Electric Vehicle Powertrain Simulation to Optimize Battery and Vehicle Performances

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***Abstract* - The design of a full electric vehicle requires the development and optimization of a complete electric powertrain, including battery, power electronics, electric machine, sensors and control system.**
When designing an electrical platform, from the very beginning of the V-cycle, it is mandatory to rely on modeling and simulation tools in order to drive the main choices and then to optimize the system. The paper presents an electric powertrain simulation platform developed under Matlab-Simulink, with the intention of optimizing performances and powertrain efficiency (highly linked with vehicle range). This platform is used in order to choose battery technology (Lithium-Ion, Nickel-Cadmium…) and dimensioning according to criteria and driving cycles.

I. Introduction

The design of a full electric vehicle (or battery electric vehicle (BEV)) requires the development and optimization of a complete electric powertrain, including battery, power electronics, electric machine, sensors and control system [1].

High-power battery is an essential organ of pure electric vehicles, because it constitutes the unique source of energy that has to supply at the same time powertrain, thermal comfort system and low-power network [2]. It is thus necessary to do the best choice for this organ, which influences vehicle range, performances and cost. Tools and methodologies are presented in this paper, allowing optimizing battery and machine architecture according to conflicting criteria (range, performances, cost) [3]. For example, a compromise has to be done between range, strongly linked with energy storage and thus with battery size, and cost.

The paper is organized as follows. Section II presents battery model used for optimization and parameterization methods using data from tests or manufacturers knowledge [4]. Different battery technologies are simulated such as Lithium-Ion, Nickel-Cadmium and Nickel-Metal-Hybride. Battery model integration within global simulation platform containing among others different models of converters and electric machines is described in section III.

Section IV is dedicated to powertrain optimization, and specially to battery pack structure optimization. Finally, we draw concluding remarks in section V.

II. Battery Modeling

Traction battery is constituted by parallel and series cells. Pack structure optimization is about choosing cell technology, number of cells and disposition within the pack (parallel and series) in order to maximize vehicle range and performances (under maximal cost constraint).

Cells are all the same for a given pack (same technology and same electric behavior). Unbalancing is not studied in the present paper. To optimize battery pack, an electrical (and thermal) cell model is required.

A. Cell Model Parameterization

Cell model comes from SimPowerSystems, a Matlab Toolbox. Parameters are technology choice and electrical data. Some of them are provided by cell supplier. Three remaining parameters are calculated by a least mean squares method from a discharge curve of battery cell: they are maximum capacity and exponential area limits.

Fig. 1 shows a correlation between simulation and physical tests results in the case of a Lithium-Ion cell. Results are satisfying, specially in medium area, corresponding to the most used setting points.

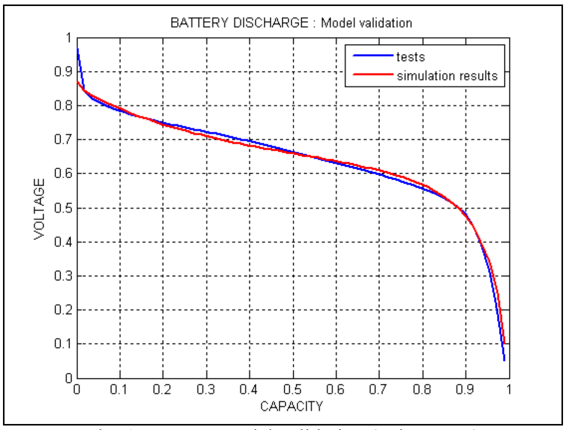

Fig. 1. Battery model validation (units = p.u.)

NB : Most figures in this paper are presented with per-unit axes (between 0 and 1).

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B. From cell model to pack model

Full pack is constituted in order to observe battery voltage or state of charge variation during a driving cycle.

Under hypothesis of a balancing pack, cell model is simply modified to build battery model. This modification consists of adding two parameters: series and parallel cells numbers. They are used as multiplying factors of some cell parameters.

A correlation between simulation results and data from tests validates pack model construction method.

Concerning modeling, outputs are battery voltage and SOC (State Of Charge) whereas input is current (Fig. 2).

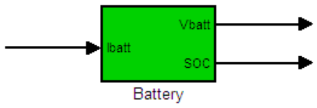

Fig. 2. Battery model

In addition to electrical characteristics, it is necessary to take into account pack mass and cost in order to optimize the system. Mass value influences range and performances. Cost value limits battery size.

III. GLOBAL SIMULATION PLATFORM

Present section concerns a global simulation platform of an electric powertrain (in which battery model is integrated) and its control strategies.

A. Power System

An electric powertrain is a closed-loop system, mainly constituted by battery, converters, motor and control structure (Fig. 3).

