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Traction group drive fed by an inverter with reduced switching frequency

Abstract*. The article presents a concept of the control algorithm for the traction group drive consisting of two cage induction motors supplied from the common inverter, which could operate with reduced switching frequency and the result of its testing on a physical model in the laboratory. These tests were conducted on a specially constructed bench, simulating in laboratory scale the true nature of phenomena accompanying the passage of the wheels through the rail crossing, associated with an abrupt change in the angular velocity of the wheels belonging to the same group drive. (****Trakcyjny napęd grupowy zasilany z falownika, pracującego z obniżoną częstotliwością przełączeń****).*

Streszczenie. *W artykule przedstawiono koncepcję algorytmu sterowania dla grupowego napędu trakcyjnego składającego się z dwóch klatkowych silników indukcyjnych zasilanych ze wspólnego falownika, mogącego pracować z obniżoną częstotliwością przełączeń i wyniki badań jego fizycznego modelu laboratoryjnego. Badania przeprowadzono na specjalnie zbudowanym stanowisku pozwalającym odtworzyć w warunkach laboratoryjnych rzeczywisty charakter zjawisk towarzyszących przejazdowi kół pojazdu szynowego przez połączenia torowisk, wiążących się z raptowną zmianą prędkości kątowej kół należących do tego samego napędu grupowego.*

Keywords: asynchronous group drive, mixed vector-scalar control, improved current control, low switching frequency.
Słowa kluczowe: asynchroniczny napęd grupowy, mieszane sterowanie wektorowo-skalarne, ulepszona regulacja prądu, niska częstotliwość przełączeń.

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Introduction

Most of the modern traction drives use the induction motors which are fed by the voltage inverters. The group drive concept is presented in Fig.1.

In general the control system is responsible for realization of the torque set-point where working conditions like traction voltage, motor speeds and currents are the input signals. The high level system calculates the output voltage vector which is realized by the low level controller - voltage inverter. Usually one bogie car has two axles with wheels which are driven by the separate motors wherein each of them is controlled by a dedicated inverter. However because of the economic reasons the most desirable situation is that both of motors are fed by single, but bigger inverter.

That simplification in construction could reduce the overall cost of the drive by 30% [4], but also brings serious considerations about its stability. It is pretty obvious that there is an internal contradiction. In the group drive both motors have strong electrical coupling because they are supplied by the same voltage source. The mechanical coupling between their shafts are the coupling between the shafts is not as rigid as the wheels rolling on rails may temporarily lose their adhesion. That configuration means that there is only one control variable – inverter output voltage and two degrees of freedom – two electromagnetic states of the motors. As the results the wheels can independently rotate with different speeds and thus create different slip frequencies what leads to motors states discrepancy [4].

The phenomenon of rapid change in wheel speed is unfortunately quite common in tramway vehicles. It can be observed when tram passes the intersection of the tracks, *i.e.* on crossroads. In this particular place wheel starts to roll on its rim instead of on rolling surface [1]. The change in point of contact between wheel and rail results in rapid change of the speed. Because of the same voltage on the motors taps the huge change in stators currents can be observed as a result of angular difference between motors fluxes.

Fortunately the overcurrent is not so destructive to the motors because of its short duration but it can lead to the damage of the inverter transistors. The significant challenge was to develop suitable control strategy which should be applied for aforementioned transient state. The aim of control strategy is stabilization of the motor which electromagnetic state deviates the most from reference one. The conducted research leads to a various control strategies with different capabilities.

