48V Electric Vehicle Powertrain Optimal Model-based Design Methodology

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***Abstract*—Battery autonomy and drive range of Electric Vehicles could be improved by smart control of the power flows requested by equipped systems. In this paper, the authors propose two energy-saving strategies, acting respectively in the electric driveline consumption minimization and in the auxiliary power allocation policy. Developed solutions aim at the reduction of the power demand, both concerning e-powertrain and sub-components, not directly related to traction purpose, enhancing corresponding driveability distance. Evaluation of the result is done through a model-based approach, using a concept e-car proposed by *Valeo* and implemented in co-simulation environment, between *Amesim* and *Simulink*. The investigated methodology appears as a useful tool for the optimal design of the vehicle sub-system and component.**

***Index Terms*—low voltage electric vehicle, energy efficiency, auxiliary management, thermal management, real driving emission, e-powertrain optimization**

I. INTRODUCTION

Nowadays, Electric Vehicle (EV) market is growing, since CO2 regulations becomes more stringent, *e.g.* norm Euro 6 [1]. Moreover, traffic ban of conventional Internal Combustion Engine (ICE) vehicles are planned in major cities (Paris, London, Los Angeles, etc.) by 2025-2030 [2]. In this context, powertrain's electrification is required, leading to massive development of hybrid and electric cars [3], [4]. Furthermore, the new mobility trend, such as car sharing or urban trip, and customers' demand for vehicle with low energy consumption, have enhanced EV solution [5], [6].

All these aspects are boosting the development of innovative torque vectoring and power management strategy, devoted to increase traction efficiency, as well as driving range of modern EVs [7], [8]. Moreover, newly design solution, e.g. By-Wire (BW) and mechatronics system [9], [10], or In-Wheel Motor (IWM) configurations [11], allows the definition of several e-powertrain architectures and the investigation of alternative traction layout [12], leading to new perspective in the power management optimization of vehicle systems and components.

Another challenging aspect of EV is the thermal comfort. Indeed hot source, in ICE vehicle, is available, which is not the case for EV. So the thermal management has to be considered in the earlier design phase, especially for battery sizing, by adding these new electric consumers (compressor and/or electric heater). Furthermore thermal comfort could be coupled with electric components cooling systems [13] to balance thermal efficiency and energy balance.

In this work, authors intend to propose specific control algorithms and policies, devoted to increase EVs driving range and autonomy, by a smart allocation and coordination of the power flows. Developed algorithms address specific needs of scalability and portability properties, as well as Real-Time (RT) capability in order to be easily tested on several vehicle . Main challenge of the activity is to reach a 20% efficiency improvement goal, in order to meet the target of the Optimization of scalaBle rEaltime modeLs and functIonal testing for e-drive ConceptS (OBELICS) project, of which the authors are partners.

Hence, this paper is focused on 48V EV powertrain optimal design methodology. To fulfill the aim of this activity, an Equivalent Consumption Minimization Strategy (ECMS) for the electric hub-motors is performed, implemented using *Simcenter Amesim*™ tools. Also, an Auxiliary Power Management Control (APMC) is proposed in *MATLAB Simulink*® environment, which could be a supporting mean to accomplish the task of reducing the overall energy consumption.

Paper is organized as follow: at first, the simulation environment is described (1D vehicle model, e-components), and the baseline layout characteristics are detailed, particularly respect to upgraded parameters, according to optimization tools. Model refinement is also achieved considering cabin thermal regulation system, as the Air Conditioning (AC). Then, independent control strategies have been introduced, aiming at improve vehicle energy efficiency: on one hand an optimized control for the e-machines (ECMS), on the other an auxiliary management strategy (APMC), both devoted to reduce the power requirement of Electric Motor (EM) and sub-system not directly related on traction performances, respectively. Virtual test results, performed using *Amesim*™*/Simulink*® co-simulation interface [12], are shown, highlighting the improvement obtained from the energy efficiency perspective. Specific driving scenario are simulated, in order to accurately reproduce real condition EV behaviors: standard urban, ARTEMIS [14] and Real Driving Emission (RDE) cycles (generated by the software) are performed [15].

