DSP-Controlled Permanent-Magnet Motor Drives for Vehicle Applications

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Abstract – **Several possibly applications of permanent magnet motor in rail and road vehicles are discussed in the paper. The main control principles for brushless PM motors are presented. The features of the chosen microcontroller are concluded. The controller based on the digital signal processor (DSP) has been developed. It implements the torque control using the field-oriented control (FOC) method. The results of laboratory model of the drive for a light electric vehicle are presented.**

1. Introduction

The growing number of internal combustion engine vehicles (ICV) increases the global exhaust emission. Moreover, the global petroleum resources are limited. Certain remedy can be the use of alternative energy sources (e.g. LPG, CNG, hydrogen) or alternative drive systems with electric motors. The latter concern primarily Battery Electric Vehicles (BEV), Fuel Cell Electric Vehicles (FCEV) and Hybrid Electric Vehicles (HEV). They do not completely eliminate the emission fumes, but limit them considerably or keep them away from city areas. An additional advantage is the remarkable reduction of noise. In USA some administrative initiatives and financial encouragement like Partnership for a New Generation of Vehicles (PNGV) or California's deadline for Zero Emission Vehicles (ZEV) have to support the researchers and manufacturers of this new technology area and increase the number of electric vehicles.

Electric motors, used in modern electric vehicles (EV's), should fulfill special requirements, such as: high power to weight ratio, high efficiency, wide field weakening range, high torque at standstill and at low speeds, regenerative braking possibilities, overload capability, ability to maintenance-free operation. In the currently produced electric vehicles (EV's), three main types of electric motors are applied [2]:

- DC brushed motor, series or separately excited,
- Induction motor (IM),
- Permanent magnet motor - brushless DC or AC (PMM).

The first type dominates at present due to the historical reasons, but it does not fulfil the all above-mentioned requirements. More prospective is the application of IM or PMSM (Permanent Magnet Synchronous Motor – the AC version of PMM). Both of them are mostly applied in the newly constructed EV's. The advantages of PMSM are higher efficiency and better cooling conditions resulted from very low rotor losses, the main drawback is the higher cost. Nowadays, due to the continuously reduction of the prices of PMSM's, taken into account easier control algorithms – especially in low speed range up to standstill, this type of the motor seems to be the winner in the competition with the other types of traction motors. This forecast refer not only electric driven cars but – as many experimental specimens show – all vehicles with electric propulsion system: from small-sized like wheelchairs, electric bikes, scooters or so-called neighbourhood EV's, thought buses or trucks, up to large high speed electric trains [4,5,6,11]. For the wheel direct drive, especially with wheel-in motors, the PMSM is the reasonably, if not one and only possibly solution, due to its relatively low mass, which contributes to reduction of unsprung mass and to better drive comfort. Such a structure without gear and differential simplifies the drive train and decrease mechanical losses but require a distributed control system. They have been experiments of EV's with a motor for every wheel as well as for each rear wheel reported [1,12,14]. Since the torque of each drive wheel can be generated and controlled independently and precisely, the better dynamic drive properties of the EV compared to ICV are expected. The time response of the electric motor for drive or braking torque is the range of 1 ms, while in the conventional ICV with hydraulic braking system is approximately hundred times slower. Thus the antiskid braking system (ABS) or traction control system (TCS) has potential better performances and the car may be safer. The structure of PMM's suitable for EV may be different in stator and – primarily – in rotor layout, like inner and outer rotor, surface mounted and interior permanent magnet, radial flux or axial flux [8,10].

This contribution proposes an exemplary control system for an EV based on the digital signal microcontroller (DSP). The laboratory model of the drive system is currently being developed in Gdańsk UT as a research project (see Acknowledgments). The block diagram of the whole drive system is shown in Fig. 1.