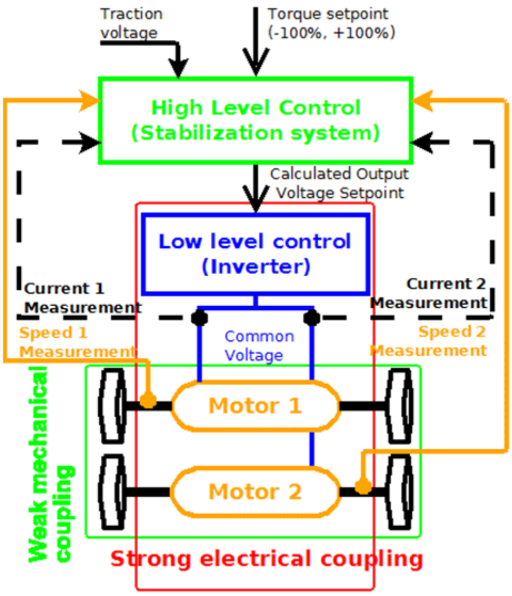

Fig.1. Traction group drive of a rail vehicle bogie

Since the work on the real tramway may be expensive and time consuming solution, it was decided to develop a dedicated laboratory test stand to study traction group drive. This rig was designed and built at the Institute of Automation, Technical University of Lodz. The concept of the laboratory test stand was based on the idea of an infinite rail which profile was characteristic of the tramway traction. Because of the compact construction and powerful microprocessor system even the most advanced algorithms can be easily tested and validated.

Theoretical model of IM for current oriented control

Dynamics of a single induction motor can be described in many ways which come from flexibility in selection of the differential equations. One can build a complete model by choosing two of four state variables from Kovacs-Racs description of an asynchronous machine. One of the possibilities is pair of equations – one for stator current i_s and second for rotor flux ψ_r. Both of them are described in synchronously rotating coordinate system, which is aligned with stator current vector as shown in Fig.2, [2, 6, 9, 10].

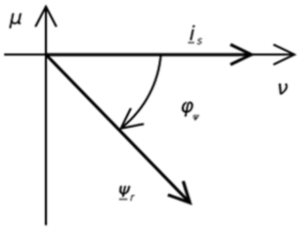

Fig.2. Stator current - oriented coordinate system (in form of Cartesian rectangular coordinates $\boldsymbol{\mu}-\boldsymbol{\nu}$, or in form of polar coordinates $|\,.\,|-\boldsymbol{\varphi}$)

In that coordinate system the electromagnetic state of an induction motor can be fully represented by the pair of vectors ψ_r, i_s and the angle between them φ_ψ [6]. The electromagnetic torque created by the motor can be derived in form (1)

$$m=-\frac{l_m}{l_r}\psi_r i_s \sin\varphi_\psi \tag{1}$$

where: l_m – magnetizing inductance, l_r – rotor inductance.

Under assumption, that motor is fed by a voltage inverter, which forces the reference current in stator windings, the motor dynamics can be described with the polar variables in relative units as shown in (2).

$$\begin{aligned}\frac{1}{\omega_b}\frac{d}{dt}\psi_r&=-\frac{r_r}{l_r}\psi_r+\frac{r_r}{l_r}l_m i_s\cos\varphi_\psi\\ \frac{1}{\omega_b}\frac{d}{dt}\varphi_\psi&=-\frac{r_r}{l_r}l_m i_s\frac{1}{\psi_r}\sin\varphi_\psi-\omega_r\end{aligned} \tag{2}$$

together with the voltage equations

$$\begin{aligned}w\frac{1}{\omega_b}\frac{d}{dt}i_{s\mu}&=-\left(r_s l_r+\frac{r_r}{l_r}l_m^2\right)i_{s\mu}+w\omega_s i_{s\nu}\\ &+l_m\psi_r\left(\frac{r_r}{l_r}\cos\varphi_\psi+\omega\sin\varphi_\psi\right)+l_r u_{s\mu}\\ w\frac{1}{\omega_b}\frac{d}{dt}i_{s\nu}&=-\left(r_s l_r+\frac{r_r}{l_r}l_m^2\right)i_{s\nu}-w\omega_s i_{s\mu}\\ &+l_m\psi_r\left(\frac{r_r}{l_r}\sin\varphi_\psi-\omega\cos\varphi_\psi\right)+l_r u_{s\nu}\end{aligned} \tag{3}$$

where:

$w=l_s l_r-l_m^2$ – leakage factor
$i_{s\mu}$, $i_{s\nu}$ – components of the stator current vector
r_r – rotor resistance
ω_b – base value of angular speed
ω_s – angular speed of reference coordinate system
ω – current angular speed of motor shaft
$\omega_r=\omega_s-\omega$ – slip frequency
$u_{s\mu}$, $u_{s\nu}$ – components of the stator voltage vector

The position ϑ_s of the synchronous with stator current vector rotating frame can be calculated as the integral of the synchronous angular speed (4).

