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Methodology of determining basic technical parameters of electric-drive car

Streszczenie. *W artykule omówiono problemy elektryczne budowy jeżdżącego prototypu samochodu, umożliwiającego przewóz osób niepełnosprawnych. Przedstawiono metodykę wyznaczania wymaganych charakterystyk trakcyjnych samochodu elektrycznego na podstawie analiz przebiegów jazdy modelu obiektu dla zakładanych miarodajnych warunków ruchu. Do wyznaczania parametrów znamionowych urządzeń głównych zastosowano metodę optymalizacji. Jako kryterium rozwiązania przyjęto warunek minimalizacji strat energii układu napędu. (**Problemy elektryczne budowy jeżdżącego prototypu samochodu, umożliwiającego przewóz osób niepełnosprawnych**)*

Abstract. *The article presents issues of electric construction of a moving car prototype which enables transport of the disabled. Methodology has been presented of determining required traction characteristics of an electric-drive car on the basis of analyses of object model driving graphs for the assumed reliable traffic conditions. Optimization method has been used for determining nominal parameters of the main devices. The condition of minimization of energy losses of a drive system has been assumed as a solution criterion.*

Słowa kluczowe: miejski samochód elektryczny, parametry znamionowe, mapy strat urządzeń układu napędu, optymalizacja.
Keywords: urban electric-drive car, nominal parameters, charts of losses of drive system devices, optimization.

Introduction

Urban electric-drive car that is being designed within the framework of ECO – Mobility project [1] (hereafter called ECO-car) is to be dedicated to transporting both the disabled and kinetically fit persons. The possibility is assumed of the use of the car in 3 configurations [2,3]: configuration I – 4 fit persons, configuration II – 1 disabled person (driver) + 2 fit persons, configuration III – 2 fit persons (one of them being the driver) + 1 disabled person. It has been established that the disabled person should get into the car on a wheelchair and stay in it during the journey no matter if he or she is a driver or a passenger. The disabled person's entrance should be possible from three sides of a vehicle (from the two sides and from the back). The above functionality assumptions significantly make the ECO–car project distinct from the construction solutions designed so far. In order to limit inertial forces influencing the person travelling in a wheelchair, it has been assumed that the driving velocity should not exceed 50km/h.

The construction of a drive system is an important task of the project. The structure of a drive system cannot limit the access of a disabled person to the car. It has been established that the designed ECO-car will be driven by two BLDC motors placed in wheels, and the turning function will be ensured by the so-called steer-by-wire system. Drive system devices will not take up any utility space of the car interior. This does not limit the possibility of lowering the vehicle's floor in order to facilitate entrance of the disabled persons.

Schematic diagram of the main circuit of the car within a complete circuit with DC/DC converter (block 6) and supercapacitor circuit (block 11) is shown in fig. 1 [4]. In this circuit, block 6 is used for fast charging of an accumulator from a three-phase socket of high power or for increasing voltage of the motor with the driving velocity higher than the nominal one, and block 11 plays the function of an additional energy source, levelling out the load of the accumulator in dynamic states of circuit supply.

Fig. 2 [4] shows a simplified circuit without the blocks mentioned above.

The objective of the present paper is discussion of methodology of determining basic technical parameters of a drive system. An example of application of the designed method has been given for a drive circuit of a structure presented in fig. 2.

