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Tuning of PI regulators in distributed control system for an electric vehicle

***Abstract**. In this paper a drive system for an urban electric vehicle is presented. The electric propulsion system consists of two in-wheel outer-rotor permanent magnet synchronous motors (PMSMs) fed by two three-level inverters. A proposed control system has been designed as a distributed one. The outer speed loop involves a master digital signal controller (DSC) whereas the inner current loops are closed using two slave microcontrollers. An effective analytical tuning of such a control system requires accurate identification of delays presented in all the paths, including the controller area network (CAN) bus used here to intercommunicate all the DSCs, the delays inherently related to a digital (sampled) nature of the system and the delay caused by a pulse width modulator. A step-by-step description of the analytical tuning of the controllers is provided. The tuning procedure respects all the identified delays and is validated experimentally in a non-mobile laboratory setup.*

Streszczenie.** Niniejszy artykuł przedstawia układ napędowy dla miejskiego pojazdu elektrycznego. Napęd elektryczny składa się z dwóch silników synchronicznych o magnesach trwałych zasilanych za pomocą trójpoziomowych falowników napięcia. Zaproponowany układ sterowania został zaprojektowany jako system rozproszony. Na nadrzędnym mikrokontrolerze zaimplementowano układ regulacji prędkości, natomiast na dwóch podrzędnych mikrokontrolerach wykonywany jest algorytm regulatorów prądu. Analityczne strojenie regulatorów wymaga dokładnej identyfikacji opóźnień występujących w systemie sterowania, w tym opóźnienia wprowadzane przez magistralę CAN, opóźnień związanych z cyfrową realizacją system oraz opóźnienie spowodowane przez modulator szerokości impulsów. W artykule opisano metody doboru nastaw regulatorów PI wraz z uwzględnieniem zidentyfikowanych opóźnień. Weryfikacja metod została przeprowadzona na laboratoryjnym stanowisku badawczym. **(Strojenie regulatorów PI w rozproszonym systemie sterowania napędem pojazdu elektrycznego).

Keywords: electric vehicle, Naslin polynomial method, optimal modulus criterion, system delays
Słowa kluczowe: pojazd elektryczny, metoda wielomianu Naslina, kryterium modułowego optimum, opóźnienia systemowe

Introduction

In the last years, the electric vehicles (EVs) have been investigated as an alternative form of transportation. They are seen as a way to reduce pollution emissions and noise from automobiles in the centre of the cities. Moreover, they have several advantages over internal combustion engine vehicles. The most important one is the possibility of applying a full torque at low speed, which gives opportunity to eliminate the clutch and gearbox. Another feature is easy feasibility of the independent drive of each wheel.

Figure 1 shows topology of the powertrain of the designed electric vehicle (ECO-Car). The vehicle drivetrain system consists of two in-wheel outer-rotor permanent magnet synchronous motors (PMSMs) mounted in the rear wheels [1, 2]. The PMSMs are fed by two three-level DC/AC inverters. The topology of inverters has been chosen to improve an efficiency of energy conversion and a quality of the output voltage waveform. The vehicle has been equipped with a hybrid energy storage system, containing $LiFePO_4$ cells and ultracapacitor stack. The ultracapacitor stack support electrochemical battery during acceleration and regenerative braking. The electrochemical battery and ultracapacitor stack are connected to the drive inverters through interleaved DC/DC converters [3].