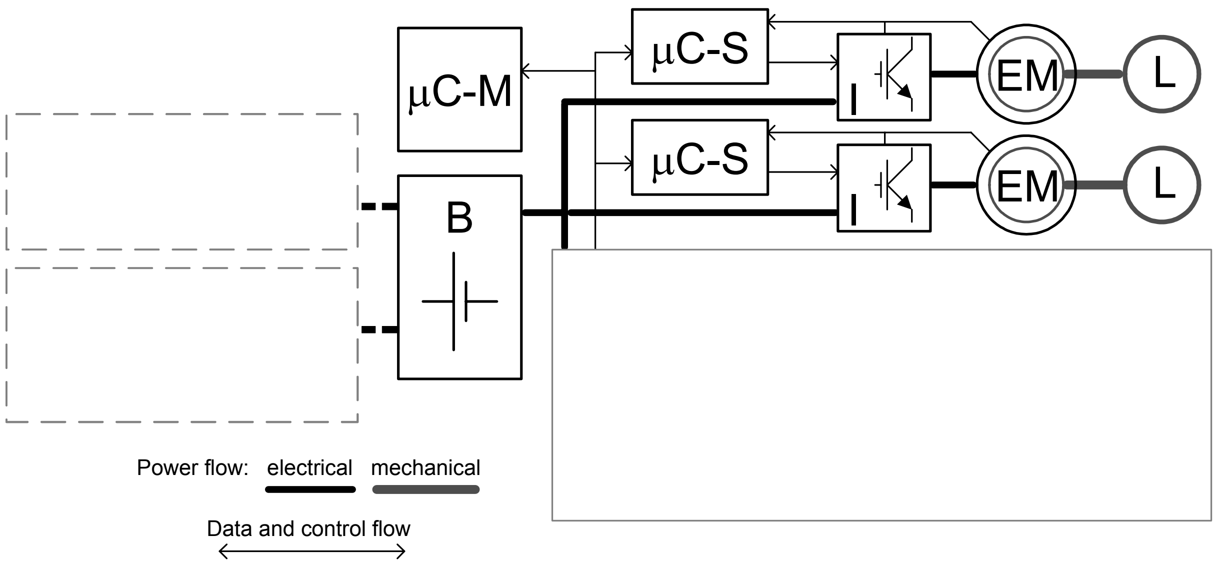

Fig.1. Block diagram of an experimental propulsion system for electric vehicle: B – battery, EM – electric motor: interior permanent magnet synchronous motor, L – load (wheel), I – inverter, μC-M – MASTER microcontroller (traction control), μC-S – SLAVE microcontroller (motor control), ICE – internal combustion engine, EG – electric generator, FC – fuel cell

Although the structure in Fig.1 is primarily considered for the BEV, it regards also the FCEV and the HEV; in those cases the control system remains the same, only the power circuit is completed with the fuel cell or internal combustion engine and electric generator respectively.

According to the actual trends the distributed structure of the control system is assumed. The MASTER controller performs the overall control of the vehicle i.e. the traction control level. The separate DSP-based controllers are provided for the motor control. Permanent magnet motors are used for vehicle propulsion. The motor with buried magnets compared to the motor with surface mounted magnets has better properties for vehicle drives because it ensures the wide flux-weakening area and has additional reluctance torque [16,17]. Hence such a version of PMM called interior permanent magnet synchronous motor (IPMSM) was chosen for the experiment, although the control of this motor is more complex.

2. DSP Microcontrollers

Selecting the appropriate microcontrollers is one of the most essential decisions by the development of the control system. Two main aspects should be taken into account: computational power and set of integrated specialized interfaces. Nowadays due to the permanent increase of integration level the DSP microcontrollers are able to perform all complex real-time motor control algorithms. Controllers dedicated to motor control mostly incorporate all application specific peripherals and now and then also the necessary software routines. Various microprocessor manufacturers offer products or product families with motion control specific features such as TMS320C24xx by Texas Instruments, ADMCxxx or ADSP-21xx by Analog Devices, MC68HC708MP16 or DSP56F80x by Motorola, SH7040 by Hitachi, SAB80C166 by Siemens etc.

In the presented experimental model of the EV's drive system the control circuit created for the motor control level is based on specialized digital signal processor ADMC300 from Analog Devices. It is a fast single-chip DSP-microcontroller (25 MIPS, 16-bit fixed-point operation, single cycle instruction execution). The architecture and operation of the chip are optimized for the control of the inverter drive system. Due to numerous on-chip peripherals the entire controller of the motor is very compact - this contributes to increase its reliability and limits the cost of the drive. The architecture of the controller and its connections to the power module are demonstrated in Fig. 2.

