Numerical Models for Electric Train Energy-Efficient Operation

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***Abstract*— The paper begins by presenting structure of the electric drives with traction induction motor used on locomotive fed from AC line. Are emphasized the main components of such a drive system: the main electric circuits, the mechanical part and the locomotive control. For the traction induction motors, which it is included in both the main electrical circuits and in the mechanical part, it is proposed the fictitious split into an „electromagnetic part" and into a „mechanical part". In order to modeling the mechanical part, they are established the equations of useful movement and it is built the structural diagram corresponding to a locomotive with „z" traction identical motors. The mathematical model and structural diagram of the mechanical part respects all the running conditions. On the structural diagram basis it is built the SIMULINK model associated of the useful movement. The implementation of the SIMULINK models is made easily (because their identical topology), starting from the adequate structural diagrams. The SIMULINK model is used to calculate the energy consumption for different running regimes and different route configurations and to identify energy efficient train control methods, avoiding utilization of complex mathematical methods. The numerical models presented can be used, with small modifications, for the study by simulation of useful movement of any type of electric vehicle.**

I. INTRODUCTION

To calculate and optimize the energy consumption of an electric vehicle through the chosen driving strategy it is necessary to build the movement model of the vehicle [1].

The general structure of the electric drives with traction induction motor used on locomotive fed from AC line contains [2], [3], [4], [5] (Fig.1):

- the main electric circuits include: traction transformer (TT), line side-converter (C4Q), L_2C_2 filter, machine-side converters (IT) and the electromagnetic part of the traction induction motor (MAT);

- the mechanical part includes: mechanical part of the traction induction motor and mechanical transmission (TM) from the electric motor to the motor wheel (RM) and

- the locomotive control includes: line-side converter control, control of the voltage-source inverter – traction induction motor ensemble (IT+MAT) and anti-slip control.

The main electric circuits (Fig.1) ensure two conversion stages of the electric energy, the first being achieved by line-sides converters and the second, by machine-side converters [2], [3], [4], [5]. In the case of AC line supply, the line-side converter is a four-quadrant converter (C4Q), associated to a voltage-source inverter (IT), which

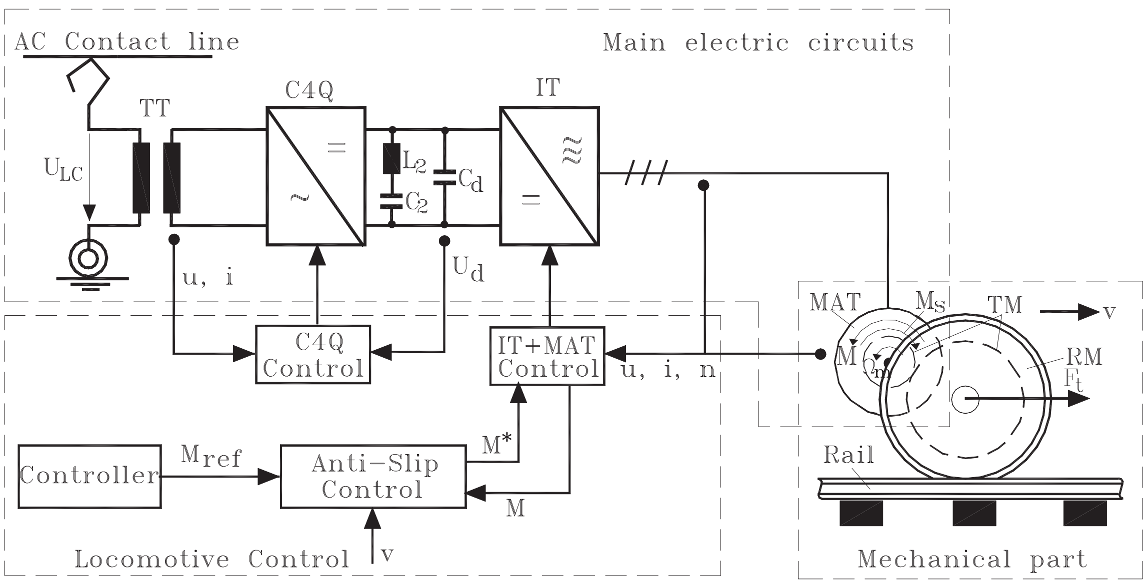

Fig.1. Electric drive with traction induction motors used in modern locomotives fed from AC contact line

