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FUZZY LOGIC SLIP CONTROLLER OF AN ELECTRIC LOCOMOTIVE

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Abstract: *The paper presents two algorithms of slip control of electric vehicles based on fuzzy logic. Since the precise measuring of the velocity of a railway vehicle can present a problem, one applied algorithm is using the signal of the measured vehicle velocity and the other is not using it. The algorithms were tested on the previously developed Simulink model of the Serbian Railways' electric locomotive of the series 444. The current regulator of the modelled locomotive is likewise successfully developed, also by application of the fuzzy logic. Both algorithms of slip control are using the estimated values of the adhesion forces on the contact of wheel/rail, derivated from the state observer of the modelled system.*

Key words: ***Slip control/Electric locomotive/Fuzzy logic /State observer/Simulink***

1. INTRODUCTION

The occurence of slippage between the drive wheels and rails presents one of the main challenges in controlling the traction force of the railway vehicles. High quality and optimal anti-slip protection are difficult to achieve because the adhesion characteristic of the contact between wheel and rail is variable in time, nonlinear and dependent on many factors, out of which the most important ones are the vehicle velocity and the conditions on the wheel-rail contact.

The results of testings [1] performed in the previous years on the locomotives of the Serbian Railways, of the series 444, have shown that there is a huge space for improvement of slip control. That is why the plan for development and application of the new, higher quality algorithms which would enable the optimal use of adhesion possibilities of a traction vehicle in different exploitation conditions, originated.

In order to design an efficient system of slip control, it is necessary to previously make a suitable vehicle model for computer simulation. Recently, an electro mechanical model of the tested locomotive was made and described [2] which has showed as adequate and reliable for the development of slip control algorithms. With the model, a simple, slip controler was made, following the type of the one which is currently implemented on the tested locomotives. The results of the simulations [2] are matching, in great part, the measurement results [1] acquired in the realistic conditions. By this it is stated that the model is of a good quality and that the algorithm of anti-slip protection, which is currently implemented on locomotives, can be optimized. In this paper the results of the application of the more advanced algorithms of anti-slip protection are shown, based on *fuzzy* logic.

2. METHODOLOGY

Adhesion characteristic is descibed by nonlinear dependence of the adhesion coeficient ξ_a on the slip velocity v_s between the wheel and the rail. In each moment it has a characteristic shape (so called adhesion curve) shown in the Fig. 1.

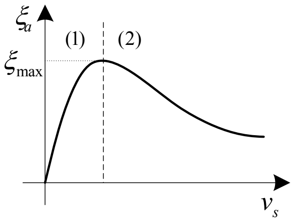


Fig. 1. *A characteristic shape of adhesion curve*

It can be seen that the maximum value of the adhesion coefficient is achieved with some, specific slip velocity value. This point separates the stable zone of adhesion (1) and the unstable zone of sliping (2). Under maximum adhesion utilization, that is, optimal control of vehicles traction force, maintaining of the operation point on the top of the adhesion curve is implied. The adhesion coefficient and the slip velocity cannot be measured directly, but only estimated with lower or higher degree of confidence. The shape of the adhesion curve and the position of extremes are unknown and stochastically variable in time. By now different mathematical models are developed which describe analitically the adhesion curve, with the possibility of simulation of different realistic conditions on the railway line. Such one [3] was used in the simulation model which is the subject of this paper.

The majority of advanced slip control systems works according to the principle of slip velocity control and maintaining of its value within the region of the stable adhesion zone. However, in the railway traffic, a precise measurement of the train longitudinal velocity can present a problem. As the most simple solution, the velocity is determined on the basis of the values of angular velocity of some non-driving wheel. On the modelled locomotive such axle does not exist, and some other velocity measuring ways, are impractical, expensive or not accurate enough, so it is desirable to construct an algorithm which does not use the train longitudinal velocity as an input of slip control system.

Here, two slip control algorithms based on *fuzzy* logic are presented. In the first one, the current of the traction motor is controlled so that the operation point is kept around the adhesion curve maximum and on the basis of the adhesion coefficient gradient and the gradient of the slip velocity. The fact that in the stable zone (region (1) in the Fig. 1) the gradients are of the same sign and in the unstable one (2) they are opposite, is used.

The second algorithm excludes the need to know the values of the vehicle longitudinal velocity. The control is done on the basis of the estimated values of the driving moment of the traction motor and the adhesion moment of the corresponding traction wheel, that is, on the basis of the gradient of these values.

