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

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Publishable Executive Summary

The objective of PANDA is to provide a disruptive and open-access model organization for an easy interconnection and exchange of models in the development process of EVs, with the goal to help reducing the time to market by 20%, thanks to advanced methods. Indeed, within the W-model process of product development, two testing stages occur, the virtual testing stage which needs off line simulation, and the real testing stage which needs real time simulation. Within the PANDA project, a unified model organization has to be developed for both stages.

This deliverable is an update of the deliverable on the development of a “PANDA” methodology able to unify the organization for flexible N-level models of electrified vehicles and their components. The objective of this deliverable is to consider feedbacks from all the PANDA works to refine this methodology, which is based on the EMR (Energetic Macroscopic Representation) formalism.

The main principles of EMR are pointed out in the deliverable: it is a functional description (not structural), relying on the natural physical causality (i.e. integral causality), and the action-reaction principle. The advantages provided by the respect of the natural causality are to reduce the solver computing time during simulation on one hand and on the other hand, to deduce systematically the control structure of the system thanks to the inversion principle. The drawbacks of EMR are linked to the integral causality respect which sometimes induces conflict of subsystems’ association, which has to be solved thanks to the physical knowledge of the system. Nevertheless, once this step is performed, the EMR of the system is ready for simulation (and control) with a minimal computing time.

The simulation of a system is generally a consequence of a modelling action (selection of the main phenomena to consider) and a representation action (organization of the model). In structural software packages, an integrated approach is generally used mixing modelling, representation and simulation. In the PANDA methodology, these different steps are clearly defined and EMR is used as a representation formalism. A key point is that the representation does not interfere with the modelling: a phenomenon should not be neglected because of a difficulty to interconnect two different subsystems due to the representation. The so-called conflicts of association should be solved without changing the modelling assumptions but by defining new equivalent functions in a holistic philosophy.

The main idea of EMR is the natural integral causality respect and the PANDA model organization has to follow this rule, whatever the complexity level of the modelling: inputs and outputs have to be chosen in agreement with integral causality. Then, the different existing simulation tools have to be analysed according to this question: is it possible to apply the EMR principle to any of them? As a result, the last part of the deliverable shows two successful examples of system simulation using EMR: one with MATLAB-Simulink©, the other with Simcenter Amesim ©, where adapted libraries have been developed in both cases. As a conclusion, EMR and its principles (functional representation, integral causality respect) constitute accurate guidelines and basis for PANDA model organization.

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1. Introduction

This deliverable is related to the PANDA methodology as unified organization for flexible N-level models of electrified vehicles and their components [PANDA 2020]. This methodology is related to WP1 “Methods” that has provided method and rules to develop a cloud of model to be used for virtual testing and real testing of various electrified vehicles and their subsystems and components[1]. PANDA aims to propose a unified model organization based on the EMR (Energetic Macroscopic Representation) formalism [Bouscayrol 2000] [Bouscayrol 2012] as a graphical guideline.

The PANDA methodology has been developed at the beginning of the project [PANDA 1.2]. The methodology has been refined from the intensive developments in virtual testing of different vehicles and real testing of different components achieved during the entire project:

- Multi-level knowledge [PANDA 2.1] and behaviour models [PANDA 2.3] of a reference battery,
- Multi-level knowledge [PANDA 3.1] and behaviour models [PANDA 2.3] of a reference e-drive,
- Common simulation platform with an EMR library in a reference software [PANDA 4.1],
- Cloud of models and sharing process using the reference software [PANDA 4.2],
- Simulation and validation of a reference battery electric vehicle (BEV) [PANDA 4.3],
- Simulation and validation of a reference fuel cell vehicle (FCV) [PANDA 4.4],
- Simulation and validation of a reference plug-in hybrid electric vehicle (P-HEV) [PANDA 4.5],
- Stand-alone Hardware-In-the Loop (HIL) testing of a battery for the reference [PANDA 5.1],
- Stand-alone HIL testing of an e-drive for the reference P-HEV [PANDA 5.2],
- Stand-alone HIL testing of an e-subsystem for the reference P-HEV [PANDA 5.3],
- Cloud-based HIL testing of a battery for the reference BEV and P-HEV [PANDA 2.2],
- Cloud-based HIL testing of an e-drive for the reference BEV and P-HEV [PANDA 3.3],
- Data Analysis of the virtual and real testing of the reference P-HEV [PANDA 5.4].

Section 2 deals with the requirements of the PANDA methodology. Section 3 is a reminder of the EMR formalism. Section 4 develops the method for building the unified model organization. Section 5 is focused on the software implementation of the PANDA methodology. Section 6 is a summary of the feedbacks from the applications of the method by the partners.

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[1] The term « subsystem » will be used in this report but it is related for real subsystems as well as for components. Indeed the border between both parts is relatively subjective and depends on the usage and on the real device.

2. PANDA objective and requirements

This section aims to define the methodology requirements for the development of multi-level model organization in the perspective of the PANDA objective.

2.1 PANDA objective

The objective of PANDA is to provide a disruptive and open-access model organization for an easy interconnection and exchange of models in the development process of EVs, with the goal to help to reduce the time-to-market by 20% due to advanced methods [PANDA 2020]. This approach can be represented by the W-model process of product development (Figure 1) which is composed of a development axis (green tasks), a virtual testing axis (purple tasks) and a real testing axis (orange tasks). The virtual testing axis consists in the simulation of components, subsystems or the complete vehicle in pure digital works. The real testing axis consists in coupling the real tested subsystem with the real-time simulation of the other vehicle subsystems using the Hardware-In-the-Loop (HIL) testing technique {Bouscayrol 2011]. A cloud of model will be organized using the PANDA model organization to be used in both testing axes: off-line simulation for virtual testing and real-time simulation for real testing.

Because of the use of subsystems (or components) in different tasks of the W-model process, the subsystem model will vary in terms of description: many physical phenomena can be considered in the most accurate model and only a key phenomenon can be considered in a simpler model. The selected model depends on the task objective. Thus the same subsystem will be described by different models of different granularities that are called multi-level or N-level models. The open-access model organization should thus enable a fast and seamless change of the model level of a subsystem in function of the task requirement (flexibility).

Because of the use subsystems in the real testing axis, the real-time simulation capability of the subsystem model is also a key issue.

Many H2020 projects are working on disruptive simulation approaches using unified models [PANDA D1.1], mostly using a co-simulation philosophy such as OBELICS [Ponchant 2017] or HIFI-ELEMENTS [Santaroni 2018]. In the case of co-simulation, the model organization is partially solved by using FMI (Flexible Mock-up Interface) despite the increase of the computation time [Deppe 2018]. Moreover, this co-simulation approach implies the coupling of classical structural software packages that is of interest for the different partners of a vehicle development project. In the PANDA approach, in order to avoid the use of co-simulation, another model organization is proposed using a functional description instead of the classical structural one [Husar 2019].

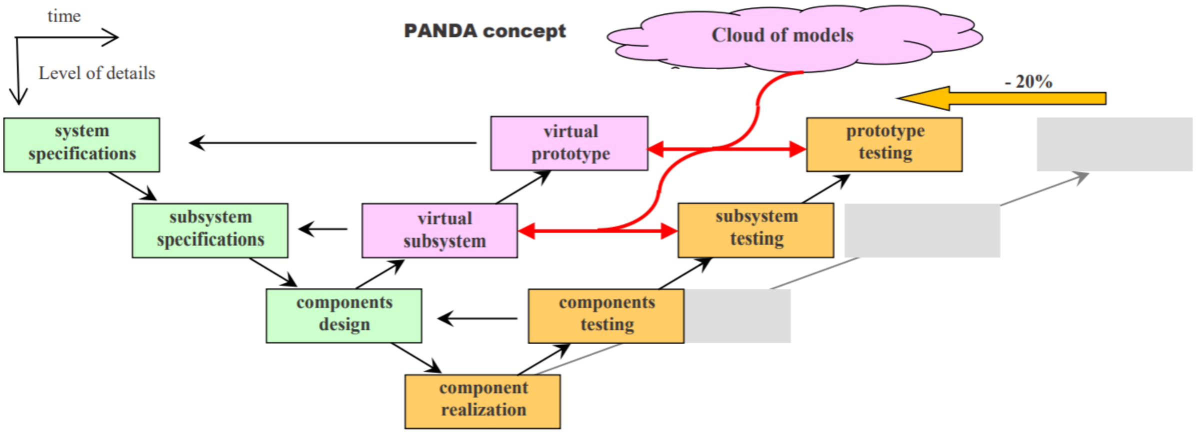

Figure 1: PANDA concept and project objective

2.2 From the real system to simulation

From a real system to its simulation, several steps can be considered [Bouscayrol 2008] (Figure 2). The first step is the modelling step where a model is built considering assumptions, i.e. phenomena to consider or to neglect. The second step is representation, where the model is organized for a better understanding. The last step is simulation, where the representation is implemented in simulation software selecting the solving method and the simulation step.

