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The Use of the Imperialist Competitive Algorithm in Optimising the Setting of the Tram Speed Controller in the Development of a Matlab-Simulink Environment

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Abstract—**Estimating the electric power used by railway vehicles is an important factor in the planning of future power consumption, looking for possibilities to reduce the use of electric power and therefore also reduce carbon emissions. To improve the estimation, we used the imperialist competitive algorithm in the optimisation process of a mathematical model of a tram vehicle. Specifically, in the setting of the proportional and summation constant of the vehicle speed controller which emulates the activity of the driver in the simulation. Our work presents a new approach to optimising the estimation of energy consumption in tram transport. The method used is based on mathematical modelling and simulation of social development in human society. To obtain the input data for the simulation, we performed a measurement of the reference speed by means of a GPS receiver located in a sample tram vehicle. Subsequently, to verify the model and energy calculation results, we measured the output currents and voltage from the traction converter station at the corresponding time. Our method achieved a 93 % match between the measured and simulated power consumption.**

Index Terms—**Energy consumption simulation; Electric traction; Electric vehicle; Metaheuristic algorithm; Optimal solution.**

I. Introduction

The expected development of electrical vehicles increases the importance of research of their parameters, especially research of electrical energy consumption during a ride of such a vehicle. Analysis and simulation of vehicle energy consumption can be used to implement improved driving techniques, which lead to energy saving and emission reduction. This applies to both vehicles with internal combustion engines and electric vehicles [1]. Different authors used different methods for vehicle ride analysis, simulation, and optimisation. They differ in terms of their level of detail and the quality of the results obtained. For example, Jakubowski *et al.* [2] propose a model that includes the mechanical and electrical subsystems of a transportation system, based on multivehicle modelling with discreet timestep power integration, to simulate vehicle movement dynamics and energy distribution and losses. But it does not deal with the speed regulator. Yildiz, Arikan, and Keskin [3] use genetic algorithms and particle swarm optimisation techniques to optimise a train speed profile, resulting in a claimed energy savings of about 20 %–30 %. Novak, Novak, Morkus, and Sivkov [4] present a simulation of the energy consumption of an electric bus in various driving cycles, and the results are verified by comparison with real world measurements. The goal is to compare various motor and gearbox configurations to find the most efficient one. The issue of speed regulation is not addressed here. The train energy consumption modelling, which includes instantaneous braking energy regeneration, is presented in [5], which can be calibrated using external data (e.g., speed), without the need for internal engine data. Speed profiles are taken from operational data. According to the authors, the predicted error of this modelling method is between 1.87 % and 2.31 %.

Through long-term scientific investigation for the purposes of energy calculation, we optimised the instantaneous vehicle power time integration method which is necessary to overcome traction resistances in individual driving modes. For the purpose of this research area, we developed a dynamic model of a tram vehicle. The simulation carried out in the Matlab-Simulink environment includes a series of influences associated with the dynamics of a journey and changes in trolley parameters in the individual track sections. The model was created by connecting block parts, some of which form more complex

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units such as a traction converter station, a controller of traction drive current and speed. An open or closed control loop is used depending on the type of electrical drive control [6]. The tram ride simulation employed a controller drive that uses a closed control loop with feedback, which is formed by electric motor revolutions and current. The controller influences the speed and size of the response of the drive parameters with respect to the required values. It is possible to use more solutions to set the controller; one of the most widespread is the heuristic Ziegler-Nichols (ZN) method based on empirical experience [7]. Although the results of the setting are only approximate to the optimal values, the advantage lies in the speed and simplicity of the setting. More precise metaheuristic methods use stochastic algorithms that create different populations; these populations are then subjected to selection depending on the type of algorithm used to achieve the optimal solution. The most frequently used type of controller for calculations and simulations of drive in a continuous-time area is the proportional integral controller (PI). Due to the need to verify the output data from the simulation against the corresponding measured values, we secured the same number of samples from the current and voltage course by using a tram ride simulation in a discrete time area. Therefore, a proportional summation controller (PS) was used for the drive simulation; by analogy, this controller is based on the PI controller [8]. The article deals with optimisation of the proportional and summation constant of the tram speed controller in the defined limits by means of the imperialist competitive algorithm (ICA); the scope of the constant optimisation was estimated according to the previous setting by means of the ZN method [9]. In the case of optimisation algorithms, one of the main parameters is the setting of the cost function whose global minimum is searched [10]. In our research, the size of the difference between the measured and simulated values of electrical energy consumption during a tram ride on the selected track section was chosen as the cost function.