In both algorithms it is necessary to perform an estimation of the adhesion force and on the basis of that also the adhesion coefficient, which is done using the state observer.

3. DESCRIPTION OF THE SIMULATION MODEL

The locomotive model can be devided into electrical and mechanical subsystem. The electrical subsystem contains nonlinear model of a dc series traction motor and single phase half wave thyristor rectifier with belonging control circuits. The mechanical subsystem describes the transmission of the driving torque from the rotor axle of the traction motor to the contact between wheel and rail, the dynamic of train movement in longitudinal direction and finally the adhesion characteristic on the contact between the wheel and rail according to the result from [3]. The controlling part of the system has the function of the anti-slip protection and regulation of the traction motor current. The simplified block-diagram of the whole modelled system is presented in the Fig. 2.

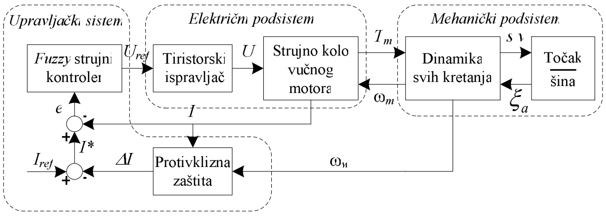


Fig. 2. *Block-diagram of the simulation model*

In order to control optimally the traction force of a locomotive it is necessary to perform the control of a traction motor current. The traction motors of the modelled locomotives are with very nonlinear characteristics ($I = f(U)$, $T_m = f(I)$) and variable and partly unknown parameters, so here too, as a logical choice, the application of some nonlinear regulator, in concrete, *fuzzy* current controller imposes itself.

Thyristor rectifier is successfully modelled, as well as the control block for control of its functioning, which is confirmed by successful simulations of the system with motor current as feedback and current controller. However, because of the wish for greater simulation speed and better simulation performance quality, as well as because of the fact that the emphasis of the paper is not on rectifier control, it was decided to exclude this block from the model, that is, consider it an unit amplifier, in further simulations, in the development of the slip control algorithms.

3.1. *Fuzzy* current regulator

A simple *fuzzy* current regulator is made, of the PI type. The controller inputs are the current error *e* and the gradient of the error *de*, while the output is the gradient of the reference voltage *du* (Fig. 3). All these values are scaled to the amplitude [-1, 1], by the factors the values of which are experimentally adjusted.

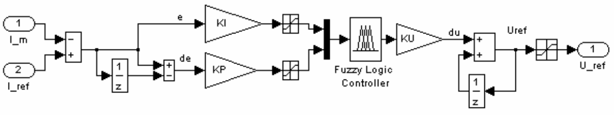


Fig. 3. *Simplified Simulink diagram of fuzzy current regulator*

The controller is of *Mamdani* type, that is, the output value (gradient of the reference voltage) is determined on the basis of the set of IF-THEN rules.

Fuzzification of the input and defuzzification of the output values is performed by definition of 7 ranges using equal triangular membership functions, as shown in the Fig. 4.

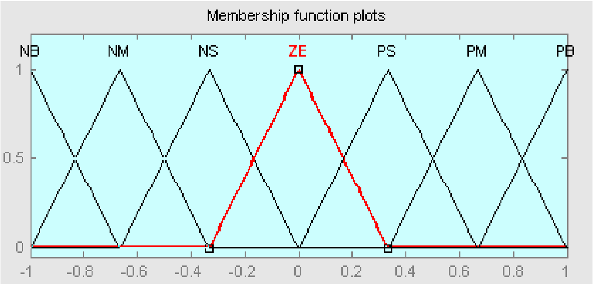


Fig. 4. *Triangular membership functions of all input and output values*

It is noticed that the fuzzy controllers are sensitive even to the smallest changes of their parameters. That especially applies to the number, position and shape of membership functions of the input and output values. However, in this paper, in all fuzzy controllers, the set of membership functions shown in the Fig. 4 is used, which gives the direction for further improvement of the control structures by using new membership functions.

In the Fig. 5 the surface which describes the dependence of output upon the normalized input values is shown, with the designed current *fuzzy* controller.