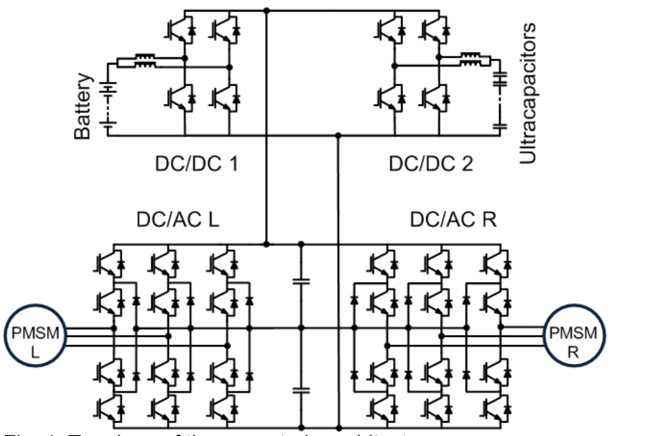

Fig. 1. Topology of the powertrain architecture

In the ECO-Car, due to using the direct-drive a control system has been designed as a distributed one. The control system includes three digital signal controllers (DSCs). One DSC operates as a master controller, the other DSCs operate as slaves. The current controllers of each motor have been implemented on the slave DSCs. The algorithm of the speed control is executed by master controller. The controller area network (CAN) bus is used here to intercommunicate all the DSCs [4-9]. It is the standard protocol in automotive applications related to on-board communication systems [10, 11]. The master and slave controllers exchange information about actual speed of each motor and reference currents. A schematic representation of the distributed control system is shown in Fig. 2.

This paper deals with the design of speed and current controllers for PMSM drive. The PI current controller has been tuned based on optimal modulus criterion [12]. For comparative purposes, two methods the Naslin polynomial [13] and the Matlab's *systune* function [14] have been used to select the PI speed controller parameters. The system delays are taken into account in the calculation of controller gains. The tuning process of PI controllers has been verified on a test rig.

Model of the drive system

The dynamic model of the PMSM in an orthogonal *dq* coordinate system can be described as:

$$u_d = R_s i_d + L_d \frac{\mathrm{d}i_d}{\mathrm{d}t} - p\omega_m L_q i_q \,, \tag{1}$$

$$u_q = R_s i_q + L_q \frac{\mathrm{d}i_q}{\mathrm{d}t} + p\omega_m L_d i_d + p\omega_m \varphi_f \,, \tag{2}$$

where: u_d, u_q – stator voltages in d and q axes, i_d, i_q – stator currents in d and q axes, R_s – stator resistance, L_d, L_q – stator inductances in d and q axes, φ_f – permanent magnetic flux linkage, p – the number of pole pairs, ω_m – rotor angular speed.

The electromagnetic torque is given by:

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

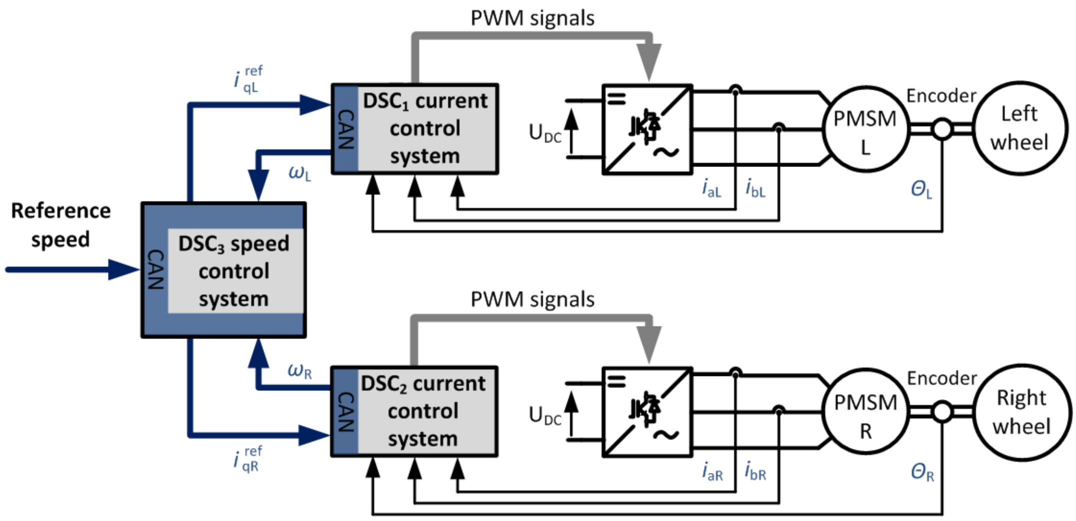

Fig. 2. Block diagram of the distributed control system

For a surface mounted PMSM, we have L_d=L_q, thus torque equation is

(4) $$T_e = \frac{3}{2} p\varphi_f i_q \, .$$

In order to eliminate the coupled term in (1) and (2), new variables

(5) $$u_{dc} = -p\omega_m L_q i_q \, ,$$

(6) $$u_{qc} = p\omega_m L_q i_q + p\omega_m \varphi_f$$

are subtracted from those equations. Considering that, the symmetric PMSM has been used for the drive system, the transfer functions for the two currents in *d* and *q* axes are the same

