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A Study of an Electric Drive of a Transport Vehicle with Simulation and Bench Testing of a Prototype

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Abstract
The paper presents the results of research, development, simulation and bench tests of electromechanical unit of the transmission of a transport vehicle with an individual drive of drive wheels aimed at applications in electric cars and cars with hybrid engines. Despite a large number of research and development works aimed at development of automobile transport vehicles (ATV) with traction electric drive (TED), theoretical and practical issues of efficient and high performance control systems for TED are not sufficiently developed so far. That situation is related to the fact that development of that kind of ATV is among the priorities for world car producers all over the world. The producers often do not disclose scientific information about their developed products, which complicates further development of TED for ATV. Thus, nowadays improvement of TED performance, including energy efficiency, is an important and topical scientific and engineering problem, which must be solved in order to develop competitive electric cars and cars with hybrid engines.

Keywords: Electric Drive, Wheelpair, Driver, Prototype, Motor, Transport Vehicle, Control System, The Generator, The Power Unit, Electric Vehicle.

Introduction

Nowadays, reasonable solution to ecological and economic problems of traditional cars is found, and it is the development of ATV with implementation of TED, technologies of control of drive motors of transport vehicles with mechanically independent drivers, which can move a vehicle jointly or independently. "Drive motor" is an electromechanical system, which is aimed at moving a transport vehicle and which consists of engine, electric drive, drive wheels and control system.

Aside from potential improvement of energy and ecology parameters, application of electric machines in drivers allows to develop and improve other performance characteristics, such as maneuverability, passability, active safety and comfort. The above-mentioned performance characteristics, as well as other performance characteristics, can be obtained by means of independent (mechanically independent) drive of drive wheels (DW) of a transport vehicle, which provides individual control of driving and braking force at each wheel. Development and application of such system is related to the solution of a number of problems, such as selection of an optimal structure and design of mechanically independent drivers of wheelpairs (WP), organization of effective control of drive motors-generators (DMG), as well as a function, which is similar to a car mechanical differential.

The review of design layouts and characteristics of mechanically independent drivers for transport vehicles allowed to carry out a comparative estimation of performance and operational characteristics, which defined efficiency of DW as a part of a transport vehicle, and to select and justify design of a prototype. At that, we estimated parameters such as controllability of DW, drive and dynamic characteristics, provision of maneuverability and passability of ATV, energy efficiency, reliability, manufacturing and project costs, weight, dimensions, etc.

Comparative analysis of characteristics allowed to recommend a variant of DW with two half shafts and mechanically independent drivers as a basic design layout; that design layout has the highest performance characteristics, as compared with other discussed variants of DW. Design layout of the mentioned DW is shown in Figure 1.

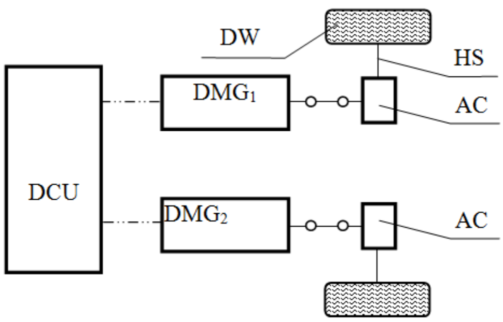


Figure 1: Design layout of WP with two half shafts, angle-change gearboxes and mechanically independent drives DCU – control unit of the drive; DMG – drive motor-generator; ACG – angle-change gearbox; MCD – mechanical coupling device of DMG and ACG; HS – half shaft; DW – drive wheels.

The accepted design solution of WP can be justified by the following advantages of the accepted variant:

- comparatively simple design;
- capability of independent control of driving and braking force at wheels in order to increase maneuverability of a transport vehicle, passability in adverse road conditions, as well as active safety;
- increase of maneuverability and controllability of a transport vehicle due to use of independent suspension;
- possibility to use WP components, which are already mass-produced.

At that, we also considered the following:

- comparative ease of engineering development with moderate material expenditures;
- possibility to decrease time of manufacturing of a prototype of WP;
- possibility to use a mass-produced chassis of a transport vehicle without its radical change;
- possibility of effective use of domestic research results and components;
- unification for a number of transport vehicles;

The main characteristics of the components of the prototype

Main parameters, which define drive and energy characteristics of WP of the selected design, are as follows:

- required driving force, torque of DW and torque at output shaft of ACG (for realization of city cycle);
- required rotary speed of DW and output shaft of ACG;
- required torque and rotary speed of DMG shaft and input shaft of ACG;
- moment of resistance at DMG shaft;
- maximum power at DW and output shaft of ACG;
- maximum power at input shaft of ACG;
- maximum consumed power of DMG and DCU;
- electricity expenditure of DCU in control cycle of ATV movement.

