Modelling of Trolleybuses in Environment MATLAB/Simulink

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Abstract. This paper deals with two models of trolleybuses created in environment MATLAB/Simulink and it simulates their behaviour during driving cycles SORT. Two types of trolleybuses were chosen for modelling. They are Škoda brand trolleybuses and each of them has got different concept of traction drives. One of them is classical concept of electric vehicle (series DC motor with resistance control – type Škoda 9Tr) and the other is currently the most used concept (asynchronous motor controlled by traction converter with IGBT – type 24Tr). Thanks to simulations it is possible to show the differences in traction properties of two generations of trolleybuses. Simulations can be done within various operating conditions. Energy consumption of modelled types of trolleybuses was evaluated based on the results of the simulations.

Keywords Trolleybus, resistance control of series DC motor, vector control of asynchronous motor, driving cycle, energy consumption, MATLAB/Simulink.

1. Introduction

Trolleybuses are the only worldwide spread conventional electric road vehicles that are destined for mass public transport. They are using a pair of trolley poles on the roof to be powered by electric energy from two parallel trolley wires.

This paper shows possibilities of calculation and simulation in MATLAB/Simulink. There were created two models of trolleybuses in this environment. One of them is classical concept of electric vehicle (series DC motor with resistance control – type Škoda 9Tr) and the other is current concept (vector control of asynchronous motor type Škoda 24Tr).

However both types have got different electrical equipment, we can mutually compare them. They have got nearly same maximal occupancy (100 passengers for 9Tr versus 99 for 24Tr) and equivalent drive configuration (two axles, rear drive axle, one traction motor).

2. Performance of Modelled Trolleybuses

2.1 Trolleybus Škoda 9Tr

Serial production of Škoda 9Tr proceeded between 1961 and 1982. Nearly 7,500 of trolleybuses 9Tr were delivered all over the world. Škoda 9Tr was popular mainly because of its simplicity, reliability, long life and good drive ability [7].

Even the design of vehicle was the same for 20 years, technical innovations were implemented. Model in MATLAB/Simulink was created based on production batches from early 1960’s (see Fig. 1).

Fig. 1. Modeled variant of trolleybus 9Tr [9].

Fig. 2. Apparatus case of trolleybus 9Tr [7].
Indirect contactor control is used for acceleration and electric braking of vehicle. Control of accelerator is semi-automatic (with automatic acceleration), but control of electric brake is non-automatic. There is a controller between pedals and contactors. There are contactors, controller, and other electrical devices in apparatus case in front part of vehicle (see Fig. 2).

2.2 Trolleybus Škoda 24Tr

Type Škoda 24Tr was produced in cooperation with Irisbus group between 2003 and 2014. It is the first type of Škoda brand trolleybus with body from bus manufacturers. Body of type Agora was used for trolleybuses Škoda 24Tr at first, but body of type Citelis was used later for majority of them. 285 vehicles were manufactured in sum.

Model of trolleybus 24Tr has got pattern in particular vehicles. There is serie of five trolleybuses with Citelis body (see Fig. 3). It has been operated in Mariánské Lázně since 2006. Three of them have got diesel generator (DG) as auxiliary power unit.

Three-phase asynchronous traction motor is powered from DC-link through three-phase voltage source inverter (traction converter). Inverter is consisted of six IGBT with freewheeling diode. There are traction converter, auxiliary converters and other components of electrical equipment in the roof unit on the front part of the vehicle roof (see Fig. 4).

Fig. 3. Modelled variant of trolleybus 24Tr.

Fig. 4. Roof unit of trolleybus 24Tr.

3. Models of Trolleybuses

Both models of trolleybuses contain traction drive, but also some other functional units of trolleybus. There were modelled only units, which significantly affect energy consumption (non-traction devices) or driving behaviour of trolleybus (pneumatic brakes).

Model of trolleybus 9Tr shows only acceleration in traction drive, because electric brake does not consume or supply energy outside traction circuit. Traction drive of trolleybus 24Tr moves between acceleration and electric braking contactless thanks to vector control, and that is why model of trolleybus 24Tr shows both.

4. Testing Environment for Models of Trolleybuses

There was created Testing Environment for Models of Trolleybuses (hereinafter Environment) in MATLAB/Simulink. This Environment was used for testing above mentioned models of trolleybuses. Block diagram of Environment presents a variant for model of trolleybus 24Tr (see Fig. 5). The diagram was simplified, and that is why it does not contain output magnitudes (power, efficiency, energy etc.). A variant for model of trolleybus 9Tr works in the same principles.