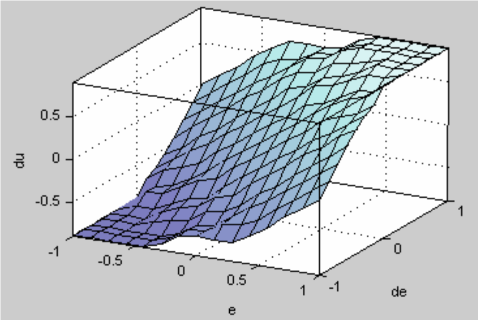


Fig 5. *Surface which describes dependence of output upon current fuzzy controller inputs*

Beside its simple structure, this controller regulates very well the motor current although the attention was not given to the further improvement of its characteristics. The time diagram of the motor current response to some characteristic reference is shown in the Fig. 6.

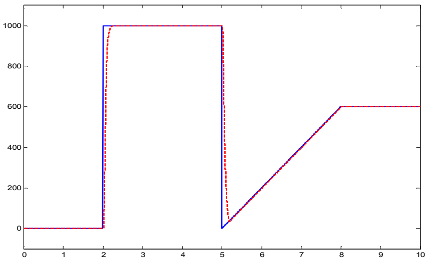


Fig. 6. *Motor current response (broken line) to the specified reference (full line)*

3.2. Adhesion force estimation

As stated in the chapter 2, what both realized slip control algorithms have in common, is the need for adhesion force estimation, that is, its gradient estimation.

For the part of the mechanical subsystem, from the traction motor shaft to the contact between wheel and rail the following is used:

$$T_m = T_a + B\omega + J_e \frac{d\omega}{dt}, \tag{1}$$

where: T_m - drive torqe of motor, transmited to the output side of the gearing box towards drive axle and wheels; $T_a = F_a R$ - adhesion force torque on the drive wheel; B - viscous friction coefficient in bearings; J_e - total moment of inertia reduced to the output side of the gear box device towards to drive axle and wheels; ω - angular speed of drive wheels.

This mechanical subsystem can be considered to be the control object the input value of which is the drive moment of motor, and the measurable output is the angular velocity of drive wheels. Since it is necessary to have, for applied slip control algorithms, the estimated value of the adhesion force and its gradient, the following is taken for the state vector: $x = [\omega \;\; T_a \;\; \dot{T}_a]^T$. On the basis of (1), the discrete object model of state space can be described with the following expressions:

$$x[k+1] = Ex[k] + Fu[k], \text{ i.e.} \tag{2}$$

$$\begin{bmatrix} \omega[k+1] \\ T_a[k+1] \\ \dot{T}_a[k+1] \end{bmatrix} = \begin{bmatrix} 1 - B\Delta T / J_e & -\Delta T / J_e & -\Delta T^2 / 2J_e \\ 0 & 1 & \Delta T \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \omega[k] \\ T_a[k] \\ \dot{T}_a[k] \end{bmatrix} + \begin{bmatrix} \Delta T / J_e \\ 0 \\ 0 \end{bmatrix} T_m[k]$$

$$y[k] = D \cdot x[k], \text{ i.e.} \tag{3}$$

$$\omega_{enc}[k] = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \omega[k] \\ T_a[k] \\ \dot{T}_a[k] \end{bmatrix}$$

ΔT is the observer discretization period.

In the Fig. 7. a block diagram of the state observer is given. The input value is the product of transmition ratio of the mechanical gearing down device and the estimated value of the motor torque, which is obtained on the basis of the known [2] nonlinear dependence of the torque upon the motor current of the modelled locomotives. The signal of the angular velocity of the drive axle is obtained from an optical encoder, containing some measuring noise.

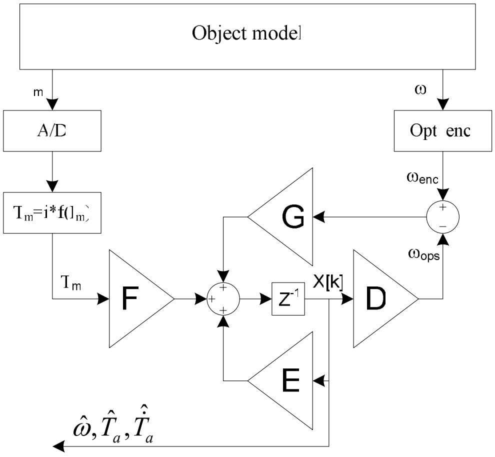


Fig. 7. *Block diagram of the state observer*

Similar observers are proposed in [4] and [5], where they are used in the system of anti-slip protection.

The observer gain matrix $G = [g_1 \;\; g_2 \;\; g_3]^T$ is adjusted in such a way that the characteristic polynomial of the observer $f(z) = \det|zI - E + GD|$ has a triple real zero, by the variation of which the observer's passband is changed. The optimal value of observer's passband width is reached experimentally.

