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EV Thermal Management "Model Based Design"

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Summary

The *thermal management* of electric and hybrid vehicles is becoming more and more complex. This is due to the multiple objectives allocated to thermal systems and organic solutions to be optimized. To address this complexity, Model-Based is used for architecture evaluation and component sizing. We propose the use of functional energy *modeling* to ensure the link between the system architects' model and multi-physical *simulation* models and to design the thermal system supervisor. The application to an *EV (electric vehicle)* illustrates the modularity of the methodology as well as its flexibility in response to the variability of equipment and objectives.

1 Introduction

The thermal synthesis of electric and hybrid vehicles is becoming more and more complex. This is due to the multiple objectives allocated to thermal systems and organic solutions to be optimized according to cost, space and performance. One example is the case of the refrigerant circuit, initially dedicated to the cabin, which is increasingly used to cool the battery. Similarly, the water circuit, initially dedicated to the internal combustion engine, must also provide cooling for the electric motor and power electronics at different temperature levels. There is also an increase in the use of heat pumps for electric vehicles, as well as fuel cells requiring specific cooling. As a result, the control of thermal management is becoming a major challenge for tomorrow's vehicles to ensure better range but also for greater safety and comfort for passengers.

To meet this complexity, the use of Model-Based provides a response element at the engineering level (with Model-Based System Engineering) and at the design level (with Model-Based Design) for the evaluation of architectures using simulation and for the sizing of components [3].

Recent work in the description of complex systems, carried out as part of a CIFRE thesis [7], has made it possible to propose a methodological approach for developing a functional energy model describing, in a modular way and using only the mathematically necessary models, the different components, sources and consumers and their interconnections [4], [8]. Applied to the mobility of a hybrid vehicle, the tools have made it possible to link the different levels of modeling (functional and multi-physical) but also to connect the different levels of control [9].

In this paper, we propose to present the extension of this approach for the treatment of heat exchange in electric and hybrid vehicles. The main extensions are the functional representation of heat exchange and distribution groups such as heat transfer fluid circuits, refrigeration circuits and heat exchangers between these circuits.

This functional model has a double target: to ensure the link between the system architects' model and the multi-physical simulation models and to design the thermal system supervisor in order to optimize exchanges in relation to the thermal comfort needs and the operating and safety constraints of the equipment.

The results of a demonstrator (electric vehicle) will be presented to illustrate the modularity of the methodology as well as its flexibility in the face of equipment and targets variability.

The design of complex systems requires multi-view and multi-business processing. This is what justifies the decomposition into subsystems. It is therefore necessary to break down the system in relation to the business organization (§2.1) while ensuring the integration and satisfaction of uses (§2.2). We propose to develop each subsystem, complex in itself, by iteratively addressing two levels of modeling to design the structural architecture and its functioning (§2.3).

Functional energy modeling concepts that provide the modularity necessary for system integration (§3) will be used to develop and test each of the subsystems (§4.1). These concepts then make it possible to connect subsystems, check their interrelationships and optimize overall energy management (§4.2).

2 Organization and composition

2.1 Breakdown by business line

The development of complex systems faces two opposing constraints. To address complexity, it is necessary to design the system as a whole and to address all the interrelationships between its components. Conversely, the development of a complex system requires breaking it down and assigning responsibility for its components to several teams, each specialized in its field.

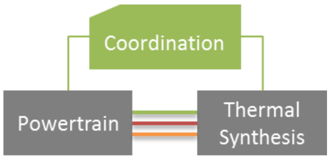


Figure 1: A breakdown by business line.

For vehicles, it is usual to define two complementary subsystems: the powertrain managing the electromechanical powers and the thermal synthesis which manages both the thermal comfort of the cab and the thermal conditioning of the equipment (Fig.1). This decomposition is justified by the business lines and reinforced by a natural frequency separation (fast electro-mechanical dynamics and slow thermal dynamics).

To ensure the proper contribution of each of the subsystems to the purposes of the overall system and to ensure interrelation during final integration, one solution is to:

- Carry out a global preliminary study specifying the subsystems using functional modeling; with a low modeling granularity, it is both possible to consider the vehicle as a whole and to avoid a precise definition of the components before their choice;
- Ensure coordination of subsystems, both at the organizational level and at the level of the overall vehicle supervisor.

2.2 Overall functional modeling

Functional energy modeling has been created to represent a complex system as a whole [8] and evaluated in the case of a hybrid vehicle [4], [10]. Based on energy links and using a low modeling granularity, this representation allows systems in simulation to be evaluated from the early design stages.

The entire vehicle model (Fig.2) represents the energy exchanges required to meet mobility and thermal comfort targets. In addition to these two effectors, the model includes electromechanical transformation, heat exchange with an external source, energy storage and a distribution block to spread energy between different consumers according to a predefined strategy. The modeling concepts will be presented in §3.

