Control algorithms in distributed system of three wheeled electric vehicle

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***Abstract*—The paper presents a concept, development and comparison of selected control algorithms used in distributed control system of a three wheeled vehicle. First simulations are carried out, then the selected algorithms are tested on a real vehicle. The article includes the description of the mathematical model of the tricycle: kinematics, dynamics, motor drives, central control system, communication network and a signal flow. The mathematical model has been implemented in Matlab/Simulink environment. The vehicle uniqueness base on that it is driven with three independent BLDC drives and equipped with generator coupled with pedals. The cyclist propels the generator, whose speed (depending an control algorithm) determines the speed of the wheels. The load of the driver varies depending on the actual load of the BLDC motors. Pedaling by wire novel idea of control scheme has been applied to the trike, which means that there is no mechanical coupling (by chain or shaft) between the pedals and the wheels of the tricycle. The lack of the standard mechanical coupling enables to implement various control methods that can be focused on: dynamic (performance) of the tricycle, energy efficiency and driving comfort. The paper discusses the problem of energy distribution between cyclist and the vehicle and focuses on control algorithms determining that distribution. Simulation are verified by experiment with waveform comparison. Analysis of research results supplemented by quality indicators. Conclusions and proposes of further investigations are presented.**

Keywords*—*electric vehicle, tricycle, modeling, BLDC motor, distributed control system, control quality rates

I. INTRODUCTION

The genesis of the article is a electric trike with unique mechanic and electronic construction, where the control system implementation due to the its kinematics and distribution is a challenge.

The article discusses the problem of motor control in three-wheeled electric vehicle. The trike that, while maintains appropriate standards may be referred to as an electric bicycle (e-bike) [1]. The vehicle uses an innovative wheels linkage with pedals. Instead of the standard coupling (by chain, shaft) pedals to the wheel, an electronic equivalent called *pedaling by wire* system is applied. The solution is based on the concept of driving the pedal generator which receives energy in controlled way through the inverter. Wheels are driven independently by three motor inverters, but only two of them are used in proposed algorithms implementation.

As it could be noticed, the described system is quite complex but flexible in the meaning of control aspects at the same time. It is possible to control the power flow in the way it is desired to fulfill normative demands for electric bicycle.

Electronic pedal engagement with drive wheels, however, is a challenge for the control system. To make the cyclist feeling close to a natural ones (when mechanical solution - chain - applied), generator speed need to be restored (with some set coefficient) in wheels as quick as possible. Same with the torque on pedals being a response from motor currents process values. That requires to implement system with high dynamics while the moment of inertia of the vehicle is much larger than in usual bike. Some attempts to control a generator for natural driver feelings were described in [2].

Wheel drives that could be controlled independently are related to the mechanical structure which need to be take account when signals are generating by central control module (CCM). Three main goals from practical point of view were defined for the CCM as follows:

- to keep desired energy flow (balance between energy consumed by motor drives and produced one by cyclist),
- to achieve high dynamic of speed and torque regulation responses (comparable to result of chain coupling as in the conventional bicycle),
- to obtain high energy efficiency of movement (by control of torque distribution in the drives in the given state).

The vehicle was presented on the figure 1 to show its real mechanical construction.

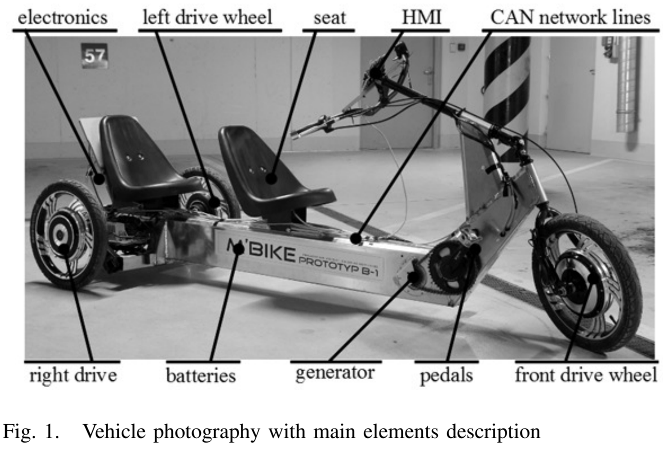


Fig. 1. Vehicle photography with main elements description

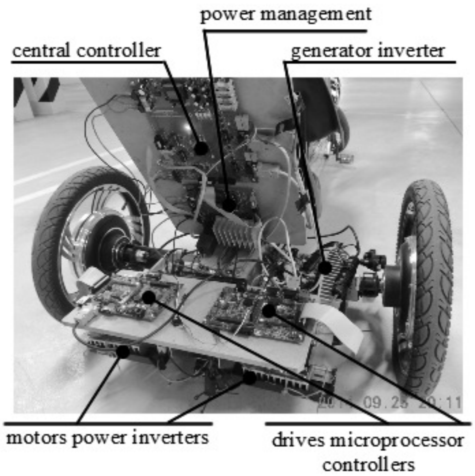


Fig. 2. Power- and micro-electronics section (rear part of the vehicle)

