TARGET BRAKING OF UNDERGROUND TRAINS DRIVEN BY AN AC AND A DC MOTOR

ANDRZEJ GOCEK

Technical University of Lodz, The Institute of Electrical Power Engineering, 18/22 Stefanowskiego St., Łódź 90-924, Poland
email: andrzej.gocek@p.lodz.pl

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Abstract: Target braking of underground trains as a function of an Automatic Train Operation ATO system has been described in this paper. A general model of target braking regulator has been shown. A quality indicator of automatic train braking process was discussed. The functionality of SOP-2 system used in the Warsaw underground was presented. The rolling stock powered by an AC and DC motor has been taken into consideration. Further research plans of target braking in Simulink have been explained.

Keywords: automatic train operation system, target braking, railway traffic control, subway, control modeling.

1 Introduction

Traffic conditions present in the underground are unique in that the distance between trains is short, they move with high speed (V~90 km/h) as well as platforms are short. Therefore, it is required to apply specialized systems which can provide traffic safety, which in terms of speed restrictions, is ensured by Automatic Train Protection (*ATP*) system. Once the system has been provided with appropriate data it can calculate safety speed for each train or all trains travelling along the same line. By executing a specified algorithm *ATP* devices do not allow to exceed safety speed as it includes control of the power transmission and braking system. The system protects against dangerous situations such as collision with the preceding train, failed braking before absolute stop, falling out on curve due to excessive speed, etc. The *ATP* system is initiated only if the driver exceeds permissible speed e.g. signalled by a semaphore [4, 6]. Automatic Train Operation (*ATO*) is another example of systems which can be of help in the underground. This one is responsible for supporting the driver of the train. Both systems can cooperate and in this case *ATP* is a master system while *ATO* is relative. The following functions can be implemented by an ATO system:

- Automatic train starting, riding and stopping,
- target braking,
- train doors opening/closing,
- driving for energy savings
- driving for schedule optimization.

Target braking is one of the most important functions performed by an *ATO* system. It relies on automatic train stopping at the stations, where braking process is fully controlled by a microprocessor device. Target braking helps to avoid dangerous situations due to stopping too far from the passenger transfer section of the platform. For instance it prevents from a serious injury when a passenger would fall into the gap between the platform and the train. Further the position where the train stops is very important at stations equipped with double-locked doors (so-called closed platforms). In this case it is required to stop the train according to the method "door to door". Precise stopping also affects the evacuation of passengers in the event of a terrorist attack [1, 5].

2. Target braking

2.1 General method of target braking

Target braking is a special case of essential train braking. It consist of progressive reduction of actual train speed V_{rz} to the permissible speed value V_d=0. The permissible speed has to be obtained at the stage of speed restriction x_d. During this process the permissible value of deceleration a_h cannot be exceeded. Automatic braking process occurs in the following situations:

- On the platform, where the train stopping has to be accurate and the actual train stopping position x_{rz} fulfils the condition of $x_{rz} = x_d \pm c$,
- by the semaphore, where the actual train stopping position is donated by $x_{rz} \pm c \leq x_d$,

  where c – admissible stopping tolerance.

Target braking is an important stage of underground train ride as it is required to stop a train in a platform with limited length. The average length of the subway train is about 100 m, length of the platform for reasons of space savings in the tunnel is very similar [1]. The process of target braking consist of two phases: motor braking phase (electrodynamic braking) and mechanical braking phase (performed by a pneumatic brake). The second stage of braking is required because of decreasing capacity of the electrodynamic braking at low speeds. Target braking process is executed by a proper control of electric motors. However, the process is more complex than it appears. Target braking operation requires solving two problems such as [1]:

- Firstly, the braking has to be initiated in appropriate distance from the stopping point.
- Secondly, the braking process has to be properly conducted.

2.2 Structure of the braking control system

The primary task of a brake control system is to obtain in the point of speed restriction x_d, permissible speed V_d with certain restrictions. To conduct this process the following data have to be obtained:

- Constant parameters: capacity of electrodynamic and mechanical braking, coordinates of the stopping points, vertical and horizontal line profile.
- Variable parameters: actual train speed V_{rz}, actual train stopping position x_{rz}, permissible speed V_d, train load and any external interferences z.

