DOI: 10.36137/2008E

Change of the Electric Traction Power Supply System in Poland From 3 kV DC to 25 kV AC

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Summary

The article compares the 3 kV DC and 25 kV AC railway electric traction power supply systems. Both systems were characterised, including their requirements in terms of power supply to traction substations, system losses and the influence of the choice of system on the parameters of railway traffic.

Keywords: electric traction power supply system, 3 kV DC system, 25 kV AC system, energy losses, catenary

1. Introduction – Historical Background

With the permission of Siemens, this article uses content from a Railway Research Institute publication [1] and a ProKolej Foundation report [2].

The starting point of the electric traction power supply system is the power source at the power station, and the endpoint is the contact of the overhead contact line with the pantograph and the return circuit system. The parameters of the electricity supplied to the traction vehicle are influenced by the parameters of the whole system, even distant and seemingly unrelated to the electric traction power supply.

During the initial phase of railway electrification, the development of power supply systems in individual European countries and even their regions proceeded independently. Decisions on choosing a particular system were made based on technical considerations, ongoing research, as well as economic, political and military factors. This sometimes led to more than one power system in a single country. Out of the many available solutions, the following four became predominant in Europe:

- 1.5 kV DC,
- 3 kV DC,
- 15 kV 16.7 Hz,
- 25 kV 50 Hz.

Additionally, many variants of AC systems were created, including 2 × 15 kV 16.7 Hz and 2 × 25 kV 50 Hz systems. Contemporary new lines are electrified using the latter system – 2 × 25 kV 50 (60) Hz – particularly in the case of high-speed ones. Which system was chosen in a given country was, in many cases, determined by the time of electrification and political and economic ties. For example, the 15 kV 16.7 Hz system developed in Germany spread to the German-speaking countries (Germany, Austria and Switzerland) and the economically linked Sweden and Norway.

Further electrification of the railways was discussed at a 1954 AICC (*Association Internationale du Congrés des Chemins de fer*) Congress held in London. The power systems in place at the time were considered in terms of power supply from the electricity system, overhead line and fixed equipment, electric rolling stock, as well as construction, operating and maintenance costs. Attention was given to the asymmetry introduced into the electricity system by the 25 kV AC system, the insulation clearances required, etc. While 27 motions (resolutions) on choosing the electric traction power supply systems were adopted at the Congress, no single system was selected. The reason was that “Each system has its own characteristics, both technically and in terms of economics and operation. These characteristics make one or the other particularly suitable under the given conditions”. The aforementioned Congress and the issues raised at it were described in detail in issue No. 1 of Problemy Kolejnictwa [Railway Reports] [3]. At the time of the AICC Congress, the 25 kV AC system was only in use in France and the Belgian Congo (now Congo), and several countries were conducting research and trials, including the UK, USA and USSR.

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The AICC Congress was the inspiration to start considering the 25 kV 50 Hz system for introduction in Poland as part of the electrification of the Polish railways – the PKP. Showing an interest in the system, the Ministries of Transportation, Heavy Industry, Mining and Energy and Communications all studied the issue, initially separately and then jointly. Numerous analyses and studies were conducted, and many discussions were held, including with experts from other countries where the 25 kV AC system had already been implemented. After ten years of work, it was decided in 1964 that the introduction of a 25 kV 50 Hz system in Poland as part of the 1961–1980 PKP electrification programme was technically and economically unsound. Among the arguments raised were the operational difficulties due to the highly branched and interconnected PKP network, the cost of building and operating the new system, the cost of rolling stock and, above all, a potential delay in the electrification of the railway lines, which had begun with the 3 kV DC system. For extensive accounts of the decisions on the possible introduction of a 25 kV 50 Hz system in Poland in the 1950s and 1960s, see [4, 5].

In the first decade of the 21st century, the idea of introducing a 25 kV AC power system in Poland was revisited, though this time in the 2 × 25 kV AC variant. This was driven by plans to build a high-speed railway, the so-called Y line, linking Warsaw, Łódź and Poznań and branching off to Wrocław, and by plans to electrify a part of the E75 line with a connection to Lithuania. In 2005, work began at the Railway Research Institute (Science and Technology Railway Centre, CNTK, at the time) on a preliminary feasibility study for the Y line. In the following years, the first standards and requirements were developed, based in part on the experience of other railways operating the AC system. A further stimulus for work on the introduction of the 2 × 25 kV AC system in Poland is the Solidarity Transport Hub (CPK) Railway Programme. Study and design work is underway, including with regard to adjusting the power supply system and overhead contact line and its components to the 25 kV AC system.

2. Characteristics of the 3 kV DC and 2 × 25 kV AC Electric Traction Power Supply Systems

2.1. 3 kV DC electric traction power supply system

In this system (Figure 1), the overhead contact lines are mostly double-end-fed from traction substations, with distances between them ranging from approximately 10 to 30 km. Sectioning locations are used on double- and multiple-track lines, particularly when the distance between substations exceeds 12–15 km. Sectioning locations enable better electrical sectioning of the overhead contact line along the supply section and a reduction in voltage drops.

It is estimated that the capacity of traction substations in Poland ranges from 8 to over 23 MW (about 11 MW on average). The substations are powered by 15 or 20 kV medium voltage (MV) lines (with a few singular 30 kV lines) and 110 kV high voltage (HV) lines. The 3 kV DC system allows traction vehicles up to about 6 MW to be properly powered.