II. BENCHMARK ELECTRIC VEHICLE: 48V ARCHITECTURE

Regarding innovation on small Battery Electric Vehicle (BEV), some Low Voltage (LV) concepts could be highlighted, as the prototype of *Mahle MEET* or *Valeo*, shown in Fig. 1 and supposed as the reference Use Case (UC) for these activities. Both manufacturers targeted applications for urban mobility, where vehicle maximum speed reaches about 100 km/h and urban traffic autonomy up to 170 km.

Hence, it appears interesting to evaluate the achievable performance in several drive cycle simulations of the investigated EV, inspired by a concept car based on *Valeo* 48 V e-machines characteristics, to meet also rural and motorway requests. According to Table I, a Four Wheel-Drive (4WD) with independent IWM architecture with a single battery pack has been supposed. Intent is the evaluation of the achievable power and drive range, to meet drive A/B segment weight car requirement.

A. Simulation Layout

The 48V electric model has been developed with *Simcenter Amesim*™ [17]. The hypothetical e-powertrain layout consist of 4 IWM connected to each wheels. Supposed EM are developed by *VALEO Industries*. Their performances (maximum and minimum torque, losses respect to shaft speed) are mapped and implemented through a model-based concept in the simulation environment (Fig. 2).

According to pre-sizing results of 4WD EV requirements, HEEDS software [17] has been used to optimize some vehicle parameters to improve the overall performance over WLTC cycle. Then, some variables (*e.g.* gear ratio, weight of the car integrating the weight of the battery) are updated through the automated process, subject to optimization objectives and constraints (*e.g.* vehicle maximum range, minimizing acceleration time). The design criteria are summarized in Table II and the resulting 48V 4WD EV concept shows similar performance compared to the recently release high voltage VW e-up [20] which has a close application target (city, rural road, highway). HEEDS has improved over 500 iterations the 4WD EV characteristics. Indeed, a 280 km range is achieved by considering a reduction of the battery SOC from 90% to 10%, which is better than equivalent EVs available on the market and increased the vehicle range by 11% compared to pre-sizing specifications. The selected battery cell chemistry is Nickel Cobalt Aluminum Oxide (NCA), because it is widely spread in EV industry [16].

Fig. 1. 48V Valeo concept car

TABLE I
48V E-MACHINE CHARACTERISTICS

EM Parameters		
Name	***Value***	***Unit***
Maximum torque	55	Nm
Maximum power	15	kW
Maximum speed	20 000	rpm
Number of phases	6 (2x3)	/

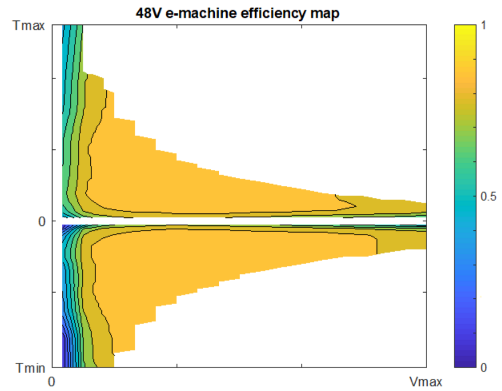

Fig. 2. 48 V e-machine efficiency map

B. Model Refinement

The AC system is also considered to refine the autonomy estimation of the vehicle in more realistic case. This subsystem could be critical in some specific condition, especially at cold or hot temperature, when its power consumption is not negligible, if compared to the driveline power.

III. Control Strategy

This section is dedicated at the description of the proposed optimal control strategy, implemented in the UC vehicle simulation model.

In particular, developed algorithms, ECMS and APMC, have the task of reducing the BEV total power consumption, acting respectively in the e-powertrain and auxiliary system regulations.

A. Equivalent Consumption Minimization Strategy (ECMS)

An optimal control of the electric machines has been implemented using the *Simcenter Amesim* Hybrid Optimization Tool (HOT). The HOT is an interactive interface dedicated to estimate the energetic potential of a vehicle architecture on a given drive cycle. In this case, the 4WD is selected. This tool is based on an optimal control allocation strategy and, specifically, on the method known as Pontryagin's Minimum Principle (PMP) [18].

