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SIMULATION OF TORSIONAL MOMENTUM AT THE OPERATIVE SHAFT OF THE RAILWAY VEHICLE WITH THE TRACTION ELECTROMOTOR FOR WAVY DIRECT CURRENT

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Abstract: *The phenomenon of mechanical resonance in the axial make of the railway vehicle with the traction electromotors for wavy direct current has been of topical interest for the railway connoisseurs for a long time. This is not randomly because mechanical resonance may cause crevices and fractures in the operative shaft. Accordingly mechanical resonance may endanger safety of railway communication. However, previous research didn't precisely investigate the influence of tension and current at the value and guise of torsional momentum at the operative shaft. Therefore, this paper defined adduced influence. Besides, this paper defined the optimal antislippage shield for all the railway vehicles with the traction electromotors for wavy direct current.*

Key words: *mechanical resonance, traction electromotors.*

INTRODUCTION

Within the capital reparation of the diode ŽS 441 series locomotives in 2006 and 2007, the modification of electric devices was realised. The modification of the diode ŽS 441 series locomotives was realised at the electric devices because the Directorate of »Serbian Railway« wanted a greater reliability in service and better environment for the railway motorman. In the modification the hightension tuner was ejected because the diode bridge was replaced with the halfconduct tiristore bridge. The traction circuit of the tiristore ŽS 444 series locomotives was realised with two bimotor units. The first and the second bimotor unit copriseed M1 and M3 and M2 and M4 traction electromotors for wavy direct current at the seperate rotary socle.Accordingly, all operative shafts of the ŽS 444 series locomotives have got the equal performace. Traction electromotors for wavy direct current in each bimotor unit are connected in a series (Fig. 1).

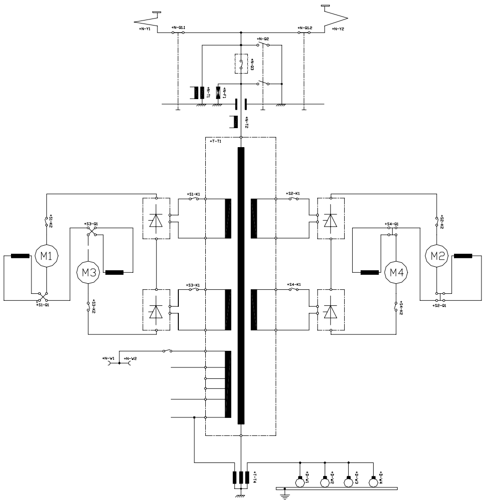

Fig. 1. Simplified traction circuit of the tiristore ŽS 444 series locomotives

For the purpose of a precise analysis of the influence of wavy direct current on the value and guise of torsional momentum at the operative shaft we are applying the operational method based on Laplase's trasformation. This method will be described in the subsequent article.

DYNAMICS AT THE OPERATIVE SHAFT OF THE TIRISTORE ŽS 444 SERIES LOCOMOTIVES

The propulsion system of the tiristore ŽS 444 series locomotives is a mechanical system which comprises the traction electromotor for wavy direct current (3), a cogged clamp (2), a torsional axle (5), a rubber clamp, a reductor (1), the operative shaft (4) and a monoblock wheel (Fig. 2) [1,2].

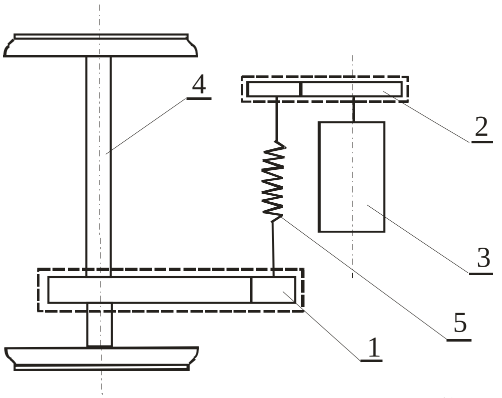

Fig. 2. Propulsion system of the tiristore ŽS 444l series locomotives

The essential running of the mechanical system is a rotation with a transfer of operative moment from the shaft of the traction electromotor to the monoblock wheel. Researches have shown that the described mechanical system may generate a strong torsional oscillation and fracture of the operative shaft [1,2].

