Simulation of Multi-Motor Propulsion System for Energy Efficiency in Electric Vehicles

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Abstract - **For a vehicle, the knowledge of components, characteristics, performances, and behaviors are some base elements for a successful simulation. Today's tools are offering instruments able to cover a such request and new possibilities appear. Choosing the right ones, representing the entire vehicle as a system of subsystems, integrating as much as possible the parameters of different components, are also few additional elements. For internal combustion engine vehicles, the generation and the transmission of the mechanical power to the wheels imply the usage of specific mechanic parts. From a single engine, the mechanical power is controlled to offer the requested torque and speed simultaneously to the vehicle wheels, passing by clutches and gearboxes. An electric propulsion, generating high torque at zero speed, and covering large speed area, implies less components for the mechanical transmissions. One single gear, a reducer, could cover the entire speed area request of the vehicle. On the other hand, it is possible to approach the generation of the mechanical power to the wheels, by using not only one electric motor, but one for each axle, or, even more, one electric motor for each wheel of the vehicle. This paper presents the usage of numerical simulation in such situations, emphasizing opportunities for onboard energy efficiency improvement, and opening new possibilities for optimization in multiple motor solutions.**

Cuvinte cheie: *vehicule electrice, motoare electrice, grup motopropulsor electric, soluţii multimotor, modelare şi simulare..*

Keywords: *electric vehicles, electric motors, electric powertrain, multi-motor solutions, modelling and simulation.*

I. INTRODUCTION

Modeling and simulation of Electric Vehicles (EV) requires good knowledge of the vehicle on technical and regulatory aspects, appropriate mathematical models for different components and especially a valuable contribution of researchers who have been working and works in the field [1]. The advantages of electric motors as high instant power, fast torque response, fast power density, low cost and high acceleration [2] are good premises for mobility usage. But even if electric vehicles present high energetic performance, the optimization remains an important feature [3] for providing higher operational range and continuing costs reduction. From the vehicle characteristics, the resistant forces can be calculated as presented in [4] and represent input data for the powertrain calculation, based on the e-drive knowledge [5]. Different architectures have been already studied, as mentioned in [6] and the improvements continue for different components of the EV.

An important attention is dedicated to the control aspects in order to generate the necessary torque and speed for the vehicle [7]-[20]. From [21] results that the torque balance between motors on the same vehicle represents a source of energy efficiency, of course preserving the vehicle stability. Energetic aspects are also studied, as presented in [22], design aspects for robot solutions [23] to high power systems [24]-[25]. And an important attention is accorded to in-wheel solutions [26]-[32]. Physical aspects are also emphasized in several studies, as for example in [33]-[35]. In [36] a simulation with interior permanent magnet synchronous motor (IPMSM) shows some advantages of a multi-motor solution. Such solution could be adapted for low autonomy needs as presented in [37]. Of course, the capability of controlling a such system could be also applied to different mobility solutions, as for example presented in [38]. From a testing cycle as input data, for the simulated system, the operating points in terms of speed and torque of the powertrain could be calculated [39]. The result is confirmed by performing a testing cycle. In this paper the simulation of an EV with two IPMSM is presented, with future possible extension to four motors. Comparisons between the results of an architecture with a single motor, and respectively two identical and different motors are possible. The involvement of each motor is seen during the testing cycles. At the end of the tests, the influence of different solutions for energy efficiency is seen on the onboard energy state.

The present paper is structured in multiple sections. Elements regarding the vehicle model as vehicle fundamentals are detailed first, with tractive effort calculation and specific considerations. A next section integrates a short description of the testing cycle used as input data and the resulted torque request for the propulsion system. It follows the studied vehicle configuration with two motors, one motor per axle with a complementary torque strategy between motors, and the possible extension to four motors, versus an initial single-motor configuration. The dedicated modules for the simulation are described in the same section, with an example of a diagram. Before the conclusion, a dedicated section presents the results obtained by the simulation, for the studied torque allocation strategies. The respective energy consuption for each case is determined at the end of each testing cycle. The Conclusion section ilustrates the improvment possibilities and general directions for physical implementation.