II. LITERATURE ANALYSIS

To achieve maximum flexibility of the system and its suitability for high power drives (aggregated up to 3 [kW]) used a complex, distributed control system based on CAN network (*Controlled Area Network*), tested and used for years in automotive industry. Topology of the system was presented in details in [3].

The article [7] presents an attempt to analyze the phenomena occurring in the vehicle drives in their original form. It assumed (according to preliminary findings) the inability to control the current/torque due to the very small stator winding inductance and the electronics limitations. In [7] the main emphasis is on a simplified model of the vehicle, but sufficiently accurate for testing control algorithms in different structures. That model is adopted and used in the research.

New construction of a dedicated inverter and the development of existing algorithms have allowed a sufficiently accurate and uninterrupted current measurement to effectively close the torque generation loop. Several control structures which implies ability of motor current measurements and use of that signals in the control system algorithms were introduced in [8]. Finally, few of proposed in [8] structures (after some modification discussed later) are finally implemented in the vehicle for experimental verification.

Because of the unique kinematic construction and driving system of presented vehicle there are hard to find other authors useful publications concern about the main topic of the paper. For example, [5] proposes control system solution, where the vehicle path is well known what is impossible to predict with human drive. Before the experimental verification, some simulations with parameters similar to the real system are made. Vehicle when testing uses two drives, while the articles: [7], [8] presents an analysis of system with three active drives. The model presented in previous papers evolve to be more accurate what is explained in the next section.

III. MODELING

A. Mechanics

The basic relations of kinematics of the model and its dynamics are shown on the figure 3, where a sketch of the vehicle in the horizontal plane together with the corresponding values are marked. The sketch with the following assumptions gives clear view of the mechanics model and its equations (1).

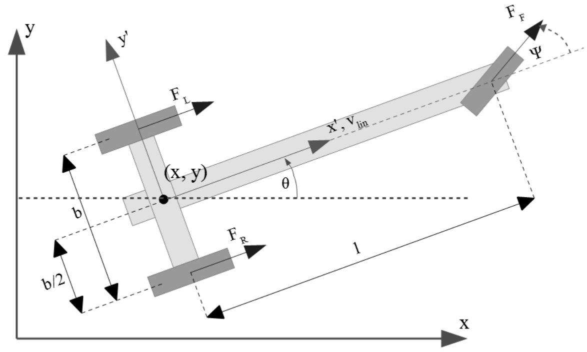


Fig. 3. Sketch of the modeled vehicle in the horizontal plane

The one of the main goals of the article is to compare different control algorithms and corresponding vehicle behavior. To reduce model complexity and make simulation time reasonable, some assumptions, so simplifications are made. It is explained in more details in [7].

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \\ \dot{\psi} \\ \dot{\varphi}_L \\ \dot{\varphi}_R \\ \dot{\varphi}_F \end{bmatrix} = \begin{bmatrix} cos(\theta) & 0 \\ sin(\theta) & 0 \\ \frac{1}{l}tan(\psi) & 0 \\ 0 & 1 \\ \frac{1}{r_L}(1-\frac{b}{2l}tan(\psi)) & 0 \\ \frac{1}{r_R}(1+\frac{b}{2l}tan(\psi)) & 0 \\ \frac{1}{r_F cos(\psi)} & 0 \end{bmatrix} \begin{bmatrix} V_{lin} \\ \dot{\psi} \end{bmatrix} \tag{1}$$

where: $x\,[m]$ – global position at x-axle coordinate; $y\,[m]$ – global position at y-axle coordinate; $\theta\,[rad]$ – global orientation; $\psi\,[rad]$ – steering angle; $\varphi_{L,R}\,[rad]$ – {left, right} wheel angle position; $l, b\,[m]$ – length, width of vehicle; $r_{L,R}\,[m]$ – radius of {left, right} wheel; $V_{lin}\left[\frac{m}{s}\right]$ – linear speed of the vehicle.