II. Theoretical Principles

The most important part of the dynamic model of the tram vehicle is the pulse width modulation (PWM) converter, which is controlled by current and speed controllers. The speed controller substitutes for the activity of the driver, who maintains the chosen speed by visually checking the speedometer and using the drive control, which sets the required value of the traction motor current.

A. Speed Controller

The proportional integral controller is the subject of long-term research, especially in traction applications in the implementation of PWM converters in railway vehicle drives [7]. Tram technology first used a continuous PI controller in connection with analogue applications in converter control circuits. A mathematical description of the equation of the ideal continuous PI controller [9] is as follows

$$u(t) = K_{\mathrm{r}} \times \left(e_{\mathrm{r}}(t) + \frac{1}{T_{\mathrm{i}}} \times \int_0^t e_{\mathrm{r}}(\tau_{\mathrm{i}}) d\tau_{\mathrm{i}} \right), \tag{1}$$

where $u(t)$ is the control variable, K_{r} is the amplification of the controller, T_{i} is the integration constant (s), τ_{i} is the integration of the variable (it changes from 0 to t), t is the time (s), and $e_{\mathrm{r}}(t)$ is the control deviation which is defined as the difference between the required and the real value of the quantity as shown in the relationship

$$e_r(t) = r(t) - y(t), \tag{2}$$

where $r(t)$ is the required value of the quantity and $y(t)$ is the real value of the quantity. Discrete controllers came to be used with the emergence of digital circuits in traction vehicle systems. The action of a discrete controller is defined in discrete time moments [8] as follows

$$t = k \times T_{\mathrm{s}}, \tag{3}$$

where k is the consecutive number of the sample (-) and T_{s} is the sampling period (s). The change in the continuous PI controller for the discrete time area was made by substituting a sum for the integration component of the continuous controller, as shown in [8]. The value of the given integral is replaced with a sum of the rectangle area which substitutes for the area under the continuous curve $e_{\mathrm{r}}(t)$ in selected discrete time moments. The width of the rectangles corresponds to the sampling period T_{s}, a forward rectangular substitution of the integral value was used, and a proportional-summation controller (PS) will be created according to the equation

$$u(k \times T_{\mathrm{s}}) = K_{\mathrm{r}} \times e_{\mathrm{r}}(k \times T_{\mathrm{s}}) + \frac{T_{\mathrm{s}}}{T_{\mathrm{is}}} \times \sum_{k=0}^{k-1} e_{\mathrm{r}}(k \times T_{\mathrm{s}}), \tag{4}$$

where T_{is} is the summation parameter (s). The resulting Z-transfer of the PS controller used in the simulation is as follows

$$G_{\mathrm{r}}(z) = K_{\mathrm{r}} \times \left(1 + \frac{T_{\mathrm{is}}}{z-1} \right), \tag{5}$$

where $G_{\mathrm{r}}(z)$ is the Z-transfer of the discrete PS controller (-).

B. Heuristic Method of the Setting the PS Controller

The heuristic-approximate method of setting the PS controller is based on the method of critical controller parameters. It is also called the "Ziegler-Nichols method" according to the scientists who invented it in 1941 in the USA. It is convenient for simulation because it is based on experimental principles; the following calculations and evaluations are based on empirical experience [9]. The resulting setting is only approximate to the optimal setting. The following procedure is used for the setting.

A constant signal is conducted to the input of the speed controller r_r(t); the summation component T_{is} is set to infinity and the amplification value of the controller K_r is increased to the critical level K_{rt}; the control circuit starts to oscillate. At the output of the controlled system $y(t)$, there is a periodic waveform with the period T_k, as can be seen in Fig. 1.

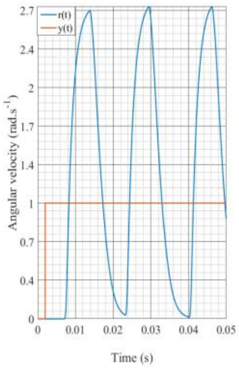

Fig. 1. Periodic oscillation with period T_k at the output of the controlled system.

The calculation of the controller amplification according to the critical parameter method is as follows

$$K_r = 0,45 \times K_{rt} \times \frac{T_s}{T_k}, \tag{6}$$

where K_r is the controller amplification (-), K_{rt} is the critical controller amplification (-), and T_k is the oscillation period of the output controller (s). Calculation of the summation component of the controller according to the critical parameter method is as follows

$$T_{is} = 0,54 \times \frac{K_{rt} \times T_k}{K_r}, \tag{7}$$

where T_{is} is the summation parameter (s).

