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Power Advanced N-level Digital Architecture for models of electrified vehicles and their components

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Abstract

The PANDA project is a Research Innovation Action from the European H2020 programme. PANDA will enable the automotive industry to speed up design and testing of innovative electrified vehicles. In the PANDA project, multi-scale and multi-domain simulation packages are developed to interconnect all components of electrified vehicles. The EMR (Energetic Macroscopic Representation) formalism is used to unify the model organization. Moreover, all the models will be shared in a cloud for both stand-alone simulation and cloud computing. On the contrary to existing solutions which are based on a structural philosophy, PANDA is focused on functional-based approach. First results are provided to compare both approaches for the simulation of an electric vehicle. The EMR-based functional library leads to a reduced computation time of 15% in comparison with a structural-based simulation. This results confirms the ability of the PANDA solution for real-time simulation in particular for Hardware-In-the-Loop testing.

Keywords: Electrified Vehicle, simulation, virtual testing, real testing, unified model organization,

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1. Introduction

The automotive market is undergoing disruptive changes. With the growing concerns for environment, fossil fuels depletion and global warming issue, more and more attention has been drawn on developing electrified vehicles to reduce the use of thermal vehicles and thus Green House Gases (GHG). For example the European Parliament adopted Regulation (EU) 2019/631 setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles in the EU for the period after 2020, *European Commission (2019)*. The EU policy will guide the passenger vehicle development for the next 10 years with targets in ZLEV cars (Zero and Low Emission Vehicles). In order to achieve the targets, the car manufactures must develop a range of hybrid and electrical vehicles adapted to the market demands. As there are many possible configurations of hybrid and electric vehicles, flexible simulation tools are requested to speed up their developments.
The market share of electrified vehicles is thus expected to grow massively in the coming decade. While electrified vehicles represented only 0.1% of the market in 2015, the number of electrified vehicles sale has doubled from 2014 to 2015 (from 600 000 to 1.2 Millions), *Internal Energy Agency* (2016). A significant growth of investment is thus required to comply with a mass production of electrified vehicles. In addition, significant changes in powertrain technology are expected, *Internal Energy Agency* (2016).
However, the introduction of new models into the market requires development times of 3-7 years and includes lot of risks and challenges due to high complexity of the developed products. There is a real incentive for OEMs (Original Equipment Manufacturers) to embrace solutions that saves time and cost without sacrificing reliability and safety. The introduction of electrified vehicles does not simplify this challenge, it rather adds to the complexity. It is especially true at early phases of electrification, since hybrid electric vehicle (HEV) concepts have both drivetrain solutions (combustion engine and electric drivetrain together). While Battery Electric Vehicles (BEVs) can contribute to a further reduction of these engineering costs with simplified powertrain concepts, the overall cost of electrified vehicles is currently higher due to expensive batteries, electric drive components, range extender solutions, etc.
The automotive industry needs to adopt a new approach for transition from thermal vehicles to electrified powertrains, as the development process is fundamentally different. Traditionally ICE (Internal Combustion Engine) manufacturers develop and assemble engines and transmissions themselves based on a vertical integration model. The situation is different in electrified powertrains. A lack of knowledge and production capacity means that car manufacturers are relying to a larger extent on suppliers to help them build electrified vehicles. Therefore, the automotive industry must be prepared to ensure a mass production of electrified vehicles by using innovative methods to significantly reduce their development and testing time.
For the testing phase, Hardware-In-the-Loop (HIL) testing becomes more and more used in the automotive industry. The first HIL tests were focused on ECU (Electronic Control Unit), whereas the Power HIL technique aims more recently to test power components through the interconnections of these components with real-time simulation of the other parts of the system *Bouscayrol (2011)*. Thus, Power HIL testing has been applied to develop various innovative vehicle components or subsystems, *Allegre (2010), Kermani (2011), Barreras (2016) Castaings (2016), Mayet (2017), Yang (2018), and Nguyen (2019).* However, the quality of the HIL test depends on the model accuracy (having in mind the real-time computation during the testing) and new dedicated ECU are developed for fast computation of dynamical models, *Abdelraham (2018).* Moreover, new HIL tests are developing using models available online, *Zhang (2018)*, which enables sharing experience from different parts of the world. All these developments are not yet achieved in structured way. Furthermore, most of the time simplified (static) models are used to enable a real-time computation, but with lower accuracy.
To develop virtual testing and real testing, a first approach would be to propose interconnection of existing simulation tools, as developed as in many H2020 European projects, *Ponchant (2017), Santaroni (2018).* This method requires the development of adapted interfaces to propose seamless integration. However, these supplementary interfaces lead to an increase of the global computation time that is not relevant for real-time simulation or testing.
In the PANDA project, *PANDA 2019*, an interconnection methodology for model organisation toward standards will be developed. A common framework will be applied in different software packages without adaptation interface. It will solve the problem of incompatibility between different models of different organisations, physical domains and levels of accuracy. PANDA intends to play a leading role in the development of software tools and methods to improve the virtual generation of new products, new technologies and integrate virtual development. These methods will support the complete generation of new electrified vehicles. PANDA will provide a methodology to interconnect simulation, subsystem tests and final products. By avoiding supplementary adaptation interfaces, PANDA is fully compatible with HIL testing. The PANDA project aims to