Modelling - As stated previously, different models can be defined for the same subsystem in function of the study objective. In PANDA, a multi-level model approach is targeted to develop a N-level model organization. For the same subsystem, different models will thus be developed. Dynamical models (for transient states), static models (only for steady states) and quasi-static models will be considered in that aim [Greenwoog 1991] [Chan 2010].

Representation – The classical model organization is the structural description where the subsystem is described using component library and component interconnections through physical links. Most of modern advanced software packages are based on this philosophy. PANDA is focused on functional description to avoid the need of co-simulation (see above). Moreover, this choice will enable to use pure causal description (i.e. physical causality, i.e. integral causality) [Hautier 2004] that leads to the reduction of the computation time [Rubin 1997]. However the causal approach requires to consider the conflict of association [Bouscayrol 2012] before simulation: if it leads to a reduction of the computational time it can be a burdening supplementary step for the user.

Simulation – Most of the actual advanced simulation packages are defined in structural philosophy as explained in the previous paragraph. PANDA uses a functional approach that is a challenging task, which requires some adaptation of actual simulation packages. Moreover, forward and backward approaches are used in function of the global objective [Chan 2010]. In a forward approach dynamical models are generally required, and the subsystem control also has to be provided. In a backward approach, generally static or quasi-static models are considered and as the control is assumed to be ideal, there is no need to develop the control. As PANDA aims to develop a general approach, both types of simulation could be possible and the related models should also be compatible for an easy switch from forward to backward simulation.

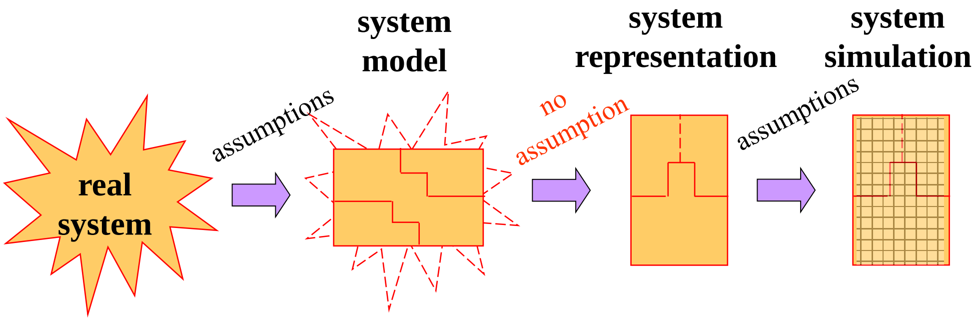

Figure 2: Different steps before simulation [Bouscayrol 2008]

2.3 Multi-level models for flexible simulation

Flexible simulation should enable to simulate a subsystem in any task of the W-model process by selecting the right model granularity. As a functional description has been selected for PANDA, the subsystems are described by inputs and outputs and their related relationships.

For flexibility, the same subsystem must have the same I/Os (Inputs/Outputs) whatever the model granularity. In that case, the subsystem model can be easily changed and interconnected to the other subsystems. Only the internal relationships will change (more or less complex in function of the phenomena to be considered in the subsystem). For the other subsystems, this change will be seamless.

It can be noted that in a structural approach, acausal descriptions are generally used. Therefore, the change of the model can lead to a causality change and thus to 1) a change of solver or 2) a change in terms of I/Os. This property is particularly used in Bond Graph (structural graphical description) [Paynter 1961], for example to consider topological changes in case of a fault during the system operation [Silva 2014].

A functional approach is selected with fixed I/Os for the different models of the same subsystem. This property enables a fast and seamless change of the subsystem models in the different tasks of the W-model process to ensure a real flexible N-level model organization.

2.4 Accurate real-time models for real testing

As the developed models can be used for real testing axis, they have to be able to be simulated in real time while offering sufficient accuracy.

In the co-simulation approach, because of the long computation time, quasi-static or static models (e.g. look-up tables or efficiency maps) are often deduced from the global simulation in order to be used in HIL testing [Ponchant 2017]. However, this reduced model is less accurate than the initial dynamical model. The long computation time is generally due to 1) the classical structural description which can contain derivative causality and 2) the FMI which requires supplementary computation time to interface the different simulation packages.

A functional approach can be acausal, non-causal or causal. The natural physical causality (i.e. the output can only be a consequence of the inputs, with a delay) is mathematically expressed by integral relationships [Iwasaki 94] [Hautier 2004]. Simple solvers for ODE (Ordinary Differential Equations) are thus sufficient and enable simulation steps related to the subsystem dynamics [Rubin 1997]. In the case of structural description as the I/Os are defined only by the subsystem interconnections, conflicts of associations [Bouscayrol 2012] occur between subsystems, which would impose the same output keeping the natural physical causality. To keep the structure of the system, non-causal relationships have to be used: 1) the physical behaviour is lost and 2) specific solvers must manage the derivative relationships leading to a longer computational time. A functional approach can thus lead to a reduction of the computational time under the condition of respecting the physical natural causality.

Moreover, in the PANDA approach the co-simulation is not considered, and the supplementary computation time (FMI algorithm) is avoided.

If dynamical models are considered, a causal organization of their equations will thus be solved by classical and fast ODE-based solver leading to accurate results in fast computational time.

The drawback of the causal functional method is that the conflicts of association must be detected and solved before the simulation implementation.

A causal-based functional approach organizes I/Os according to the exclusive natural physical causality. This property enables reduced computational time even in case of dynamical models. But conflicts of associations must be detected and solved before simulation

2.5 Graphical description for unified organisation

Different graphical descriptions are more and more used to describe complex systems, such as block diagrams, Bond-Graph (BG) [Paynter 1961], Causal Ordering Graph (COG) [Hautier 2004], Power Oriented Graph (POG) [Zanassi 1996] or Energetic Macroscopic Representation (EMR) [Bouscayrol 2000]. They enable a unified and global description of the system [Karnopp 1975], and can be decomposed in structural and functional description [Bouscayrol 2005], [Gawthrop 2007].

Structural graphical descriptions such as Bond Graph, keep the priority to the subsystem topology [Karnopp 1975]. The causality is defined in a second step with priority to the natural physical causality, but derivative causality can be used to respect the subsystem structure [Gawthrop 2007].

Functional graphical descriptions such as block diagrams or EMR, give the priority to the system functionality. In the classical block diagrams, the physical natural causality (integral relationships) is preferred but not mandatory. In COG and EMR, the natural causality is exclusive [Bouscayrol 2012]. Both tools enable a systematic deduction of control schemes of the subsystem. If this property is not a key one for PANDA, it could be of interest in a forward simulation where the subsystem control is required (see section 2.1). Finally EMR is based on Systemics and presents a more “Macroscopic” view of the system and includes association rules to detect and solve conflicts of associations.

The EMR formalism is selected for the unified models’ organisation because it is a graphical formalism (synthetic and unified view) based on a functional approach (flexibility) using exclusively the natural physical causality (adapted for real-time). Moreover, control schemes can be systematically deduced from the EMR of a subsystem and association rules have to also be defined to solve conflicts of association.

3. EMR formalism

This section is devoted to the presentation of the EMR formalism as the framework for unified model organisation for the PANDA project. The EMR formalism is described in [Bouscayrol 2012] where most of the contents of this section come from. More details can also be found in the EMR website [EMR 2022] where the presentations of the annual international EMR summer schools can be found. Only the key aspects of EMR are summarized in this deliverable.

3.1 EMR history and applications

EMR has been initiated in 2000 for electro-mechanical systems [Bouscayrol 2002]. This graphical formalism is a functional description based on the exclusive natural causality [Iwaski 1994] [Hautier 2004] and the interaction principle of Systemics [Bouscayrol 2000]. EMR is a graphical organization of models of energy conversion for a systematic deduction of control schemes [Bouscayrol 2012]. In 2010, EMR has been extended to any multi-physical energy conversion [Boulon 2010a]. EMR has also been used to organize HIL testing [Bouscayrol 2009] for its ability to develop real-time model. Since 2016, EMR is also used for the organization of EMS (Energy Management Strategies) of energy conversion systems [Castaings 2016]. In PANDA, EMR will be used for development of simulation models of electrified vehicles based on a unified model organisation.

