Schematics and design of traction converters and control algorithms of traction electric drives

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INTRODUCTION

Recently there can be seen a wide introduction of electro-mechanical drivetrains (EMD) in various vehicles: passenger and commercial cars, buses and coaches, wheeled and tracked agricultural and industrial tractors, road-building and forestry machinery etc. While before it was reasonable to use an EMD in high-power vehicles (locomotives, haul trucks), now the development of power and control electronics, electric machines has allowed to widespread the range of vehicles with an EMD toward lower powers.

To provide competitive advantages of an EMB over other types of drivetrains (mechanical, hydro-mechanical), high requirements are demanded from characteristics of all the components of traction electric equipment sets (TEES). For instance, according to the US Department of Energy (DoE) in 2015 electric machines (EM) in the TEES' structure of an EMD should have parameters above 1.3 kW/kg, 5 kW/l and should cost less than 7 $/kV; power converters should parameters above 12 kW/kg; 12 kW/l and cost below 5 $/kW. Efficiency of power converters (PCv) + EM should be more than 93%.

Russian electric corporation RUSELPROM has recently developed complete TEES for EMD of various vehicles, including all TEES' components – electric generators and traction motors, power converters (PCvs) for their control, microcontrollers for all the TEES components (PCvs and others, including an internal combustion engine (ICE)), auxiliary power systems and cooling systems (CSs).

The present paper will describe some schemes and designs of the developed integrated intelligent DC/AC PCvs for control of the motor - generators (MG) and traction motors (TM), frequency and vector control algorithms applied in microcontrollers of these converters. The paper will show results of benchmark and field trials of TEES of EMDs of various vehicles.

SCHEMATICS AND DESIGN OF POWER CONVERTERS FOR TRACTION ELECTRIC DRIVE

In the Figure 1 there is given a generalized block diagram of the complete TEES for an EMD of a vehicle with the wheel formula 4x4 with individual motor-wheels.

For control of the MG in the generating mode (traction) and motoring mode (ICE starting and compression braking by means of the diesel) there is used a bi-directional voltage-source invertor. This PCv (MG PCv) should provide regulation of voltage and power at the DC-bus, allowing optimum loading of the diesel and its operation in a maximum fuel efficiency mode within all operating modes of the vehicle. Also it should provide regulation of speed and torque at the MG output in the motoring mode to guaranty an optimum diesel starting and compression braking by the diesel.

For control of each traction motor there are applied four-quadrant voltage-source inverters. These PCvs (TM PCvs) should provide regulation of speed and torque at the output of traction motors according to the setup signals from the vehicle's controls taking into account an available power of the diesel which can be directed for traction. Also they should provide an inverse recuperation of the braking energy from traction motors to the DC-bus.

For the today's level of development of power electronics the best solution for such PCvs are IGBT-based DC/AC converters.

Considering the highest requirements to the TEES components in reliability, compactness, efficiency, service conditions, such PCvs should have:

- full-bridge configuration of the power circuit of an inverter with modern IGBT / SFRD devices;

- intelligent schemes of drivers for control of all power switches with built-in of protections from over-currents, overvoltages, overheat, and excessive drop of feeding voltage;

- built-in sensors of power switches' temperature, output currents, DC-bus voltage, source voltage;

- low-inductance DC-bus with the film filter capacitor;

- effective cooling system of power devices and the DC-bus filter capacitor;

- noise-resistant communication channels from drivers to the operating microcontroller.

