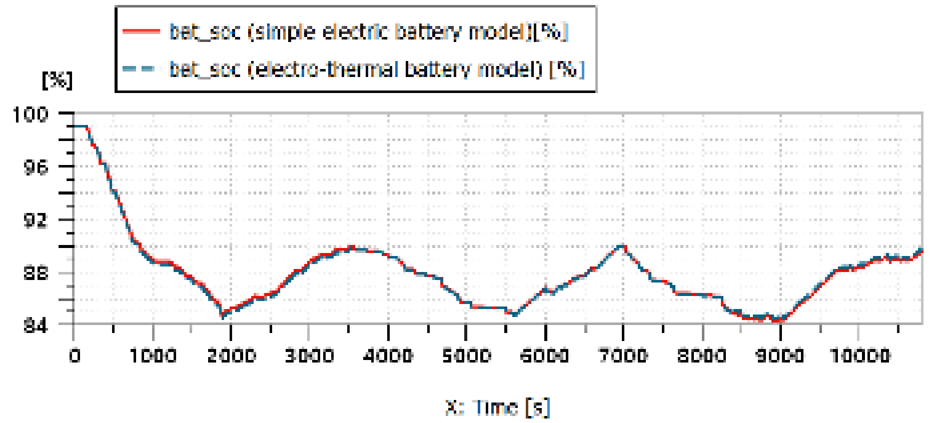


Figure 33 Battery state-of-charge for two-level battery models.

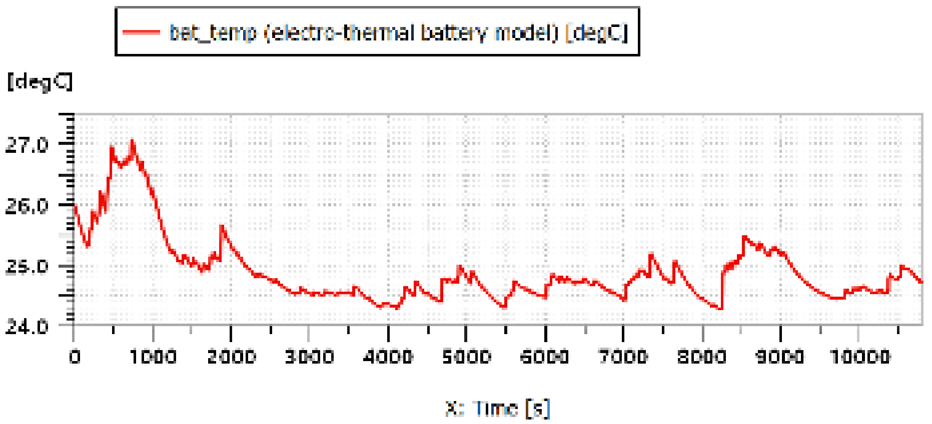


Figure 34 Temperature evaluation for the level 2 battery model

The built FCV model proves to be capable of multi-level simulation using the EMR methodology, though the example of multi-level battery model. The model base can be extended for other models as well, to allow for flexible simulations that can be used at different stages of the virtual system development.

