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ENERGY EFFICIENCY OF ELECTRIC MULTIPLE UNITS IN SUBURBAN OPERATION

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Contents

Symbols and abbreviations

a	– acceleration
B	– magnetic flux density
D	– duty cycle
d	– deceleration
E	– energy
F	– motive force
f	– frequency
G	– conductance
g	– gravitational acceleration
I, i	– current
i_r	– curve resistance
J	– moment of inertia
k	– rotating mass coefficient
L_f	– inductance of field windings
M	– mechanical torque
m	– mass
O	– occupancy rate
P	– power
R'	– kilometric resistance
R_w	– motor windings resistance
S	– electromechanical switch
s	– slip (in induction motor)
T	– period
t	– time
U, u	– voltage
U_{d0}	– idle traction substation voltage
v	– velocity
W	– motion resistance force
x	– absolute location
η	– efficiency factor
η_{reg}	– regenerative braking efficiency
μ	– surface adhesion coefficient
σ	– material conductivity

τ	–	absolute time
Φ	–	flux
φ	–	phase angle between voltage and current (for power factor computation)
ω_r	–	angular velocity

AC	–	Alternating Current
AGV	–	Automotrice à Grande Vitesse (High Speed Electric Multiple Unit)
ATO	–	Autonomous Train Operation
BART	–	Bay Area Rapid Transit
BEMU	–	battery electric multiple unit
CFD	–	computational fluid dynamics
DC	–	Direct Current
DoD	–	depth of discharge
EEA	–	European Environment Agency
EMU	–	Electric Multiple Unit
ERTMS	–	European Rail Traffic Management System
ETCS	–	European Train Control System
EV	–	electric vehicle
FEM	–	Finite Elements Method
GNSS	–	Global Navigation Satellite Systems
GTO	–	Gate Turn-Off thyristor
HVAC	–	Heating, Ventilation and Air Conditioning
ID	–	identifier
IGBT	–	Insulated Gate Bipolar Transistor
IPEMU	–	independently powered electric multiple unit
JR	–	Japan Railways
LZB	–	Linienförmige Zugbeeinflüssung (Continuous Train Influence)
MARTA	–	Metropolitan Area Rapid Transit Atlanta
MGU-K	–	motor-generator unit – kinetic
OS	–	operating system
PI	–	Proportional-Integral controller
PKP	–	Polskie Koleje Państwowe (Polish State Railways)
PM	–	Permanent Magnet
PMDP	–	Plzeňské Městské Dopravní Podniky (Pilsen City Transport Company)
PSR	–	Przekaźnik Samoczynnego Rozruchu (automatic acceleration controller)
PT	–	podstacja trakcyjna (traction substation)
RER	–	Réseau Express Régional (Regional Express Network)
RMSE	–	root mean square error
RNG	–	random number generator
SDB	–	Supply Data Bus
SG	–	Savitzky – Golay filter
SKM	–	Szybka Kolej Miejska (Rapid Urban Railway)
SN	–	Section Number, supply section identifier

SoC – State of Charge
SQP – Sequential Quadratic Programming
TS – traction substation
UIC – Union Internationale des Chemins de fer (International Union of Railways)
VDB – Vehicle Data Bus
VVVF – Variable Voltage, Variable Frequency
WKD – Warszawska Kolej Dojazdowa (Warsaw Commuter Railway)
WUT – Warsaw University of Technology
ZNTK MM – Zakład Naprawy Taboru Mińsk Mazowiecki (Rolling Stock Repair Company in Mińsk Mazowiecki)

1. INTRODUCTION

1.1. Basis for the analysis

Growing importance of decarbonization of economy implies modernization of energy sources and rationalization of energy usage. Because virtually all of the environmentally friendly power is generated as an electrical energy, intensified electrification of basically all industries is the result [37]. This is especially highlighted in case of transportation, where electromobility is being dynamically developed, in form of the electric cars, but also smaller vehicles like electric bicycles, drones and small sized aircraft [2, 13, 71, 117, 147]. While transition to electrified individual transportation allows for reduction in emissions, it does not address the general low efficiency of the individual transport means itself, especially in highly urbanized areas characterized with large population density [16, 19, 90, 131]. Therefore, electric public transit is a logical solution to a growing movement demand within agglomerations [10, 13, 77, 85, 112, 143, 138, 142, 155].

