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# RESEARCH ON TRACTION DRIVE WITH PERMANENT MAGNET SYNCHRONOUS MOTOR

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## 1. Introduction

Our field of research is aimed at traction drive with PMSM for application of rail transport and city local transport in particular. Advantages of PMSM are known well. The torque moment from point of view of dimension and weigh of drive is greatest advantage. This characteristic makes possible realization so-called direct drive (i.e. drive of axle or wheels without use of any gears) from electric traction point of view. Direct drives with other motors (e.g. asynchronous motors) are not possible to make in practice because they have big dimensions. Application of simple direct wheel drive enables realization of low-floor vehicle.

Our goal of research is made sturdy control algorithm for this traction drive. Calculational sophistication of algorithm is also followed, so that it will be possible to use two control algorithms into microprocessor control unit. Of course, every drive is necessary to feed from own inverter in case of individual drive of wheel by PMSM. In case of two control algorithms into microprocessor control unit (i.e. one unit controls two inverters), the solution leads to appreciable structure savings e.g. for multiple-axle vehicle: This represents double number of wheel drivers which each of them has to have own inverter. In the case, one unit controls two inverters: This presents only half of control unit.

Research is proceeding in two levels. At the first level of the research, we concern with the simulation of this drive inclusive of its control. Comparison of characteristics of various control algorithms is purpose of simulations.  At the second level of the research, algorithms are tested by testing stand with direct drive of tram wheel. This testing stand was lent from Research institution rail vehicles to laboratories of Jan Perner Transport Faculty. Detail description of stand is in next chapter.

## 2. Testing stand with PMSM

A testing stand of direct drive PMSM was lent to Jan Perner's Transport Faculty one year ago. It was made by VÚKV (Research Institute of Rail Vehicles Prague). The testing stand consists of traction PMSM, tram wheel and "rotating rail" (second wheel). Fig. 1 shows described testing stand.

***Obr. 1** Zkušební stav se synchronním trakčním motorem se zatěžovacím asynchronním strojem*

***Fig. 1** Testing stand with PMSM during adaptation and connected loading asynchronous engine*

PMSM is placed on silent blocks in frame of stand. Silent blocks allow swing of motor in vertical axis. Motor drives tram wheel by shaft without any gearing. Tram wheel is placed on a swinging arm in bearings. Cardan joint of driving shaft is placed inside of tram wheel. Tram wheel is pneumatically pressed to the “rotating rail”. Pressure is variable from 4 kN to 50 kN.

PMSM is a prototype of traction motor for low-floor trams. It was made by VÚES Brno (Research Institute of electric machines Brno). The motor has inner rotor and its stator is cooled by liquid. Table 2 shows several characteristics of motor.

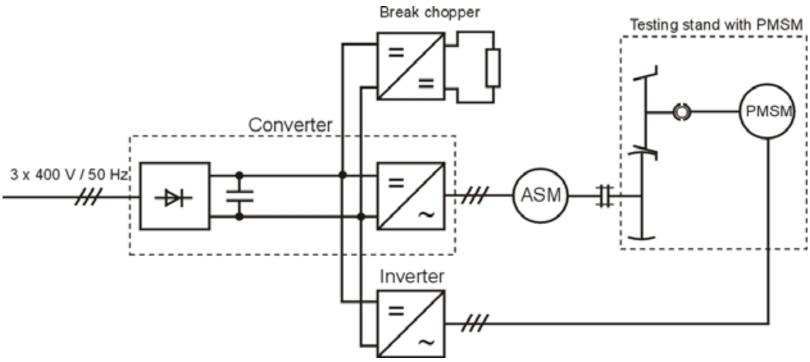
***Tab. 1*** *Charakteristiky motoru*

***Table 1*** *Motor characteristics*

| | |
|---|---|
| Nominal power | 58 kW |
| Nominal torque | 852 Nm |
| Nominal speed | 650 rpm |
| Nominal current | 122 A |
| Maximal torque | 2000 Nm |
| Maximal speed | 1000 rpm |
| Maximal current | 368 A |
| Number of poles | 44 |