(7) $$G_{RL} = \frac{\frac{1}{R_s}}{1 + s\frac{L_q}{R_s}} = \frac{K_{RL}}{1 + sT_{RL}} \, .$$

The mechanical equation describing behaviour of PMSM motor is

(8) $$\frac{d\omega_m}{dt} = \frac{1}{J}(T_e - rF_R) \, ,$$

where: r – wheel radius, F_R – resistance force.

The resultant moment of inertia J is a sum of the moments of inertia from motor J_m, wheel J_w and the one associated with the vehicle J_v

(9) $$J = J_m + J_w + J_v \, .$$

The motor is supplied from voltage source inverter (VSI) controlled by using PWM method. VSI is approximated by the first order transfer function

(10) $$G_{PWM} = \frac{K_{PWM}}{1 + sT_{PWM}} \, ,$$

where: K_{PWM} –VSI gain, T_{PWM} –delay caused by a pulse width modulator.

The reference signal of PWM is updated once per period. Therefore, it has been assumed that delay T_{PWM} is equal a half of the PWM period [15, 16].

The delays occurred in control system are caused by filtering of speed $T_{m\omega}$, CAN bus T_{CAN} as well as the calculating algorithms of the slave DSCs T_{d1} and the master DSC T_{d2}. Each of the delays have been approximated as first order transfer function [15, 16, 17].

A discrete PI controller with anti-windup shown in Figure 3 has been adopted in the simulation and the experimental studies.

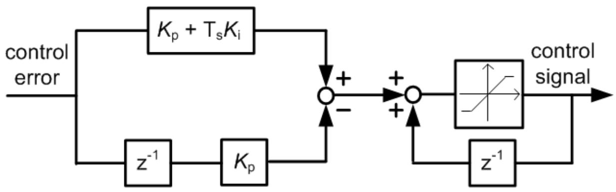

Fig. 3. Anti-windup PI controller block diagram

PI controller design

<u>Current controller</u>

A plant of current control loop is described by the transfer function

(11) $$G_c = \frac{K_{PWM} K_{RL} K_{mc}}{(1 + sT_{d1})(1 + sT_{PWM})(1 + sT_{RL})} \, ,$$

where: K_{mc} – measurement gain of the current.

In the plant, the dominant time constant is given by

(12) $$T_c = T_{RL} = \frac{L_q}{R_s}$$

and sum of small time constants is as follows

(13) $$T_{c\Sigma} = T_{d1} + T_{PWM} \, .$$

To design PI current controller, the plant transfer function (11) can be approximated by

(14) $$G_{co} = \frac{K_c}{(1 + sT_c)(1 + sT_{c\Sigma})} \, ,$$

where: K_c – gain of the plant.

The gain of the plant is equal to

(15) $$K_c = \frac{K_{PWM} K_{mc}}{R_s} \, .$$

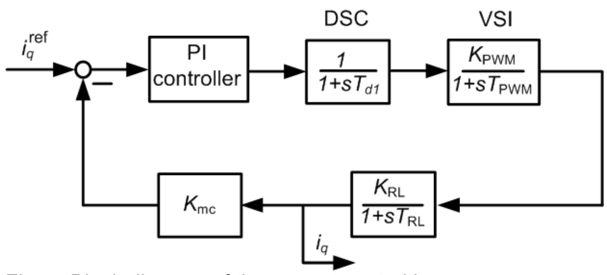

Fig. 4. Block diagram of the current control loop

Parameters of PI controller are obtained by using the modulus optimum method for the transfer function (14). This method ensures that the magnitude of the closed loop transfer function is almost equal to 1 in the widest possible frequency range. The block diagram of the current control loop is shown in Figure 4.
The proportional K_{pc} and integral K_{ic} gain of the PI current controller is obtained from:

(16) $$K_{pc} = \frac{T_c}{2K_c T_{c\Sigma}},$$

(17) $$K_{ic} = \frac{1}{2K_c T_{c\Sigma}}.$$

<u>Speed controller</u>

In order to determine gains of PI speed controller, the transfer function of closed loop current control should be calculated by substituting equations (12-17) and is equal to

(18) $$G_{cc} = \frac{\frac{1}{K_{mc}}}{2T_{c\Sigma}^2 s^2 + 2T_{c\Sigma}s + 1}$$

and assuming that $2T_{c\Sigma}^2$<<1:

(19) $$G_{cc} \approx \frac{\frac{1}{K_{mc}}}{1 + 2T_{c\Sigma}s}.$$

The transfer function for the plant shown in Figure 5 is given by

(20) $$G_v = \frac{\frac{K_{m\omega}1.5p\varphi_f}{K_{mc}J}}{s(1+sT_{d2})(1+s2T_{CAN})(1+s2T_{c\Sigma})(1+sT_{m\omega})},$$

where: $K_{m\omega}$ – measurement gain of the speed.

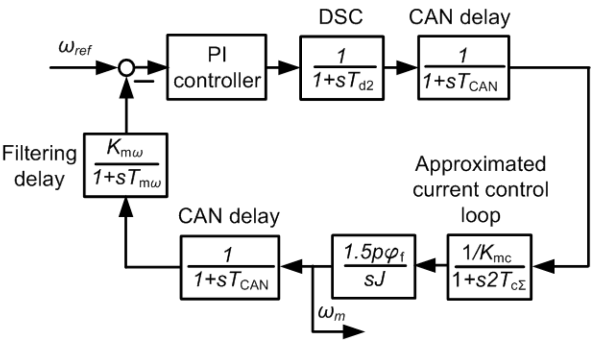

Fig. 5. Block diagram of the speed control loop

The sum of small time constants is expressed by

(21) $$T_{v\Sigma} = 2T_{CAN} + T_{d2} + T_{m\omega} + 2(T_{d1} + T_{PWM}).$$

The gain of the plant is equal to

(22) $$K_v = \frac{K_{m\omega}1.5p\varphi_f}{K_{mc}J}.$$

The transfer function of plant (20) can be approximated with the transfer function

(23) $$G_{vo} = \frac{K_v}{s(1+sT_{v\Sigma})}.$$

The proportional gain and integral gain can be calculated by using the Naslin polynomial method:

(24) $$K_{p\omega} = \frac{1}{\alpha K_v T_{v\Sigma}},$$

(25) $$K_{i\omega} = \frac{1}{\alpha^3 K_v T_{v\Sigma}^2},$$

where value of α factor affects rise time and overshoot in the process control.
The speed controller designed by Naslin polynomial method is compared with the controller tuned by the Matlab's *systune* function. The *TuningGoal.StepRejection* class [18] is used to specify a desired response for a step disturbance. The pseudocode with the *systune* function is described in Appendix. The parameters of the drive with PMSM and values of delays are presented in Table 1.

Table 1. The parameters of PMSM and the values of delays

Parameter	Value
R_s	1.1 Ω
L_q, L_d	15.57 mH
J	0.0201 kgm^2
p	4
T_{PWM}	50 μs
T_{d1}	100 μs
T_{d2}	100 μs
T_{CAN}	2000 μs
$T_{m\omega}$	2500 μs

Values of the speed and current controller parameters used in simulation and experiment are shown in Table 2.