3.3. Slip control

The first algorithm of anti-slip protection works on the basis of the relation of slip velocity gradient and the adhesion coefficient. The fact that in the stable region of the adhesion curve (Fig. 1) both gradients have the same sign and in the unstable one the opposite, is used.

Slip velocity is equal to the difference of velocity of the wheel rim at the place of contact with the rail and the longitudinal velocity. Signal of angular velocity is taken from the state observer instead of directly from the encoder because of the existence of a significant quantization measuring noise, which is also even increased by differentiation before entrance into *fuzzy* controller so:

$$v_s = \hat{\omega}R - v \;\Rightarrow\; \dot{v}_s = \dot{\hat{\omega}}R - \dot{v} \tag{4}$$

The train velocity can be estimated on the basis of the minimal angular velocity of drive axles. This velocity estimation method is satisfactory until the situation with the simultaneous slipping of all axles appears, when the estimated velocity value greatly varies from the real one. This is confirmed by the simulations. In this paper the results of simulations which were performed using the exact train velocity value from the mechanical subsystem are shown, that is, it is considered that the velocity value is known.

The adhesion coefficient gradient is obtained on the basis of the estimated value of adhesion moment differential from the state observer:

$$\hat{\dot{\xi}}_a = \frac{\hat{\dot{F}}_a}{N} = \frac{\hat{\dot{T}}_a}{RN}. \qquad (5)$$

The *fuzzy* controller output is the compensation gradient of the motor current reference, which is added from outside to the given value of the current reference.

In the Fig. 8 the simplified diagram of this control structure is shown.

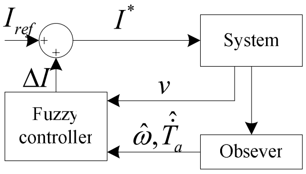


Fig. 8. *Block diagram system of anti-slip protection which uses train velocity*

The principle for definition of the set of IF-THEN rules of the *fuzzy* controller is the following: if it is stated, on the basis of the value of the adhesion coefficient gradient and the slip velocity, that the operating point is in the stable zone, the current compensation is positive and higher as the point is further from the top of the adhesion curve [6]. If the operating point is in the unstable zone, that is, if slipping appeared, a negative compensation of the current reference is determined.

The surface which describes the dependence of output values upon the input values is given in the Fig. 9.

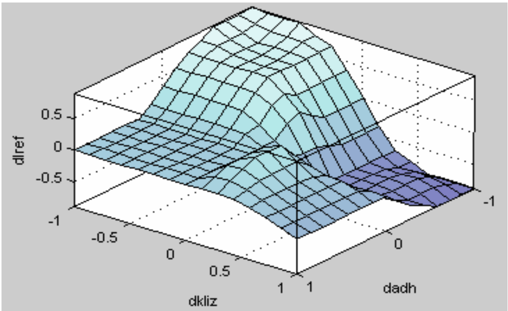


Fig. 9. *The control surface of the first type of fuzzy controller*

The second type of the slip control algorithm does not use the vehicle velocity signal, so it is more simple for application in practice but also possesses (as expected) a bit worse characteristics. It is analyzed the relation of adhesion moment gradient T_a, received from the state observer, and the motor moment T_m obtained on the basis of the measured value of the traction motor current (Fig. 10).

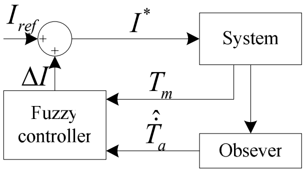


Fig. 10. *Block diagram of the anti-slip protection system which does not use vehicle velocity*

If the drive moment of a motor increases and the adhesion moment decreases, the system is certainly in the unstable zone of the adhesion curve and the motor current reference must be reduced [7]. The logic for adjusting of the IF-THEN rules set is similar to that in the previous case, and by that also the control plane, shown in the Fig. 11.

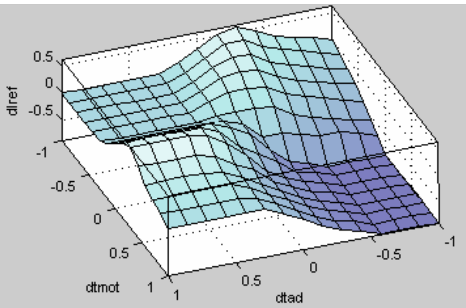


Fig. 11. *The control surface of the second type of fuzzy controller*

4. SIMULATIONS RESULTS

As an illustration of the results of the paper, two simulations with the same parameters were performed, only with the different applied slip control algorithms. Time diagrams of the most important quantities were shown: train velocity, angular velocity of one drive axle, current of the corresponding motor and the movement of the operating point over the adhesion curves.

