THE DIESEL LOCOMOTIVE WITH VECTORIAL COMMAND SYSTEM FOR ASYNCHRONY TRACTION ENGINES AND THE ESTIMATION OF THE ROTOR TIME CONSTANT

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Abstract:

The paper treats the railway diesel-electric traction on new principles for the command and adjusting of asynchrony, taking in consideration their vector command related to the traction engine's rotor time constant.

Introduction

The diesel-electric traction must function on the Romanian Railways based on principles of economic and distinctive performance.

Electric transmission with asynchrony traction engines on diesel locomotives and diesel trains must be provided with command and adjusting systems based on asynchrony engine's vector control principles that will take in consideration the weight on axis, its rotations, the asynchrony generators and diesel engines powers. All that must work based on economic distinctions that take in consideration the variable time parameters of the power engines. The most used, in the traction regime as well as in electro-dynamic regime, is the traction engine, with a focus on its rotor. Even if the wiring of the rotor is in short-circuit and it's winding are calculated for power of 0,5-1,6 MW, the rotor time constant plays an important role in the performance and optimal characteristics definition.

This paper plans to approach the problem in a theoretical perspective, showing function diagrams and function schemes from real conditions of exploitation for diesel-electric locomotives with electric transmission, synchronic generator and asynchrony traction engines with the rotor in short-circuit.

1. Asynchrony traction engine's parameter variation due to the rotor time constant.

Vector adjusting of the asynchrony traction engine is done to by rotor flux. This type of adjusting is done in real time using numeric systems.

Until now there are several methods of vector adjusting with the adaptation of parameters to the optimization characteristics.
- Reactive power estimation method, at optimal *cos φ* and constant values;
- Gratian's method of power parameters characteristics;
- Vector sum error method, used by Kubota for the control of speed and positioning systems, with rapid dynamic response;
- Do-Mi method of adaptation based on vector adaptive control;

Next we will show the theoretical basis of the Do-Mi adaptive method.

Electromotive tension induced by the rotor flux $\underline{e_r^s}$ in stable system α – β is calculated with:

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$$\underline{e_r^s} = \underline{u_s^s} - r_s \underline{i_s^s} - \frac{i_s}{\omega_n}\frac{d\underline{i_s^s}}{dt}$$

obtained for the stator tension formula in stable system $\alpha - \beta$:

$$\underline{u_s^s} = r_s \underline{i_s^s} + \frac{1}{\omega_n} I_s \frac{d\underline{i_s^s}}{dt} + j f_s \Psi_r^s \frac{I_m}{I_r}$$

The result of $(\underline{e_r^s})^*$ model is determined by imposing the rotor flux vector $(\psi_r^s)^*$ in relation with:

$$\left(\underline{e_r^s}\right)^* = \frac{1}{\omega_n}\left(\frac{I_m}{I_r}\right)^* \frac{d\left(\Psi_s^r\right)^*}{dt} \tag{1}$$

end

$$\begin{cases} \Psi_{r\alpha}^* = \Psi_r^* \cos\Theta_k^* \\ \Psi_{r\beta}^* = \Psi_r^* \sin\Theta_k^* \end{cases} \tag{2}$$

so the electromotive tension components induced by the rotor flux becomes:

$$\begin{cases} e_{r\alpha}^* = -e_r^* \sin\Theta_k^* \\ e_{r\beta}^* = -e_r^* \cos\Theta_k^* \end{cases} \tag{3}$$

where

$$e_r^* = f_s^* \left(\frac{I_m}{I_r}\right)^* \Psi_r^*$$

The error between the tow methods is caused by the rotor time constant, the $\Delta(r_r/I_r)$ correction signal and it is calculated due to the vector sum error criteria:

$$\Delta\frac{r_r}{I_r} = e_{r\alpha} e_{r\beta} - e_{r\beta}^* e_{r\alpha}^* \tag{4}$$

These criteria can be formulated also like this

$$\Delta\frac{r_r}{I_r} = e_{r\alpha}\cos\Theta_k^* - e_{r\beta}^* \sin\Theta_k^* \tag{5}$$

Do-Mi method has a very good convergence, it depends on the stator resistance witch fluctuates with the temperature. Like other methods based on the induced electromotive tension evaluation, the method doesn't work at zero rotations or at stand by functioning of the diesel engine and main synchrony generator. In traction engine stand by only the correction mechanism stops because the error of the vector sum is zero. Actually zero rotations of the asynchrony traction engine and diesel engine stand by, losses are minimal, the current, traction power and couple are equal to zero.