Applicable means of transport depend on potential passenger numbers, route length, existing infrastructure and terrain within intended operation zone. Moving smaller number of people can be realized with electric buses or trolleybuses, while large cities require efficient railway-based systems, like subway or suburban railway [16, 19, 131]. However, enlargement of transport network or introduction of new connections into existing system results in increased energy demand. To accommodate more rolling stock and ensure reliable operation of the whole system, appropriate power supply is needed, for both new and modernized routes [3, 10, 40, 42, 54, 121, 145, 153]. Because of this, analyses are required to find the optimal parameters of the rolling stock and infrastructure [30, 49, 50, 85, 142].

New vehicles have often higher power and are more demanding when it comes to energy quality (e.g. require high enough line voltage). It is important to verify, if vehicle will be adequate for desired task and if it will not cause disturbances in power supply [12, 15, 26, 37, 83, 95]. Moreover, the growth of electrical energy prices motivates research for energy efficiency improvement, through vehicle design but also driving technique and timetabling. Energy management strategy is an important factor too, especially for hybrid and storage-powered vehicles [113]. Depending on route geometry and vehicles used, optimization of velocity profile allow to save about 10 – 20% of energy [18, 40, 54, 121, 142]. Use of multi-objective optimization algorithms can improve that to about 30%, which translates to substantial reduction of operating costs. Integrated means that both velocity profiles of multiple vehicles and the timetable are optimized simultaneously, with some of the applications designed for on-line operation. In papers [27, 85, 153, 155] authors proposed multiple optimization methods, with different levels of complexity. However, their validation was carried out only for specific cases, and many of those have high requirements infrastructure-wise in order to use in real system.

Currently, the need for precise evaluation of energy consumption of a rail vehicle before making an order is widely acknowledged. There are many approaches to the problem, with varying complexity.

The simplest method operates on assumption of constant parameters of line voltage, efficiency factors and even simplify velocity profile to trapezoidal shape or assume ideal braking energy recuperation [13, 80, 125]. Such approach might be sufficient for timetabling or generalized energy calculations, however for the power supply and losses analysis use of more advanced models is advisable.

One of such methods assume single vehicle movement, computing electrical parameters of the whole transport system through superposition [17, 38, 96]. While the method is viable, determination of energy regeneration and potential impact of pantograph voltage on traction drive performance is challenging.

The most complex programs are designed to simulate whole system simultaneously, allowing for in-depth analysis of energy flow and efficiency as well as accurate values of currents and voltages [29, 136–138, 156]. However, program stability and computation performance are a major challenge, often limiting such applications to simulate single section of power supply, or at best, single route. Those programs are also developed for one certain task and often cannot be used for different analysis.

There is also commercial software available – allowing for calculations of energy consumption and timetables. However, those programs are developed aiming for maximum versatility and used primarily for timetabling [31, 32, 110, 140]. Considering number of input parameters needed to run the simulation and output data, usability of such software is limited. Algorithms used are also unknown, being internal secret of companies developing the programs, and implementing custom modifications or extensions is not possible. Some of the developers also employ “calculations as a service” business model. This is especially true for more advanced simulators that allow for multi-vehicle analysis [102, 135]. Because of this, commercial software cannot be considered well-suited for research purposes.

Despite large number of analyses of energy efficiency in transportation systems aimed at reduction of energy consumption, most researchers focus heavily on development of advanced optimization algorithms (using for timetabling or velocity profile setting) or the power supply [21, 54, 70, 85, 91, 121, 145, 153]. The vehicle itself in such analyses is often being oversimplified, despite consuming the most energy in analyzed system.

On the other hand, papers on traction drives analyze the vehicle in idealized conditions or even only the drive itself are presented. They assume simplified operation conditions, such as theoretical routes or trapezoidal velocity profiles, often skipping the power supply part entirely [3, 10, 12, 35, 41, 75, 88, 92, 146, 150]. While every element of the transportation system need to be depicted accurately in simulation in order to provide meaningful results, there are very few analyses that attempt to do so [64, 114, 159].

Every program based on mathematical model that computes parameters in continuous time domain can be characterized as dynamical system [69]. Such model contains dynamic sets of data, and both relations between the sets as well as operations within the system are specified within the program. For the electric traction system, vehicles and power supply elements can be considered as dynamic sets, relations between them are determined by the system structure and the operations are defined by all the equations coded within the model. However, for certain applications, discrete systems are a better fit – discontinuous changes in signal values are useful for modeling logical systems with finite number of states, such as communication networks.

There is a possibility of implementing discrete system under dynamical system [72]. Such solution can be used for describing dynamical systems where subsystems working in continuous time exchange information or are controlled by discontinuous signals. Example of this can be found within industrial communication networks, where devices performing continuous–time tasks communicate through common transmission medium called data bus (wired or wireless), using discrete–time protocol [103, 152]. For models involving multiple subsystems that exchange information, adoption of such solution seems advantageous.