We had to append other auxiliary systems to testing stand (system for cooling and pneumatic system). Also system for absolute rotor angle determination was completed. The system is necessary for PMSM torque control. Four-pole resolver is used for angular position sensing. Resolver output signals are processed by integrated Resolver-to-digital converter (R/D converter). Processing circuit for resolver signals is described in [1]. The circuit also generated 10 kHz feeding signal for resolver. The converter resolution is 12 bits it means 4069 positions per half a mechanical turn or 372 positions per electric turn of motor (used PMSM has 44 poles). The converter returns data in parallel and serial form and also it simulates IRC sensor output. Simulated IRC output allows quick transmission of angular position information to DSP (Digital signal processor). Our control system for PMSM uses simulated IRC signal during drive running. Parallel form is used at specific moments of control system to locate absolute rotor position (IRC signal gives only relative position).

Asynchronous engine will be used for loading testing stand. The engine has similar parameters like PMSM used in testing stand. Engine has these parameters: nominal power 55 kW, nominal voltage 380 V and nominal speed 589 rpm. Work on connecting of loading engine is in progress at the present time. Block diagram in figure 2 shows final layout of experimental workplace. Loading engine will be fed by converter. DC-bus of converter will be used for feeding PMSM inverter. Due this situation, the operation of whole workplace will be effective. Loses of drive will be covered by mains (3 × 400 V, 50 Hz). Break chopper will be also connected to the DC-bus. Break chopper will be important during failure of converter or inverter.



***Obr. 2*** *Blokové schéma zkušebního pracoviště se zkušebním stavem se synchronním motorem s permanentními magnety*

***Fig. 2*** *Block diagram of experimental workplace including testing stand with PMSM*

## 3. Control algorithms for traction drive

Torque control is a base for traction drive control algorithm. At present a vector control is mainly used for torque control of synchronous motor. Principle of this vector control is the same like asynchronous motor vector control. In contrast with asynchronous motor the flux current component of current is null in constant flux control mode because PMSM is excited by permanent magnets. In this mode stator current space vector is orthogonal to flux vector and thus to induced voltage vector. In this mode torque is proportional to RMS value of phase current as shown in (1).

$$M = \frac{3}{2} p_p (\Psi_d i_q - \Psi_q i_d) = \frac{3}{2} p_p \Psi_d i_q = \frac{3}{2} p_p \Psi_d I; \quad i_d = 0 , \qquad (1)$$

Where:

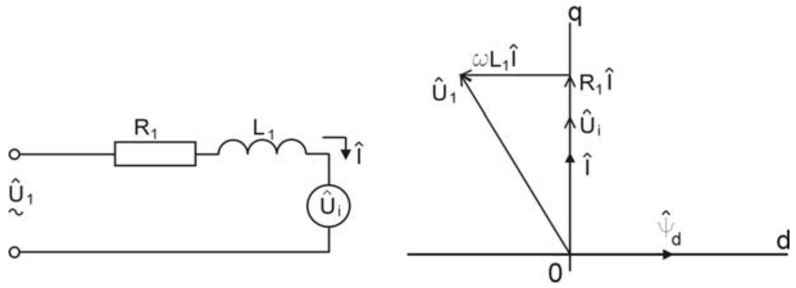
| | |
|---|---|
| M........................................ | inner torque of motor |
| $\Psi_d$, $\Psi_q$.................................. | components of magnetic flux vector |
| $i_d$ ........................................ | flux current component |
| $i_q$ ........................................ | torque current component |
| I........................................ | stator current space vector modulus |

Equation (2) describes the stator circuit. Equivalent stator circuit and corresponding phasor diagram are shown in figure 3.

$$\mathbf{U_1} = R_1\mathbf{I} + j\omega L_1\mathbf{I} + \mathbf{U_i} , \qquad (2)$$

Where:

| | |
|---|---|
| $U_1$........................................ | terminal voltage phasor |
| $R_1$........................................ | resistance of stator winding |
| I........................................ | stator current phasor |
| $L_1$ ........................................ | inductance of stator winding |
| $U_i$ ........................................ | induced voltage |