2. The influence of asynchrony traction engine's rotor time constant on the performance of the vector command system

If the time constant value is different from the real value, the rupture between the Ψ_r rotor flux control and m_e electromagnetic couple will be lost. Like so, the transition response of the field oriented system is deteriorated. This phenomenon can be called vector command recalibration.

The main reason for vector command recalibration is the changing in r_r rotor resistance due to the temperature and layer effect. Rotor inductivity l_r may be considered constant because the engine fluctuates at constant rotor flux and the saturation level remains the same. In this case we can take into consideration the fact that the time constant variation is due only to the rotor resilience. The 1 and 2 figures we present the numeric simulation of controller recalibration effects due to rotor time constant variation. The simulation was done for the indirect vector system presented in figure 3. From the analysis of the results we can observe that the response of the system is optimal (fast couple answer, no oscillations) in the case of rotor time constant correct input. For the cases in witch imposed rotor resilience differs form the real one, the system has a different oscillated response form the optimal one. Due to the fact that rotor resilience determines the dynamic performances of the indirect vector system, it's imposed a calculation of orientation error, witch, in there turn, determines rotor flux and electromagnetic couple error.

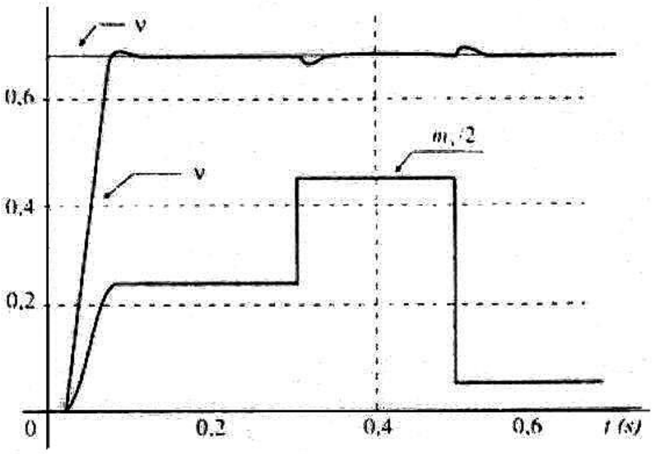

Fig. 1 The response of the indirect vector adjusting system, at variations of m_s couple variation for $(I_r/r_r)^* = (I_r/r_r)$.

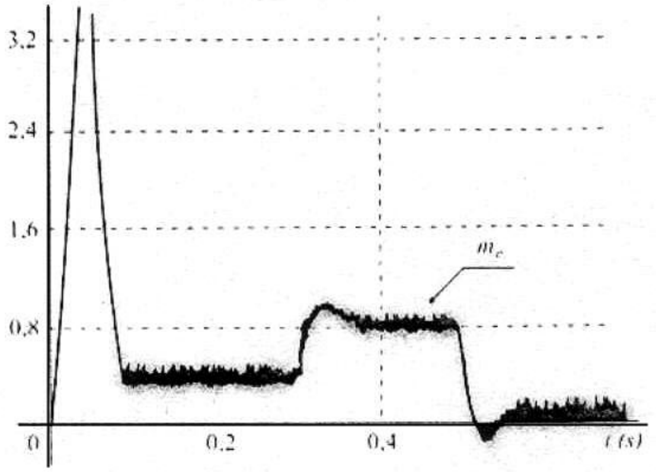

Fig. 2 m_e electromagnetic couple for $(I_r/r_r)^* = (I_r/r_r)$.