The values of main characteristics of components of the prototype of WP with mechanically independent drives were defined using driving and energy calculation of a basic transport vehicle.

Selection of DMG maximum power for WP drivers was carried out by value of maximum required power for movement of a basis ATV in city cycle. At that it was taken into consideration that characteristics of DCU prototype due to optimized control allow electric machine to provide torque, which is 2...3 times higher than nominal values from technical data provided by producers [1-2]; at that, maximum power of DMG can be two times higher than nominal values. That statement is proved by the presented experimental data.

The value of gear ratio of ACG [3] was selected considering the following conditions:

- gear ratios are to be maximally close to gear ratios of cars, which were the objects of the study (i=4.188; i=5.125);
- it must comply with standard values of gear ratios of ACG from standard values provided by producers;
- special development of ACG with non-standard values of gear ratios must be avoided.

ACG with i=5.0 met the aforementioned requirements.

Functionality of main components of the prototype

Motor-generator

Functionality:

- transformation of electric energy of the primary source into mechanical energy for the drive of drive wheels;
- transformation of mechanical energy of WP rotation into electric energy in braking generation mode.

In order to improve economic efficiency of the realized engineering solutions and to reduce expenditures for development of drive motor of special design, we used three-phase induction motor with squirrel-cage rotor of 5AMX132S4 type, which provided good electromechanical characteristics for realization of calculated parameters presented above.

Angle-change gearbox

Functionality:

- transformation of torque and rotary speed of a DMG shaft (decrease of rotary speed/increase of torque from DMG to WP);
- transfer of rotation between two shaft with perpendicular axes.

DMG-ACG coupling

Functionality:

- mechanical keyless coupling of DMG rotor and input shaft of ACG;
- compensation of minor misalignment of the connected shafts and elastic oscillations.

Flanged coupling

Functionality:

- mechanical keyless connection of output shaft of ACG with flange of the drive shaft;
- compensation of minor misalignment of the connected shafts and elastic oscillations.

Drive shaft of WP hub drive

Functionality:

- transfer of torque from ACG to WP hub at variable angle.

Depending on the features of a chassis of a transport vehicle, drive shafts on a basis of constant-velocity universal joint (CVUJ) can be used as components of WP instead of driveline.

Methodology

Figure 2 presents generalized design of AC TED on the basis of induction motor (IM). Control system of TED features circuits for direct control of torque and magnetic flux of a motor. If necessary it is possible to bypass external circuit for control of the speed of the motor.

Legend of Figure 2: SR – speed regulator (TED rotary speed); TDG – torque definition generator; TR – torque regulator; FLR – flux linkage regulator for stator (or rotor); FC – frequency converter; SD – surveying device; $\hat{M},\omega,\hat{\Psi}$ – current values of electromagnetic moment; angle revolution frequency of rotor and flux linkage of TED, M^*,ω^*,Ψ^* – their control values; U_d, I_d – output voltage, current of power supply source (PSS); $\mathbf{\Omega}_{\max}$ – vectors of acceptable values of voltages, currents and flux linkages in the system; $\mathbf{u}_s, \mathbf{i}_s$ – vectors of current values of voltage and current of TED stator; $\mathbf{U}_s^*$ – vector of control values of current for FC; $\hat{\mathbf{\Theta}}$ – assessed parameters of TED; M_C – moment of resistance to TED motion reduced to rotor of TED. There and in further values marked with bold font are vectors and matrices; for upper indexes, "^" – values evaluated by the model of TED by surveying devices; "*" –control values for control system; for lower indexes "max" and "min" – maximum and minimum values of corresponding values.

"Optimizer" unit is aimed for formation of the set values of flux linkages Ψ^* on the basis of TED by the desired criterion of optimality on the basis of the current frequency ω and setting of moment M^*, taking into account all restrictions on resources of power units in the system $\mathbf{\Omega}_{\max}$.

System of direction control of AC TED moment

Regulating capabilities of modern AC TED are similar to DC TED due to use of advanced methods of frequency control of AC electric machines; in particular, in of those methods called method of direct moment control (DMC) [4] became widely spread in the last decade. As compared to classical vector control systems of TED, DMC systems have the following advantages [5-6]:

- simple realization due to absence of coordinates transformation operations stationary system to rotating system (and backwards), absence of pulse-length modulator (PLM) of voltage and regulators of projection of current vector of stator;
- high dynamics of circuits of regulation of flux linkage of stator (SFL) and moment due to application of hysteresis regulators and table of optimum values of keys for FC.