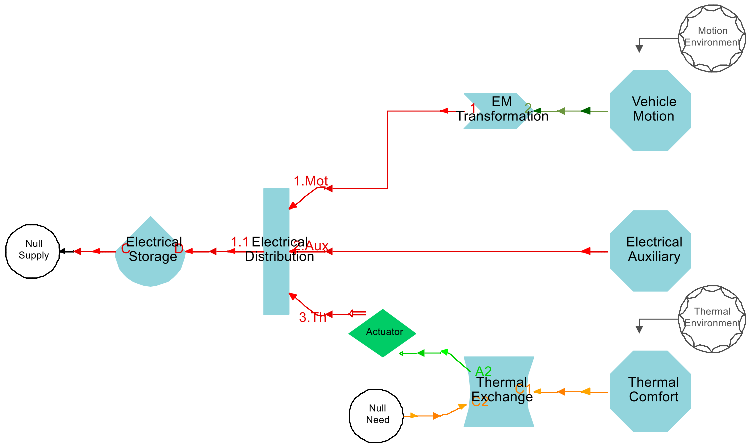


Figure 2: Simplified functional energy model of an electric vehicle

The results in Fig.3 represent the main system variables: missions (vehicle dynamic and cabin temperature), power distribution and the state of charge of the energy storage unit. The simulation model allows to make a first energy analysis with an estimate of the overall consumption during a WLTC cycle with different external temperature levels.

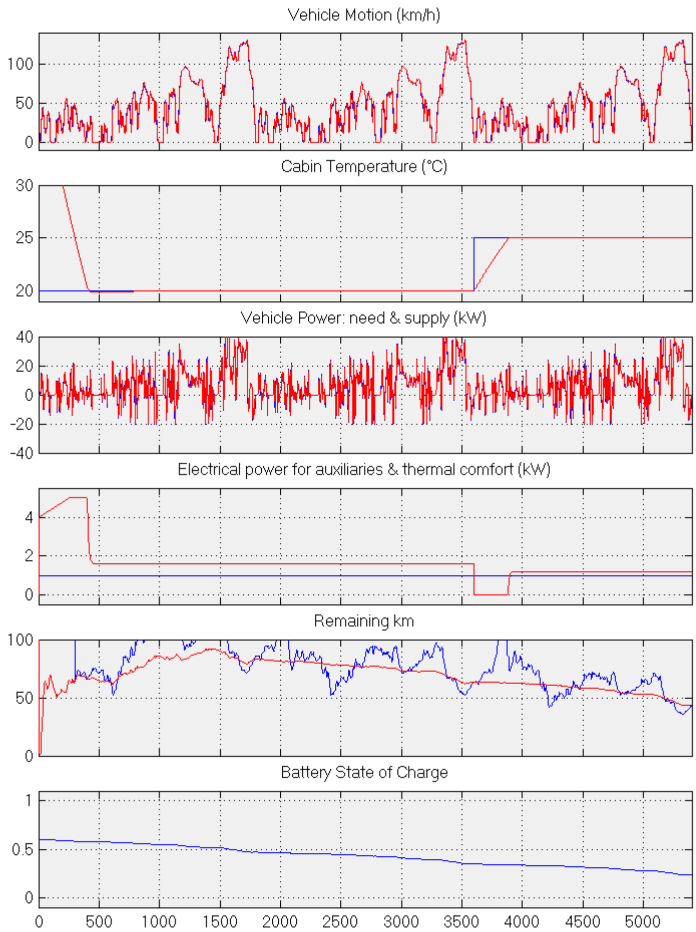


Figure 3: Energy management of mobility and thermal comfort

In addition to an initial verification of functional choices, this model makes it possible to specify the specification of subsystems by providing dynamic power profiles to be produced, stored or distributed.

Moreover, the use of modular formalism facilitates integration and ensures relationships between subsystems.