$$\vartheta_s=\int_0^t(\omega_r+\omega)dt \tag{4}$$

The control variables of dynamic system (2) are stator current vector i_s and slip frequency ω_r. By proper calculation of these values it is possible to achieve independent control of an electromagnetic torque m and rotor flux variables ψ_r and φ_ψ . Moreover from (2) comes important information about rotor flux time constant. For the medium power units which are widely used in the traction vehicles it is to about 0.5 s. This becomes important when there is a request to change electromagnetic state in shortest possible time what occurs quite often during emergency braking or in case of wheel slip [5]. Moreover rapid change in angular position caused by the passing through the crossroads also rotates the rotor flux vectors. The uncontrolled discrepancy cannot be compensated by the current regulators. However the feed forward reference value of the stator voltage can be calculated from (3) what improves the response of the control system in case of such disturbance [4, 10].

The presented description of the single induction motor can be extended to the case of the traction group drive. The electromagnetic states can be shown as in Fig.3. States variables are stator current vectors $i_s^{(1)}$, $i_s^{(2)}$ and rotor flux vectors $\psi_r^{(1)}$, $\psi_r^{(2)}$ which fulfil appropriately transformed equations (2) and (3). To complete description the proper constraints must be introduced. On the electrical side both models are coupled with the same stator voltage vector u_s which is used to shape the excitation variable – inverter output current vector $i_f=i_s^{(1)}+i_s^{(2)}$. However it is not possible to properly describe mechanical part *i.e.* by averaging parameters of the motors, *i.e.* angular speeds. That is because the wheels are not directly coupled and some discrepancy in speeds is allowed and sometimes even desired. Instead there was proposed description of the mechanical side by introducing angular positions $\vartheta_s^{(1)}$, $\vartheta_s^{(2)}$ of the reference frames for both electromagnetic states.

These new variables can also be considered as the additional excitation variables. The step change in these angles caused by the impulse change in the corresponding speed seriously influences the stability and controllability of the group drive.

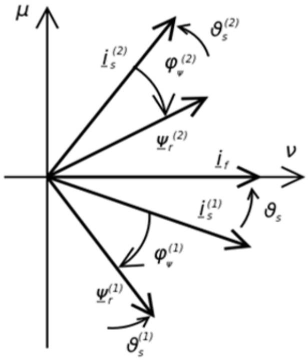

Fig.3. The electromagnetic states of the traction group drive

Fundamental difficulty derived from the presented dynamic model is that step change in angular speeds can affect only one motor. In that case there is a rapid discrepancy in angular positions what influences the produced torques (1) and the currents (3) in the stators windings because of the stator voltage constraint.

The final result of that disturbance is the uncontrolled increase in currents amplitude and emergency shutdown. The main constraint is that there is only one control variable – inverter output voltage and two independent disturbances – the angular speeds.

Current-oriented indirect torque-flux control (C-O ITFC) with a special method of stator voltage vector reconstruction

It is well known, that the base for many indirect and sensor-less vector control algorithms proposed for induction motor drives is the internal, subordinated stator current vector controller. This is necessary even if the motor is fed by the voltage inverter. The PI controllers with various modifications are the state of the art of the current waveform shaping [16]. Very often for improving efficiency of proposed current control algorithms, to the output of the current controller is added a component compensating the electromagnetic force created in the motor's windings. However such compensation is in many cases not sufficient. Because of the great importance of an exact stator current control for all asynchronous drives, it is rather obvious, that the most convenient coordinate frame for describing the motor electromagnetic state should be a stator current vector oriented polar coordinate system shown in Fig.2 [9].

The appropriate choice of induction motor electromagnetic state variables is especially important for the traction purposes where precise control of internal torque is significant only for the low speed and for the high speed it is enough to control only rotating speed through the proper voltage vector set-point. It is entirely possible due to the proposed by the authors of the novel control method. The proposed current – voltage method is based on the concept of the rotor inverse model which was proposed many years ago by one of the authors [2, 4, 5, 6]. The core idea is to combine the feed-forward calculated control value enabling compensation of the electromagnetic force with the prediction of the expected dynamic change (Fig.4). The prediction is obtained from the reverse model, also called by authors “state stimulator”.

