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A. SZELAG (WARSAW UNIVERSITY OF TECHNOLOGY, POLAND)

Warsaw University of Technology, Electric Traction Division, Pl. Politechniki 1, 00-661, Warszawa, tel.:+48 22 234-72-17, fax:+48 22 625-75-24, e-mail: adam.szelag@ee.pw.edu.pl

APPLICATION OF MODELING AND SIMULATION TECHNIQUES AS METHODS FOR FEASIBILITY STUDIES AND DESIGN IN ELECTRIC TRACTION SYSTEMS

Introduction

Modeling means creation of a model (imitation) representing a given object (system) and consists in the development of such a new (physical or virtual) object (system), which would have the features and would operate as the being represented (imitated) system. Making experiments with operation of the derived model (solving model) for the set of predefined conditions is called *simulation.*

The obvious advantages of modeling and simulation, as a research method, include:

- possibility of solving the problems, which cannot be resolved due to other easier methods, and the research on the actual object is impeded;
- the possibility of fast research and analysis of different variants,
- easiness in the change of input parameters of the researched circuits; but there also occur obstacles such as:
  - scarcity of universal models(a generalization of the model causes significant complications);
  - complication and significant workload required for software.

Each year the scope of application of modeling and simulation expands. The development of computer technology in recent years resulted in a new approach to the research work on ETS viewed as a complex electromechanical system. Methods of computer-aided analysis, design and simulation are using system of the electrified transport (fast railway, suburban railway, tram trolleybus, metro) with emphasis put on the energy consumption and compatibility, as well as limitations resulting from the impact on technical infrastructure and environment. The process of analysis and design of ETS has to be sufficiently enough so as to provide proper and safe operation of the actual system, in accordance with the tasks imposed by the freight and that the proposed technical solutions would be technically feasible in obtaining the lowest possible effort but also environmental friendly.

Methods of computer-aided design and simulation are used at the design stage of system (analysis of ETS as a whole) and at the transition to the design of individual subsystems and their components. An important step is to define ETS subsystems and their interrelations in the processing and transmission of energy. Detailed analysis of the transformation and power transmission as well as related parameters (energy consumption for traction purposes, efficiency, capacity, instantaneous power, maximum, medium, replacement and installed power, and the level of their utilization, overload, etc.) allow not only to design the system, but also to conduct studies on the operation of the various subsystems under the states of normal and emergency operation.

This issue is important for subsystems of transmission and distribution of electricity: power supply networks (PSN), traction substation (TS), catenary (C), circuits of electricity conversion in the electric traction vehicles (ETV), track circuits (TC). Study work in the field of ETS differs from the analysis conducted in the range of not-rail electricity supply (urban, industrial). First of all, we are dealing here with a few basic differences:

- circuits supplying traction vehicles have changeable typology with respect to the motion of traction vehicles (changeable point of power delivery), what causes the changeability of parameters of the ETS supplying circuit (voltage and resistance changes at the point of current consumption) significantly influencing the ETS characteristics as energy recipients and their traction capacities,
- occurrence of the fast changing in time traction load, which value depends on the power, currently collected by the ETV on a track,
- in the zone of ETS influence (around the railway line and trackside equipment) occur subsystems with various types of supplying voltages (HV-high voltage and MV-medium voltage AC, 3kV DC, AC, LV- controlling and signaling devices of different frequencies)
- Modern methods of analysis and computer implementation allow a more accurate reflection of the actual functioning of the ETS system, including the phenomena, which often have been overlooked,

or considered just in fragments. The degree and extent of simplifying assumptions depend on the purpose of the work, available resources and the required level of specificity of the conducted analysis.

Formulation of simulation models of the complex system, such as ETS, requires not only analytical, theoretical, but also a methodological approach and includes:

- formulation of a sufficiently accurate model of the actual system (object) with the formalization of phenomena occurring in the system,
- development of an algorithm for modeling and selection of strategies for problem-solving, a strategy that would be optimal with respect to goals to be achieved, calculation time, technical capabilities of equipment, requirements concerning output and input data,
- application of simulating models for problems solving -according to the range of analyses: preliminary, design, research and didactics.

Development of ETS models usually begins with determining the set assumptions, concerning:

a) object and the aim of model creation

b) range of application and users

c) requirements toward models, field of covered issues, degree of specificity and complexity,

d) applied tools (devices), which would be employed in the process of implementation (execution) of a model.

Functional aims - define tasks to be fulfilled by the developed models, e.g. when the task is to rationalize energy consumption in the ETS system, models are to:

- realistically describe the energy and power consumption in the actual conditions and forthcoming ETS systems including types of lines (international main lines, national main lines, secondary, freight and suburban lines),
- enable the allocation of energy into useful energy (traction), the energy of own needs, losses in vehicles, losses in the catenary, losses in substations, power transmission losses in the power system etc. as well as define relations and feedbacks between particular elements of a system, its parameters, input and output values,
- provide measures that would enable the development of a simulation model for the analyses aiming at obtaining technical efficiency of traction systems, which can be tested in theory (performed simulations) before their application in practice. Models should allow for the evaluation of the efficiency of various measures, so that these could be introduced that will prove, in concrete terms, to be most effective.

When the task is to analyze the compatibility of various subsystems and electronic devices, functioning in the ETS, models should take into account interactions, such as the influence of the variable component of the traction current flowing in rails on the possibility of disrupting the control and signaling circuits.