$$a_{lin} = \frac{F_{lin}}{m} = \frac{\left(\frac{T_L}{r_L} + \frac{T_R}{r_R}\right)cos(\psi) - k_{FT}V_{lin} - F_D}{m} \tag{2}$$

where: $a_{lin}\left[\frac{m}{s^2}\right]$ – acceleration; $F_{lin}\,[N]$ – resultant accelerating force; $T_{L,R}\,[Nm]$ – drive torque of the left, right wheel; $r_{L,R}\,[m]$ – radius of the respective wheel; $k_{FT}\left[\frac{Ns}{m}\right]$ – coefficient of the resistive force linearly dependent on vehicle speed (loss of motion); $F_D\,[Nm]$ – external disturbance force (e.g. as the result of overcoming obstacle).

B. Motor drives

There are three identical brushless DC motor (BLDC) drives built in wheels, while only two of them are powered and move the vehicle. The input of the BLDC is voltage signal U_m and the output is generated torque T_m. Motor speed is feedback signal from vehicle mechanic part of model. Motor is modeled in the simulation environment as an first-order inertia block as follows:

$$T_m(s) = k_e I_m(s) = k_e \left(\frac{U_m(s) - k_e \omega_m}{R_m(1 + \frac{L_m}{R_m} s)} \right) \tag{3}$$

where: $T_m\,[Nm]$ – generated electromagnetic torque; $U_m\,[V]$ – applied motor voltage; $I_m\,[A]$ – motor current; $R_m\,[\Omega]$ – motor model equivalent resistance; $L_m\,[H]$ – motor model equivalent inductance; $k_e\,\left[\frac{Nm}{A}\right]$ – torque constant; $\omega_m\,\left[\frac{rad}{s}\right]$ – motor speed.

Applied motor voltage is generated in power inverter (INV). MOSFET based three phase inverter (INV) are used in the vehicle with the pulse width modulation (PWM) frequency of 20 [kHz]. The model of the INV was modified comparing to presented in [7], [8] so the PWM modulator was added replacing the constant delay. Simulation current waveforms are different from experimental ones when non-linear modulator is omitted.

The drive controller depending on the investigating algorithms is simple P gain block (in voltage based control system - CS), current PI controller (torque based CS) or cascade PI controller (speed based CS). Controllers are with output limitations (current/voltage limits) and anti-windup algorithms (when integral part applied). When torque based CS applied, speed controller is placed in the central unit, so the CAN is a medium closing the speed control loop (propagate process value and set point).

C. Control system

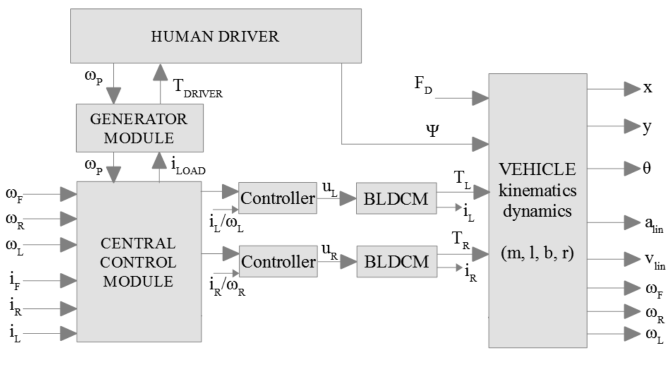


Fig. 4. Control system overview

As mentioned in the introduction, there is central control module (CCM) as the CAN network node. This module links the generator with motor drives. The generator torque is computed basing on drives currents (with proportional factor) along with the response from the artificially modeled inertia (increasing the naturalness feel of cyclist and the dynamics of response to the speed reference changing) [2]. Four different control structures (CS) are discussed in the paper:

- voltage based system with current limitation block in drive controller (CS1),
- speed based system with linear current controller in one-wheel drive (CS2),
- speed based system system of one wheel and supportive voltage based for another one (CS3),
- torque based system (current controller implemented in motor drive) with speed loop closing in the central control module (CS4).

The main difficulty for the CCM is that the simulation of chain coupling require high speed and torque response dynamics, while kinematics of the vehicle force differentiate rotary speeds of wheels (for example when changing direction or as an effect of difference in diameters of wheels). That means that the simple speed based control system used independently in all drives is practically not applicable because of forcing constant speeds by drives controllers algorithms ([7]).