The dynamic balance of the operative shaft of the traction electromotor for wavy direct current is described by the next equation [1,2,3]:

$$(1) \qquad J_m \frac{d\omega}{dt} = M - M_m$$

where J_m is the inertial moment of rotating mass with angular speediness ω. The inertial moment J_m is a sum of inertial moment of the traction electromotor for wavy direct current ($550\, Nms^2$), inertial moment of the cogged clamp ($2\, Nms^2$), inertial moment of the torsional axle ($3\, Nms^2$), inertial moment of the rubber clamp ($10\, Nms^2$) and inertial moment of the lesser gear of the jagged reductor ($10\, Nms^2$). Therefore, the inertial moment is $J_m = 575\, Nms^2$ [3]; ω – angular speediness of the operative axle of the traction electromotor for wavy direct current; $M(t)$ – transient value of rotating moment at the operative axle of the traction electromotor for wavy direct current; $M_m(t)$ - transient value of rotating moment oncoming from idler force; D – diameter of the monoblock wheel (D=1210 mm); i- transfer ratio of the jagged reductor (i= 3,65).

Figure 3 shows the courses of the operative moment M_0 and the rotating moment M_v of the reaction force $\vec{F}_v$ ($\vec{F}_v = -\vec{F}_v\,'$). J_0 in Figure 3 denominates the inertial moment of rotating mass with angular speediness ω_0. The inertial moment J_0 is the sum of inertial moment of the larger gear of the jagged reductor ($180\, Nms^2$); inertial moment of the operative shaft ($340\, Nms^2$) and inertial moment of the monoblock wheel ($1600\, Nms^2$). The total inertial moment is $J_0 = 2120\, Nms^2$ [3].

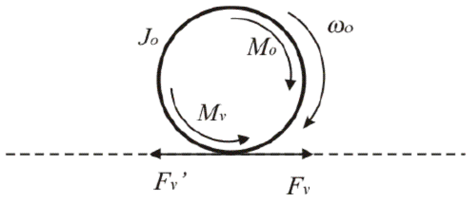

Fig. 3. Courses of the operative moments M_0 and M_v

The equation of dynamic balance for the shown system in Figure 3 is:

$$(2) \qquad J_0 \frac{d\omega_0}{dt} = M_0 - M_v$$

where

$$(3) \qquad \omega_0 = \frac{2}{D} \cdot v = \frac{\omega}{i}$$

$$(4) \qquad M_0 = \eta \cdot i \cdot M_m$$

$$(5) \qquad M_v = \frac{D}{2} \cdot F_v$$

$\eta = \mathbf{0{,}975}$ (grade of utility according to the IEC- 349)

Based on equations (1) and (4):

$$(6) \qquad J_m \frac{d\omega_*}{dt} = \frac{M_n}{\omega_n}\left(M_* - M_{0*}\right)$$

where

$$M_{0b} = M_{0n} = \eta \cdot i \cdot M_n = 27924{,}8849\ Nm$$

Based on equations (2) and (5):

$$(7) \qquad J_0 \frac{d\omega_0}{dt} = M_0 - \frac{D}{2} \cdot F_v$$

The equation of running of the mechanical system is:

$$(8) \qquad m \frac{dv}{dt} = F_v - \sum F_{ot}$$

where: m – mass of each operative shaft ; $\sum F_{ot}$ - total reaction forces ($\sum F_{ot}$ is the sum of friction force of the wheel-rail system; friction force in a shaft bolster; friction force of air; reaction force on a slope; reaction force on a curvature and reaction force of inertia of locomotive.

Based on the former equations:

$$\left(J_0 + m \cdot \left(\frac{D}{2}\right)^2\right)\frac{d\omega_{0*}}{dt} = \frac{M_{0n}}{\omega_{0n}}\left(M_{0*} - M_{Fv*}\right) \quad (9)$$

where: $\omega_{0n} = \frac{\omega_n}{i} = 35{,}8438\,\frac{rad}{s}$;

$M_{Fv*} = \frac{\frac{D}{2}\Sigma F_{ot}}{M_{0n}}$ - comparative value of reaction momentum.