II. VEHICLE FUNDAMENTALS FOR THE MODEL

Following the description in [36], the vehicle has more than 100 years of history. The forces distribution during different usage (starting, braking, cornering) and different aspects related to maintenance and usage had been studied in the past [40]-[43]. The general behavior of the vehicle did not change, but the modeling and simulation capabilities have given a new dimension for researchers, but also for development time. In vehicle performance modeling, establishing the physical model is fundamental. It relates to the forces transmitted through the wheels to the ground, the force received directly on the body of vehicle and also through the wheels [1].

A. Vehicle Dynamics and Modeling

Considering M, the mass of the vehicle and g, the gravitational acceleration, the gravitational force acting on the vehicle

$$G = Mg\,, \tag{1}$$

gives a normal component on the road,

$$G_n = Mg\cos\alpha\,, \tag{2}$$

where α is the grade angle.

The classic case of forces on a vehicle is illustrated in Fig. 1.

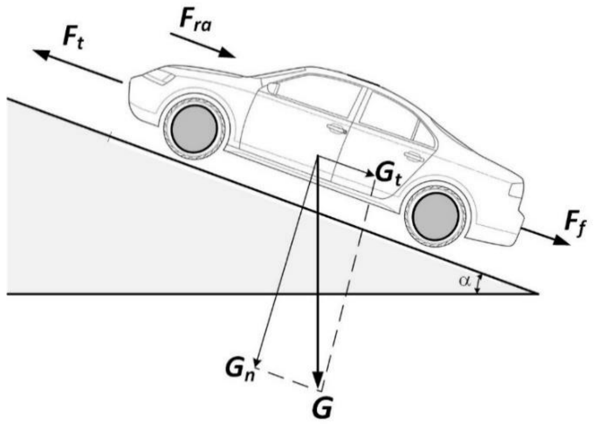

Fig. 1. Forces on the vehicle moving uphill (α > 0).

The rolling resistance force is

$$F_f = fMg\cos\alpha\,, \tag{3}$$

where f represents the rolling resistance coefficient, as a linear function of the vehicle speed V.

The next formula could be used for most common range of tires inflation [1]:

$$f = 0.01\left(1 + \frac{V}{160}\right). \tag{4}$$

The grading resistance force is

$$G_t = Mg\sin\alpha\,. \tag{5}$$

In order to simplify the calculation, $\sin\alpha$, is replaced by the grade value α, when the road angel is small.

The air pressure creates a force resisting the vehicle motion, depending linearly on the air density, ρ, the vehicle frontal area, S, the shape of the vehicle characterized by the aerodynamic drag coefficient C_x and the square of the speed:

$$F_{ra} = \frac{1}{2}\rho S C_x \left(V - V_w\right)^2\,, \tag{6}$$

where V is the vehicle speed and V_w the wind speed on the vehicle moving direction.

B. Specific Behavior During Vehicle Movement

On the road, possible disturbing effects appears and, of course, additional solicitations on the vehicle. In front of changes in its external environment, the vehicle reacts. Its response represents the characteristic behavior of the vehicle in such situations.

The normal forces applied on each wheel change during driving. The Fig. 2 represents the air flow around the vehicle.

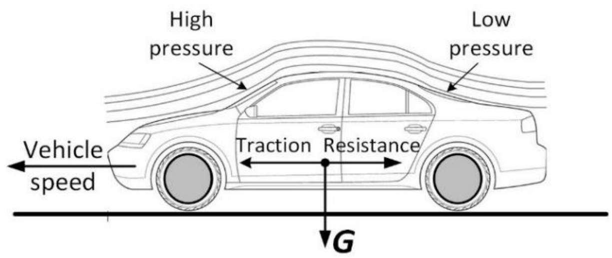

Fig. 2. Shape drags.

At speed, the higher frontal pressure is “charging” more front wheels and discharging the rear ones. A similar situation appears when the vehicle is braking. For the electric motors powering the front of the vehicle is the moment to provide an increased traction force, or make a better energy recuperation on braking.