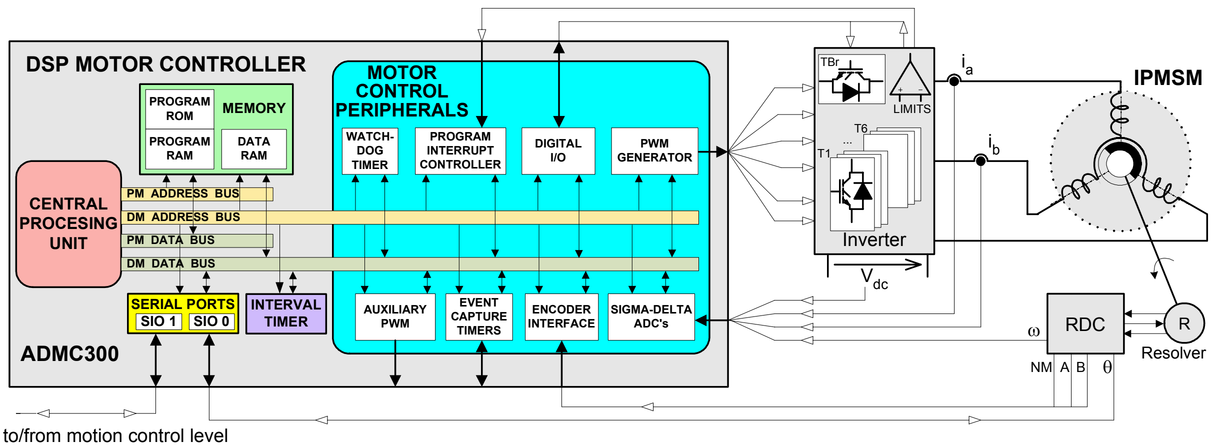

Fig. 2. Functional block diagram of motor control circuit based on ADMC300 microcontroller

The programmable three-phase PWM generator is used to generate the modulated voltage for the motor. The maximum time resolution of the PWM generator pulses reaches 40 ns and the maximum switching rate ranges from about 3 kHz with 12-bit resolution, to about 100 kHz with 8-bit resolution; in the developed drive the value near 10 kHz was used. The PWM control unit automatically introduces the programmed dead times into the switching patterns, eliminates pulses below a certain width. Also it switches off and disables all PWM outputs when any external fault signal is received (e.g. in the case of short circuit).

The block of 12-bit sigma-delta Analog-to-Digital Converters (ADC) allows simultaneous sampling of five different analog signals with the maximum frequency above 32 kHz. The most important feature of the ADC system is the ability to synchronize its operation to the PWM pulse pattern. It reduces the system sensitivity to the noise induced by transistor switching. The appropriate sampling contributes to filter out the current ripple resulting from the switching cycle of the inverter. In the discussed drive controller the ADC converts signals of motor phase currents, inverter input voltage and motor speed. The analog signal of motor speed is outputted by Resolver-to-Digital Converter (RDC).

The angular rotor position is measured using resolver and RDC converter circuit. The RDC calculates a 12-bit angle value and transmits it in the serial form to the Serial Input-Output port (SIO) of the processor. Resolvers are rotor angle transducers with better ability for vehicle application as optical encoders or magnetic sensors. They are operable in very wide temperature range; they also resist dirt and mechanical shock. With a typical carrier frequency of 10 kHz the time response by decimal of millisecond fulfils the requirements of control dynamics and the precision exceeds that of magnetic sensor. The sensorless control of the motor was considered by system concept; but computational effort, poor accuracy and difficulty to attain stable operation by regenerative braking do not induce to implement such a control method.

Another factor determining the choice of ADMC300 microcontroller in the described application is the built-in subroutine block in the ROM memory of the processor, including the procedures typical for drive applications, e.g. Clarke & Park's coordinates transformation. The processor is also equipped with universal Parallel Input-Output port (PIO) used for switching of the brake transistor and for monitoring of the limit and fault conditions of the drive. Another serial port is used for communication with the MASTER computer.

The processor includes also the encoder interface, primarily foreseen for the drives with incremental encoder where precise position control is needed. In our drive concept, since RDC emulates an encoder, this processor capability allows more precise calculation of rotor speed and acceleration compared with the algorithm based on the analog speed signal. It should facilitate the detection of adhesion loss i.e. the wheel slip by acceleration and the wheel lock by braking.

The flexible and powerful interrupt control unit of the processor allows synchronizing of essential software routines. The control loops are included inside the interrupt service routines, initiated by programmed events of the motor control peripherals. It ensures the right sequence of detailed control functions by minimized time delay of the whole control loop.