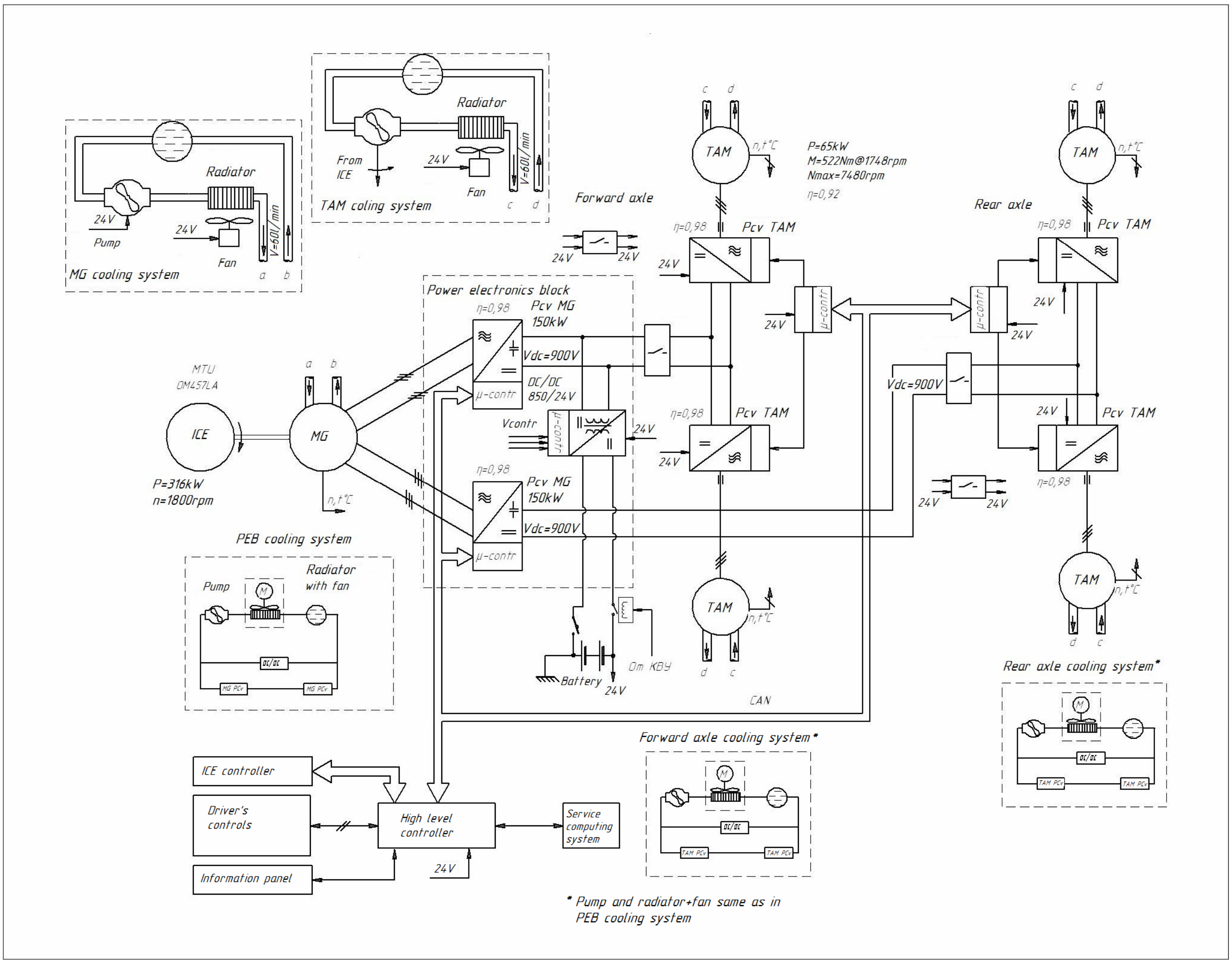

Figure 1. Block diagram of the TEES of an EMD for 4x4 vehicle.

All circuitry and the utilized electric- and radio-components, and the PCv design should provide uninterruptable operation in a wide range of ambient temperatures (usually from –40 to +55ºC), and mechanical influences of operational conditions of the vehicle.

One of possible decisions of such PCvs is application of integrated intelligent power converters of the leading world manufacturers specially developed by them for transport applications.

The most vivid example of such PCvs are Semikron modules – SKAI1, SKAI2 which functional block diagrams are shown in Figure 2, and outlooks are given in the Figure 3.

Modules can be delivered with built-in DSP microcontroller.

Modules provide operation with DC-bus voltage up to 900V, continuous output current 300A, 400A is peak (to 20 sec).

With the integrated liquid cooling (antifreeze or oil) modules have impressive specific parameters:

- specific power above 25 kW/kg;

- specific volumetric power above 20 kW/l;

- efficiency above 98 %.

The design of modules provides a class of protection IP54 for SKAI1 and IP67 for SKAI2.