2.3 Canonical composition of subsystems

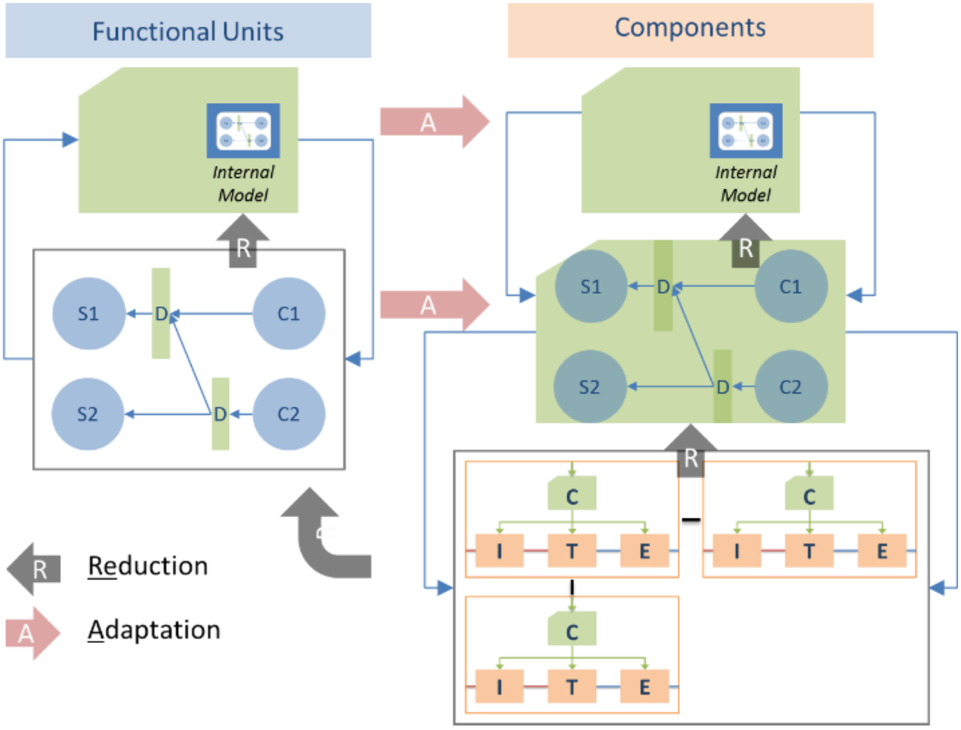


Figure 4: Canonical composition of subsystems

The functional model represents the exchange of energy flows between the different components. The flow controller of each subsystem can be extracted from it and connected to the controlled components [9]. The principle is to replace the simplified model included in the functional blocks with a link to the physical component controllers.

We deduce a canonical composition for each subsystem (Fig.4) with:

- A technological or organic architecture with its control;
- An assembly of components (functional blocks) with flow management;
- A finalization block allowing overall coordination at the vehicle level.

The final architecture thus obtained includes three interconnected system levels, each representing the entire system from a specific point of view.

3 Modeling concepts

The concepts introduced in previous work have been demonstrated on the hybridization of motor vehicles with electrical and mechanical consumers [7]. From a modeling perspective, this work is based on the theories of systemic modeling [6] and the use of modular functional blocks (components) to represent a complex energy system by simple assembly (§3.1). Fig.5 shows an example of such a coupling with the formalism adopted in this work. The model allows to control the energy flows of a hybrid vehicle (mechanical - green highlighting - and electrical - red highlighting -). The distribution blocks (rectangles) allow the necessary energy to be allocated to consumers on the sources (electrical and fuel) according to a predefined priority. They also make it possible to distribute the energy produced to consumers (in this case mobility and electrical auxiliaries) according to a predefined strategy. These distribution blocks may contain either heuristic logic or a more advanced optimization algorithm [1], [2].

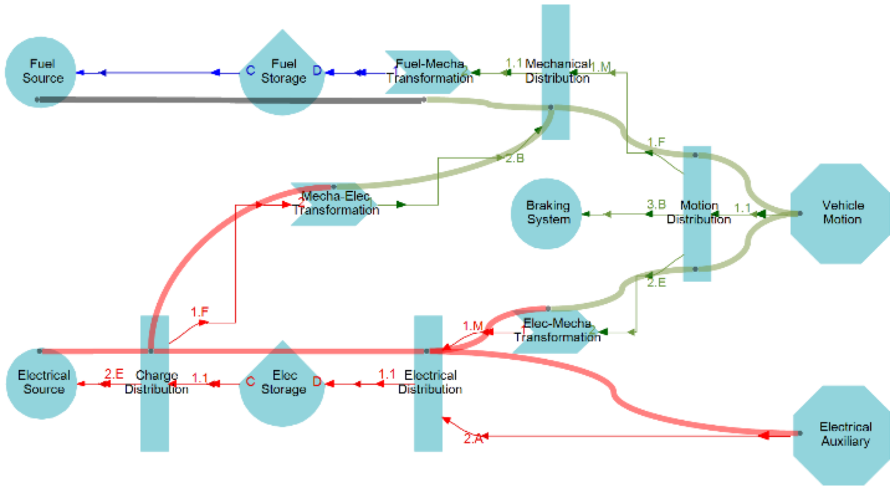


Figure 5: Electromechanical functional model of a PHEV

In order to simultaneously process thermal synthesis (application introduced in §2.2), it is necessary to extend the modeling concepts to heat exchanges (§3.2) and in particular:

- Heat exchange between two circuits (air, water, refrigerant);
- The dissipation or recovery of heat losses from an energy transformation; example of a conventional propulsion system that requires thermal conditioning but can also provide heat for air conditioning.

3.1 Components for effective assembly

The use of components is made to meet a need for modularity: to connect functional elements without pre-defining the source or consumer to which it must be connected. The element therefore reacts to the flows it receives (Fig.6) and not to the nature of the component to which it is connected. This black box representation favors, by construction, the definition of the relations between blocks.

