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Dynamic Model for the Energetic Optimization of Turbocompound Hybrid Powertrains

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Abstract

This paper presents the simulation activity carried out to analyze the power flows and the energy breakdown of an innovative hybrid-turbocompound powertrain, which will be employed in the 2014 F1 championship. The analyzed powertrain consists in a supercharged internal combustion engine integrated by two electric machines – connected respectively to the turbocharger shaft and to the engine shaft – a static converter and a battery.
Simulations through Matlab-Simulink were carried out both in race and in qualifying conditions, obtaining useful information about the electric machines and battery duty cycles and about the calibration of the system operational algorithms during one lap.

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Keywords: Hybrid Powertrain; turbocompound; dynamic simulation; energy analysis.

1. Introduction

In the last years, the researchers have focused their attention on the development of new road vehicles propulsion systems featured by a low environmental impact. In fact, nowadays the fossil fuelled road vehicles constitute the quasi totality of the circulating park; moreover, the trend of the vehicles number for the future years is increasing.

Nomenclature	
β	Compression Ratio [-]

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η	Isentropic Efficiency [-]
c_p	Specific Heat Capacity [kJ/kg K]
FIA	Fédération Intérnationale de l'Automobile
ICE	Internal Combustion Engine
J	Inertia [kg m^2]
k	Isentropic Exponent [-]
λ_v	Volumetric Efficiency [-]
KERS	Kinetic Energy Recovery System
$\dot{m}$	Mass flow rate [kg/s]
M	Torque [Nm]
MGU-H	Motor-Generator Unit – Heat
MGU-K	Motor-Generator Unit – Kinetic
n	ICE rotational speed [r/min]
p	Pressure [Pa]
P	Power [kW]
R	Gas Constant [kJ/kg K]
SOC	Battery state of charge
T	Temperature [K]
ω	Turbocharger rotational speed [rad/s]
t	Time [s]
V_t	Displacement [m^3]
Subscripts	
0	ICE inlet conditions
a	Air
C	Compressor
e	Exhaust
f	Fuel
T	Turbine

There is thus a rising necessity for reducing the vehicles fuel consumption, with the related decrease of pollutant emissions [1].

Technological innovation has brought to the development of new propulsion systems; among these, a very important role is played by the hybrid technology, intended as the synergic employ of two different types of energy conversion systems (typically, a thermal engine and electric motor/generators) installed on the vehicle, operating through the integration of electro-technologies in the powertrain. In this way, it is possible to optimally exploit the features of the two different systems (electric and thermal), allowing for example to recover the conservative energies (kinetic and potential) during a mission, with the result to obtain higher powertrain global efficiency values and consequent reduction of consumption and emissions [2].

Another important innovation regarding the automotive field is the introduction of the turbocompound technology, intended as an exhaust gas turbocharger group designed to provide, other than the compression of the intake air, a net work production. This system is able to assure a higher exploitation of the energy contained in the exhaust gases. An intelligent employ of the turbocompound system is its integration within the hybrid vehicle scheme [3,4]; thanks to a high speed electric machine, the net work produced by the turbocharger group is converted into electric energy and is employed for propulsion or stored in battery. This system is included in the FIA regulations [5] for the 2014 Formula 1 championship.

This paper aims to investigate the behavior of a hybrid-turbocompound system applied to a Formula 1 vehicle through computer dynamic simulation, in order to research the correct employ of the innovative powertrain scheme and the sizing of its main components. The study was worked out for different circuits, both in qualifying and in race conditions.

In the following, after a description of the turbocompound scheme, the simulation model is described, and is used to make tests in different missions. The tests allow the monitoring of the system crucial parameters such as the power of the electric machines and battery and the battery state of charge (SOC).

2. The hybrid turbocompound system applied to the Formula 1

In 30 June 2011, the FIA (Fédération Intérnationale de l'Automobile) technical commission published the new regulation for the 2014 Formula 1 championship; this imposes the substitution of the presently installed V8 2.4 l with a V6 1.6 l engine equipped with turbocompound system, that integrates an improved version of the current KERS energy recovery system. This new powertrain is expected to supply a power in line with the old one assuring a net primary energy saving. Table 1, reporting the old and the new regulation, highlights the philosophy change occurred: while before the logic was to assign a limitation to the vehicle power, today the limitation is imposed in terms of fuel flow rate; in this way, the most competitive powertrain is the one that maximizes the global efficiency, since it will deliver the maximum power to the wheels.

Table 1. Extract from the FIA F1 2014 technical regulation [5] and comparison with the previous rules (2011).