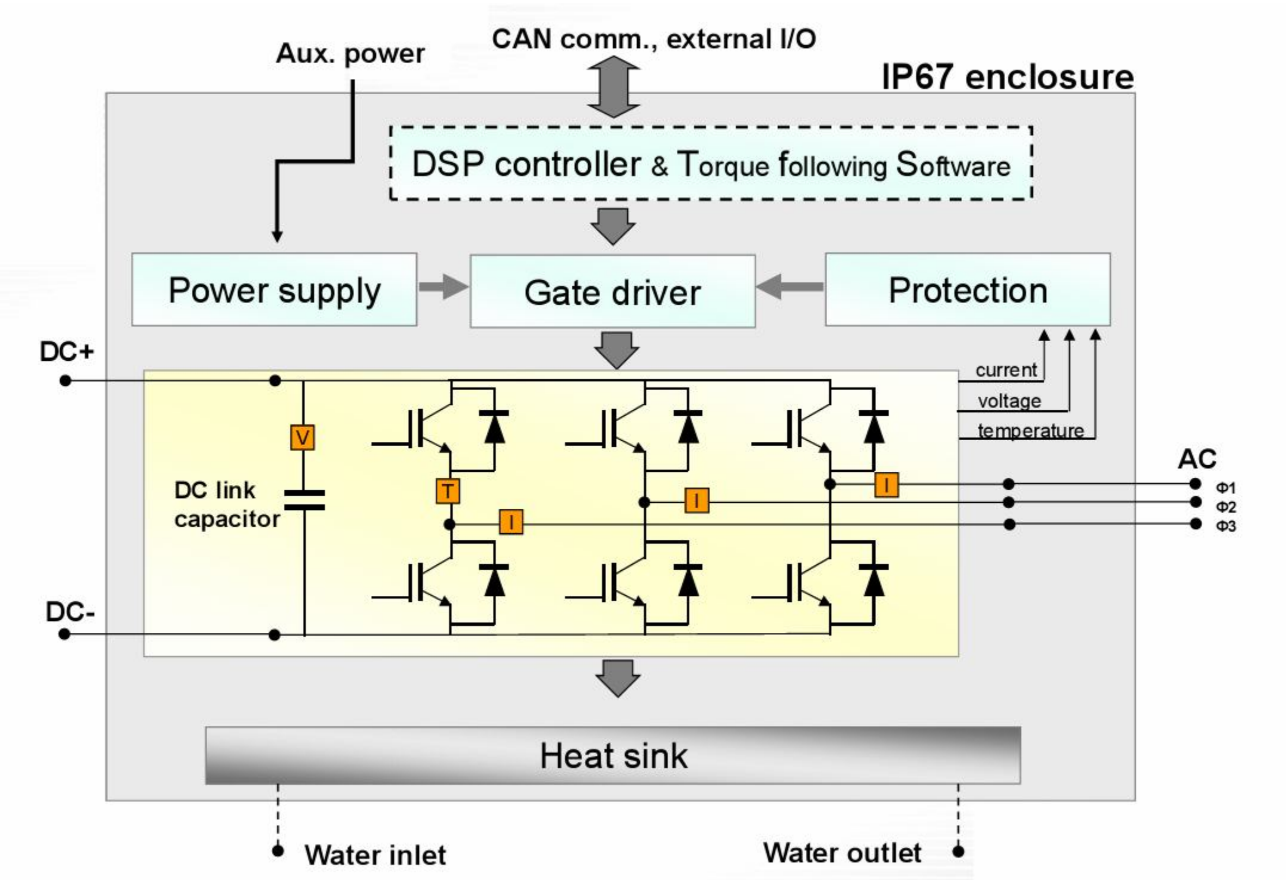

Figure 2. Functional block diagrams of modules SKAI1 (SKAI2).

Figure 3. Outlooks of modules SKAI1 (left) and SKAI2 (right).

Modules with additional TEES components – operation microcontroller, pre-charge circuit, sensor of a leakage current, auxiliary power supply circuits and elements of the liquid cooling system are mounted into the power electronics block (PEB). One of examples of the PEB with a protection class IP67 is represented in the Figure 4.

Similar compact intelligent power converters with the integrated liquid cooling produce various companies:

- ARENS (POWERPAC);
- BAE SYSTEMS (PCS);
- TM4 (C0300HV);
- BRUSA Elektronik (DVC5x7);
- UQM (Power Phase HD);
- Zytek (250kW Inverter);
- STW (Power MELA Inverter);
- SEVCON (Gen4)
- Kollektor (MC 2230/400).