EMR is thus a graphical formalism to describe energy conversion systems (Energetic) in a cognitive[2] Systemics approach (global view i.e. Macroscopic) by a specific organization of the models of its subsystems (Representation) for a purpose of control organization (functional representation).

EMR has extensively been used in various applications (non-exhaustive list of journal papers) mainly for development of control and EMS of innovative multi-physical systems:

- Original power electronics structures [Delarue 2003] [Bouscayrol 2005]
- Original electrical drives [Chen 2010] [Li 2019], including multi-phase drives [Semail 2003] [Sandulescu 2014],
- Piezoelectric actuators [Nguyen 2014] [Ghenna 2018],
- Fuel Cell systems [Chrenko 2009] [Boulon 2010b] [Agbli 2011],
- Various energy storage systems [Azib 2011] [Heidrai 2015] [Castaings 2016] [Lopez 2017] [Trovao 2017] [Goussian 2019] [German 2020],
- Renewable energy applications [Bouscayrol 2009] [Lhomme 2012] [Solano 2016] [Barakat 2019],
- Automatic (electric) subway [Mercieca 2004] [Allegre 2010] [Mayet 2014b],
- Railways and subway supply infrastructures [Mayet 2016] [Mayet 2017] [Ramsey 2021],
- Hybrid locomotive [Mayet 2014b] [Baert 2014] [Agbli 2016],
- Various Hybrid electric trucks [Boulon 2010] [Lhomme 2017] [Mayet 2019],
- Thermal vehicle [Lhomme 2011] [Horrein 2015] [Desrevaux 2021],
- Various Hybrid Electric Vehicles [Letrouvé 2013] [Cheng 2013] [Horrein 2016] [Lhomme 2017],
- Various Electric Vehicles [Silva 2014] [Horrein 2017] [Nguyen 2019] [Desrevaux 2019],
- Various Fuel Cell vehicles [Solano 2011] [Ettihir 2016] [Depature 2018] [To 2019] [Badji 2020]

3.2 EMR basic elements

In order to organise the model of energy conversion system for control purpose, only 4 energetic functions are sufficient [Bouscayrol 2012]: source of energy, storage of energy, conversion of energy and distribution of energy. EMR is thus based on 4 basic pictograms to describe these functions. Other pictograms have been defined to manipulate the models: switching between two models and power amplification to avoid model repetition.

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[2] A cognitive approach is based on the internal knowledge of the system contrarily to the cybernetics approach (i.e. black box approach).

3.2.a. Fundaments

EMR is based on two main principles (causality and interaction) that lead to define the pictogram properties.

Causality principle – The causality principle indicates that the output can only be a consequence of the inputs, and a delay is thus obtained [Iwasaki 1994]. This causality induces that the output is an integral function of the inputs [Hautier 1996]. The respect of the causality is the respect of the physical behaviour.

Interaction principle – The interaction principle indicates that any action of subsystem 1 to subsystem 2 leads to a reaction from subsystem 2 to subsystem 1. In energy conversion systems, the product of the action and reaction variables leads to the power exchanged between both subsystems [Bouscayrol 2000].

3.2.b. Main graphical rules

The details of the EMR graphical rules are given in Appendix.

Globally the green colour is devoted to the energy sources (terminals of the system), the orange colour to the energy conversion subsystems (power systems), the blue colour to subsystem control and the purple colour to virtual subsystems (estimation or real-time models).

In terms of causality, there are two categories of elements: 1) causal elements with output delayed from inputs and 2) rigid elements with no delay between inputs and outputs. For rigid elements no specific sign is associated in the related pictograms. For causal elements, a slash is inserted in the related pictogram. Any element containing an oblique bar inside has thus outputs delayed from its inputs.

In terms of interactions, the connections between elements are described by two (thick closed) arrows[3] of different directions indicating the action and the reaction. The action and reactions variables can be scalar or vectors.

3.2.c. Basic elements

Source Element - In EMR, source elements are terminals elements i.e. environment of the studied system. They are described by light green ovals with a dark green border (Figure 3). They can be generator and/or receptor of energy. They can have an information input (thin open arrow).

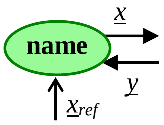

Figure 3: Source element

Accumulation Element - In EMR, accumulation elements induce an internal storage of energy, which yields a state variable and thus a delay between I/Os [Hautier 2004]. They are described by crossed orange rectangles with a red border (Figure 4).

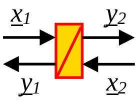

Figure 4: Accumulation element

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[3] thick closed arrows represent power variables while thin open arrows represent information variable (e.g. control signals)

Conversion Element - In EMR, conversion elements convert energy without any internal energy storage, which yields no delay between I/Os. They are described by orange squares (mono-domain conversion) or orange circles (multi-domain conversion) with red border (Figure 5). Conversion element can have information input (thin open arrows) to tune the energy conversion (not mandatory).

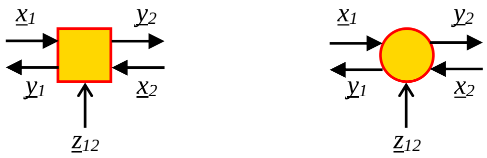


Figure 5: Conversion element (mono and multi-domain)

Coupling Element - In EMR, coupling elements distribute energy between several subsystems without internal energy storage. They are described by overlapped orange squares (mono-domain distribution) or overlapped orange circles (multi-domain distribution) with red border (Figure 6).

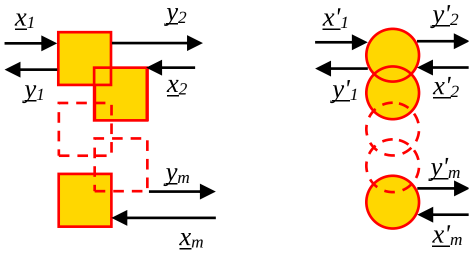


Figure 6: Coupling elements (mono and multi-domain)

Other Elements – Switching elements enable switching between different models when there is a change of topology [Lhomme 2011]. They are described by several connected orange rectangles. They do not represent a part of the system, but a variable connection between models. Adaption elements enable to consider a single equivalent subsystem instead of several subsystems giving the same power [Mayet 2014a]. It is a way to simplify the system. They are represented by orange rectangles with “>” or “<” inside to highlight the reduced and full-power parts.

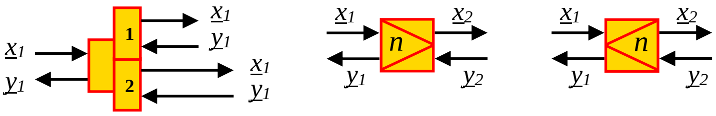


Figure 7: Switching and adaptation elements

Concluding remarks – Energy losses can be considered in any EMR element (by equivalent resistance, frictions, etc. or by efficiency rate). For the studied systems, only accumulation elements have fixed I/Os because of the energy storage (i.e. causality): they impose I/Os to other elements. Only conversion elements have information inputs: they will be used to control the whole system.

3.3 EMR of a complete system

The EMR of a complete system is composed of the association of the EMR elements of each component. But, as EMR is a graphical causal functional description, conflict of associations may occur. These conflicts should be solved to keep the exclusive physical causality.