However, application of relay regulators is the cause of the biggest disadvantage of the DMC systems: speed of switching of power keys, which depends on width of hysteresis curves of regulators is not constant, which leads to increase of -commutation loses in FC, increased pulsation of IM moment as compared to the vector control method. That disadvantage can be avoided by means avoiding use of relay regulators during use of PLM of output voltage of FC instead of table of optimal switching [7-12].In further IM control systems, which are built according to that principle will be referred as "direct moment control with PLM" systems (DMC-PLM).

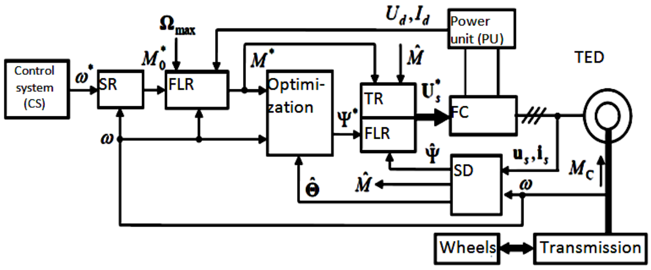


Figure 2: Generalized functional layout of TED control system on the basis of IM and CVUJ

The paper presents the control system of IM moment, which is realized in stationary coordinate system with linear regulators of moment and flux linkage of stator (FLS), which allows to simplify design of the electric drive control system, and provide high dynamic quality characteristic to PLM systems.

The basis for DMC-PLM system is mathematical model of IM in orthogonal stationary coordinate system (α,β), connected with stator; the model is derived from mathematical model of generalized electrical machine [13]:

$$\begin{cases} p\Psi_{s\alpha} = -R_s i_{s\alpha} + u_{s\alpha}; \\ p\Psi_{s\beta} = -R_s i_{s\beta} + u_{s\beta}; \end{cases} \quad (1)$$

$$\begin{cases} pi_{s\alpha} = -\dfrac{i_{s\alpha}}{T_0} - \omega_r i_{s\beta} + \dfrac{\Psi_{s\alpha}}{L_\sigma T_r} + \dfrac{\omega_r \Psi_{s\beta}}{L_\sigma} + \dfrac{u_{s\alpha}}{L_\sigma}; \\ pi_{s\beta} = \omega_r i_{s\alpha} - \dfrac{i_{s\beta}}{T_0} - \dfrac{\omega_r \Psi_{s\alpha}}{L_\sigma} + \dfrac{\Psi_{s\beta}}{L_\sigma T_r} + \dfrac{u_{s\beta}}{L_\sigma}; \end{cases} \quad (2)$$

$$M = 1.5 z_p (\Psi_{s\alpha} i_{s\beta} - \Psi_{s\beta} i_{s\alpha}). \quad (3)$$

where R, L – active resistance and inductance; indexes "s,r,m" correspond to values of stator, rotor and magnetization circuit; ω_r – electric angle rotation frequency of rotor; z_p – number of pairs of poles; M– electromagnetic moment; $\sigma = 1 - \dfrac{L_m^2}{L_s L_r}$ – coefficient of dissipation of IM magnetic field; $L_\sigma = \sigma L_s T_r = \dfrac{L_r}{R_r \tau_s} = \sigma T_r$ $\tau_s = L_\sigma / R_s$ – time constants of rotor and stator circuits; $T_0 = (1/\tau_s + 1/\tau_r)^{-1}$.

Differentiation of (5) gives the equation, which describes dynamics of change of moment of control voltage:

$$pM = -M/T_0 + k_M U + k_M W_1, \quad (4)$$

where U, W_1 – control and perturbation actions of moment regulation circuit;

$$U = u_{s\beta}\Psi_{s\alpha} - u_{s\alpha}\Psi_{s\beta}; \quad (5)$$

$W_1 = \omega_r L_\sigma (\Psi_{s\alpha} i_{s\alpha} + \Psi_{s\beta} i_{s\beta}) - \omega_r \Psi_s^2 - z_p Q / k_M$, $Q = 1.5(u_{s\beta} i_{s\alpha} - u_{s\alpha} i_{s\beta})$ – reactive power; $k_M = 1.5 z_p / L_\sigma$.

After multiplication of the first equation of the system (3) on value $\Psi_{s\alpha}$, second equation on $\Psi_{s\beta}$ and their addition, we obtain the following:

$$(1/2)p\Psi_s^2 = V + W_2, \quad (6)$$

where V, W_2 – control and perturbation actions of SFL circuit;

$$V = u_{s\alpha}\Psi_{s\alpha} + u_{s\beta}\Psi_{s\beta}; \quad (7)$$

$$W_2 = -R_s(\Psi_{s\alpha}i_{s\alpha} + \Psi_{s\beta}i_{s\beta}). \quad (8)$$

The derived equations (6), (8) allow to propose structural layout of control circuits of FLS and moment, which is presented in Figure 3. FC is characterized by single transmission coefficient by voltage and frequent delay by time T_μ, which is equal to the period of modulation signal.