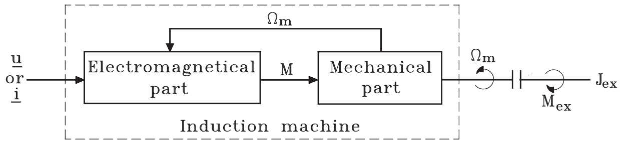

Fig.2. Functional parts of traction induction motors

represents the machine-side converter (Fig.1).

In the power schemes of motor electric vehicles, the traction induction motor it is the final element from the equipments chain by conversion of energy. After all, it achieves the electromechanical conversion of energy making thus possibly the movement. Like complex electromechanical system, the induction motor will have decomposed functionally between an electromagnetic part and a mechanical part (Fig.2).

Both the M electromagnetic torque and the Ω_m mechanical speed of rotor, they intervene like internal variables, by interaction, between those two functional parts. In the motor vehicle case, the mechanical part of traction induction motor it is coupled (through the transmission intermediation) with the motive axle and can be modeled in the shape of the useful movement or/and the elastic mechanical transmissions [3], [4], [5]. For can be connected, the models must be achieved in accordance to the same principles, indifferently that they describe the phenomenon by electric nature or mechanical nature.

The structural diagram of electromagnetic part can be coupled both with the structural diagram of machine converter through the intermediation of the input variables us and output variables is and with the structural diagram of mechanical part through the intermediation of input quantities Ω_m and output quantities M.

II. Mathematical Model of Mechanical Part

In any electric vehicle, the developed electromagnetic torque of the traction electric motors is transmitted of the motor wheels. These, through turning, establish the translation movement of the vehicle on the rail [2], [3], [4].

Because the rotation movement of the motor wheels it is "attached", through transmission, of the traction motor rotor movement, it results that the motor wheels movement equation can be deduced from the motor equation which these are coupled with. Thus, the motor torque transmitted of the motor wheels it is $M_R=i\cdot\eta_t\cdot M_2$, where M_2 is the developed useful torque of the traction motor, i is the transmission ratio and η_t is the transmission efficiency. At the running radius $r=D_r/2$, the motor torque M_R it corresponds it the motor force F_0[N] at wheels [3], [4], [5]

$$F_0 = \frac{M_R}{D_r/2} = \frac{2}{D_r} \cdot i \cdot \eta_t \cdot M_2 \quad (1)$$

In the slip absence, the peripheral speed v of the motor wheels (which they are turned with the angular speed Ω_0)

$$v = \Omega_0 \cdot \frac{D_r}{2} \quad (2)$$

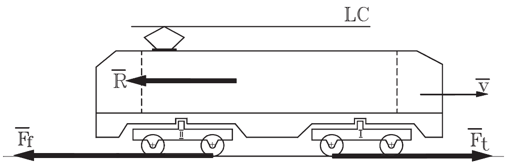

Fig.3. External forces which they establish the movement.

it is the same with the translation movement speed (on the rail) of the vehicle. As $\Omega_0=\Omega_m/i$, where Ω_m it is the angular speed of the traction motor rotor, it results that

$$v = \frac{D_r \cdot \Omega_m}{2 \cdot i} \quad (3)$$

The relations (1) and (3) are fundamentals in the traction calculations. They allow the establishment of the vehicle characteristics depending on the useful torques quantity M_2 and on the angular speed of the shafts of the all its traction motor (in the equality case of the diameters of the all motor wheels).

In the running, both under its traction motors action and under the rail resistance influence, it achieves the useful translation movement of the all vehicle in the long rail.

Moreover, the useful movement of the train it is established only of the external forces action. These can be (Fig. 3):

- motor active forces (of traction), with the resultant $\overline{F_t}$ (of controllable magnitude, which they operate on the sense and direction of the useful movement);
- braking active forces, with the resultant $\overline{F_f}$ (of controllable magnitude, which they operate on the useful movement direction, but on the contrary sense of the speed vector $\overline{v}$) and
- train resistance forces with resultant $\overline{R}$.

