A&QT-R 2004 (THETA 14)
2004 IEEE-TTTC - International Conference on Automation, Quality and Testing, Robotics
May 13 – 15, 2004, Cluj-Napoca, Romania

ANALYSIS OF THE MULTI-MODEL ANTI-SLIP CONTROL WITH DC TRACTION MOTORS BY DIESEL ELECTRIC LOCOMOTIVES

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Abstract: In a previous work [6], the slip phenomenon was modelled, using algebraic and differential equations governing the process. Based on this model in SIMULINK, in the actual paper, the authors study the behaviour of the anti-slip systems. This complex equipment: anti-slip brake system, anti-slip system with voltage diminishing, etc. is common for Diesel Electric locomotives of series 060-DA. The results of the simulations give the possibility to estimate the performance of the anti-slip equipment, to establish the set of the proper control parameters and to anticipate the effects in parameter changing.

Key words: Diesel Electrical locomotive, DC traction motor, anti-slip equipment, numerical simulation

1. INTRODUCTION

In a general strategy of the train start, the driver sets an imposed value of the acceleration, achieved by a certain traction force. To do this, the motor voltage (U_a) must be gradually risen and an armature DC motor current arises. The DC motor torque is transferred to the rail, producing a tractive force (F_{tr}):

$$F_{tr} = T_w / r \tag{1}$$

where (r) is the wheel radius. The tractive force is counterbalanced by the friction force:

$$F_{tr} = F_{fr} = \mu \cdot G_a \tag{2}$$

with (μ) the friction coefficient and (G_a) the vertical load on the axle (wheels). In this case, the locomotive traction force is the sum of each wheel force. But, it is possible, if the rail is wet or dirty, the friction coefficient decreases so that:

$$T_w > \left(\mu^* \cdot G_a\right) \cdot r \tag{3}$$

and the slip wheel-rail starts. The angular speed (Ω) of this axle is greater than the speed of the remainder ones, hence:

$$\Omega > \frac{v_{tr}}{r}. \tag{4}$$

The total traction effort diminishes and the system wheel-rail is wearing out prematurely.

In order to reduce or to avoid this process, some control systems are today in use, but, by each train-start, one important task of the driver is to supervise the train

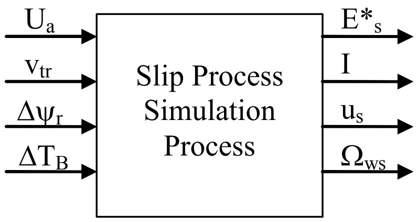

Figure 1. Simulation scheme for the wheel-rail slip

speed and the traction motor currents and voltages. The shortening of the slip time interval and the re-adhesion process depend strong on the driver experience and skill.

The start and the development of the slip phenomenon was presented in [6] and a nonlinear simulation scheme was conceived. A simplified version is presented in figure 1. The inputs are:

- the motor voltage (U_a);
- the train speed (v_{tr});
- the variation of the adhesion coefficient ($\Delta\psi_r$);
- the brake-torque (ΔT_B).

The outputs are:

- the DC motor slip voltage (E_s^*);
- the traction motor group current (I);
- the linear (supplementary) slip speed $U_S = \Omega_w \cdot r$; the wheel speed is $\Omega_w = \Omega_{tr} + \Omega_{ws} = \frac{v_{tr}}{r} + \frac{u_s}{r}$;
- the angular (supplementary) slip speed (Ω_{ws}).