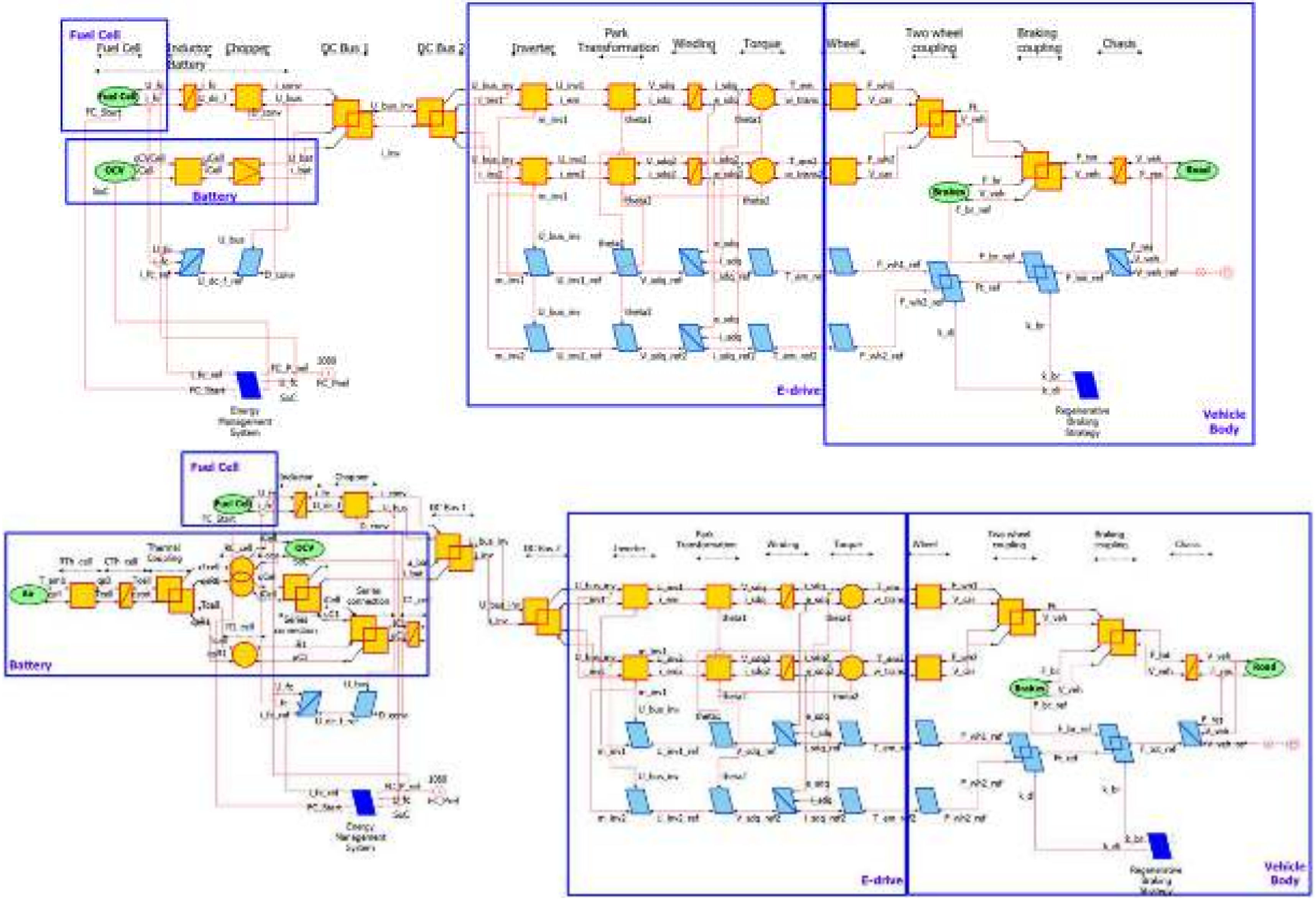


Figure 35 Simcenter Amesim© implementation of Mobypost EMR model with multi-level battery model.

4.3 Cloud computing

Cloud computing offers a flexible and cost reducing alternative for the user when he is not in possession of a performant computing device. It helps also in the case of not having direct access to a computer with Simcenter Amesim© licence on it [PANDA D4.2].

Simulations of the FCV model have also been done with the Cloud computing platform used in PANDA. The model has been transferred to the Cloud computing platform using the Panda explorer tool developed in PANDA, where a simulation was executed using the vehicle velocity cycle in Figure 2.

The simulation time-of-execution is comparable between the simulation ran on the personal computer and the simulation ran on the virtual machine Figure 36. The performance specifications of the computing machines are shown in Figure 37. The Cloud machine offers computation time similar to the local computer, considering the performances of both machines.