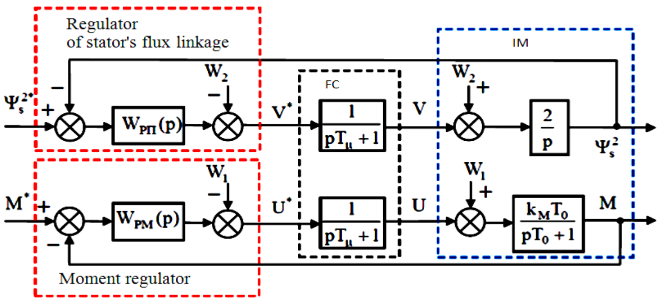


Figure 3: Structural layout of closed circuits of regulation of flux linkage of stator and IM moment

Transfer functions of an object (IM-FC) through circuits of SFL and moment has the following form:

$$W_\Psi(p) = \frac{\Psi_s^2(p)}{V^*(p)} = \frac{2}{p(T_\mu p + 1)};$$

$$W_M(p) = \frac{M(p)}{U^*(p)} = \frac{k_M T_0}{(T_0 p + 1)(T_\mu p + 1)}. \quad (9)$$

Figure 4 presents functional layout of induction drive with DMC-PLM in stationary coordinate system connected with stator. At output of regulators of moment and SFL control signals are formed U^*, V^*, which allow to define control voltages $u^*_{s\alpha}, u^*_{s\beta}$ for creation of PLM algorithm during solution of (7) and (9):

$$u^*_{s\alpha} = \frac{V^*\hat{\Psi}_{s\alpha} - U^*\hat{\Psi}_{s\beta}}{\hat{\Psi}_s^2}; u^*_{s\beta} = \frac{U^*\hat{\Psi}_{s\alpha} + V^*\hat{\Psi}_{s\beta}}{\hat{\Psi}_s^2}. \quad (10)$$

Current values of moment and SFL are calculated via currents and voltages of stator, at that, the latter are defined via voltage of DC circuit U_d and algorithm of PLM operation. Basics equations for assessment of the aforementioned values are (3) and (5).

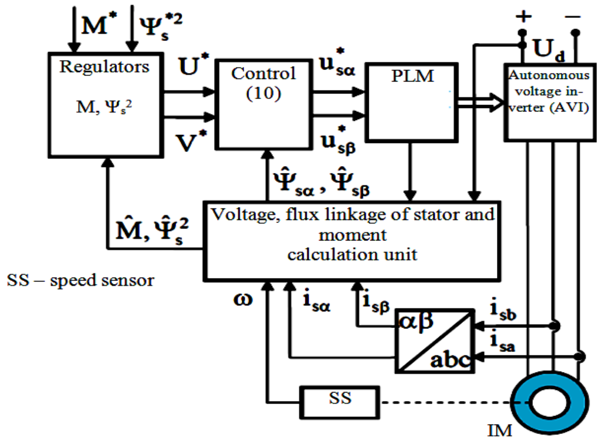


Figure 4: Functional layout of induction electric drive with DMC

In unit of coordinate transformations $(abc - \alpha\beta)$ components $i_{s\alpha}, i_{s\beta}$ of stator current vector are calculated on the basis of phase currents i_{sa}, i_{sb}:

$$i_{s\alpha} = i_{sa}; i_{s\beta} = (i_{sa} + 2i_{sb})/\sqrt{3}.$$

It is worth mentioning that in the presented control system of IM we used only simple calculations (addition, subtraction, multiplication and division). It allows to use cheap microprocessors in the control system of TED.

For the comparison of characteristics and energy parameters of the electric drive with the designed DMC-PLM method and traditional PLM method with hysteresis regulators of moment and FLS we carried out the imitation simulation of movement of the electric drive on the basis of IM of type with power supply from 520 V accumulator battery (Figures 5 and 6).

Figures 5 and 6 present time diagrams of IM moment (M), its control value (M*), speed (N), modulus of FLS vector (Ψ_s, Ψ_s^*), phase current (I_{sa}) and current of accumulator battery.

Results

Despite the simple design, the proposed scheme of IM PLM guarantees sustainability of the control system, high dynamics of the electric drive and high accuracy of surveying of control values of moment with its low pulsations. With aim of comparison of energy parameters of TED for various methods of control let us introduce parameter of specific expenditure of power source energy w_a (in the discussed case – traction accumulator battery (TAB)) for a cycle of movement of the electric drive:

$$w_a = \frac{E_a}{\varphi},$$

where $\varphi = \int_0^{T_c} \omega dt$ – is total mechanical angle of rotation of the rotor of the engine, which is equivalent to distance covered by TED during carrying out transport work during drive cycle;

$E_a = \int_0^{T_c} P_a dt$ – energy used by TAB during total time of movement of TED during drive cycle T_c, which includes phases of acceleration, coasting and braking.