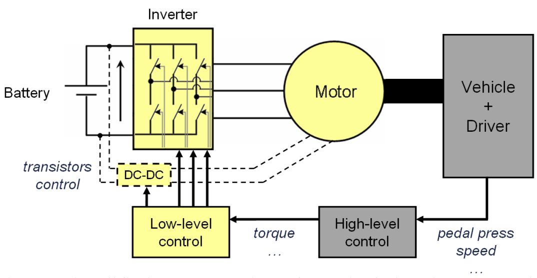

Fig. 3. Simplified representation of a typical electric powertrain

B. Electric motor and torque control

The three-phase Motor considered in this paper is a Synchronous Machine (SM), represented in Park coordinate (a,b,c) → (d,q). Two SM technologies are considered: Wound Rotor (WRSM) and Permanent Magnets (PMSM).

WRSM presents three degrees of freedom and PMSM only two as it will be explained in this section.

The electrical equations of stator (and rotor for WRSM) are given in [5].

Motor torque equation is as follows:

$$C_e = \frac{3.p}{2}.\left(i_q.\Phi_d - i_d.\Phi_q\right) \quad (1)$$

with :

p : Pole-pair number

i_d, i_q : Stator currents [A]

Φ_d, Φ_q : Stator magnetic fields [Wb]

Magnetic saturations are taken into account: inductance and magnetic field parameters depend on stator and rotor currents through non-linear complex equations.

Powertrain architecture with WRSM, presented in Fig. 3, provides three degrees of freedom: two stator currents i_d, i_q and rotor current i_f.

In PMSM case, only two degrees of freedom are available (stator currents).

Concerning powertrain torque control, from the motor torque reference $(C_e)_{ref}$, two or three currents references are defined: $i_{d\ ref}$, $i_{q\ ref}$ ($, i_{f\ ref}$).

Two control strategies with criteria on performances ("torque maximization strategy") and range ("losses minimization strategy") are briefly described below.

Torque maximization

For WRSM, rotor current is set at its maximum value:

$$i_f = i_{f\max} \quad (2)$$

Concerning stator current, i_d and i_q are chosen in order to verify following equation:

$$\Phi_d.i_d + \Phi_q.i_q = 0 \quad (3)$$

Indeed, torque expression can also be written:

$$\vec{C}_e = \frac{3.p}{2}.\vec{\Phi} \wedge \vec{I} \quad (4)$$

$$\text{with} \quad \left| \begin{array}{l} \vec{\Phi}\left(\Phi_d, \Phi_q\right) \\ \vec{I}\left(i_d, i_q\right) \end{array} \right.$$

$\left|\vec{\Phi} \wedge \vec{I}\right|$ is maximum when $\vec{\Phi} \perp \vec{I}$.

$$\Rightarrow \vec{\Phi} \cdot \vec{I} = 0 \quad (5)$$

Optimization problem to solve is recapitulated in following table:

TABLE I
TORQUE MAXIMIZATION STRATEGY

Degrees of freedom	$\left(i_d, i_q\right)$
Criterion to minimize	$f\left(i_d, i_q\right) = \left\|\Phi_d.i_d + \Phi_q.i_q\right\|$
Constraint	$\left(C_e\right)_{ref} = \frac{3.p}{2}.\left(i_q.\Phi_d - i_d.\Phi_q\right)$

Losses minimization

The cost function to minimize represents global losses in powertrain (apart from battery losses).

Analytic expressions are used and parameterized with data from tests. Following losses are taken into account:

- Conduction and switching losses in converter(s)
- Copper, core and mechanical losses in electric machine.

All losses expressions are explicit towards optimization variables.

In WRSM case, rotor current i_f is a degree of freedom.

Strategies comparison

Fig. 4 shows a global efficiency map obtained with torque maximization strategy (previously presented and frequently used in literature [6], [7], [8]).

This strategy is compared with losses minimization strategy (Fig. 5 and Fig.6).

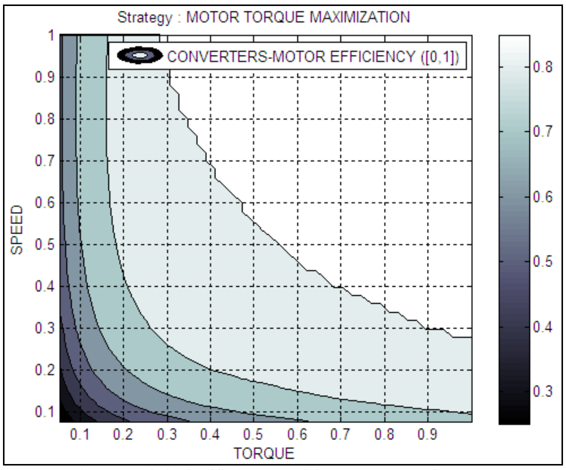

Fig. 4. Global efficiency with a strategy of torque maximization (units = p.u.)