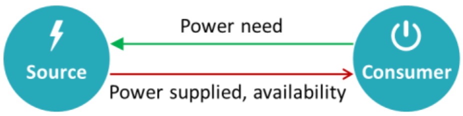
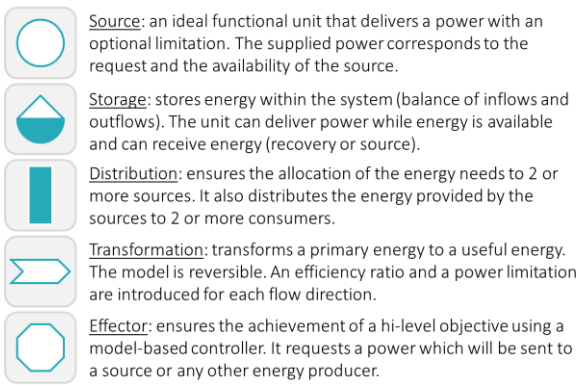


Figure 6: Energy flows between components

The nature of the flows exchanged is of the EMI type (Energy, Matter or Information). The flow is bidirectional, with demand (from consumer to source) and supply (from source to consumer).

Each component provides an elementary service with a set of consistent functionalities. In addition, the components are reusable and ensure a modular approach to the architecture with better readability, thus addressing the complexity of the controlled systems.

The main components are presented in the table below with their pictogram inspired by [11]. They represent functional units that potentially correspond to a technological solution.



	Source: an ideal functional unit that delivers a power with an optional limitation. The supplied power corresponds to the request and the availability of the source.
	Storage: stores energy within the system (balance of inflows and outflows). The unit can deliver power while energy is available and can receive energy (recovery or source).
	Distribution: ensures the allocation of the energy needs to 2 or more sources. It also distributes the energy provided by the sources to 2 or more consumers.
	Transformation: transforms a primary energy to a useful energy. The model is reversible. An efficiency ratio and a power limitation are introduced for each flow direction.
	Effector: ensures the achievement of a hi-level objective using a model-based controller. It requests a power which will be sent to a source or any other energy producer.

3.1.1 Extension of functional concepts - Heat exchange between circuits

Thermal management is commonly based on exchangers between conditioning circuits (water, air, refrigerant). As a first approximation, the circuits can be represented by thermal energy distributors with a possible energy cost (to run pump, compressor, fan, etc.).

On the other hand, the exchange between two circuits cannot be represented by the blocks introduced in §3.1.

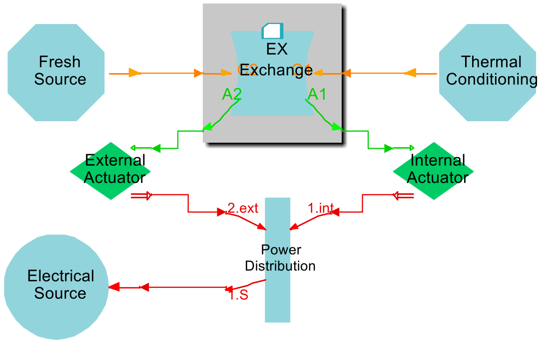


Figure 9: Heat exchange between two circuits and associated energy cost

The new component presented in Figure 9 represents this type of exchange with:

- Symmetrical treatment of the two thermal ports: no distinction between the two circuits to which the exchanger will be connected;
- The desired heat exchange is ensured by conditioning the circuits: use of actuators with energy cost.

The exchanged power is given by: $$P = \varepsilon . min(c_p . Q) . (T_1 - T_2) \quad (1)$$

Where P is the exchanged power, ε the efficiency of the exchange, T, cp and Q are the temperature, calorific capacity and flow rate of each of the circuits.

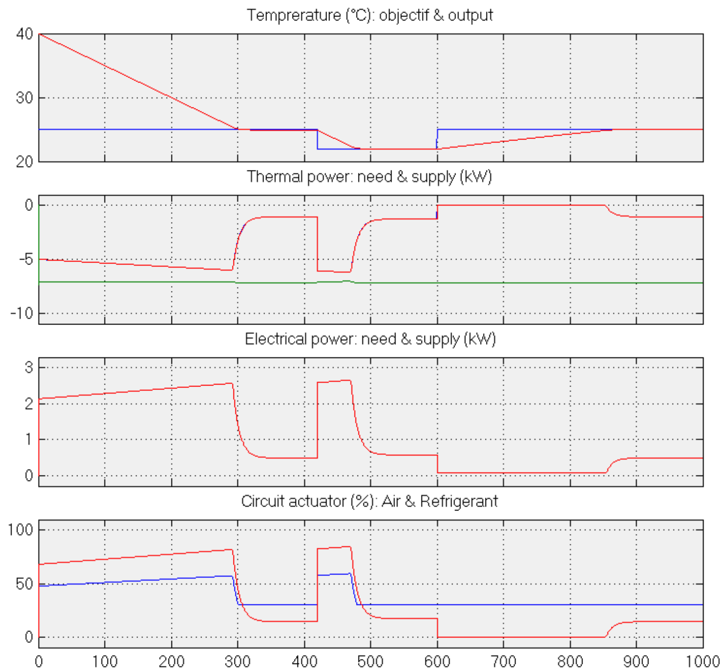


Figure 10: Thermal conditioning of an equipment by exchange with a cold source

The scenario in Figure 10 illustrates how this functional block works. The temperature of the system to be conditioned (axis 1) is controlled to its set point by energy exchange with the cold source (axis 2). The circuits are conditioned by actuation (axis 4) which induces an energy cost (electrical power - axis 3).