Structural aims define architecture (structure) of the developed models; describe how models are formulated from the viewpoint of their effective use. Therefore, it is usually assumed that the ETS model has a modular structure, which means that each module (model subsystem) can be developed separately, then tested and verified and included into the functional structure of ETS model. Thanks to this, model of each subsystem can be used independently and modified (or removed) with no need of structural changes of model of a whole system, which would require major reconstruction and modification. This is possible if the model of subsystem is replaced by a preconceived sets of input values, which change in the function of time, and generated previously during a process of simulation or when they are averaged (e.g. during switching off the module regarding the traction power supply system (TPSS), it can be assumed that voltage on the ETV current collectors has a constant value or changes according to the set run, e.g. stochastically).

Structure of ETS models

ETS model may have a modular structure, and ETS as a complex system can be described by a finite number of subsystems. With computer simulation, it entails a certain amount of subprograms interacting with each other and with the main program. Moreover, the structure of ETS model should be sufficiently flexible so as new modules could be inserted e.g. resulting from the introduction of a new rolling stock, new construction of power facilities, changes in terms of traffic, the application of new technologies. At the same time when the connections and relations between the modules (subsystems) are included, a model of ETS will have a complex character.

The main technical requirement posed to ETS (and subsystems) is to ensure conditions for reliable movement for demanded traffic (TD), which should be accomplished in the presence of dependences between subsystems and lead to the situation where traffic output (TO) will correspond with the demanded traffic (TD). By setting transport (TD) one introduces macroscopic data aggregated for the whole ETS. Values as demanded electric energy (EE) and resulted transport work (TO) are also of macroscopic character and do not provide information about conditions of functioning of particular subsystems (fig. 1).

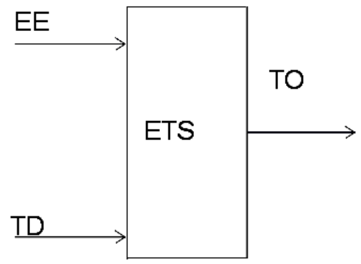

Fig. 1. ETS model at the highest level of aggregation

The description of the ETS as a complex system for functional analyses can be seen at different levels of aggregation:

- ETS as a system (the highest level of aggregation) with a low degree of detail, using as data an annual, average forecast of mobility (fig. 1);
- ETS as a system decomposed into a set, associated with each finite number of subsystems (the lower level of aggregation, higher degree of specificity e.g. use of schedules and simulation of the system for peak hour traffic) (fig. 2);
- microscopic observation of selected issues in the elements of subsystems (e.g. I_c current of the selected ETS in steady-state conditions of a period of milliseconds with the performed analysis of FFT etc.) (fig. 3).

In this paper, the adopted methodology is considered to be a set of mutually dependent subsystems (Fig. 2): TT, ETS, TPSS, and TS, PSN [1-3, 6-8,11-14] that simplifies the process of formulation, modification and computer implementation of models. Particular attention should be paid to the interactions between the subsystems that decide about realization of transport (ETS) and traction power supply system (TPSS) as well as to the TS disturbing influence on the power supply network (PSN) and current harmonics taken by ETV on the traffic control circuits [4, 15-18]. For the detailed analysis regarding the issues occurring in micro-scale, the models that can be used are disaggregated with varying level of specificity and the phenomena are considered at different time scale, for the creation of which results obtained from models of higher aggregation scale (Fig. 1) can be used.