During the vehicle start and acceleration phases, the inertia is “charging” more the rear part of the vehicle. The increased traction forces have to be on this side. Such considerations push not only to control better the electric motors on the vehicle, but also to design and implement different motor types for rear and front side of the vehicle. For improved performances of the vehicle, it is also possible to design for example two electric motor types acting in parallel on the font side (or rear side) of the vehicle, one acting more for low speed and another for high speed.

Similar situations appear between lateral sides of the vehicle on lateral wind conditions or, left or right road inclination (often met in off-road conditions).

The vehicle’s stability has to be controlled during precedent situations. Differences between rotational speed and torque from one wheel to the other could result in uncontrollable vehicle, especially at high-speed values.

The complexity of the model increases by integrating the cornering aspects. The angles of steering wheels are not identical, and the rotational speed has to increase on the exterior side. A mechanical differential simplifies the control when an electric motor is dedicated to each axle. A more complex situation includes a dedicated motor for each wheel.

To exemplify the trajectories of the wheels when cornering, a schematic view is illustrated in Fig. 3.

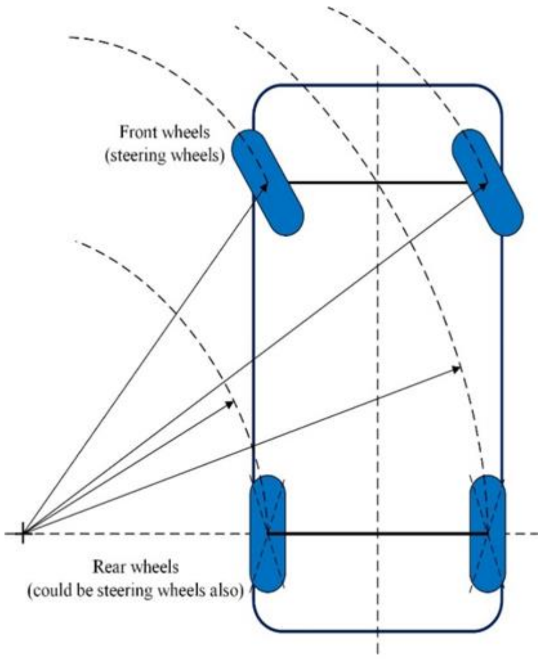

Fig. 3. Schematic view of wheels trajectories in the case of cornering.

For better cornering, the rear wheels could receive inclination angles (not identical to the correspondent frontal ones) adding supplementary constraints to the model.

C. Wheel Sleep and Tractive Effort Considerations

The tractive effort

$$F_t \geq F_{ra} + F_f \,, \tag{7}$$

for acceleration and constant speed movement.

F_t is limited by the tire-ground adhesion. The maximum tractive effort is calculated similarly to (3) but using this time a tractive effort coefficient instead of the rolling resistance one. When the adhesive capabilities between the tire and the ground are not enough to support the tractive effort, the respective wheel will spin on the ground. The tractive effort will depend on the type of ground. The elasticity of the tire will generate a good adhesive capability on dry asphalt road, but much less adhesive capability on ice. Following measurements in real conditions, the maximum tractive effort relates to the slipping of the wheel, s:

$$s = \left(1 - \frac{V_t}{V_r}\right) \times 100 \,, \tag{8}$$

where, V_t is the speed of the wheel (measured in the center of the wheel), and

$$V_r = \omega \times r \,, \tag{9}$$

where ω and r represents the angular speed and the radius of the wheel.

For braking, the slip can be expressed similarly:

$$s = \left(1 - \frac{V_r}{V_t}\right) \times 100 \,. \tag{10}$$

The maximum tractive effort will depend on the vertical load of the tire, N and a function of the tire slip, $a(s)$:

$$F_t = a(s) \times N \,. \tag{11}$$

The dependence is approximatively linear, due to the elasticity of the tire. As specified in [1], the peak tractive effort is reached at a slip of 15-20%. After that the relation becomes non-linear and for normal driving, the precedent values are to be considered as a superior limit.