4 Demonstration on a hybrid electric vehicle

In accordance with the process suggested in §2, this paragraph presents the results of the design of the two subsystems (powertrain and thermal synthesis), their integration and the verification of their relationships.

Subsystem design and physical-control connection: following the specification (§2), each subsystem is treated separately following the same steps:

- Detailed functional energy modeling corresponding to organic-functional choices;
- Connection to the multi-physical model and control (details of structural relationships).

4.1.1 Powertrain and vehicle movement

The functional energy model is the one in Fig.5 corresponding to a PHEV.

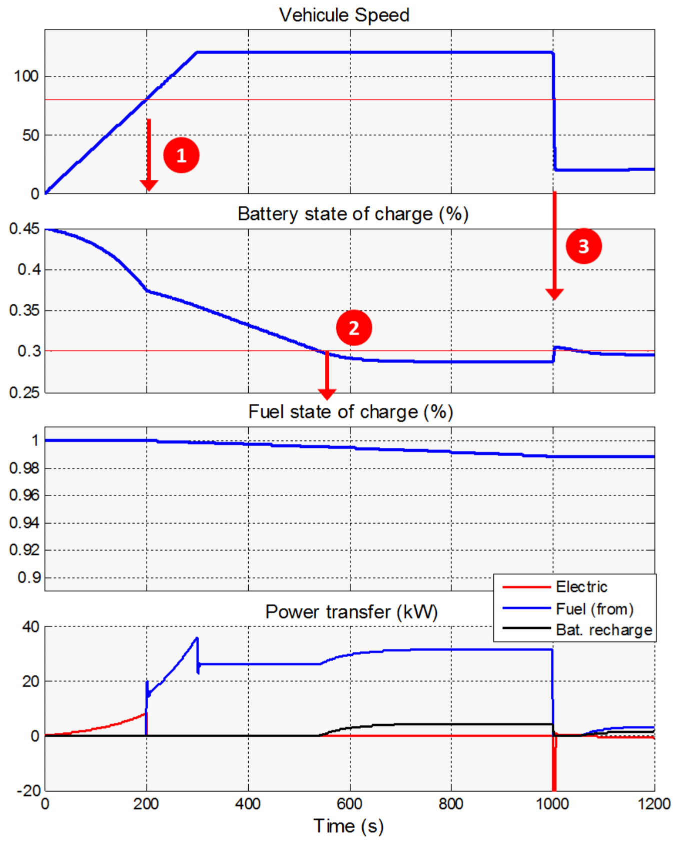


Figure 11: Energy management principles for the mobility of a PHEV

The basic scenario in Fig.11 illustrates the energy management strategy chosen for the powertrain. During start-up, the electrical source is used to move the vehicle until a speed limit of 80km/h is reached (event 1); the power is then supplied by the conventional network (fuel). When the storage capacity reaches a lower limit (event 2), the storage unit is recharged by the fuel network via an electromechanical transformation (black signal from axis 4). Finally, during braking at the end of the scenario (event 3), the braking energy is recovered and used to recharge the storage unit.

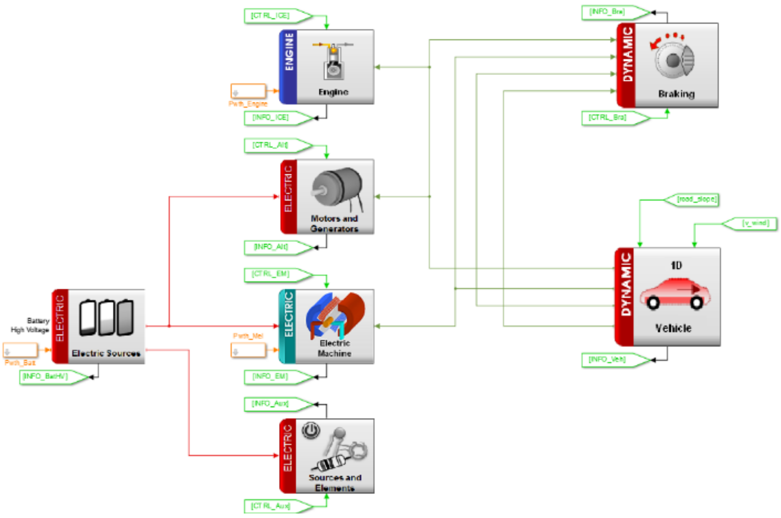


Figure 12: Electromechanical model of the powertrain

The multi-physics model in Fig.12 represents the main technological units of a hybrid powertrain: the vehicle dynamics, the braking system, the various engines (internal combustion engine, electric traction motor and alternator), the power battery as well as a set of electrical auxiliaries representing various vehicle consumers.