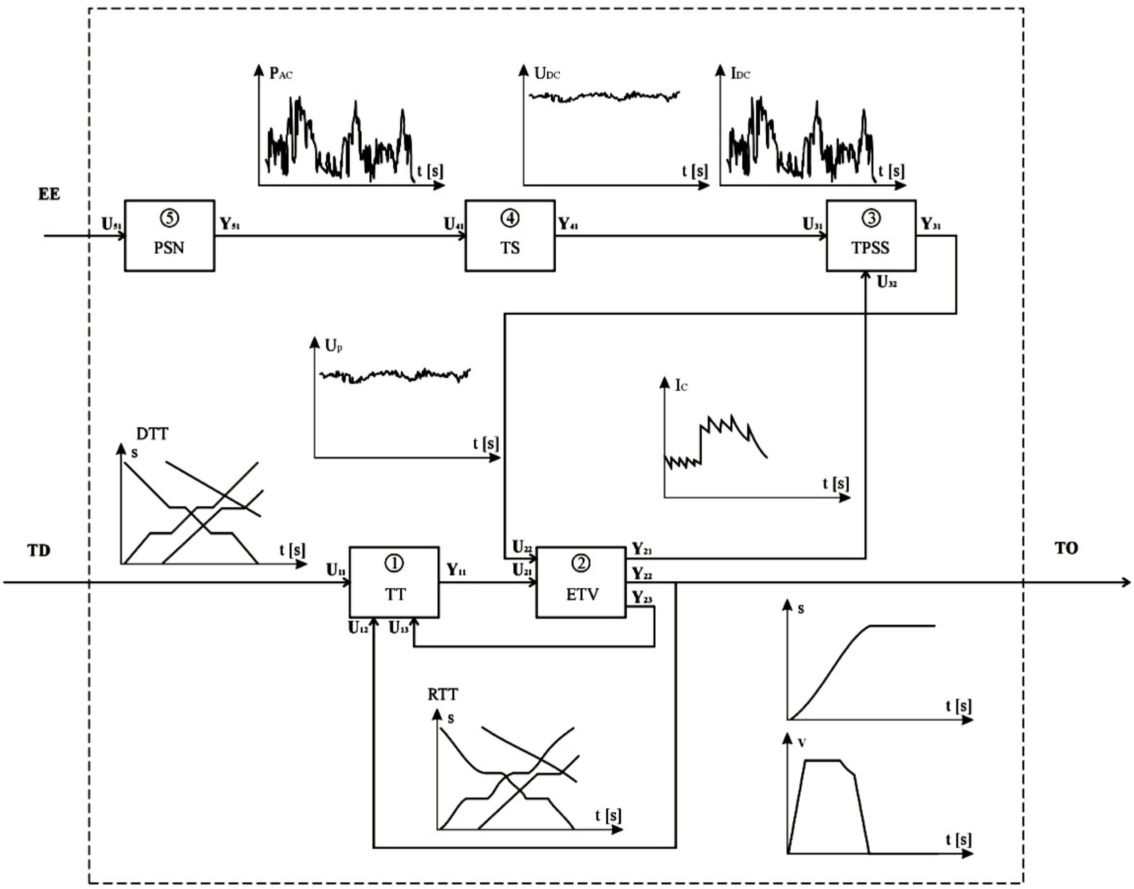

Fig. 2. Functional scheme of ETS system after decomposition into subsystems and presentation of exemplary time runs (time axis scaled in seconds) of input and output values: TT – time-table; DTT – demanded time-table, RTT – actual (resulted) time-table, TD – transport demand, TO – transport output

It allows to take into account mutual dependencies between subsystems and their components as well as their influence on the obtained results of simulation (Fig. 2), which later undergo the process of aggregation (T-transport output, EE-electric energy consumed by the ETV) [9-12] in order to be compared with assumptions (TD–transport demand) and calculations of ratios, which characterize ETVs (unitary energy consumption). It should be also considered that an independent examination of the various subsystems and their analysis at excessive level of aggregation, as it was observed in some other methods applied [5] accounted for a substantial simplification.

Therefore, the use of such methods should be reviewed to assess if the obtained accuracy is proper taking into account the purposes of analysis. Similarly, at the stage of model formulation limitations and aside conditions, which define the range of conducted analyses or the application of models, should be considered. They might be resulted from physical properties of the analyzed systems, but also from the assumed standards or imposed requirements. Those variants, which are not forbidden by the limitations (do not fulfill the requirements) constitute permissible variants (achievable).

Generalized scheme model of ETS system decomposed to the sub-models is presented in Fig. 2 [11, 13], where matrixes of values have been determined:

U-input, **Y** - output and **Z** - disturbances influencing from the outside on the various subsystems in the ETS system composed of n-number ETV (i=1,...n), m- TS and

U_{11} – matrix of defined transport flow and parameters (masses m_i, locomotives types t_i, speed v_i (t) etc.) of) of i^{th} ETV,

$U_{12}=Y_{22}$ – location $s_i(t)$ and speed $v_i(t)$ of i^{th} ETV,

$U_{13} – Y_{23}$ - acceleration $a_i(t)$) of i^{th} ETV,

$Y_{11}=U_{21}$ – set manner of running of ETVs,

$U_{22}=Y_{31}$ – matrix of voltages $U_{pi}(t)$ on collector of of i^{th} ETV,

$Y_{21}=U_{32}$ – matrix of currents $I_{ci}(t)$ collected by of i^{th} ETV,

$U_{31}=Y_{42}$ –current of feeder $I_{zj}(t)$ and TS $I_{cj}(t)$, U_{dj} voltage at DC bus-bars of j^{th}-TS,

$U_{41}=Y_{51}$ – power P_{ACj} and traction substation current I_{ACj} flowing in PSN, U_{Acj} voltage on AC bus-bars of j^{th} TS,

U_{51}- voltage U_{SEj} and short circuit power S_{zwj} of electric power system (EE) at the point of PSN connection to the supplying TS.

Dynamic model of the ETS system can be presented in the generalized manner in shape of set of equations describing the respective subsystems

$$\frac{d\mathbf{X}_i(t)}{dt} = f_i(\mathbf{X}_i(t), \mathbf{U}_i(t), \mathbf{Z}_i(t)); \qquad (1)$$

$$\mathbf{Y}_i(t) = \mathbf{G}_i(\mathbf{X}_i(t), \mathbf{U}_i(t), \mathbf{Z}_i(t)), \qquad (2)$$

where i = 1..5 and structural equations

$$\mathbf{U}_i = \mathbf{H}_i \mathbf{Y}_i, \qquad (3)$$

where $\mathbf{X}_i(t)$ – vector of state variable of i^{th} subsystem.

Dimensions of the matrix structural equations depend on the number and types of ETVs moving along the railway line, the TPPS system and number of traction substations TS (m) as well as their scheme of supply by the power system.

After the presentation of the overall structure of the ETS, next step is to formulate specific dependencies describing operation of various subsystems and relationship between them. The shape of mathematical dependencies (1)-(8) will rest on types of issues to the analysis of which will be suitable.

$$U1 = \begin{bmatrix} u11 \\ u12 \\ u13 \end{bmatrix} = \begin{bmatrix} u11 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} y21 \\ y22 \\ y23 \end{bmatrix} \qquad (4)$$

$$U2 = \begin{bmatrix} u21 \\ u22 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} y11 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} y31 \\ 0 \end{bmatrix} \qquad (5)$$

$$U3 = \begin{bmatrix} u31 \\ u32 \\ u33 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} y41 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} y21 \\ y22 \\ y23 \end{bmatrix} \qquad (6)$$

$$U4 = u41 = y51 \qquad (7)$$

$$U5 = \begin{bmatrix} u51 \\ u52 \end{bmatrix} = \begin{bmatrix} u51 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} y41 \\ y42 \end{bmatrix} \qquad (8)$$

Dimensions of the matrix structural equations depend on the number and types of ETVs moving along the railway line, the TPPS system and m-number of traction substations TS as well as their scheme of supply from the power system. After the presentation of the overall structure of the ETS, next step is to formulate specific dependencies describing operation of various subsystems and relationship between them. The shape of mathematical dependencies (1)-(8) will rest on types of issues to the analysis of which will be suitable.