B. Auxiliary Power Management Control (APMC)

Aim of this control strategy is to optimize the usage of Heating, Ventilating and Air Conditioning (HVAC) system, in order to reduce its consumption when critical condition occurs, e.g. in low State of Charge (SOC) situation, or when high level of power are demanded by the EMs to fulfill the traction demand.

TABLE II
BEV CHARACTERISTICS

Desing Criteria	**48V 4WD BEV**	**VW e-Up**
Range WLTC Class 3	280.8 [km]	258 [km]
Max Acceleration 0 – 100 [km/h]	11.96 [s]	11.9 [s]
Max Speed	140 [km/h]	130 [km/h]
Mass of Vehicle with conductor	1094.4 [kg]	1310 [kg]
Battery Capacity	42.5 [kWh]	36.8 [kWh]
Gear Ratio	8	unk.

In particular, the APMC will trigger the activation of a so-called *ECO-mode*, useful to increase the remaining vehicle driving range by minimizing the power demanded by the auxiliary system, while ensuring cabin temperature comfort. The activation of this control method is based on the following parameters:

- Battery SOC: when the storage system is approaching the full discharge condition, this control policy is enabled;
- Battery Discharge Current Limit (DCL): once evaluated the maximum value of the discharge current the storage system can experience, is evaluated respect to the actual request from the DC bus. When demanded current is higher then DCL, which is estimated from SOC and temperature of the battery [19], ECO-mode will trigger.

Based on this information, it is evident that the APMC require a synergetic integration with the vehicle , especially Battery Management System (BMS) and Motor Control Unit (MCU), which provide SOC DCL and required current estimations, fundamental for the strategy application.

ECO-mode regard the controlling policies of the AC system. In particular, intervention concern the regulation of the admitted temperature bandwidth for the cabin and related control gains, acting on the thermal regulation loops. The involved sub-system are:

- Blower: the device which establish the mass of mixed air flowing in the cabin. It's a composition of fresh air (coming from outside the vehicle) and recirculated air. ECO-mode activation enlarge the dead-zone of the temperature control loop;
- Evaporator: similarly at the blower intervention, in ECO-mode higher output temperature are tolerated;
- Compressor: it's regulation method involves two nested feedback control loops, temperature and speed. Intervention concern only the first one, reducing the Proportional Integral Derivative (PID) controller gains and increasing temperature dead-zone.

A simplified flow chart of the APMC is visible in Fig. 3. At the vehicle starts, an initialization procedure begin, consisting in the data acquisition from the main vehicle Control Unit (CU): BMS and MCU. This task, recursively iterated ad each time steps of the APMC, allows the verification of two different *if* statements: (1) the value of current SOC is below a specified desired value? (2) The total current absolute value requested is above admitted DCL? Results of the rules are evaluated through an OR logical operator. If verified, ECO-mode will trigger, otherwise no action on auxiliary systems regulation is performed.

IV. Simulation Results

Proposed campaign tests, performed in the model of Fig. 4 and implemented in a co-simulation environment, can be grouped in two branches:

- *Standard Driving Cycles*: mainly used for the model verification and the controllers calibrations; results concern these tests are also useful to asses the performances of proposed ECMS control policy and different thermal system solutions, if compared to the output of simulations performed on a baseline 4WD EV;
- *RDE Cycles*: adopted for the purpose of accurately estimated BEV performances and Efficiency Improvement (Eff Imp) allowed by proposed control strategies, accounting road slope and external temperature variations.

A. Standard Driving Cycles

1) Model verification: Vehicle model has been verificated on *JC08* driving cycle under different initial SOC conditions. This test is repeated several times to assess the effect of the ECMS controller functionalities. The Eff Imp is calculated according (1), considering the average energy consumption (kWh/100km) of the 4WD model without thermal regulation system, as reference for the metrical evaluation.

$$\eta = \frac{E_{baseline} - E_{ECMS}}{E_{baseline}} [\%] \tag{1}$$

Looking at Table III, could be noticed that a strong efficiency improvement is achieved, allowed by the usage of optimal e-motor controlling method, especially in urban conditions. On investigated standard driving cycles (*JC08* and *WLTP*), an increase of more than 10% is reached. Nevertheless, such cycles don't consider neither the thermal effect, nor the landscape, e.g. the slope of the road. So these enhancement should be considered overestimated, if compared with more realistic operating scenario.