	F1 2011	F1 2014
Thermal Engine		
Displacement	2˙400 cm^3	1˙600 cm^3
Architecture	V8	V6
Max. engine rotational speed	18˙000 r/min	15˙000 r/min
Supercharging	Forbidden	Exhaust gas supercharger
Max. fuel flow rate - absolute	No limit	100 kg/h
Max. fuel flow rate - related to the engine rotational speed	No limit	Q = 0.009 n[r/min]+5.5 for n≤10˙500 r/min
Electric System		
Energy recovery	Through KERS	Through MGU-K and MGU-H
Storable energy during the race	No limit	Energy released by MGU-K to Energy Storage System cannot overtake 2 MJ per lap
Usable energy during race	Energy released by KERS cannot overcome 400 kJ/lap	Energy released by Energy Storage System to MGU-K cannot overtake 4MJ per lap
Max. power for electric propulsion/deceleration	60 kW	120 kW
Battery SOC		The difference between maximum and minimum SOC cannot overtake 4MJ in each instant the vehicle is on the circuit
Time of active (acceleration) electric propulsion	6,67 s	No limit

In Figure 1 is depicted the layout of the propulsion system in object. It is composed by an ICE provided with a turbocharger connected to an electric machine (indicated as MGU-H – Motor Generator Unit Heat – in the image), a second electric machine mounted on the ICE primary shaft (indicated as MGU-K– Motor Generator Unit Kinetic) and an energy storage system, typically a battery. These components are interconnected in order to exchange energy flows. Through the proper conversions, the electric machines may exchange energy with each other, or interact with the storage system. For example, during a braking phase, the MGU-K behaves as a generator and the energy produced is in part stored in battery and in part delivered to the MGU-H, which behaves as a motor and keeps the turbocharger at the required rotational speed in order to minimize the turbo-lag.

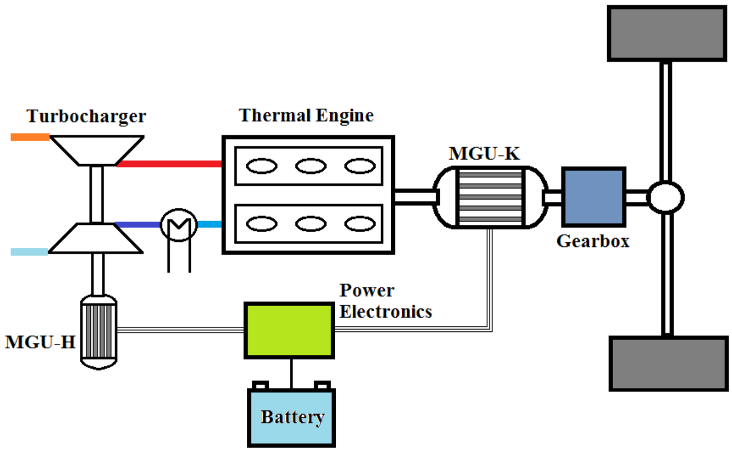

Fig. 1. Powertrain layout.

2.1. System operational logics

The operational logics implemented in order to optimally manage the system are described in this paragraph. Due to the very different objectives searched, the "race" and the "qualifying" configurations of the system are characterized by different logics and will be treated separately.

Race configuration: The battery SOC must be constant (within a certain tolerance) at the end of each lap.

- *Full load* (maximum pedal angle): the MGU-K provides to the wheels all the power produced by the MGU-H. The power flowing from the battery to the MGU-K has a feedback on the battery SOC, so that below a certain SOC threshold the logic limits the power supplied to the MGU-K.
- *Braking*: part of the vehicle kinetic energy recovered by the MGU-K and converted into electric energy is directly delivered to the MGU-H to keep the turbocharger group at an imposed rotational speed; the remaining part is stored in battery.
- *Release*: the energy required to keep the turbocharger group at an imposed rotational speed through the MGU-H is taken from the battery.
- *Acceleration after a release phase*: in the first phase of the transient, as soon as the gas pedal is pressed, energy is taken from the battery and supplied to the MGU-H, to re-accelerate the turbocharger group; once the latter has reached its design speed, the MGU-H can receive energy from the turbocharger group; therefore, in the second phase the MGU-H provides electric energy directly to the MGU-K, which contributes to accelerate the vehicle. The battery state of charge plays a very important role: in fact, according to the SOC, it is possible to provide an increase of the power supplied to the MGU-K which contributes to the acceleration, by taking more energy from the battery.