The relatively low voltage supplying traction vehicles in the 3 kV DC system results in high currents. The consequence of this is the need for overhead contact lines with a large cross-section and contact wires and catenaries with the best possible conductivity. The overhead contact lines used in Poland have

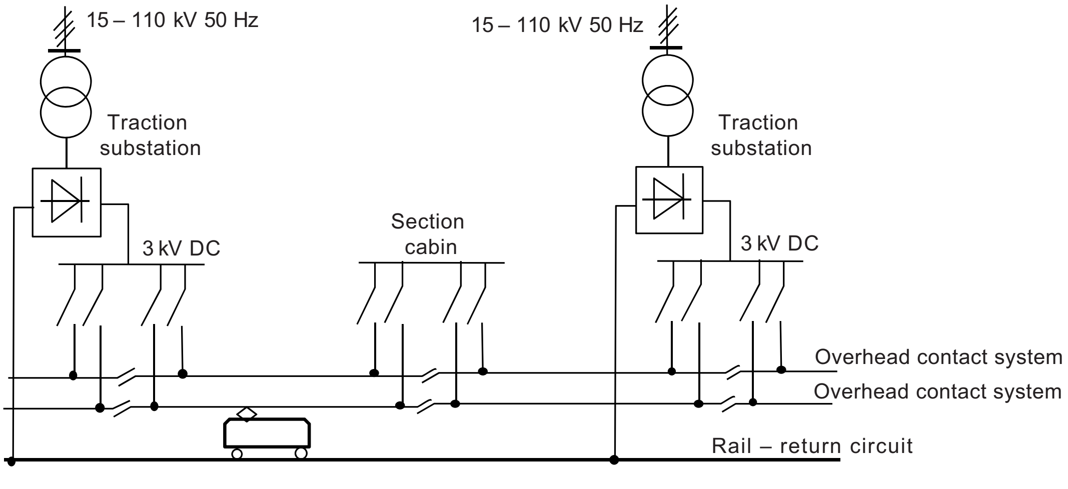

Fig. 1. Simplified schematic of a 3 kV DC electric traction power supply system [6]

a cross-section of 320 to 450 mm^2; those used elsewhere in Europe have cross-sections of as much as 610 mm^2. Figure 1 shows a simplified schematic of a 3 kV DC power system.

A traction substation, supplied with up to 30 kV and equipped with two rectifiers, occupies an area of about 1,700 m^2. When the substation is supplied with 110 kV, the area occupied increases to approximately 4,000 m^2. Sectioning locations, depending on the design (container or building), occupy an area of up to 100 m^2. Calculating the land occupation for power supply facilities per 1 km of railway line, the result ranges from 75 m^2 (for substations supplied with MV, located every 24 km, and with sectioning locations) to 330 m^2 (for substations supplied with 110 kV, set up every 12 km).

2.2. 2 × 25 kV AC electric traction power supply system

The 25 kV 50 (60) Hz AC system, including the 2 × 25 kV AC variant, is used in many countries in Europe and worldwide. In some of these countries, it is used on the entire electrified railway network; in others, it is operated on high-speed lines, with conventional lines powered by DC systems. Vehicles powered by the 25 kV AC system can reach up to about 20 MW. Figure 2 shows a simplified diagram of the 2 × 25 kV AC system and its operating principle.

A characteristic feature of this system is transformers installed in traction substations and featuring two 25 kV secondary windings each. The common centre terminal of these windings is earthed and connected to the buses and the return line. The output terminal of one of the windings is connected to the mains and that of the other winding is connected to the secondary feeder wire. Another distinguishing feature of this system is the autotransformers installed between substations approximately 10–15 km apart. These are connected between the mains and the secondary feeder wire. The advantage of this solution is that the voltage between the overhead line and the contact rails is 25 kV and the power transmission from the substations to the autotransformers is up to 50 kV. This results in smaller voltage drops in the power system, enabling greater distances between traction substations. The average distance between substations ranges from 20 to 70 km. An additional advantage of this system is that the return current flow through the rails is significantly reduced. Between the autotransformer closest to the train on the substation side and the substation itself, the return current flow through the rails is reduced virtually to zero.

At least two 10 to 60 MVA transformers are installed in each traction substation of the 25 kV 50 Hz system. The power supply of such substations requires a minimum voltage of 110 kV, while the basic voltage should be 220 or 400 kV.

The overhead power supply in a 2 × 25 kV 50 Hz system is two-phase, and as such, an asymmetry is introduced into the electricity system when the substation is supplied from a three-phase system, which should not exceed 1%. With single-phase transformers, this requirement can be met if the electricity system's short-circuit power is at least 100 times that of the transformer. One solution to reduce asymmetry is to use Vv or Yd transformers in substations. These transformers introduce half the asymmetry of

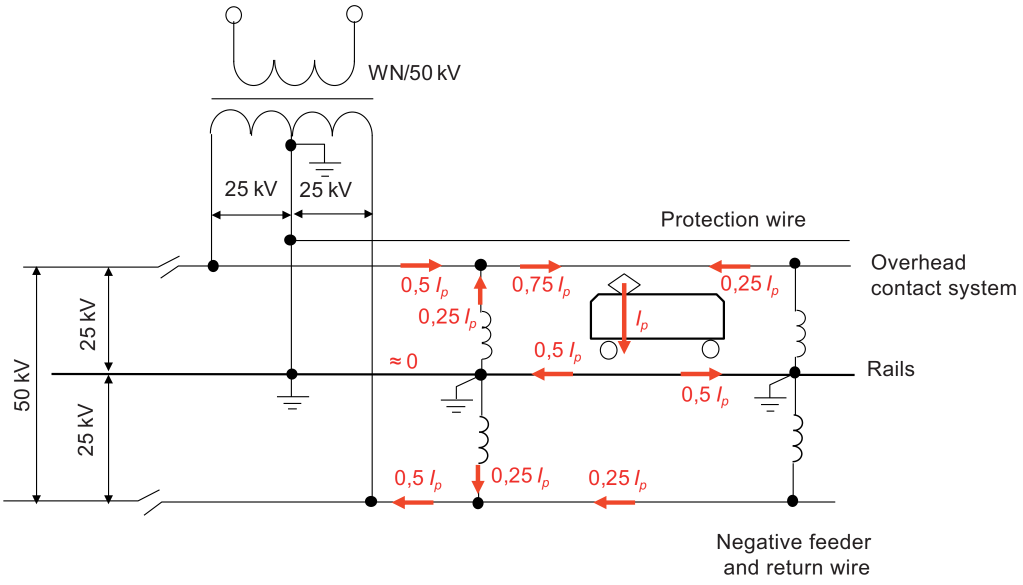

Fig. 2. Simplified schematic and operating principle of a 2 × 25 kV 50 Hz electric traction power supply system [own elaboration]

single-phase transformers, but their design is more complex and the voltage between the mains and the auxiliary supply is lower at 43.3 kV. Another solution is Scott, Le Blanc, Woodbridge and Roof-Delta transformers, which introduce an asymmetry close to zero; however, their highly complex design makes them exceedingly rare. Moreover, such transformers result in the transmission of energy from substations to autotransformers at around 35.4 kV rather than 50 kV. This is why the use of mainly single-phase transformers is envisaged in Poland, as stipulated in the Solidarity Transport Hub Standards [7].