4.1 Fundamental Operating Principles of Models of Trolleybuses

The basement of Environment is formed by equation of motion, with inputs tractive effort \( F_t \) and load force \( F_l \). The difference of those forces \( F_t - F_l \) equals acceleration force \( F_a \). Acceleration force consist of two parts i.e. linear \( F_{la} \) and rotational \( F_{ra} \). Rotational part is considered as constant \( 5 \% \ F_{la} \) in Environment [4]. Linear acceleration force \( F_{la} \) determines acceleration \( a \), velocity \( v \), speed \( v_{max} \) and distance \( s \). There are feedback interconnections of these magnitudes to block of trolleybus model and to another block in the Environment.

4.2 Input parameters

The user of environment can choose different values of inputs parameters, which are shown in Tab. 1. It is also possible to change voltage of trolley wires \( U_{trolej} \), but it was considered to be constant as nominal value (600 V DC) for provided simulations.

4.3 Determination of Load Force

Value of load force is given by sum of three driving resistance, i.e. rolling resistance, aerodynamic drag and hill climbing forces. For calculation of load force is necessary to know the value of slope \( \text{stoup} \) and the weight of trolleybus \( m \). It is possible to choose invariable or variable slope during driving cycle.
Fig. 5. Simplified block diagram of Testing Environment for Models of Trolleybuses (variant for model of trolleybus 24Tr)

<table>
<thead>
<tr>
<th>parameter</th>
<th>symbol</th>
<th>possible values</th>
</tr>
</thead>
<tbody>
<tr>
<td>driving cycle</td>
<td>jc</td>
<td>1 = SORT 1 – urban; 2 = SORT 2 – mixed; 3 = SORT 3 – suburban; 4 = personal for testing</td>
</tr>
<tr>
<td>presence of diesel generator (DG) *</td>
<td>DA</td>
<td>0 = trolleybus without DG; 1 = trolleybus with DG</td>
</tr>
<tr>
<td>number of passengers</td>
<td>cest</td>
<td>allowable range from 0 to 99</td>
</tr>
<tr>
<td>slope **</td>
<td>stoupn</td>
<td>allowable range from -50 to +50 %</td>
</tr>
<tr>
<td>variable slope</td>
<td>p_stoup</td>
<td>0 = deactivated → invariable slope; 1 = activated</td>
</tr>
<tr>
<td>command for heating</td>
<td>top</td>
<td>0 = switched on; 1 = switched off</td>
</tr>
<tr>
<td>command for ceiling lamps for passengers</td>
<td>svit_cest</td>
<td>0 = switched on; 1 = switched off</td>
</tr>
</tbody>
</table>

* only for model of trolleybus 24Tr
** for variable slope it means absolute value of maximal slope

Tab. 1. Input parameters of simulations and their possible values.

4.4 Driving Cycles

Models of trolleybuses are controlled according to desired velocity ($v^*\). Value of desired velocity depends on distance a simulation time. One of the four offered driving cycles can be chosen to simulate, i.e. personal for testing and three SORT cycles.

Driving cycles SORT were developed for vehicles of category M2 and M3 (road vehicles with more than 9 people on board). Each type of SORT cycle consists of three parts. Every part has got three subparts, i.e. constant acceleration from zero to maximal velocity of part, holding these velocity and constant deceleration up to stop.

In the SORT project was defined 5 essential parts of driving cycles. They have got different maximal velocity from 20 km/h to 60 km/h in steps of 10 km/h. Three fundamental driving cycles SORT were compiled from essential parts for typical operating models, i.e. urban (SORT 1), mixed (SORT 2) and suburban operating model (SORT 3). Parameters of fundamental driving cycles are presented in Tab. 2.

<table>
<thead>
<tr>
<th>designation of driving cycle</th>
<th>first part</th>
<th>second part</th>
<th>third part</th>
<th>total distance moved [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>maximal velocity [km/h]</td>
<td>distance [m]</td>
<td>maximal velocity [km/h]</td>
<td>distance [m]</td>
</tr>
<tr>
<td>SORT 1 – urban</td>
<td>20</td>
<td>100</td>
<td>30</td>
<td>200</td>
</tr>
<tr>
<td>SORT 2 – mixed</td>
<td>20</td>
<td>100</td>
<td>40</td>
<td>220</td>
</tr>
<tr>
<td>SORT 3 – suburban</td>
<td>30</td>
<td>200</td>
<td>50</td>
<td>600</td>
</tr>
</tbody>
</table>

Tab. 2. Performance of fundamental driving cycles SORT (data source [5]).
5. Results of Simulations

Two aspects were taken for evaluation of simulation. Courses of significant magnitudes were tracked in first aspect and overall results of simulation were considered in second aspect. Total and partial specific energies are meant as overall results.