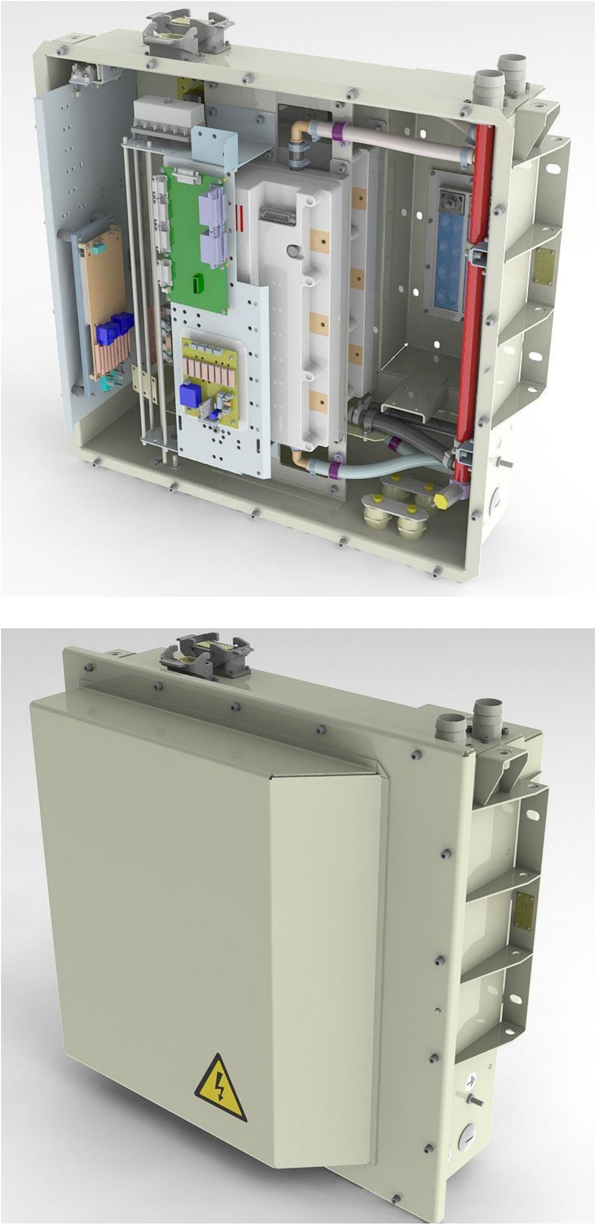

Figure 4. PEB with SKAI1.

Characteristics and description of designs of these PCvs, their application examples in certain vehicles will be given in the report presentation.

Semikron modules SKAI1 and SKAI2 have been used in projects of TEES of a wheeled agricultural tractor “Belarus-3023” with power class 300 h.p. [1–3] and city 12-m hybrid buses with diesel ICE of 180–250 h.p. class: “LiAZ-5292” (from Likino Bus Works), “Vitovt” (from Belkommunmash), “A5072” (from Bogdan) and “Sitiritm” (from Volgabus) [4-6].

For expansion of functionality of power electronics blocks with several PCvs which parameters were defined by results of operational trials of tractors and hybrid buses and which could not be realized by the serially produced modules SKAI, RUSELPROM–ElectricDrive Ltd. have developed original circuitry and designs of PEBs with power IGBT modules of several manufacturers.

Figure 5 shows the design of the PEB for TEES of the tractor "Belarus-3023" built on the base of power IGBT-modules SKiM93 and identical by its dimensions and connecting sizes to the PEB shown in the Figure. 4. PEB specific power is above 5 kW/kg.

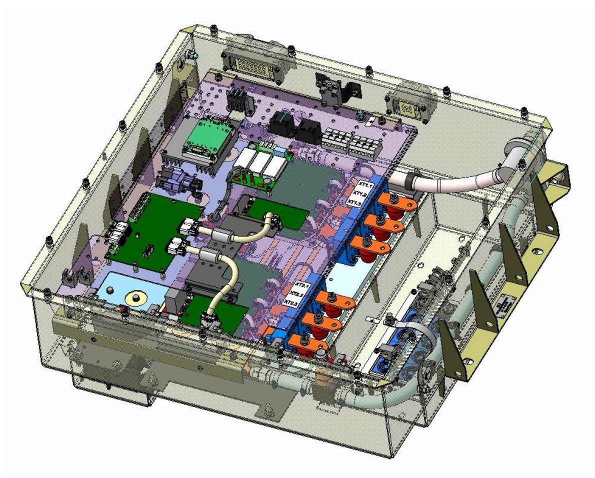

Figure 5. Power electronics block with SKiM93.

Design of the SKAI2-based PEB for the TEES of a hybrid bus is shown in the Figure 6. Its specific power is 5 kW/kg

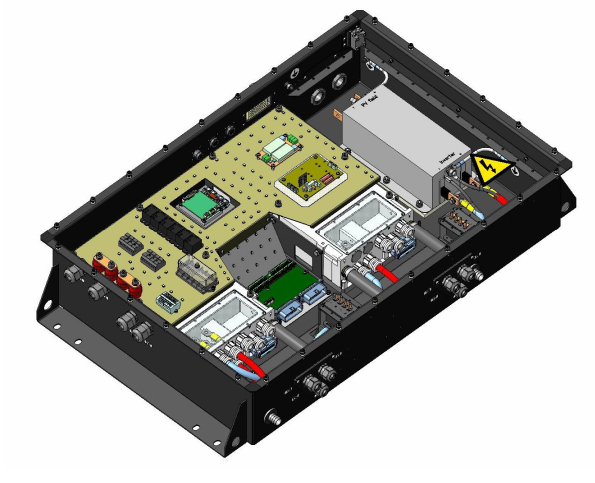

Figure 6. SKAI2-based PEB for the TEES of a hybrid bus.