– The advantage of the parameter setting method is the simplicity of the calculation; it was used in practise.

– The disadvantage of the method resides in only approximate values of the controller parameters; in the case of more demanding applications, it is necessary to perform optimisation.

C. Metaheuristic Method of PS Controller Setting Using the Stochastic Algorithm

Metaheuristic methods use stochastic optimisation methods for the purposes of creating a population of possible solutions from which the most optimal solution in relation to the cost function will be chosen according to the selected algorithm. The proposed method uses socio-political human development as a source of inspiration for the development of the optimisation strategy [10].

ICA simulates the interaction between a weaker country known as a colony and its possessing imperialist within several subpopulations called “empires”. In other words, the most powerful colony in each empire is its relevant imperialist. The power of an empire depends mostly on the imperialist and partially on its other colonies.

An imperialist tends to absorb not only the colonies in its empire but also the ones in the other empires. The former constitutes a local search, while the latter may result in a global search. These imperialists compete with each other to take control of colonies in other empires. Consequently, some weak empires will collapse during optimisation, while more powerful ones will become larger [11].

From a certain point of view, the ICA can be considered a social counterpart of genetic algorithms because certain procedures are similar within optimisation [12]. It is necessary to perform the following optimisation operations using the imperialist competitive algorithm:

– To define the cost function - a percentage difference between the measured and the simulated electrical energy consumption of the converter station during the rail vehicle ride. The aim of optimisation is to find a global minimum of the cost function. On condition that the calculation of the simulated consumption of the converter station is lower than the calculation of the measured consumption, the following relationship applies

$$z_d = 100 - \left(\frac{S_e}{N_e} \times (100) \right), \tag{8}$$

where z_d is the cost function - the difference between the measured and the simulated electrical energy consumption of the converter station (%), S_e is the modelled electrical energy consumption of the converter station during the tram ride (kWh), and N_e is the measured electrical energy consumption of the converter station during the tram ride (kWh).

– The creation of the initial value population by means of stochastic methods with even distribution for substitution in the proportional and summation parameter of the speed controller as shown in Fig. 2. The scope of the generated values was set for guidance according to previous results, calculated PS controller parameters by the critical value method. In the ICA algorithm terminology, individual population values are designated as countries [10].

– The division of countries into empires and colonies - gradual substitution of the individual generated values in the PS speed controller parameters, and depending on the evaluation of the cost function, two best countries become the imperialists, and the others are designated as colonies. The colonies are divided between the imperialists proportionately according to their value of the cost function.

– Other parameters of the ICA algorithm are the number of decades, the assimilation coefficient, and the revolutions. On the basis of empirical experience, it is presumed that a change may occur in the positions of colonies within a certain time period, ten years; the colonies may reach the imperialist countries or overtake them in their cost function value. This is why the colony values are multiplied by the assimilation or revolution coefficient, they are substituted in the PS speed controller parameters, and their new position is set according to the evaluation of the cost function. The country with the lowest-cost function position is gradually removed, and only one country remains on the position of the imperialist. If the results are satisfactory, the cycle of the ICA algorithm can be concluded.

Figure 3 shows the behaviour of the global minimum of the cost function according to the number of iterations of the algorithm. The global minimum of the cost function is reached after the completion of the third cycle.

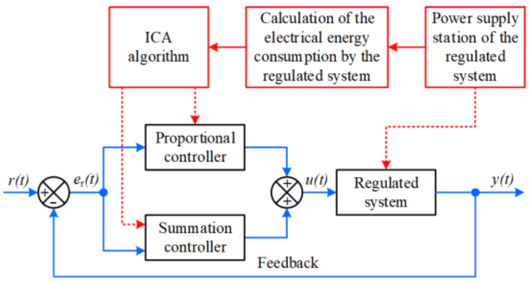

Fig. 2. Control of the discrete PS controller by the ICA algorithm.