In general, they will be the differential equations, algebraic equations and schemes of operations (algorithms) functional, characteristics. Example of the application of state variable method used for the description of mutual interaction of ETV-TPSS subsystems for the ETS are presented in [2, 8, 10-13].

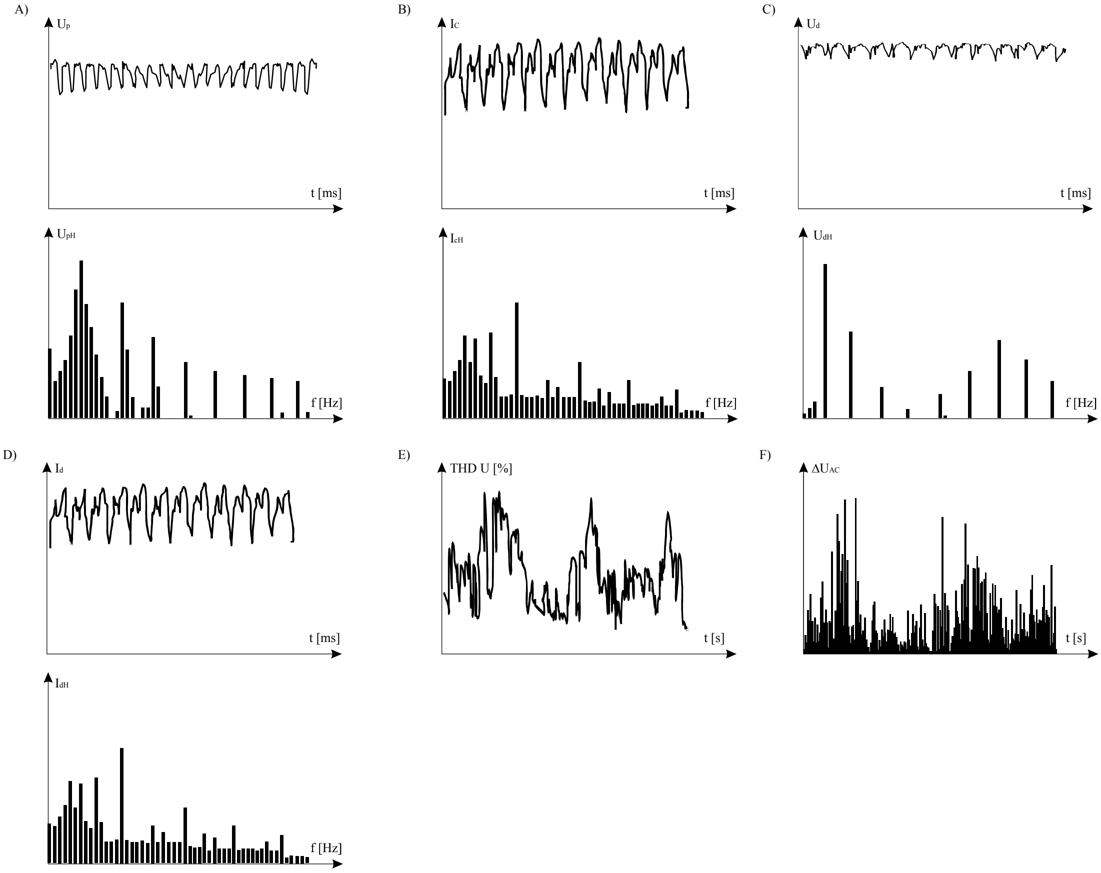

Fig. 3. Exemplary graphs of chosen input and output quantities from the fig.2 after specification and performing of harmonics analysis with application of FFT (A, B, C, D) as well as analysis of disturbances – voltage total harmonic distortion THD U (E) and voltage fluctuation ΔU_{AC} (F)

Traffic demand as input for power supply system load simulation

Electrical load, voltage and currents in the circuits of ETS depend on a type of traffic, rolling stock and TPSS applied. Therefore, the basic set of data taken for modeling of the functioning of the ETS is a set transport workload - traffic output (Fig. 1) resulting from actual or re-casted demands for transport services (usually given per a defined year). This traffic flow B should undergo de-agreggation so to perform a determination of an organization and technology of transport service, i.e division traffic flow B into specific j^{th} transport service B_{pj} (freight, passenger etc. of n-number) and k-types of ETV trains B_{pji} (of m-number, for each of them is declared: mass, average $v_{śrji}$ and maximum v_{maxrji} speed, rated power P_{ji}) in the j^{th} transport service [5-8, 10-13, 16].

The following relationships are satisfied

$$B = \sum_{j=1}^{n} B_{pj} \tag{9}$$

$$B_{pj} = \sum_{i=1}^{m} B_{pji} \tag{10}$$

In accordance with the timetable, trains on a set k^{th} section of an L_k route do have specific time lag of Δt_{ki} and locations l_{ki} as well as time of planned stops Δt_{pki}. In typical situations of ERL operation, ETV traffic takes place due to a specified timetable (passenger trains), or intended for use by freight trains, routes reserved in the timetable, with the elements of a random nature (disturbance of traffic, unplanned shutdowns, speed slowdowns, disruptions in the supply system etc.).