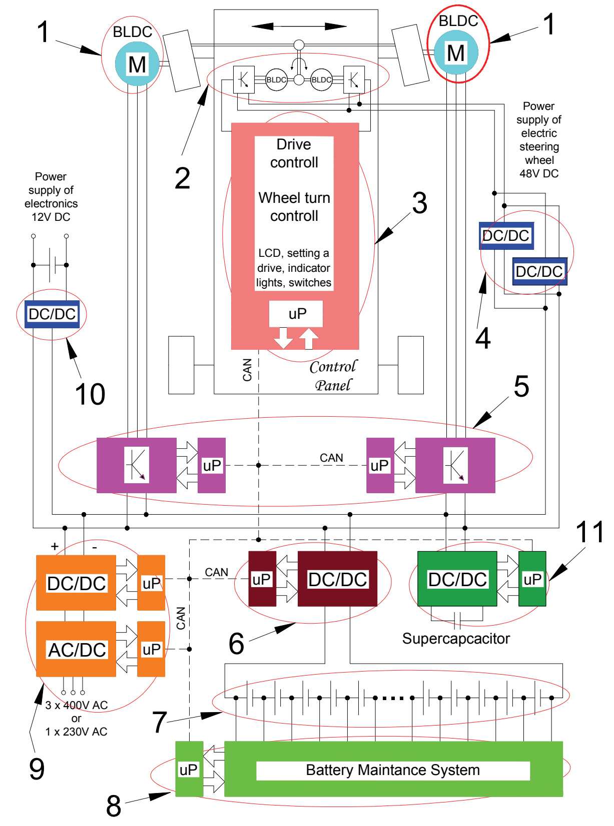

Fig. 1 [4]. Block diagram of ECO-car drive within a complete circuit. Indications: 1 – BLDC-type electric motors with a direct wheel drive, 2 – steer-by-wire system, 3 – control panel, 4 – single voltage converter for supplying steer-by-wire system, 5 – driving converter, 6 – double voltage converter for supplying driving converters and for charging batteries at vehicle's stop (also for energy recuperation when braking), 7 – accumulator battery, 8 – battery monitor system, 9 – network loader, 10 – single voltage converter for charging accumulator supplying steering system, 11 – supercapacitor system

Main circuit model

Circuit model of a drive system has been presented in fig. 3. It has been assumed that with basic steering of a motor, two bands of armature winding that are connected in series are supplied in turn [5]. Currents in phase bands of a motor are switched on and off at strictly determined positions of a rotor in relation to a stator. At these positions, modules of consecutive circuit induced voltages are equal. In a three-phase machine there are six basic transistor switchings. In each time interval between basic switchings, a state of commutation and a state of conduction is distinguished.

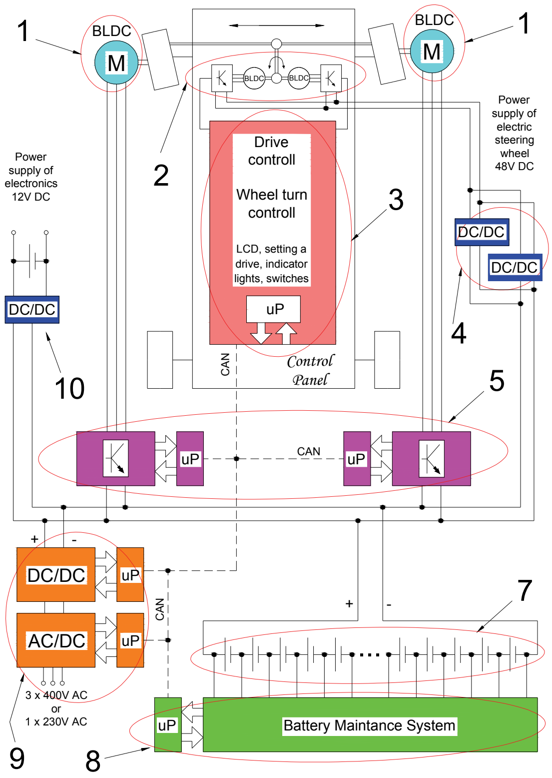

Fig. 2 [4]. Block diagram of ECO-car drive in a simplified circuit. Indications as in fig. 2.

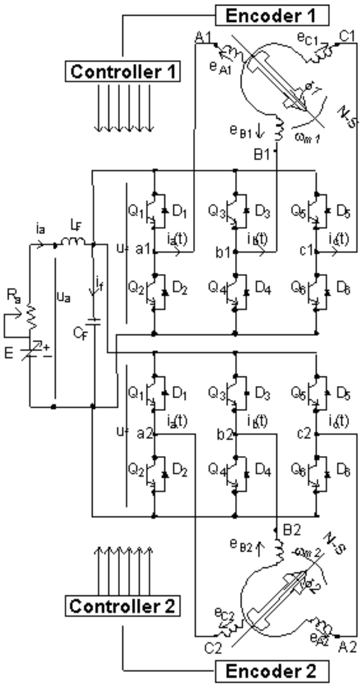

Fig. 3. Model of main circuit of a car for a drive system configuration presented in fig. 2.