The first tested structure is very simple. The reason of implementing is that open-loop, voltage-controlled motors are yielding and drives should easily fit to work states at different rotary speeds and same applied voltage (with some acceptable unbalance). The current limitations basing on the linear PI controller (turning on when current limit is overcome) what protects motors and converters from damage. The second structure with speed control loop was introduced to increase dynamics of the vehicle. The idea of the third structure was to compromise high system dynamics and usage of two motors beside one as in CS2 with no constant speed forcing by drives. CS4 gives well current balancing and dynamics, but the speed loop is closing by CAN network which may be more risk for driver when system failure occurs, so the appropriate security needs to be applied.

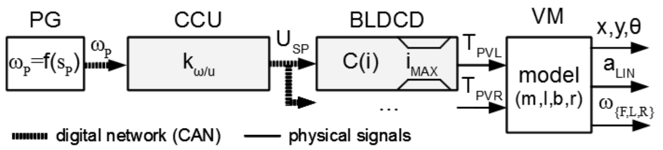


Fig. 5. Block diagram of the CS1

Figure 5 shows a generalized structure of the motors control system, which includes: a generator driven by pedals (PG), the central control unit (CCU) and two brushless DC drives ($BLDCD$). Listed only one direction of signal flow responsible for the movement of the wheels. Pedaling speed (ω_p) is scaled by coefficient $k_{\omega/u}$ depending on the current electronic gear resulting in a preset voltage value (U_{SP}) for two drives. The voltage motors are limited after exceeding a maximum current value i_{MAX}). Two electromagnetic torque signals (T_{PV}) generated by the drives are extortions to the mechanical part of the vehicle model(VM). Elements of the distributed control system integrates CAN network, which is schematically shown.

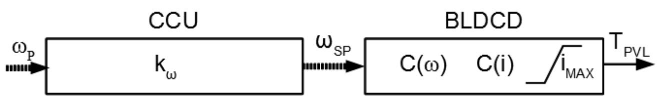


Fig. 6. Block diagram of the CS2

The second analyzed control structure ($CS2$) is shown on the figure 6. $BLDCD$ consists of cascade connected speed ($C(\omega)$) and current ($C(i)$) linear controllers with PI structure and output limitations (i_{MAX}, u_{MAX}) respectively. Controllers P and I gains are Ziegler-Nichols method based (comes from simulation model). Finally, gains are reduced to make sure the real system stability in the face of the distortions, so the model parameters uncertainly.

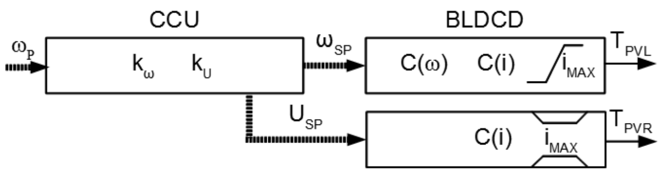


Fig. 7. Block diagram of the CS3

The structure form figure 7 was completed by voltage based supportive drive. It is introduced to use both the drives (to get better dynamics response) while two parallel working motors in the structure from figure 6 are not practically implementable.

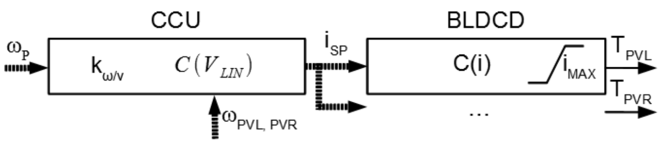


Fig. 8. Block diagram of the CS4

The last analyzed structure is that from figure 8. The conception is based on moving speed controller from the drive microprocessor unit to control central module (CCM). The CAN network is a medium for transferring data about current set point value, so drives rotary speeds as an feedback signal.

IV. Simulation and Experimental Results

A. Quality rates

There are proposed six quality rates computed from simulated and four for experimental signals to verify tested variations of control algorithms:

$R1$ – medium currents/torque unbalance $[A]$:

$$i_{ua} = \frac{\sum_{n=0}^{N}(max(i_{L,R}(n)) - min(i_{L,R}(n)))}{N} \quad (4)$$

,

$R2$ – maximum currents/torque unbalance $[A]$:

$$i_{um} = max_{n=0}^{N}(max(i_{L,R}(n)) - min(i_{L,R}(n))) \quad (5)$$

,

$R3$ – maximum achieved acceleration during tests $[m/s^2]$,

$R4$ – maximum achieved speed $[m/s]$,

$R5$ – simulation time as an derivative of the computational complexity $[s]$,

$R6$ – energetic efficiency $[W/W]$:

$$\eta_m = \frac{\sum_{n=0}^{N}(T_L(n)\omega_L(n) + T_R(n)\omega_R(n))}{\sum_{n=0}^{N}(u_L(n)i_L(n) + u_R(n)i_R(n))} \quad (6)$$

Rates R5 and R6 are computed only based on simulation results.