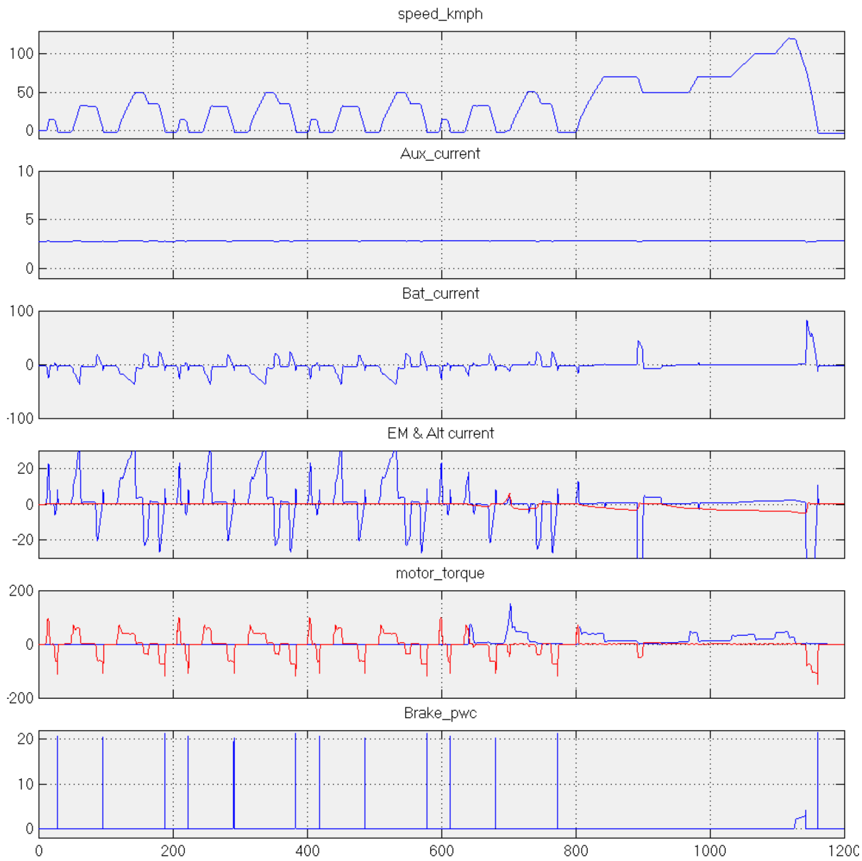


Figure 13: Energy behaviour of a PHEV over a NEDC cycle

The multi-physical model was connected to the functional energy model according to the method introduced in [9]. The functional model becoming the model for the vehicle's energy management strategy.

Fig.13 shows the simulation evaluation results for a NEDC consumption cycle. We find the physical signals (speed, currents, torques, braking pressure) and a behaviour that validates the strategy designed using the functional model.

4.1.2 Thermal synthesis

In the case of an electric vehicle, cooling is provided either by direct exchange with outside air or by exchange with a cooling circuit (Fig.14).

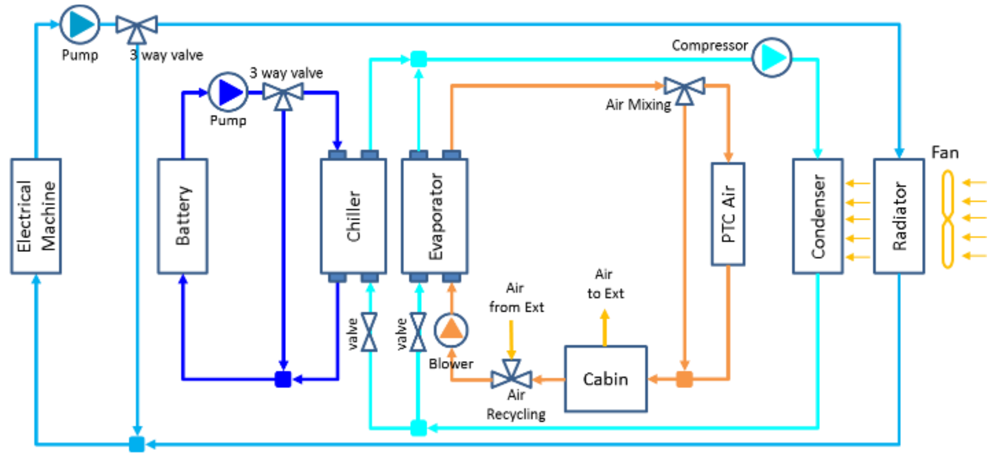


Figure 14: Diagram of the cooling circuits of an electric vehicle

The separation into several circuits results from the temperature level constraints of the elements to be cooled. This leads to complexity due to the need to optimise sizing and operation by pooling the sources of costs: the refrigerant is used to cool the cabin and the battery; the outside air is used in all circuits.

The functional model in Fig.15 represents this subsystem and reproduces its main functions:

- Cooling of electrical and electronic components by exchange with outside air;
- Cooling of the battery and passenger cabin by exchanging with the refrigerant circuit;
- Exchange between the refrigerant circuit and the outside air.