Table 2. The parameters of PI controllers

	PI current controller	PI speed controller			
		α = 2	α = 3	α = 4	*systune*
K_p	4.1	14.2	9.4	7.1	14.4
K_i	293.3	511.4	151.5	63.9	507.0

Simulation and experimental results

The drive system with the PMSM, inverter and the designed controllers have been tested in Matlab/Plecs environment.

The experiments have been carried out by using a non-mobile laboratory setup (Fig. 6). The drive was equipped with the VSIs and the digital signal controllers TMS320F3335.

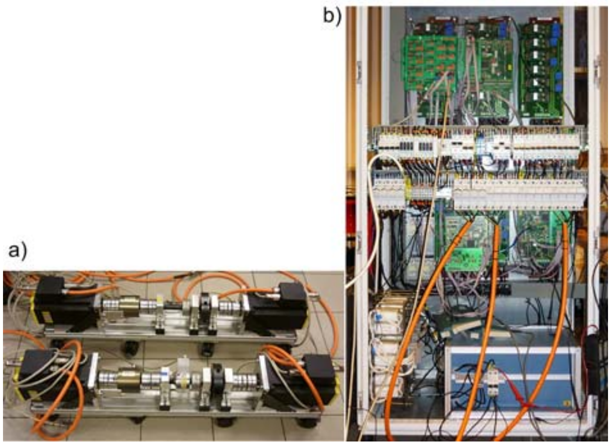

Fig. 6. Non-mobile laboratory setup: a) PMSMs set, b) power electronic equipment

Figure 7 shows the i_q current response for the step change in the reference current from 0 to 10 A. The tuned current controller provides the response without overshoot and the settling time of about 0.05 s. The relatively slow dynamics of the response is caused by the employed anti-windup scheme (Fig. 3). The experimental result shown in Figure 8 corresponds with the simulation result in Figure 7.

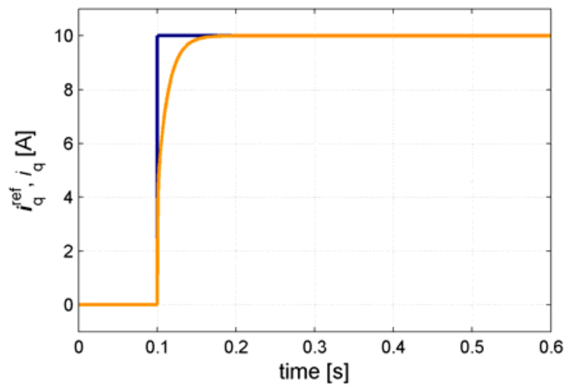

Fig. 7. Simulation result for current response

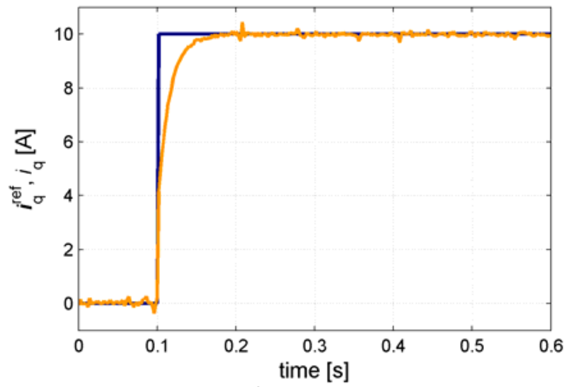

Fig. 8. Experimental result for current response

Figures 9 and 10 depict the speed response of the control system for the step change in the reference speed from 0 to 50 rad/s. The step of load from 0 to 100% occurs in 0.7 s and returns to 0 in 1.4 s. In the simulation and experimental studies speed controller was examined for various values of *α* factor.

Figures 11 and 12 show the speed response of the control system with speed controller tuned by *systune* function. The speed is with almost zero overshoot and satisfying control performance.