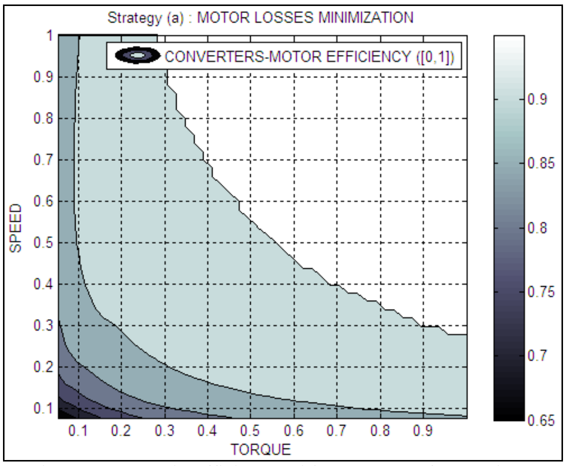

Fig. 5. Powertrain efficiency with a strategy of motor losses minimization (units = p.u.)

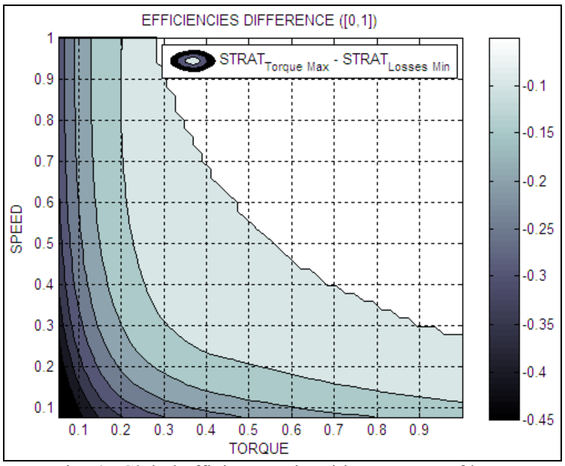

Fig. 6. Global efficiency gain with a strategy of losses minimization vs. motor torque maximization (units = p.u.)

Losses minimization strategy allows increasing efficiency, especially for low torques area, where a maximal rotor current is not necessary.

Conclusion on motor modeling and control

Motor control is studied in this paper because optimizing efficiency or performances with only motor characteristics does not make any sense. Efficiency hardly depends on motor control strategy.

IV. Vehicle Performances Optimization

This part of the paper is dedicated to architecture optimization, and especially to battery structure optimization. Converters, machine and related control laws are frozen (motor command optimization has been studied and optimized in previous section). Only battery has variable parameters in terms of technology and of pack size.

Three scenarios have been identified:

- *Scenario 1* - Vehicle range maximization under costs constraints: as described in a next part, it is about driving as many New European Driving Cycle as possible with a completely charged battery.
- *Scenario 2* - Range and performances maximization: performances correspond to accelerations from arrest and from different initial speeds.
- *Scenario 3* - Range maximization and costs minimization.

Only results linked with first scenario are presented in this paper.

Once scenarios have been defined, it is necessary to determine degrees of freedom.

Concerning battery, there are four parameters: cell capacity [A.h], cell voltage [V], number of cells in a full pack and pack structure. Technology (Lithium-ion, Nickel-cadmium and Nickel-Metal-Hydride) appears in the two firsts characteristics (cell capacity and voltage). It is hardly linked with parameterized cell models (presented in section II).

Finally, three degrees of freedom are identified for battery structure optimization:

- parameterized cell model
- number of cells in series
- number of cells in parallel.

These parameters directly influence battery voltage and global capacity.

A. Links between battery parameters (voltage and capacity) and optimization criteria (vehicle range and performances)

Relation between battery capacity and vehicle range is obvious.

Concerning battery voltage parameter, it has an impact on losses and thus on vehicle range [9]. Fig. 7 shows converters and motor efficiency according to motor speed and torque for three different battery voltages. Results are obtained with a losses minimization strategy (presented in previous section). The clearer area is, the higher motor efficiency is. For example, for a speed of 0.6 and a torque of 0.2, best efficiency is obtained with a medium battery voltage.