III. Preparation of the Study

A. Input Data

A set of data has to be generated to perform the simulation. Usually, it represents requests in terms of speed evolution during a period of time. The vehicle has to follow the requests, aspect confirmed by specific measurements.

The test has to be the same for all situations, allowing at the end the possibility to compare the results obtained for each one. For the present simulation, a normalized testing cycle is used to run different configurations of the vehicle.

Fig. 4 presents the speed evolution for the FTP75 test.

Fig. 4. Speed request during the testing cycle (FTP75).

From the speed evolution results the acceleration request. Using the vehicle data, a classic sedan type, and following the calculation model presented in section II, it is possible to obtain the torque request.

B. Vehicle Configurations and Sepcific Data

A mono-motor EV with a full traction system is considered as reference. The configuration is shown in Fig. 5, and on the Fig. 6 is presented the requested torque for the electric motor as a result of the vehicle configuration, input data and resistant forces calculation.

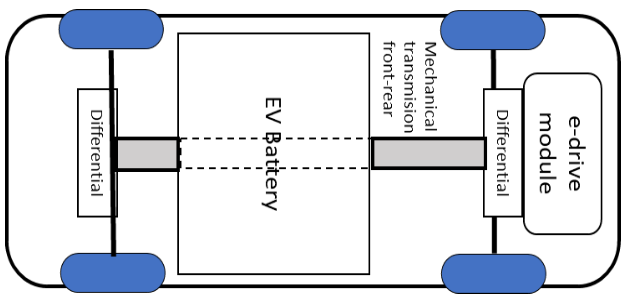

Fig. 5. Reference vehicle configuration.

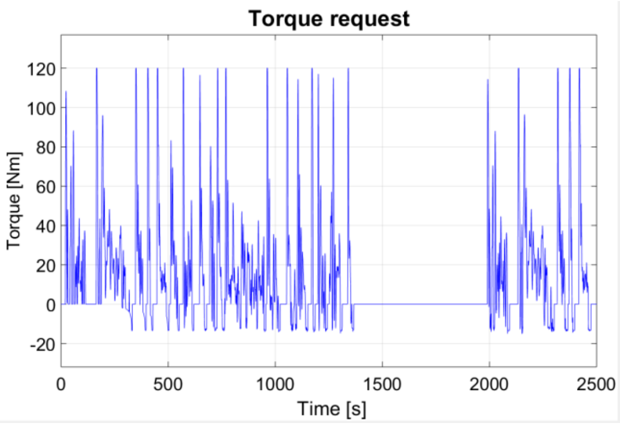

Fig. 6. Torque request in initial configuration.

In order to cover the request, for the present study, two different IPMSM motors will be involved. The most powerful motor is attached to the rear axle. Fig. 7 shows the correspondent configuration for the vehicle.

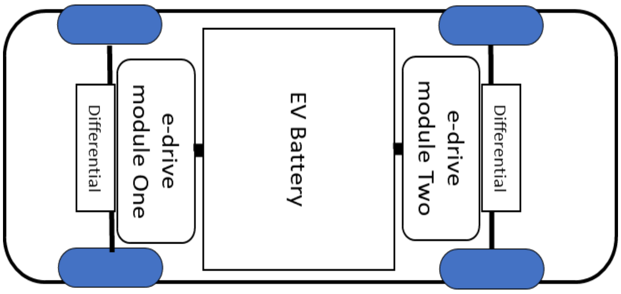

Fig. 7. Vehicles configuration for the study.

A dedicated mechanical differential is kept on each axle of the vehicle, but there is no more any mechanical link between axles as in the configuration with a single motor. A same battery is used for both motors, but each motor controller receives dedicated torque command. The total torque request for the powertrain is covered by adding the contribution of each motor.

A future possible extension to four motors is presented in Fig. 8.

