Abstract: Network of railway lines of international importance in Poland makes over five thousand kilometres of double-track electrified on 3kV DC. Political and economical changes in Poland started in 1989 influenced process of modernisation of railways, according to the requirements of transport policy of European Union. During 1990s many feasibility studies have been performed concerned, among others power supply system, within framework of Polish State Railway and internationally sponsored projects. All these studies resulted in working-out technical concepts of modernisation of traction power supply in order to improve their effectiveness and capacity according to the traffic prognosis. The paper presents the methodology applied during the study works and some technical results of the performed analysis.

Keywords: electric traction system, power supply, feasibility study

1. ELECTRIFIED RAILWAY LINE (ERL) AS A COMPLEX SYSTEM

There is presented in the paper the derived methodology of the assessment of the short-term and long-term activity and investments in order to make the operational of the ERL being effective and rational. The policy of EC up to 2020 assumes significant increase of transport work on ERL. It increases standards to be achieved by ERL. The operational requirement toward ERL is to provide the technical conditions for safe, reliable and corresponding to the defined timetable traffic of trains. The main functional aim of traction power supply system - delivery enough quantity energy (EE) with the demanded quality to allow electric traction vehicles of ERL performing traffic (PT) according to the prognosis - defined traffic flow (B) (Fig. 1). Internal and external influence factors on the energy consuming by railway transport are emphasised, with the focus put on the energy market and transport policy of the state.

Due to complexity of the 3kV DC ERL a system approach to the problem is applied (Szelag&Mierzejewski 2000, Szelag 2002). System analysis allows describing influence of the specific subsystems and their elements on the global energy consumption taking into account internal and external restrictions. For the purposes of the study the ERL has been divided into the following sub-systems (Fig. 1):
- AC power supply system (PUN),
- DC power supply system (traction substations TS and DC network-DCPS),
- Electric railway rolling stock (ETV),
- Operational and control system (TT).

The first two subsystems transform and deliver energy to the trains, but the last two subsystems creates the demand for power and energy consumption. So energy rationalisation is a task requiring to take into account practically all aspects of operation of ERL. The key point is the analysis of ERL trated the multivariable system.

The approach is oriented on the methods and the means allowing not only for decreasing energy consumption both for traction needs (operational) and non-traction (auxiliary, operation of infrastructure) but as well reduction energy losses and lowering the expenses spent by the railways on electrical energy and investments.
Internal mutual interdependencies define not only influence of the specific subs-systems and their elements on the energy consumption but as well on the cost of energy and the influence of the measures undertaken during the process of energy saving on the operation and parameters of the subsystems. The problem of energy consumption optimisation may be transferred to the analysis of the system based on the criteria including assessment of the unitary energy consumption of traffic and the effectiveness of the spent operational, maintenance and investment costs with the share of these costs in global financial coefficients of the railway line and with the relation to the income from traffic service. As far as the costs of energy are easy to separate the singling-out the share of total railway income to traction power supply division is difficult and may be assessed for instance according to the share in global investment expenditure.

Exemplary the share of electrical energy costs in global budget of Polish State Railways has been increased from 5.5% (1996) to 7% (1998 and 1999) (about 600mln PLN) of costs of operation of Polish State Railways (1999). Total energy consumption was 4.375,1 GWh (1998), (82,9% of it - traction energy). The observed trend is that the electrical energy cost is increasing with the decreasing traffic and the energy usage. It is resulted from higher electrical energy cost increase then the inflation. So the undertaking the measures leading to the rationalisation of energy usage are justified, as a way to lower operational costs of railways.

2. METHODOLOGY

Special multi-criterial methodology was derived for the purposes of feasibility-study works (Capasso et al. 1997. Feasibility study, 1997). The methodology allows taking into technical requirements, and standards, unitary energy, investment level and the operational and
maintenance costs to have the global and partial profitability assessed. The methodology is based on the following assumptions:

- finding the solution of a technical structure of AC and DC power supply for the defined traffic flow and the organisation of traffic,
- calculation, according to the defined criteria the traffic capacity of the railway for the pre-certain structure of power supply and the describing the requirements for the organisation of traffic,
- verification, having in mind energy consumption, of the elements of the assumed organisation of traffic volume and trains time-table

Operational study and system analysis create basis allowing to find the proper measures taking into account:

- the usefulness of the solution,
- multivariant options,
- mathematical description of technical and economic issues of the energy usage,
- assessment of the advantages and drawbacks of the implementation of the option taking into account uncertainty and risk.