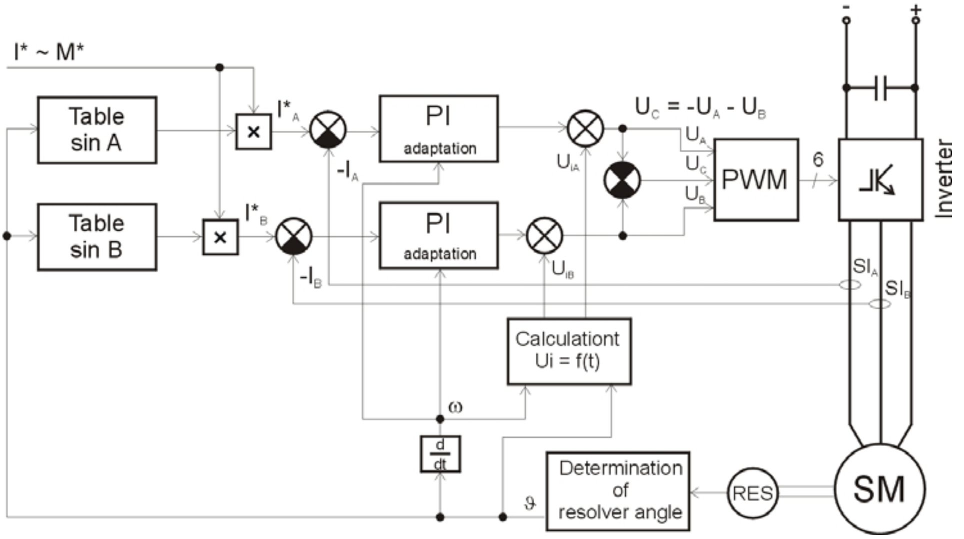


***Obr. 3*** *Náhradní obvod a fázorový diagram vektorově řízenéhé synchronního motoru*

***Fig. 3*** *Equivalent circuit and phasor diagram of vector controlled synchonous motor*

### Phase current control algorithm

The algorithm is based on control of actual phase currents. Setpoints of phase currents are sinusoidal. Phase displacement between setpoints is 120°. Magnitudes of current setpoints are proportional to a torque setpoint. Phases of current setpoints are derived from actual value of rotor angular position. Current space vector is controlled to be concentric with induced voltage. It means that actual value of phase current is maximal at the moment when rotor flux vector is orthogonal to profile of this stator winding. Then the phasor diagram in figure 3 is valid. This control needs no coordinate conversions which have height requirements to computing power of controller. It allows implementation of two control algorithms into one controller.



***Obr. 4*** *Blokové schéma regulace fázových proudů*

***Fig. 4*** *Block diagram of phase current control algorithm*

Block diagram of phase current control algorithm is shown in figure 4. Current setpoints for phases A and B are calculated from actual angular position and current magnitude setpoint (proportional to torque setpoint). Control deviations are calculated from setpoints and actual currents in subtraction elements. Control deviations are sent to PI controllers. Two-state controllers are also applicable. However we do not suppose that for traction application due to EMC. EMC of electric traction is described in [2]. Setpoint values have harmonic course (frequency from 0 to hundreds of Hz) thus the PI controllers have to have very fast response. An adaptation of constants of PI controllers is suitable for optimal PI controller settings within the whole frequency range. The constants are adapted with actual speed. See in (3).

$$\begin{aligned} P &= P_1 + P_2 \cdot \omega \\ I &= I_1 + I_2 \cdot \omega \end{aligned} \tag{3}$$

Where:

P ..........................................proportional action element coefficient

I............................................integral action element coefficient

Actual induced voltage is added to PI controller output to reach better behavior of whole control algorithm. The induced voltage is calculated from actual speed, motor voltage parameter and actual rotor angular displacement. Equation (4) is valid for instantaneous values of stator variables. We will get this equation when we generalize (2).

$$u_1 = R_1 i + L_1 \frac{di}{dt} + u_i = u_{PI} + u_i \tag{4}$$

Where:

$u_{PI}$ ........................................PI controler output setpoint voltage

$u_i$ ..........................................induced voltage

PI controller basically generates desired value of voltage drop in stator winding impedance. The impedance consists of resistance and inductance of one phase of stator winding. Controller controls current in first order system. PI controller is suitable for controlling this type of system.

Current controllers are used in A and B phases. Setpoint voltage of C phase is calculated from equation: $u_A + u_B + u_C = 0$. It simplified control algorithm and also it suppressed direct component in setpoint voltages in PWM modulator input. Direct component of phase voltages increased in control algorithm with three PI current regulators in each phase and nonzero integral component.