The MASTER microcontroller primarily has to control the traction of the vehicle through the torque distribution related to the driver's command. If more complicated control algorithms should be implemented to prevent a wheel from spinning, skidding or blocking by variable adhesion conditions on each wheel, the dynamical model of the vehicle will be used. The actual values of speed, acceleration and torque for each wheel have to be obtained and the vehicle speed estimation will be necessary. It demands the use of microcomputer with relatively high computational power. Although in final application a specially developed controller can only be applied, for the laboratory experiments the use of portable PC is more comfortable.

In Fig. 3 the homogeneous hierarchical structure of the control system including hardware and software is shown. The tasks assignments to the appropriate controllers representing proper control level of the vehicle and the interconnections between them are detailed illustrate.

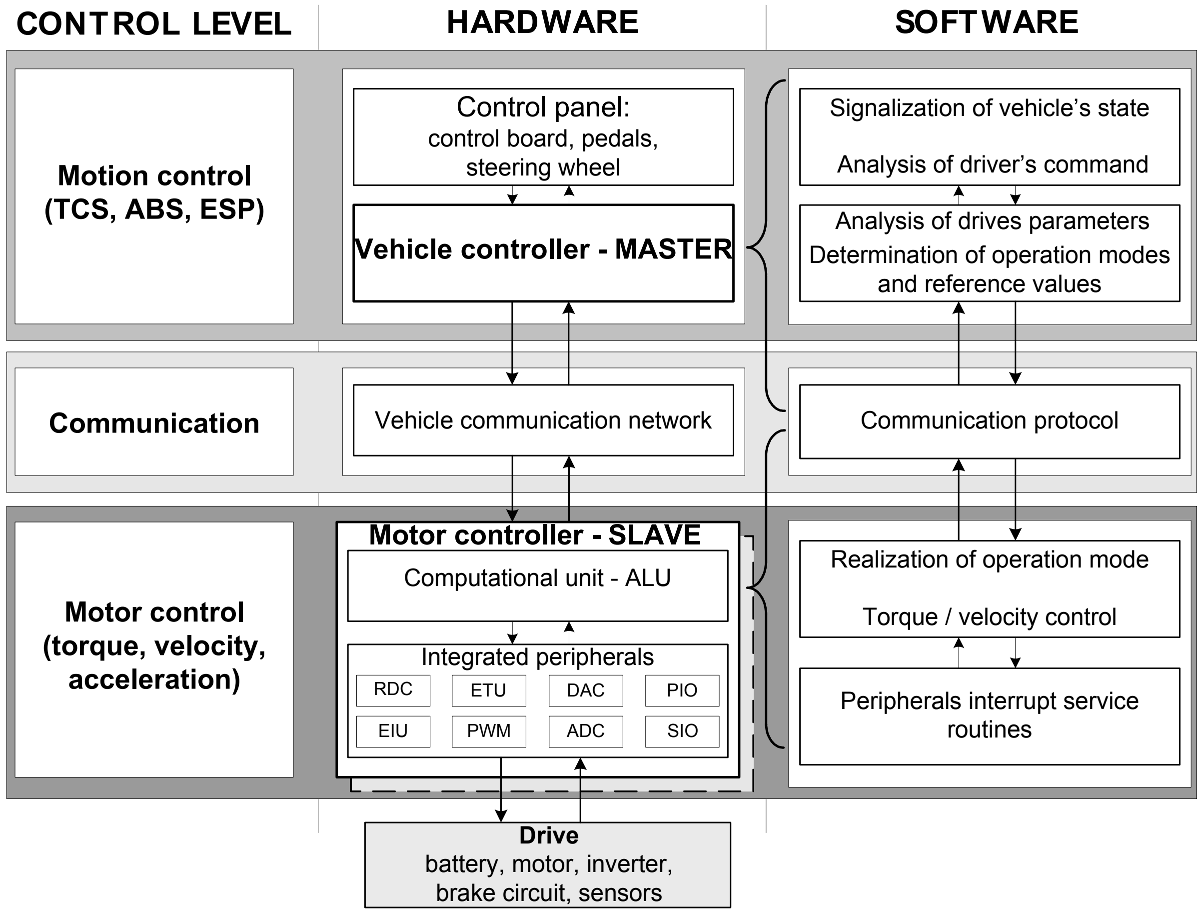

Fig. 3. Hierarchical structure of the control system

One of the most essential software modules is the communication protocol. To realize the motion control algorithm the actual values of torque, velocity or acceleration must be sent to the MASTER controller. As above referred all these values are requested in order to limit the slip of the several wheels. With the transmission rate of 115.2 kBaud used in the system the data frame including 10 bytes of data - except mentioned parameters also the status of the SLAVE controller as well identification and verification byte – the maximal time response delay do not exceed 1 millisecond. The motion controller transmits to the motor controllers the start and stop commands, the reference and limit values of torque, velocity and acceleration, the values of selected parameters e.g. gain factors for torque or velocity control loop in case of need. All transmitted information must be receipted in defined time interval, otherwise the drives will be turned off and the transmission failure will be signalized. Due to the adopted star-configuration of the communication network, permissible by a small number of the connected controllers, the data flows between MASTER controller and both SLAVE controllers occur simultaneously.