The circuits are represented by heat (or cold) distributors with an energy cost that will later be connected to the powertrain.

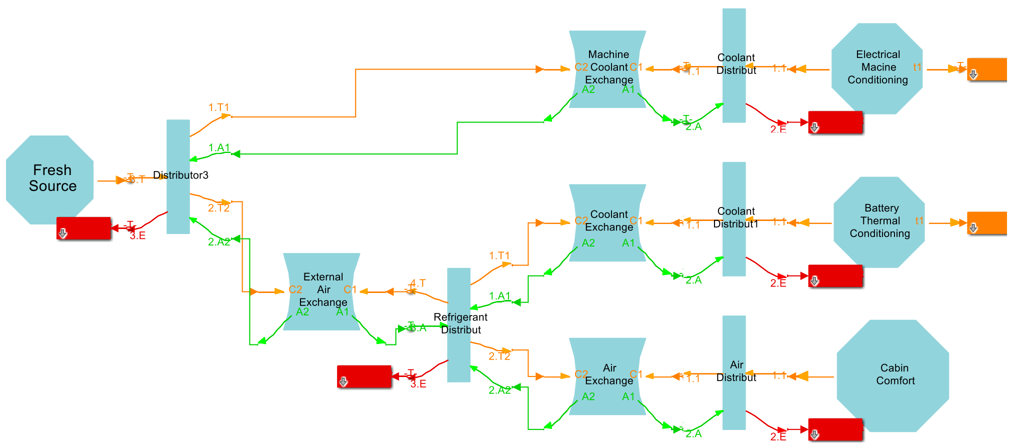


Figure 15: Functional energy model representing the thermal synthesis of an EV

The functional model was connected with the thermo-fluid model representing in detail the different thermal circuits.

Fig.16 shows, on a simple scenario, the compromise to be addressed in the case of an energy limitation. We placed ourselves in an unfavourable case (outside temperature of 45°C, steep slope 10%). Two cases are presented: on the left with a cabin prioritization and on the right with an electric machine prioritization. The axes present the different signals: temperatures (cab, battery and machine), main actuators (axis 4, compressor and fan) as well as the distribution of flows in the refrigerant circuit (axis 5, cab and battery).

Without the use of sophisticated algorithms, functional modeling has allowed the control of the system to be mastered, including with (deliberately) underestimated sizing.

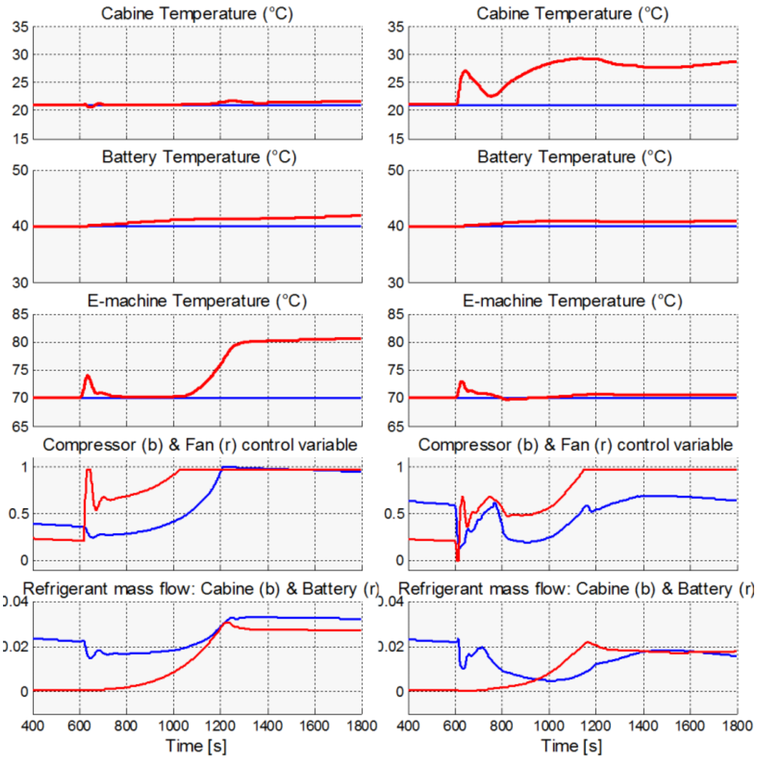


Figure 16: Cooling boundary management

4.2 Verification of interrelationships and energy optimization

This last part is devoted to the integration of the models of the two subsystems and to the overall verification of the vehicle's properties. It was done in the case of an electric vehicle (Fig.17) with:

- Physical links (electrical and thermal) between the two subsystems;
- Control links between each subsystem and its flow control (extract from the functional energy model);
- EMI links between the two flow controllers and information links with the overall coordination of the EV.