2) Thermal model verification: ARTEMIS drive cycles [14] has been used, dedicated to accurately simulate thermal effects on BEV performances in different external weather conditions, as well as cabin target temperatures. With such cycles, different HVAC technologies (Heat pump & electric heater) have been investigated for the reference UC.

As shown in the plots of Fig. 5, heat pumps allow to improve energy consumption, if compared to electric heaters (SOC increases of 7% and thermal energy consumption reduced by 53.6%) while ensuring same heating performances: both steady states are at 20°C target temperature, with almost the same transient phase, though electric heater is 100 s faster at reaching desired value. Indeed, the heat pump Coefficient of Performance (CoP) is about 3.

B. Real Driving Emission (RDE) Cycles

RDE cycles are frequently used and widely adopted in recent literature [15], since can give to designer a more

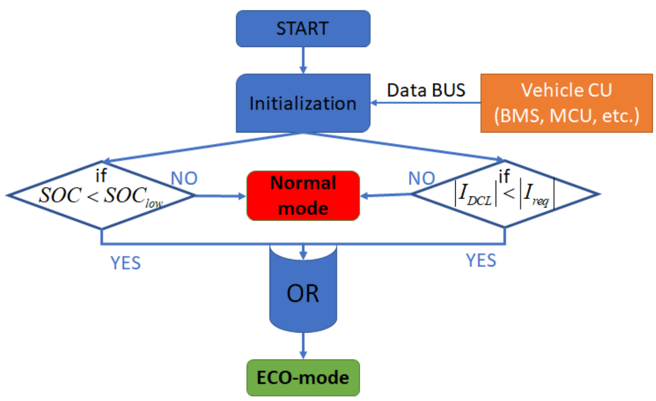

Fig. 3. APMC flow chart

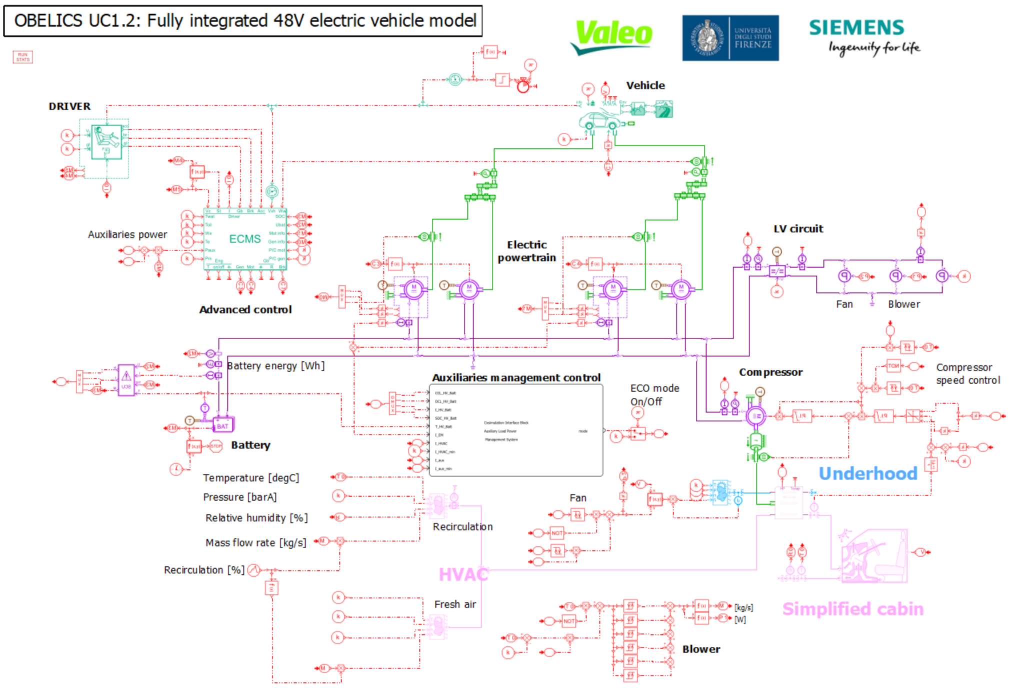

Fig. 4. Fully integrated 48 V electric vehicle model

accurate performance overview of the vehicle, by accounting more variables for their definition. In particular, different operative conditions respect time, beside speed reference, can be considered, e.g. temperature, altitude, city, extra-urban, highway and so on. Performed cycles reply the real driving condition of *Barcelona* and *Gratz* cities (Fig. 7), specifying different temperature and altitude values during the tests. The model Accuracy Improvement (Acc Imp) is calculated considering the refined 4WD Amesim model at 20°C as baseline. The average energy consumption increases due to activation of thermal system (AC, heat pump) and the growth is visible in Table IV. Thus, final SOC is reduced in hot case by 4% and cold case by 9% compare to baseline, as shown in Fig. 6. Indeed, required thermal system power is rather high to reach expected cabin temperature.