Another example of PEB is a PEB using modules T-PM J-Series from Mitsubishi. Unique parameters and a design of these modules used earlier in 650V-class modules for the TEES of hybrid car Prius, allow to create the highly reliable compact PCv with an output current 150/200A, DC-bus voltage up to 900V. In the Figure 7 there are given T-PM J-Series module function block diagram and its outlook, and in the Figure 8 there is shown a simplified assembly scheme of an inverter bridge with such modules.

The general structure and functional block diagram of PEB based on modules T-PM J-Series is similar to these shown in the Figure 2.

With the same parameters (150/200A, 900V) there is developed a PCv with IGBT-modules SKiM63 from Semikron. The PCv's structure includes also a driver plate on the basis of SKYPER 42-LJR, three sensors of an output current, a DC-bus voltage sensor, low-inductance (about 9 nHn) laminar DC-bus with the film filter capacitor. Drivers provide a protection from DC-bus overvoltages, auxiliary voltage drop, overcurrent, overtemperatures of power switches (there is used temperature sensors of module SKiM63) with a soft short-circuit shut-down. There is also applied an active clumping circuit that has allowed, along with the design of the DC-bus, to use 1200V-class IGBT devices with a voltage on the DC-bus up to 900V.

Liquid cooling is applied in both PCvs (with T-PM J-Series and SKiM63 modules).

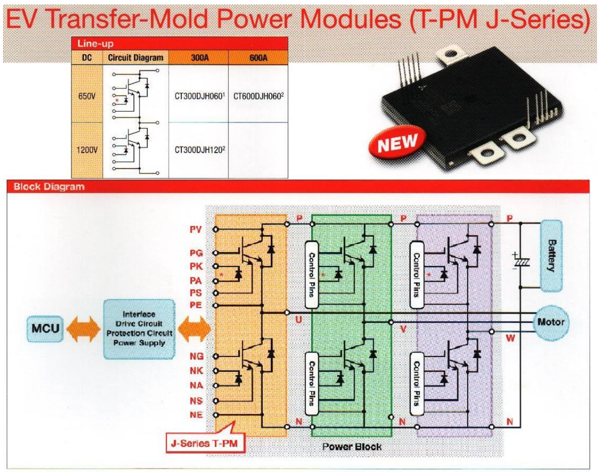

Figure 7. Parameters, outlook and functional block diagram of T-PM J-Series modules.

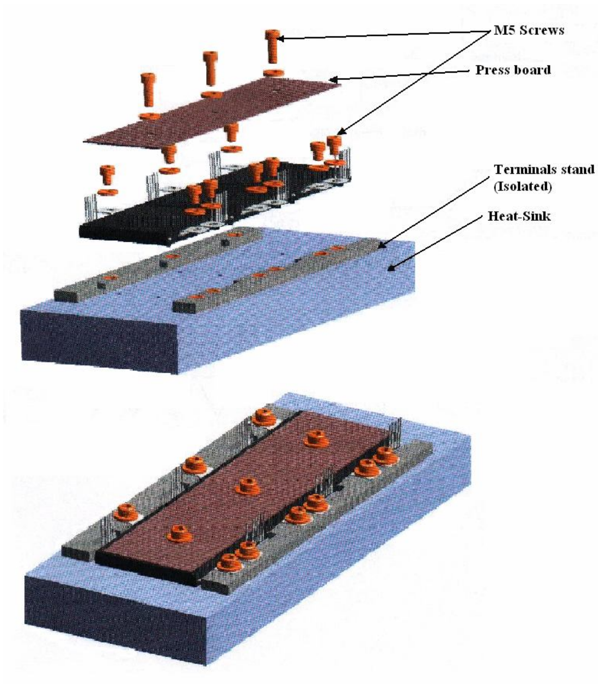

Figure 8. Simplified assembly scheme of an inverter bridge with T-PM J-Series modules.

CONTROL ALGORITHMS OF TRACTION ELECTRIC DRIVES

One of the basic requirements to TEES of an EMD is the greatest possible efficiency in the required speed range, frequently – in the overall vehicle's speed range. Along with requirements for high EM and PCv efficiency it also imposes special requirements to control algorithms of PCvs in traction electric drives.

Minimization of weight and dimensions of the electric machines on the board a vehicle, operating conditions of traction drives and the requirement of their optimization in terms of minimum losses (characteristic for traction drives) lead to relatively wide range of variation of EM parameters: mutual inductance L_m, active stator R_s and rotor R_r resistance, rotor time constant T_r.

Algorithms of loss optimization applied in vector systems, namely: optimization at equal magnitudes of magnetizing and active currents I_d=| I_q | (according to the Park's equations with I_s=*min*) are essentially worse than a real optimization by the criterion of a minimum losses (maximum efficiency). It is especially clear at high frequencies and rather low loads where losses are considerably higher in steel than in windings.