B. Testing signals

The testing extortions in simulation emulates human driver behavior. Because it is hard to obtain same extortions in experiment with human driver (especially in dynamic states), comparison focus on stable states: moving with the constant speed, turning left/right with constant steering angle, gaining maximum possible speed.

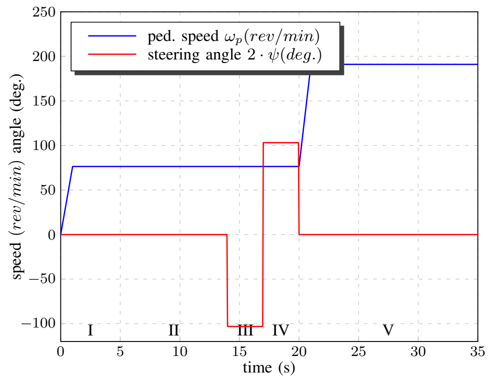


Fig. 9. Input signals of the model for testing purposes

C. Results

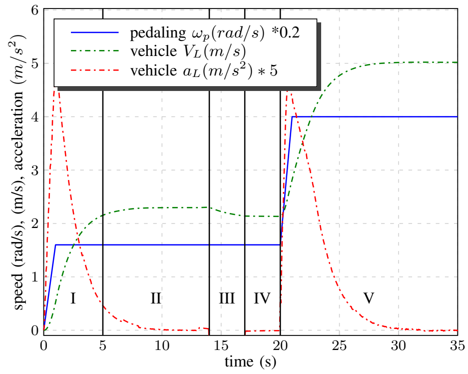
While signals from simulation waveforms are continuous, signals from experiment are cut from full record to fit the stable states time periods and will be discontinuous. Waveforms are marked with corresponding sections (vehicle states): I - start process, II - constant speed (at around 10 [km/h]), III - turning left, IV - turning right, V - achieving maximum speed.

The simulation and experimental results are set together to show relations between them. Two types of waveforms are presented:

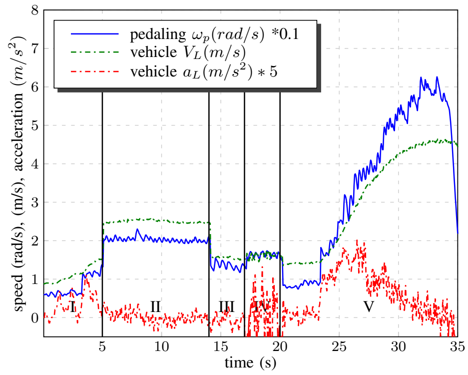
- for speeds analysis (with process values of speed set point, vehicle linear speed and vehicle acceleration to show dynamics),
- for currents analysis (with process values of left and right drive currents to show potential torque generation unbalance at different vehicle states).

Four different structures of the control system are testing (CS1, CS2, CS3, CS4 – as described in the $controlsystem$ subsection) on the simulations and experiment. The results in the form of selected waveforms are presented on the following figures.

Figure 10 and 11 shows speed, acceleration and current waveforms for control structure 1. In general, all states of movement on simulations and experiment are similar, besides acceleration which has lower value when real system testing (caused by the resistive torque on pedals). Stable state on constant speed 2,5 [m/s] gives same currents value. Current differences between left and right drive are caused by differs in motors parameters (5-10% in L,R,ke values). Maximum reached speed is about 5 [m/s]. Figures 12 and 13 shows, that speed controlled loop gives more dynamics in current/torque generation.