Based on the equations (6) and (9), angular speedinesses ω and ω_0 have got forms in the complex domain:

$$\omega = \frac{M_n \cdot (M_* - M_{0*})}{J_m \cdot \omega_n \cdot s} \quad (10)$$

$$\omega_0 = \frac{M_{0n}\left(M_{0*} - M_{Fv*}\right)}{\left(J_0 + m\left(\frac{D}{2}\right)^2\right) \cdot \omega_{0n} \cdot s} \quad (11)$$

The torsional moment of the operative shaft:

$$M_t = k \cdot \Delta\theta \quad (12)$$

$$\Delta\theta = \frac{1}{i}\theta - \theta_0 \quad (13)$$

(14) $\omega_0 = \frac{d\theta_0}{dt}$ in the complex domain $\theta_0 = \frac{\omega_0}{s}$

(15) $\omega = \frac{d\theta}{dt}$ in the complex domain $\theta = \frac{\omega}{s}$

where k – torsional constant of operative shaft. The torsional constant of the leaves part of the operative shaft (i.e. part of the operative shaft from the jagged reductor to the near monoblock wheel) is $k_1 = 553\, 10^6\ Nm \cdot rad^{-1}$. Torsional constant of the lenghter part of the operative shaft (i.e. part of the operative shaft from the jagged reductor to the further monoblock wheel) is $k_2 = 9{,}8 \cdot 10^6\ Nm \cdot rad^{-1}$ [3]; θ_0 - banking of operative shaft induced by the wheel-rail system.

RESONANCE FREQUENCY OF THE OPERATIVE SYSTEM

As

$$\theta_0 = \frac{\frac{k}{i}}{\left(J_0 + m \cdot \left(\frac{D}{2}\right)^2\right) \cdot s^2 + k}\,\theta \quad (16)$$

transfer function W_M is:

$$W_t = \frac{M_t}{M} = \frac{1}{\left(J_m \cdot k + \frac{k}{\eta \cdot i^2}\left(J_0 + m \cdot \left(\frac{D}{2}\right)^2\right)\right) \cdot s^2} \cdot \frac{\frac{k}{i}\left(J_0 + m \cdot \left(\frac{D}{2}\right)^2\right) \cdot s^2}{\left(\frac{J_m \cdot \left(J_0 + m \cdot \left(\frac{D}{2}\right)^2\right)}{J_m \cdot k + \frac{k}{\eta \cdot i^2}\left(J_0 + m \cdot \left(\frac{D}{2}\right)^2\right)} \cdot s^2 + 1\right)} \quad (17)$$

The dominant poles of the transfer function W_M define the resonance frequency of the operative system. The resonance frequency of the operative system is determined by the next equation:

$$\omega = \sqrt{\frac{J_m \cdot k + \frac{k}{\eta \cdot i^2}\left(J_0 + m \cdot \left(\frac{D}{2}\right)^2\right)}{J_m \cdot \left(J_0 + m \cdot \left(\frac{D}{2}\right)^2\right)}} \quad (18)$$

Based on the equation (18), resonanse frequencies of the leaves and lenghter of the operative shaft are:

$$\omega_1 = 526{,}87\ \frac{rad}{s} \quad (19)$$

$$\omega_2 = 70{,}14\ \frac{rad}{sec} \quad (20)$$

TORSIONAL MOMENT AT A SLIPPAGE OF THE OPERATIVE SHAFT

Based on the former equations, we made a program in MATLAB-SIMULINK to simulate the torsional momentum at the operative shaft (Fig 4).

We received a chronological variety of torsional momentum of the lenghter part of the operative shaft according to Fig. 5 when we were starting from this simulation program. We assumed that a slippage of the operative shaft appeared because of nuisance value of traction coefficient at $M_{Fv*} = \dfrac{\frac{D}{2}\Sigma F_{ot}}{M_{0n}} = 1$ Traction coefficient at this environment is defined by the next term:

$$F_v > \mu \cdot Q_a \Rightarrow \mu < \frac{M_{0n}}{\frac{D}{2} \cdot Q_a} = \frac{27924{,}8849}{\frac{1.21}{2} \cdot 200000} = 0{,}23$$