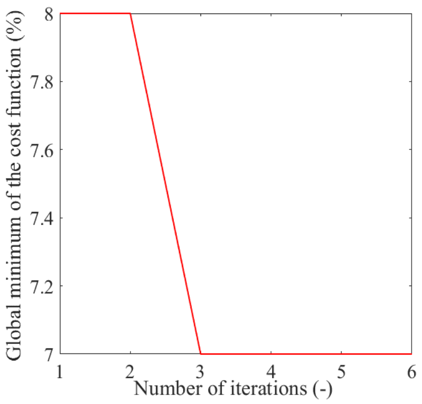

Fig. 3. Behaviour of the global minimum function depending on the number of iterations.

– The advantage of the method is the optimal setting of the PS controller parameters; the results of the previous less exact method of the critical parameters can be used to set the scope of the initial population.

– The disadvantage of the method resides in the fact that the method is more complicated; to obtain an optimal result, it is necessary to gradually substitute or change a higher number of ICA algorithm parameters; there are also higher demands on computer hardware because the ICA algorithm starts the model in Simulink more times in sequence to evaluate the cost function; in the case of a higher input population, the optimisation of the PS controller parameters takes tens of minutes.

III. EXPERIMENTAL METHODS

A model was created in the Matlab-Simulink development environment for the purposes of calculating the energy consumption by time integration of the instantaneous power of the rail vehicle; the advantage of this model lies in the simulation of the dynamical behaviour of the model, which is influenced by more impacts simultaneously. To verify the modelled values, a measurement of the output currents and voltage of the converter station Vřesinská was conducted during a tram ride in the section between the tram stations Vřesinská and Zátiší.

A. Tram Ride Model in the Matlab-Simulink Environment

First, a digital model of the track was built using the data downloaded from geological websites; then this model was used to calculate the ascent and curve resistance, as can be seen in Fig. 4. For the control of the PS speed controller used in the tram model, it was necessary to calculate the referential data of angular speed of the tram traction motors. Another necessary mechanical calculation for the input data of the model, which can be seen in Fig. 5, is the corresponding torque of the direct current motor, which is substituted for the traction motors in the simulation [13]. The corresponding torque can be calculated from the required tractive force. The tram load value, which includes passengers and track resistance components, determines the required value of the tractive force on the perimeter of the wheel. The simulation time can be shortened in direct relation to the real time, and it is possible to carry out the evaluation and changes in the model parameters faster.

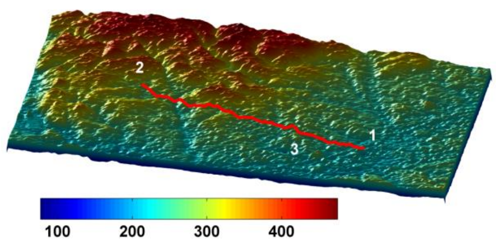

Fig. 4. Digital model of the track with an elevation indicator; the red line shows the track. The tram ride started at the station Vřesinská, which is marked by number 1 in the figure, and ended at the station Zátiší, which is marked by number 2. The power supply of the track was provided by the substation Vřesina, which is marked by number 3.

The model that is a substitute for the connection of the drive and other circuits of tram vehicle T6A5 is shown in Fig. 5. The tram drive model works in two quadrants, it simulates the ride of a tram both in its movement and in braking. When the speed data loaded from Workspace are higher than 0, the main contactor switches on - designated as No. 5 in Fig. 5 - and positive voltage is connected to the anode of GTO thyristor No. 6. Switch No. 15 switches the drive winding on motor No. 7 serially with a keeper. The speed controller maintains the motor revolutions through a subordinate current controller which switches the gate of GTO thyristor No. 6 via a hysteresis relay for the ride mode.

Electrodynamic braking to resistance in tram T6A5 is effective up to the speed of 4 km×h^{-1}, the simulation therefore uses a logical condition according to which the electrodynamic braking mode can be switched on at speed higher than 4 km×h^{-1} and deceleration of the tram speed of 8 km×h^{-1} on condition that GTO thyristor No. 6 is switched for the ride mode.