### Field oriented control algorithm

Goal of the control algorithm is the same like previous algorithm – concentric current space vector with induced voltage. Control algorithm process values in d-q frame which is referred to rotor. Due the transformation (Clarke - Park), three phase currents are transformed to two components – flux component and torque component. The transformation is performed by (5).

$$i_d = i_a \cdot \cos(\theta) + \left( \frac{1}{\sqrt{3}} i_a + \frac{2}{\sqrt{3}} i_b \right) \sin(\theta)$$
$$i_q = -i_a \sin(\theta) + \left( \frac{1}{\sqrt{3}} i_a + \frac{2}{\sqrt{3}} i_b \right) \cos(\theta) \qquad (5)$$

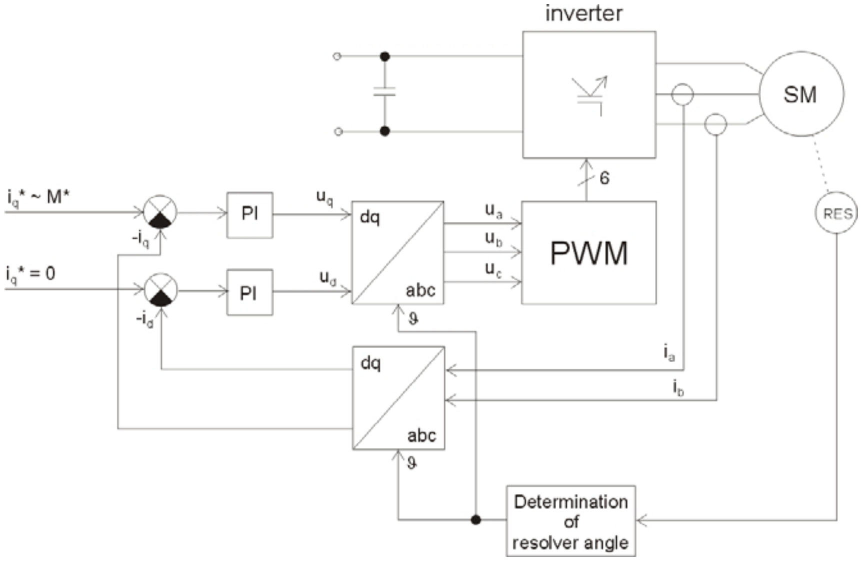
Where

$i_d$, $i_q$ ......................................flux and torque current components

$i_a$, $i_b$ ......................................phase currents

$\theta$...........................................actual rotor position

To reach concentric current space vector with induced voltage, control algorithm keeps flux component zero. Torque component is proportional to torque setpoint.



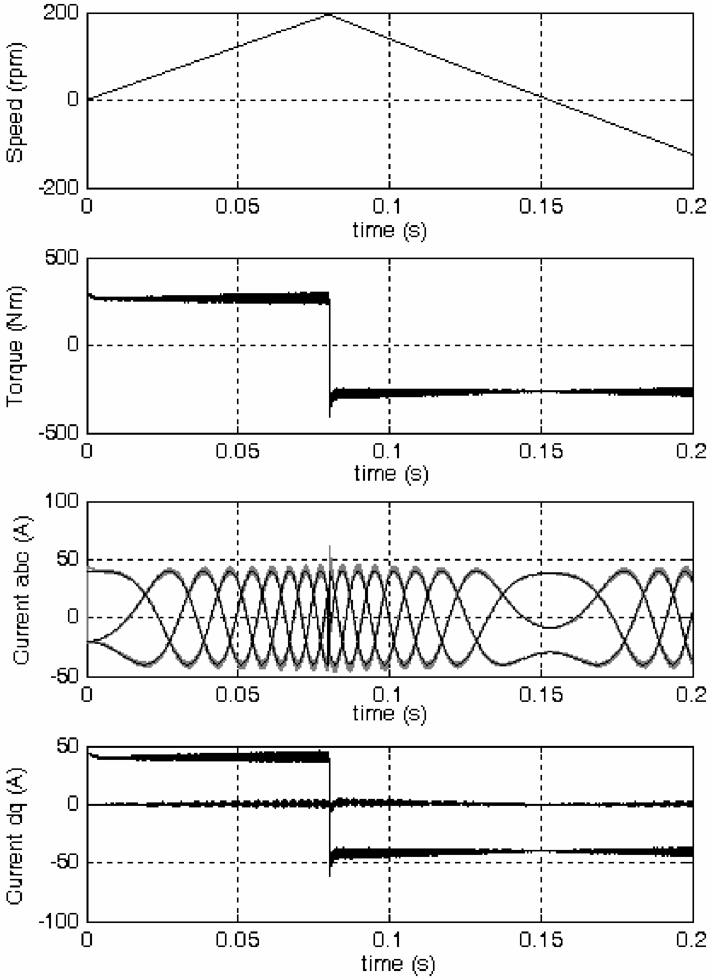
***Obr. 5*** *Blokové schéma vektorové regulace v d-q souřadnicích*