Preparation of data for modeling of freight trains traffic can be resolved into defining the k^{th} section of L_k route and T_k specified period of possible use of routes of traffic in the timetable, on which it is possible to lead freight trains (fig.4), where it is indicated:

N_{ok} - line capacity in the period T_k,

Δt_{mink} - the minimum possible time lag between the possible routes of trains,

n_k - the maximum number of trains that can simultaneously be on the L_k section (minimum time interval Δt_{imink}) due to technical and safety limitations, resulted from the applied control and signaling systems.

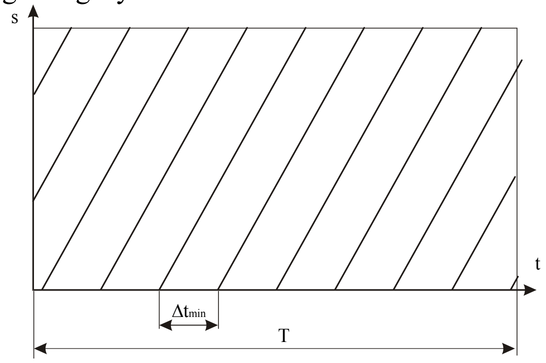

Fig. 4. Scheme of transport routes for a section of ERL

The relations between these parameters are as follows

$$N_{ok} = \frac{T_k}{\Delta t_{\min k}} \tag{11}$$

$$n_k = \frac{N_{ok} L_k}{T_k v_{\acute{s}rk}} \tag{12}$$

The implementation of transport schedule, established in the timetable is only possible if one ensures the maintenance of the assumed v_{av} - medium speed of trains of each category on sections.

Failure to meet the average speed v_{av} can lead to a disruption in the conduct of traffic and becomes a limitation in the implementation of set transport flow. Useful power of locomotives P_l, providing the maintaining of set values of a train's speed are conditioned by the capacity of the traction power supply, i.e. effectiveness of energy delivery with demanded current and voltage level in catenary.

The increase in mass and speed of trains will cause an overload or capacity of the supply network with reduction of quality and quantity of energy delivered to the vehicle, thus reducing the P_l power of the locomotive, results in a lower speed. For each configuration of power supply, there is a *limited volume of transport* B_g (divided into different categories B_{jg} and types of trains B_{jig}) after exceeding this limit, TPSS becomes unwieldy in a sense of power and energy supply or due to the criteria of proper supply by the PSN [11, 12, 15-22].

Thus, with such a TPSS configuration it is not possible to implement the requested transport B. Exceeding the limits of transport volume for a given structure of power supply induces the modernization of TPSS. An assessment of a timetable construction and its impact on the functioning of ERL requires an analysis of all possible variants of the timetable with combinations of masses, speeds and power of trains. In methods used for the dimensioning of ERL equipment [6, 8, 11-13], typically only a part of timetable is being used, regarded as the critical load (the period of peak traffic, traffic with the highest power consumption and rated power of trains).

Any schedule or a compilation of the number of trains and their masses for a given section can be characterized by statistical layout of frequency of occurrence of a given train category. It is possible to use pseudo-random number generator of a specified distribution (e.g. Poisson's), which allows to take into account the random nature of the occupancy of the route by a freight train or occurring disturbances Z_1 (Fig. 2) of a different nature (e.g. unscheduled stop). In a similar manner one can take into account the variability of entry times of trains on a section (random variation in the spacing between trains), additional, unplanned stops, and their distribution (e.g. by usage of pseudo-random number generator to determine if the signal of a semaphore allows or not for the entry to the next section, deviations from the time stops at stations, etc. In such a manner one can obtain a range of possible to occur, variations of motion patterns, which constitute models of TT schedules, forming an input data for a simulation of ERL operation.

The timetable model (TT) can be presented in a graphical form as a diagram of a route in a function of time t, t.i. s= f (t) (fig.4), for each of p trains, passing a section at given time. This chart is presented in a simplified form as a line, consisting of sections between adjacent traffic checkpoints. In the model TT as the ERL subsystem (fig.2) following set of input values has been adopted

$$U_{11}=\{s_{ri}(t),m_i,t_i, t_{pi},v_{\acute{s}rzi},v_{maxi}(s_i),P_p(s_i),R_r(s_i)\} \tag{13}$$

where $s_{ri}(t)$ – scheduled location of i^{th} ETV in a function of time t,

m_i - mass of i^{th} ETV, i=1..p,

t_i –locomotive type of i^{th} ETV,

t_{pi} – type of i^{th} ETV (passenger, freight, traction unit, high speed train of speed up to 200km/h, train with tilting body, etc.),

$v_{pmax}(s_i)$ - speed limit speed of i^{th} ETV on a section of a route s_i,

$P_p(s_i)$ – vertical profile of a line (inclination) on a section of a route s_i,

$R_r(s_i)$ – horizontal profile (curves) on a section of a route s_i.

And matrixes

$$U_{12} = \begin{bmatrix} v_1(t_j) & a_1(t_j) \\ \dots & \dots \\ v_p(t_j) & a_p(t_j) \end{bmatrix}; \qquad (14)$$

$$U_{13}=[\, s_1(t_j), \dots, s_i(t_j), \dots, s_p(t_j)]^T, \qquad (15)$$

where

$s_i(t_j)$ – location of i^{th} ETV in time t_j,

$v_i(t_j)$ – speed of i^{th} ETV in time t_j,

$a_i(t_j)$ – acceleration of i^{th} ETV at time t_j.