3.3.a. Association rules

Association rules deal with conflict of associations [Bouscayrol 2012]. A conflict of association is detected when two elements want to impose the same output (or state variable). If two accumulation elements would like to directly impose the same output, they will be merged to impose this variable as a unique equivalent accumulation element. In the case when two inductors (1) and (2) in series, the same current is imposed: an equivalent inductance is defined (3). The structural description composed by two inductors is translated in a functional description by a unique equivalent inductance (Figure 8).

$$L_1 \frac{d}{dt} i + R_1 i = u_1 - u_2 \tag{1}$$

$$L_2 \frac{d}{dt} i + R_2 i = u_2 - u_3 \tag{2}$$

$$L_{eq} \frac{d}{dt} i + R_{eq} i = u_1 - u_3 \quad \text{with} \quad \begin{cases} L_{eq} = L_1 + L_2 \\ R_{eq} = R_1 + R_2 \end{cases} \tag{3}$$

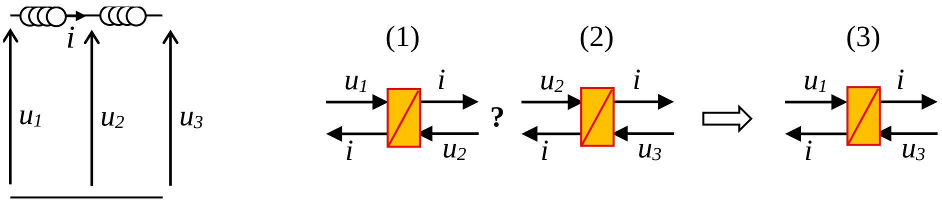


Figure 8: Merging rule: example of inductors

If two accumulation elements want to impose indirectly the same output through conversion elements, there is also a conflict of association. The permutation rule should be first used to put the accumulation elements close each other. Modelling equations should be defined to keep the global behaviour. The merging rule should then be used to define an equivalent accumulation element. In the case of two shafts (4) and (5) connected through a gearbox (6), a conflict of association occurs. After the permutation and the merging rules, an equivalent shaft (7) is defined. The structural description is composed of 3 physical elements and the functional EMR description is composed of two equivalent functions (Figure 9).

$$J_1 \frac{d}{dt} \Omega_1 + f_1 \Omega_1 = T_1 - T_2 \tag{4}$$

$$J_2 \frac{d}{dt} \Omega_2 + f_2 \Omega_2 = T_3 - T_4 \tag{5}$$

$$\begin{cases} \Omega_2 = k\Omega_1 \\ T_2 = kT_3 \end{cases} \tag{6}$$

$$J_{eq} \frac{d}{dt} \Omega_2 + f_{eq} \Omega_2 = T_2 - T_4 \quad \text{with} \quad \begin{cases} J_{eq} = \frac{J_1}{k^2} + J_2 \\ f_{eq} = \frac{f_1}{k^2} + f_2 \end{cases} \tag{7}$$

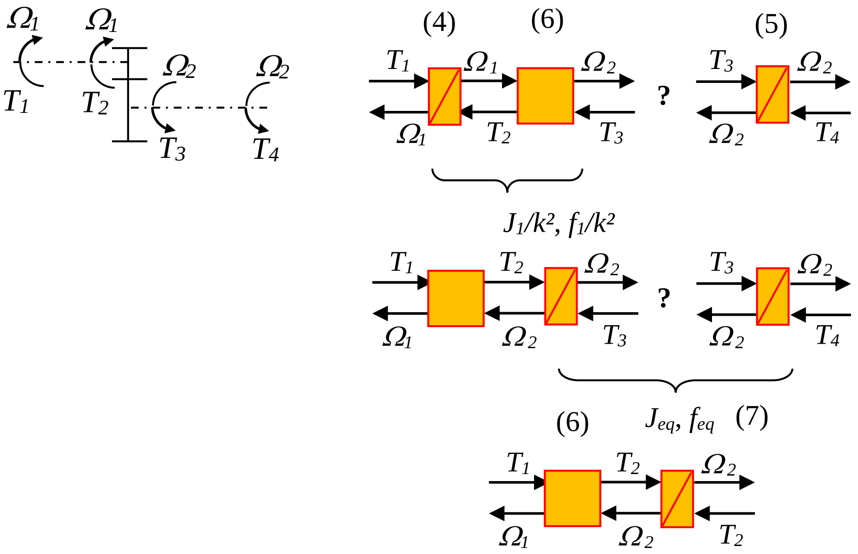


Figure 9: Permutation and merging rules: example of shaft and gearbox

3.3.b. Global EMR

The EMR of the complete system is thus composed of the connected EMR elements after solving the different conflicts of associations using the permutation and merging rules. Several permutations can be requested for solving a conflict of association. A subway traction system [Bouscayrol 2005], also used in [PANDA D1.1] is given as an example (Figure 10). The armature of two DC machines are connected in series. In the EMR, an equivalent armature winding is defined (Figure 11).

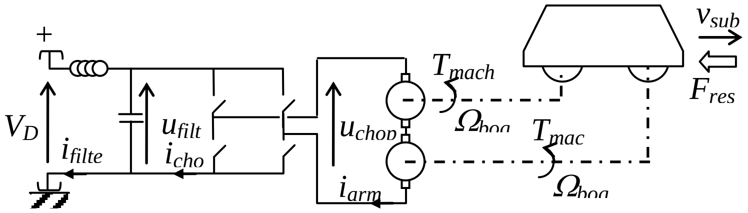


Figure 10: Structural description of the studied subway traction system

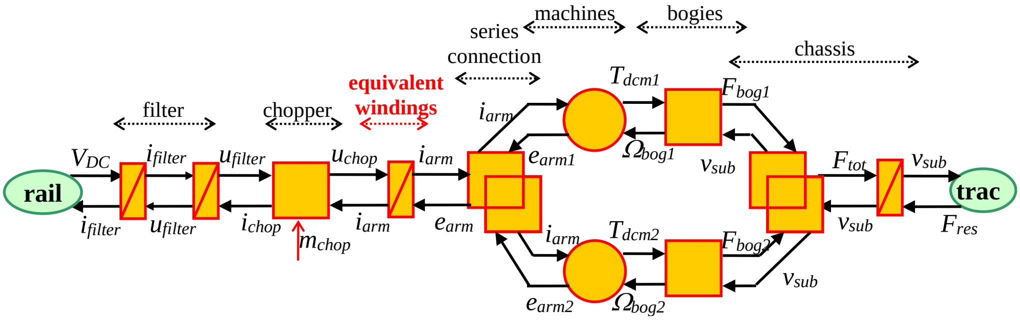


Figure 11: EMR of the studied subway traction system

3.4 Deduced control and EMS

Inversion-based control schemes can be systematically deduced from the EMR of a system using inversion rules [Bouscayrol 2012]. First the tuning path is defined. Second, a theoretical control scheme is deduced. Third, a practical control scheme is derived. Even though the control organisation is not directly the aim of PANDA, the deduction of control schemes is presented in this subsection. Therefore the control and energy management of electrified vehicles were a part of the vehicle to be simulated during the development phase.

3.4.a. Tuning path

The tuning path is the causal way from the variable to act on the system to the variable to be controlled. In the case of the subway traction system, the tuning variable is the chopper modulation input m_{chop}, and the variable to be controlled is the subway velocity, v_{sub} (Figure 12). It can be noted that the tuning path is independent on the power flow direction: in the case of the subway, the velocity should be controlled by acting on the modulation input whatever the power flow direction, traction mode or regenerative braking mode.

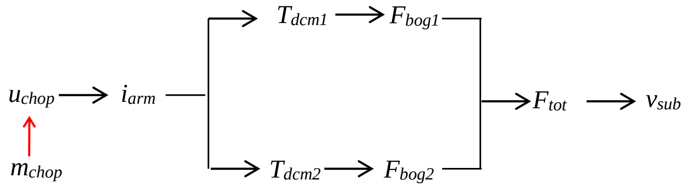


Figure 12: Tuning path of the studied subway traction system

3.4.b. Maximal Control Structure (MCS)

The Maximal control Structure is obtained by inverting the tuning path with the assumptions of possible measurements of any variable. The inversions of accumulation elements are realized through closed-loop controller to respect the causality principle [Hautier 2004]. The inversions of conversion elements are realized by direct inversions of the model relationships (open loop). The inversions of coupling elements require distribution and weighting inputs to be defined by the stately level (or EMS, Energy Management Strategy in the vehicle domain) [Bouscayrol 2000]. The organisation of the control scheme is thus obtained by a mirror effect. This control scheme is called Maximal Control Scheme because it requires a maximum of sensors and control operations [Bouscayrol 2012]. All control elements are depicted by light blue parallelograms, the closed-loop operation by paralegals with an oblique bar (i.e. delay), the strategy by dark blue pictograms. The MCS of the studied traction systems is presented (Figure 13). In the case of the subway, a distribution input k_R and a weighting input k_W have to be defined by the strategy level [Mercieca 2004].