The results of the simulation of main energy parameters are presented in Table 1.

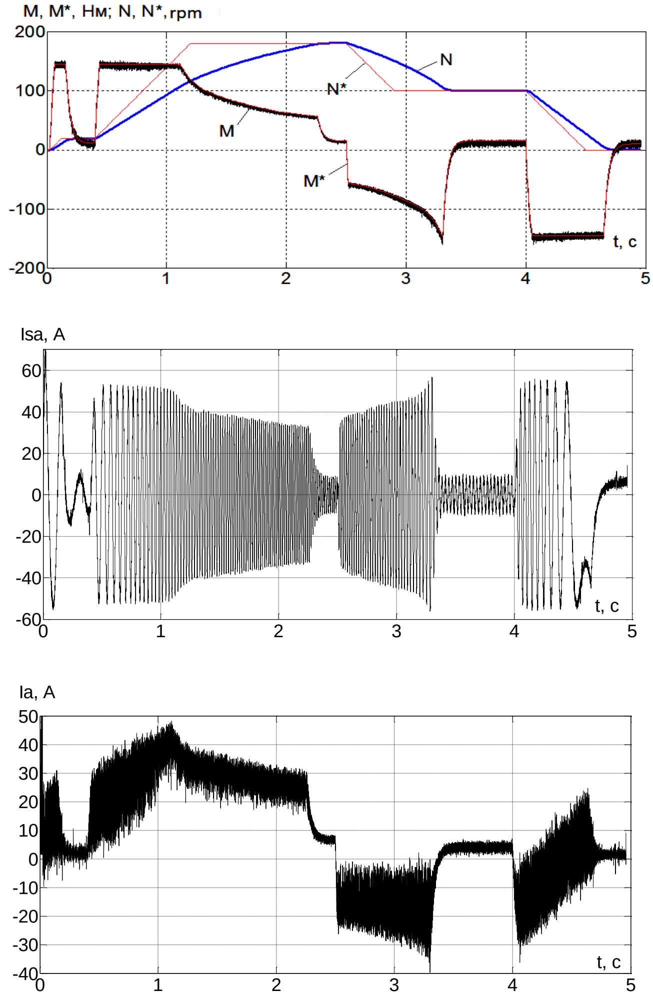
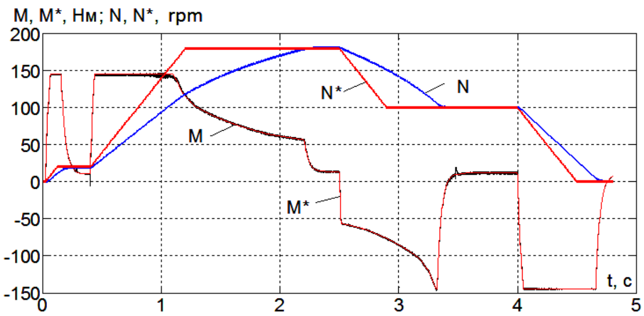


Figure 5: IM characteristics with traditional PLM



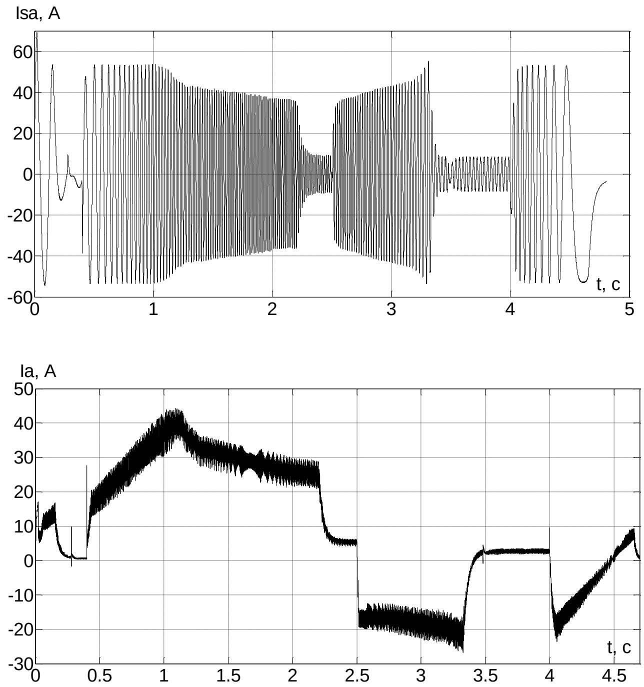


Figure 6: IM characteristics with DMC-PLM

Table 1: Main energy parameters of TED with various methods of control

Method of control	Parameters				
	E_1	E_a	φ	E_1/φ	E_a/φ
	J		radian	J/Radian	
PLM with hysteresis regulators	21021	22191	516.2	40.72	42.99
DMC-PLM	19285	20359	516.2	37.36	39.44

The analysis of the data from the Table 1 shows that there is advantage of energy parameters of the proposed DMC-PLM method as compared to traditional PLM method.