For determining the position of a rotor, and so the moments of switching on transistors, a sensor of shaft location will be used. Voltage regulation (rotational velocity of a motor) is done by means of PWM modulation. In order to level out the pulse of a varying component of accumulator current, the moments of switching on transistors in converters 1 and 2 should differ by half the impulsing period. More complex steering algorithms are expected to be tested, taking into account dynamic changes of angles of switching on bands and changes of joining angles of over 120 electric degrees [6,7].

General description of methodology of determining basic parameters of main devices of a drive system

Structural diagram of the assumed computational method is presented in fig. 4. Similar methodology was used in the paper [9] for dimensioning induction traction motors for trams. Input values are the assumed vehicle parameters and the requirements determined by reliable traffic conditions and given driving methods (v(t)). The output values are among others nominal parameters of drive devices with which energy consumption in a drive model is the lowest. The method is based on using modeling, simulation and optimization techniques. Modeling issues encompass the tasks of construction of vehicle models and a drive system.

The first task of this procedure is determining the required maximum values of load parameters (understood as maximum values of temporary graphs of such values characterizing load as power, force and speed on vehicle wheels). These values are determined on the basis of a certain limited number of results of model vehicle movement, the so-called theoretical runs in accordance with given driving methods defined by reliable conditions. What is indispensable for such a procedure is a vehicle model in a nominal, mathematical and simulation form. The result of this task is determining a short-term (with maximum values) and continuous traction characteristics of a vehicle.

The second task of the method discussed in the present paper is determining nominal parameters of devices being part of the system (motor, converter and accumulator). The solution of the task ensures minimum energy loss within a circuit having driven over the given distance in accordance with a defined method of driving. The variables in the task are the coordinates of the point within the area limited by a short-term traction characteristics defined earlier. On their basis nominal parameters of drive devices are eventually calculated. The constants in the task are the parameters determining the driving method and traffic conditions. In the presented method there is a possibility of further development of optimization model. What can be considered as additional criteria is for instance the cost of construction of the system or the weight of its devices. Conducting calculations for the structures of the system shown in (fig. 1 or fig. 2) will allow for its assessment and a proper choice of a final system.

Vehicle model

It has been assumed that the vehicle will be modeled as a rigid body of weight *m*. It is also assumed that the driving wheel rolls on the road without a slip. Transference of driving moment from motor to wheels occurs by means of a rigid shaft without reduction gearbox. Mechanical energy of the motor changes into kinetic energy (rotational motion of transmission shafts and progressive motion of the body of the car) and energy of losses (for counteraction of rolling resistance forces and aerodynamic resistance) or potential energy gain while driving on a slope. The equations of the drive motion get a known form:

(1) $$\frac{d\omega_S}{dt} = \frac{1}{J}\left(T_e - T_0 - T_v - T_i\right)$$

(2) $$\omega_S = \frac{d\alpha_S}{dt}$$

where:

(3) $$J = J_S + mR^2$$

(4) $$T_v = RF_v$$

(5) $$T_i = RF_i$$

where: J – reduced moment of driving inertia, R – radius of a driving wheel of a car, T_e – electromagnetic torque of a motor, T_v –reduced torque from rolling resistance and aerodynamic forces, T_i – reduced torque from additional resistance to motion forces on a hill, T_0 – torque of mechanical losses of a motor, F_v – rolling resistance and aerodynamic forces, F_i – force of resistance to motion on a hill, α_S – angle of rotation of a motor shaft, ω_S – motor angular velocity.

Calculations with the use of a model were conducted with the assumption that the value of weight parameter of m = 1300 kg. The method of determination and the values of the other parameters of the model resulting from it are presented in [5].