The performed analysis and simulation studies have shown, that the main measures leading to the electrical energy rationalisation may be defined within two groups:

- long-term as:
  - modernisation of AC and DC power supply networks,
  - introducing into service new type of rolling stock,
  - modernisation of track (proper profile, liquidation of speed-limits)

The area of the implementation is resulted from the previous negligence and the application of non-effective solutions.

- short-term (low-investment) are based on the organisational changes in:
  - traffic,
  - energy delivery (lower tariffs, special agreements, time-zone tariffs etc.).

Energy consumption and losses are determined not only by the technical factors (level of technical solutions of equipment and energy consumption by rolling stock) but organisational and process engineering. Decreasing of energy usage on traction needs is possible due to:

- optimisation of vehicles’ movement, timetable, sequences of trains, which may be obtained by application o automatic control and management,
- proper matching locomotives and trains (power, speed, weight, distance, route profile),

Reduction of losses for traction needs may be obtained by:

- implementation of proper power supply schemes and installations,
- energy saving equipment,
- spreading peak loads during longer periods to limit excessive rush load and make traction load more uniform, increase reliability and availability of power delivery systems.

When problem of rational operation of ERL is analysed one has to take into consideration not only technical but as well financial and economic aspects of the problem. Final assessments have to take into consideration all the above mentioned aspects in order to be complex and credible as the improvement of traffic service and competition between different means of transport cause increase of speed. This must cause increasing of energy consumption. From the other side it may happen that the measures to reduce energy consumption are more expensive then the received savings. In the study (Rationalisation..., 1998) rationalisation of energy usage was treated as process of reduction of: global energy consumption, and power demand, operational, maintenance and investment costs in area of energy delivery. Due to significant restrictions and conditioning the rationalisation of energy consumption was defined as:

- orientation towards reduction of energy consumption,
- reducing costs of energy and demanded power
- defining the rational level of required investments in power supply.

So the rationalisation of the electrical energy should be, according to the authors of the paper, understood as follow:

- when possible, reasonable and economically justified reduce energy consumption, having in mind the traffic demand and quality of service,
- everytime and everywhere reduce costs of energy.

Minimisation of electrical energy usage in railway transport, treated as independent and superior optimisation task may lead to a need to fulfil technical standards requiring unjustified high investment costs. The rational solution will be a compromise between the consumption
energy and its costs, investment and operational costs and the income. Similarly, when as superior criteria minimisation of losses is assumed the required ‘ideal’ technical solution is reached at a very high cost of investment. Practically, if the technical requirements towards effective power supply of the locomotives of trains are reached (voltage level at the pantograph, reliability) and the investment costs are 100% with the average efficiency of power delivery 92÷93%, then for the ‘ideal’ power supply system (optimal according to the criteria of minimising losses) the increase of efficiency in 2÷3% will require investments at level of 200÷300% compared with the variant technically effective. So it is justified, due to financial aspects, to accept the compromise solution. The general requirements for the main railway line power supply are presented in Table 1. The amount of investments to be spent on the modernisation of 3kV DC power supply to enhance its technical standard and power delivery capacity is shown in Fig. 2.

### Table 1. Fixed installations of 3kV DC power supply of main railway lines (assumed requirements).

<table>
<thead>
<tr>
<th>v&lt;sub&gt;max&lt;/sub&gt; [km/h]</th>
<th>120</th>
<th>160</th>
<th>200</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catenary [mm&lt;sup&gt;2&lt;/sup&gt; Cu]</td>
<td>320</td>
<td>320</td>
<td>440</td>
<td>440</td>
</tr>
<tr>
<td>Traction substations (TS) *</td>
<td>2 x PD16</td>
<td>2 x PD17</td>
<td>2 x PD16</td>
<td>2 x PD16</td>
</tr>
<tr>
<td>Traction cabins</td>
<td>+</td>
<td>—</td>
<td>—</td>
<td>— / +</td>
</tr>
<tr>
<td>Distance TS-TS [km]</td>
<td>25</td>
<td>15</td>
<td>15</td>
<td>12 – 15</td>
</tr>
<tr>
<td>Installed power in TS [kW/km]</td>
<td>425</td>
<td>748</td>
<td>704</td>
<td>880</td>
</tr>
</tbody>
</table>

*PD16 – 5.8 MW 12-pulse rectifier group supplied by 15kV voltage, PD17-6.4 MW 12-pulse rectifier group supplied by 110kV voltage.