The executing system has to perform the following tasks (in the given order):

1) determine x_0 point for starting the braking process,
2) determine the actual train position x_{rz} and begin to measure the actual train speed V_{rz},
3) calculate the braking speed V_h,
4) calculate in real time the braking force F_h and control the braking process.

The steps from enumeration *1-3* are measurement and compute operations. Therefore, these steps are not affected by the integrated train braking system. The above-mentioned actions in no. *4* have a control-execution nature and are related to the integrated braking system [1]. The structure of this system is shown in Fig. 1.

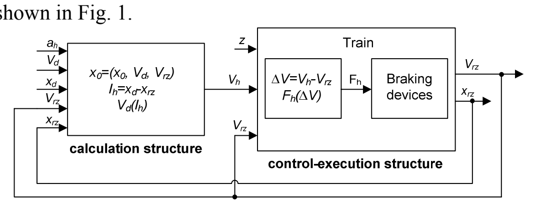

Fig.1. Structure of the automatic braking system [1]

The above-mentioned calculation structure consists of the following tasks:

a) to determine initial braking point x_0,
b) to calculate the distance l_h – between the front of the train x_{rz} and the point of speed restriction x_d,
c) to generate the theoretical braking curve $V_h(l_h)$.

The tasks of the control-execution structure are as follows:

a) Calculation of the difference ΔV between braking speed V_h and the actual train speed V_{rz},
b) determination of the braking force F_h and execution of the braking process (electrodynamic and mechanical).

Braking devices are implementing the braking process with a specified value of braking deceleration a_h. The braking control system cooperates with motor and pneumatic control circuits for the proper train stoppage. To provide optimal braking quality it is required to perform three optimum controlling phases [1]:

I. The phase of progressive accumulation of braking deceleration to maximal value.
II. The phase of braking with maximal delay.
III. The phase of progressive decrease of braking deceleration to a zero value.

2.3 Quality of the braking process

Evaluation of the braking quality takes into account static *(*Δ_d*)* and dynamic *(*Δ_v*,* Δ_a*)* parameters:

- static: accuracy of train stopping,
- dynamic: accuracy of braking control process and execution of the theoretical braking curve $V_h(l_h)$.

The quality of braking process indicator allows to assess the value computationally [1]:

$$I_r = \alpha \cdot \Delta_d + \beta \cdot \Delta_V + \gamma \cdot \Delta_a \qquad (1)$$

where:

$$\Delta_d = \left| x_{rz}(t_k) - x_g \right| \qquad (2)$$

$$\Delta_V = \int_{t_0}^{t_k} (V_h - V_{rz})^2 dt \qquad (3)$$

$$\Delta_a = \int_{t_0}^{t_k} (a_h - a_{rz})^2 dt \qquad (4)$$

α, β, γ – constant importance factors of the quality indicator components.

3. Solutions of target braking in the Warsaw underground

3.1 The no. I underground line in Warsaw

On the 1st line of Warsaw underground, traffic safety provides a system commercially called SOP-2. It is a type of an ATP system which is enriched in ATO system function – the target braking of train in the platform. The SOP-2 performs its tasks by a continuous data transmission, which is achieved by using a wire loop placed between the track [2, 3]. There are used two basic types of rolling stock: Russian series 81 trains driven by a DC motor and Alstom Metropolis trains powered by an AC motor.

3.2 Rolling stock driven by a serial DC motor with a resistance start-up

The initiation of the target braking process is fixed in software. The whole process consist of uploading four characteristics of the distance from the stopping point, to the vehicle microcomputer memory (Fig. 2).

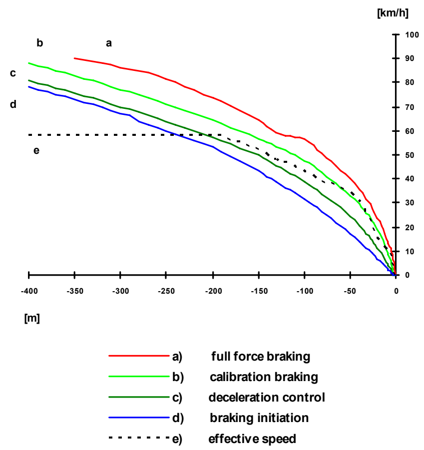

Fig.2. Speed curves controlled during target braking of train 81 type [2]