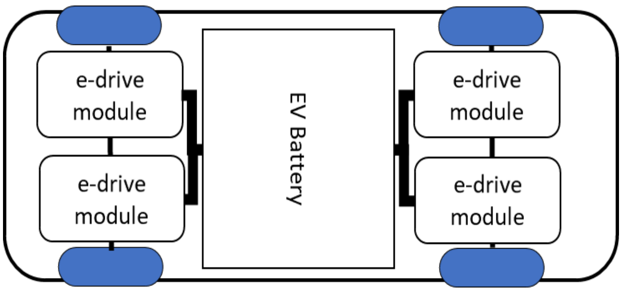

Fig. 8. Future configuration with four motors.

Each wheel receives a dedicated e-drive module including the electric motor. The wheels on the same axle have to receive identical motors in order to reduce the complexity of the control. A dedicated control for each wheel has to act under all driving wheels supervision. In the case of a modular extension form one single-motor to two motors, and, respectively, four motors a dedicated battery could integrate each module. For physical implementation reasons, also a single battery could deserve all modules.

C. Main Modules for the Simulation

For the simulation, the MATLAB environment has been chosen, as multiple functions and facilities are already available. Once the model is implemented, it offers several possibilities to analyze different configurations for different input data, compare the results, and improve it.

A general view on simulation modules is represented in the next figure.

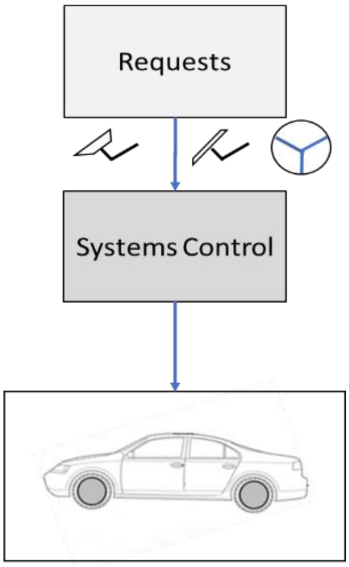

Fig. 9. Main modules for the simulation.

In the Fig. 9 the vehicle box represents the systems that an EV integrates. Behind it, on one side, there are the EV battery model, motors models and their control with their specific characteristics. On the other side, there are the mechanical systems ensuring the link from the motor axles to the ground, with their inertia and other characteristics. The model of the vehicle body has the characteristics mentioned in section II.

The “Systems Control” box presents the models for energy management and powertrain control.

The “Requests” box integrates the input data. As input data, the testing cycle is transformed in requests for the vehicle by modeling this transformation in data for the vehicle control.

Usual characteristics of a classic vehicle are kept, as for steering system and mechanical braking. The capabilities are improved by the usage of the electric motors. For example, the brake command is resulted from the torque request when the reduction of the torque implies an additional resistant force than the resistant forces acting on the vehicle at the moment. A negative torque is created by transforming the motors in electric generators. Limitations related to electric motors capabilities and battery charging aspects require the intervention of the mechanical braking system. It could work in parallel with the electric motors acting as generators.

A more structured look into the modules is shown in the next figure.

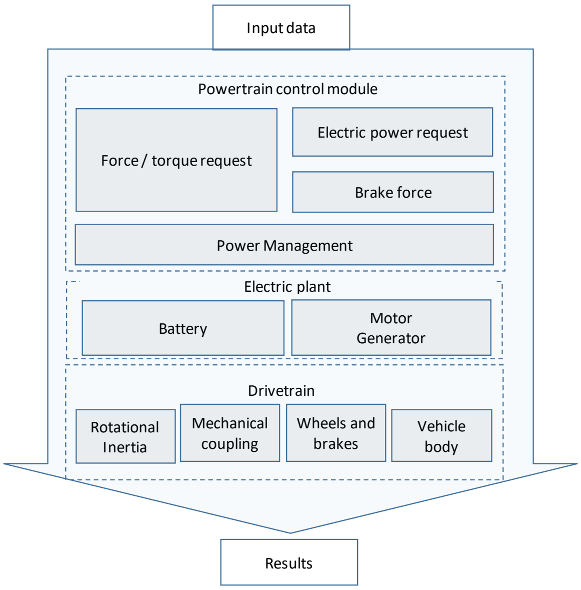

Fig. 10. Modules main components [36].