At cold and hot ambient condition, the influence of the AC system on the battery range is not negligible and must be taken into account in the early design phase of the EV, especially for the battery sizing.

C. Subsystem integration

After studying subsystems in standalone, the next step in the development process is the integration of these in the EV model, in order to verify the consistency of the fully integrated solution. Comparison study has been performed

TABLE III
STANDARD DRIVING CYCLES SIMULATION RESULTS

Initial battery conditions: SOC 90% and 20°C		
Control	***Driving Cycle***	***Eff. Imp. [%]***
ECMS	WLTC	16.5
	JC08	10.3

TABLE IV
PERFORMANCE COMPARISON UNDER REALISTIC CONDITIONS

RDE cycle simulation results		
RDE Cycle	***Temperature***	***Acc. Imp. [%]***
Gratz	35°C	13.9
	0°C	29.6
Barcelona	35°C	14.2
	0°C	28.6

with RDE cycles at 35°C, to ensure realistic behaviour in the vehicle energy consumption estimation.

To go further, it appears interesting to study the effect of APMC on the average consumption, based on the previous model integrating ECMS and AC thermal system. The whole co-simulation environment, already introduced in Fig. 4, allows estimation of the Eff Imp in realistic conditions, assessed on RDE Gratz and Barcelona cycles. The results shown in Table V enhances that energy improvement is achieved thanks to APMC. Indeed, as illustrated on Fig. 8 the ECO mode reduces the HVAC system current consumption which increases battery autonomy.

An non-secondary advantage of this implementation is computational time efficiencies, even considering increasing complexity of the phenomena involved by vehicle subsystems models. Indeed, virtual tests are running 11.5 times faster than real time. So, models can be easily integrated in RT hardware to validate the control algorithms.

V. Conclusions and Future Developments

In conclusion, e-powertrain architectures, vehicle characteristics and components sizing have been investigated through vehicle model simulation in *Amesim*, according to the test procedure of Table VI. EV performance improvement is reached through optimization of vehicle parameters (HEEDS