3. Principles of motor control

In modelling the PMM, the machine equations in the rotor reference frame are used. The flux, current and voltage equations of the PMM model may be written shortly in space vector notation as [1]:

$$\lambda_d = L_d i_d + \lambda_{\mathrm{m}}, \tag{1}$$

$$\lambda_q = L_q i_q, \tag{2}$$

$$\mathbf{i}_{dq} = i_d + j i_q = i_{dq} \exp(j\Theta_e), \tag{3}$$

$$\mathbf{v}_{dq} = v_d + j v_q = v_{dq} \exp(j\Theta_e), \tag{4}$$

$$v_d = R_s i_d + \frac{d\lambda_d}{dt} - \omega_s \lambda_q, \tag{5}$$

$$v_q = R_s i_q + \frac{d\lambda_q}{dt} + \omega_s \lambda_d. \tag{6}$$

where i_d, i_q, v_d, v_q L_d, L_q, λ_d and λ_q are the *d*-, *q*- axis components of the stator current, voltage, inductance and flux linkages, respectively, λ_m is the flux linkage due to the rotor magnets linking the stator, R is the stator resistance, ω_s and Θ_ε are the electrical angular velocity and the electrical angle of rotor position, respectively.

The electric torque equation of a PMM by neglecting the damping effects is [13]:

$$T_e = \frac{3p}{2}[\lambda_m i_q - (L_q - L_d) i_d i_q], \tag{7}$$

where p is the number of pole pairs.

The dynamic equation of a PMM is:

$$T_m = J\frac{d\omega_r}{dt} + B\omega_r + T_L \tag{8}$$

where J is the moment of inertia, ω_r the mechanical rotor speed, B the damping coefficient, T_L is the load torque.

For the surface-magnet machine $L_d = L_q$, this eliminates the second term in Eq. (7) and $T_e = \mathrm{k_T} i_q$, where $\mathrm{k_T}$ is the motor torque constant. For buried magnets motors $L_d \neq L_q$ and such a motor is called IPMSM. The sample geometry for this type of machine is shown in Fig. 4. Equations (1) to (7) represent the standard model for a PMM with sinusoidal flux linkages for either the surface-mounted or buried magnet cases. For high torque and high efficiency operations several control methods were proposed, in which the *q*- axis current and also *d*-axis current are controlled according to the maximum torque-per-armature current trajectory for constant torque operations. For operation above the base speed, the air-gap flux is weakened by the demagnetizing effect due to the *d*- axis armature reaction [15-17]. The relationship between the electromagnetic torque and *q*- axis current is non–linear.