***Fig. 5*** *Block diagram of field oriented control algorithm*

Block diagram of field oriented control algorithm is shown in figure 5. Flux component setpoint is zero in case of full flux operating of PMSM. Torque component explicitly determines the torque of PMSM. Common PI controllers are used in both control loops. Voltage setpoints in d-q frame are outputs of PI controllers. To transform voltages from d-q frame to abc there is block performing inverse Clarke – Park transformation. Curent component setpoints are constant or slowly changing values. Due this, the control algorithm performs good behavior through whole speed range of PMSM drive. However the frame transformations increase demands on computing power. More about this method is in [3].

## 4. Simulatons of control algorithms

The application MATLAB Simulink was used for simulations of control algorithms and PMSM drive. Parameters of PMSM were the same like real PMSM described in chapter II. Inertia torque of PMSM was simulated lower to reach faster simulations. There is no influence to simulated control algorithms.



***Obr. 6** Simulační sekvence pohonu při použití regulace fázových proudů*

***Fig. 6** Simulating sequence of phase current control algorithm*

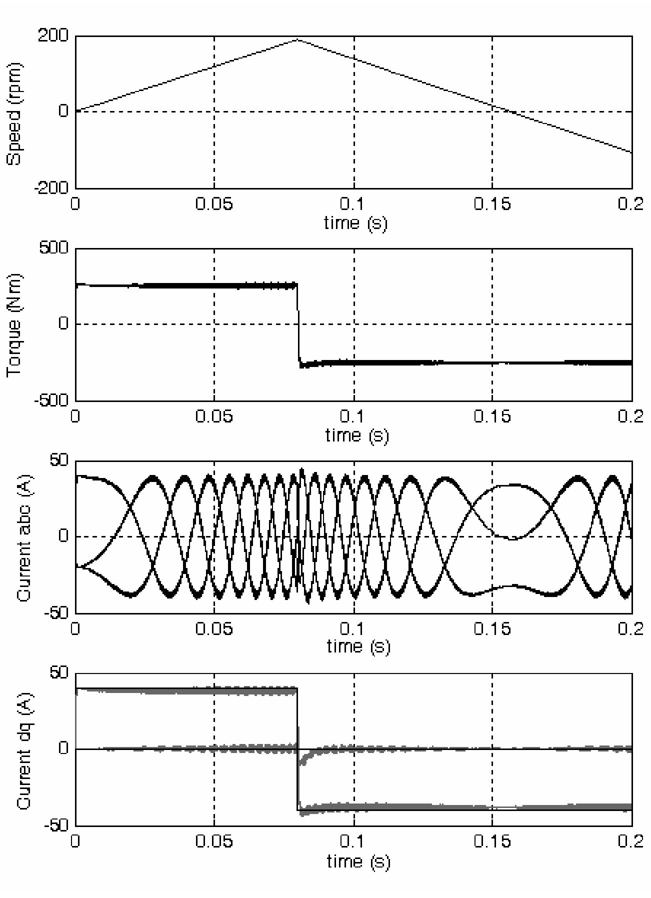
Both of described control algorithms were simulated. Simulated block diagram can be split to four functional units.