take benefit of these recent developments and propose a more global and unified framework, which reduces the development and testing time of power subsystems of electrified vehicles.
A typical problem of commercial software is that the outputs and the inputs of subsystems are not clearly or systematically defined in a physical way across the entire collection of models, *Chrenko (2019)*. Thus unexpected problems may occur when connecting subsystems together. This approach is called structural description where the priority is given to the physical organization of the systems (topology) that leads to user-friendly building of the simulation. On the contrary, a functional approach focus on inputs and outputs of the components/subsystems to respect the physical causal behaviour. This organization leads to a better system understanding and a fast computation time, *Rubin (1997)*, *Hautier (2004)*. In PANDA the EMR (Energetic Macroscopic Representation) formalism, *Bouscayrol (2012)*, is used to organize the subsystem connexions in a functional approach.
The PANDA philosophy is presented in this paper and the simulation of a commercial battery electric vehicle is provided as an example. The interest in using a functional-based simulation instead of a structural-based one is discussed in terms of computation time.

2. The PANDA project

2.1. Cloud of models

Traditionally, industrial products are developed according to the V-model (Fig. 1). On the left side in green (development axis), the overall system specifications (e.g. driving range of an EV) are broken down into subsystem specifications (e.g. battery capacity) and finally into component design (e.g. battery design). Once the components are built, on the right side in orange (testing axis) everything is tested and integrated, from component level (e.g. a physical battery) to finally a working prototype (a working EV). The advantage of the V-process is the consistent feedback between design (left side) and validation (right side), which leads to fewer real prototypes. However, the V-model is still a time-consuming process.

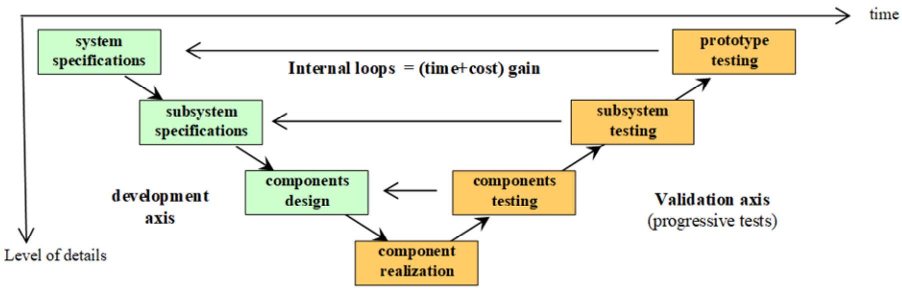

Fig. 1 The V-model of product development

PANDA will make the development process faster by adding a virtual validation axis and re-arranging the V-model to a W-model (Fig. 2). While simulations are already used to reduce the number of physical tests, the high accuracy needed at the system level currently requires a lot of computational effort. That makes existing simulations too slow for real-time models. In PANDA, multi-scale and multi-domain simulation packages are developed to interconnect all components of electrified vehicles. Thus virtual components can be as easily connected and tested as components in real life. A cloud of models will be developed to supply both the virtual and real testing. A unified organization is required for a seamless interconnection of these models.