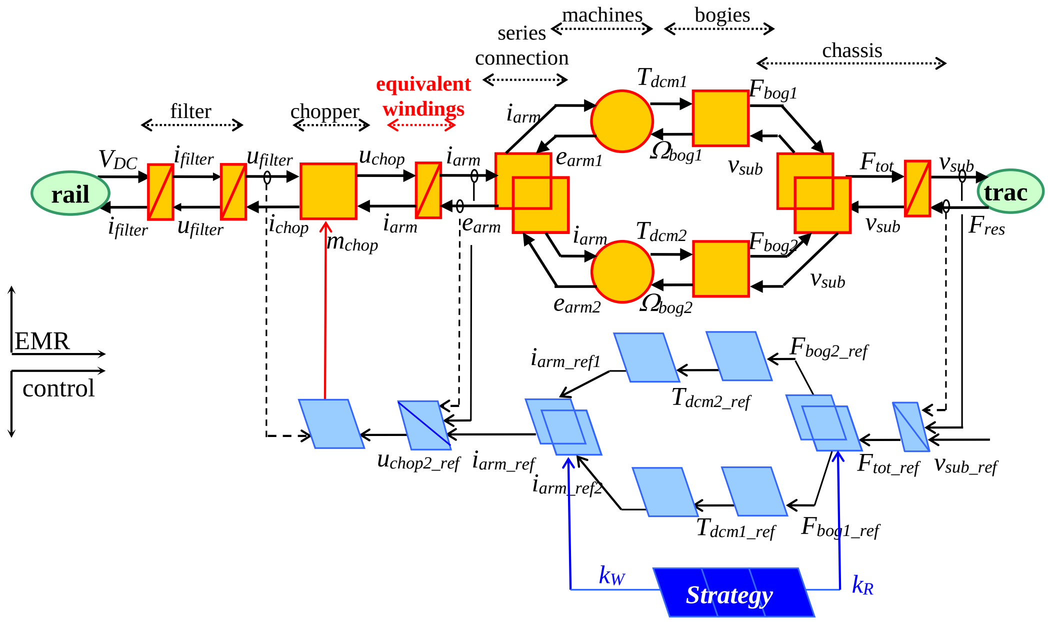


Figure 13: Maximal Control Structure of the studied subway traction system

3.4.c. Practical Control Structure

A practical control structure is then obtained by simplifications and estimations of non-measured variables. If a unique MCS is possible for the same system and same technical requirements, several practical control structures are possible in function of the simplifications. Estimation elements are depicted by purple pictograms (copy of the component models). A practical control scheme of the subway traction system is presented (Figure 14): a master-slave control is used and only the front bogie is controlled: no more strategy is required to distribute energy (i.e. an implicit equi-distribution is realized). Moreover some control elements have been merged. For example, the velocity controller directly delivers the current reference (the gains of the inversion of the conversion elements are merged with the controller gains). Some disturbances (dashed lines) are also neglected. Finally, the velocity is estimated from the measurement of the rotation speed of one machine. Of course, all these simplifications lead to reduced performances while reducing the cost of implementation (less sensors, lower capacity for the electronic control unit). In the case of the subway, if a disturbance occurs on the slave bogie, no management will be ensured.

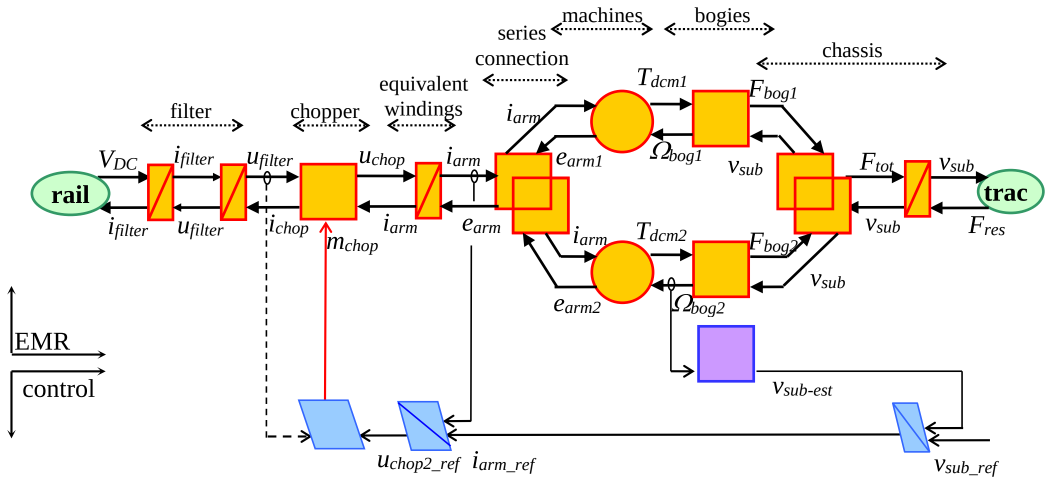


Figure 14: Practical Control Structure of the studied subway traction system

3.5 EMR and multi-level models

EMR has also been used as a guideline for model reduction. Dynamical models of electrical drives (including inverter, Park’s models and control) have been replaced by static models (equivalent global efficiency maps) keeping the same global I/Os [Letrouvé 2010]. This property has been intensively used for the development of EMS of HEVs in order to simplify the vehicle model for the development of the strategy rules [Horrein 2015] [Castaings 2016] [Pam 2017] [Nguyen 2019], for reduction of the computation time in real-time applications or complex optimization [Mayet 2014a] [Li 2019] [Desreveaux 2019] or global modelling for unknown parameters [Depature 2017]. The I/Os of the reduced model are exactly the same as the initial model and that enables to keep the initial causality despite the model simplification, and even though some dynamics are neglected.

In the case of the subway traction systems, the supply rail and the source can be merged in a single equivalent source (and the equivalent dynamics can be neglected) (Figure 15). Moreover, an equivalent bogie can be considered (unique equivalent gain) by merging the machine and the wheel. Finally the chopper, the inductance and the current controller can be replaced by a static model assuming an ideal control, no internal dynamics and 100% of efficiency (intermediate model can of course be considered):

$$\begin{cases} i_{arm} = i_{arm-ref} \\ i_{chop} = \dfrac{i_{arm} e_{arm}}{u_{filter}} \end{cases} \qquad (8)$$

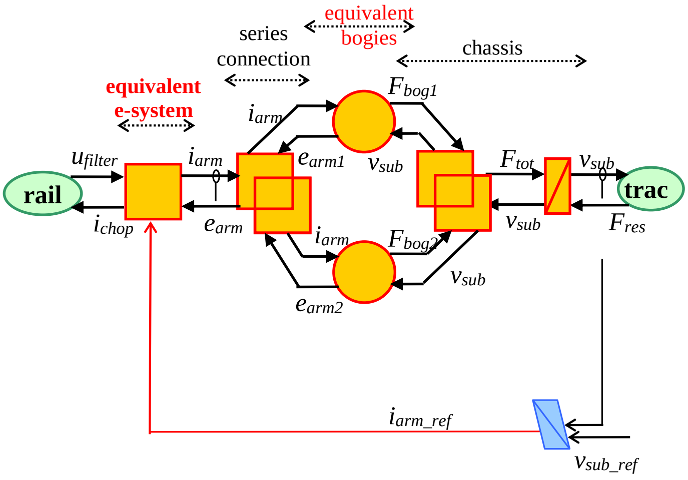


Figure 15: Reduced model of the studied subway traction system

4. PANDA methodology

This sections aims to explain how the EMR formalism is used in the PANDA philosophy.

EMR is a graphical formalism to organise the models of multi-domains energy conversion systems for a deduction of their control organization. To achieve this goal (organization of control schemes), EMR is focused on a functional description based on the exclusive use of the natural physical causality. Moreover, EMR has been developed within the framework of Systemics (or System theory) [Astier 2012] to propose a more general and global view of the entire studied system. The principle of Holism is thus a key point to solve conflicts of association in order to conserve the physical causality [Bouscayrol 2012]. As a consequence only ODEs (Ordinary Differential Equations) are used in EMR leading to a reduced computation time. However, a functional approach is more difficult to handle by engineers because an in-depth understanding of all physical phenomena are required. Moreover, the conflicts of association must be detected and solved before any simulation. That is why structural-based software packages are nowadays more and more used, “pick and place” action are user-friendly, and the solver has to detect and solve the conflicts of associations.

PANDA aims to propose a unified model organization for flexible and multi-level organisation of electrified vehicles. In section 2, it has been demonstrated that a functional approach leads to better flexibility while avoiding “convergence algorithm” and the associated computation burden. PANDA is thus developing a disruptive approach because most of the H2020 on-going projects on vehicle modelling are focused on a structural approach. Moreover, the exclusive use of the physical causality leads to lower computational time compared to an acausal description because of no derivative relationship to manage. This property is of interest for simulation / optimization of complex vehicle powertrains; moreover, it is a key point for real-time simulation for HIL testing.