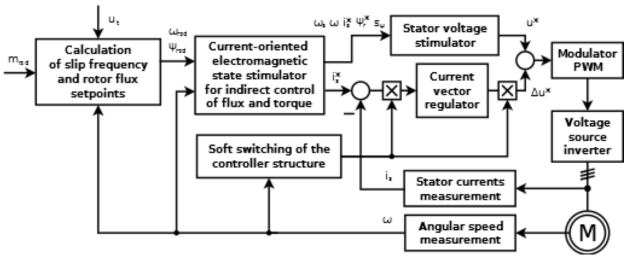

Fig.4. Control scheme of the IM drive with current-oriented indirect torque and flux control (C-O ITFC) proposed for traction applications

That solution allows for full control of the electromagnetic state using the current regulators for the low speed. The increase of the speed is followed by the smooth switch to the voltage control. This allows adjusting the mean value of current and flux. The scheme of the indirect control system shown in the Fig.4 consists of two parts: the inner control loop of the current and outer one of the flux [9,10]. The task of the outer loop is forcing of calculated set-point of the current vector on the basis of the torque set-point. For the internal control loop it is appropriate to assume that the synchronous rotating reference frame of the dynamic model is aligned to the actual value of the current vector set-point.

To increase ability of the drive to work with very low switching frequency of the inverter a special algorithm of the IGBT firing pulses modulation is proposed. Common property shared among most of the vector oriented control methods for the induction motors is shaping the current waveform by the rotating voltage vector with the desired accuracy. It is done mostly with use of the pulse width modulation with the assumption that average voltage vector during pulse's period should be equal to the required set-point [2]. However for the low switching frequency also the angular position of the vector should be taken into account. In this condition the voltage at the motor's clamp should be treated during long pulse period as the sequence of the space vector voltages. The distortions introduced by the phase delays in realization of the voltage vectors must be compensated in the control method [12-17].

The concept of the modulator is not to provide calculation of the optimal sequence for actual angular position of the rotating reference frame. The idea is that modulator should do it inversely. For the actual angular speed of the synchronous coordinate system the modulator task is to calculate the optimal switching frequency to fit the required voltage vector into the nearest optimal angular position which was calculated offline. The optimal sequence can be found easily because it must fulfil the requirement of the symmetry to provide the lowest distortion level. The modulator structure is shown in Fig. 5, where:

ω_{out} – angular speed of the voltage vector,
u^* – the voltage vector set-point in the Cartesian coordinate system.

While the output signals are:

f_{imp} – the switching frequency of the PWM,
u_z – equivalent voltage vector calculated by PWM.

Internal signals, corresponding to its internal state are:

k_v – the number of the equivalent vectors,
θ – angular position of required voltage vector,
δ – angular position of selected equivalent vector,
f_{imp} – the base switching frequency of the PWM,
Δf_{imp}– correction of the switching frequency.

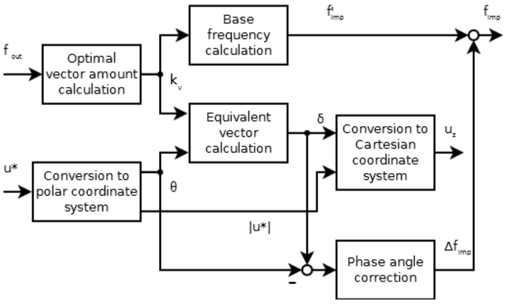

Fig.5. Block scheme of the proposed modulator

During application of the presented control method the distortions introduced by the realization of the voltage vectors become the serious problem. The calculation of the angle position of the individual voltage space vectors presents the significant and complex numerical problem. However the authors proposed to introduce special vector modulator which can properly realize the required voltage vector in the optimal sequence. This element works as an intermediary layer and allows for implementation of any vector oriented method in the low switching inverter.

The reference drive, where each motor has its own inverter coupled with control system, is presented in [5, 9, and 10]. In that case the electromagnetic states are under full control. The disturbance in one drive does not propagate or influence the second and the discrepancy of the reference set-point is quickly cancelled. The current waveforms are stabilized and the inverter output current is under control.

Group traction drive laboratory stand

Classical approach to construction of stands suitable for investigation of drives is the interconnection of motor and generator with a rigid shaft. However in this system it is not possible to study the group drive together with characteristic for that drive dynamic states in which rapid change of angular speed of one of the dynamic states is observed. Therefore it was desirable to create novel stand suitable for such investigations.