Control of DMG as part of the prototype of WP is realized in form of the unified DCU. DCU is the device, which carries out transformation of electric energy from primary source and automatic realization of optimized control of DMG in movement and generator modes by setting of the system controller of WP of ATV.

Selection of direction of development and engineering solution in the part of the prototype of DCU are based on the number of control parameters, which define high efficiency of the drive of the driver of the WP driver of ATV, including the following:

- drive parameters, which are sufficient for realization of the required dynamic parameters of ATV;
- provision of drive and energy characteristics in the range of change of voltages of primary source of electric energy;
- efficiency of use of energy by drive of driver during control (specified) cycle of motion of ATV;
- efficiency of regenerative braking, which is realized by DMG in generator mode, and decrease of load on

device of mechanical (hydraulic) braking of ATV;
- weight and volume of DCU functional blocks of WP, their design adaptation to forms and dimensions of vacant spaces in standard structure of ATV body and cab;
- reliability and long service life of DCU of WP;
- safety in operation;
- comparative cost of production and operation of DCU of WP.

Structural layout of DCU are presented in Figure 7, where
BR – braking rheostat;
PCU – power commutation unit;
APS – auxiliary power source;
DCI – DC inverter;
SPT – set of power voltage transformers;
ACU – automatic control unit;
OCP – operating control panel.

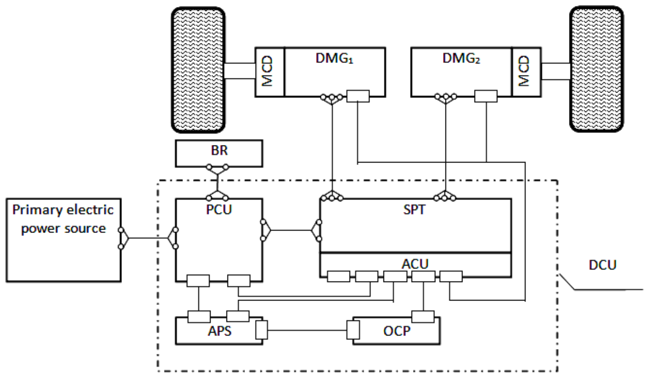


Figure 7: Structural layout of functional components of DCU prototype

The components of the system are grouped according to the structural layout into minimal number of functional units, which provides the following advantages:
- possibility of independent manufacturing, adjustment of structurally finished large units, their installation in the systems and complex tests on testing bench and ATV;
- organization of maintenance and repair by means of target automated diagnosis and operative replacement of failed functional units for operational units with the following repair using the specialized companies;
- decrease of labor and material expenditures for production and operation of DCU.

The key part of DCU, which directly carries out automated control of drive DMG and control of condition of DCU components, is DCI.
DCI can be designed in a form of a single unit, in which voltage transformers for two DMG of WP are hybrid, and in the form of separate units – one DCI for each DMG of WP; the latter variant was implemented in DCU prototype. The accepted variant of DCI design is justified by the reason of optimal positioning of DCU components on ATV.
Testing of prototypes of WP and DCU as a part of WP was carried out using the specially designed testing bench, which included the following components: loading devices, control devices, instruments and registration equipment. It is worth mentioning, that energy source during testing was three-phase power network with the following transformation of AC into DC, which was used for power supply of DCU. Imitation of loading of traction electric drives-generators of WP was carried out using controllable DC loading device. The composition of functional electric layout of the testing bench for experimental studies is presented in Figure 8.

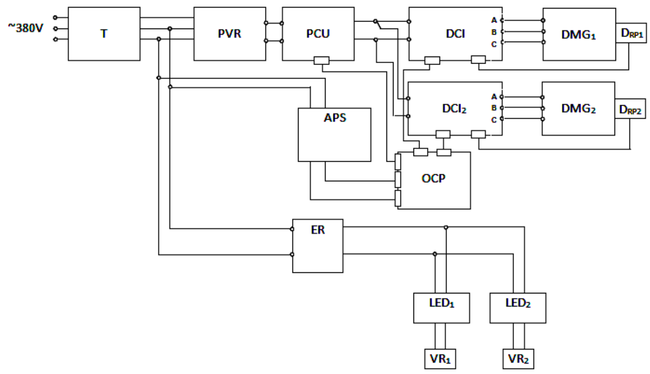


Figure 8: Functional electric layout of the testing bench for experimental studies of WP and DCU, where: T – controlled transformer; PVR– power voltage rectifier; PCU – power commutation unit; APS – auxiliary power source; DCI – DC inverter; OCP – operating control panel; DMG – drive motor-generator; ER – excitation regulator of LED; LED – loading electric device; VR – voltage regulator of LED; D_{RP} – rotor position sensor.