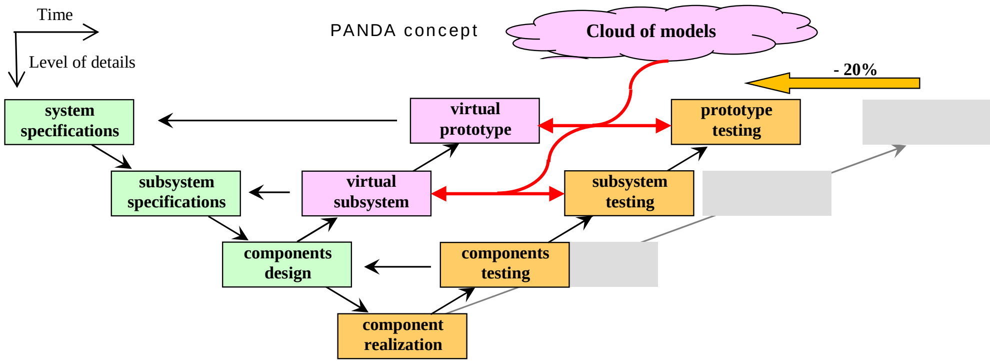

Fig. 2 The W-model of PANDA

2.2. Structural and functional description

The different simulation packages can be classified in two categories. In the case of a structural-based simulation, the system is described by components connected by real links. Libraries of components are available and the user has just to connect these components as in the real life with respect to their physical interconnections. The advantage of structural-based descriptions is user-friendly. However, inputs/outputs (I/Os) of the components are sometimes non compatible (conflict of association) that leads the non-respect of the natural causality of the system and/or the use of specific algorithms to solve these conflicts, *Von Bertalanfly (1968), Iwasaki (1994).* The fact that inputs and outputs do not respect the natural causality (i.e. output are obtained after the input change) makes the system analysis difficult. Moreover the use of derivative causality or specific solving algorithms lead to increase the computation time.

In functional-based simulation, the system is described by functions connected by virtual links (i.e. variables). The drawback of functional-based description is that the user has to define the function and I/Os of each component, then solve the conflict of associations before simulation. But if the functions are defined with the respect of the natural causality, the system analysis is easier to perform, *Hautier (2004).* Moreover, the computation time is minimized thanks of the use of classical solvers for OED (Ordinary Differential Equations), *Rubin (1997).*

However, most of the actual simulation packages are developed based on structural description philosophy, because of it is user-friendly and benefits of the use of fast computation solvers. As industrial companies intensively use these types of software, there are many projects to propose co-simulation using several structural-based software tools, *Ponchant (2017), Santaroni (2018).* Adapted interfaces are thus developed such as FMI (Flexible Mock-up Interface) for an exchange variables in synchronized way. But FMIs lead to an increase of the computation time. For these co-simulation projects, HIL testing is considered with simplified models to reduce their computation time, e.g. static models using look-up tables, *Ponchant (2017).* The accuracy of the tests is thus reduced.

2.3. PANDA organization and reference vehicles

The technical Work Packages (WPs) are organized from a methodological level to a real testing level.