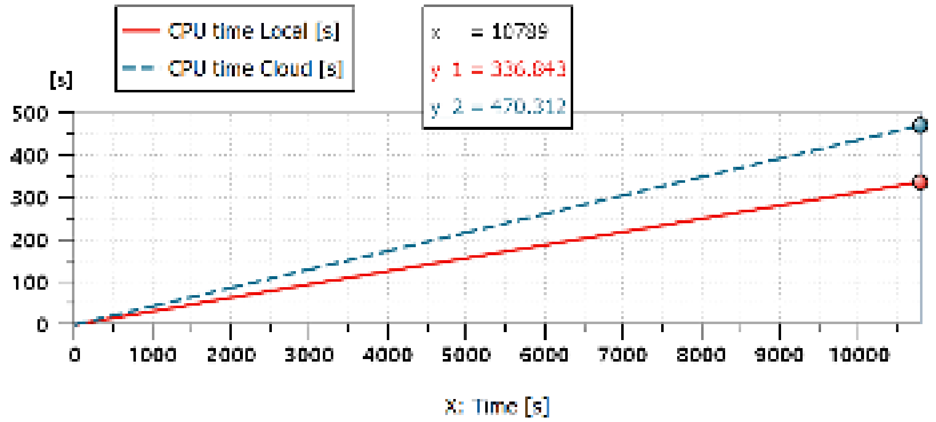


Figure 36 Simulation time-of-execution comparison between Cloud and local.

Stand-alone computer specifications	Cloud computing specifications
Processor: Intel Core I7-9850H @ 2,60GHz Installed memory (RAM): 32,0 GB Operating system: Windows 10 Enterprise	Processor: Intel Xeon E5-2666 v3 @ 2,90GHz Installed memory (RAM): 15,0 GB Operating system: Windows Server 2012 R2

Figure 37 Computing machines performance specifications.

The FCV model developed in PANDA permits simulation on the Cloud computing platform. It allows fast simulations to be executed without the need of a performant but expensive device or in the case of not having access to a computer with Simcenter Amesim© license on it. In conclusion, the developed FCV model can be simulated on the Cloud platform which offers great flexibility in terms of executing simulations for virtual vehicle development process.

4.4 Simcenter Amesim and Matlab Simulink simulation comparison

The results of the FCV simulations carried in Simcenter Amesim© and Matlab Simulink© are compared to see if there are any differences (Figure 38-45). Comparison in made based on the driving cycle in Figure 2.

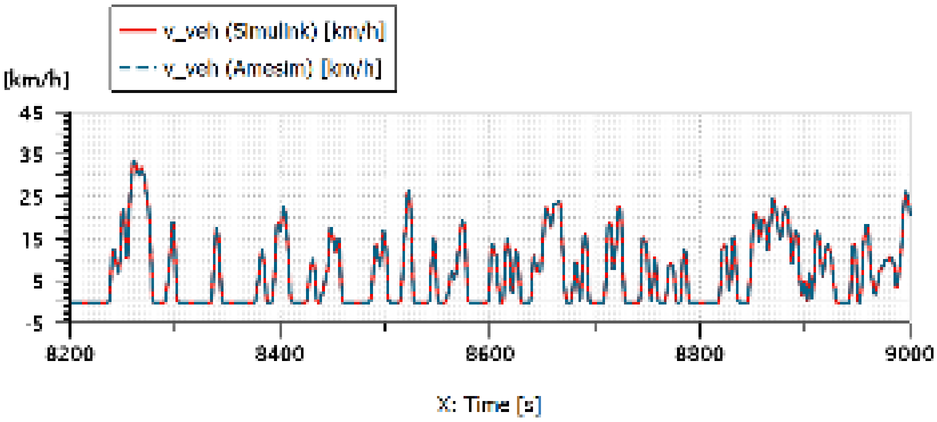


Figure 38 Vehicle speed.