During testing of prototypes we obtained the following results:
- Relationships between control signal (task) of OCP and external effects.
- Relationships between output signals of feedback sensors (FS) by voltage (D_U), current (D_I) and rotation frequency (D_f) from external actions.
- Characteristics of carrying out of operative functions by PCU.
- Results of registration and evaluation of output voltage U_f and I_f of DCI phases.
- Characteristics of drivers of WP are defined, including:
- relationship of torque of DMG to frequency f_2 for constant (set) values I_f in range $I_{f\ nom.} \leq I_f \leq 3I_{f\ nom.}$ (Figure 9) in order to establish relationship of f_2 frequency from I_f value for maximum values of $_{MD}$ = M_{max}, which define optimum relationship between M_D and I_f (Figure 10).
- mechanical characteristics of DMG and WP are established (Figures 11 and 12). At that, we defined the range of adjustment of mechanical characteristic of DMG $M_D(n)$ and WP at optimal relationship M_D (I_f) in the range of frequency of rotation of rotor of DMG $0 \leq n \leq 1430$ rpm and maximum DMG moments (M_{Dmax}=196 N·m; M_{WPmax}=1900 N·M);
- possibility to realize smooth adjustment of torque in

range of change of rotation frequency of DMG rotor $0 \leq n_D \leq 2900$ rpm and DW $0 \leq n_{VK} \leq 580$ rpm was proved.

- Results of registration and evaluation of quality of transition processes in the system DCI-DMG during carrying out of task in mode of operation of the electric drive according to standardized ATV movement chart (Figure 13), including:
- sustainable (without overcontrol) reaching of the specified value I_f by signal from OCP;
- maintaining of the specified I_f in acceleration mode;
- transfer to specified I_f in the mode, which corresponds to the coasting of DMG;
- transition of DMG to generator (regenerative) braking.
- decrease of I_f to I_f=0 at stop of ATV;
- reverse of DMG shaft rotation at realization of backwards movement of ATV.

The main results of the experiments are presented in Figures 9-13.

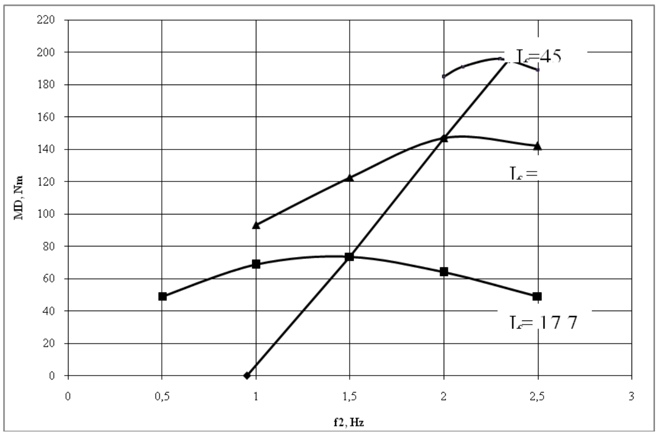


Figure 9: Relationship between torque of DMG and f_2 frequency with constant values of I_f

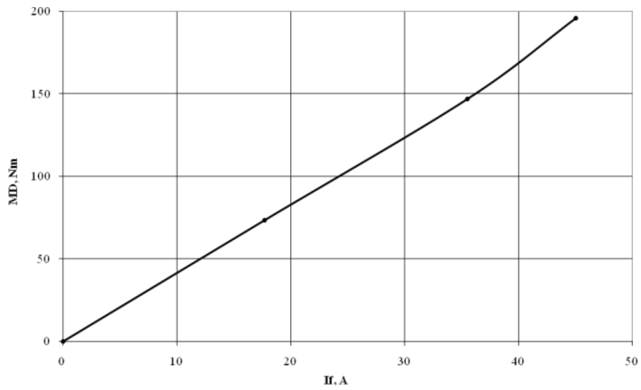


Figure 10: Optimal relationship between torque of DMG of driver of WP and phase current