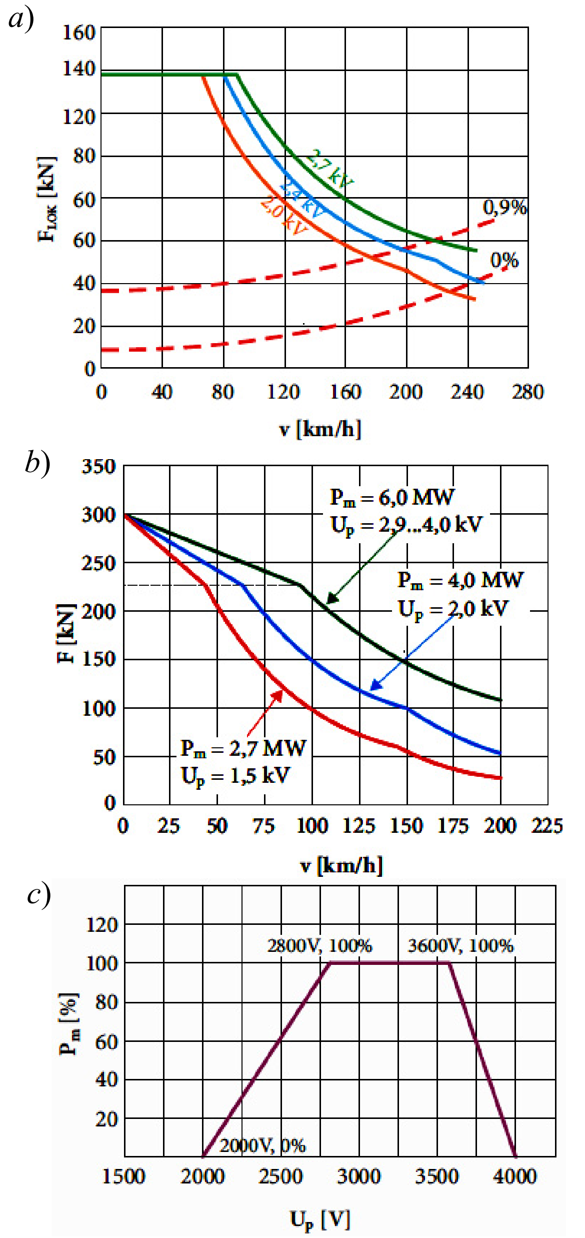

Fig. 5. Exemplary traction characteristic with voltage Up at its pantograph dependence: *a*) electric traction unit (EMU) for speed over 200 km/h; *b*) 6 MW loco; *c*) interregio EMU

It is important to take into account influence on voltage in catenary on traction characteristics (fig. 5).

The following matrix constitutes output values

$$Y_{11}= [z_{s1}(t), \dots, z_{si}(t), \dots, z_{sp}(t),]^T \qquad (16)$$

where

$z_{si}(t)$ –set mode of ETV i^{th} drive (starting, constant speed, braking etc.), i = 1..p

In a typical, model cycle of an ETV drive the following phases of motion can be distinguished:

- start-up/ increase of speed (F>0, acceleration a>0),
- ride with constant speed (if possible to be accomplished by a control and locomotive drive system) (a=0),
- coasting (F=0; a<0),
- braking (a<0).

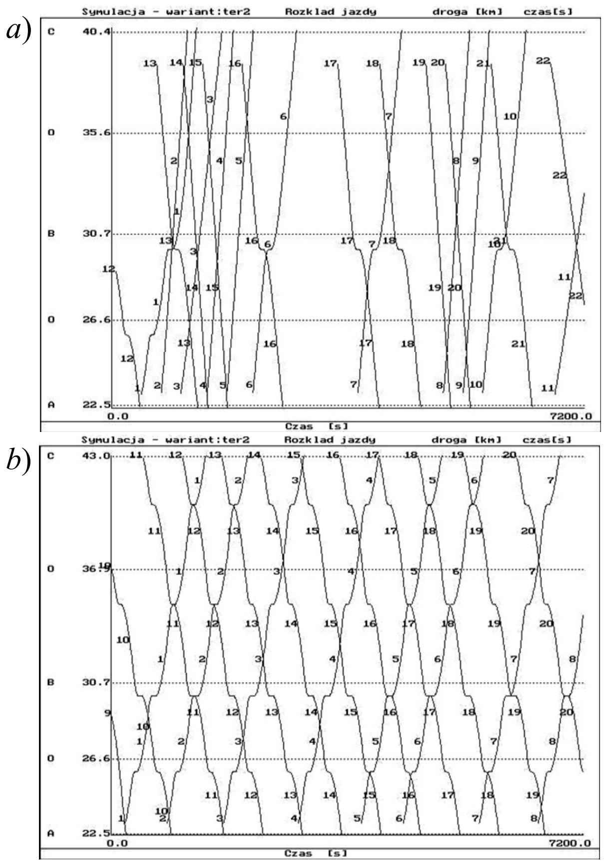

Fig. 6. Different time tables: *a*) mixed traffic; *b*) regular suburban traffic

The superior task of the traffic modeling is to keep scheduled time T_{ci} of the ETV running on a section (fig. 6) acc. to the assumed type of traffic with taking into account voltage level and its influence on ETV's traction characteristics (fig. 5). For this purpose, special algorithms are to be developed to recalculate traction characteristics of trains versus voltage and to maintain the desired average speed $v_{śrz}$ of ETV, by controlling the instantaneous (at a given time step t_j) ETV speed $v(t_j)$ and comparing it with the predicted speed (in a given time step, t_j) to obtain the average speed $v_{śrp}$ (t_j) [11, 12, 16].