EMR is thus a relevant formalism within the framework of PANDA, even though PANDA is not focused on control development.

4.1 Different steps for building simulation

As indicated in section 1, before simulation, there are two major steps that are the modelling and the representation [Bouscayrol 2008]. In the perspective of a flexible simulation organization, these steps can be completed.

Technical requirements – The first work is to define in a clear way the simulation objective, in particular which phenomena to consider for the system as a whole, and indirectly for the different subsystems. For example, if the objective is to calculate the energy consumption of the studied vehicle, it is of prime importance to consider the energy efficiency of the different components. Moreover, as defined in EMR, the border of the studied system should be clearly identified: what will be inside the system and what will be outside the system (environment i.e. source element depicted by green oval pictograms).

Modelling of subsystems – The modelling of each subsystem must be done independently without considering the other subsystems; therefore the modelling will focus on the physical phenomena to consider in the subsystems. A cognitive approach is required to develop knowledge models from the physical laws. This point is crucial to assess that the natural physical causality is determined in a proper way. Generally, the components have to be modelled on a system level in order to be connected to other components. The modelling also deals with the energy sources: their model should be developed to have the right interaction with the studied system.

As previously explained, it is noted that the components must be studied with no regard to the others. In that way, there is no risk in re-considering the modelling assumptions in order to solve a possible conflict of association. The model must only be in agreement with the phenomena to consider, whatever the difficulty to coupling it with another model.

EMR of subsystems – The EMR of each subsystem should be defined independently to the others. Only the sources and the accumulation elements have fixed I/Os. Other elements have floating I/Os. Some physical elements will be described by a unique energetic function, but other elements will be decomposed in several coupled energetic functions. For example a vehicle chassis is described by a coupling element (coupling of traction and braking forces) and an accumulation elements (energy storage in the mass) [Bouscayrol 2012]. It is the difference between a structural description and a functional description.

EMR of the entire system – The EMR elements will thus be connected to form the whole system. Conflicts of association will surely occur as functional and causal descriptions are used. These conflicts of associations will be detected by the incompatibility of the I/Os due to the accumulation elements. The conflict of associations will be solved from the guide of the merging and permutation rules. In that case some physical devices (structural description) will be described by a unique EMR element (functional description). This operation will lead to rewrite the model equations in order to consider the Holism principle of Systemics, i.e. to consider the right interactions between elements.

Control of entire system – When the EMR of the entire system is properly defined, the control scheme can be deduced if necessary. The inversion rules lead to the Maximal Control Structure (ideal theoretical control scheme) or Practical Control Structures (practical control organization assuming a lack of performances). The control tuning can be realized in a second step: selection of the closed-loop controllers and calculation of their parameter as a function of the target performances.

Simulation of entire system – The EMR and the associated control can thus be implemented in a dedicated software (see section 5). The model equations derived from the modelling step and the solving of conflict of association, will be used for describing the internal relationships of each EMR element. The control operation derived from the control step will be used for describing the internal relationships of the control elements.

It should be noticed that most of the time should be spent to describe the right model before simulation. This time is generally neglected when a structural software is used: the user has just to pick the components from the library and to connect them in the simulation window. The modelling step is more and more neglected that can lead to non-relevant results. The representation step is also neglected and the solving of the conflicts of associations is under the responsibility of the solver. This structural approach cannot enable a systematic deductions of the right control schemes even though experts can rapidly find it. In this structural case, the quality of the simulation results will also depends on the quality of the solver to detect the conflicts of association and the way to solve this conflicts.

4.2 Initial models

As the I/Os are defined by dynamical models according to the physical causality, when multi-level models are required, the most accurate one including all the dynamics should be considered first. This will enable defining the EMR elements and I/Os according to this model level. Other models can thus be deduced by simplification rules but keeping the same global I/Os.

It can be noted that most of the static models are a reduction of dynamical models and their control (see § 3.5). In that case, before the reduction of the model, the control of the dynamical model must be defined in an intermediary step.

This property is obvious for knowledge models derived from the physical laws. But it is more complex for behaviours models often defined from black box approach. Even in that case, an initial model with the right I/Os should be defined. The modelling process can thus be defined a model (using Artificial Intelligence other algorithms) from these defined I/Os.

5. Software implementation

EMR is a graphical formalism independent of the modelling method and of the simulation tools. EMR has been intensively used in MATLAB-Simulink © which is a functional toolbox. Moreover, MATLAB-Simulink © is coupled with real-time controller board such as dSPACE for a direct compilation of control programs. Research activities of ULille are conducted using EMR, but this formalism is also used in education activities [Bouscayrol 2007] [Lhomme 2012] [Bouscayrol 2015] using the Simulink library developed by L2EP [EMR 2022].

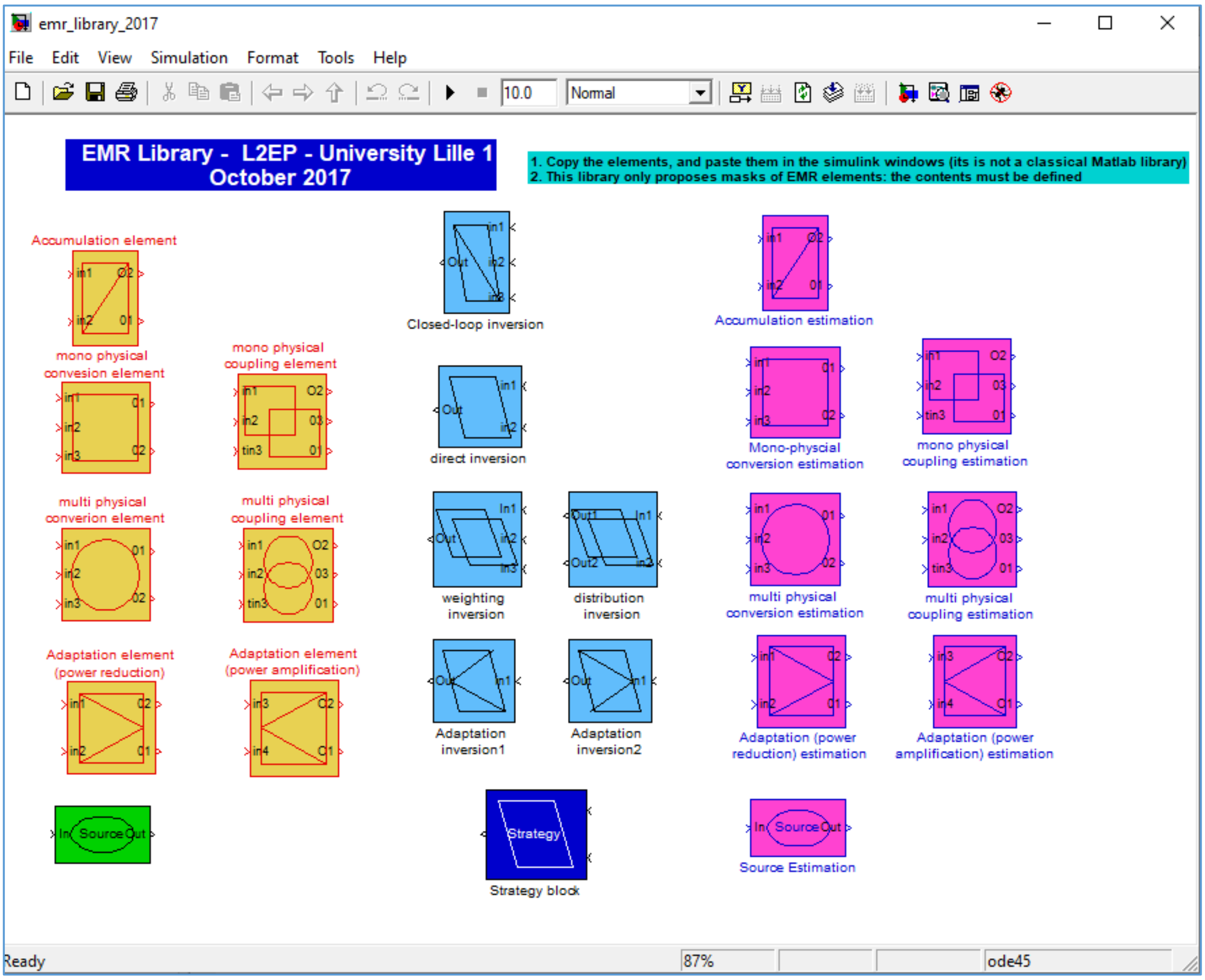
However, structural software have also been used using thanks to handmade EMR libraries such as PSIM [Delarue 2010], 20SIM (Bond-Graph software) [Silva 2014], or Typhoon HIL Software [Genic 2017]. Within the framework of PANDA, a real EMR library has also been developed in Simcenter Amesim [Husar 2019].