Limiting the asymmetry introduced by the power system into the electricity system is achieved, among other things, by feeding successive transformers from different phases. This causes the overhead line voltages on successive sections to be phase-shifted with respect to each other. Not only does this prevent double-end feeding of the overhead power line and parallel operation of substations, but the individual overhead line sections must also be separated by phase separation sections. Another solution to minimise asymmetry, especially when powering substations from an electricity system with insufficient short-circuit power, is to use converters that change voltage from three-phase to single-phase. An example of such a solution is the Siemens Sitras SFC Plus. An additional advantage of using converters is that the overhead line can be double-end-fed and phase separation sections are dispensed with. A prerequisite for this solution is synchronising the converters feeding neighbouring substations.

3. Overhead Contact Line in 3 kV DC and 2 × 25 kV AC Systems

In the 25 kV AC system, the currents drawn by the trains are more than eight times lower than in the 3 kV DC system for the same traction vehicle power. Further, in the 2 × 25 kV AC system, the current flowing through the contact line from the traction substation to the autotransformer downstream of the train is approximately half that of the train (see Fig. 2). This enables a significant reduction in the overhead contact line cross-section compared to a 3 kV DC system. The cross-section of contact and messenger wires in the 2 × 25 kV AC system is mostly determined by the mechanical strength of these components. In the AC system, doping copper with other metals, mainly magnesium and tin, to improve the mechanical performance of contact wires and overhead line wires, is also possible at the expense of degrading the electrical performance.

Since the mass of the overhead contact lines in the 2 × 25 kV AC system is lower than in the 3 kV DC system, it would follow that the overhead contact line support structures in the AC system could have a lower mechanical strength than in the DC system. Yet, this assertion is only valid for 1 × 25 kV AC system lines and speeds up to 250 km/h, for which the contact and messenger wire tension forces in both systems are comparable.

Apart from contact and messenger wires, additional power supplies and protective aluminium wire are often installed on 2 × 25 kV AC system support structures. Figure 3 illustrates the differences in overhead line design between the 2 × 25 kV AC and 3 kV DC systems.

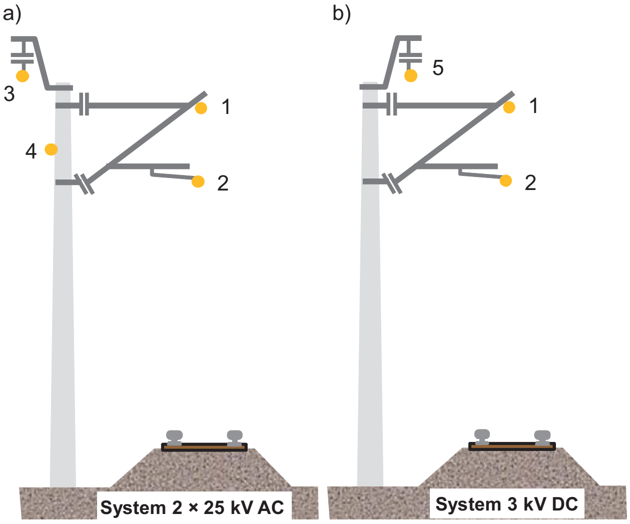

Fig. 3. Example of arrangement of the overhead contact line elements on a pole [8]: (a) 2 × 25 kV system; (b) 3 kV DC system; 1 – messenger wire, 2 – contact wire, 3 – feeder, 4 – protection wire, 5 – group protection wire

Designed for speeds exceeding 250 km/h, contact lines in the 2 × 25 kV AC system utilise one contact and one messenger wire. Made of Cu, CuAg0.1, CuMg0.2 and CuMg0.5, the contact wires have cross-sections of 120 and 150 mm^2. The contact wire tension ranges from 15 to 31.5 kN. The messenger wires are made of copper or BzII alloy and have cross-sections of 65 to 120 mm^2. Their tension is 14–16.25 kN.

For comparison, contact lines in a 3 kV DC system with a top operating speed of 250 km/h comprise two contact wires and two messenger wires. Their parameters are as follows:

- 2C120-2C-3 line [9]:
  - contact wires: 2 × 100 mm^2; Cu or CuAg0.1; total tensile force: 21.18 kN,
  - messenger wires: 2 × Cu 120 mm^2; total tensile force: 31.76 kN;
- “Direttissima” line [10, 11]:
  - contact wires: 2 × Cu150 mm^2; total tensile force: 30 kN,

  - messenger wires: 2 × CuCd 160 mm², total tensile force: 30 kN;
- FR 5AV line [10]:
  - contact wires: 2 × Cu150 mm², total tensile force: 37.5 kN,
  - messenger wires: 2 × Cu 120 mm², total tensile force: 30 kN.

The unit weights of the overhead contact line were calculated based on the data in [9–15]. The calculations were carried out as part of [1], the results of which were published in [2]. For a summary of the calculations, see Table 1.

Analysing the data in Table 1, it is evident that the total weight of the elements suspended on the support structures is similar in both systems despite the smaller contact wire cross-sections in the 25 kV AC system lines. Further, the tension forces of contact and messenger wires must be considered when determining the mechanical strength of the support structures.

4. Comparing the Basic Parameters of 3 kV DC and 2 × 25 kV AC Power Systems

Table 2 summarises the basic parameters and requirements of 3 kV DC and 2 × 25 kV AC electric traction power supply systems [1, 4].