Conclusions

The presented in the paper formal models of the ERL have been applied in a form of software and implemented for simulation analysis of different 3 kV DC railway systems with a variety of traffic: suburban, mixed passenger and freight, freight, intercity to asses power demand and energy delivery adequacy of the designed power supply system during different feasibility studies [11-13]. Some exemplary results of application of the derived methods are presented in the paper, showing opportunity for research and design in electric traction created by application of modeling and simulation techniques (fig. 7, 8).

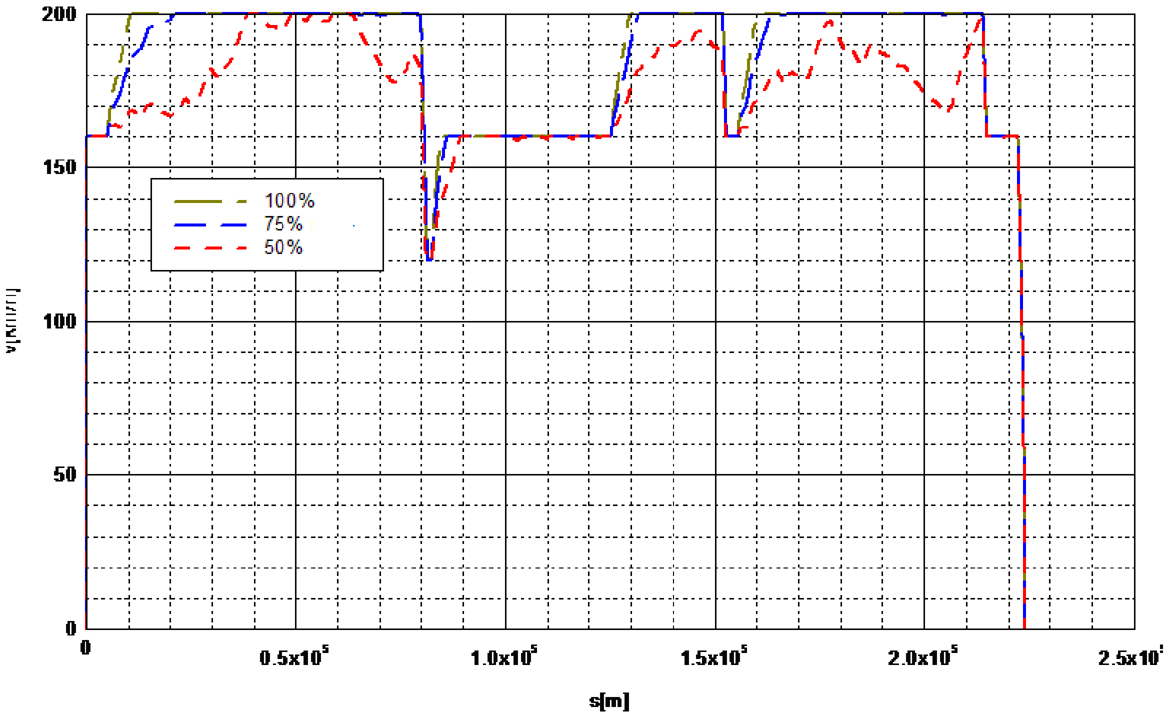

Fig. 7. Speed versus position of 500-t train with 6 MW locomotive acc. to available power (100%, 75% and 50% of nominal) limited by catenary voltage (results of exemplary simulation)

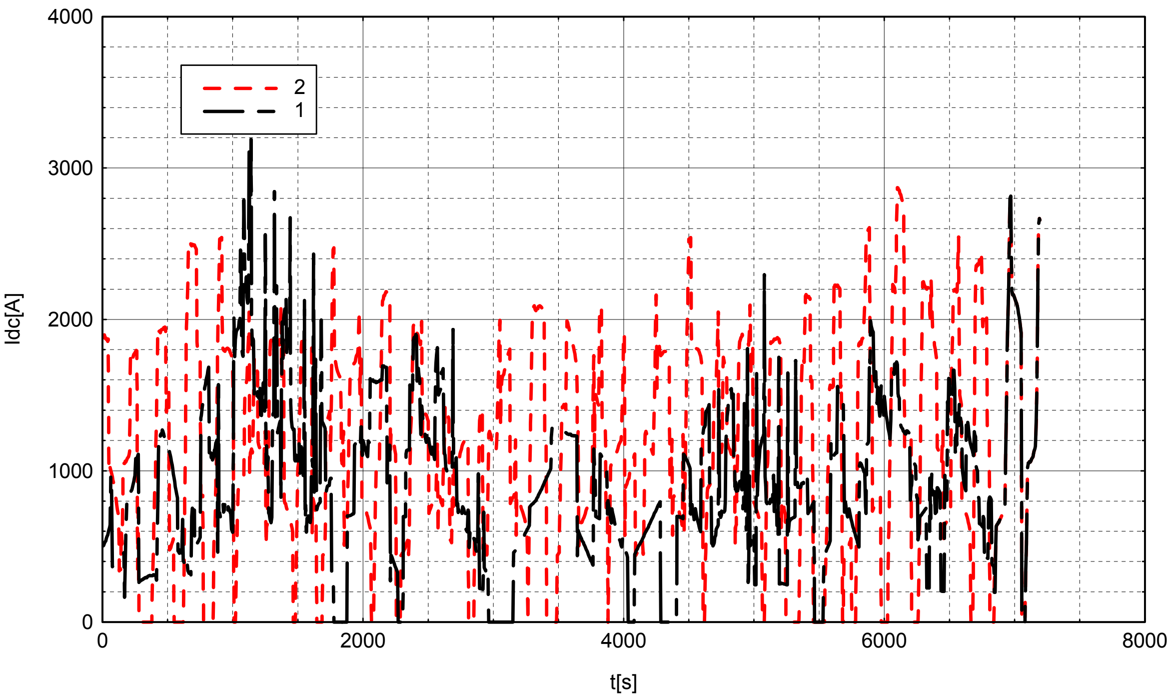

Fig. 8. A 3 kV DC traction substation load current acc. to the type of traffic:
1 – mixed traffic (fig. 6, *a*); 2 – suburban traffic (fig. 6, *b*)