The active forces $\overline{F_t}$ (of traction) and $\overline{F_f}$ (of braking) they operate not simultaneously in none running regime (presence of one it is equivalent to the exclusion of other), while the train resistance it is presented all the time, even in the active forces absence (in the coasting regime without current).

The train resistance forces, between with the traction characteristics of the high-speed train, they permit the useful movement study of the vehicle. In these conditions the useful movement equations is [3], [5], [6]

$$m^* \cdot \frac{dv}{dt} = F - R\,; \quad m^* = m \cdot \xi \quad (4)$$

where F it is F_t in traction regime or - F_f in braking regime, and ξ is the coefficient of increase the mass of the train that take account to the presence and weight of the turning parts from the train structure (ξ=1.06…1.2).

Thus, through the coefficient of increase the mass agency it can make abstraction of the turning parts presence, replacing the real mass "m" of the train with a "fictitious mass" $m^*=m\cdot\xi$ found in translation movement with the speed "v", the same of the considered train. From the physical viewpoint, this is equivalently with fictitious replace of the mechanical system of rigid solid parts through a material point with inertial mass $m^*=m\cdot\xi$.

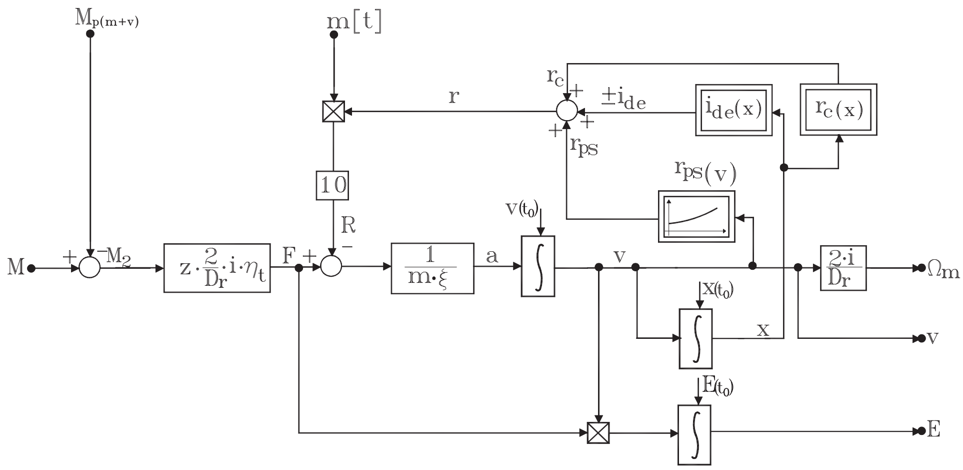

Fig.4. Structural diagram of useful movement

For the dynamic aspect approach of the useful movement it is necessary a mathematical model. In this purpose it is considered a electric vehicle of mass m[t] and coefficient of increase the mass ξ having the specific train resistance r [daN/t]. On the useful movement duration, the speed $v(t)$ and the distance $x(t)$ they are ruled at the equations

$$m \cdot \xi \cdot \frac{dv}{dt} = F - R \; ; \; \frac{dx}{dt} = v \tag{5}$$

If the movement has been made under the useful torques action M_2 (identical), developed of those "z" traction motors of the electric vehicle, then in accordance with the relations (1) and (3)

$$\Omega_m = \frac{2 \cdot i}{D_r} \cdot v \; ; \quad F = z \cdot \frac{2}{D_r} \cdot i \cdot \eta_t \cdot M_2 \tag{6}$$

Moreover, if the mass m of the train it is expressed in [t], the total train resistance R[N] it is established by

$$R[N] = r[daN/t] \cdot m[t] \cdot 10 \tag{7}$$

Energy consumption is calculated by

$$E = \int P dt = \int F \cdot v \; dt \tag{8}$$

The equations ensemble (5), (6), (7), (8) they form the mathematical model of the useful movement. Written together, in the shape of

$$v = \frac{1}{m \cdot \xi} \int (F\text{-}R) dt \; ; \quad \Omega_m = \frac{2 \cdot i}{D_r} \cdot v; \quad x = \int v \cdot dt \; ;$$
$$F = z \cdot \frac{2}{D_r} \cdot i \cdot \eta_t \cdot M_2 \; ; \quad R = (r_{ps}(v) \pm i_{de}(x) + r_c(x)) \cdot m \cdot 10 \tag{9}$$
$$E = \int P dt = \int F \cdot v \; dt$$

allow the structural diagram construction of useful movement (Fig. 4). In the mathematical model (9) was replaced the specific train resistance r with its components: the main specific train resistance r_{ps}, the specific train resistance on level tangent track i_{de} and the specific train resistance due to curves r_c.