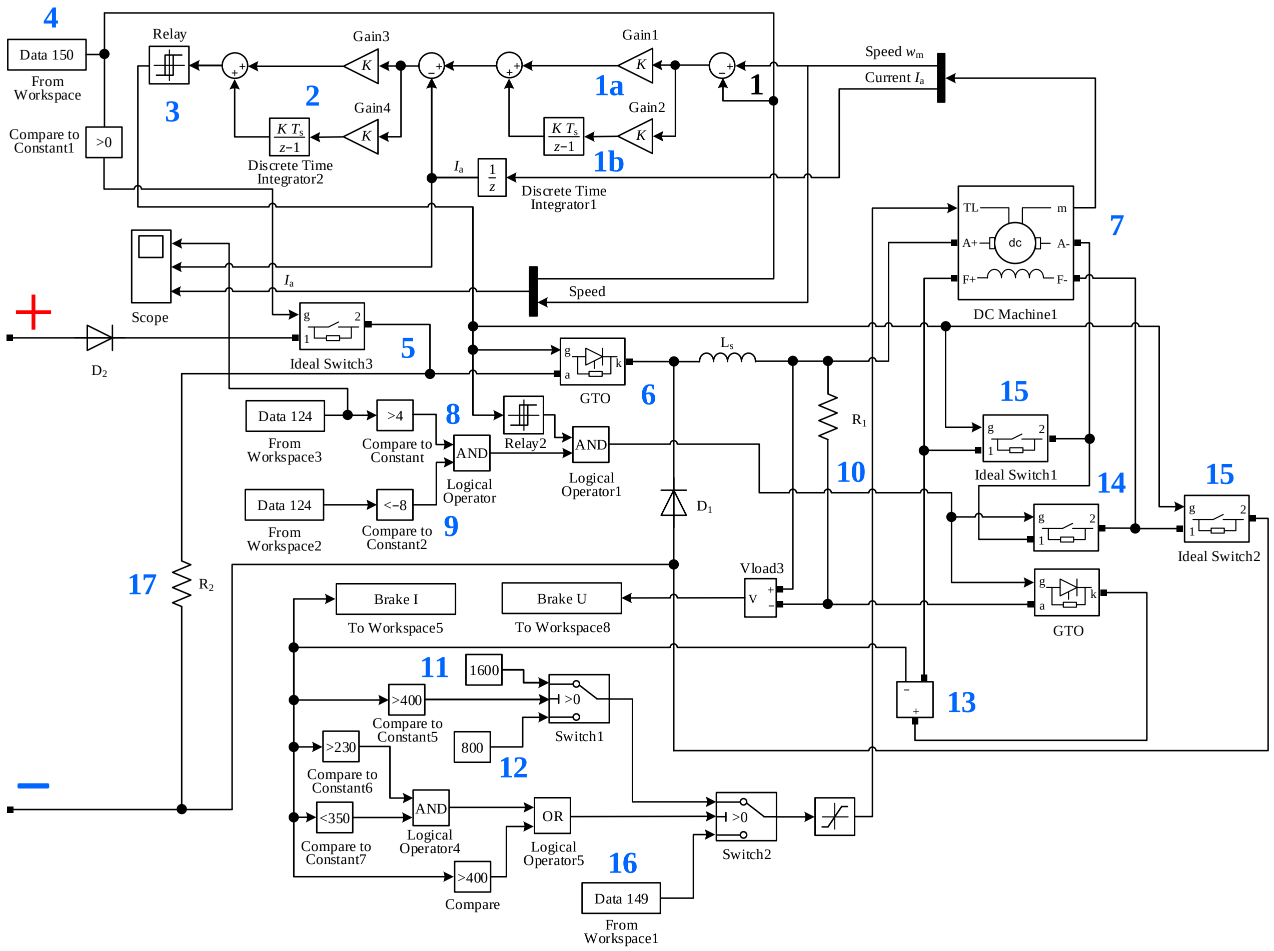

Fig. 5. PWM converter with a series wound DC motor. The individual parts are numbered according to their order: 1 - Speed controller; 1a - Proportional member; 1b - Integrative member; 2 - Current controller; 3 - Relay, switching hysteresis of the PWM converter; 4 - Reference data of the tram vehicle speed, reading from Workspace - (rad.s^{-1}); 5 - Main contactor; 6 - GTO thyristor; 7 - Series wound DC motor; 8 - Lowest speed block during braking; 9 - Braking slowdown block; 10 - Braking resistance; 11 - Mechanical brake 1st stage; 12 - Mechanical brake 2nd stage; 13 - Brake current sensor; 14 - Brake mode switch; 15 - Run mode switch; 16 - Reference data of the corresponding torque on the shaft of the traction motor, reading from Workspace - (Nm); 17 - Auxiliary drives.

B. Measuring Station for Calculating the Energy Consumption and Data Recording in the Rail Vehicle

To compare the measured values of electrical energy consumption with the modelled values, we conducted measurements on a tram track that is powered from one direction and that forms the 9 km long section between the stations Vřesinská and Zátiší. The measurement was carried out at the converter station Vřesina; the connection of the measuring station can be seen in Fig. 6. The most important part of the measuring station is a laptop with the operating system Windows and the virtual instruments LabVIEW. In addition, a measurer with a USB card and input dividers was used. The time of the measurement application on the laptop was set by means of the GPS signal [14].