For the analysis of the effects due to rotor resistance change, we will consider that the system is stable. We will presume that r_r real rotor resistance differs with a k_r factor from the one set by the r_r^* control system:

$$r_r = r_r^* + \Delta r_r = k_r r_r^* \tag{6}$$

Using the system setup by the rotor flux equation and the rotor tension equation, we obtain an equation system:

$$\begin{cases} \underline{\Psi_r^e} = x_m \underline{i_s^*} + x_r \underline{i_r} \\ 0 = r_r \underline{i_r} + j f_r^* \underline{\Psi_r^e} = k_r r_r^* \underline{i_r} + j f_r^* \underline{\Psi_r^e} \end{cases} \tag{7}$$

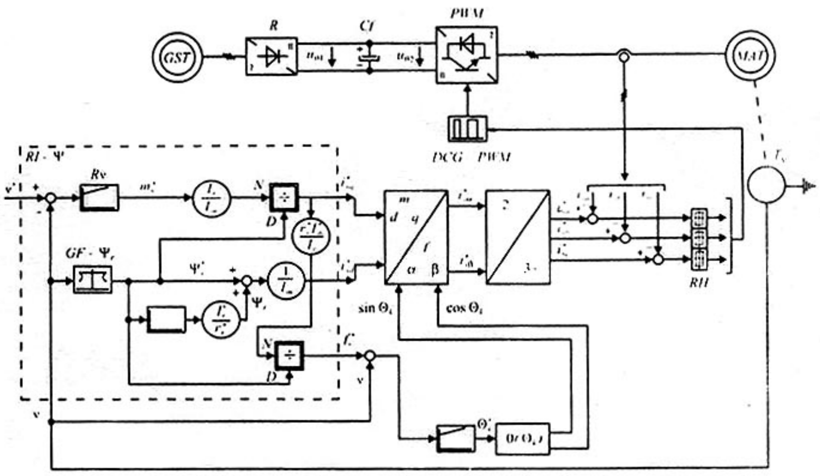

Fig. 3 Indirect vector system with PWM tension inventor regulated in current

Eliminating the $\underline{i_r}$ rotor current, after some simple algebra calculations we can deduce the $\underline{\psi_r^e}$ estimated rotor flux with the formula:

$$\underline{\Psi_r^e} = x_m \underline{i_s^*} + \frac{j f_r^* x_m x_r}{k_r^* + j f_r^* x_r}\underline{i_s^*} = x_m\left(1-\frac{j f_r^* x_r}{k_r r_r^* + j f_r^* x_r}\right)\left(i_{sd}^* + j i_{sq}^*\right) \tag{8}$$

where: $\underline{i_s^*}\left(\underline{i_s^*} = i_{sd}^* + j i_{sq}^*\right)$, f_r^*, r_r^*, Ψ_r^*, Ψ_{rd}^*, m_e^* represent the values imposed by the control system and i_r is the real rotor current

In the 8th relation we will replace the components of the stator current fazor, i_{sd}^* and i_{sq}^* with:

$$r_r i_{rd} + \frac{Id\Psi r}{dt} = 0$$

$$x_r i_{rd} + x_m i_{sd} = \Psi_r$$

The rotor flux becomes:

$$\begin{aligned}\Psi_r^e &= x_m\left(1-\frac{j f_r^* x_r}{k_r r_r^* + j f_r^* x_r}\right)\left(\frac{\Psi_r^*}{x_m} + j\frac{\Psi_r^* f_r^* x_r}{x_m r_r^*}\right) = \\ &= \frac{k_r\left(r_r^* + j f_r^* x_r\right)}{k_r r_r^* + j f_r^* x_r}\Psi_{rd}^* = \Psi_{rd}^e + \Psi_{rq}^e\end{aligned} \tag{9}$$