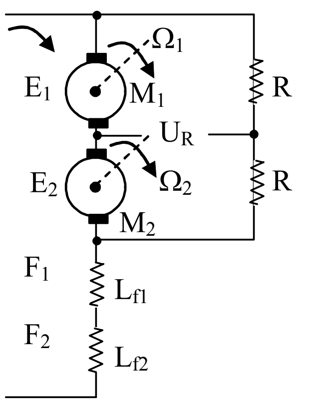

Figure 2. Slip voltage sensing

2. ACTUAL ANTI-SLIP SYSTEMS PERFORMANCE ANALYSIS (FOR DIESEL ELECTRIC LOCOMOTIVE: 060-DA)

In the case of the series 060-DA Diesel-electric locomotive, the supplementary slip speed (u_S) [1] is sensed in a bridge circuit, consisting of the motor armatures and two identical resistances (R, R), figure 2. For instance, if the motor (E_1) starts to slip [5], results:

$$E_1 = k_{Ev}^* \cdot \left(k_{\Phi_1} \cdot I + k_{\Phi_2} \cdot \sqrt{I}\right) \cdot \left(v_{tr} + u_S\right);$$
$$E_2 = k_{Ev}^* \cdot \left(k_{\Phi_1} \cdot I + k_{\Phi_2} \cdot \sqrt{I}\right) \cdot \left(v_{tr}\right)$$

and

$$U_{rA} = \left(E_1 + E_2\right)/2 - E_2 = k_{Ev}^* \cdot \left(k_{\Phi_1} \cdot I + k_{\Phi_2} \cdot \sqrt{I}\right) \cdot \left(\frac{2v_{tr} + u_S}{2}\right) - - k_{Ev}^* \cdot \left(k_{\Phi_1} \cdot I + k_{\Phi_2} \cdot \sqrt{I}\right) \cdot v_{tr} = k_{Ev}^* \cdot \left(k_{\Phi_1} \cdot I + k_{\Phi_2} \cdot \sqrt{I}\right) \cdot \left(\frac{u_S}{2}\right) = E_s^* \quad (5)$$

If the slip-phenomenon yields, the slip (angular) speed rises, practically in the same rate as the voltage $\left(E_s^*\right)$; when $E_s^* > E_{s.treshold} = E_{s.trh}$, an electromagnetic relay activates the anti-slip (automatic) control system. It consists (in a general case) of two specific equipments:

a) the anti-slip mechanical braking system;
b) the anti-slip electromechanical regulator: it controls the Diesel-engine speed and the main generator voltage;

If the action of the anti-slip systems is not strong enough and the supplementary speed slip does not vanish, the driver can activate the pneumatic sand-spreading system. It increases the friction coefficient and, the re-adhesion process can start, even in the most difficult situations.

In order to shorten the slip-evolution and to minimize its effect, the anti-slip systems must be as fast as possible. Under the technical limitation and possibilities, the faster is the anti-slip brake: an electrovalve, activated by the electromagnetic relay, sets a reduced air pressure **directly** in the brake-cylinders of the locomotive. On the "sliping"-wheels (but, unfortunately, on all wheels), acts a braking torque (ΔT_B). For a small diminishing of the friction coefficient the slip-phenomenon ceases but the train speed does not rises or even decreases for a time-period.

The process dynamics can be approximated by a first order differential equation:

$$T_B \cdot \frac{d\left(\Delta T_B(t)\right)}{dt} + \Delta T_B(t) = K_B \cdot c(t) \qquad (6)$$

where c(t) is the logical signal, given by the electromagnetic relay: c(t) acts as an unitary step signal. The time constant (T_B) can be find empirically [1] with:

$$T_B \cong 2.5 \div 3.5 \ [\text{sec}]$$

but the gain (K_B) depends on more factors: in the simulation it was selected an averaged value [1]: $K_B = 2.5$.

The effect of the additional brake-torque (ΔT_B) on the train speed was also approximated by the equation:

$$T_v \cdot \frac{d\left(\Delta v_{tr}(t)\right)}{dt} + \Delta v_{tr}(t) = K_v \cdot \Delta T_B(t) \qquad (7)$$

with the estimated values [1]:$T_v = 10$ [sec] and $K_v = (3 \div 2)$, $E_{s,trh} = 30$ [V].