By means of this scheme ("coupled" at the structural diagram of electromagnetic part of traction motor) can be simulated the useful movement of any electric vehicle as compared with the concrete control modality of this. Accordingly they are obtained the running diagrams $v(t)$ and $x(t)$, too. The modification of vehicle mass, of dependences $i_{de}(x)$ or $r_c(x)$, specific to certain vehicle or route, can be easily operated, obtaining an exact mathematical model, which it respects all the running conditions.

In the motor wheels diameters inequalities case, the scheme suffers a minor change, the total force F resulting like sum of partial forces developed by each motor partly.

III. SIMULINK MODEL

The SIMULINK model corresponding to the useful movement of the electric vehicle can be easily implemented, having with a view the topological comparison with the associate structural diagram (Fig. 5).

An immediately example of the utilization of the SIMULINK model it is the running diagrams drawing, that illustrate the dynamic aspect of the electric vehicle.

The running diagrams of the electric train are drawn on the traction and braking characteristics basis and of the conditions imposed of route.

The traction and braking characteristics consort any presentation, however summarily would be, of an electric train. For example, it has been considered the ETR 500 italian high speed train case, for which, except the traction and braking characteristics, they have more represented the train resistance, too, corresponding to the different specific features of the route (through the declivities consideration) (fig.6).

In the blocks „Ft(v)" and "Ff(v)" (fig.5) they are implemented the traction and braking characteristics of the ETR500 train. The model is based on the useful movement model, at which the main input variable it is supplied of the block „F", which it models the useful movement phases:

- starting phase,
- running at constant speed phase,
- coasting phase and
- braking phase.

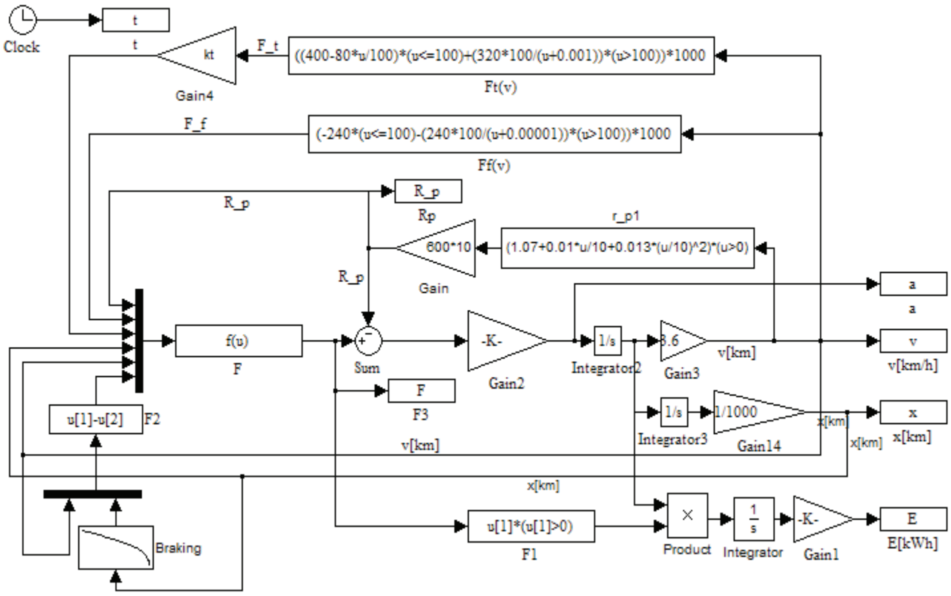

Fig.5. SIMULINK model of useful movement “um.mdl”