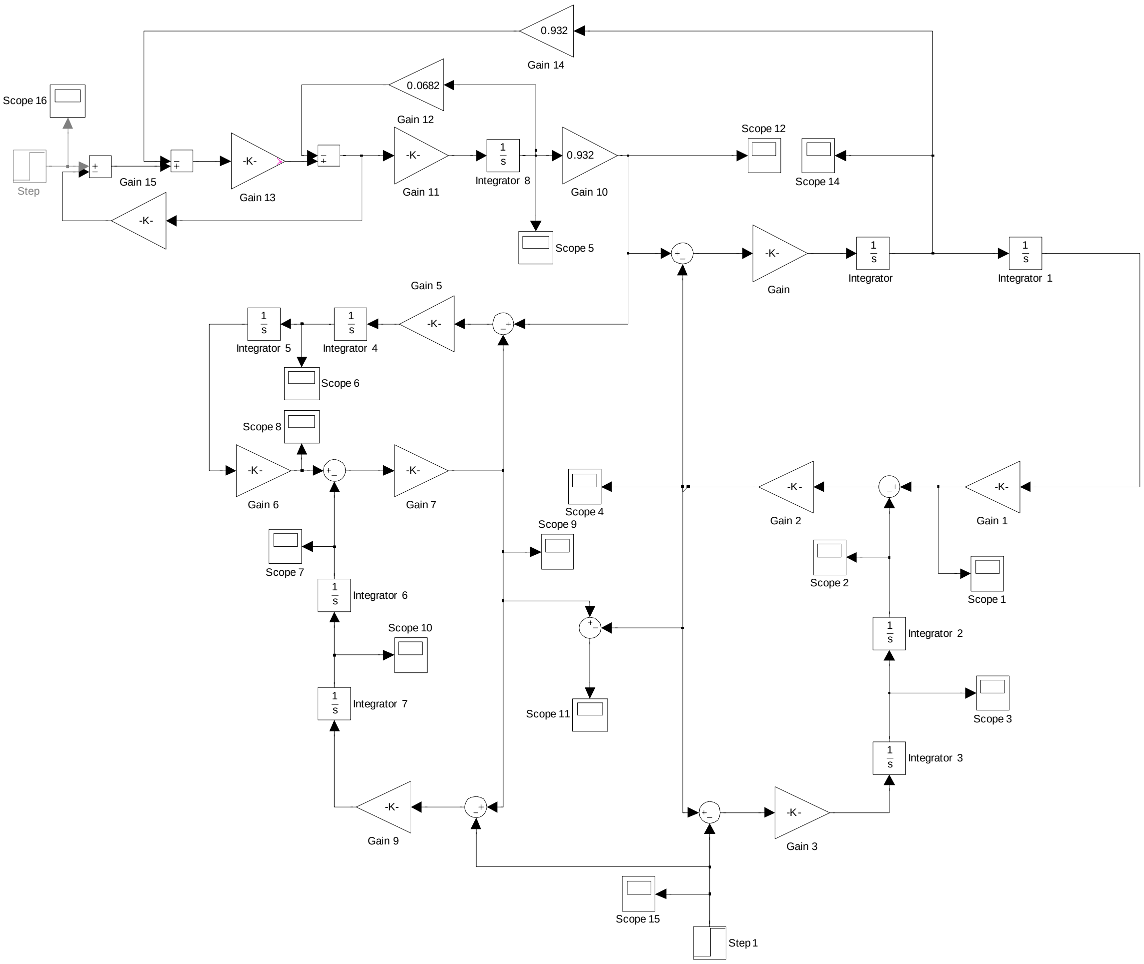

Fig. 4. The program in MATLAB-SIMULINK to simulate of the torsional momentum at the operative shaft

We also assumed that the rotating moment of the operative shaft of the traction electromotor for wavy direct current is determined with:

$$M(t) = \frac{33}{32} \cdot k_0 \cdot I_{sr}^2 (1 + \frac{16}{33} \cos 2\omega t + \frac{1}{33} \cos 4\omega t) = M_{sr} (1 + a_1 \cos 2\omega t + a_2 \cos 4\omega t) \tag{21}$$

where M_{sr} - in between value of rotating moment of the operative shaft of the traction electromotor for wavy direct current; $a_1 = \dfrac{16}{33}$ - factor amplitude of a circular frequency $2\omega = 628 \dfrac{rad}{s}$; $a_2 = \dfrac{1}{33}$ - factor amplitude of a circular frequency $4\omega = 1256 \dfrac{rad}{s}$.