- WP1 “Methods” focuses on the definition of the rules of the organization methodology and relevant real-life scenarios for virtual and real testing of electrified vehicles.
- WP2 “E-storage” will provide multi-scale multi-domain models of batteries according to the PANDA methodology. Moreover, a “cloud real testing” of a battery will be achieved as demonstration.
- WP3 “E-drive” will provide multi-scale multi-domain models of e-drives according to the PANDA methodology. Moreover, a “cloud real testing” of an e-drive will be achieved as demonstration.
- WP4 “Virtual testing” will provide a simulation environment for the PANDA methodology including cloud facilities. Reference vehicles will be simulated in Stand-Alone and Cloud virtual testing.
- WP5 “Real testing” will provide progressive real test of the different electrical subsystems of the reference P-HEV.

The flexibility of the PANDA methodology will be demonstrated on three reference vehicles to achieve the innovations (they will be described in the final paper).

- a Battery Electric Vehicle (BEV), the Renault Zoe from Groupe Renault
- a Fuel Cell Vehicle (FCV), from the FP7 European Project MobyPOST, *Faivre (2013)*,
- a Plug-in Hybrid Electric Vehicle (P-HEV), demon car from Valeo

The PANDA value chain (Fig. 3) is composed of 4 universities (concepts), 3 SME (innovative parts), 2 Tier-1 automotive suppliers, 1 car manufacturer and 1 certification company.

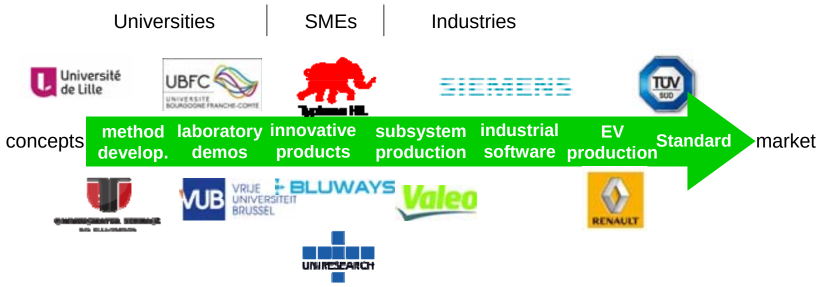

Fig. 3 The PANDA value chain

3. Common formalism and software

In order to develop the organization method and the cloud of model, PANDA will be based on a graphical formalism for model organization. Moreover, an industrial simulation package (SimcenterAMESim) will be used to demonstrate the applicability of the method.

3.1. Energetic Macroscopic Representation (EMR)

EMR is not a modeling tool, it is a graphical formalism to organize models and controls of multidisciplinary systems, *Bouscayrol (2012)*. The specific pictograms of EMR (see Appendix) describe energy sources, energy storage, energy conversion, energy distribution and control operations. All I/Os of each component are exclusively defined according to the physical causality (i.e. an output is an integral function of inputs i.e. an output is delayed from inputs), *Iwasaki (1994), Hautier (2004)*. EMR is thus a cognitive functional description that leads to an easy understanding of the power flows within the system. In contrast to structural description, interconnection of different subsystems should lead to difficulties in order to respect the physical causality principle. In fact, conflicts of association should be resolve by the designer and not by the solver of the structural software.

3.2. Simcenter AMESim

Simcenter AMESim, a well-know structural software in automotive industry, is an integrated, scalable system simulation platform which allows engineers to virtually assess and optimize the mechatronic systems' performance, *Simcenter (2019)*. This commercial software package is composed of a suite of tools for modeling and analysis of multi-domain systems comes with a set of standard and optional libraries of predefined and validated components, covering different physical domains, all directly executable within the Simcenter AMESim solvers.
Ready-to-use multi-physics libraries combined with application and industry-oriented solutions supported by powerful platform capabilities let engineers rapidly create models and accurately perform analysis.
It has been selected to support the PANDA organization method and to develop the cloud of models and the cloud computing. As most of the actual simulation packages, Simcenter AMESim is based on a structural philosophy. The vehicle model development consists in connecting its components from available libraries. AMESim is based on Bond-Graph, which is a structural graphical formalism, *Gawthrop (2007).*

4. Simulation of an BEV using the EMR library of AMESim

4.1. Studied electric vehicle

The studied BEV is the ZOE from the Groupe Renault (Fig. 4). Its traction system is composed of a Li-ion Battery of 23 kWh Ah, an electric drive of 65 kW (synchronous machine), a gearbox, a differential, two driven wheels and a total mass of 1.47 ton.