Reliable traffic conditions

It has been assumed that the car will fulfill the following motion conditions :

- *1* – driving at constant velocity equaling the assumed maximum value of driving velocity V_{max} = 16.67 m/s,
- *2* – driving on a reliable hill of the inclination of i_h = 7 % at constant velocity V_h = 8.33 m/s in a required period of time t_h = 1hour,
- *3* – driving of a vehicle of a minimum equivalent weight 1064 kg on an individual garage ramp of maximum admissible inclination defined by construction law (25 %),
- *4* – start-up acceleration 1.5 m/s2 within velocity range up to the value of 6.94 m/s,
- *5* – overtaking acceleration equaling 0.5 m/s2 at the velocity of 8.33 m/s,
- *6* – electric braking delay 1.6 m/s^2 within velocity range from the value of 5.55 m/s up to stopping,
- *7* – driving of a vehicle of a maximum equivalent weight 1300 kg on a multi-space garage ramp of maximum admissible inclination defined by construction law (20 %)

Traction characteristics

Short-term, maximum traction characteristics of a vehicle restrict from the upper limit the maximum values of forces determined on the basis of the solutions of motion equations (1,2) for the assumed reliable conditions and model parameters (weight, motion resistance, etc.). Sample maximum traction characteristics of a car (F – maximum force on the wheels depending on driving velocity) and basic motion resistances (W – rolling resistance and aerodynamic forces in the function of driving velocity on a straight and flat distance) are presented in fig 5. Additionally, points have been indicated in this figure (indicated by digits) which are determined for particular reliable conditions. It results from these characteristics that the drive must ensure large overload capacity of the force.

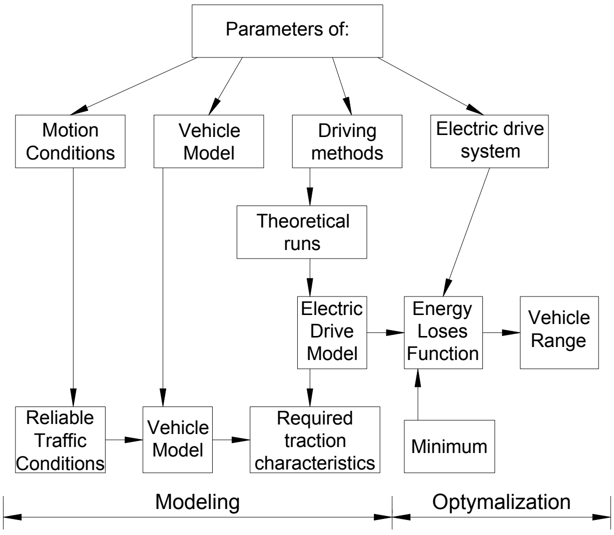

Fig. 4. Structural diagram of the method of determining basic parameters of main devices of the drive system.

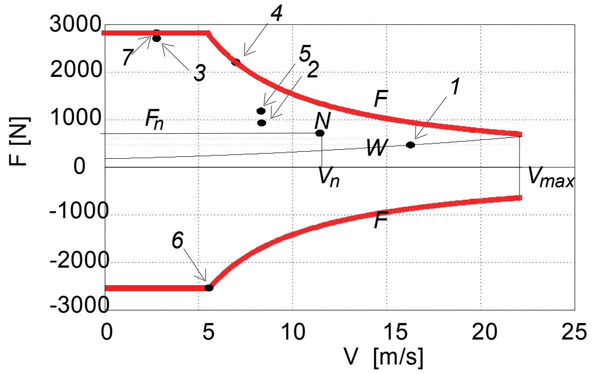

Fig. 5. Short-term, maximum traction characteristics on vehicle wheels and resistance to motion.

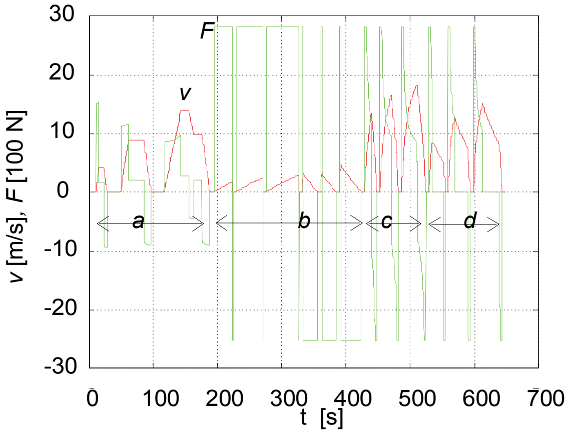

Fig. 6. Graphs showing velocity and forces of mixed driving. Indications: *a* – European driving cycle, *b* – entry and exit from garage, *c* – forceful driving cycle, *d* – normal driving cycle.