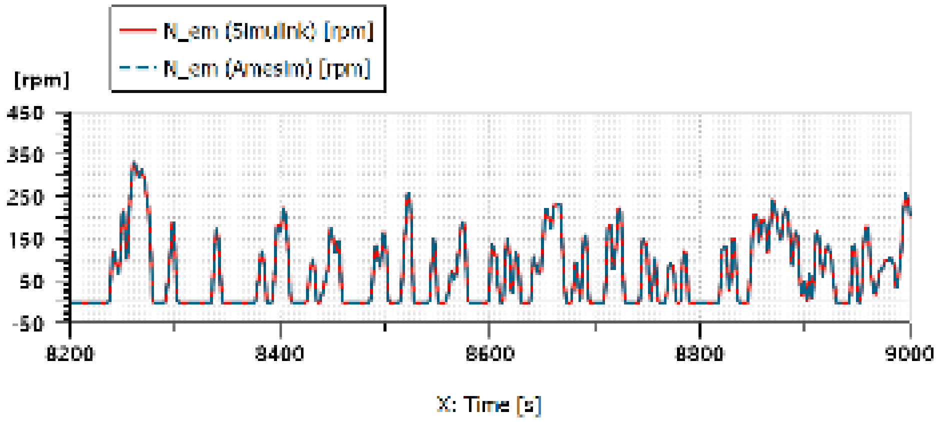


Figure 39 E-drive motor rotating speed.

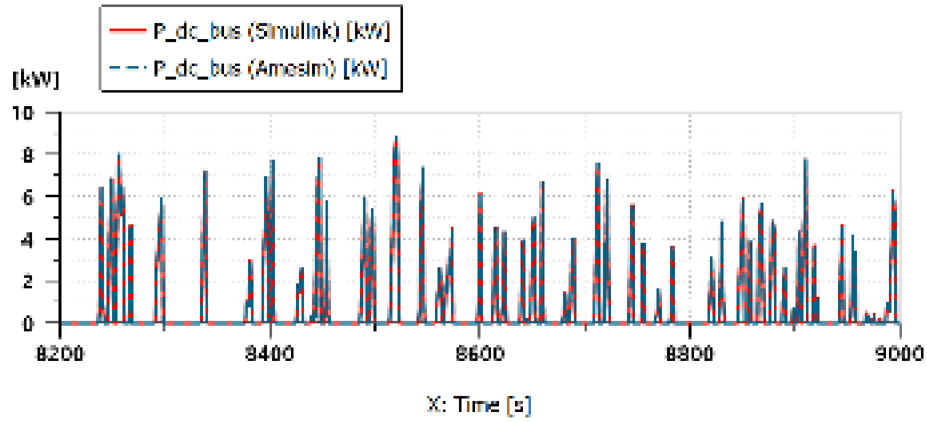


Figure 40 Total power consumptions of two e-drives measured in the DC side.

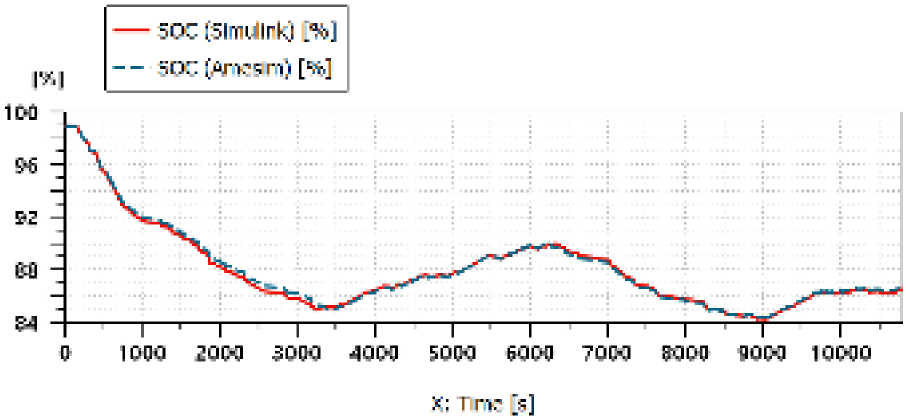


Figure 41 Battery SOC.