In [7] there are described vector control algorithms with optimization of efficiency in wide ranges of power and speed, with identification of parameters of traction asynchronous machines (AM) and with adjustment of an equivalent circuit to the varying parameters. Algorithms are realized in the PCvs' microcontroller of the PEBs from the TEES of the tractor "Belarus-3023" and TEES of hybrid buses.

On the Figure 9 there are given experimentally gained benchmark traction characteristics of TEES of a tractor "Belarus-3023". It is clear that total EMD efficiency (from MG shaft to the asynchronous TM shaft) is 87% practically in the whole range of speeds of the traction drive.

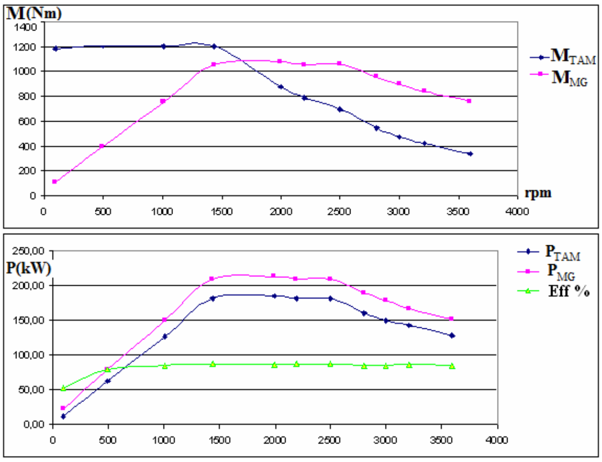

Figure 9. Traction characteristics of the TEES.

Application of vector control algorithms in traction electric drives with asynchronous MG and TM in vehicles with an EMD compared with frequency control systems, has a set of distinctive advantages, namely:

• High operation speed and dynamic accuracy of current, torque, and voltage regulation. Typical values of time constants of regulation of these variables in vector control system lay from tens μsec to several msec. For comparison: in frequency drives of tens-hundreds kW class time constants of regulation of these variables are measured in seconds and are defined by rather high rotor time constant.

• Higher quality indicators practically in all the basic operating modes of a vehicle: start, acceleration, braking, positioning, low-speed movement and others.

• More simple coordination of dynamics of an ICE (ICE in vehicles with EMD or in hybrid vehicles), and drives with MG and TM.

• Availability of minimization of capacitor on the DC-bus.

• More comprehensive utilization of resources of inverter's power switches and higher stability and reliability of drive's operation due to more effective control of phase currents and DC-bus voltage in transient modes; possibility of maximum approach of peak current to the level of overcurrent protection.

There is also realized a "classical" algorithm of vector control submitted by Texas Instruments for 28xx series of DSP microcontrollers. The algorithm's block diagram is presented in the Figure 10.

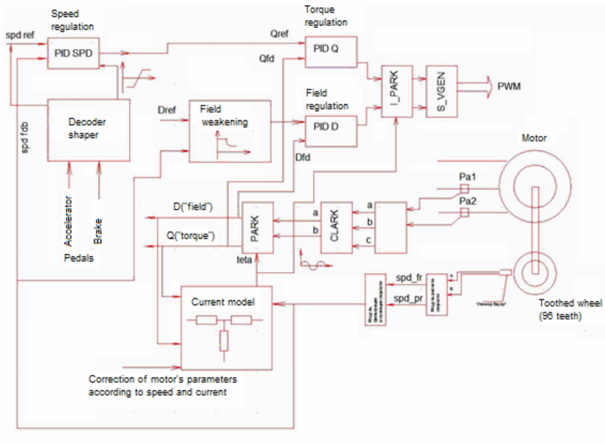

Figure 10. Block diagram of a "classical" algorithm of vector control.

The information on two motor's output phase currents and motor speed is necessary for correct operation of the algorithm. In Clark's module the third "missing" current of W-phase is restored and three-phase current is transformed to two-phase system. This is so-called transformation to the generalized model of a two-phase asynchronous drive. As a result we have two sine-wave currents with a quadratic phase-shift.

Further by means of Park's transformation and the module of the current machine's model there is made a transformation into rotating co-ordinate system oriented according to an angle of rotor and stator flux linkages. By means of these manipulations there are got two current components: D and Q.

D component is magnetizing current (reactive current) of an AM (analog of an excitation current of a DC motor with independent excitation). Q component is an active current of an AM. This current is proportional to the motor's torque. It is an analog to an armature current in a DC machine.