If the r_r^* rotor resistance is equal to $r_r(k_r - 1)$, we can observe that $\underline{\Psi_r^e} = \Psi_{rd}^*$. We decompose the flux fazor from the rotor estimated based on the two components of the d – q system, witch is oriented after the real flux fazor. This decomposition is done to determine the error that appears between the flux and real couple (Ψ_r, m_e) and the error imposed by the (Ψ_r^*, m_e^*) control system. The 9th fazor equation, decompose in the two components d and q becomes:

$$\begin{cases}\Psi_{rd}^e = \dfrac{\left(k_r r_r^*\right)^2 + k_r\left(f_r^* x_r\right)^2}{\left(k_r r_r^*\right)^2 + \left(f_r^* x_r\right)^2}\Psi_{rd}^* \\ \Psi_{rq}^* = \dfrac{k_r\left(k_r - 1\right) f_r^* r_r^* x_r}{\left(k_r r_r^*\right)^2 + \left(f_r^* x_r\right)^2}\Psi_{rd}^*\end{cases} \tag{10}$$

According to the 10th system, the vector system's fazor diagram looks like the 4th figure, indicating the functioning values and the effect of the vector command recalibration.

The orientation error due to the variation in the rotor resistance is determined with:

$$\varepsilon_r = \mathrm{arctg}\frac{k_r\left(k_r-1\right)f_r^* r_r^* x_r}{\left(k_r r_r^*\right)^2 + k_r\left(f_r^* x_r\right)^2} \tag{11}$$

We consider an under-excitation of the engine ($\Psi^e_{rd} < \Psi_r$), if the rotor's resistance is lower the one of the control system, and an over-excitation ($\Psi^e_{rd} > \Psi_r$), if the engine's resistance is higher.

A variation of ±25% of the engine's rotor resistance determines, at high slips, a variation of approximately ±25% of the rotor flux. This rotor flux variation is presented in figure 5

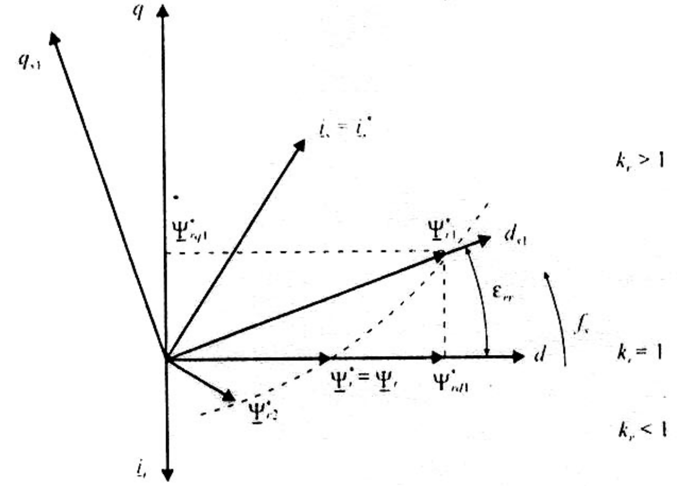

Fig. 4 Orientation error in the case of a vector command recalibration

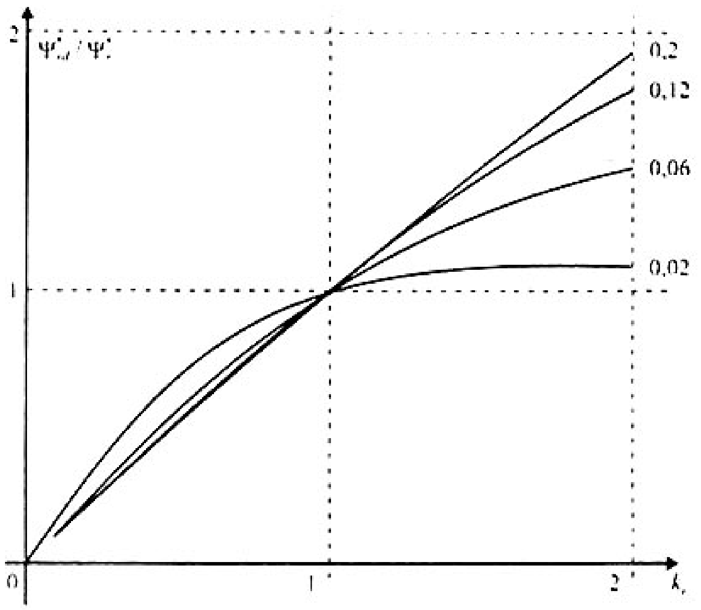

Fig. 5 Real flux variation due to the variation of rotor resistance, at f_r = constant