(6) $$k_{F\_\max} = \frac{F_{\max}}{F_n}$$

Point N is a sample point of nominal constant work of the drive: v_n – nominal constant velocity of the car, F_n – nominal constant force of the car. U_{s_n} – nominal voltage of supply. For the assumed method of motor steering

(7) $$U_{s\_n} = \frac{v_n}{v_{\max}} U_{a\_\min}$$

it has been assumed that it is possible to obtain maximum velocity v_{max} at minimum accumulator voltage U_{a_min}

Reference driving cycles and theoretical runs

The notion of a driving cycle defines specified velocity graphs of a drive over several road distances separated by periods of stopovers. Cycles defined in such a way unambiguously describe the driving method of a vehicle. The cycles find application in determining the conditions of continuous and maximum loads of drive devices. In calculations of theoretical runs, typical cycles are used of standardized velocity graphs or new requirements are determined. The following cycles have been used in the present paper:

- *1* – ECE European Driving Cycle (standardized driving cycle for testing fuel consumption of a combustion vehicle),

  2 – entry and exit from a multi-space garage on platforms of a given length of 25 m, 50 m, 75 m
- *3* – forceful drive (minimum-time) of 3 road distances of the lengths 150, 300 and 450 m,
- *4* – normal drive of 3 road distances of the lengths 150, 300 and 450,
- *5* – MIXED DRIVE A run combining the driving cycles defined above: the European driving cycle + entry and exit from garage + forceful drive of 3 road distances + normal drive of 3 road distances.

Cycles from 1 to 5 are not standardized and have been specified by the authors of the present paper. Fig. 6 presents the results of theoretical runs, that is the graphs of velocity and forces on car wheels for the mixed cycle obtained on the basis of solutions of motion equations (1,2) of a vehicle model of given parameters.

Motor losses

Total losses emitted in a machine at given current *I* and specified angular velocity ω can be determined by the following relation:

(8) $$P_t = P_{CuN}\left(\frac{I}{I_N}\right)^2 + (P_{FeN} + P_{m\omega_N{}^2})\left(\frac{\omega}{\omega_N}\right)^2 + P_{m\omega_N}\left(\frac{\omega}{\omega_N}\right) + P_{mt}$$

where: symbols with *N* index mean nominal values respectively: P_{CuN} - winding losses, P_{FeN} - core losses, $P_{m\omega_N{}^2}$ - mechanical losses proportionate to ω^2, $P_{m\omega_N}$ - mechanical losses proportionate to ω, P_{mt_N} - mechanical losses caused by dry friction, I_N and ω_N angular current and velocity.

After introducing weight coefficients determining the contribution of particular kinds of losses to nominal losses P_{tN}:

(9) $$a = P_{CuN}/P_{tN}\,,\ b = (P_{FeN} + P_{m\omega_N{}^2})/P_{tN}\,,$$

$$c = P_{m\omega_N}/P_{tN}\,,\ d = P_{mt_N}/P_{tN}$$

Relation (8) takes the form of:

(10) $$P_t = \left[a\left(\frac{I}{I_N}\right)^2 + b\left(\frac{\omega}{\omega_N}\right)^2 + c\left(\frac{\omega}{\omega_N}\right) + d\right]P_{tN}$$

It results from (9) that $a + b + c + d = 1$

Efficiency of the machine within the range of engine work with a given moment *T* and angular velocity ω can be determined by the relation:

(11) $$\eta_s = \frac{T\omega}{T\omega + P_t}$$

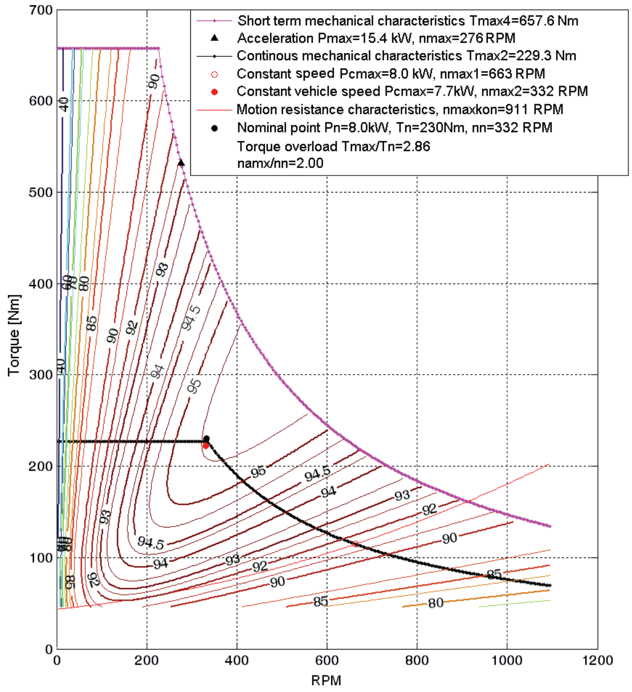

Fig. 7. Motor efficiency chart (thick lines) and generator efficiency chart when T_N=230 Nm, n_N=332 rotations/min

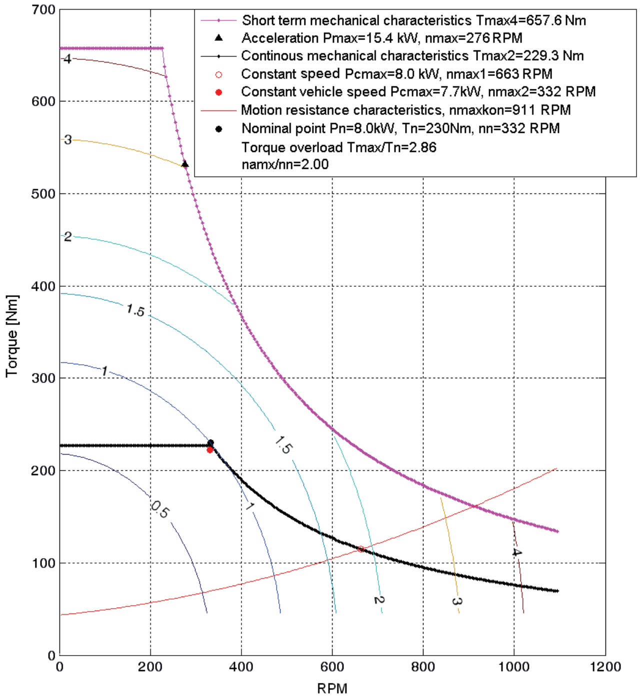

Fig. 8. Motor losses chart when T_N=230 Nm, n_N=332 rotations/min

Efficiency of the machine within the range of generator work with a given moment *T* and angular velocity ω can be determined by the relation:

$$\eta_s = \frac{T\omega - P_t}{T\omega} \tag{12}$$

Additionally assuming the proportionality of the moment and the current, which is right in the case of a machine with permanent magnets and in the case of an induction machine with direct moment steering we obtain the expression of losses with a given moment *T* and rotational velocity *n*.

$$P_t = \left[a\left(\frac{T}{T_N}\right)^2 + b\left(\frac{n}{n_N}\right)^2 + c\left(\frac{n}{n_N}\right) + d \right] P_{tN} \tag{13}$$

Expression (13) together with relations (11) and (12) make it possible to determine efficiency charts and losses within the area limited by the maximum traction characteristics.

Fig. 7 shows an efficiency chart within the range of motor and generator work of an electric machine when nominal parameters equal: TN=230 Nm, nN=332 rotations/min. Fig. 8. presents a losses chart in the form of isolines determining their multiplication factor in relation to nominal values.