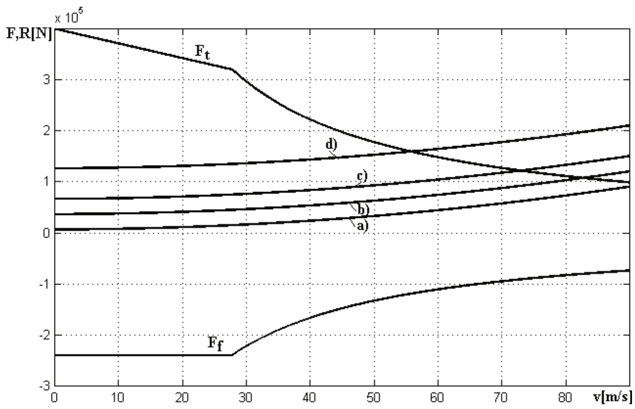

Fig.6. Traction and braking characteristics and 4 values of train resistance of ETR 500 italian high speed train, m=600t

a) i_{de}=0; b) i_{de}=5; c) i_{de}=10; d) i_{de}=20

Also, in the "Braking" interpolation block (Fig.5) is implemented the braking diagram of train, that is useful for calculating of the braking distance.

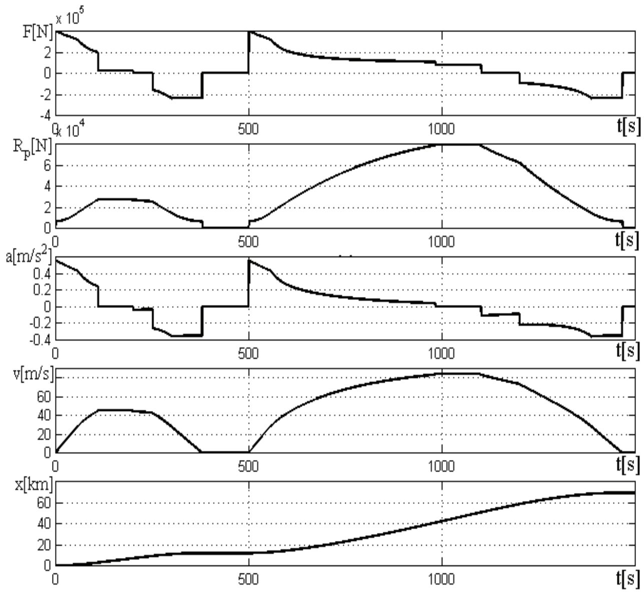

Fig.7. Running diagrams of high speed train ETR500

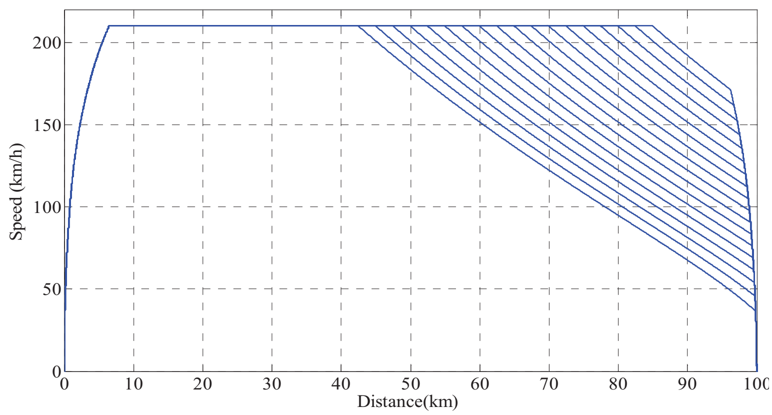

Fig.8. Running diagrams for maximum speed 210km/h

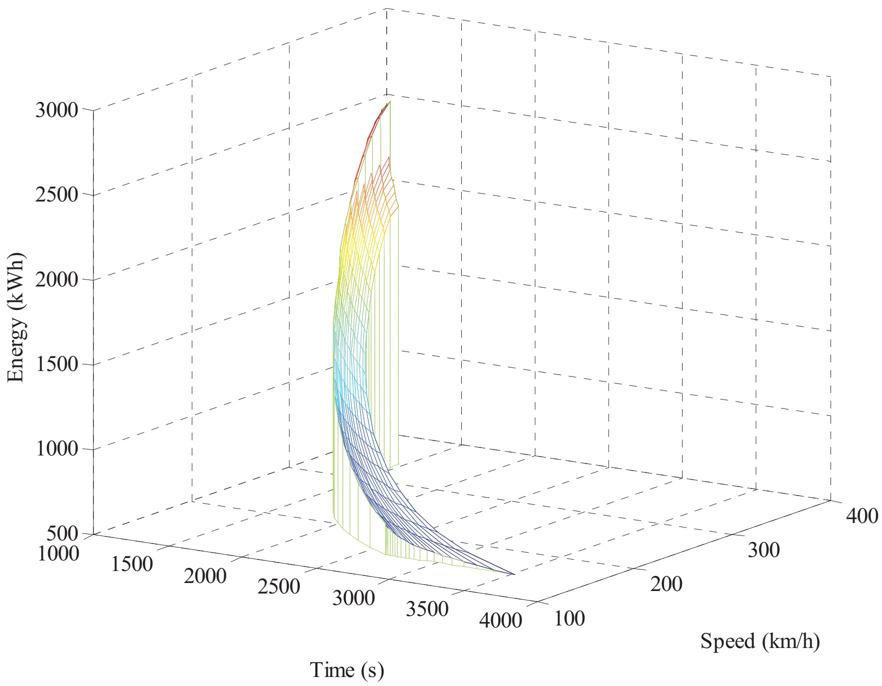

Fig.9. Energy as a function of time and speed

By means of this SIMULINK model (Fig.5) they have been drawn the running diagrams corresponding to a test route of the high-speed train, on its route has been reached the speed of 44,44 m/s (160 km/h) and respectively of 83,33m/s (300 km/h). They have been drawn the variations of the force, of the train resistance, of the acceleration, of the speed and of the distance (Fig.7).

Moreover, the model allows the calculation of energy consumption for different running regimes and different route configurations.