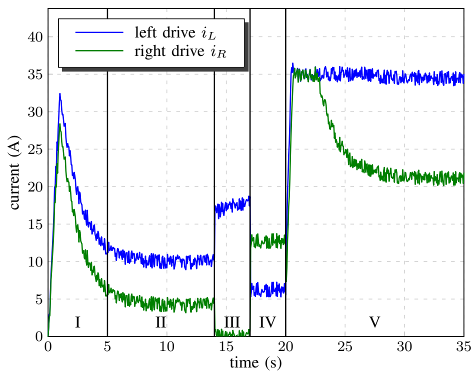


(a)

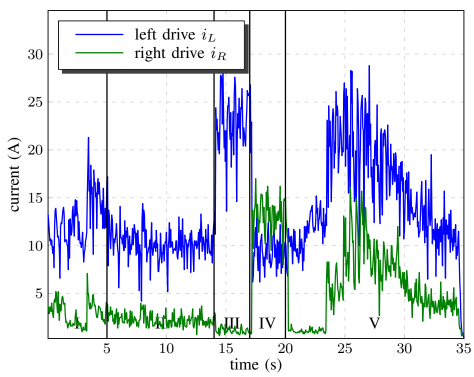


(b)

Fig. 10. Speed waveforms for CS1 (a) – simulation, (b) – experimental



(a)

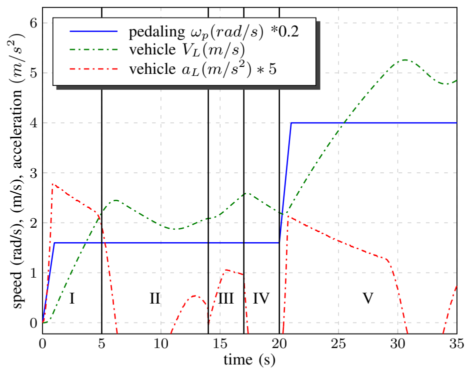


(b)

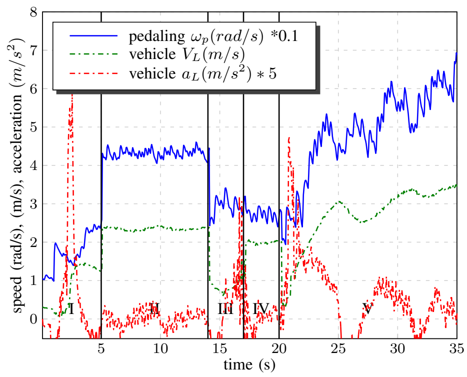
Fig. 11. Current waveforms for CS1 (a) – simulation, (b) – experimental

Maximum accelerations in real vehicle are even higher than in CS1 beside there is only one drive used in CS2. Speed response in simulation results has overshoot, in experiment stable state was recorded after oscillations decay. Same oscillations are visible in region V of figure 12b and on current waveforms. Lower amplitudes of currents in real system are derivative of milder extortion signal damped by resistive torque on pedals. Speed regulation loops either in simulations and experiment works, but need to be verified to reduce overshoot in signals.

Adding supportive, voltage controlled in open loop drive results in better dynamics and maximum speed and acceleration achieved. Simulation and experimental results are comparable, especially in constant speed stable state (region II). Signals overshoot visible on waveforms from CS2 are much reduced by additional drive. Analyze of waveforms from figures 16 and 17 representing results of CS4 implementation shows that the main advantage of that CS is achieved - currents balance. It means that in all the time and vehicle states torque generated in each drives are same, so the maximum possible dynamics could be achieved. The partial-time unbalance (section V of figure 17b) is caused by inability to control the current through the achievement of electromotive forces comparable to the supply voltage level (at high speeds). Signal oscillation clearly seen in simulation results from large delay (speed loop closing through CAN network) comparable to PI controller sets. Those oscillation at comparable periods but strongly suppressed are visible also in experimental results. To achieve better quality of control the delay must be reduced so the PI speed controller recalculated.



(a)



(b)