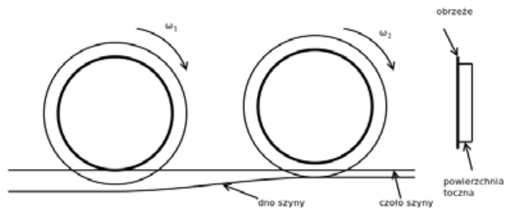

Fig.6. Change in wheel angular speed during passing the crossroad

Fig.7. The laboratory stand for modeling transient state of group traction drive

Designed stand (Fig.7) models passing through the crossroads, during which tramway ceases to roll on the main surface of the wheel, while it starts to roll on its rim (Fig. 6). It causes the change in wheel diameter followed by rapid change in wheel angular speed while its linear velocity remains unchanged due to significant inertia of the vehicle.

Due to enormous dimensions, power and weight of real drive systems the stand was built to scale, where as a scale coefficient ratio of vehicle weight to its power calculated on the motor side was employed – due to proper phenomena modeling this coefficient should not be below 8 kg/kW. The main concept of the stand design is the opposite situation compared to the real drive – motors with powered wheels are static, while rails are mobile.

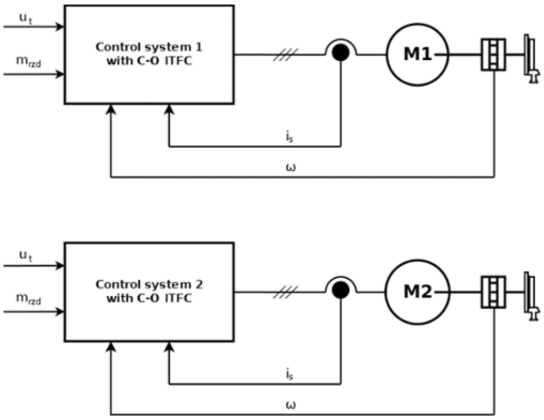

Fig.8. Block scheme of the bogie drive with independent vector control systems for each of the two motors, using two independent voltage inverters

Simulation results calculated for the computer model of the group drive laboratory stand

Laboratory stand shown in Fig. 7 offers the opportunity not only to test a group drive, i.e. when both motors are fed from common inverter, but also to compare the behavior of the motors when they are controlled entirely independently of each other, *i.e.* when two separate voltage inverters are used for their feeding. At the beginning of testing different versions of control algorithm proposed for the asynchronous group drive, some simulations using PSIM-Powersys software was performed.

In Fig.9 are shown the results for fully independent control of both motors of the bogie depicted in Fig.8.

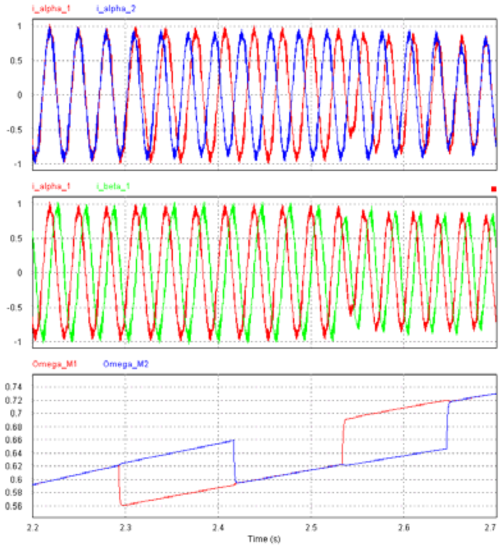

Fig.9. Comparison of the stator current vectors (alpha component), feedback signals for the first controller and angular speeds of the motors in case of the use of the independent inverters.

However the traction group drive with one inverter does not offer such high flexibility in shaping state of the system. It structure is shown in Fig. 10, where the main system is arithmetic-logic current and speed transducer. This element is responsible for the evaluation of the current electromagnetic states of the motors.

Because it is not possible to fully control both of them the main challenge is to provide method for selecting motor which should be stabilized. The main criterion should be that inverter output current amplitude should not exceed the limits of the inverter's transistors. In the frame of research the different control strategies were validated. Most exemplary results were obtained when the current control loop uses the feedback calculated as the nonlinear (switching) function:

1) Selection of the feedback signals from the motor with a averaged speeds and stator currents.
2) Selection of the feedback signals from the motor with a higher speed or higher stator current amplitude.