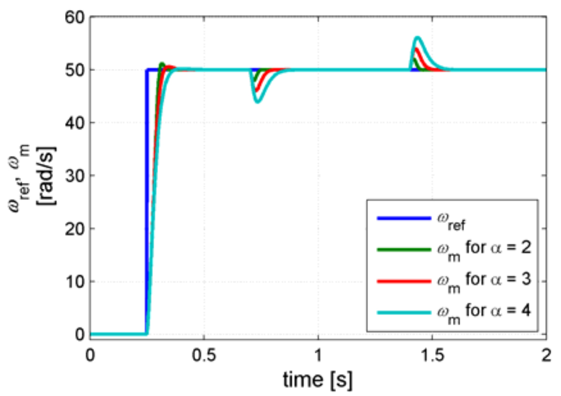

Fig. 9. Simulation results for speed response

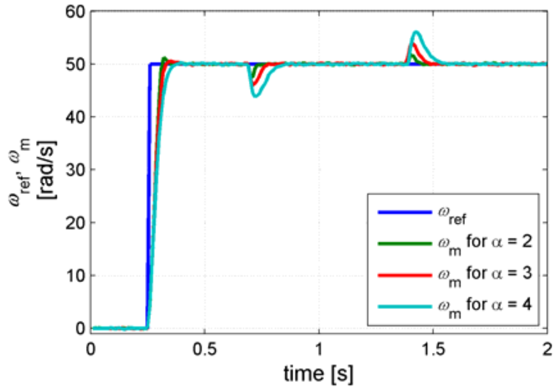

Fig. 10. Experimental results for speed response

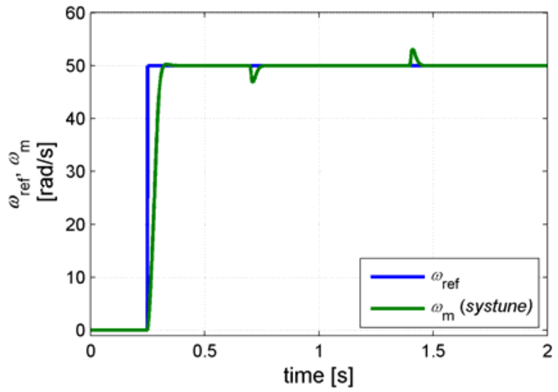

Fig. 11. Simulation result for speed response with PI controller tuned by *systune* function

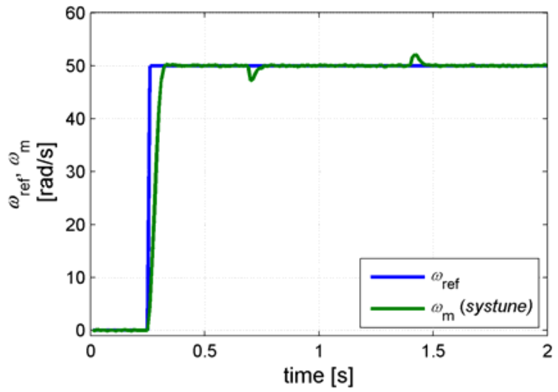

Fig. 12. Experimental result for speed response with PI controller tuned by *systune* function

Conclusions

This paper presents design approach of the controllers for the distributed control system of EV. A mathematical model of drive system, including all delays occurring in the control loops, has been developed. The model has been used to synthesize the speed and current control loops of the drive. The method of modulus optimum was used to derive expressions for the parameters of PI current controller. The PI speed controller was tuned by Naslin polynomial method as well as the *systune* Matlab's function. Presented results clearly indicate that including the communication delay is essential to proper tuning of speed controller. The simulation and experimental results validate the correctness of the designed controllers.

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Appendix

M-script for the PI speed controller tuning:

```
ST0 = slTuner('PI_Speed','PI Controller');
addPoint(ST0,'load');
addPoint(ST0,'wm');
Req = TuningGoal.StepRejection('load','wm,0.06,0.15,0.5);
Options = systuneOptions('RandomStart',10);
[ST1,fSoft,~,Info] = ST0.systune([ Req ],Options);
```

PI_speed – the simulation model.
PI Controller – name of PI speed controller.
load – name of disturbance input.
wm – speed measurement.
Req – the requirement sets a minimum standard for rejecting step disturbances.
[ST1,fSoft,~,Info] - the systune output.

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