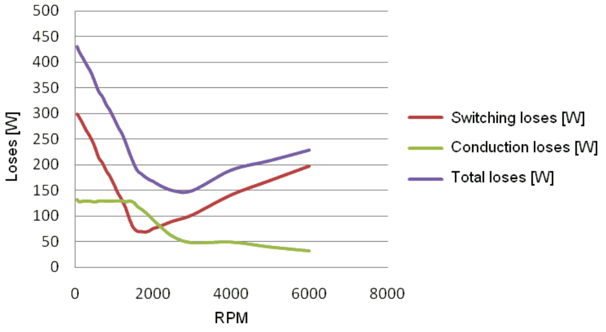

Fig. 9. Sample graphs of converter power losses

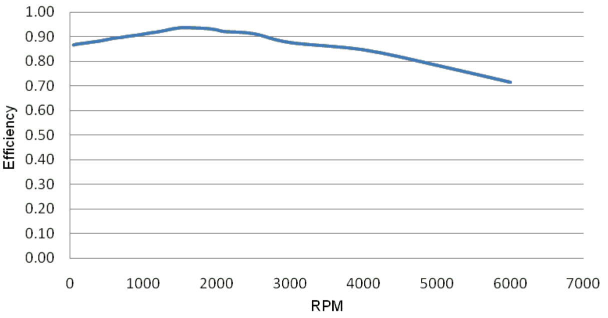

Fig. 10. Sample graph of converter efficiency

Converter losses

Converter energy losses are divided into conduction and switching losses. Conduction losses depend on the value of conduction current, whereas switching losses depend on the frequency of switching. When determining losses it was established that the receiver of energy would be BLDC motor with a trapeze induction graph [4] realizing given traction characteristics in two regulation spheres of velocity limited by maximum moment and maximum power. In this case, converter energy losses depend on the required motor current and its rotational velocity on the shaft. Sample graphs of converter losses and efficiency have been shown in fig. 9 and 10.

Accumulator losses

Parameters of voltage-current characteristics *U*(i_a) of modern lithium-ion accumulators first of all depend on: the degree of charging *k*, temperature of links ϑ and current i_a. These relations can be defined in the following way [8]:

$$U(i_a, \vartheta, t) = E(i_a, \vartheta, t) - R_a i_a \tag{14}$$

$$E(i_a, \vartheta, t) = c_k k(i_a, \vartheta, t) + \Delta E \vartheta \tag{15}$$

$$k(i_a, \vartheta, t) = \frac{1}{Q_n}\left\{ \int_0^t \alpha[i_a(t)]\beta[T(t)] i_a(t)dt + Q_0 \right\} \tag{16}$$

where additionally : *E* – inner voltage *sem* of the battery in reference temperature, ΔE – temperature deflection *sem* from reference value, c_k – proportionality coefficient between *sem* of reference and degree of charging, α - current coefficient of charging, β – temperature coefficient of charging, *Q* – accumulator charge (“capacity”, ”charging” of a battery)

In accordance with pattern (15), in accumulator temperature equaling reference temperature (ΔE = 0), inner resistance R_a is the value describing inclination of voltage-current characteristics *U*(i_a) of the substitute circuit (fig. 3) in the environment of current i_a. After transformations we obtain:

$$R_a = \frac{c_k k - U}{i_a} \tag{17}$$

Resistance defined in this way is difficult to determine without the knowledge of actual power of heat losses of the accumulator at the point of work of voltage-current characteristics *U*(i_a). Therefore, in the computational model of power losses of the accumulator, the values of inner resistance defined by the manufacturer have been adopted.

Realization of computational method

The proposed method of determining basic technical parameters of a drive (diagram – fig. 4) has been realized within computational environment Matlab – Simulink. In the designed software, chart calculations of converter and accumulator motor losses have been included inside the so-called “charted” Simulink sub-systems with adequately defined entries and parameter sets.