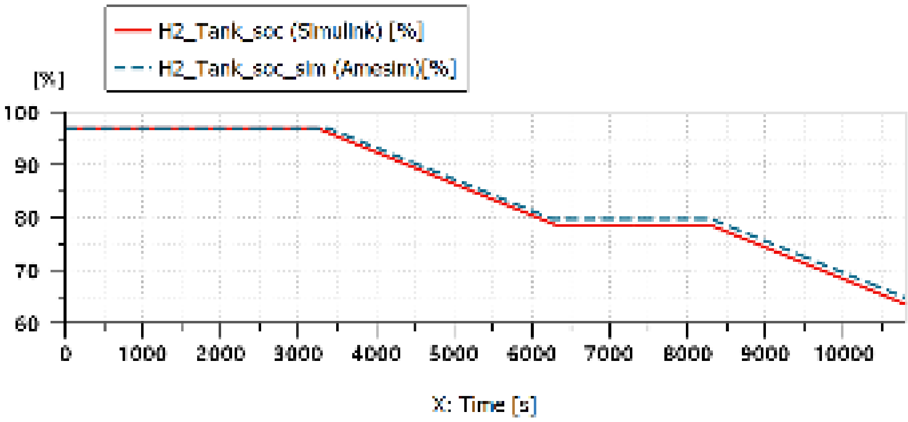


Figure 42 H2 tank SOC.

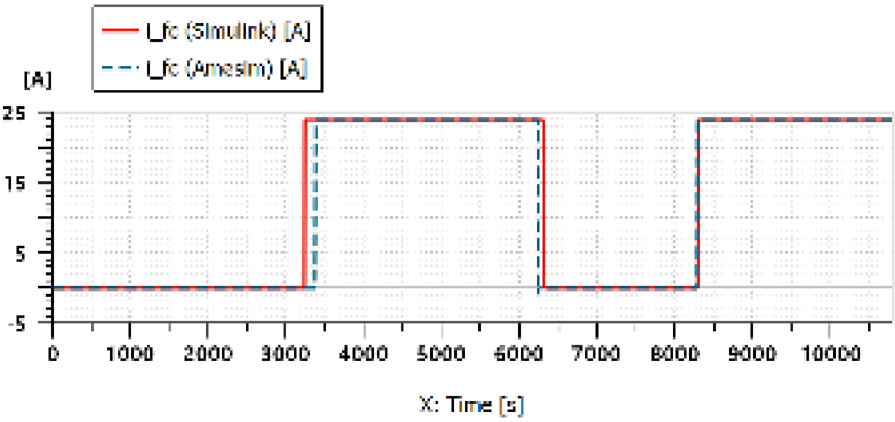


Figure 43 Fuel cell current.

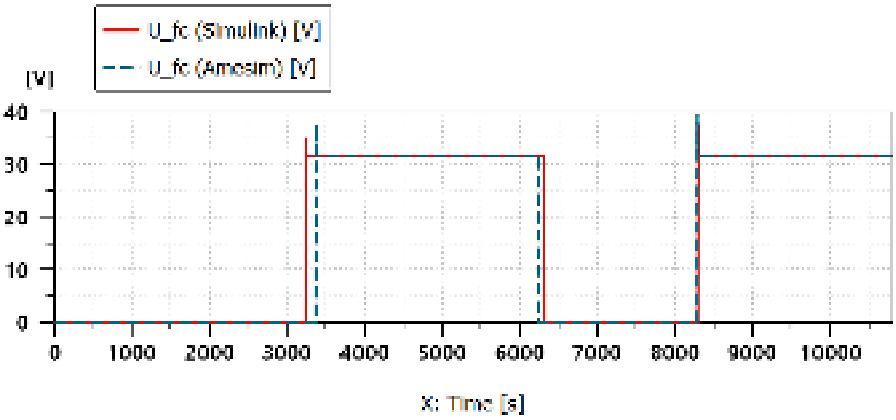


Figure 44 Fuel cell voltage.