The electromagnetic couple will have an error in regard to the imposed value m_e^* due to the flux error. For the calculation of the couple ($m_e = \Im\{\underline{\Psi_r^e}\ \underline{i_r^{conj}}\}$) we have to determine the rotor current fazor $\underline{i_r}$ (i_{rd} and i_{rq}). The notation $\underline{i_r^{conj}}$ was used to differentiate between the conjugate and the imposed value (*). The rotor current fazor is calculated by taking into consideration the 10th equation system. This will give:

$$\underline{i_r} = \frac{jf_r^* x_m}{k_r r_r^* + jf_r^* x_r}\underline{i_s^*} = -\frac{\left(f_r^*\right)^2 x_r r_r^*\left[1-k_r\right] + jf_r^*\left[k_r\left(r_r^*\right)^2 + \left(f_r^* x_r\right)^2\right]}{r_r^*\left[\left(k_r r_r^*\right)^2 + \left(f_r^* x_r\right)^2\right]}\Psi_{rd}^* \qquad (11)$$

The components of the rotor fazor become:

$$\begin{cases} i_{rd} = -\dfrac{\left(f_r^*\right)^2 x_r r_r^*\left[1-k_r\right]}{r_r^*\left[\left(k_r r_r^*\right)^2 + \left(f_r^* x_r\right)^2\right]}\Psi_{rd}^* \\ i_{rq} = -\dfrac{f_r^*\left[k_r\left(r_r\right)^2 + \left(f_r^* x_r\right)^2\right]}{r_r^*\left[\left(k_r r_r^*\right)^2 + \left(f_r^* x_r\right)^2\right]}\Psi_{rd}^* \end{cases} \qquad (12)$$

The electromagnetic couple is calculated taking into consideration the estimated flux projection (10th equation system) and the rotor current projection:

$$m_e = \Im\left\{\underline{\Psi_e^r} \cdot \underline{i_r^{conj}}\right\} = \Psi_{rq}^e i_{rd} - \Psi_{rd}^e i_{rq} =$$

$$= \frac{\left(\Psi_{rd}^*\right)^2 f_r^*}{m_e^* r_r^*}\left[\frac{k_r\left(k_r-1\right)^2\left(f_r^* r_r^* x_r\right)^2}{\left[\left(k_r r_r^*\right)^2 + \left(f_r^* x_r\right)\right]^2} + \frac{\left(k_r r_r^*\right)^2 + k_r\left(f_r^* x_r\right)^2}{\left(k_r r_r^*\right)^2 + \left(f_r^* x_r\right)^2}\right] \qquad (13)$$

in this case, the imposed couple is equal to the one of the asynchrony traction engine, if the machine's rotor resistance is equal to the imposed one. In the 6th figure we present the machine's couple variation due to the rotor resistance variation.

The same as in the case of the flux, a ±25% variation of the rotor resistance determines at large slips the same variation of the machine's couple in regard to the imposed value.

To minimize the consequence of the parameter variation, the identification of r_r rotor resistance became a very important problem. Recently, the use of high speed DSP makes possible the use of static techniques, like the *Kalaman filters* (KF) and *extended Kalaman filters* (EKF) theory.

3. The variation of the rotor time constant with the traction engine's couple

Figure 6 presents the diagram that orders the rotor time constant variation K_r in regard to the balance of real and imposed couples (m_e / m_e^*) at the asynchrony engine's shaft.