Qualifying configuration: No feedback control on the battery SOC.

- *Full load* (maximum pedal angle): the MGU-K supplies to the wheels its maximum power value (120 kW), taking energy in part from the batteries and in part from the MGU-H;
- *Braking:* see race configuration.
- *Release*: see race configuration.
- *Acceleration after a release phase*: in the first phase of the transient, energy is taken from the battery and supplied to the MGU-H, to re-accelerate the turbocharger group up to its design speed; once the acceleration transient is exhausted, the turbocharger is at its design speed and the MGU-H delivers all its power produced to the MGU-K. The battery supplies the remaining power needed to operate the MGU-K at its maximum power.

3. Description of the model

3.1. The RACE simulation model

The RACE simulator is a Matlab-Simulink dynamic model of the system composed by the turbocharged ICE, the MGU-H, the MGU-K and the battery. The simulator is aimed to quantify the power and energy flows exchanged between all the powertrain sub-systems during one lap in different grand prix circuits. This allows to determine the sizing of the main electric components and to test different management strategies for the system. To attain these goals, the RACE simulator was built in order to perform the following functions:

- represent correctly all the powertrain components and sub-systems, by means of operational maps. This feature allows to adapt easily and rapidly the model to the modifications decided by designers during the vehicle set-up.
- acquire all the possible circuits of a Formula 1 championship season. The mission data are uploaded in the form of tables containing engine rotational speed, accelerator pedal angle, brake pedal angle and gearbox transmission ratio in function of time.
- calculate the power flows in all the powertrain components starting from the power at the engine shaft level, known from the mission data; the simulator then proceeds backwards along the energy chain, calculating time by time the power flows involved for the different components.
- integrate all the logics and control algorithms for the various components, allowing their evaluation in terms of functional and energetic results.
- allow the sizing of the energy storage system and of the electric components cooling system; the sizing is possible once all the power and energy flows, so as the duty cycles, are known.

It is worth to underline that the vehicle time law is considered known; hence, the model does not predict the lap time. However, this was not the goal of the present study, which was instead aimed at implementing a computational tool able to determine the system energy balance during a typical lap, in order to provide an overall sizing of the main electric components.

The simulation model is composed by different modules, namely: the *pre-processor*, allowing a guided data-entry phase, in order to define the features of the powertrain sub-systems, the mission and the control logics; the *simulator*, which calculates the power flows involved during the lap and integrates them in time, in order to obtain the powertrain energy breakdown; the *post-processor*, displaying the calculations results; the output data can be represented both in terms of time history (diagrams with time) and in terms of integral parameters over a lap.

In this work, the authors did not carry out a detailed modeling activity of all the components turned to the construction of specific operational maps; this activity will be eventually carried out by the technicians in charge of the powertrain development (engine and turbocharger designers, electric machine engineers…), who own the expertise in their respective fields. Instead, the authors confined themselves to build the maps required by the simulator basing on simplifying (but realistic) assumptions. For example, the thermal engine operational map was derived from a numerical model based on a pseudo-real Sabathé cycle.

3.2. The turbocharger – MGU-H group model

One of the work fundamental aspects regarded the transient behavior study of the group composed by turbocharger [6,7] and MGU-H machines. This activity was carried out to evaluate the MGU-H electric energy consumption in different conditions, so that considerations about the system best management strategy can be made. The issue was addressed implementing a dynamic model able to describe the matching between engine and turbocharger group. The model is based on the following equations:

$$P_C = \frac{\dot{m}_a}{\eta_C} c_{p\_a}\, T_a\left(\beta_C^{\lambda\_a} - 1\right) \qquad (1)$$

$$P_T = (\dot{m}_a + \dot{m}_f)\eta_T c_{p\_e} T_e\left(1 - \beta_T^{\lambda\_e}\right) \qquad (2)$$

$$P_T - P_C + P_{MGU-H} = J\,\omega\left(\frac{d\omega}{dt}\right) \tag{3}$$

where $\lambda = (k-1)/k$, k being the isentropic exponent. Through Equations (1) and (2) the power of turbine and compressor are calculated. The dynamic behavior of the group is known through Equation (3), which includes also the term P_{MGU-H}, accounting for the power provided (negative) or absorbed (positive) by the MGU-H machine.

Equation (3) can be written in terms of torque:

$$M_T - M_C = J\,(d\omega/dt) - M_{MGU-H} \tag{4}$$

where M_T is the torque supplied by the turbine, M_C is the torque required for the compressor; J is the inertia of the whole group; M_{MGU-H} is the term accounting for the torque supplied or required by the MGU-H machine.