Comparing further with a DC machine it is necessary to introduce field weakening, which means reduction of the magnetization current dependently on the AM speed. This option is introduced in the AM's constant power zone (by means of polynomial or in a table form). In the constant torque zone this current is constant.

In the applied algorithm there is used regulation with restriction of speed and torque. If the speed setup and an actual speed differ, there is applied a maximum setup torque on the AM's shaft. If these speeds are equal, the torque is decreased to zero. Depending on a sign of the error, the traction machine can operate both in generating and motoring mode.

In different conditions and transient modes of algorithm's operation there may be necessary to restrict an active current component Q. This condition occurs if the source voltage is not enough for simultaneous achievement of the required D and Q currents. In this case there is applied a technique of adaptive regulation of the Q setup dependent on the saturation of an exit of the D regulator. After deriving the adjusted outputs of D and Q components they are transformed into steady-state coordinates by means of the inverse Park's transformation.

Finally currents are transformed from the two-phase into the three-phase system and are imposed to the motor windings by means of PWM signals and inverter.

There is implemented a new software from the Texas Instruments - **InstaSPIN™-FOC** where there is realized vector control algorithm for various types of three-phase motors – AMs, synchronous (with permanent magnets, reluctance machines). This software allows:

- Automatic definition of motor's parameters;
- Automatic adjustment of current regulators;
- Calibration and measurement of machine's parameters during its operation;
- Optimization of a magnetizing current and slip (depending on the required torque (efficiency optimization)).

It includes the modernized speed regulator with faster achievement of the set mode compared to the classical algorithm.

For vehicles with the high values of electro-mechanical constants (diesel locomotives, super haul trucks, and powerful tractors) there are also developed and realized algorithms of frequency control which are more stable at variations of system parameters and at existing restrictions. Despite slower response compared to vector systems, frequency systems do not superimpose any restrictions on EMD in the majority of applications.

The frequency control algorithm of traction electric drives contains following operations in a control cycle:

a. Current measurement. Transformation to □□frame. Determination of square of the module and the module of current.
b. Definition of an electric power.
c. Definition of a mechanical power. Definition of power losses and efficiency.
d. Measurement of the rotor movement. Algorithm of the condition observer – estimation of variables of mechanical movement.
e. Input of the speed/torque setup. Speed regulation (with restriction of an integral component). Voltage and temperature measurement. Calculation of the torque setup value.
f. Input of the voltage setup. Voltage regulation (with restriction of an integral component). Calculation of the torque setup value.
g. Functional torque restrictions.
h. Calculation of the current setup value (as a function of torque and slip setup).
i. Calculation of the optimum slip (as a function of current setup). Temperature compensation.
j. Current regulation. Calculation of the amplitude and slip (with correction of the amplification factor).
k. Calculation of limits of integral components of speed and voltage regulators, and torque restriction.
l. Shaping of source voltage (coordinate transformation of the voltage vector, normalization, current restriction, dead time compensation, vector normalization).
m. PWM, shaping of the PWM setup for a following calculation cycle of the control.

All the described above algorithms are patented.

Few words should be added concerning control of all TEES components.

In tractors "Belarus 3023" with an EMD on the base of TEES from the RUSELPROM-ElectricDrive Ltd. control of the traction equipment is carried out by the high level controller (HLC) which performs the two main tasks:

- Controls tractor traction modes according to the setup from the tractor driver and provides protection and diagnostics of TEES operation;

- Provides the coordinated control of an ICE, MG and TM so that to coordinate power flows and to ensure a realization of the first task in the limits defined by ICE power restrictions and maximum TM torque.

Control of power flows (CPF) coordinates operation of the TM, MG and ICE. Power required for movement in the mode set by the tractor driver is calculated in the PCv's controller and is applied as the setup value for the CPF algorithm. Because there is no kinematic connection ICE-wheels in the EMD, ICE rpm are no more defined by the tractor's speed and the chosen transmission step, and there occurs an ability to choose the ICE operating mode within an optimum operation point at the map of the ICE's specific fuel consumption.

In transient modes, and at excess of maximum power of the ICE and/or MG there may occur mismatch of the powers, produced by the ICE-MG and demanded by the TM. In this case there is possible, for example, an ICE shut-down caused by an overload. To avoid it, there is implemented a feedback reducing the setup of an MG torque and thereby leveling flows of the generated and consumed power.

Field trials of a prototype series of tractors "Belarus-3023" have shown that these tractors have productivity higher by up to 20% compared to similar serial tractors "Belarus-3022" with a mechanical drivetrain, produce higher traction torque, consume less fuel (by 10-15% at plough, by 20-25% at easier works, e.g. cultivation or chiseling, by 40 % at transport works).