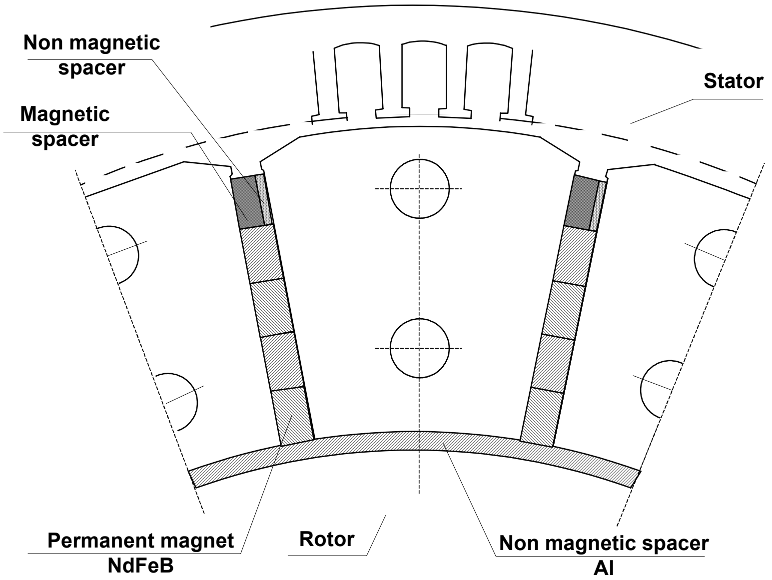

Fig. 4. Geometry of interior permanent synchronous motor

When the PMM is fed from an inverter, the armature current and voltage may not exceed the inverter/motor current and dc-link/motor ratings. These constraints can be expressed as:

$$i_s = \sqrt{i_d^2 + i_q^2} \le I_{\max} \tag{9}$$

$$v_s = \sqrt{v_d^2 + v_q^2} \le V_{\max} \tag{10}$$

where $I_{\max}$, $V_{\max}$ are the available current and voltage of the inverter and motor.

Fig. 5 shows the structure of control scheme associated with the DSP microcontroller, IPMSM motor and resolver. The torque control is reduced to the regulation of both current vector components. The reference values i_d*, i_q* are calculated in torque control trajectories block. Eqs. (7), (9) and (10) are represented in the block. In the control program the inverter output voltage components in rotating reference frame V_d i V_q are calculated as follows:

$$V_d(n) = u_d(n) + k_P \Delta i_d(n) + k_I \sum_{m=0}^{n} \Delta i_d(m), \tag{11}$$

$$V_q(n) = u_q(n) + k_P \Delta i_q(n) + k_I \sum_{m=0}^{n} \Delta i_q(m) \cdot \tag{12}$$

As it is seen from Eq. (11) and Eq. (12), they are the sum of voltages resulting from the motor model (u_d, u_q) and output voltages of PI-controllers for both current components, where n is the time step, k_P, k_I are control gains and Δi denotes current errors of the appropriate components. The voltages u_d, u_q are calculated as below:

$$u_d = R_s i_d - \omega_e L_q i_q , \tag{13}$$

$$u_q = R_s i_q + \omega_e L_d i_d + \omega_e \lambda_m . \tag{14}$$

Eqs. (13), (14) are based on the steady-state voltage equations from Eqs. (1), (5) and (6).

The respective block (*abc*/*dq*), executing Clarke & Park transformation, converts the phase currents into rotating reference frame. The dead time compensation is realized in non-ideality correction block. It is especially important in traction drives with regard to the essential problem of torque pulsations reduction. The switching times of inverter transistors are calculated in the modulator block using **S**pace **V**ector Pulse Width **M**odulation technique (SVM) [3].