- PMSM model

- Inverter model and DC source model
- PWM modulator model
- Control block

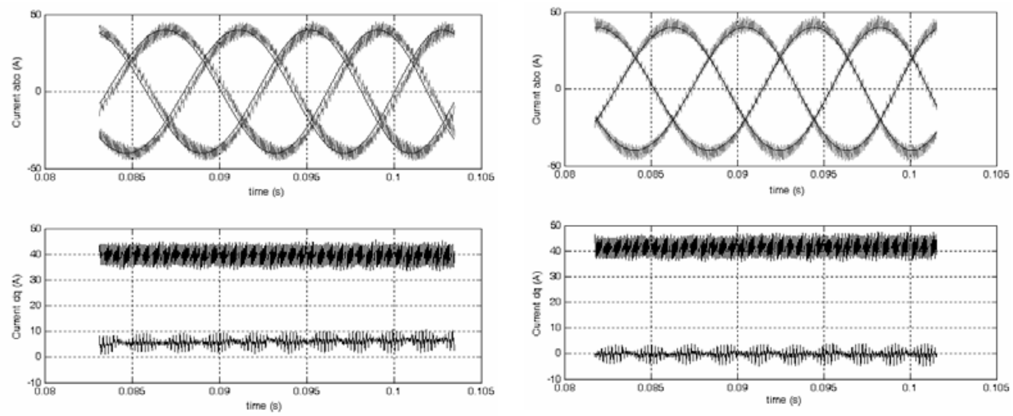
First three units were the same for simulations of both control algorithms.

Comparison of both algorithms is shown in figures 6 and 7. Figures show time behavior of speed, torque, phase currents and current components. There is simulated starting of PMSM to 200 rpm, subsequently electrodynamic brake and changeover of rotation direction. Sequence was simulated for DC-bus voltage 200 V and PWM frequency 5 kHz. The figures demonstrate simulation of both algorithms. The algorithms have similar behavior.



***Obr. 7** Simulační sekvence pohonu při vektorovém řízení v d-q souřadnicích*

***Fig. 7** Simulating sequence of field oriented control algorithm*



*Obr. 8 Vliv kompenzace indukovaného napětí. Vlevo: bez kompenzace. Vpravo: správně kompenzované indukované napětí.*

*Fig. 8 Influence of induced voltage compensation. Left: No compensation. Right: Correct compensation.*

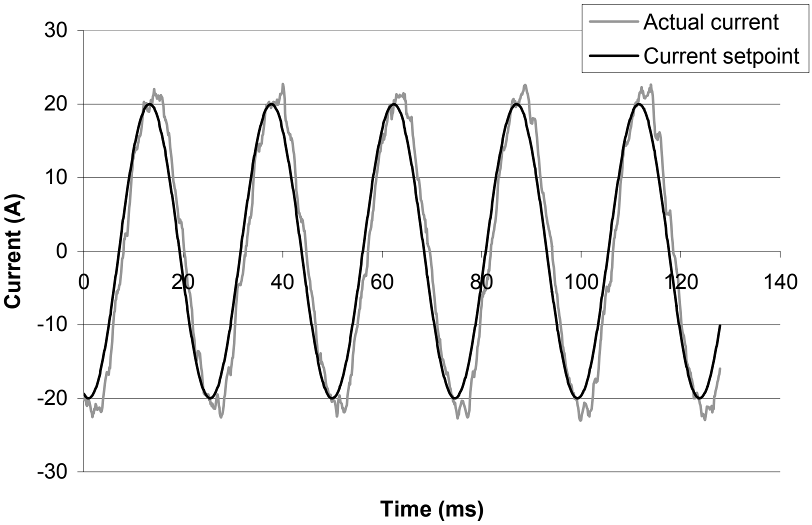
It was necessary to append block of induced voltage compensation and adaptive PI controllers to phase current control algorithm. Influence of induced voltage compensation is demonstrated in figure 8.

Incorrectly compensated induced voltage causes nonzero flux current component. If induced voltage is not compensated, actual current gets behind the current setpoint and it causes positive flux current component. If induced voltage is overcompensated, it causes negative flux current component. It is unwanted flux weakening of PMSM. Both failures cause an increase in magnitude of phase current and ineffective current utilization.

The field oriented control algorithm is sturdy and more insensitive to setting up of PI controllers than previous algorithm. Although no decoupling block of currents component is used, the algorithm does not cause positive or negative flux current component.