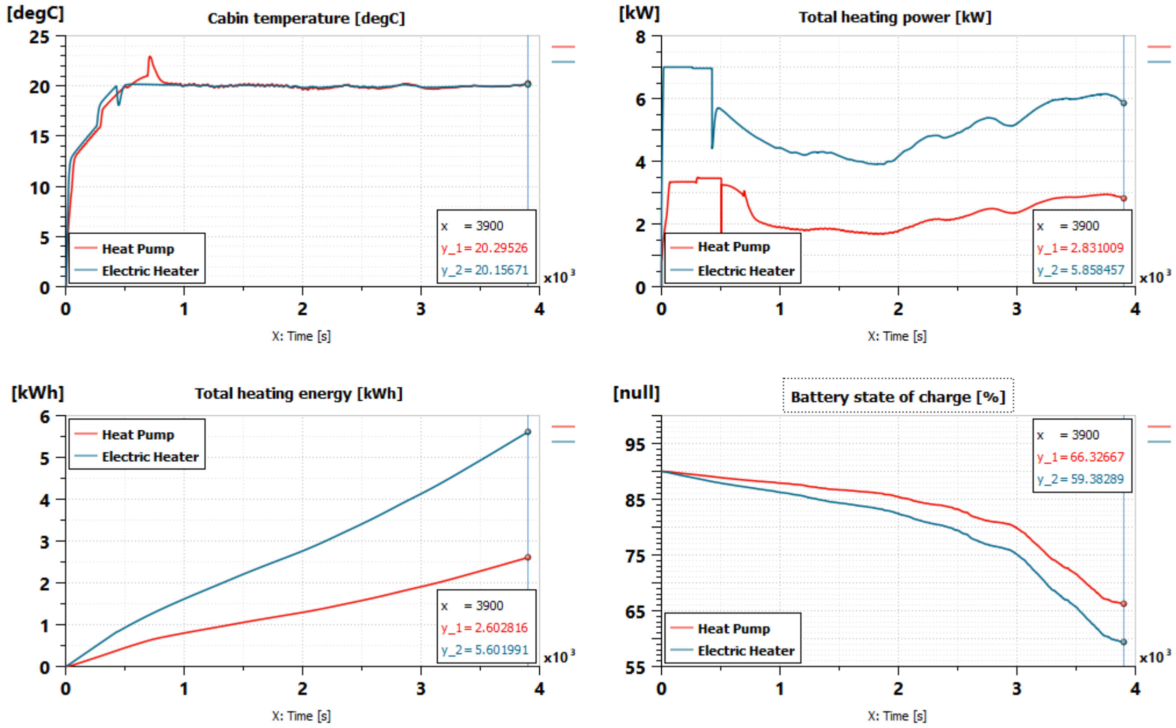

Fig. 5. Thermal system solutions comparison on ARTEMIS cycle: Cabin temperature (top-left); Heating power (top-right); Heating energy (bottom-left) and SOC (bottom-right)

tool), development of advanced control strategies (ECMS, APMC) and innovative components (heat pump): Fig. 8 summarize the achievement permitted by the investigated thermal system solutions. Moreover, realistic conditions are considered by means of specific driving cycles (ARTEMIS, RDE), to refine average consumption. In particular, multiple 48 V EV simulation models have been developed to investigate efficiency improvement within a short development time.

Regarding efficiency improvement, an average result of the relative improvement evaluated with different cycles, (WLTC, JC08, city cycle) and specific to both ECMS and APMC strategies, has been summed up in Table V. Investigated strategy could bring from 4% up to 8% of improvement of energy consumption in the performed RDE cycles scenario (Barcelona and Gratz).

Increasing models complexity allows reliable EV behavior and provide precise energy consumption estimations, despite the computation time grows. Therefore, it is worth noting to proceed according to a methodology that could save development time, while ensuring simulation accuracy.

Further work could focus either on a more accurate EV model through implementing a battery cooling system (which is a constant power source reducing battery range) or on another advanced control strategy, as Brake Blending [7], [8], [10], [12], to increase energy savings.

Acknowledgment

This project has received funding from the European Union's (EU) Horizon 2020 research and innovation program under grant agreement No 769506. The information and views set out in this publication does not necessarily reflect the official opinion of the EC. Neither the EU institutions and bodies nor any person acting on their behalf, may be held responsible for the use which may be made of the information contained therein.

TABLE V
INFLUENCE OF THE AUXILIARIES MANAGEMENT CONTROL ON THE VEHICLE MODEL WITH OPTIMAL E-MOTOR CONTROL

Initial conditions: SOC 90% and 35°C			
Layout	*RDE Cycle*	*APMC*	*Eff. Imp. [%]*
ECMS	Gratz	OFF	4.46
		ON	7.4
ECMS	Barcelona	OFF	5.44
		ON	8.79

TABLE VI
DESIGN EXPLORATION

Complexity	Thermal System	Control Strategy	Cycles
Standard	N/A	Default Vehicle Control Unit	WLTP JCO8
Advanced	Heat Pump Air Conditioning	ECMS APMC	ARTEMIS RDE