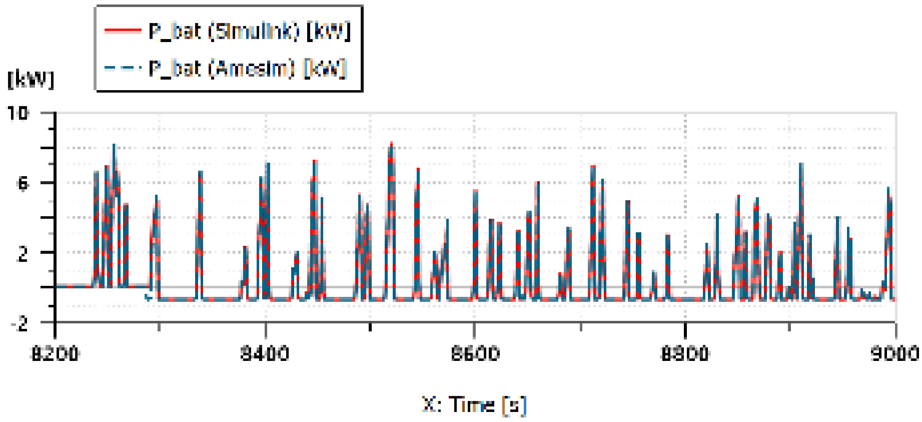


Figure 45 Battery power.

The differences are due to the different fixed-step ODE solver algorithms and their different mathematical implementation in the software. In Matlab-Simulink© we used FixedStepAuto (ode 3 Bogacki-Shampine), while in Simcenter Amesim© the Runge-Kutta of order 3 was used, both with a fixed step of 1 ms.

The error between the Simcenter Amesim© ($P_{dc-bus,Amesim}$) and Matlab-Simulink© ($P_{dc-bus,Simulink}$) power for every time step in percentages and is calculated according to the equation (27).

$$err(P_{dc-bus}, t) = \frac{|P_{dc-bus,Amesim}(t) - P_{dc-bus,Simulink}\ (t)|}{\max\ (P_{dc-bus,Amesim})} 100\% \tag{36}$$

The average error of the power is

$$mean\big(err(P_{dc-bus})\big) = 4.24\% \tag{37}$$

The error between the Simcenter Amesim© ($SOC_{bat,Amesim}$) and Matlab-Simulink© ($SOC_{bat,Simulink}$) battery state-of-charge is calculated according to the following equation.

$$err(SOC_{bat}) = \frac{|SOC_{bat,Amesim} - SOC_{bat,Simulink}|}{\max\ (SOC_{bat,Amesim})} 100\% \tag{38}$$

The average error of the SOC is

$$mean\big(err(SOC_{bat})\big) = 0.16\ \%. \tag{39}$$

Differences are acceptable as Figures 40-45 show an error of 4.24% for the DC bus power and an error of 0.16% for the battery SOC, between Simcenter Amesim© and Matlab Simulink©. These results show that the EMR model of the fuel-cell vehicle is validated and can be easily implemented in different software, as we have presented the implementation in Simcenter Amesim© and Matlab Simulink©.

5. Discussion and Conclusions

5.1 Discussion

The simulation presented in this document represented the virtual testing of the selected fuel cell vehicle, Mobypost. Many other tests on the road are made and the results are compared with the simulations. The results show that using the PANDA project proposed model organization method on a real FCV can be a very efficient way for the virtual testing in vehicle's development stages. The model of each component is designed dedicatedly and validated by PANDA participants. For considering La Poste test scenario, battery energy simulation with error of 4.45%, compared with on track measured data are shown in this document. Also, DC bus energy simulation error of 2.05%, compared with on track measured data, is obtained using our models. The main error is apparently due to a battery model where parameters were not updated from the battery ageing.