Fig. 4 The studied Renault ZOE

4.2. EMR of the studied vehicle

The EMR of the vehicle is defined by using the modeling equations of each component. The battery and the road are considered as energy sources (green oval). The inverter is a conversion element (orange square) as the gearbox and the wheels. The synchronous machine is composed of an accumulation element (windings, crossed orange rectangle) and a conversion element (orange circle). The differential distributes the energy to the wheels (overlapped orange squares). The chassis merges the energy from both wheels (overlapped orange squares) and store energy in its mass (crossed orange rectangle). All modeling equations can be found in *Desreveaux (2020)*.
The control scheme (blue parallelogram) is directly obtained from the EMR thanks to a mirror effect. It leads to define the measurements and the closed-loop controls (crossed light blue pictograms). This method has been successfully used for simulation and HIL testing of BEV, *Horrein (2017)*, HEV, *Boulon (2013)*, FCV, *Solano (2011)*, Thermal vehicles, *Horrein (2015)*, subways, *Allègre (2010)* , hybrid trains, *Mayet (2013)*, BEV using hybrid energy storage subsystems, *Castaings (2016)*, *Nguyen (2019)*, etc.

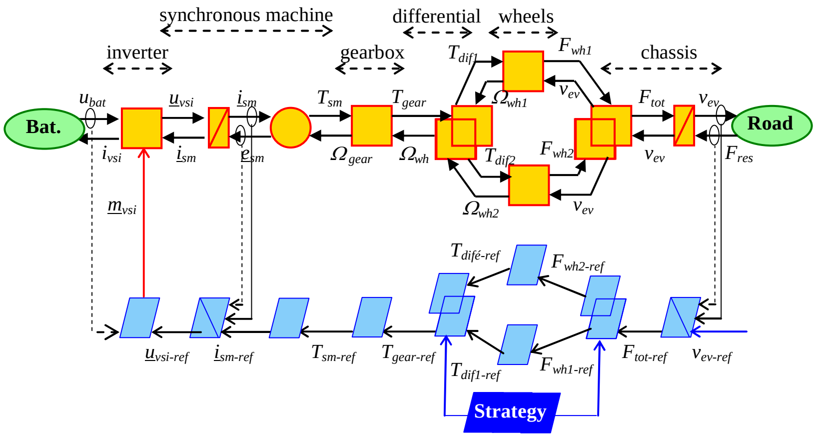

Fig. 5 EMR and inversion-based control of the Renault ZOE traction system

The model has been simulated first using Matlab-Simulink © and its EMR library, *Desreveaux (2019)*. The simulation has been compared with a test on a real vehicle for a real urban driving cycle (Fig. 6). The measured velocity has been considered as input for the simulation. The error of the simulation is only of 3% on the global energy consumption, *Desreveaux (2019)*.

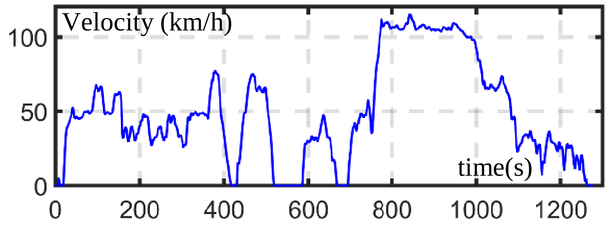

Fig. 6 Velocity measured during of the urban driving cycle

4.3. Simulation of the studied vehicle

An EMR library has thus been developed in AMESim for PANDA, *Husar (2019)*. The model of the studied BEV has been implemented in AMESim using this library (Fig. 7). A simple NEDC driving cycle is considered.