Inside the electric plant, the torque allocation between the two motors follows a complementary strategy. An implementation with visible thresholds is presented in Fig. 11.

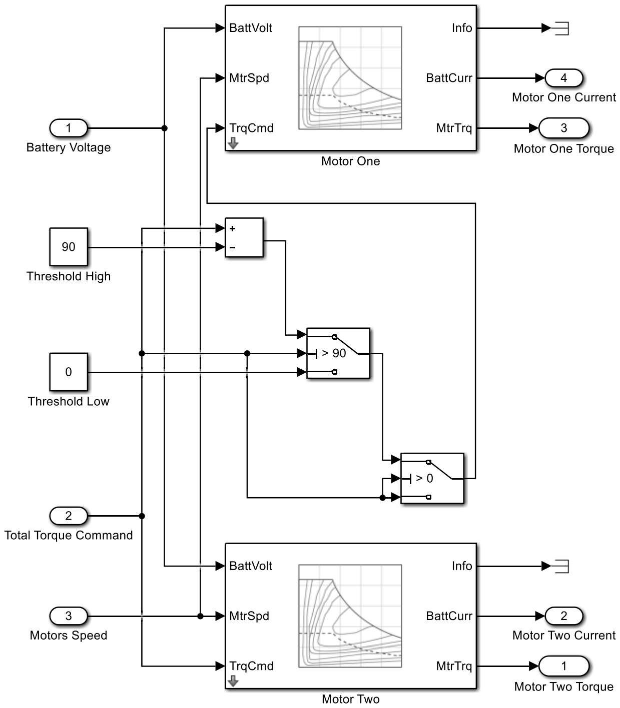

Fig. 11. Complementary torque allocation diagram with two motors.

Motor One and Motor Two integrate specific characteristics, covering together the request in terms of power, torque, and speed for the propulsion system of the vehicle.

In this case, the „threshold high" represents the torque capabilities of the biggest motor.

IV. Results and Discussions

The torque request values result from the Fig. 6. Maximum, minimum and mean values are integrated in the Table I.

TABLE I.
TORQUE DATA

Minimum torque request	-15.05 Nm
Maximum torque request	120 Nm
Mean torque during the cycle	11.72 Nm

Applying the testing cycle with a single motor, at the end it results the evolution of the state of charge of the battery (SOC) in this vehicle configuration, as presented in Fig. 12.

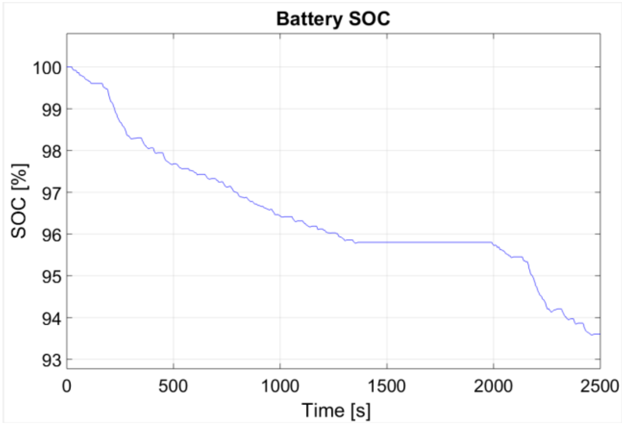

Fig. 12. Battery SOC with a single motor.

At the end of the test, it can be observed that the SOC value is 93.58 %.

The configuration of the vehicle with two different motors is considered, in two cases. For the first case, the charge is affected starting with the biggest motor and after that the smallest one. In the second case, the smallest motor is charged first. It means that the two motors will produce torque in the same time, only if the capacity of the first charged motor is exceeded.

During the simulation for the first case, the resulted torque on Motor One, which is the biggest motor, is presented in Fig. 13.