For hybrid city buses there was accepted a series drivetrain configuration with supercapacitor power storage. Application of this configuration has allowed getting the following advantages at optimum design of all the TEES components (MG, TM, power and control electronics, parameters of the power storage) and minimum additional TEES cost:

- Lower emissions level at driving in a city cycle;
- Economy of 25÷30% of fuel;
- Possibility of ICE start from the power storage without a starter;
- Possibility of generation and recuperation of the electric power;
- Lower power ICE (15÷20%) with the same traction torque at wheels;
- Higher comfort (noise, vibration, controllability);
- Higher bus reliability and life.

In the Figure 11 there are shown waveforms of hybrid bus TEES operation in a typical city cycle NAMI-2. There is shown high dynamics of bus acceleration and braking, which cannot be achieved by traditional buses. There is also shown an effective utilization of braking energy for recuperation into the power storage and its full use in the following acceleration.

Following stage of TEES's development for hybrid buses is their application together with the gas ICE working on a compressed natural gas (CNG Hybrid Bus). It will allow both to compensate drawbacks of classical CNG buses, and to receive a highly effective, non-polluting, cost-effective vehicle.

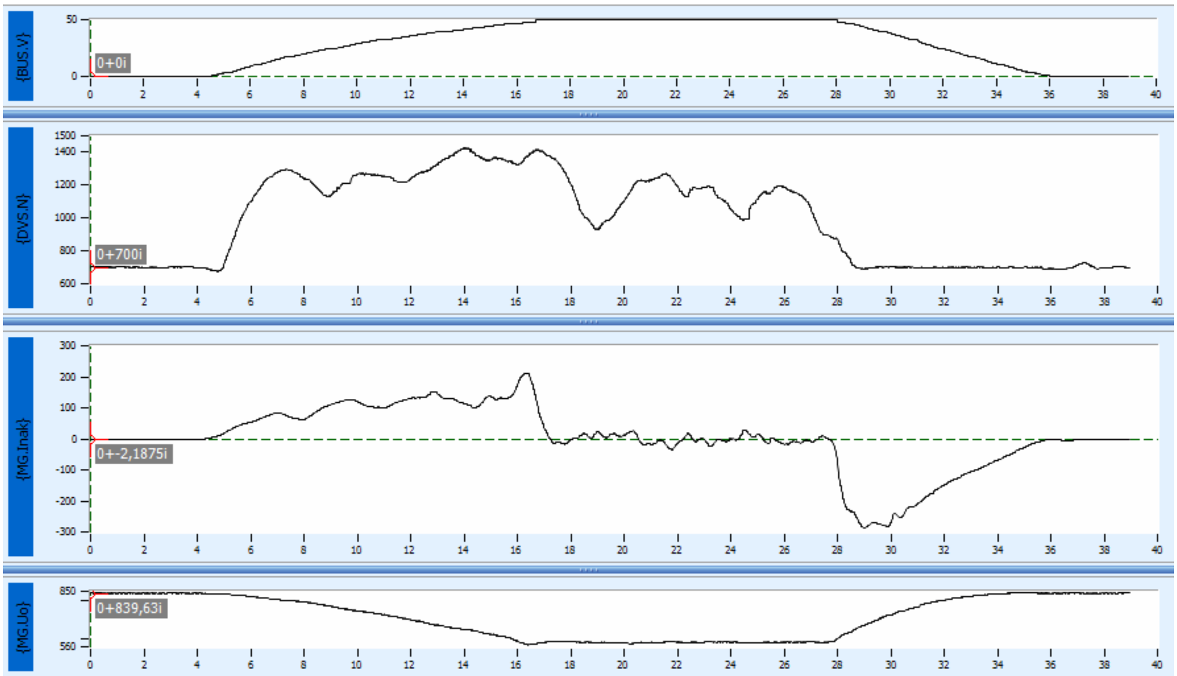

Figure 11. Characteristics of TEES operation of the bus "Bogdan A5072 hybrid" in a typical city cycle NAMI-2 (from top to bottom: bus speed - km/h, ICE speed - rpm, storage current – Amps, DC-bus voltage - V).

CONCLUSIONS

In the Russian electric corporation RUSELPROM there are developed and prepared for a serial production a series of complete sets of a traction electric equipment for EMD of various vehicles, including hybrid.

The series includes several types of motor – generators in power range from 100 to 390 kW, traction motors in power range from 65 to 250 kW, the power converters covering these ranges, featuring high, best class parameters of specific power, efficiency, and cost.

For these converters there are developed algorithms of efficiency-optimum vector and frequency control of traction electric drives, adjusted and tested. All algorithms, as well as original algorithms of vehicular control are patented.

There are ongoing works for expansion of the field of EMD application in various industrial and special purpose vehicles.

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