The system behavior is known once is determined the interaction between the turbocharger group and the ICE, which means finding the values of β_C and $\dot{m}_a$. These quantities derive from the matching between the map of the compressor and the map of the ICE. For the first one, a commercial compressor map (providing $(\dot{m}_a, \beta_C)$ curves for different ω values) was utilized; for the second one, the following Equation (5) was implemented:

$$\dot{m}_a = V_t \frac{p_a \beta_C}{R T_0} \lambda_v \frac{n}{120} \tag{5}$$

T_0 being the intercooler outlet temperature. This equation allowed to determine the flow rate aspirated by the ICE in function of the compressor compression ratio for the different operational conditions.

In this discussion, the turbine behaves as a choked nozzle. The turbine inlet conditions derive from an elaboration (according to [6]) of the ICE outlet conditions, which are calculated by the pseudo-real Sabathé cycle numerical model.

The model is used in the following manner:

- as initial conditions, the ICE and turbocharger rotational speeds at the beginning of the transient are provided, so as the ICE acceleration ramp for each gearbox transmission ratio;
- a reasonable value of the turbo-lag is established. This value, set to 0.3 s, determines the acceleration $d\omega/dt$ that the group needs to assure, which is provided as input;
- the matching between ICE and turbocharger allows to calculate moment by moment the compressor and turbine power;
- the power P_{MGU-H}, needed to sustain the turbocharger group speed during the braking and release phases, is calculated through Equation (3), by difference between P_T and P_C;
- the model is run for all the possible operational conditions, obtaining the MGU-H power maps in the IV quadrant. The model outputs are given, for each possible combination of initial conditions, in the form of maps (M_{MGU-H}, t) (M_{MGU-H} being calculated by Equation (4)) and (ω, t).
- introducing said maps in the RACE model, the power required/supplied by the turbocharger group in each acceleration phase can be calculated, so as the energy spent.

The following data are introduced in the model as parameters:

- Inertia of the MGU-H = 0.000112 kg m^2;
- Inertia of the turbocharger group = 0.00045 kg m^2;
- Turbine isentropic efficiency = 0.75;
- Compressor isentropic efficiency = 0.68.

The aim of this model is not to determine the precise dynamics of the turbocharger – MGU-H group; the main goal is supply to the RACE software reasonable operational maps in order to obtain sufficiently realistic results; the simplified turbo-group dynamics, characterized by the imposition of the turbo-lag value, is not expected to significantly influence the results in terms of energy balance. The knowledge of the turbocharger group correct behavior is expected to be provided by the experts in the field.

4. Results

In this section the results of the simulation tests carried out are presented and commented. First, are presented the results of the turbocharger – MGU-H dynamic model, that will be useful to proceed to the complete powertrain simulation.

The RACE model was then run to show the power and the SOC values in function of time for different circuits, both in qualifying and in race conditions. Also, the influence of the rotational speed at which the turbocharger – MGU-H group is maintained during the braking and release phases of a lap was investigated.

In the following dissertation, the power assumes positive values when entering the battery and when exiting from an electric machine (generator).

4.1. Results of the turbocharger – MGU-H model

In Figure 2 is reported the MGU-H torque in function of time during an acceleration transient, assumed a turbo-lag of 0.3 s and a shaft initial rotational speed of 80 kr/min. The diagram shows that the electric machine passes from a phase of torque supply to the turbocharger to a phase of torque absorption, the latter beginning once the group has reached its design speed of 120 kr/min. At this speed, the electric machine switches from the "motor" to the "generator" mode, as it starts to recover the exhaust gas energy.

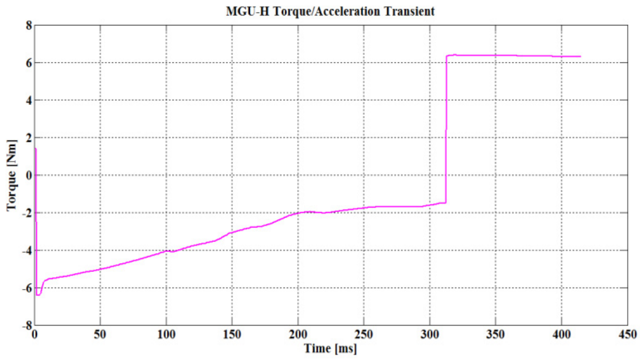

Fig. 2. MGU-H torque during acceleration transient.