This section is devoted to the implementation of the EMR formalism in MATLAB-Simulink © as a functional-based tool, and in Simcenter Amesim © as a structural-based simulation package.

5.1. Implementation in Matlab-Simulink ©

A MATLAB-Simulink EMR library has been developed for research and education activities since 2008 [EMR 2022] (Figure 16). This library is in open access on the EMR website. It is composed of power subsystems (orange), control subsystems (blue) and estimation subsystems (purple) with dedicated masks from the EMR pictograms.

The different subsystems are empty and when the user double-clicks on the icon, he/she can fill the subsystems using the functional library of Simulink. For example, the chassis of a vehicle can be described using a transfer function in an "accumulation element" subsystem (Figure 17).



EMR Library - L2EP - University Lille 1
October 2017

1. Copy the elements, and paste them in the simulink windows (its is not a classical Matlab library)
2. This library only proposes masks of EMR elements: the contents must be defined

Figure 16: EMR library in Matlab-Simulink ©

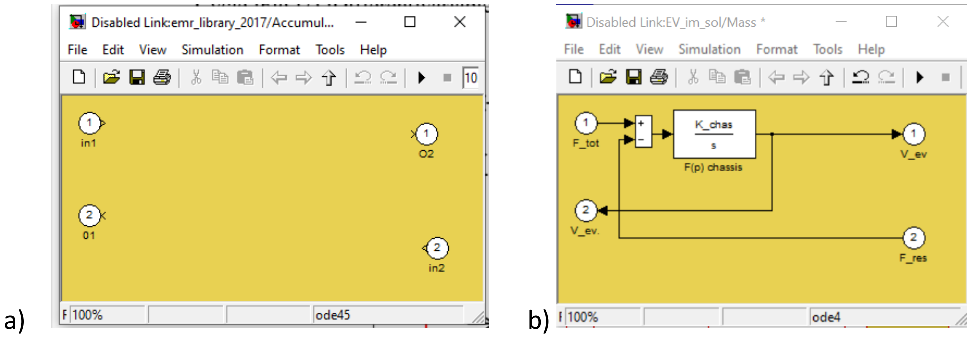


Figure 17: Example of a vehicle chassis MATLAB-Simulink ©: a) initial element, b) complete element.

Thus, to describe the full system, after defining the EMR including solving the conflict of association, the user can “drag and drop” the elements from the EMR library, complete the various blocks by mathematical relations, and link the different elements. An example of electric vehicle is provided [Bouscayrol 2007] (Figure 18).

It can be noted that the EMR of the system is not exactly transposed in this software due to the I/O of the Simulink subsystem: all the inputs are in the same side and all outputs are in the opposite side. This drawback can lead to some confusion.

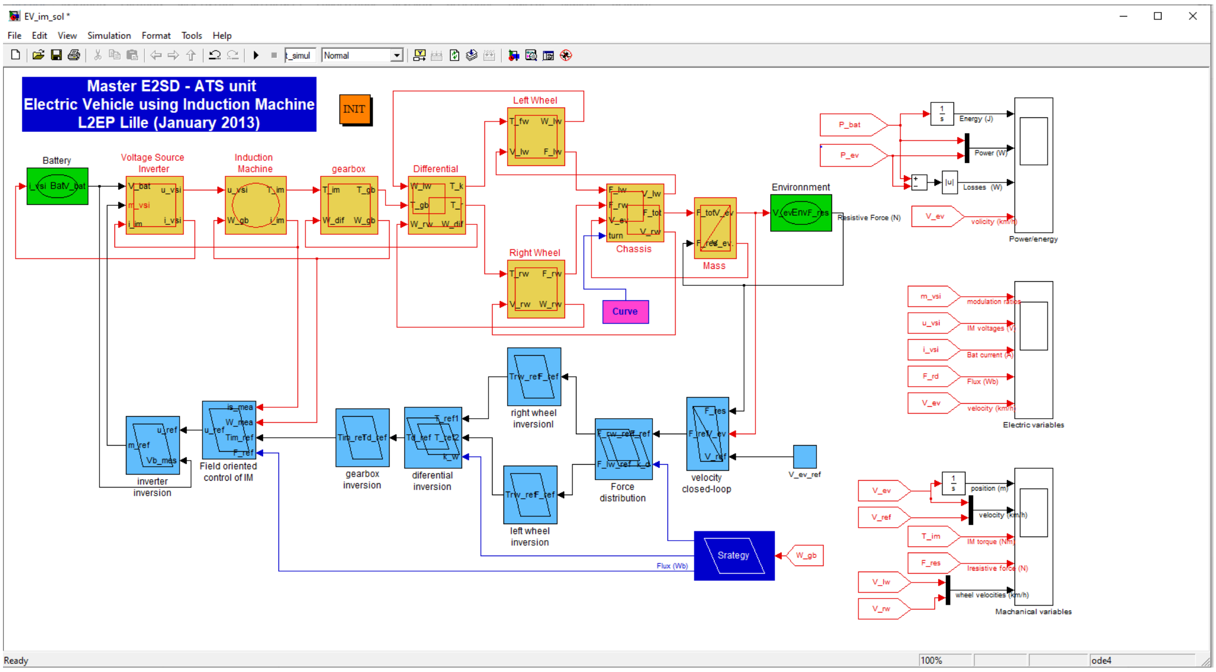


Figure 18: Example of the traction of an electric vehicle in Matlab-Simulink © [Bouscayrol 2005]

5.2. Implementation in Simcenter Amesim ©

A dedicated EMR-library has been developed in Simcenter Amesim © (Figure 19) within the framework of the PANDA project [Husar 2019]. This library also contains the different types of elements such as the energy source (green), systems elements (orange), control elements (blue) and estimation elements purple.

It can be noted than the pictograms are strictly depicted as the EMR formalism using the same graphical rules. Moreover, the I/Os have been defined according to the EMR rules that enable an easier transcription and reduces the number of crossed links.

The contents of the EMR elements of the library can be filled using the mathematical equations of the studied element using the “signal & control” library.

An example of the EMR of the traction system of an Electric Vehicle is given [Husar 2019] (Figure 20). It is clear that this simulation implementation is closer to the initial EMR than the one developed in MATLAB-Simulink ©.