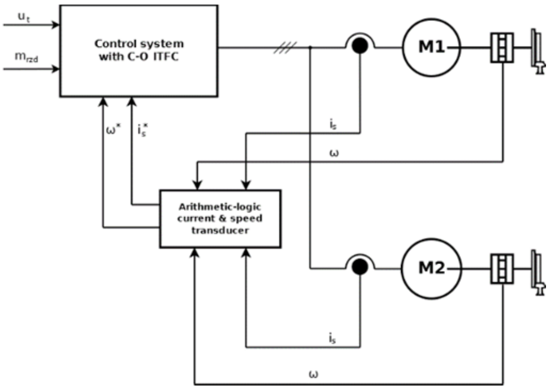

Fig.10. Block scheme of the bogie drive with one voltage inverter and only one common current-oriented indirect torque-flux control system based on averaged measurements of stator currents and shaft speeds of both motors

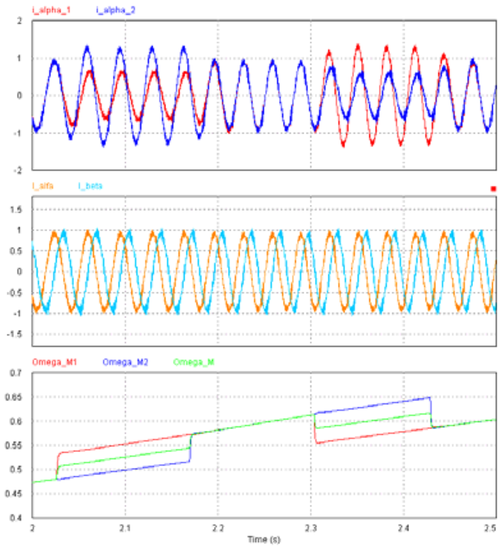

Fig.11. Comparison of the stator current vectors (alpha component), feedback signals for the averaged signals and angular speeds in case of the use of the control strategy 1

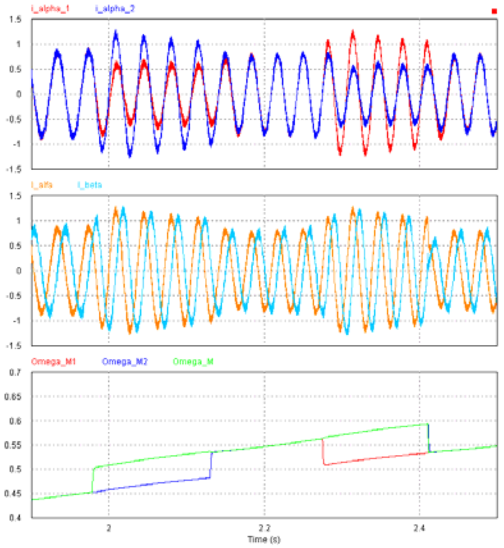

Fig.12. Comparison of the stator current vectors (alpha component), feedback signals for the first controller and angular speeds of the motors in case of the use of the control strategy 2.

In case of use of the first control strategy the results are presented in Fig.11. After step change in the angular speed of the motors the stator currents waveforms reflect the disturbance of the electromagnetic states. The change in the amplitude of the inverter output current remains stable. However the use of the second control strategy produces more interesting results. In that case the similar fluctuations in the stator currents can be observed but they do not influence the oscillations in the inverter output currents (Fig. 12). The presented examples show that the proper selection of the control strategy can produce completely different results. In the end the second strategy leads to the most promising solution for the traction group drive and may be implemented in the real environment.

Transients observed at the laboratory stand during the tests of the real group drive

A master (A) - slave (B) drive control system, with a current-controlled motor (A) and a voltage-controlled motor (B) following (A), leads to instantaneous overcurrents in the stator windings of motor (B) (Fig. 13).