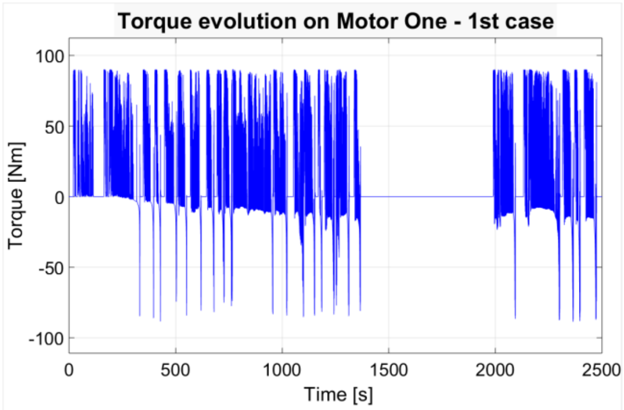

Fig. 13. Torque on the biggest motor in the first case.

The torque evolution for the Motor Two in the 1st case is presented in Fig. 14.

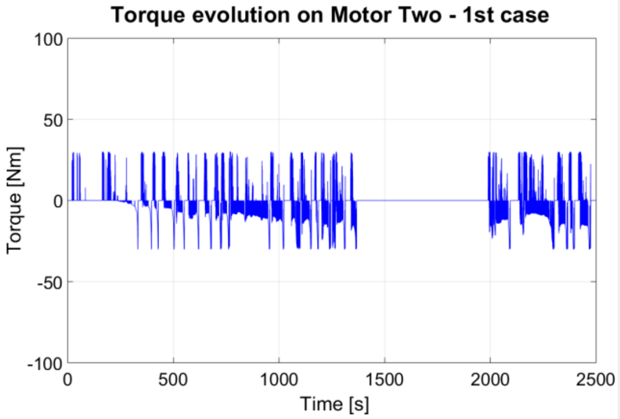

Fig. 14. Torque on the smallest motor in the first case.

The energy of the battery is monitored during the test. Fig. 15 presents the SOC evolution for this case.

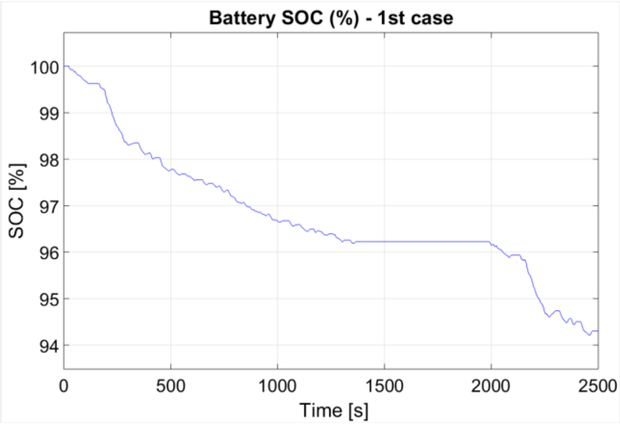

Fig. 15. Battery SOC with two motors in the first case.

At the end of the testing cycle the available electric energy in the battery reported to the energy at the beginning of the cycle is 94.21%.

As mentioned before, during the second case, the smallest motor is charged first. On Motor One, the torque is presented in Fig. 16.

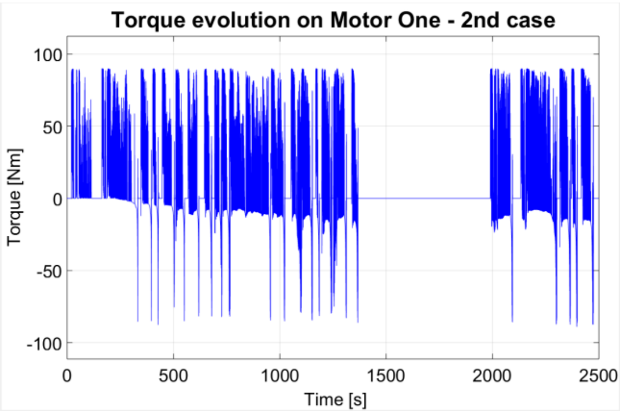

Fig. 16. Torque on the biggest motor in the second case.

The torque evolution of the Motor Two for 2nd case is presented in Fig. 17.