Table 1

Summary of parameters of exemplary overhead contact lines [4, 8]

Overhead line	Summarised cross-section [mm²]	Total overhead line mass [kg/m]	Power supply system	Maximum train speed [km/h]
2C120-2C-3	440 Cu	3.90	3 kV DC	250
FR5AV	540 Cu	4.79	3 kV DC	250
Direttissima	620 Cu	5.55	3 kV DC	250
FR25AV	270 Cu + 450 Al	4.22	2 × 25 kV AC	300
TGV	185 Cu + 576 Al	3.96	25 kV AC	260/300
Madrid-Sevilla line	195 Cu + 480 Al	3.61	2 × 25 kV AC	200/300

Table 2

Parameters and requirements for 3 kV DC and 2 × 25 kV AC power supply systems [1, 4]

Parameter/requirement	3 kV DC	2 × 25 kV AC
Power supply	double-end	single-end
Substation rated output voltage	3.3 kV AC	from 39.9 to 55 kV[2]
Distance between substations	10–25 km	20–70 km
Sectioning locations	Supportively, approximately in the middle of the supply section and otherwise as required based on the line layout	Required every 10–15 km
Substation rated power	8–23 MW; 11.22 MW on average	20–120 MVA
Autotransformer rated power	–	10–15 MVA
Supply voltage	15–110 kV	(110), 220, 400 kV
Asymmetry	none	Depending on the transformer type
Area occupied by power facilities	75–330 m²/km of line	>180 m²/km of line
Vehicle rated power	6 MW	20 MW
Overhead contact line weight	up to 5.55 kg/m	up to 4.22 kg/m
Tensile force: **contact wire** **messenger wire**	 up to 18.75 kN up to 15.88 kN	 up to 31.50 kN up to 16.25 kN

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[2] According to STH Standards [7], single-phase transformers with a rated output voltage of 55 kV 50 Hz are expected to be used in Poland.

Although the distances between substations can be much greater in the 2 × 25 kV AC system than in the 3 kV DC system, they remain roughly similar due to the need for autotransformers between power supply facilities. It should also be noted that AC system substations require a higher voltage supply, and only in exceptional cases is it acceptable to supply them with 110 kV.

5. Impact of the Power Supply System on Timetable Compliance

According to the Energy TSI [16, 17] and EN 50388-1 [18] referenced therein, the electric traction power supply system, regardless of its design, should offer the performance required to meet the planned train timetable. The objective of the electric traction power supply system is to provide each train set with sufficient power to meet the timetable at a reasonable cost. The ability of trains to achieve their intended operating parameters, including running speed and acceleration, depends on the ability to draw the required amount of electricity from the overhead contact line. Both acceleration and running speed have a fundamental impact on journey times, i.e. meeting the timetable.

The higher the speeds, weights and acceleration, the more energy the train draws from the power supply system. In the energy transmission system from the power supply system to the train, one of the most sensitive factors is the contact between the pantograph pads and the contact wires of the overhead contact line. The contact area is very small due to the circular shape of the contact wire and its wear and the condition and dimensions of the contact pads. The contact remains mobile while the train moves, with the contact force between the two components ranging from several to tens of newtons. This type of system is prone to arcing between the contact elements. The likelihood of this occurring is greater the higher the travel speeds and current draw.

The use of the 3 kV DC system, as well as studies on its use to power lines with running speeds above 200 km/h, carried out in Poland and other European countries like Italy, have shown that the maximum running speed of trains powered by this system is about 250 km/h due to the dynamic interaction of the pantograph with the overhead line and the quality of current draw. On the other hand, due to the high current flow through the contact wire/contact pad interface, the power consumed by one pantograph should not exceed about 7.5 MW (this corresponds to a vehicle of about 6 MW including the supply of non-traction loads).

This has been legally sanctioned by Section 7.1.1. of the Energy TSI [16, 17]: “New lines with speed greater than 250 km/h shall be supplied with one of the AC systems listed in point 4.2.3 (a) and (b).” This means Poland must use a 2 × 25 kV AC system on railway lines adapted for running speeds exceeding 250 km/h. For this reason, further comparison of systems will be limited to running speeds up to 250 km/h.

The electric traction power supply system, much like any electric system, suffers voltage drops. These are directly proportional to the resistance (impedance) of the circuit and the current flowing through it. While the cross-section of a single 3 kV DC system line is more than twice that of the 2 × 25 kV AC system, and in the AC system the voltage drops are influenced by the inductance of the line, the voltage drops in the overhead line of the AC system are lower. This is due to the current flowing through the line. The current drawn by the train in the 2 × 25 kV AC system is more than eight times lower than in the 3 kV DC system. Moreover, the energy transmitted from the traction substation to the autotransformer closest to the train is at 50 kV (see Fig. 2). Also, the voltage drops on the other power supply system components (traction substations, feeder lines, etc.) in the 2 × 25 kV AC system are lower than for the 3 kV DC system. A detailed comparison of these systems in this respect is presented in Chapter 5.

This results in the relative magnitude of voltage drops in the 2 × 25 kV AC system being considerably lower than in the 3 kV DC system. As such, the distances between AC system substations can be significantly greater compared to the DC system.

To avoid excessive voltage drops in the power system, EN 50388-1 [18] requires vehicles above 2 MW to be equipped with current (power) reduction systems in the event of a voltage drop in the overhead line. Figure 4 shows the extent of current (power) reduction.

The value of factor a in Figure 4 for the 3 kV DC and 25 kV AC systems is 0.9. The implication is that the train should reduce the current (power) drawn when the voltage at the pantograph is below 2700 V in the case of the 3 kV DC system or 22.5 kV in the case of the 25 kV AC system to limit the voltage drop in the overhead line.