The electromechanical anti-slip regulator has a complex structure: the electropneumatic valve (driven by the electromagnetic relay) from the mechanical regulator of the Diesel-engine and the (hydraulic) distribution system for the hydraulic actuator of the field governor controller of the main generator. The field controller changes the resistances from the main generator field circuit in order to control the voltage applied to the traction motors. The dynamics can be described by a high order differential nonlinear equation, but the authors proposed an approximation:

$$\frac{\Delta U_a(s)}{c(t)} = \frac{K_u \cdot e^{-s\tau_u}}{s\left(T_u s + 1\right)} \qquad (8)$$

with [1]: $\tau_u \cong 1.5$ [sec], $T_u = (4 \div 5)$ [sec] and $K_u \cong 1.5$ [p.u].

The "driver action" is a delayed sudden action, able to increase the friction (or "adhesion") coefficient and to suppress in a very "hard" manner the wheel slip.

The complete model of the anti slippage block diagram for simulation is given in figure 3.

3. THE MULTIMODEL NUMERICAL SIMULATION USING SIMULINK

Based on the general simulation block-diagram given in figure 3, the detailed simulation schema for the anti-slip process is presented in figure 4.

The simulation program is based on the following supposed situation ("scenarios"):

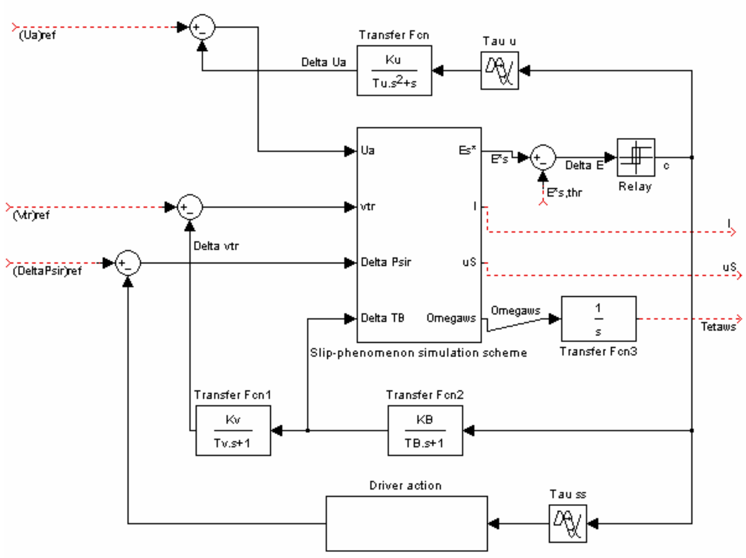

Figure 4. The anti-slip simulation block diagram

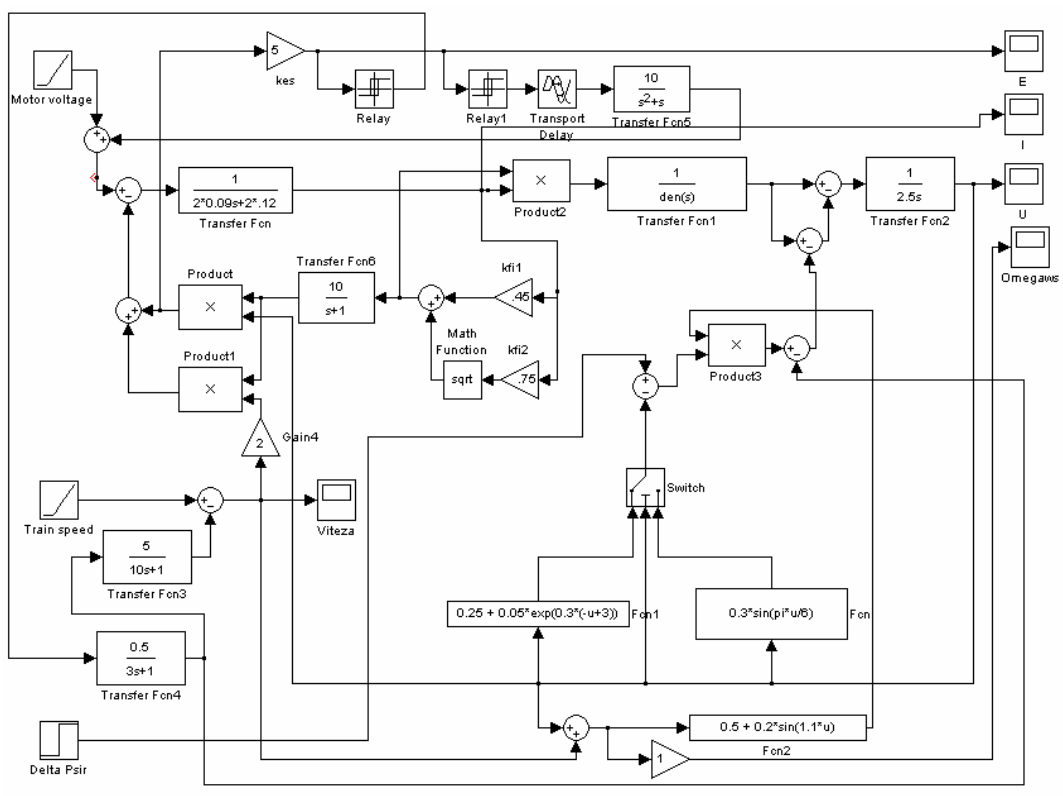

Figure 4 The detailed simulation scheme for the anti-slip process

a) for a "small" decay of the friction ("adhesion") coefficient $(\Delta\psi_{ref})_a$, the partial brake system, activated by the voltage (E_s), is able to reduce the wheel slip: it is important to analyze the supplementary slip speed (u_s) and the wheel angle (θ_{ws})

performed during the slip. In the figure 5 are presented the evolution of the: supplementary electromotive force (E_s, figure 2), supplementary wheel slip speed (u_s), motor current (I), angular wheel speed (Ω_{ws}), train speed (v_{tr}) and the "chattering" of the electromagnetic relay.