Based on Fig. 5, we can conclude that the torsional moment of the lenghter part of the operative shaft quite quickly rises during the slippage of the operative shaft. This moment was achieving the value of $\dfrac{M_{t1}}{M_{0n}} = 23$ ($M_{t1} = 6{,}42$ MNm) in a quite short period of $t \leq 0{,}3s$. Consequently, torsional moment during the slippage of the operative shaft will permanently impair the lenghter part of the operative shaft.

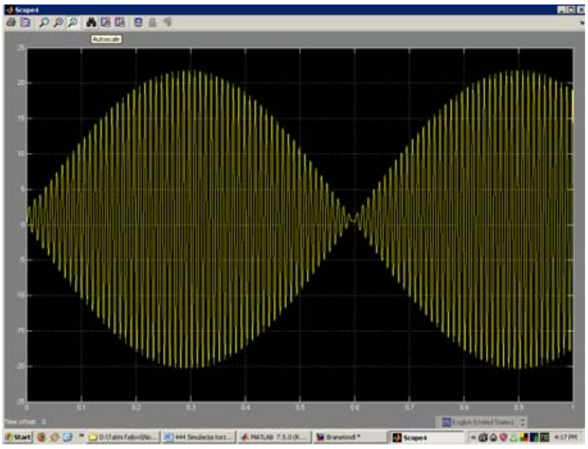

Fig 5. Dependence $\frac{M_{t1}}{M_{0n}} = f(t)$

If we curtail the value of factor amplitude of a circular frequency from $a_1 = \frac{16}{33}$ to $a_1 = 0{,}1$, the dependence $\frac{M_{t1}}{M_{0n}} = f(t)$ during the slippage of the operative shaft will be according to Fig.6. (Factor amplitude of a circular frequency may dwindle if we enlarge iductance of central silencer).

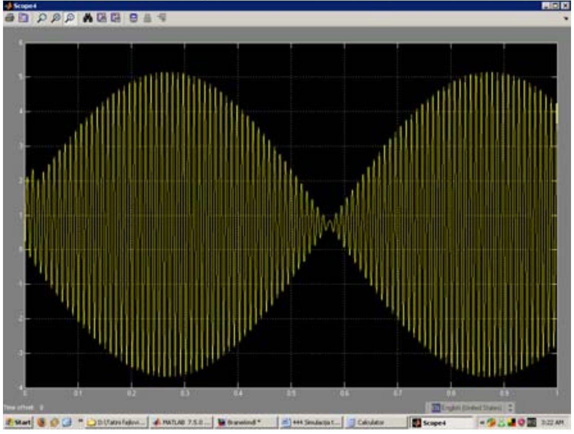

Fig. 6: ***Dependence*** $\frac{M_{t1}}{M_{0n}} = f(t)$ ***at*** $a_1 = 0{,}1$

Based on Fig 6, we can conclude that the torsional moment at $a_1 = \frac{16}{33}$ is five times smaller than the torsional moment at $a_1 = 0{,}1$ during the slippage of the operative shaft. Peak value of the torsional moment of the lenghter part of the operative shaft at $a_1 = 0{,}1$ is attained in $t = 0{,}25s$. Besides, our program for simulation showed that the peak value of this moment further dwindled while we were further dwindling the factor amplitude of a circular frequency $2\omega = 628\frac{rad}{s}$.

If we commute the diode or asymmetrical thiristore rectifier with the symmetrical thiristore rectifier, we'll receive a passable value of the torsional moment with the circular frequency $\omega = 2\pi \cdot f = 2\pi \cdot 50 = 314\frac{rad}{s}$. The dependence $\frac{M_{t1}}{M_{0n}} = f(t)$ during the slippage of the operative shaft with the circular frequency $\omega = 2\pi \cdot f = 2\pi \cdot 50 = 314\frac{rad}{s}$ and $a_1 = 3$ is shown in Fig.7.