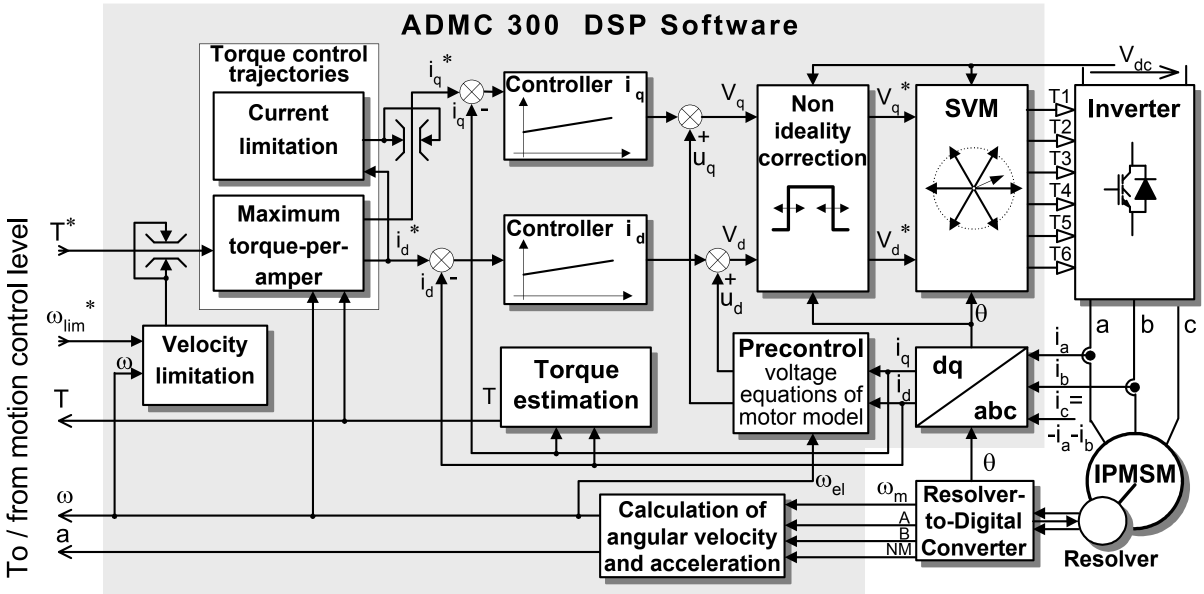

Fig. 5. The proposed control scheme for the IPMSM

In order to avoid the loss of adhesion, the MASTER controller calculates torque reference value and also the speed limit based upon the maximal realizable acceleration and the referenced torque [1]. This velocity limitation reduces the desired torque only if the actual speed of the wheel reaches the limit value. It is functional in each operation mode: by acceleration and by braking.

4. Experimental results

Fig. 6 shows the photograph of the experimental setup, which consists of the IPMSM motor, DC generator, transistors inverter and controller.

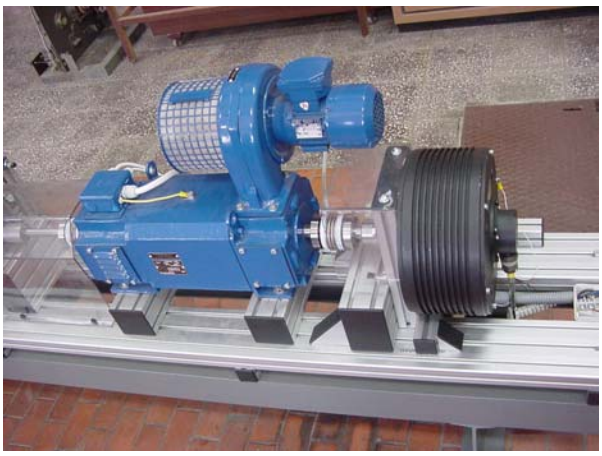
Fig. 6. Photograph of experimental setup

At present the motor control algorithm and the communication protocol are tested by the use of the PC computer as MASTER controller and one drive controller. The IPMSM motor with nominal torque value of 50 Nm was used for experiments. The implementation of the motion control will occur in the near future.

The torque control algorithm is based on two PI controllers for d and q components of the motor current vector. The PI controllers provide satisfactory regulation quality only for slight deformations of the flux linkage waveforms from the sinusoidal shape. In the used motor this condition was fulfilled – the example waveforms of the induced back-emf of the motor are presented in Fig. 7. The geometry of the motor was shown in Fig. 4.

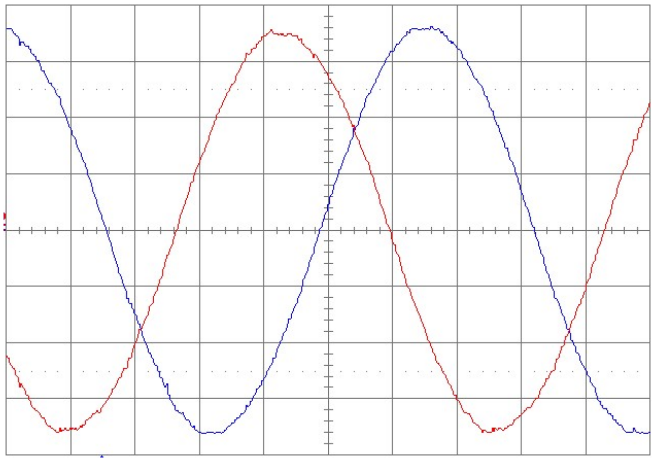

Fig. 7. Back-emf waveform of experimental PM synchronous motor

Fig. 8 presents exemplary waveforms of the calculated current components by the motor start with limited load in the constant torque region. In this low torque area the i_d current component approximately equals zero and the i_q current component reflects the electromagnetic torque.