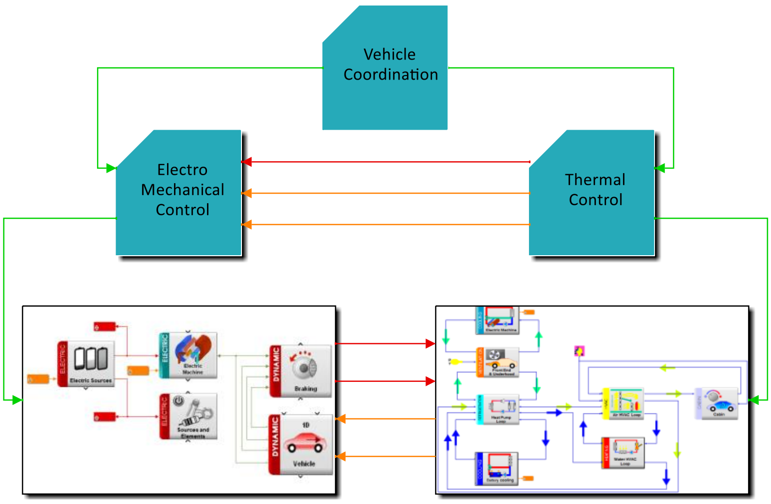


Figure 17: Model of an EV integrating mobility and thermal synthesis

The results presented below correspond to the EV's behaviour with a WLTC cycle. The second cycle is carried out with a slope of 6%, thus increasing the mechanical power and cooling requirements.

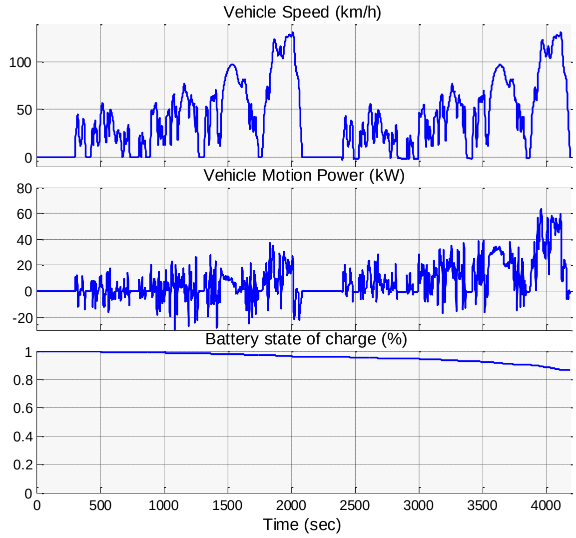


Figure 18: Mobility of the EV with a WLTC cycle

Figure 18 shows the main mobility variables: speed, battery charge state and power used by mobility. There is an increase in power (axis 2) in the second cycle corresponding to the slope driving.

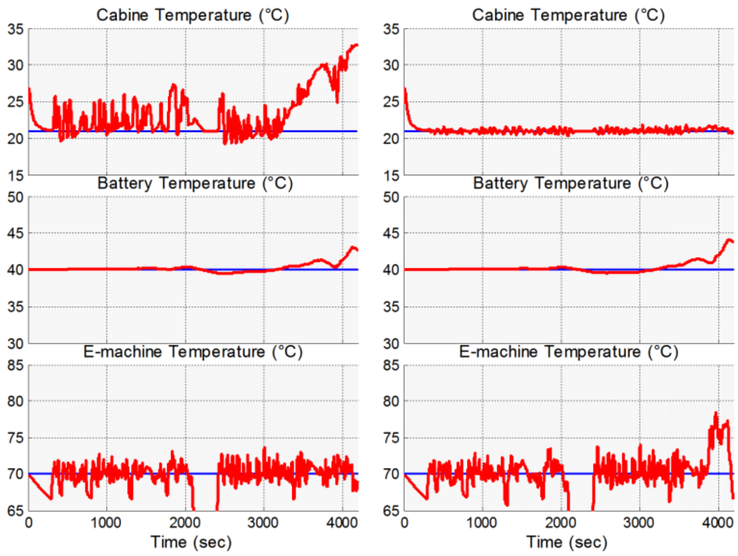


Figure 19: EV thermal exchanges with two control configurations

Figure 19 shows the heat exchanges for two control configurations: high priority to cooling the electric machine (left) and better weighting for thermal comfort (right). The results are discriminating during the second cycle (slope driving) where, only the second strategy makes it possible to achieve all the objectives of thermal synthesis.

An additional use of this global model is the presetting of the coordination module with a possibility of optimization: control parameters, dimensioning of components...

5 Conclusion

A methodology for modeling and evaluation in simulation of complex systems has been introduced and evaluated on an electric vehicle taking into account mobility and thermal synthesis.

Based on two connectable modeling concepts (multi-physical and functional energy), this methodology:

- Allows system evaluation from the early design stages;
- Ensures the consistency of the decomposition into subsystems by pre-defining their contributions to the overall system and facilitates the integration of their model;
- Provides the energy flow regulation model essential for the proper functioning of the system.

In addition, the method ensures modularity (which facilitates implementation) and flexibility.

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