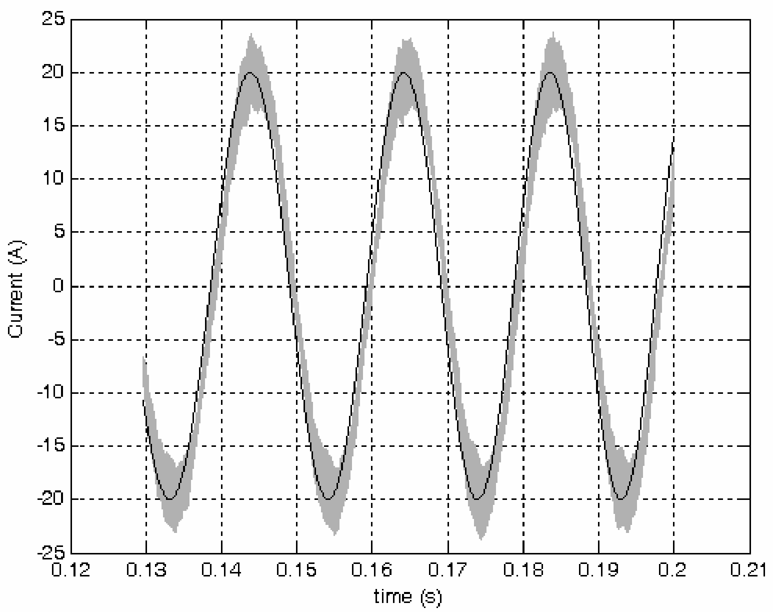
## 5. Application of control algorithms

At the present, the first control algorithm has been used partially. The reason is correction of testing stand for connection of stationary load motor. PMSM was feed by inverter with integrated elements IGBT. Control of inverter was made by DSP Texas Instruments TMS320F240 [4]. In future, we want to replace this DSP by DSP TMS320F2812 witch has 12 × PWM outputs. This is condition for application of two control algorithms of control two inverters. Figure 13 shows workspace during testing of drive.



***Obr. 9*** *Ukázka skutečných průběhů proudů stažených z DSP. Frekvence proudu je cca. 50 Hz a napětí ve stejnosměrném mezibvodu 200 V*

***Fig. 9*** *Real time behaviors of currents downloaded from DSP. Frequency is approx. 50 Hz, DC-bus voltage 200 V*



***Obr. 10*** *Simulace pohonu za podmínek zobrazených na obr. 9*

***Fig. 10*** *Simulated actual drive state shown in Fig. 9*

The first control algorithm, which does not make use of constants of PI regulator, is mentioned in this paper. This solution brings obvious delay and creation of flux current component. Figure 14 shows real time behaviors of currents downloaded from DSP during experiments. Next figure 15 shows process of simulation which represents actual drive state.

## 6. Conclusion

The simulations, which are described in this paper, demonstrate: Both control algorithms are realized and they bring good results. Control of phase currents is more sensitive to setting up of PI regulator, particularly at generation higher frequencies. Ratio of frequency of PWM modulator and the 1st harmonic of generated current affects negatively the control quality. If the ratio decreases, then actions number of regulator in a period of generated current is less. This makes an increase of the actual value of current over a setpoint value.

It turned out the solution of placement of decoupling block of components between PI regulator and PWM modulator is suitable for control of flux and torque current component. This unit eliminates dependence of components on each other which increases dynamic characteristics complete algorithm. The compensation block of inductive voltage for first control algorithm works similarly. The first control algorithm, which does not use Clarke-Park's transformation of coordinates, is positively simply from point of view calculation sophistication. Other increase of calculation sophistication of control in d-q frame can be expected by usage of decoupling block.