Fig. 7 EMR-based simulation of the Renault ZOE in AMESim

In order to define the benefit of the new EMR-based functional library, the same vehicle is also simulated using the classical structural library of AMESim (Fig. 8). For a fair comparison, the same control scheme (deduced from the EMR of the vehicle) is used in this structural-based simulation.

Because the same models are used in both descriptions, the simulation results are exactly the same for the NEDC. However, the computation time of the functional-based simulation is 15% lower than the computation time of the structural-based simulation (Fig. 9). Different fixed simulation steps have been considered using the same computer to confirm this result. In the structural-based description, the natural causality is not always guaranteed that leads to more computation time. This result highlights the interest of developing functional-based library in the framework of fast simulation with applications to real-time HIL testing.

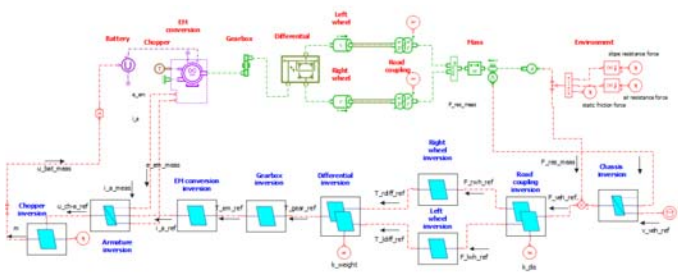

Fig. 8 Structural-based simulation of the Renault ZOE in AMESim

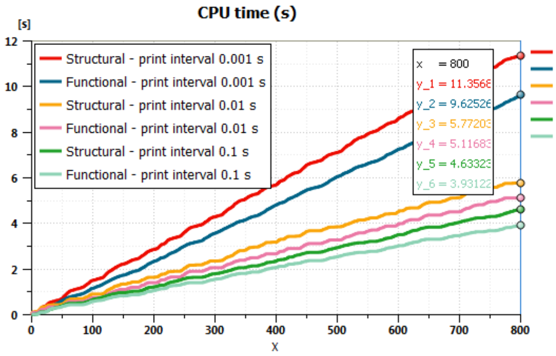

Fig. 9 computation CPU time vs. simulation time (800 s) for different simulation steps

5. Conclusion

In the PANDA project, a functional model organization is proposed to structure the different models of components/subsystems of electrified vehicles. This type of model organization allows I/Os of the model to be in accordance with the causality principle. In that aim, the EMR formalism is used to organize the models to the causality principle. A dedicated EMR-based functional library has been developed in Simcenter-AMESim, which is a structural software. The first reference vehicle of PANDA (a commercial battery electric vehicle) has been simulated using the classical structural library and the new functional library. The EMR-based library allows the reduction of the computation time by 15% using the same model, the same control and the same simulation step.
This functional approach enables thus a fast simulation computation that is compatible with real-time simulation and HIL testing. This organization will be used for a cloud-based and stand-alone digital simulation for virtual and real testing of innovative components. The end result will be that virtual components can be as easily connected and tested as components in real life, enabling the automotive industry to drastically speed up the design and testing of innovative electrified vehicles.

Acknowledgements

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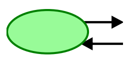
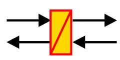
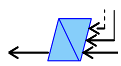
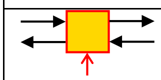
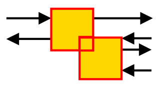
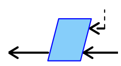
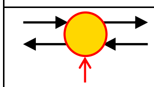
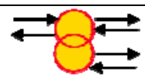
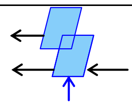
Appendix: EMR Pictograms

	Source element (energy source)		Accumulation element (energy storage)		Indirect inversion (closed-loop control)
	Mono-physical conversion element		Mono-physical coupling element (energy distribution)		Direct inversion (open-loop control)
	Multi-physical conversion element		Multi-physical coupling element (energy distribution)		Coupling inversion (energy criteria)