Example 1

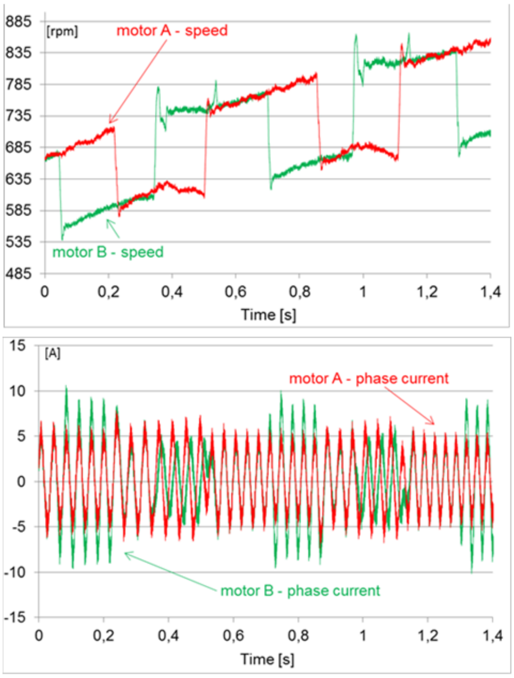

Fig.13. Motor A is the master and motor B is the slave. In this case is used the vector control based on the arithmetic average of the currents measurements of motors A and B, and the measurement of motor A shaft speed

These overcurrent become a bit smaller after the introduction of the feedback current in vector control system of measuring the average value of stator currents A and B (Fig. 14).

Example 2

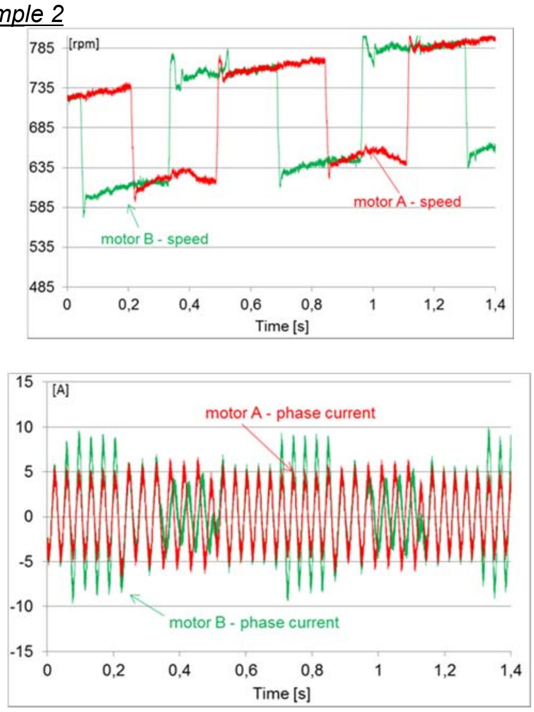

Fig.14. Motor A is the master and motor B is the slave. In this case is used the vector control based on the arithmetic average of the currents measurements of motors A and B, and the measurement of motor A shaft speed

Conclusions

The article presents results obtained during research in the field of the traction group drive. The regular traction drive incorporates two motors with separate inverters. The renewed concept of common inverter may decrease total cost of manufacture and maintenance due to the reduced number of parts but also brings important questions about stability. It source is only one degree of freedom for the control system because both motors are fed by the same stator voltage. However this strong electrical coupling is not followed by the mechanical one – the motors can rotate with different speeds. This gives two disturbance variables what makes the whole system sensitive and hard to control.

The critical event for the traction group drive is passing through the crossroads of the tramway tracks when the rapid change in the motor speeds occurs. This is a result of the change point of contact between wheel and rail from rolling surface to rim. There is another disturbance after crossroads when wheel starts to roll on its surface. These events force the impulse change in the angular speed of the motors what introduces angular discrepancy between rotor fluxes. This is finally seen as the sudden overcurrent event which can lead to the emergency shutdown of the whole drive.

However the cost reduction in comparison to the drive with two inverters is strong motivation for developing the control method which can stabilize the electromagnetic states in case of the presented disturbance. This requires either opportunity to work with a real drive or accessing the dedicated laboratory stand. For the former the special rig was designed according to the concept of the reverse model. The infinite rail – the massive rotating wheel with special rim profile models the track along the crossroads. The double wheel construction fully reflects the dynamics of the group drive and enhances the interesting phenomena. Moreover in comparison to classical motor to motor constructions the presented one reflects the complexity of torque transfer through the wheel – rail contact. The flexibility in setting the spring press force allows for creating different operating conditions and modeling phenomena like wheel slipping during braking or accelerating. Moreover it is also possible to use different rim profiles of the small wheels to test completely distinct control problems.

The laboratory test stand gives the opportunity to check and validate different control strategies for providing stabilization of the group drive in case of the considered disturbances. Moreover it was also possible to verify the simulation results with different working conditions and set-points.

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