### References

1. ČAMBÁL M., NOVÁK M., NOVÁK J. *Study of Synchronous Motor Rotor Position Measuring Methods. in 13th International Conference on Electrical Drivers and Power Electronics*. 2005. pp. 62-66. ISBN 953-6037-42-4.
2. DOLEČEK R., ČERNÝ O. *Analysis of 25 kV, 50 Hz traction supply system at Czech Railways. Journal WSEAS Transactions on power systems Issue 7*, Volume 1, July 2006, pp. 1259-1266 ISSN 1790-5060.
3. SIMON E. *Implementation of a Speed Field Oriented Control of 3-phase PMSM Motor using TMS320F240,* Texas Instruments Aplication Report, September 1999.
4. NOVÁK J., GREGORA S., SCHEJBAL V. *Hardware for Real - Time AC Drive Analyses, in Proceedings of International Conference on Electrical Drives and Power Electronics*, CD-ROM – T4.3 C14, pp. 380 – 383, Vysoke Tatry, Slovakia 2003

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### Resumé

## REGULAČNÍ STRUKTURY PRO TRAKČNÍ POHON SE SYNCHRONNÍM MOTOREM S PERMANENTNÍMI MAGNETY

Jiří ŠIMÁNEK, Ondřej ČERNÝ, Radovan DOLEČEK

Článek popisuje výzkum robustní regulační struktury pro trakční pohon s PMSM. Jsou zde popsány dvě navrhované struktury. První ze struktur je regulace fázových proudů, která je založena na regulaci okamžité hodnoty proudu ve všech fázích motoru. Druhou ze struktur je regulace fázových proudů v dq osách. V článku jsou uvedené struktury porovnávány a jsou zde uvedeny výsledky ze simulací obou struktur. Dále jsou zde uvedeny dílčí výsledky z měření na trakčním pohonu s PMSM o výkonu 58 kW, na kterém byla aplikována regulace fázových proudů.

## Summary

## RESEARCH ON TRACTION DRIVE WITH PERMANENT MAGNET SYNCHRONOUS MOTOR

Jiří ŠIMÁNEK, Ondřej ČERNÝ, Radovan DOLEČEK

The paper deals with the description of our research in the field of the traction drive control. The aim of the research is the robust control algorithm for traction drive with permanent magnet synchronous motor (PMSM). The first chapter of the paper deals with the description of a workplace where the research is performed. The workplace contains a testing stand with PMSM, loading asynchronous motor, frequency converter and auxiliary systems. The testing stand contains the low speed PMSM, tram wheel and rotary rail. The wheel is powered by the PMSM directly without any gearings. The PMSM with nominal power of 58 kW was made by VÚES Brno (Research Institute of Electric Machines Brno) like prototype tram traction motor. Due this stand our experiments are applied to the drive with parameters similar to real traction drive of trams.

Next chapter is focused on theory of PMSM control. The control is oriented on current space vector position and magnitude. The orthogonality of current space vector and rotor flux vector is the aim of the control. The description of two designed control algorithms is in this chapter, too. The first algorithm is called phase current control which is based on the sinusoidal commutation algorithm of DC brushless motor. Due the several improvements this algorithm has better behavior at higher motor speed than original algorithm. The second algorithm is field oriented control. Both of the algorithms were simulated and the first algorithm was applied to the real drive.

The chapter 4 brings results of the simulation. The MATLAB Simulink software has been used for the simulations. The comparison of behavior of both algorithms is mentioned at the end of this chapter.

The last chapter brings comparison of simulation results and results from experiments on testing stand. Only the phase current control algorithm was applied to the stand until now, therefore the chapter does not bring any comparison of results of field oriented control with real measurement yet.

## Zusammenfassung

## REGULIERUNGSTRUKTUREN DES FAHRANTRIEBES MIT DEM PERMANENTMAGNETSYNCHRONMOTOR

Jiří ŠIMÁNEK, Ondřej ČERNÝ, Radovan DOLEČEK

Der Aufsatz behandelt die Forschung von einer robusten Regulierungstruktur des Fahrantriebes mit dem Permanentmagnetsynchronmotor (PMSM). Es wird zwei entworfenen Strukturen beschrieben. Die erste Struktur ist eine Phasenströmenregulation, die auf der Regulation der Augenblickstromwerte in allen Motorphasen begründet sei. Die andere Struktur ist eine Phasenströmenregulation in DQ Achsen. Diese Strukturen werden in dem Aufsatz verglichen und die Simulationresultaten der beiden Strukturen sind angegeben. Auch die Teilresultate der Fahrantriebsmessungen auf den 58 kW Leistungpermanentmagnetsynchronmotoren mit Phasenströmenregulation sind angegeben.