Fig. 12. Speed waveforms for CS2 (a) – simulation, (b) – experimental

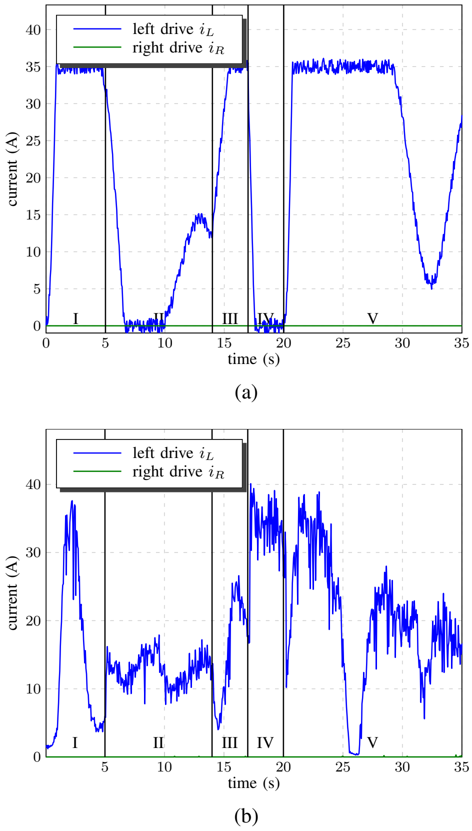


Fig. 13. Current waveforms for CS2 (a) – simulation, (b) – experimental

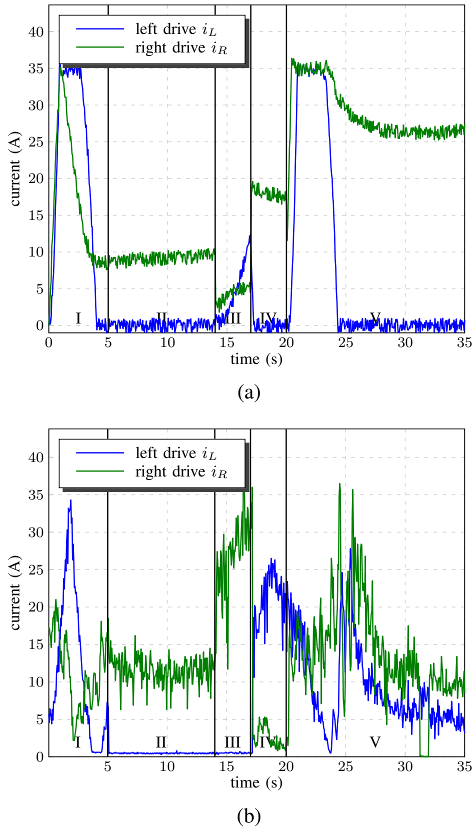


Fig. 15. Current waveforms for CS3 (a) – simulation, (b) – experimental

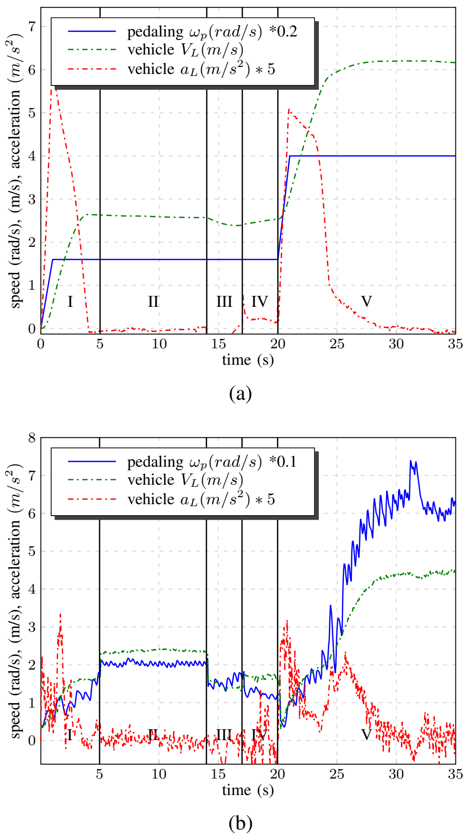


Fig. 14. Speed waveforms for CS3 (a) – simulation, (b) – experimental

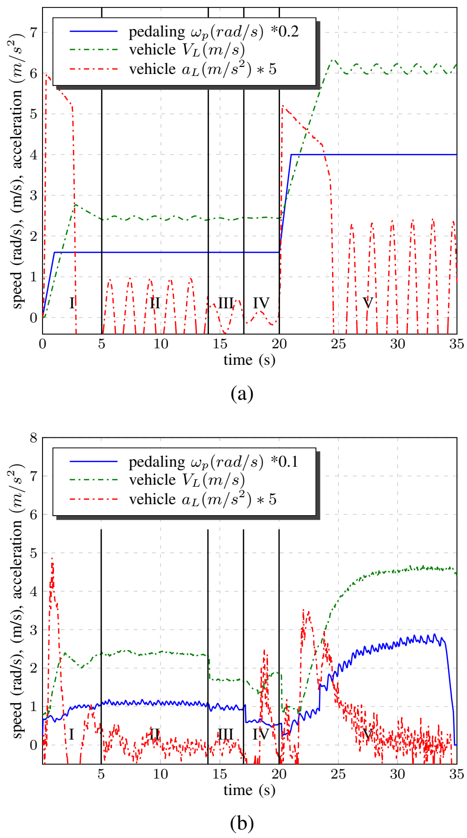
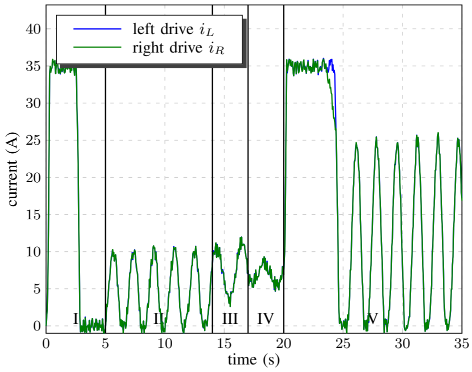
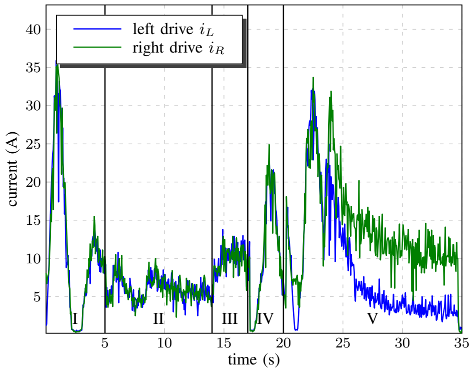


Fig. 16. Speed waveforms for CS4 (a) – simulation, (b) – experimental



(a)



(b)

Fig. 17. Current waveforms for CS4 (a) – simulation, (b) – experimental

TABLE I. COMPARISON OF CONTROL SYSTEMS QUALITY (SIMULATION)

NO.	UNITS	CS1	CS2	CS3	CS4
R1	$i_{ua}[A]$:	8,38	20,71	14,48	0,17
R2	$i_{um}[A]$:	17,78	35,15	31,05	6,43
R3	$a_{max}[m/s^2]$:	1,02	0,56	1,17	1,20
R4	$v_{max}[m/s]$:	5,02	5,26	6,20	6,34
R5	$t_{sim}[s]$:	92,25	78,69	94,97	89,47
R6	$\eta_m[W/W]$:	0,71	0,55	0,62	0,67
SUMMARY	[PTS] :	9	4	7	16

TABLE II. COMPARISON OF CONTROL SYSTEMS QUALITY (EXPERIMENT)

NO.	UNITS	CS1	CS2	CS3	CS4
R1	$i_{ua}[A]$:	9,79	18,12	11,24	3,32
R2	$i_{um}[A]$:	26,60	40,10	36,00	18,90
R3	$a_{max}[m/s^2]$:	0,40	1,18	0,67	0,97
R4	$v_{max}[m/s]$:	4,64	3,52	4,54	4,67
SUMMARY	[PTS] :	6	3	4	11

Computed rates shown that the proposed control system structures significant differs from each other. It is confirmed that the currents unbalance in voltage based control system (CS1) are at acceptable level, while CS2 and CS3 gives poor rates at this aspects. CS4 either in simulation and experimental is characterized by the best overall quality of the investigated control structure. It is also important that comparable summary results are computed from simulation and experiment verification.

V. CONCLUSIONS

Four different control structures for three-wheel vehicle with a novel concept of electric gear are shown in the article. After waveforms analysis it may be said that model was verified by experimental results with some differences arising from the simplifications and difficulties to take into account the human factor (vehicle driver). A good indicator of the convergence of the model are the summary results of quality indicators in the table for the simulation and experiment. The ratio of the achieved score for individual control structures are almost the same in both tables.

The above leads to the conclusion that the greatest potential for an implementation and development has structure CS4 (central speed loop closed by CAN interface with same current/torque set point for each motor drives), which is characterized by top quality indicators. CS1 (open-loop voltage-based control with current limitation) is practical because of its simplicity, but reduction of the achievable dynamics need to be take account if applied. CS2 and CS3 (as an combination of CS1 and CS2) works, but practical implementation due to the low quality rates is limited. The structure CS4 will be subjected to further evolution, in particular for achieving better performance (increased dynamics rate while reducing overshoot in speed control circuit).

The vehicle model will be developed to obtain better convergence with real system. An important change is the introduction of a three-phase motor nature in terms of the electronic commutation taking account. Switching processes and variability of the magnetic flux in the presence of interference in the feedback signals are the cause of significant fluctuations of currents recorded in a real system, what is not visible in simulation waveforms.

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