In the first place, the relation between energy consumption and the value of the assumed nominal parameters was tested. In the calculations, a set of parameters determined by coordinates of points indicated by red marks + in fig. 14 has been assumed. Moreover, it has been established that the drive system realizes one chosen driving cycle. Sample calculation results for the driving method defined according to cycle 5 MIXED DRIVE are presented in fig. 13. High level of changeability of consumed energy can be noticed in this figure. This means that the question of the right choice of nominal parameter values is important and leads to significant energy savings. This part of calculations also showed that the driving method also has significant influence on the values of nominal parameters with which energy consumption is the lowest. This relation was analyzed in the second part of calculations. Sample results of analyses are shown in fig. 14. Digits from 1 to 5 mark the points at which minimum energy consumption was achieved during the run in accordance with the cycles indicated with these numbers. In this way, five sets have been achieved of the values of nominal parameters of the drive system optimally matched in respect of energy with a given driving cycle. The next part of calculations was conducted with the assumption that for dimensioning of the drive system only one set of nominal parameter values can be selected. It is equivalent with the choice of one reference cycle. In order to picture this issue it was investigated in what way the vehicle’s range depends on the driving method with the same value of energy. Assuming, for example that the vehicle’s devices are dimensioned on the basis of point *1* with ECE reference cycle, the ranges were calculated with the driving according to the other cycles. The range of a vehicle with the ECE driving cycle equals 135 km, normal – 90 km, forceful – 60 km, mixed cycle – 54 km, and according to the cycle in garage – only 9 km. If, on the other hand, the drive system was dimensioned on the basis of point *2* with the garage reference cycle, then the range of a vehicle would increase to 35 km. However, the ranges of vehicles driving according to the other cycles would decrease. For instance, the range of a vehicle driving according to ECE cycle would decrease from 135 to 70 km. What follows from the analysis of calculations is that energy consumption of a car of drive parameters selected for driving in accordance with a chosen reference cycle and covering the same distance according to other driving methods, increases proportionally to the distances between points of optimum solutions. In fig. 14, for example, the distances between points 1 and 2 are the biggest. Thanks to a proper choice of nominal parameters of the drive system, the range of a vehicle driving in accordance with a particular cycle can be significantly lengthened with a given energy value.

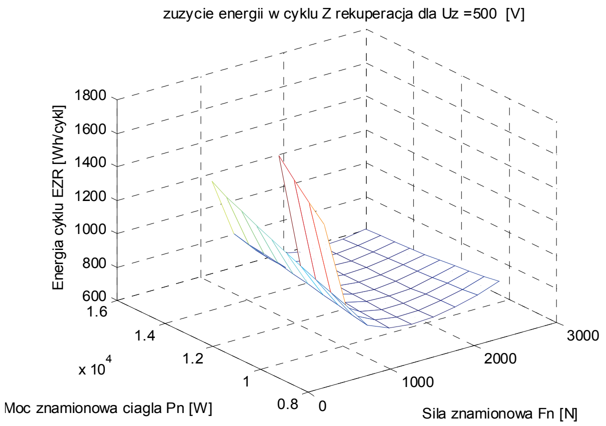

Fig. 13. Sample graphs of energy consumption function of a mixed drive with a constant value of nominal voltage *Uz* = 500 [V].

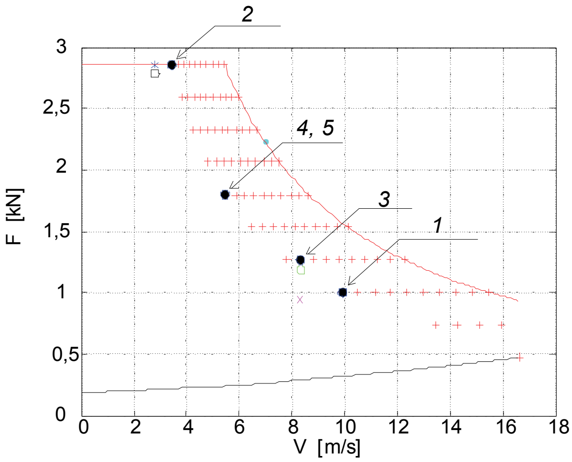

Fig. 14. Characteristics of the required maximum power and points of nominal work guaranteeing minimum energy consumption for the considered runs: 1 – ECE, 2 – entry and exit from garage, 3 – forceful drive, 4 – normal drive, 5 – mixed drive (ECE drive + entry and exit from garage + forceful drive + normal drive).

Summary

The article has presented methodology of determining basic technical parameters of a drive system of an electric-drive car on the basis of analyses of object model drive graphs for the assumed reliable traffic conditions. The methodology encompasses application of modeling, simulation and optimization techniques. It has been assumed that a solution criterion will be minimum energy consumption lost in the circuit with the vehicle driving over a given distance in accordance with a specified driving method. Variables in the task are the coordinates of the point within the area limited by short-term traction characteristics. On their basis, nominal parameters of the main devices of a drive (accumulator, converter and motor) are eventually calculated. Constant values in the task are parameters determining the driving methods and traffic conditions. In the method presented, there is a possibility of further development of optimization model by additional criteria, for example, construction cost of the drive or the weight of its devices.

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