Due to higher voltage drops in the 3 kV DC system than in the 2 × 25 kV AC system, there is a higher probability of the need to reduce the train current (power) in the DC system than in the AC system. This probability rises as the train’s power increases, which is related to its speed and weight. This is illustrated in Figure 5. The green rectangle in Figure 5 indicates the section of the line where it was necessary to limit the current drawn by the train (red run) due to low voltage at the pantograph (blue run). As a result, the train

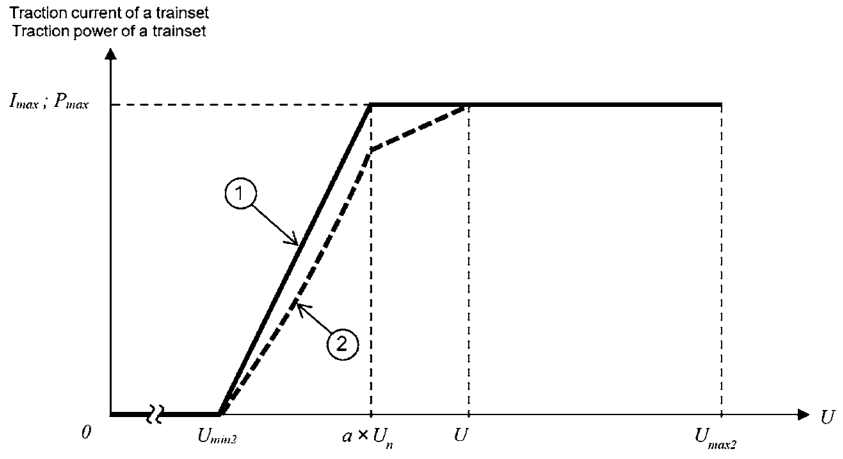

Fig. 4. Current (power) reduction of a traction vehicle [18], where: $U_{\min2}$, U_n; $U_{\max2}$ – per EN 50163:2004 [19]; $I_{\max}$ – maximum traction current drawn by the trainset at a nominal voltage (without auxiliary power); $P_{\max}$ – maximum power at the wheels; 1 – traction power limitation due to linear limitation of traction current below a × U; 2 – linear limitations in two stages of traction current below a × U_n

could not achieve the desired acceleration, resulting in a non-uniform increase in its speed (grey line) from zero to the maximum speed indicated by the yellow line. Further, a reduction in the train's current (power) affected its performance on another line section, causing the speed to drop below the scheduled speed value. As a consequence of the reduced current (power), the train was delayed.

To travel at a certain speed or achieve a certain acceleration, a train of a specific weight requires the same power, regardless of the power system used. While minimal differences in power demand may arise due to the efficiency of the traction vehicle in AC and DC systems, these are negligible. Therefore, it can be assumed that if the overhead contact line voltage does not drop below the rated voltage and the running speed is up to 250 km/h, the type of power supply system does not influence the braking and speed regardless of train parameters. This requires efficient power supply systems.

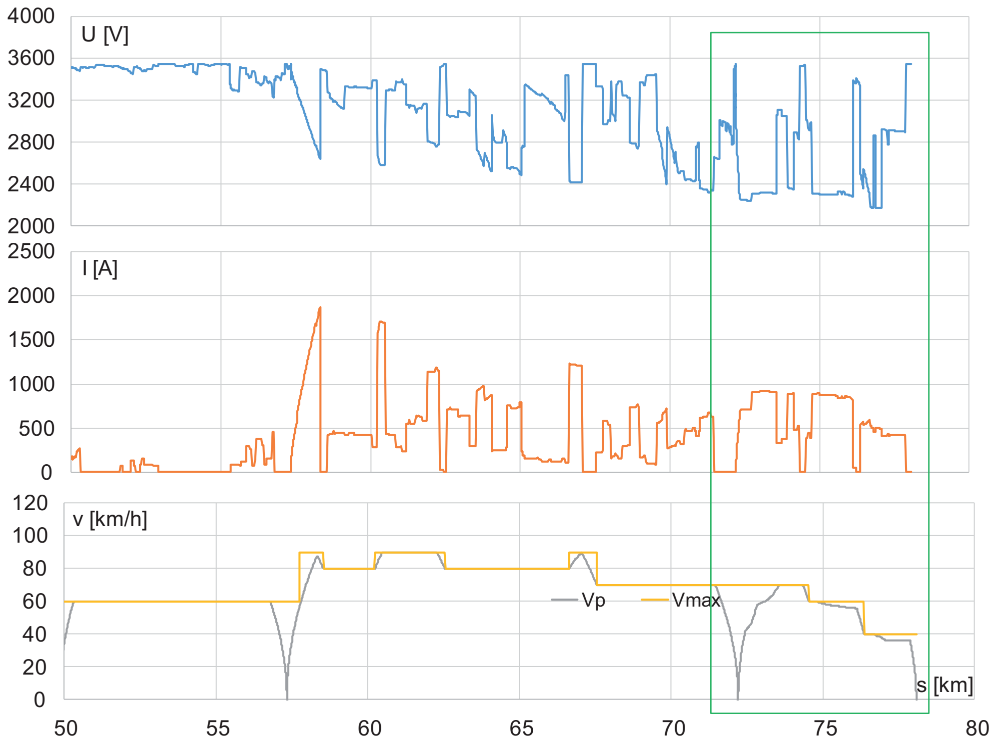

Fig. 5. Example of the influence of the voltage value in the overhead contact line on the necessity to reduce the train's current (power) and performance reduction [as described in the text]

In summary, the type of power supply affects train performance for speeds above 250 km/h, which is the limit for the 3 kV DC system, as the 3 kV DC system is more susceptible to voltage dips than the 2 × 25 kV AC system. This results in a greater likelihood of the need to reduce the current (power) of trains, particularly high-powered trains, i.e. in inter-regional freight and passenger traffic. A reduction in current (power) affects train acceleration, potentially preventing it from reaching maximum speed, effectively increasing journey times and compromising the ability to meet the planned timetable. If the power supply system provides the rated voltage on the overhead contact line, the voltage type does not affect the ability to meet the timetable (achievable speeds up to 250 km/h, accelerations, running time and maximum weights).

6. Energy Consumption and Losses of 3 kV DC and 2 × 25 kV AC Systems

The energy consumption and losses of the 3 kV DC and 2 × 25 kV AC systems were determined based on simulations [20] performed using the EN 50641-compliant Sidytrak software [21]. For both systems, simulations and analyses were performed for a hypothetical double-track line, the parameters of which were taken from EN 50641 [21]. Figure 6 shows the line profile and station location.

Six trains are running on the line:

- 4 HS trains with a top speed of 200 km/h,
- a freight train with a top speed of 100 km/h,
- a regional train – EMU with a top speed of 160 km/h.