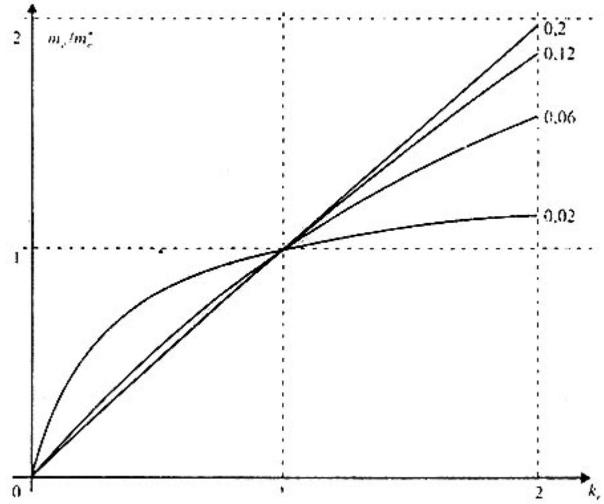

Fig. 6 Machine's couple variation due to rotor resistance variation at f_r = constant

Figure 7 establishes the value of the rotor time constant with the asynchrony engine's parameter error vector sum method (current, flux, angle speed).

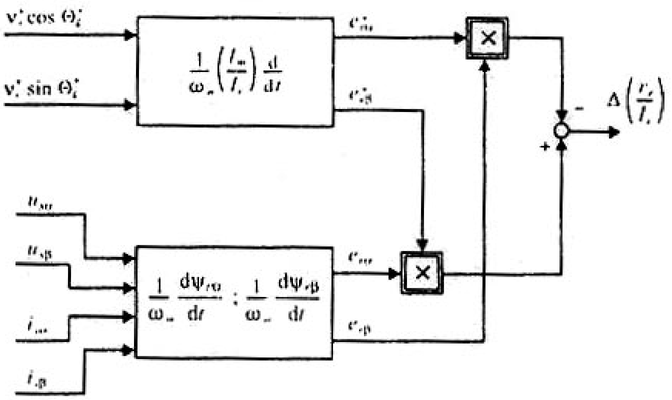

Fig. 7 Rotor time constant estimation
thru the vector sum error method

The 8^{th} figure presents the general schematic for asynchrony type traction engine vector control, diesel-electric traction.

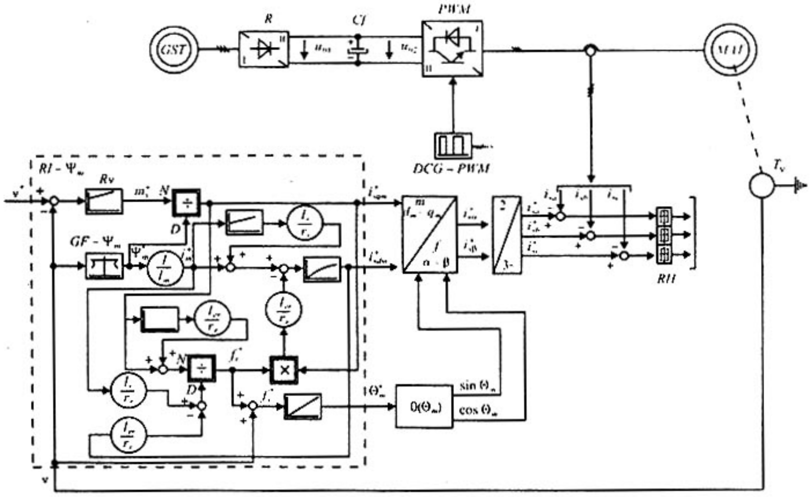

Fig. 8 Adjusting vector system for flux oriented asynchrony engine with PWM tension inventor current commanded with tree histerezis regulators

Final arguments

Based on the Do-Mi method we can establish optimal characteristics for automated adjusting of power engines (diesel engine, synchrony generator, asynchrony traction engine) for modern diesel-electric traction. This permits the obtainment of economic performances and optimal railway exploitation parameters.

New types of diesel locomotives and diesel-electric motorailer must be equipped with this kind of command systems and vector control.

Bibliografie

[1] V. Tulbure, D. Mihăilescu: Locomotive diesel. Sisteme moderne de comandă şi reglare automată. Editura Tehnică, Bucureşti, 2004;

[2] D. Mihăilescu: Locomotive şi trenuri electrice cu motoare de tracţiune asincronă. Editura Didactică şi Pedagogică, Bucureşti 1997;

[3] D. Mihăilescu, V. Tulbure: Comanda şi reglarea locomotivelor cu motoare de tracţiune asincronă. Editura ALL, Bucureşti, 2001;