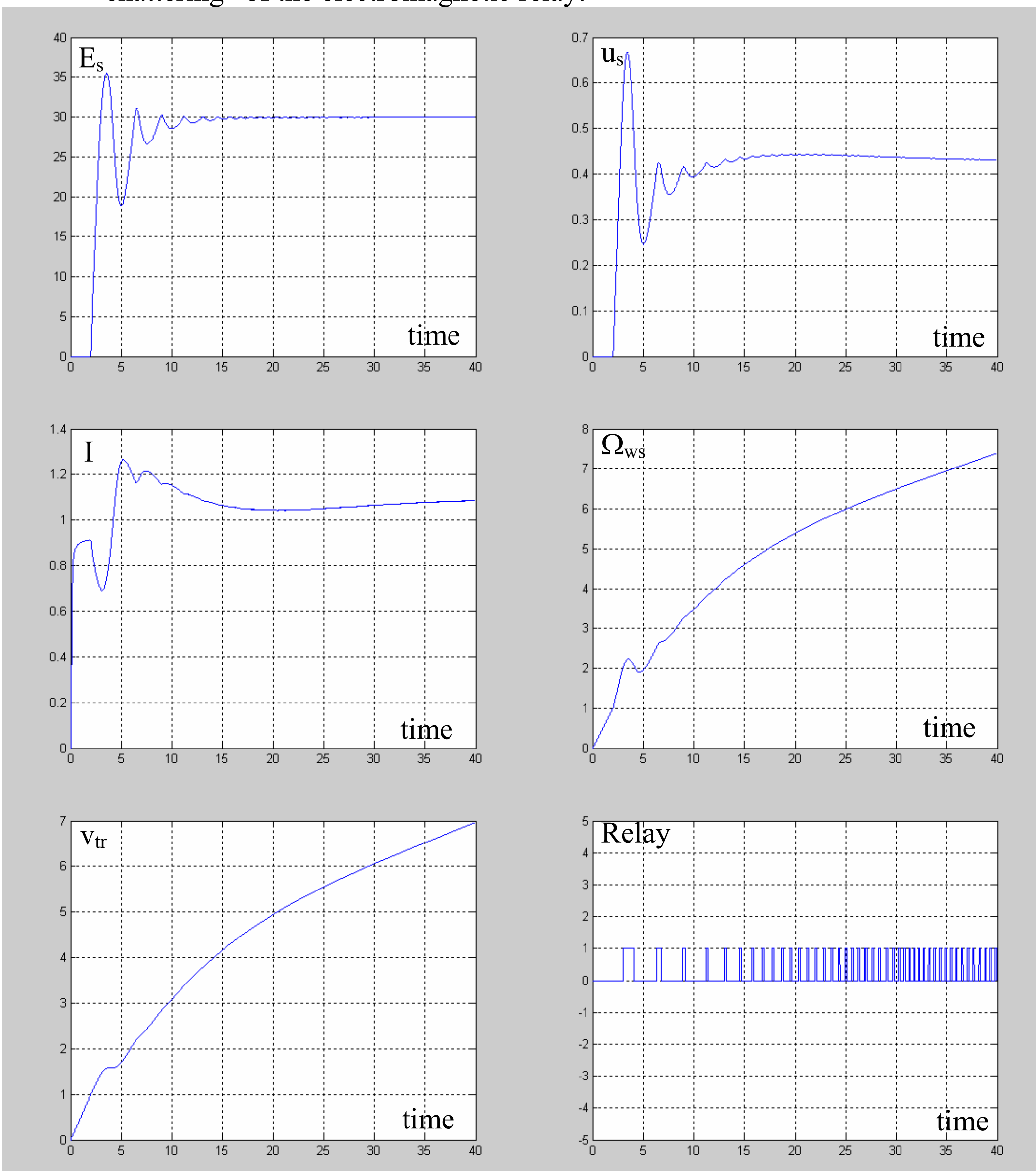

Figure 5. Simulation results

a) for a "middle" decay of the adhesion coefficient $(\Delta\psi_{ref})_b$, the both anti-slip systems (partial brake and motor voltage diminishing) are activated: the final objectives are the same;

b) for a "great" change of the adhesion coefficient, the driver intervention is necessary.

In the figure 6 is shown the evolution of the supplementary peripheral wheel speed (u_s), corresponding to the four situations: without anti-slip, with brake anti-slip system and with brake anti-slip system + motor voltage diminishing system and two gain values: $K_u = 8$, $K_u = 17$.

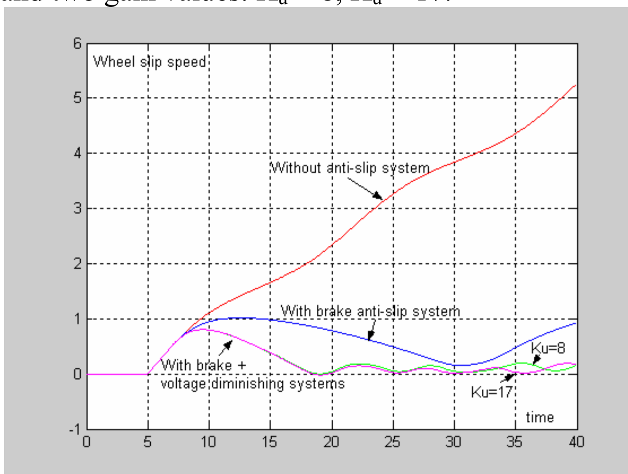

Figure 6 Evolution of the supplementary peripheral wheel speed (u_s)

4. CONCLUSIONS

The simulation program highlights some important problem arising in the anti-slip process. Some of there are:

1. The response-time of the anti-slip equipment is very important in order to reduce the slip undesirable consequences of the wheel slip but with the actual structure of the Diesel Electric locomotive, this parameter is strongly restricted;
2. The group-action (that means: action on all wheels of the locomotive) and not a selective one only on the slipping wheel reduces the traction effort and increase the train start time;
3. "Chattering" phenomenon may arise during the slip suppression, very difficult to prevent and to reduce or to remove.

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