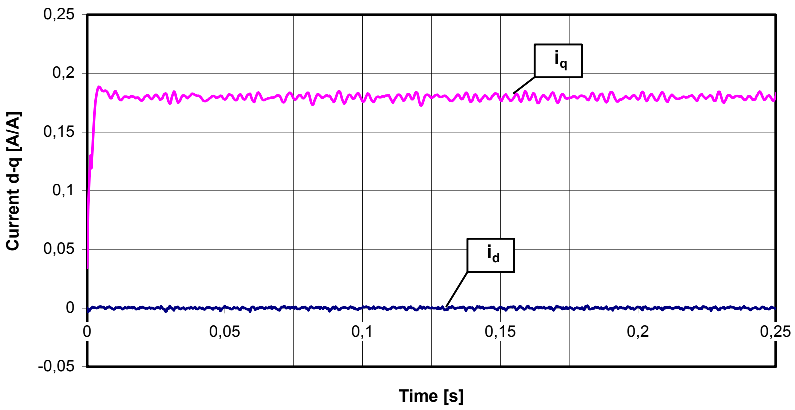

Fig. 8. Current components by the motor start with limited load in the constant torque region

In Fig. 9 the waveforms of estimated torque and motor speed in constant torque and constant power area are shown.

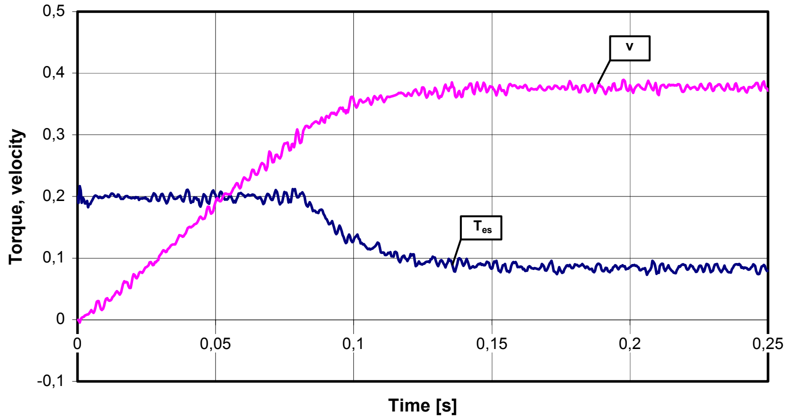

Fig. 9. Estimated torque and motor speed in constant torque and constant power area

Fig. 10 presents the oscillogram of phase current and motor speed during start of the motor.

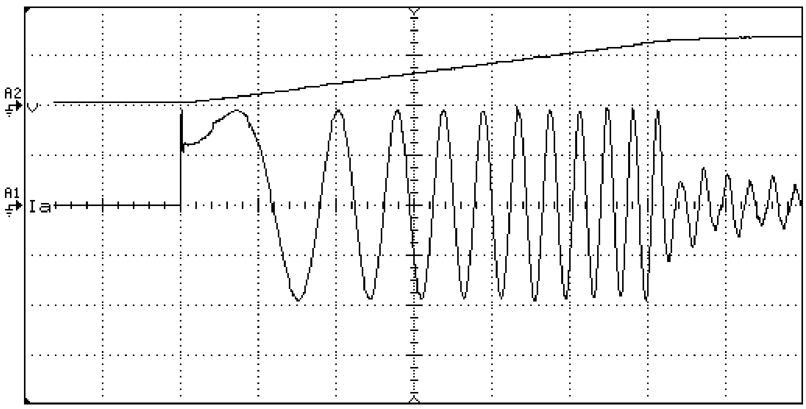

Fig. 10. Waveforms of speed (upper line) and phase current of motor (lower line).

5. Conclusions

The Zero Emission Vehicles will compete with conventional cars propelled by internal combustion engines in city areas in the near future. There are many solutions of the vehicles electric drive systems proposed in the recent years, but the chances for new more effective designs are still present. Especially interesting seems to be propulsion system with direct wheel drives based on IPMSM's, including separate motor controllers and one central motion control unit. The presented study of such a system is the continuation of earlier research, which has been devoted DSP-controlled small sized drives with surface mounted PMSM [3,9]. The application of the specialized DSP, which includes the built-in peripherals, required for feedback with the motor and inverter, remarkably simplifies the architecture of the motor controller. The high-speed operation of the processor allows the use of the complex control scheme for IPMSM based on FOC method including field-weakening range by relatively short time response of the control loop. The entire hierarchical control system is now being developed, but the results of the first experiments already promise to achieve the satisfactory motion control of the vehicle model.

6. References

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