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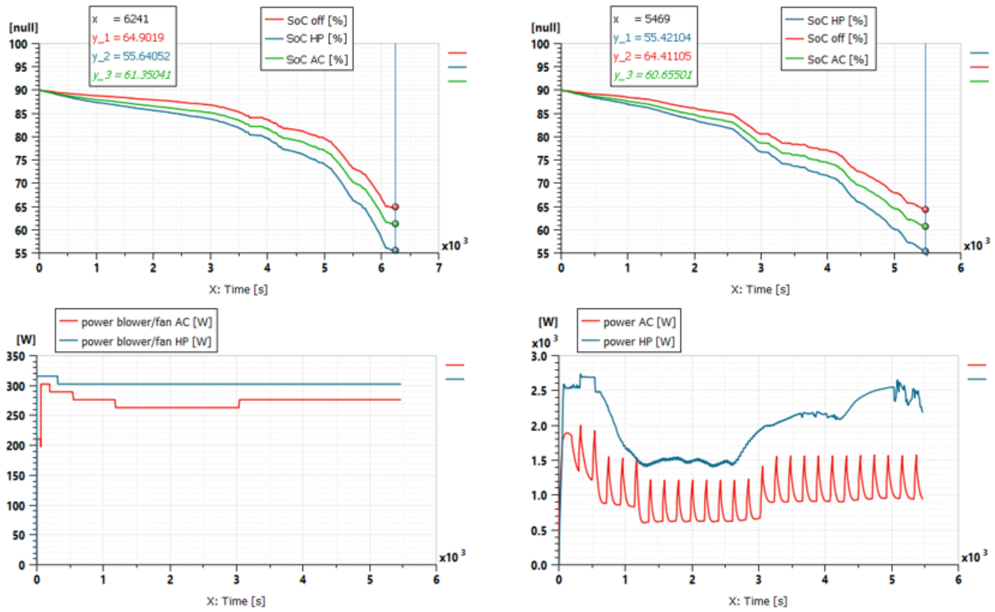

Fig. 6. Comparison on RDE Gratz (right) and Barcelona (left) at different ambient temperature: SOC (top) and thermal system power (bottom)

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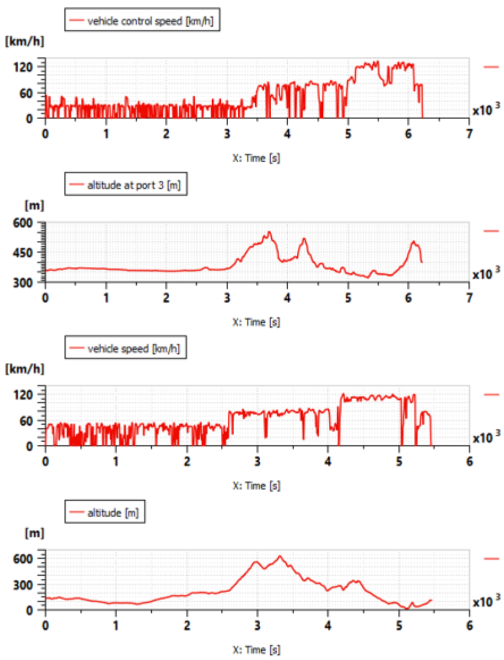

Fig. 7. RDE cycles (Gratz on top, Barcelona on bottom)

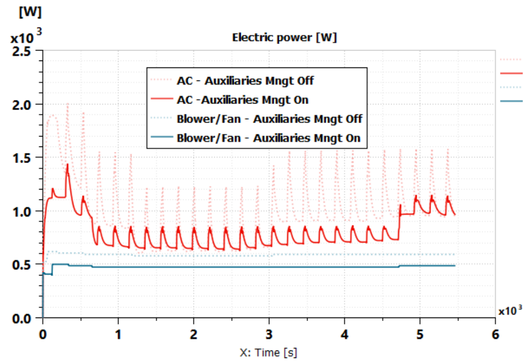

Fig. 8. influence of the APMC on the EV model with advanced e-motor control during RDE Barcelona cycle, (battery SOC on top, HVAC solutions power on bottom)

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