1.2. Research theses

Analysis of the source literature shown the scarcity of comprehensive models that could allow for in-depth analysis of electric vehicle as a part of transportation system. Seeing potential benefits that better accuracy of such calculations would bring, author decided to focus on development of an original software, which will provide results of practical significance, implementable in real transport systems.

Consequently, the author stated research theses:

1. Implementation of data bus structure within electrified transport system model improves its versatility and scalability. Therefore, model is useful for complex power supply layouts, found in electrified urban transport networks.
2. Implementation of optimized velocity profile using trackside signs executable by human driver improves energy efficiency of the whole transport system in relation to current operating conditions. The signs define movement phases: acceleration/cruising, coasting and braking, along with set velocity.
3. Consideration of passenger flow and variability of velocity profiles improves accuracy of transport system energy efficiency calculations. Obtained results constitute for a large set of data that can be further used in statistical analyses.

1.3. Dissertation objectives

In order to prove stated research theses, author defined dissertation objectives that include:
- Development of novel simulation models for comprehensive, in–depth analysis of energy efficiency of vehicles operating in suburban electrified transportation systems;
- Implementation of vehicle model accounting for its drivetrain electrical and mechanical characteristics along with power supply model, that allow for computation of all parameters necessary for energy efficiency evaluation;
- In-depth analysis of electrified transport system operation, based on large set of measurements, data published by the system operator and technical documentations;
- Simulation of energy efficiency of selected vehicle classes under realistic operating conditions;
- Verification of obtained results for analyzed system and for alternative electrified transport network;
- Proposal of method allowing for energy-saving measures such as optimized velocity profiles that is simple and quick to implement in real systems.

1.4. Scope of the research

The scope of this dissertation is as follows:
- Analysis of source literature, focusing on subject matter of energy consumption and efficiency in electrified suburban railway systems. That included both power supply and vehicle drivetrain construction, its auxiliary needs, possibility of energy storage implementation and impact of operating conditions, like passenger service, timetable and velocity profile (chapter 2).
- Review of existing simulation methods, looking into their advantages, shortcomings and possible room for improvements (chapter 2).
- Development of novel models of the vehicle, power supply and traffic control allowing for detailed analysis of the energy flow, losses assessment and energy efficiency under realistic operating conditions (chapter 3).
- Analysis of operation of a suburban rail vehicles in typical conditions, assuming actual transportation network, technical parameters of analyzed infrastructure and rolling stock and large set of recorded data (chapter 5, 6).
- Verification of the results of the simulation against measured data from real objects, including electrical and mechanical parameters (chapter 4).
- Proposal for implementation of an algorithm allowing for optimization of energy consumption, defining the most significant parameters that need to be taken into account (chapter 7).
- Analysis of energy efficiency using optimized velocity profiles, showing potential for energy savings (chapter 7).
- Summarization of obtained results, proving the stated theses and indicated possibilities of further development of the work (chapter 8).

Novel aspects of the dissertation include:

- Introduction of industrial data network structure into electrified transport system model, which improves versatility and computation performance;
- Adaptive structure of the model: elements of the vehicle or power supply are easily replaceable for different analyses; simulating every part independently is possible also outside the main program;
- Simulation of interconnected systems: each vehicle can be of different type, follow different route and schedule; power supply can have different parameters for each section; interconnected systems (e.g. tram and trolleybus) or smart grids can be analyzed;
- Statistic-based determination of input parameters for the analysis;
- Original algorithm for automatic analysis of large set of recorded vehicle run data, that returns the summary of all velocity profiles;
- Implementation of original semi–randomized velocity profile selection, with variable probabilities based on runs recorded in real system;
- Unique control algorithm: vehicle movement is controlled by the set of logical functions, with the Permission function being the highest in hierarchy;
- Implementation of passenger flow data, which impacts mass of the vehicle, and consequently, its movement dynamics and energy consumption;
- Variability of station dwelling time: this includes not only prolonged stops at main stations, but also random variability occurring in real systems;
- Consideration of weather conditions: air temperature has an impact on heating and air conditioning, and dry, wet or icy conditions have a consequences in wheel adhesion. This can vary with time and/or distance;
- Differentiation between route and power supply section: parameters of the route (inclination, curvature) are independent from power supply – the vehicle can change track during the run or travel outside the electrified route if equipped with energy storage;
- Original approach to energy consumption optimization, which is practically implementable with minimal cost and infrastructure requirements;
- Scalability: it is possible to simulate a whole day of the network operation or focus only on short timeframe, with reduced timestep – as the initial parameters are loaded from external file;
- Evaluation frame: it is possible to simulate only a part of larger system, where vehicles enter and leave analyzed fragment – but all the calculations are carried out only for the selected part.