### 3. TRACTION ENERGY CONSUMPTION

Energy consumption for traction needs is strictly dependent on the traffic and the type of service, specifically by the following parameters: speed (maximum and average), power demand (maximum and average), mass, distances between stops, density of trains (during rush hours an average per day). Traffic service, creating the income for the railway operator is performed by a number of categories of trains, from which some are more, while other less profitable. In general freight traffic makes profit, qualified passenger trains are close to cover the costs of operation, while passenger traffic has to be subsidised. From point of view of energy consumption and the income it happens that the most energy consumes a train, which makes the least income. As a factor for assessment of the ‘rationality’ and ‘energy saving quality’ of the operation of a railway line the ratio of the actual costs of energy to assumed minimal costs (‘ideal solution’) and fulfilling the technical criteria set in Table 3 may be applied.
Fig. 2. Cost $K$ of modernization of 3kV DC power supply system elements in order to reach the required low resistance parameters.
Fig. 3. Results of simulations: a.) average power demand $P_{sr}$, b.) unitary energy consumption $j$; c.) unitary net energy consumption $j_n$ as a function of average speed $v$ and mass (distance 100km without starting).
Fig. 4. Distribution of 15-min. power demand $P$ of a traction substation, a.) low utilisation of peak power, b.) high utilisation of peak power demand.

Table 3. Proposed technical criteria for assessing traction power supply system.

<table>
<thead>
<tr>
<th>No</th>
<th>Criteria</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Short-circuit detection</td>
<td>$I_{\text{sec min}} &gt; I_{\text{load max}} (P_{\text{pmax}})$; $P_{\text{mean}} \rightarrow P_{d}$.</td>
</tr>
<tr>
<td>2.</td>
<td>The level of utilisation of peak power demand $P_d$</td>
<td>$m_{\text{peak}} = P_{\text{mean}}/P_d = A/(T \cdot P_d)$ where: $m_{\text{peak}} \in (0,4 \div 0,5)$ $0,4$ – for low density traffic line, $0,5$ – for high density traffic line (Fig. 3).</td>
</tr>
<tr>
<td>3.</td>
<td>The level of utilisation of the installed power $P_i$</td>
<td>$n_i = P_{\text{mean}}/P_i = A/(T \cdot P_i)$ $n_i \rightarrow k_i$, $m_{\text{peak}}$ $k_i = P_{sz}/P_i$ $k_i$ – coefficient of redundancy $(0,66 \div 0,85)$ $n_i \in (0,264 \div 0,425)$</td>
</tr>
<tr>
<td>4.</td>
<td>Time of utilisation of peak power $P_d$:</td>
<td>$T_d = A/P_d = m \cdot T$ $(2800 \div 3500h)$</td>
</tr>
<tr>
<td>5.</td>
<td>Time of utilisation of the installed power $P_i$:</td>
<td>$T_i = A/P_i = nT$ $(1850 \div 2950h)$</td>
</tr>
</tbody>
</table>

where:

$P_{\text{mean}}$ – average power, $A$- energy consumption, $P_d$ – peak power demand, $P_i$ – installed power.

4. TECHNICAL CRITERIA AND STANDARDS

Preparing the study of modernisation options of ERL one must to work-out the scenario of strategic activities in order to introduce solutions including modern technological and technical measures according to the international bodies (UIC, IEC, EC) recommendations and standards. As partial tasks within the assumed strategy the following may be mentioned:

- interoperability,
- reliability,
- minimisation of investment and operational costs,
- improving of safety,
- implementation of ETCS/ERTMS systems,
- reducing of negative influence of railway lines on infrastructure and the environment.