After crossing the braking initiation curve (***d***) the braking process is initiated. Braking takes place according to the course of the calibration braking curve (***b***), which was designated during a man-braking . The full braking force (***a***) and deceleration control (***c***) curves are responsible for the proper execution of target braking. The underground line is divided into a certain number of spacing blocks, which have been assigned with unique sequence numbers. The wired loops lengths are identical to the spacing blocks. In the area of the stations all spacing blocks are the same. The main idea of braking is based on the comparison of the coordinates of actual train position with the coordinates of the inscribed braking characteristics in the form of curves. The calculated difference has an impact on the controlling signals. Coordinates of the measured route from the stopping point are obtained from the number of a spacing block. The current train position and the real speed value is also measured by a tachometer, thereby the actual distance from the stopping point can be counted [2].

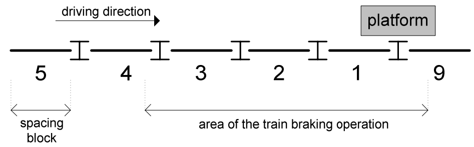

Fig.3. Numbering of track sections [2]

When the train approaches the no. 3 spacing block area (Fig. 3), the system counter is positioned approximately with a constant value of the distance remaining to the stopping point. Next, the measured value of the actual driven distance is subtracted. In the region of spacing block no. 2, 1, 9 similar calculations are made. Final adjustment occurs 50 metres before the stopping point due to a wire loop crossing. Series 81st trains normal braking can be divided into three stages. The first stage concerns braking with maximum resistance of the braking resistor and smooth adjustment of motor coil excitation (48%÷100%). The second stage involves a camshaft operation, which relies on reducing the value of resistance in the braking structure. Electrodynamic braking becomes ineffective below the value of 10 km/h; therefore, in the third stage the train is stopped with the use of pneumatic brakes. The target braking force is controlled by the influence of camshafts on the control circuits. Camshafts controlling circuits are coupled with the current adjustment block. When the voltage of camshafts circuits is disabled, in the first stage during regulation of motor coil excitation the current considerably decreases. In the second stage a voltage interrupt holds the camshafts in place and the current decreases gradually to a very small value. Renewed movement of the shaft ensures emerged control voltage. The camshaft achieves subsequent adjustments every 0.16 seconds – the brake control current increases progressively. Proper control of camshafts duration times enables the realization of the calibration braking curve [2].

3.3 Rolling stock driven by an AC motor

Operation of the target braking structure can be divided into several phases presented in the Fig. 4. The braking route consist of tracking the reference braking curve (Fig. 5), while electrodynamic braking takes place and driving trough the access road (with the impetus and next pneumatic braking).

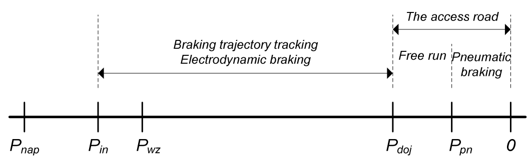

Fig.4. Characteristic points of target braking process [2, 3]

Explanation of the Figure 4:
P_{nap} – traction drives disabling,
P_{in} – regulator initiation,
P_{wz} – start of tracking the calibrated braking trajectory,
P_{doj} – end of tracking the calibrated braking trajectory (the regulator disabling),
P_{pn} – pneumatic brakes start.

If the train crossess the appropriate wire loop, the braking process will be initiated. The road and the speed are measured. Respective braking commands are given as a result of comparison of the actual distance and the calibration curve distance from the stopping point. After crossing the drive-off curve the drive is turned off and the braking procedure starts. The drive-off curve is calculated continuously by the braking force controller and it is based on the reference braking curve. At point Pnap the drive is turned off. At Pin the braking force controller starts to work, however, due to a delayed action of the controller the trajectory tracking begins at Pwz point. At Pdoj the train has to achieve a speed of 10 km/h, also the electrodynamic braking is turned off and the trajectory tracking is finished. Afterwards the train rolls free and the precise train stopping is now based on the pneumatic braking characteristic. At point Ppn pneumatic brakes are being activated. The pneumatic braking force operates with a constant value until the train is stopped. The control of driving and braking processes is performed by the operating current. The SOP-2 units are connected with the train controlling circuits. Electrodynamic braking is the basic type of braking and takes place according to the braking force reference characteristic (Fig. 6). During the braking process the current varies from 4 mA to 20 mA. This corresponds to the braking deceleration from 0 m/s2 to 1,3 m/s2. The current control ensures a smooth control of the deceleration [2, 3].