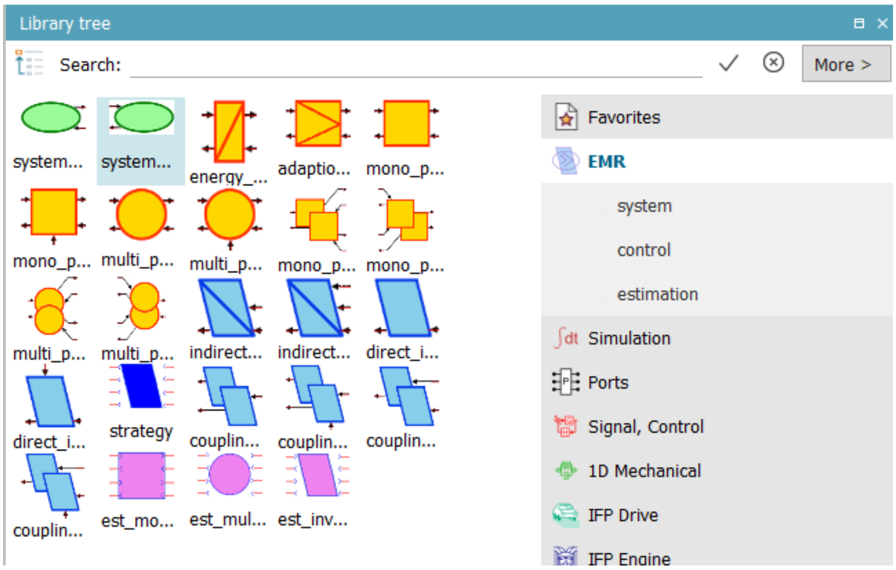


Figure 19: EMR library in Simcenter Amesim ©

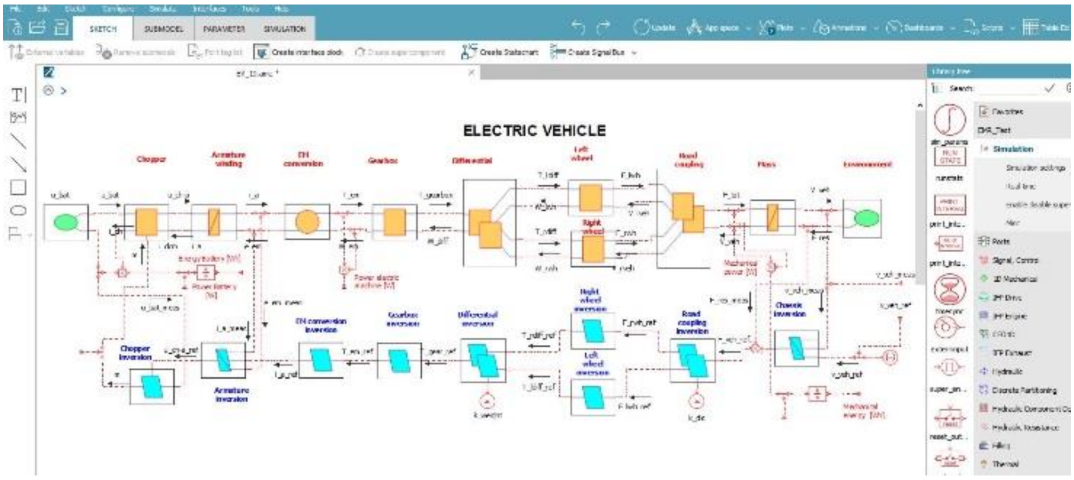


Figure 20: Example of the traction of an electric vehicle in Simcenter Amesim © [Husar 2019]

6. Experiences from PANDA

This section contains the lessons from the use of the PANDA methodology all along the project.

6.1. Training in the EMR method

First, the EMR formalism requires some training before using the PANDA methodology. Most of the PANDA partners were not aware of EMR, and have to learn this formalism before the development of library, models, simulation or HIL testing. Such a training period is a drawback of the method.

From the experience of SISW, especially from engineer in charge of the development of the EMR library, a 4 weeks training has been estimated, and another 4 weeks has been required in the development of a first vehicle simulation. On the contrary for scientists already aware with the formalism (e.g. Master student of University of Lille, where EMR is taught), only 2 weeks have been required in the development of a first vehicle simulation. This point highlights the importance of EMR in education of engineers or the need of a dedicated training.

6.2. Multi-level models & interoperability

Different models of batteries [PANDA 2.1] [PANDA 2.3] and of e-drive [PANDA 3.1] [PANDA 3.2] have been developed with strictly the same inputs and outputs. This I/Os organization has enabled a seamless change of model granularity for the simulation of the BEV [PANDA 4.3], the FCV [PANDA 4.4] and the P-HEV [PANDA 4.5]. This interoperability has been highly appreciated by the different partners.

For the knowledge models [PANDA 2.1] [PANDA 3.1], respecting the fixed I/Os requires to rewrite some of the modelling equations, but the work is not so complex. Moreover, the partners have appreciated that these fixed I/Os can be used as a guideline for model reduction.

For the behaviour models [PANDA 2.3] [PANDA 3.2], the I/Os have been fixed from the natural causality defined in the knowledge models. Once again, this guideline has been appreciated in particular for the behaviour model deduced from Artificial Intelligence (IA) in order to develop the model from a set of experimental data. However, the expression of the derived model has shown some difficulties to be implemented in the simulation [PANDA 2.3]. This point should be studied in future works. But, black box models have also been derived from knowledge models [PANDA 3.2]. Such a confidential model is of a prime importance to keep the industrial property of an innovative subsystem. Industrial partners strongly appreciate this possibility.

6.3. Functional description & flexibility

The causal organization enables the respect of the physical behaviour. The integration principle requires action and reaction variables between subsystems in accordance with the power. These properties require to organize the equation in a functional way. The conflicts of associations have to be solved directly by the user before simulation. If this resolution needs more preparation time, it has some relevant advantages.

First, the computation time is lower than for a classical structural organization. The solver has no more conflict of association to detect and does not require solving procedure or derivative computation. A comparison using Simcenter Amesim © has demonstrated that the same model of a BEV can save 15% of computation time using functional organization instead of a structural one [Husar 19]. For that study, the same control (derived from EMR) has been considered and only the power system was changed (structural description from component library and functional description from EMR library).

Second, as I/Os are defined according to the causality, a high interoperability has been demonstrated. A direct translator has been established between Simcenter Amesim © and Typhon HIL Control Centre (and its EMR library) [PANDA 5.1]. Moreover, for cloud-based HIL testing, part of the real-time model was computed in Typhoon ECU and part of the real-time model was computed in the cloud using Simcenter

Amesim ©. This co-simulation has been achieved without FMI thanks to the strict organization of I/Os [PANDA 2.2] [PANDA 2.3].

Third, this causal organization of I/Os enables the development of the right power interfaces for power HIL [PANDA D1.4]. As the power interface is the link between a real device (hardware) and a virtual device (software), the real-time model of the virtual device should be organized in respect with the physical behaviour of the real device under test.

7. Conclusion

The PANDA methodology is based on the EMR graphical formalism as a guideline. This choice has enabled a more flexible simulation and reduced computation time. However, more preparation is required for the user before building the system simulation.

The PANDA methodology can be summarized in several steps.

- The first step consists in the definition of the technical requirements in a clear way, at the system level, but also at the subsystem level for the definition of the requested accuracy of each subsystem.
- The second step is to model separately each subsystem from the considered physical phenomena depending on the global objective and the required accuracy.
- The third step is to describe the system using EMR, **detect the conflicts of association and solve these conflicts** using dedicated rules.
- The fourth step is to deduce a control scheme from the EMR using inversion rules (EMR methodology).
- The last step is to implement this EMR and control in a simulation tool using EMR functional libraries.

This method has been intensively used with functional-based software such as MATLAB-Simulink ©, using dedicated functional libraries. On the PANDA project, SISW has also developed an EMR library in Simcenter-Amesim ©, which is a structural software. Moreover, Typhoon has extended its existing EMR library in Typhoon HIL Control Centre, which is a software dedicated for real-time simulation. These 3 simulation packages have been used in PANDA because of the usage of the different partners. The manual translation (MATLAB-Simulink © to Simcenter Amesim © and vice-versa) or the automatic translation (Simcenter Amesim © to Typhoon HIL Control Centre) demonstrate the portability of the PANDA method based on the EMR formalism. New software and new translator will surely be developed in future works.

Despite the required training period, this disruptive simulation method has demonstrated valuable properties that enable interoperability, flexibility, portability, and fast simulation. The PANDA can thus achieve its target to reduce the development time thanks to the proposed method. An analysis of the potential gain is provided in [PANDA 6.6] with a reduction up to 24% of the lead-time (time-to-market excluding the business pre-study and the plant development) by using the PANDA methodology all along the W-model of the vehicle development.

8. Deviations from Annex 1

There is no deviation in terms of contents and the rules of the methodology of an open-access unified model organisation have been derived from the EMR formalism.

Due to the COVID-19 crisis, there have been some delays in building and delivering the battery system (Bluways) and real-time simulator (TY). These delays have been included in the project extention that was approved by INEA. The delays have not affected the final results. There is no other deviation according to the amended GANTT chart.

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Table 1: 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)
7			
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-BT	TUV SUED Battery Gmh.

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Appendix 1 – Abbreviations / Nomenclature

Table 2 List of Abbreviations / Nomenclature

Symbol / Shortname	
BEV	Battery Electric Vehicle
EV	Electrified Vehicle
EMR	Energetic Macroscopic Representation
FCV	Fuel Cell Vehicle
FMI	Flexible Mock-up Interface
HEV	Hybrid Electric Vehicle
HIL	Hardware-In-the-Loop
I/O	Input / Output
MCS	Maximal Control Structure
ODE	Ordinary Differentiate Equation
P-HEV	Plug-in Hybrid Electric Vehicle

Appendix B – 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
	Daniela CHRENKO (UBFC)	Cristi IRIMIA (SISW)	Adrien GENIC (TY)	Alain BOUSCAYROL (ULille)
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