Within the framework of EC documents the trans-European railway network will be created and all the railway operators, under specified conditions, will have rights to access to the railway infrastructure. It requires unification of standards applied to the power supply of different AC and DC systems delivering electrical energy to multi-system locomotives. In order to fulfil these requirements the effective and reliable electric traction power supply systems have to be assured. These tasks are being performed with wide application of specific modelling and simulation methods of analysis and design process. Worked-out multi-criteria feasibility studies and projects are necessary for defining the needed area of modernisation and investment with financial and economic CBA, which allows finding optimal, according to the assumed criteria.
The basic parameters for assessment of effectiveness and quality of the power supply are following:

- level of voltage $U_p$ at vehicle’s pantograph,
- equivalent currents $I_z$ in catenary, feeders and traction substations,
- maximal currents $I_{z\text{max}}$ in catenary and traction circuits,
- efficiency $\eta_{p}$ of supply circuits,
- minimum $I_{z\text{min}}$ and maximum $I_{z\text{max}}$ short-circuit currents;
- current/voltage harmonics (individual k-harmonic amplitudes $A_k$ and total harmonic distortion factor -THD) and load fluctuations causing voltage flickers,
- stray currents defined by longitudinal resistance rail-earth $r$ [$\Omega$/km] and voltage drop rail-earth $\Delta U_{sz-z}$;

which makes a set of technical criteria:

$$\text{min./ max. } \{U_p, I_z, I_{z\text{max}}, \eta_{p}, I_{z\text{min}}, I_{z\text{max}}, \text{THD, } A_k, r, \Delta U_{sz-z}\}$$

The reliability of energy supply depends on the quality of the installations, assembling, proper operation and their nominal parameters (current, voltage). Overloading capacity and overvoltage withstanding is an important aspect of operation of the power supply devices, mainly transformers, cables and high-speed breakers. There is presented in Fig. 6 measured currents and voltages in high-speed breaker circuit during clearing a short-circuit with return multi arc-over across an arc chamber.

The most vulnerable element of the power delivery circuit is catenary due to lack of the redundancy. The voltage at the pantograph $U_p$ is a significant parameter having influence on the delivered power by the traction drive system and its efficiency $\eta_{p}$. For different conditions of operation for the delivered mechanical power $P_{m}$ electrical power $P_{el}$ depends on the voltage $U_p$ and current:

$$P_{\text{mech}} = F_p \cdot v_p \quad (2)$$
$$P_{el} = U_p \cdot I_p \quad (3)$$
$$P_{\text{mech}} / P_{el} = \eta_{p} \quad (4)$$

where:

$F_p, v_p$ - traction force and speed of the locomotive.

The exemplary influence of the voltage $U_p$ on the average speed of the train with asynchronous drive system locomotive system (results of simulations) is shown in Fig. 5. This explains the strict requirements towards the maintaining high UIC voltage standards for high speed lines on DC voltage and the needs to modernise power supply systems, especially DC type during the process of creation of Trans-European Railway Network. Putting into service high power locomotives will be effective on the condition that the power supply system has enough capacity to deliver enough power to them. So new UIC criteria for calculations of voltage at the pantograph of the locomotive was imposed:

$$U = \frac{\sum_{i=1}^{n_{\text{max}}} \frac{1}{T_{i}} \int_{0}^{T_{i}} U_{P_{\text{panto}}} * I_{P_{\text{panto}}} * dt}{\sum_{i=1}^{n_{\text{max}}} \frac{1}{T_{i}} \int_{0}^{T_{i}} I_{P_{\text{panto}}} * dt}$$

where:

$I_{\text{panto}}$ - i-th locomotive current,
$U_{\text{panto}}$ - voltage at pantograph of the i-th locomotive,
$T_i$ - time of running of the i-th locomotive.

This criterium is practically for only usage with the simulation software.
Fig. 6 Voltage and currents in the 3kV DC circuit of a traction substation during clearing a short-circuit with return-multi arc-over across the arc chamber [3].

CONCLUSIONS

1. The described in the paper methodology with usage modelling and simulation, treating 3kV DC electrified railway as system allows to undertake complex analysis taking into account mutual interactions between subsystems.

2. Practical results of the undertaken works using the presented modelling and simulation methodology was made basis for modernisation of 3kV DC main railway lines in Poland included into Trans-European Railway Network Corridors.

3. High speed railway lines electrified on DC voltage requires high technical standards to be kept, which must be taken into account during the feasibility study works.

4. The effective 3kV DC power supply means not only reliability and quality of power delivery to trains but as well minimisation of negative influence on the neighbouring technical infrastructure.

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