The train parameters were taken from Section 6.3 of EN 50641 [21], which specifies train weights, rotating mass factor, traction characteristics, efficiency, auxiliary power, resistance to motion, maximum accelerations, etc.

The process of meeting the timetable defined based on EN 50641 [21] and shown in Figure 7 was reproduced during the simulation.

The assumptions, which are the same for both power supply systems, made it possible to compare energy consumption and losses when following the same timetable.

In the simulations for the 3 kV DC system, it was assumed that the line is powered from 9 traction substations located every 12.5 km from 0 to 100 km mark. The substations are equipped with two PD-17S units supplied at 15 kV, with 6.3 MVA transformers. Figure 8 shows the substation power supply system and the parameters of its components. In the 3 kV DC system, the contact line has a total cross-section of 450 mm^2.

In the 2 × 25 kV AC system, the substations are supplied from a 220 kV electricity system with a 5 GVA short-circuit power, using 30 km long AFL-8 lines with a 350 mm^2 cross-section. The overhead line is supplied from two substations with two transformers of 25 MVA and Uz = 10%. The autotransformers in the sectioning locations are 10 MVA and Uz = 1%.

Table 3 summarises the locations and powers of the power supply facility in the two compared systems. The applied power of the substations supplying the simulated line is similar in both systems: in the 3 kV DC system, it is 0.98 MW higher than in the 2 × 25 kV AC system.

The overhead contact line cross-section for the 2 × 225 kV AC system simulation was adopted from EN 50641 [21] with the following values:

- contact wire – 120 mm^2 Cu,
- messenger wire – 70 mm^2 BzII,
- negative feeder – 288 mm^2 Al.

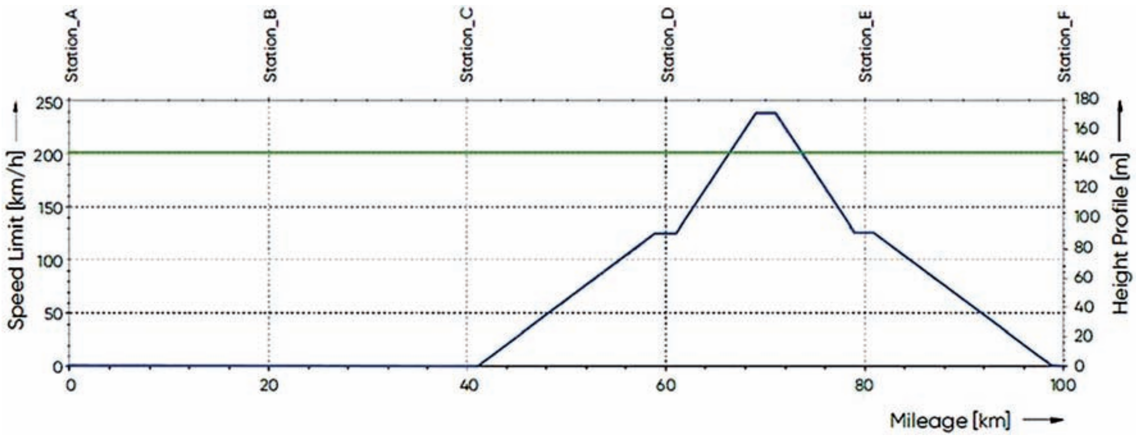

Fig. 6. Height profile of the line and speed limit [1, 2, 20, 21]

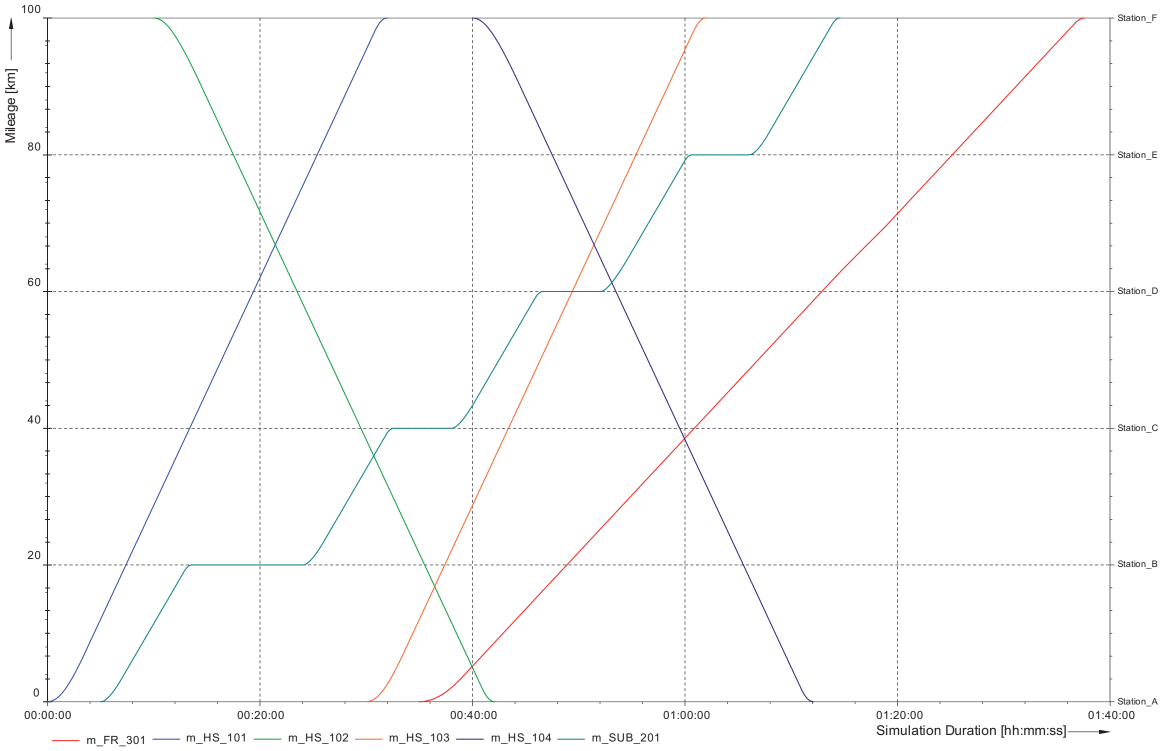

Fig. 7. Timetable adopted for the simulation [1, 2, 20, 21]