5.1 Courses of Significant Magnitudes

Graphical user interface (GUI) was created in environment MATLAB. Thanks to GUI it is possible to compare behaviour of both models of trolleybuses. All parameters shown in Tab. 1 are enabled to set in GUI (see Fig. 6), and then simulation is perform in both models with them. GUI allows displaying courses from both models in common axis (see Fig. 7) both versus time and versus distance. Courses are plotted for velocities, accelerations, forces, slopes, powers and efficiencies of traction drives.

![Fig. 6. Setting of simulation in GUI.](image)

![Fig. 7. Example of tab with time courses in GUI.](image)

Second part of driving cycle SORT 3 was selected to show the results of simulations (see Fig. 8 and 9). There are displayed time courses velocities and forces. Fig. 8 is for decent 30 % and Fig. 9 for slope 30 %. Other parameters of simulations were set identically, i.e. 50 passengers, minimal non-traction consumptions and variant of trolleybus 24Tr without DG. Minimal non-traction consumptions suppose switched off heating for both models of trolleybuses and switched off ceiling lamps for passengers for model of trolleybus 24Tr.

![Fig. 8. Time courses of second part of driving cycle SORT 3 during invariable descent 30 % and upon occupancy 50 passengers and minimal non-traction consumption.](image)

![Fig. 9. Time courses of second part of driving cycle SORT 3 during invariable slope 30 % and upon occupancy 50 passengers and minimal non-traction consumption.](image)

5.2 Overall Results of Simulations

Only total and partial specific energies are tracked in overall results of simulations. Specific energy ($e$) is meant as energy in kWh per one kilometre of distance. These specific energies were detected from simulations:
• taken from trolley wires ($e_{trolej}$)
• taken by traction drive ($e_{tpo}$)
• consumed by non-traction devices ($e_n$)
• supplied from traction circuit to DC link ($e_{tpd}$, only for model of trolleybus 24Tr)
• wasted in brake resistor ($e_b$, only for model of trolleybus 24Tr).

Trolleybus 24Tr can supplied energy from DC link to trolley wires (i.e. recuperated), but that was not modelled. Specific energy wasted in brake resistor ($e_b$) presents amount of energy, which is possible to recuperate.

Following balance equations are valid between specific energy in models. Relation (1) is for model of trolleybus 9Tr and relation (2) is for model of trolleybus 24Tr:

\[
e_{trolej} = e_{tpo} + e_n
\]

\[
e_{trolej} + e_{tpd} = e_{tpo} + e_n + e_b + \text{losses}.
\]

120 simulations were carried out for each of models of trolleybuses (9Tr, 24Tr without DG and 24Tr with DG).

It is combination of four occupancies (0, 35, 70 and 99 passengers), five slopes (-50, -25, 0, 25, 50 ‰), three fundamental driving cycles SORT (see 4.4) and minimal or maximal non-traction consumption. Graphs of specific energy versus slope were created from resulting values. Examples of these graphs are shown in Fig. 10 and 11.

### 5.3 Comparison of Energy Consumption of Modelled Trolleybuses

It is not clearly define, which from modelled type of trolleybuses is more economical according to specific energy taken from trolley wires ($e_{trolej}$). It depends always on the operating conditions.

When 60 simulations were carried out for minimal non-traction consumption, trolleybus 9Tr has got lower energy consumption in 38 cases against trolleybus 24Tr without DG. The reason is low weight of 9Tr (8,990 kg against 11,900 kg for 24Tr without DG), but also its much less non-traction consumption. Conversely specific energy taken by traction drive ($e_{tpo}$) was for trolleybus 9Tr lower only in 11 cases out of 60. Traction drive of trolleybus 24Tr is therefore more economical than traction drive of trolleybus 9Tr.
6. Conclusion

This paper shows possibilities and ways of modelling electric vehicles in MATLAB/Simulink environment. Precisely they are two equivalent types of Škoda brand trolleybuses (9Tr and 24Tr) with different concept of traction drive in this environment.

According to the results of this research, it is obvious that implementation of current saving innovations does not lead to decrease of energy consumption in real life. New technologies help to keep the electric consumption at the same level even though the weight of vehicle is much higher and number electric devices is increasing.

References

About Author...

Martin KLÁN was born in Mariánské Lázně in 1992. He has been interested in electric public transport, primarily trolleybuses and trams, since his childhood. His interest brought him to Faculty of Electrical Engineering CTU in Prague. He studied bachelor’s degree in branch Applied Electrical Engineering (2011 – 2014) and consequently master’s degree in branch Electrical Machines, Apparatus and Drives (2014 – 2017) there. He dealt with modelling of trolleybuses in MATLAB/Simulink in his diploma thesis. He continues in this theme within doctoral degree studies at the Department of Electric Drives and Traction FEE CTU. His dissertation topic is optimisation of road electric traction system for mass transportation, which is supervised by Prof. Jiří Lettl.