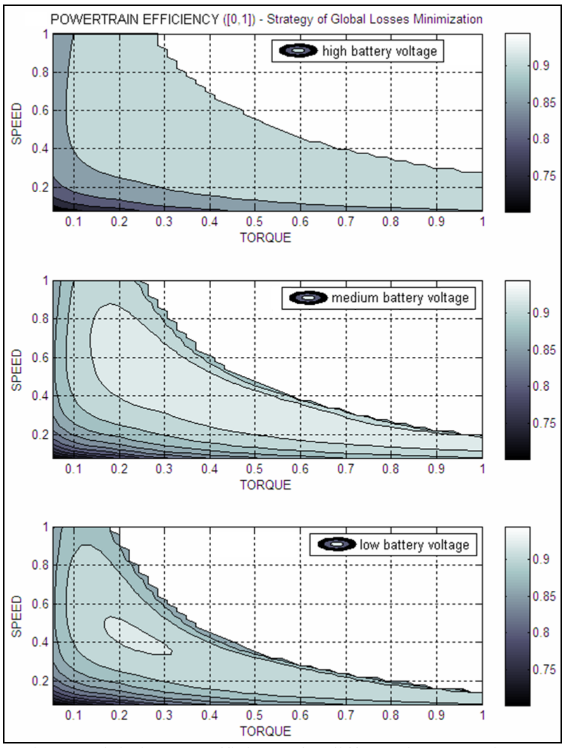

Fig. 7. Global motor efficiency for different battery voltages (units = p.u.)

Not only powertrain losses, but also vehicle performances are significantly impacted by battery voltage: we observe variations of characteristic torque/speed curve for the motor due to battery voltage (Fig. 8).

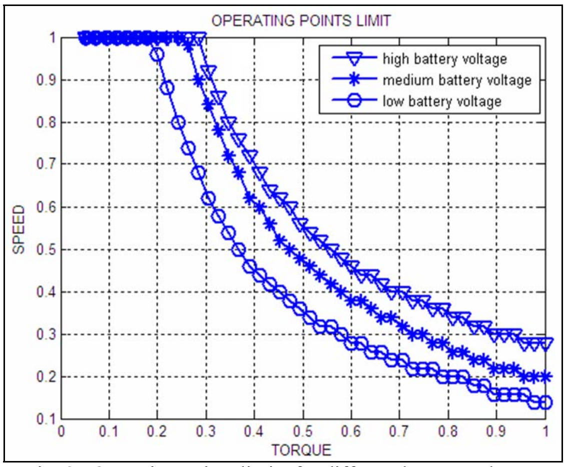

Fig. 8. Operating points limits for different battery voltages (units = p.u.)

B. Vehicle range maximization (scenario 1)

In order to study impact of battery and machine choice on vehicle range, a New European Driving Cycle is repeated in simulation and we observe how many times it is possible to perform the cycle until battery, initially completely charged, becomes empty. We use the three degrees of freedom previously presented (parameterized cell model, number of cells in series, number of cells in parallel), that directly impact battery voltage and capacity.

Fig. 9 shows normalized results obtained for a given cell model.

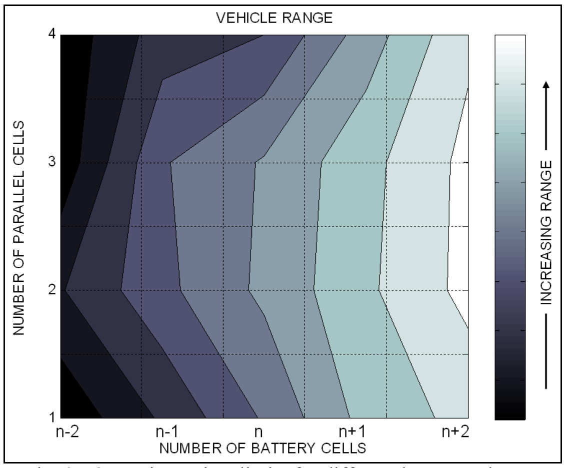

Fig. 9. Operating points limits for different battery voltages (units = p.u.)

The clearer area is, the higher vehicle range is. A first evident observation is that vehicle increases with the number of cells (horizontal reading of the graph). We secondly observe (by vertical reading of the graph) that for the same number of cells, range depends on battery pack structure (branches number). For example, for n cells, maximum of range is obtained with a two branches-pack (n/2 cells on each branch). These results have to be connected with those on Fig. 7 (variation of powertrain losses with battery voltage).

CONCLUSION

We have presented different models of electric vehicle powertrain organs in this paper. They have been developed with the intention of optimizing performances and powertrain efficiency (highly linked with vehicle range). Consequently, models are as much simplified as possible. Further, explicit formulations depending on degrees of freedom are preferred.

In a second step, we have studied optimization of these criteria (range and performances). In order to do this, it is advisable to be interested at once in powertrain control laws ("software" optimization) and in system architecture ("hardware" optimization). These two optimizations are complementary and can be independently performed with loopback. For example, we can size battery and machine by using static energetic maps, then design control laws by using dynamic models and finally optimize battery pack structure.

A last point to be noted is the necessity of using dynamic models (and not only static models) when we are interested in powertrain sizing in terms of vehicle range and performances. Indeed, for same energetic characteristics (quantity of energy in battery), range varies according to pack organization structure (numbers of parallel and series cells) and according to the way electric machine is piloted. This variation is taken into account when are modeled battery voltage variations and powertrain losses evolution according to dynamic setting points.

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