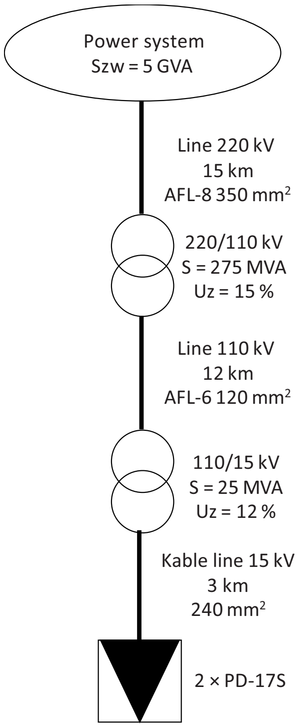

Fig. 8. Simplified scheme of the substation power supply in the 3 kV DC system [1, 2, 20]

The simulation shows that, with the assumed timetable, the total energy consumption of the trains is the same for both power supply systems, amounting to 14 697 kWh in 1 hour and 40 minutes (6000 s). This is confirmed by the conclusions in Chapter 5. In the simulations for both systems, the voltage at the trains' pantographs did not fall below $0.9U_n$, so there was no need to reduce the trains' current (power).

The energy losses in the power systems were as follows:

- 1464 kWh in the 3 kV DC system,
- 363.4 kWh in the 2 × 25 kV AC system.

Losses represent 9.97% in the case of the 3 kV DC system and 2.47% for the 2 × 25 kV AC system, respectively, in relation to the energy consumed by the trains. Table 4 summarises the value of losses on the various components of the power systems and their relative magnitude against the total losses. This data is also presented graphically in Figures 9 and 10.

Analysing the simulation results obtained, the following conclusions can be drawn:

1. The losses in the 2 × 25 kV AC power system are more than four times lower than in the 3 kV DC system.
2. Compared to the 220 kV electricity system and lines, the energy losses in the 3 kV DC system are more than seven times lower. This is because the 220 kV lines are assumed to be half as long as in the 2 × 25 kV AC system and because the traction substations are connected to the electricity system

Table 3

Location and power of power supply facilities in the 2 × 25 kV AC and 3 kV DC system [21]

Location in [km]	2 × 25 kV AC		3 kV DC	
	Substation/sectioning cabin	Installed power [MVA]	Substation	Installed power [MV]
0.0	AT01	10	PT1	11.22
12.5	AT02	10	PT2	11.22
25.0	PT1	2 × 25	PT3	11.22
37.5	AT03	10	PT4	11.22
50.0	AT SP (centre sectioning cabin with phase separation)	2 × 10	PT5	11.22
62.5	AT04	10	PT6	11.22
75.0	PT2	2 × 25	PT7	11.22
87.5	AT05	10	PT8	11.22
100.0	AT06	10	PT9	11.22

Table 4

Traction power supply system losses in 3 kV DC and 2 × 25 kV AC systems [1, 2]

Traction power supply system component	3 kV DC		2 × 25 kV AC	
	Losses [kWh]	Relative losses [%]	Losses [kWh]	Relative losses [%]
220 kV electricity system and lines	1.06	0.07	7.89	2.17
220/110 kV transformers	0.72	0.05	–	–
110 kV lines	5.34	0.36	–	–
110/15 kV transformers	203.30	13.82	–	–
15 kV lines	27.16	1.86	–	–
Traction substations	415.40	28.37	149.50	41.14
Overhead contact line	812.00	55.47	206.00	56.69
In total	1463.98	100.00	363.39	100.00

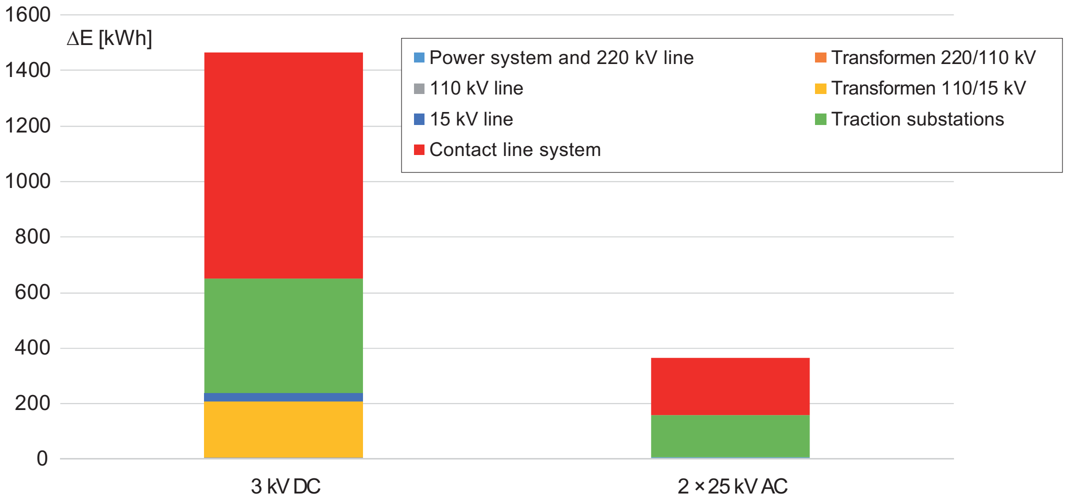

Fig. 9. Energy losses in 3 kV DC and 2 × 25 kV AC power systems [1, 2]