The basic simulations parameters are:

- the current reference at the beginning of the simulation increases linearly from 0 to 1500 A;
- at the beginning of simulation, adhesion conditions are favorable ($\xi_{a\max} \approx 0.3$), from 20. to 50. second they are worse ($\xi_{a\max} \approx 0.25$), and then again good;
- at the moment $t = 25\text{s}$ the gradient of current reference of 400A is imposed.

The first simulation results:

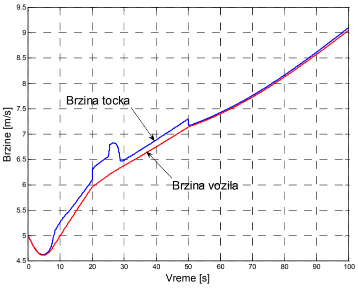


Fig. 12a. *Time diagram of train and drive wheel velocities*

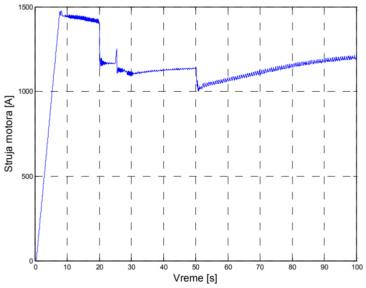


Fig. 12b. *Time diagram of the traction motor current*

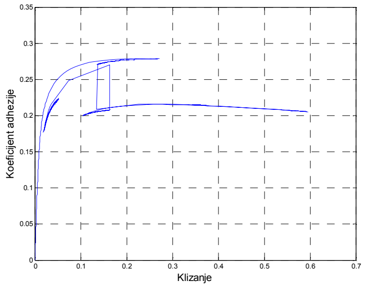
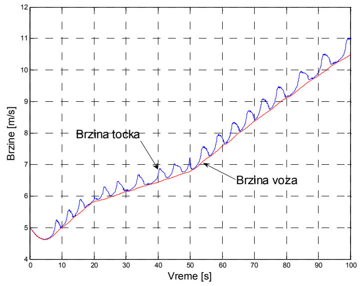


Fig.. 12c. *Movement of the operation point over adhesion curves*

The second simulation results:



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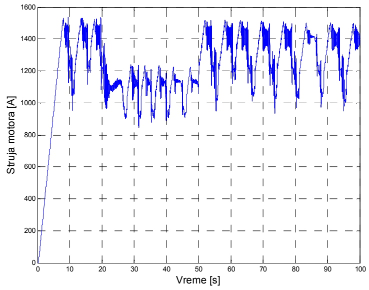

Fig. 13b. *Time diagram of the traction motor current*

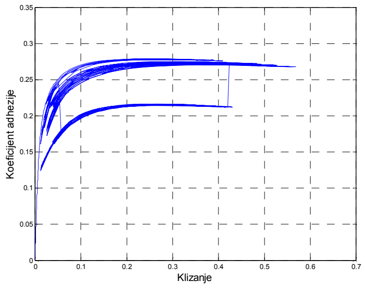

Fig. 13c. *Movement of the operating point over adhesion curves*

5. CONCLUSION

The use of the *fuzzy* logic in designing of the control algorithms in control of the traction force is a good choice, which was confirmed by the results of the performed simulations.

The first algorithm which is demonstrated performs refine regulation of the traction force, with minimal oscillations of the traction motor current, which is an obvious advantage. But it is limited by the problem of recognition of the exact value of a vehicle velocity, and thus there is space for development and application of some methods for exact measuring or estimation of train velocity.

The second algorithm is more capable of regulating abrupt and unforeseen negative influences, maintaining the operating point in the stable zone of adhesion curve. However, the current oscillations are too big, which can certainly be improved by finer adjustment of the *fuzzy* controller's parameters.

The choice of the observer's passband width encounters conflicting requests for elimination of angular wheel velocity measurement noise and for faster response. It was noticed that the changes of the values of both noise and state response delay require also the change of the *fuzzy* controller structure. Because of this, the direction of further research goes toward a better estimation of the desired quantities, e.g. by synthesis of Kalman state estimator.

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