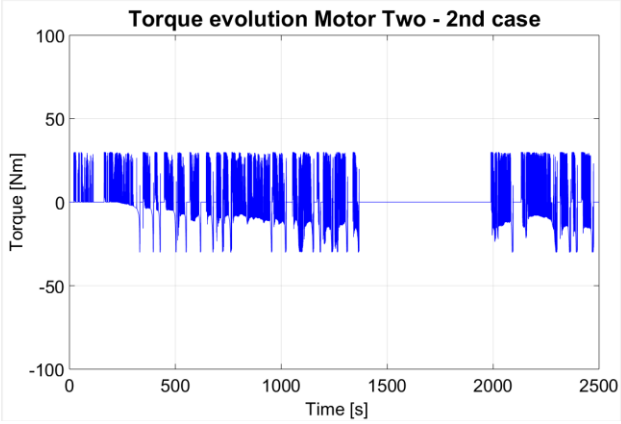

Fig. 17. Torque on the smallest motor in the second case.

It is visible that the Motor Two is much more involved than in the first case.

The battery SOC for the 2nd case is presented in Fig. 18.

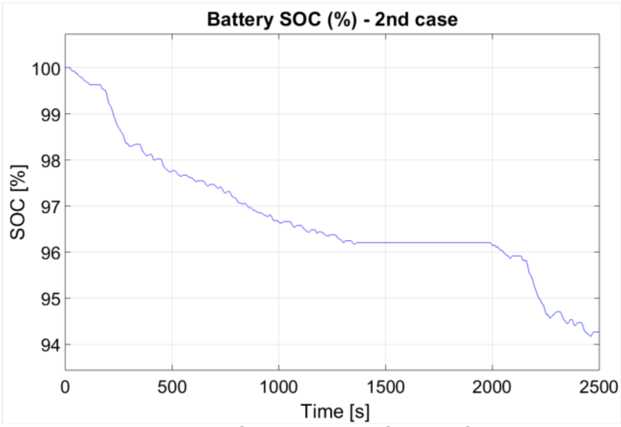

Fig. 18. Battery SOC with two motors in the second case.

For this second case, at the end of the testing cycle, the available electric energy in the battery reported to the energy at the beginning of the cycle is 94.17%.

Each simulation started with the same electric energy stored in the battery. It can be observed that during the same testing cycle, the vehicle with one single motor would consume 10.88% more energy than the bi-motor vehicle in the first case, and 10.12% more energy than the bi-motor vehicle in the second case.

In [36] the tested multi-motor vehicle had two identical motors and also generated improvement on energy usage than the same vehicle with a single motor. Passing to four motor solution would mean to replace each motor studied in the present paper with two smaller and identical motors. From this point of view, this will be similar to [36], and new possibility for improving energy efficiency appears.

For a smaller vehicle, the two-motor solution has been studied in [21] using the criterion of the optimal load reparation between the two motors. Also, in [39] different percentual repartition criteria have been analyzed. The present paper comes with simulation based on a new criterion for the bi-motor solution, analyzed in two cases.

V. CONCLUSION

A bi-motor solution has been simulated and analyzed in this paper using a new charging repartition criterion based on the different capabilities of each motor. The simultaneous functioning of the motors has been reduced to the situations when the capabilities of the first charged motor are exceeded. The results confirm improvement in the energy efficiency usage compared to the equivalent solution with a single motor.

For real situations, the application of different torque allocation criteria in a multi-motor solution, is first of all conditioned by safety. Additional optimizations for more performance in terms of speed, acceleration, deceleration and improvements in electric energy consumption, have to perform under stability control of the vehicle.

Also, the vehicle configuration represents an important element for generating improvement on onboard energy efficiency. For the same configuration, different optimization scenarios can be applied. There are no general criteria to cover all real situations. The optimization process can include diverse techniques to involve the electric motors, depending on the state of the vehicle as accelerating, decelerating, cornering, running at constant speed etc.

In parallel with the optimization studies, new electric motors are analyzed. The results of such research activities are influenced by the capabilities of the motors. More performant motors will generate better results for multi-motor solutions in EV.

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First author – 50%
First coauthor – 30%
Second coauthor – 20%

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