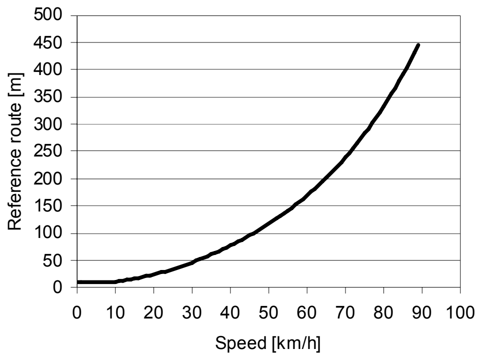

Fig. 5. Reference braking curve [2]

The train is braking with a delay calculated in the system or predetermined by the driver. The system is designed to select always a higher value of deceleration. With an output current loop a 8-bit control current signal is transmitted to the encoder. In two additional input current loops, the current signals are changed into voltage. The first is equivalent to the system deceleration value, while the second to the deceleration predetermined by the driver [2, 3].

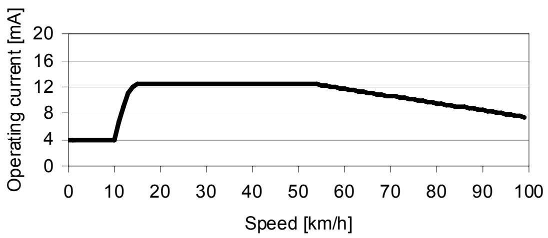

Fig. 6. Braking force reference characteristic [2]

3.4 Simulation studies

It is necessary to investigate the influence of drives on the target braking accuracy. For this purpose a simulation model is being formed. The simulation model takes into account ride and control dynamics, train physics, line profiles etc. The AC drive model includes a PID regulator. For a DC drive with a resistance riot, start-up resistances have to be taken into consideration. A functional simulation model has been proposed (Fig. 7). It consist of train structure, controller block and braking initiation layout. Train dynamics and physics are presented by the motor characteristics (Ms, Mh), parameters of braking system (ah – retardation capability), start-up resistances characteristics (Rh) and train weight. Braking initiation block decides about drive disabling and initiation of the braking process (Fh, Fn). For this purpose a braking characteristic s(V) is needed. The line parameters are represented by speed V(s) and route s blocks. The regulator maintains the braking force according to a s(V) characteristic and the train parameters. Finally braking accuracy is being calculated as the distance between the adopted and the actual stopping point.

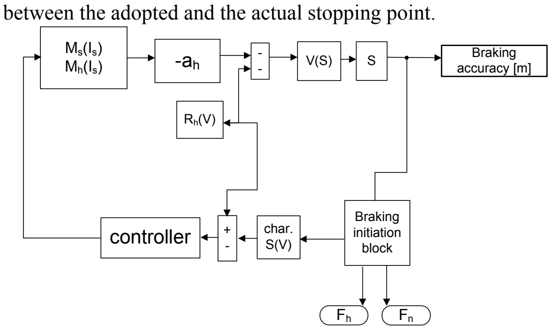

Fig.7. Target braking simulations – a functional model of a DC drive with a resistance start-up

4. Conclusions

The solutions of target braking described in this paper provide the accuracy of braking in the range of ±0,5 to ±1,5 meters for Series 81st trains and in the range of ±0,3 to ±0,5 meters for Alstom Metropolis trains. Braking solutions discussed here are dedicated only to the beforehand mentioned types of trains. It is assumed that the quality and accuracy of target braking depends on the performed traction drive control. Furthermore, the phase of mechanical braking does not affect accuracy of target braking. Target braking process has to be carried out in the manner below:

- Rapid deceleration changes causes jerks which are negatively perceived by the passengers e.g. passengers are falling down,
- as short as possible, braking in a long time causes a decrease in commercial speed.

Currently undertaken studies deals with the examination of traction drives influence on the quality of target braking. For this purpose a SIMULINK model is being prepared.

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