The introduction of the (M_{MGU-H}, t) and (ω, t) maps in the RACE model allowed to determine the time history of power supply and demand for the MGU-H during a lap, and thus the energy required by the electric machine for each acceleration.

4.2. Results of the RACE simulations

1) Race conditions

The simulations in race conditions allowed to analyze the power flows entering and exiting the battery and to make considerations about the system control logics. In the following, are reported the results of the simulations for the Monza circuit. Three different values of the turbocharger group speed during braking and release phases were evaluated in the tests, namely 110 kr/min, 80 kr/min and 50 kr/min, provided a 120 kr/min design speed for the component. In the diagrams, the abscissa axis indicates the time scale in quarters of second [0.25 s].

Figure 3 represents the power of the MGU-H machine in function of time. The diagrams show that the power required to sustain the turbocharger group at the desired speed during braking and release phases is rather low for 50 kr/min speed (about 12 kW), while for 110 kr/min case it is around 67 kW; however, the diagram shows that the power required to re-accelerate the group up to the design speed in a time of 0.3 s (turbo-lag) rises up to 130 kW for the 50 kr/min case. These 130 kW are supplied by the battery, whose power output needs to be sized accordingly.

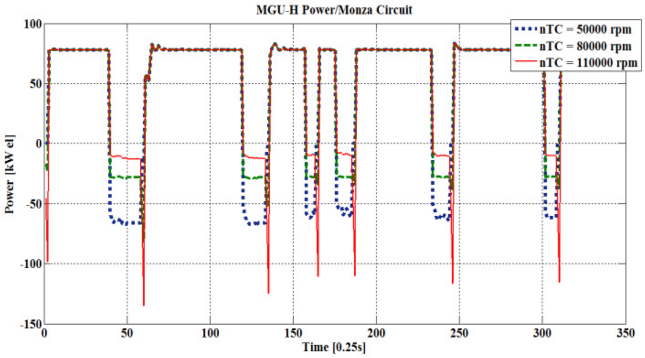

Fig. 3. Power of the MGU-H in the Monza circuit for different fall speeds of the turbocharger.

The curves reported in Figure 4 are representative of the MGU-K duty cycle for the three values of turbocharger speed fall in braking and release. The curves indicate the amount of time for which each power value is supplied (negative) or absorbed (positive) by the machine. The information provided by the curves is strictly connected to the stress on the component and to the energy dissipated by Joule effect. Hence, it is useful in view of the proper sizing for cooling system and electric components.

As visible, in the 50 kr/min case the MGU-K supplies its maximum power of 120 kW for a rather long time (about 27 s) during the lap, with respect to the 80 and 120 kr/min cases.

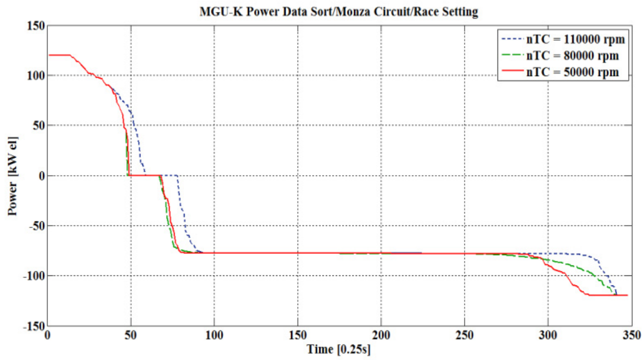

Fig. 4. MGU-K power duration curve.

Keeping a lower turbo-group speed during the release phases involves high stress of the battery, which is required to supply high power peaks to accelerate the turbocharger group shaft. This is remarkable in Figure 5 which represents the time history of the battery power. In the 50 kr/min case, the negative peaks reach almost 270 kW, because the battery needs to feed both the MGU-H and the MGU-K (the power supplied to the latter depends on the battery SOC in the race mode). This trend is confirmed by the absolute value of the battery power averaged with time, which is another simulation output, very useful to size the cooling system. In the 50 kr/min case the average power value is 22.2 kW, versus 18.0 kW and 16 kW for respectively 80 and 110 kr/min cases.

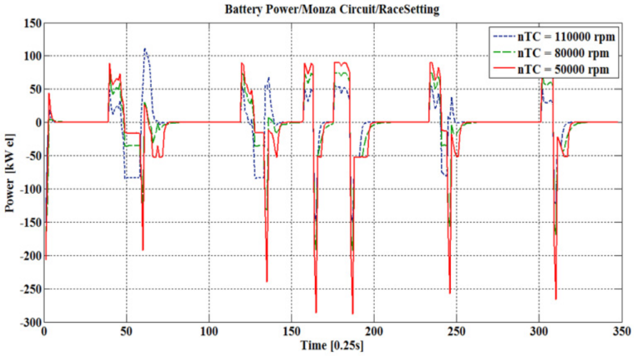

Fig. 5. Battery power, history with time for different fall speeds of the turbocharger in race setting.