For example, it can be obtained the running diagrams for a distance of 100 km, a maximum speed of 210 km/h and different values of the starting position braking (Fig.8). For each of these cases, is calculated the value of the consumed energy and can be determined its minimum value. Thus, using the same model, can be obtain the surface corresponding to the dependence $E(T, V)$ (Fig.9), where T is the travel time and V is the maximum speed corresponding to the different running diagrams.

By means of this surface, to an imposed value of running time T = 2500 s (for example by schedule reasons), can be obtained the dependence shown in Fig.10, that has a minimum for the maximum speed v = 160km/h.

IV. CONCLUSIONS

The presented model take account of the particularity of the vehicle and route and it is relatively easy of implemented and of used.

Related to other energy optimization techniques found in literature [1],[8],[9],[10],[11], the presented SIMULINK model avoid utilization of complex mathematical methods.

This model can be useful in the establishment of an energy efficient train control methods, based on the best utilization of the installed load. The respective methods are implemented then in the computer control system on the electric vehicles, contributing at the circulation safety increase, at the decrease of consumptions and allowing even a possibly ATC (Automatic Train Control) [2], [3], [12], [13].

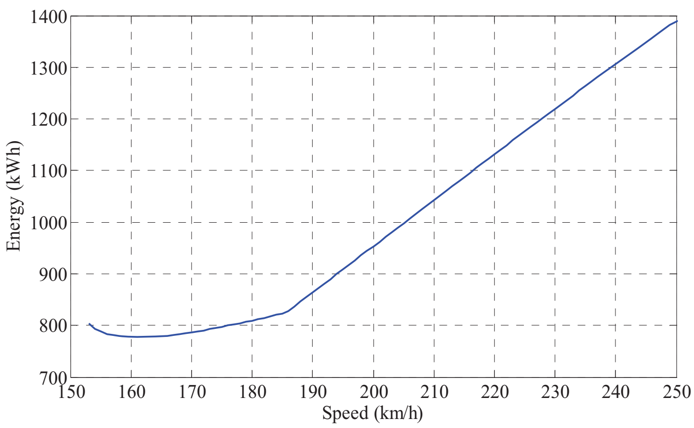

Fig.10. Energy as a function of speed

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