Procedure of model development and energy efficiency analyses were shown for electrified transport systems of SKM Trójmiasto (suburban railway) and PMDP Pilsen (Czech Republic, trolleybus system).

Abstract

Rising numbers of agglomeration residents cause increased need for people movement on daily basis. Because of congestion of local roads, limited parking space and rising fuel prices providing mass transit based on electric traction is a logical solution. While the electric rail vehicles are considered highly efficient in themselves, they should be analyzed as a part of a transport network, because energy consumption depends on operating conditions of a whole transport system. Information about energy efficiency of whole system operating under realistic conditions is a basis for research into energy savings. Such data is also useful when modernization of traction power supply, timetable planning or ordering new rolling stock is planned.

This thesis presents approach to analysis of energy efficiency of a suburban rail network, using novel models developed on the Matlab/Simulink basis. Necessary features and requirements for such models were determined thru in-depth review of the source literature in all applicable fields: electrified transportation systems, electric multiple units construction, vehicle drivetrains and finally, existing simulation methods. Existing and applied methods for improvement energy efficiency of electrified transportation were identified.

Original model of electrified transportation system was developed. It can be characterized by unique implementation of the data bus structure that allows for simulating complex transport systems in a straightforward way while retaining high computation performance. Because every part of the program is an independent sub-model, the only limitation to size and complexity of analyzed system is the available computing power.

Verification of the model accuracy was conducted. Precision of vehicle dynamics simulation against recorded run was presented for a reference fragment of analyzed railway line, for an electric multiple unit. Validation of the results for the transport network, generated using the whole model was carried out for exemplary transport network, where detailed measurement data was available (trolleybus system in Pilsen, Czech Republic). Obtained results confirmed accuracy of the developed model, with computed voltage error being consistently below 2% figure, and difference between measured current and final energy balance were below 5%.

Parameters of the analyzed transport system were assumed using technical datasheets, catalogues, tender documentation and a large set of recorded run data. Only vehicles capable of regenerative braking – equipped with induction motor drives were included. Vehicle models take into account detailed parameters, like load and velocity-dependent

efficiency, impact that pantograph voltage has on vehicle power and rheostatic braking and relation between the weather and motive force application and heating system operation. Passenger flow was also included – number of passengers carried by the trains varies along the route and during the day, impacting the vehicle mass and consequently, its movement dynamics and energy consumption. Novel control algorithm was implemented, allowing for semi-random selection of velocity profile for every station-to-station fragment, following the variable selection probability established thru large recorded run data set analysis.

Energy efficiency analysis for suburban railway system of SKM Trójmiasto was carried out, limiting the scope to railway line no. 250 between stations Gdańsk Śródmieście and Gdynia Redłowo. Simulation was executed assuming the whole day of operation, assuming regular workday schedule. Computed daily energy consumption is 56,4 MWh, while recuperation rate lies typically between 25 and 26%.

Practical and easy to implement approach to velocity profile optimization for electric multiple unit was proposed. Presented method allows for energy savings of about 8% while retaining the same travel time, simultaneously reducing drivetrain losses. Possibilities of further energy consumption reduction were suggested.

Conducted research demonstrated that implementing model structure inspired by industrial communication networks improves model scalability and versatility, as it was used for two different electrified urban transport systems, with different power supply layouts. Moreover, proposed approach to energy consumption optimization, based on trackside signs and manageable by human driver was shown to improve energy efficiency of the whole system. This work also includes implementation of passenger flow and variable velocity profiles, which allowed for improvement of calculation accuracy.

Efektywność energetyczna elektrycznych zespołów trakcyjnych w ruchu podmiejskim

Rozwój obszarów aglomeracyjnych skutkuje zwiększeniem zapotrzebowania na przewóz osób. Ze względu na kongestię sieci drogowej, ograniczoną przestrzeń parkingową oraz rosnące ceny paliw, logicznym rozwiązaniem jest zapewnienie sieci transportu publicznego opartą na trakcji elektrycznej. Chociaż pojazdy elektryczne można uznać za wysokowydajne, powinny być one analizowane jako element składowy zelektryfikowanego systemu transportowego, ponieważ ich zapotrzebowanie na energię jest zależne od warunków pracy tego systemu. Wiedza na temat efektywności energetycznej sieci transportowej pracującej w realistycznych warunkach stanowi podstawę do poszukiwania oszczędności energetycznych. Dane te są także przydatne przy planowaniu modernizacji układu zasilania trakcyjnego, planowania rozkładu jazdy lub zakupu nowych pojazdów.