2) Qualifying conditions

In case the FIA rules imposed the employ of one only size of the battery both for race and for qualifying, the qualifying tests would provide the sizing of the battery, being the most stressing conditions for this component. In fact, in the qualifying conditions it is convenient to employ all the stored energy in one lap to obtain a better time.

In qualifying conditions, the absolute value of the average battery power is much larger than in race conditions: in the 50 kr/min case the average power value is 48.9 kW; in the 80 kr/min case it is 46.1 kW; for the a110 kr/min it is 43.0 kW. In fact, as visible in Figure 6, the MGU-K during a qualifying lap in the Monza circuit supplies its maximum power (120 kW) for almost all the time during the full load phases.

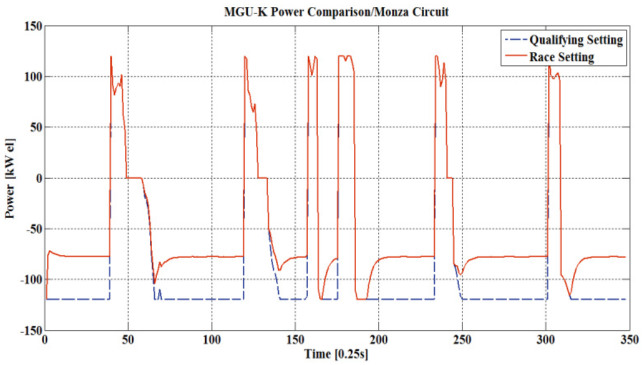

Fig. 6. MGU-K power: comparison between race and qualifying settings.

For the qualifying simulations, a battery with a storage capacity of 4 MJ (considered as the energy difference between the higher and lower limit allowed for the battery state of charge) was employed; the value of 4 MJ is in line with the FIA regulations (see Table 1).

The tests were carried out for the Spa Francorchamps circuit, very long and fast and thus energetically onerous in the qualifying phase. In Figure 7 is reported the instantaneous value of the battery state of charge during a lap, for the three different fall rotational speeds of the turbocharger group.

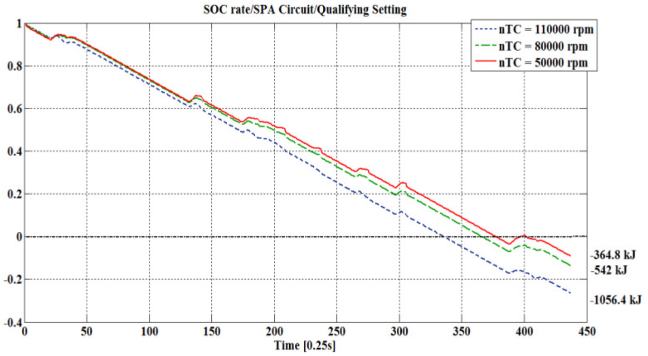

Fig. 7. Battery state of charge (SOC) in qualifying for the Spa-Francorchamps circuit.

As expected, all the 4 MJ of stored energy are exhausted before the lap is concluded. The best configuration in terms of energy saving is the 50 kr/min case, which keeps a higher value of the SOC for all the lap.

5. Conclusions

This paper focused on the energetic analysis of a hybrid turbocompound system applied to a Formula 1 vehicle. The study was carried out with the help of dynamic simulators developed in the Matlab-Simulink environment. The RACE model, reproducing the complete powertrain, resulted a very versatile tool, being able to receive as input the different missions, the operational maps of all the components and the system management logics. The simulations were useful to understand the energetic flows involving the powertrain sub-systems, to test different management strategies of the turbocharger group during the race and to have an idea of the sizing data of the different hardware components.

The hybrid turbocompound technology can be employed also for commercial automotive vehicles, trucks for heavy transport, buses, railway and naval applications. One example of turbocompound application today in commerce is the Iveco Cursor 13 Turbocompound, equipping the Stralis tractor, rated 441 kW; in this case, the extra power produced by the turbocharger is delivered to the wheels through gear and hydraulic coupling.

The presented model can be applied to effect energetic breakdown analyses in all the mentioned cases.

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