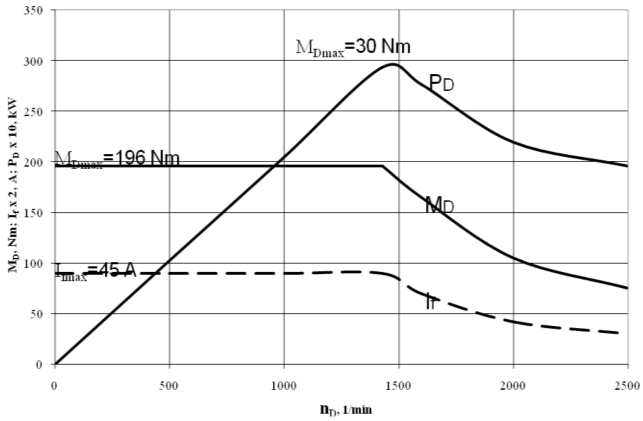


Figure 11: Relationship between moment, shaft power and phase current of DMG of WP driver and the frequency of rotation of the rotor

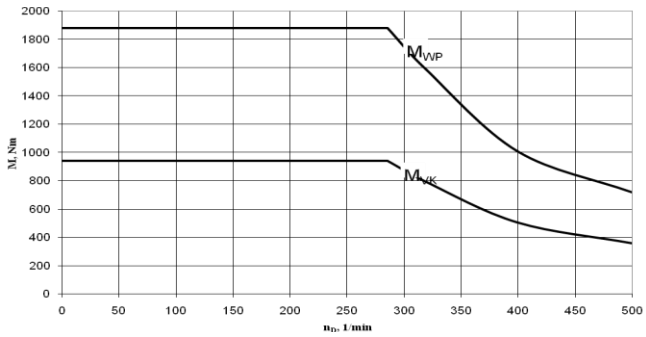


Figure 12: Relationship between moment at DW M_{VK} and total moment MWP of WP and frequency of rotation of DW

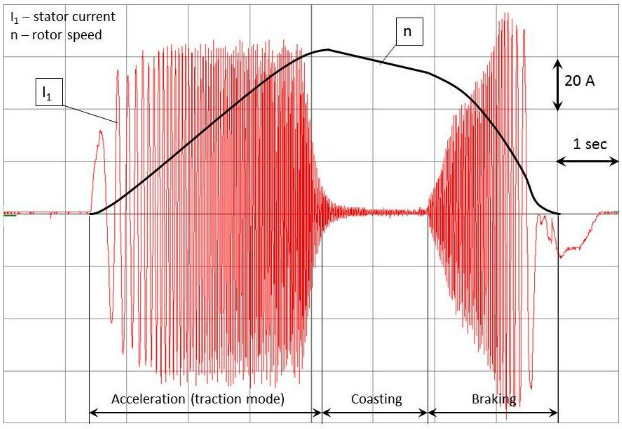


Figure 13: Change of phase current and frequency of rotor rotation of DMG with alternation of modes of WP prototype: acceleration-coasting-braking

Discussion

The development of regulators of the proposed design DMC-PLM is based on differential equations of first order, which describe analytical relationships between dynamics of change of moment, FLS and control voltage. It allows to use standard methods of setting up of regulators during design of the electric drive (by engineering optimum criteria and by symmetrical optimum criteria), which allows to reduce time of development and adjustment of the electric drive control system.

The proposed system of DMC IM features simple design and high performance of TED (high speed, low moment pulsations), which is important for applications in automobile transport field.

The obtained characteristics of experimental specimens, including obtained values of the equivalent maximum speed of WP and DCU – 50 kW and maximum achieved moment of WP – 1900 N·m allow to use the latter as components of forward and rear axle of ATV (electric cars and cars with hybrid engines) with total weight up to 3.5 ton.

Engineering solutions and manufactured prototypes of WP and DCU has the following features:

- small sizes;
- possibility to apply them as components of forward and rear axle of ATV (electric cars or cars with hybrid engines) with total weight up to 3.5 tons, which is provided by the achieved values of equivalent maximum power of WP and DCU of 60 kW and maximum moment of 1900 N·m.
- possibility of rational placement of components of WP and DCU as parts of chassis of mass-produced ATV;
- possibility of individual control of torque and frequency of rotation of each driver of WP, including with aim to increase maneuverability and passability on adverse road conditions, as well as for active safety pf ATV;
- application of non-contact non-maintenance DC machines as DMG of drivers of WP;
- use of high performance low-maintenance ACG as components of the prototype of WP;
- efficient transformation and transfer of torque, as well as low values of acoustic noise emission during operation of mechanical parts;
- optimized weight and dimension of WP components (including DMG and ACG) and DCU.

Conclusion

In the presented research and development work we manufactured and tested unified electromechanical unit of transmission of ATV, which included prototypes and DCU, which provided a number of high traction and dynamics characteristics, increased maneuverability, active safety and decreased power consumption.

The obtained results of theoretical and experimental studies may be used for carrying out works related to the development of prospective transport vehicles, such as electric cars and cars with hybrid engines.

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