Niniejsza rozprawa porusza tematykę analizy energetycznej systemu szybkiej kolei miejskiej przy wykorzystaniu nowej generacji modeli bazujących na środowisku Matlab/Simulink. Niezbędne cechy i wymagania dla modelu zostały oparte na przeglądzie literatury dotykającej tematyki zelektryfikowanych systemów transportowych, budowy elektrycznych zespołów trakcyjnych oraz ich układów napędowych oraz istniejących metod symulacyjnych. Zidentyfikowano istniejące oraz stosowane sposoby zwiększenia efektywności energetycznej transportu zelektryfikowanego.

Opracowano autorski model zelektryfikowanego systemu transportowego. Jego cechą jest nowatorska implementacja magistrali danych, umożliwiająca łatwe symulowanie złożonych zelektryfikowanych systemów transportowych przy zachowaniu wysokiej wydajności obliczeń. Ponieważ każdy z elementów składowych jest niezależnym modelem, jedynym ograniczeniem złożoności badanego systemu są dostępne zasoby komputera.

Przeprowadzono weryfikację dokładności modelu. Precyzję symulacji dynamiki ruchu pojazdu zaprezentowano dla elektrycznego zespołu trakcyjnego poruszającego się na referencyjnym odcinku linii kolejowej. Walidację strony energetycznej modelu przeprowadzono bazując na danych oraz wynikach dla sieci trolejbusowej w Pilźnie (Rep. Czeska). Osiągnięte wyniki potwierdziły skuteczność opracowanego modelu, gdzie rozbieżność obliczonego napięcia nie przekroczyła 2% względem pomiaru, a błąd prądu oraz końcowa różnica w bilansie energii zawarły się poniżej 5%.

Parametry badanego systemu zostały ustalone na podstawie kart katalogowych producentów, dokumentacji technicznych i przetargowych oraz dużym zbiorze zarejestrowanych przejazdów. Założono wykorzystanie wyłącznie pojazdów wyposażonych w napędy z silnikami indukcyjnymi, umożliwiające hamowanie odzyskowe. Modele pojazdów uwzględniają szczegółowe parametry, jak zależna od obciążenia napędu sprawność, wpływie napięcia zasilania na dostępną moc pojazdu oraz załączenie hamowania rezystorowego, a także wpływa warunków pogodowych na przeniesienie siły napędowej oraz pracę systemu ogrzewania. Wzięto pod uwagę potoki pasażerów – liczba osób przewożonych przez poszczególne pociągi zmienia się z czasem oraz wzdłuż trasy, wpływając na masę pojazdu, a tym samym jego dynamikę ruchu i energochłonność. Zaimplementowano nowatorski algorytm sterowania, który dla każdego odcinka międzyprzystankowego wybiera losowo jeden z możliwych profili prędkości, przy czym prawdopodobieństwo wyboru jest zgodne z ustalonym w toku badań systemu transportowego. Profile prędkości pojazdu zostały ustalone na podstawie analizy dużego zbioru danych rejestracji przejazdów.

Dokonano analizy energetycznej systemu transportowego Szybkiej Kolei Miejskiej w Trójmieście na odcinku linii 250 pomiędzy stacjami Gdańsk Śródmieście oraz Gdynia Redłowo. Obliczenia wykonano dla jednej doby pracy systemu, przy założeniu rozkładu jazdy dla dnia roboczego. Obliczone zużycie energii waha się w granicach 56,4 MWh, natomiast sprawność odzysku energii pomiędzy 25 a 26%.

Zaproponowano metodę optymalizacji energetycznej, która jest łatwa w implementacji w rzeczywistym systemie transportowym. Opracowany sposób pozwala na redukcję zużycia energii o około 8% przy zachowaniu dotychczasowego czasu podróży, jednocześnie redukując straty w układzie napędowym. Zwrócono uwagę na możliwe dalsze zabiegi zmierzające do zwiększenia oszczędności.

Na podstawie przeprowadzonych badań wykazano, że modele o strukturze wzorowanej na magistrali danych zwiększają skalowalność oraz wszechstronność programu, który był użyty w analizie dwóch różnych zelektryfikowanych miejskich systemów transportowych, o różnej strukturze układu zasilania. Ponadto, zaproponowana metoda optymalizacji energetycznej, wykonalna przez człowieka przy użyciu znaków przytorowych pozwala na poprawę efektywności energetycznej systemu transportowego. Rozprawa omawia również implementację potoków pasażerskich oraz zmienności profili prędkości, co zwiększa dokładność obliczeń.