In the same time period, the speed and position of the rail vehicle was recorded by the GPS receiver integrated in a mobile phone and the Android application GPS Logger. The GPS receiver was placed inside the T6A5 tram vehicle, as can be seen in Fig. 7.

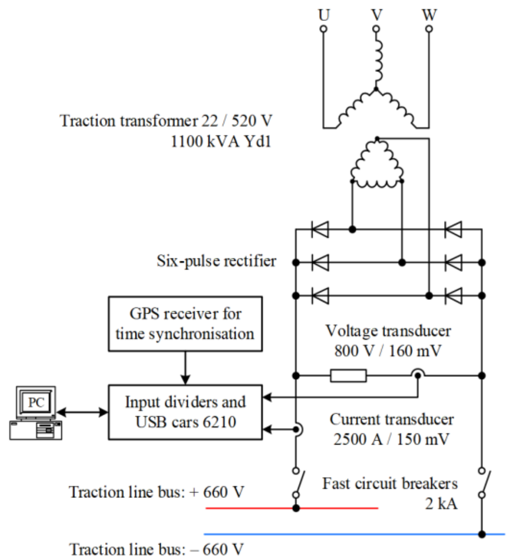

Fig. 6. The connection of the measuring station to calculate the energy consumption at the converter station Vřesina.

Fig. 7. GPS receiver inside the tram marked with number 1.

GPSLogger used the GPS signal from the Android phone to log the coordinates in a GPS or KML file at regular intervals. The application stores the recorded data on the MicroSD card in a file with the GPX extension; this file includes information about latitude and longitude, speed, time, and altitude. It also records the number of detected satellites and their spatial dispersion. The distances of the individual track sections were calculated by a command, distance on the surface of referential ellipsoid WGS84, this is a geodetic standard defined in 1984 which approximates the real shape of the Earth. It is related to the imperfect geometric shape of the Earth and the different distributions of its mass with regard to its centre. It is also used to calculate the distance in the GPS system.

Of the two simulations performed, the first was performed with the speed controller set up using the Ziegler-Nichols method. The second was performed for a controller set up using ICA. The results of both simulations are shown in Fig. 8, along with the measured values.

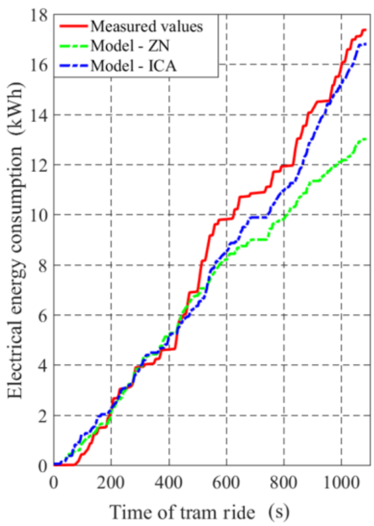

Fig. 8. Comparison of the electrical energy consumption during a tram ride calculated from the measured and modelled values when setting the PS speed controller of the tram using the ZN and ICA methods.

IV. Conclusions

The evolution methods of optimisation used inspired by human social processes have proved to be suitable even for solving technical optimisation problems. This article solved the problem of calculating the PS speed controller constants for the chosen tram vehicle by means of simulation in a Matlab-Simulink environment. The Ziegler-Nichols method was used in the first setting of the PS controller. This method is simple, but it also has its disadvantages. The second setting procedure used the imperialist competitive algorithm; this method is more complicated but achieves more precise results in the calculation of electrical energy. The model using the controller setting using the ICA method resulted in a higher accuracy in predicting the energy consumption compared to other methods. Compared to the measured results of electrical energy consumption during a tram ride, there was a 93 % correspondence using the ICA method, whereas when the ZN method was used for setting the controller, the model results corresponded by 75 % with the measured values. The accuracy of some other models used by different authors shows the following results. The dynamic and energy model presented in [15] indicates a deviation from the measured data between 1.4 % and 27.9 %. The authors of the energy consumption and emissions model [16] report an average deviation of 15 %. The method described in [4] achieves a deviation of up to 7 %. This shows that the ICA model with its deviation of 7 % is quite accurate.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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