5.2 Conclusions

This report presents the virtual testing of the FCV with validation. The concept of the FCV and the tested FCV Mobypost that is developed for daily postal delivery applications are briefly described. The components in FCV including the fuel cell system, the battery pack, the DC-DC converter and the e-drive system are modelled and organized using the EMR formalism. These components' models are connected to compose the FCV model to be implemented in the virtual testing of the FCV. Mobypost was tested in a three-hour driving cycle to cover the most use cases of the postal delivery. The simulation results were compared with the measurements from the tests and under 5% error was achieved for the battery energy evaluation and 2% error was achieved for the DC bus energy evaluation. The system-level behaviours of the Mobypost were accurately simulated, in terms of the current, the voltage, the power, and the SOC of fuel cell system and battery pack, the power demands of e-drives, and the vehicle's dynamic motion. The developed model is thus validated and proved to be credible in the virtual testing. The simulation was implemented in the Matlab-Simulink© environment. The EMR modelling architecture enables the developed FCV model being used in other simulation software such as the Simcenter Amesim©, which is also tested by the partners of the PANDA project. The parameters required in the Mobypost model are available in the vehicle development stages, and don't involves the complicated identification processes. The developed FCV model in this report provides an efficient tool for the system/component design and testing, which is very favourable to reduce the development cost by means of "W-model" concept proposed in PANDA.

6. Deviations from Annex 1

There are no deviations with respect to the description of work.

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Table 5: Project Partners

#	Type	Partner	Partner Full Name
1	UNIV	ULille	Université de Lille
2	IND	SISW	Siemens Industry Software SRL
3	UNIV	VUB	Vrije Universiteit Brussels
4	IND	VEEM	VALEO Equipement Electriques Moteur SAS
5	UNIV	UTCN	Universitatea Tehnica Cluj Napoca
6	SME	TY	Tajfun HIL (Typhoon HIL)
8	UNIV	UBFC	Université Bourgogne Franche-Comté
9	SME	UNR	Uniresearch BV
10	IND	RTR	Renault Technologie Roumanie
11	SME	Bluways	BlueWays International bva
12	IND	TUV	TUV SUD Battery Testing Gmbh

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Appendix A – Quality Assurance

As part of the quality assurance procedure:

- The following questions should be answered by all reviewers (WP Leader, peer reviewer 1, peer reviewer 2 and the technical coordinator);
- Questions answered with NO should be motivated. The author will then make an updated version of the Deliverable. When all reviewers have answered all questions with YES, only then the Deliverable can be submitted to the EC.

NOTE: For public documents this Quality Assurance part will be removed before publication.

Question	WP Leader	Peer reviewer 1	Peer reviewer 2	Technical Coordinator
	Cristi Irimia	Walter Lhomme	Gabriel-Mihai Sirbu	Alain Bouscayrol
1. Do you accept this deliverable as it is?	YES	YES	YES	YES
2. Is the deliverable completely ready? If not, please indicate and motivate required changes.	YES	YES	YES	YES
3. Does this deliverable correspond to the DoW?	YES	YES	YES	YES
4. Is the Deliverable in line with the PANDA objectives?	YES	YES	YES	YES
a. WP Objectives?	YES	YES	YES	YES
b. Task Objectives?	YES	YES	YES	YES
5. Is the technical quality sufficient?	YES	YES	YES	YES

Appendix B – Abbreviations / Nomenclature

Table 6 List of Abbreviations / Nomenclature

Symbol / Shortname	
FCV	Fuel cell vehicle
PEMFC	Proton exchange membrane fuel cell
EMR	Energetic Macroscopic Representation
PMSM	Permanent Magnet Synchronous Motor
SOC	State of Charge
EMS	Energy management system