Based on Fig. 7, we can conclude that the substitution of the diode rectifier or the asymmetrical with modern symmetrical thiristore rectifier relates to a passable value of the torsional moment during the slippage of the operative shaft. Besides, this substitution will eject the cascade switch and simplify the traction transformer. This substitute may also enable the application of recuperative brake. Consequenly, we believe that the modern symmetrical thiristore rectifier may eliminate the impairing of the lenghter part of the operative shaft during the slippage. With this rectifier the existing antislippage shield of the ŽS 441, ŽS 461 and ŽS 444 electrolocomotives. will be enough speedy though now it is not.

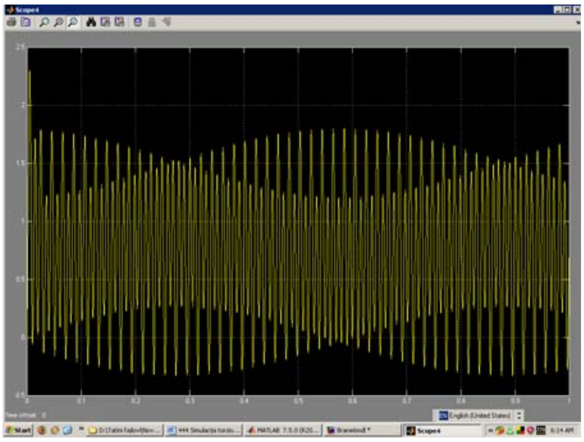

Fig. 7: Dependence $\frac{M_{t1}}{M_{0n}} = f(t)$ **for**

$$\omega = 314\frac{rad}{s}$$

CONCLUSION

The torsional moment of the lenghter part of the operative shaft rises quite quickly during the slippage of the operative shaft. This moment was achieving the value of $\frac{M_{t1}}{M_{0n}} = 23$ ($M_{t1} = 6{,}42$ MNm) in quite a short period of $t \le 0{,}3s$. Consequently, torsional moment during the slippage of the operative shaft will permanently impair the lenghter part of the operative shaft.

The torsional moment at $a_1 = \frac{16}{33}$ is five times smaller than the torsional moment at $a_1 = 0{,}1$ during the slippage of the operative shaft. The peak value of the torsional moment of the lenghter part of the operative shaft at $a_1 = 0{,}1$ is attained in $t = 0{,}25s$. Besides, our program for simulation showed that the peak value of this moment further dwindled while we were further dwindling the factor amplitude of a circular frequency $2\omega = 628\frac{rad}{s}$.

The substitution of the diode rectifier or the asymmetrical with modern symmetrical thiristore rectifier relates to a passable value of the torsional moment with the circular frequency $\omega = 2\pi \cdot f = 2\pi \cdot 50 = 314\frac{rad}{s}$ during the slippage of the operative shaft. Besides, this substitution will eject the cascade switch and simplify the traction transformer. This substitution may also enable the application of recuperative brake. Consequenly, we believe that the modern symmetrical thiristore rectifier may eliminate the impairing of the lenghter part of the operative shaft during the slippage.

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СИМУЛИРАНЕ НА ТОРЗИОННИ МОМЕНТИ ПРИ ДЕЙСТВАЩ ВАЛ НА ЖЕЛЕЗОПЪТНО ВОЗИЛО С ТЯГОВ ЕЛЕКТРОМОТОР ЗА РИФЕЛОВАН ПОСТОЯНЕН ТОК

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Резюме: *Явлението механичен резонанс в осовия модел на железопътно возило с тягов електромотор за рифелован постоянен ток е от актуално значение за железопътните познавачи от дълго време. Това не е случайно, защото механичният резонанс може да причини пукнатини и счупвания в действащия вал. Следователно механичният резонанс може да застраши безопасността на железопътните съобщения. Предишните научни изследвания обаче не са проучили точно влиянието на напрежението и тока върху стойността и вида на торзионните моменти на действащия вал. С тази цел този доклад определя изтъкнатото влияние. Освен това се дефинира оптималната противоплъзгаща защита за всички железопътни возила с тягови електромотори за рифелован постоянен ток.*

Ключови думи: *механичен резонанс, тягови електромотори.*