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The paper presents different aspects and approaches towards application modeling and simulation techniques. It is discussed the different approaches to the modeling of the traction power supply systems. ETS model has presented like a modular structure, and ETS as a complex system can be described by a finite number of subsystems. In this paper, the adopted methodology is considered to be a set of mutually dependent subsystems that simplifies the process of formulation, modification and computer implementation of models. The presented in the paper formal models have been applied in a form of software and implemented for simulation analysis of different 3 kV DC railway systems with a variety of traffic: suburban, mixed passenger and freight, freight, intercity to asses power demand and energy delivery adequacy of the designed power supply system during different feasibility studies. Some exemplary results of application of the derived methods are presented in the paper, showing opportunity for research and design in electric traction created by application of modeling and simulation techniques.

Keywords: electric traction, system, decomposition, modeling, routines, characteristic, time table.

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А. ШЕЛОНГ (ВАРШАВСЬКИЙ ТЕХНОЛОГІЧНИЙ УНІВЕРСИТЕТ, ПОЛЬЩА)

Варшавський технологічний університет, Відділ електричної тяги, Площа Політехніки 1, 00-661, Варшава, тел. :+48 22 234-72-17, факс:+48 22 625-75-24, ел. пошта: adam.szelag@ee.pw.edu.pl

ЗАСТОСУВАННЯ МОДЕЛЕЙ І ТЕХНОЛОГІЙ МОДЕЛЮВАННЯ ЯК МЕТОДІВ ДЛЯ ТЕХНІКО-ЕКОНОМІЧНОГО ОБҐРУНТУВАННЯ ТА ПРОЕКТУВАННЯ СИСТЕМ ТЯГОВОГО ЕЛЕКТРОПОСТАЧАННЯ

У даній статті представлені різні аспекти та підходи до створення прикладних моделей і прикладних методів моделювання. Представлено різні підходи до моделювання систем тягового електропостачання. СТЕ представлена як модульна структура, система електропостачання як складна система може бути описана кінцевою кількістю підсистем. У цій роботі прийнята методологія, в якій передбачається, що система електропостачання є поруч взаємно залежних підсистем, що спрощує процес формулювання, формалізації та комп'ютерного представлення моделей. Представлені в статті математичні моделі були реалізовані у формі програмного забезпечення і застосовувалися для аналізу і моделювання різних систем тягового електропостачання постійного струму 3 кВ з безліччю типів руху: приміський, змішаний – пасажирський і вантажний, вантажний, інтерсіті для оцінки навантажень на систему тягового електропостачання під час різних техніко-економічних обґрунтувань. Стаття містить деякі експериментальні результати застосування методів моделювання, що показують можливості їх застосування для аналізу і проектування систем електричної тяги.

Ключові слова: електрична тяга, система, декомпозиція, моделювання, процедура, характеристики, розклад руху.

Внутрішній рецензент *Сиченко В. Г.* Зовнішній рецензент *Сокол Є. І.*

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А. ШЕЛОНГ (ВАРШАВСКИЙ ТЕХНОЛОГИЧЕСКИЙ УНИВЕРСИТЕТ, ПОЛЬША)

Варшавский технологический университет, Отдел электрической тяги, Площадь Политехники 1, 00-661, Варшава, тел.:+48 22 234-72-17, факс:+48 22 625-75-24, эл. почта: adam.szelag@ee.pw.edu.pl

ПРИМЕНЕНИЕ МОДЕЛЕЙ И ТЕХНОЛОГИЙ МОДЕЛИРОВАНИЯ КАК МЕТОДОВ ДЛЯ ТЕХНИКО-ЭКОНОМИЧЕСКОГО ОБОСНОВАНИЯ И ПРОЕКТИРОВАНИЯ СИСТЕМ ТЯГОВОГО ЭЛЕКТРОСНАБЖЕНИЯ

В данной статье представлены различные аспекты и подходы к созданию прикладных моделей и прикладных методов моделирования. Представлены различные подходы к моделированию систем тягового электроснабжения. СТЭ представлена как модульная структура, система электроснабжения как сложная система может быть описана конечным числом подсистем. В этой работе принята методология, в которой предполагается, что система электроснабжения является рядом взаимно зависимых подсистем, что упрощает процесс формулировки, формализации и компьютерного представления моделей. Представленные в статье математические модели были реализованы в форме программного обеспечения и применялись для анализа и моделирования различных систем тягового электроснабжения постоянного тока 3 кВ со множеством типов движения: пригородное, смешанное – пассажирское и грузовое, грузовое, интерсити для оценки нагрузок на систему тягового электроснабжения во время различных технико-экономических обоснований. Статья содержит некоторые экспериментальные результаты применения методов моделирования, показывающие возможности их применения для анализа и проектирования систем электрической тяги.

Ключевые слова: электрическая тяга, система, декомпозиция, моделирование, процедура, характеристика, расписание движения.

Внутренний рецензент *Сыченко В. Г.* Внешний рецензент *Сокол Е. И.*