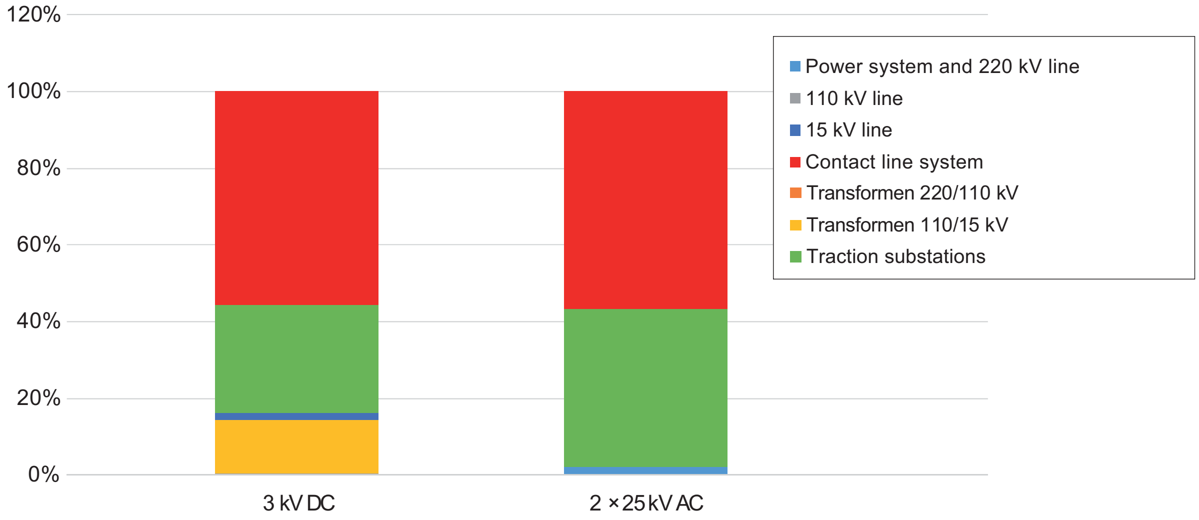

Fig. 10. Breakdown of energy losses by component in 3 kV DC and 2 × 25 kV AC power systems [1, 2]

at nine points in the 3 kV DC system but only at two points in the 2 × 25 kV AC system. As such, smaller currents flow to the individual substations, resulting in reduced voltage drops and energy losses.

3. In the case of the 3 kV DC system, energy losses in the electricity system/traction substation system arise mainly in transformers that reduce the voltage from 220 kV to 110 kV and then to 15 kV. In the 2 × 25 kV AC system, losses are only related to the transmission of energy (sometimes over long distances), as reducing the voltage supplied to the substation is not necessary. As such, energy losses in the 3 kV DC traction substation supply system are about thirty times higher than in the 2 × 25 kV AC system.
4. Despite the comparable total capacities of the traction substations in both supply systems, due to the higher currents present in the 3 kV DC system, energy losses in the DC system's traction substations are more than two and a half times higher than in the AC system.
5. While the cross-section of a single 3 kV DC system line is more than twice that of the 2 × 25 kV AC system, and in the AC system the voltage drops are influenced by the inductance of the line, the voltage drops in the overhead line of the AC system are lower. This is due to the fact that the current drawn by the train in the 2 × 25 kV AC system is more than eight times lower than in the 3 kV DC system and that in the 2 × 25 kV AC system the power transferred from the substation to the autotransformer closest to the train is at 50 kV. This results in overhead line energy losses in the 2 × 25 kV AC system being four times lower than in the 3 kV DC system, for the same train power.

7. Conclusions

Multi-system traction rolling stock is in widespread use and extensive infrastructure, including interface stations where power system changes would occur, is no longer necessary. Properly designed system separation sections, mainly installed outside railway junctions and large stations, are now sufficient. Thus, most of the technical reasons for the decision not to introduce the 25 kV 50 Hz system in Poland in the late 1950s and early 1960s have disappeared.

When comparing the 3 kV DC and 2 × 25 kV AC electric traction power supply systems, one should consider not only the number of and distance between traction substations and the design of the overhead contact line but also the entire substation power supply system. Notably, both systems feature sectioning locations, except that in the 3 kV DC system they improve the parameters of the power supply system, and in the AC system they are necessary because they house the autotransformers necessary for the system's operation. Consequently, the power supply facilities (traction substations and sectioning locations) are set up every 10–15 km in the case of both systems. Therefore, the area occupied by power facilities per 1 km of railway line is similar for both systems.

As the 2 × 25 kV AC system loads the individual phases of the electricity system unevenly, an undesirable asymmetry arises. To keep the level of asymmetry at an acceptable level, the short-circuit power of the electricity system should be much higher than that of the traction substation. In the case of single-phase transformers, which are preferred in Poland [7], the short-circuit power should be at least 100 times the power of the transformers. It follows that the voltage supplying the substations should be 220 and 400 kV.

Reducing the impact of the 2 × 25 kV AC system on the electricity system is possible by using three-phase to single-phase converters; however, this increases the cost of building and operating the power system.

In a 3 kV DC system, traction substations do not introduce voltage asymmetry in the supply lines, and avoiding the introduction of disturbances exceeding the permissible values into the electricity system is prevented by the use of 12-pulse rectifiers and adequate short-circuit power at the substation supply site.

In a 2 × 25 kV AC system, the overhead line support structures carry the weight of an auxiliary feeder and protective conductor in addition to the messenger and contact wires. Consequently, even though the cross-sections of the 2 × 25 kV AC contact lines are about two times smaller than those of the 3 kV DC system, the weight of the suspended cables and wires is comparable for both systems.

As the current drawn by the train is more than eight times lower in the 2 × 25 kV system and no voltage-reducing transformers are required in the traction substation supply system, energy losses are about four times lower than in the 3 kV DC system.

The quality of the contact wire/contact pad interface limits the running speed in the 3 kV DC system to about 250 km/h. In contrast, this factor has less impact on the train running speed in the 2 × 25 kV AC system, enabling much higher speeds. Further, the AC system has lower voltage drops in the traction power supply system. As a result, the likelihood of trains powered by this system having to reduce their current (power) consumption is lower than in the 3 kV DC system, which in turn has less of a limiting effect on train performance.

The type of power supply system does not affect train acceleration and maximum speeds (up to 250 km/h), effectively having no impact on journey times and the possibility of meeting the planned timetable, as long as the traction power supply system provides the rated voltage at the pantograph.

In conclusion, it is impossible to state unequivocally which of the compared overhead contact line supply systems is superior, provided that the running speed does not exceed 250 km/h. It must be stressed that when planning the introduction of a 2 × 25 kV AC system in Poland, the expansion of the high-voltage electricity system or using three-phase to single-phase converters should be considered. Poland has almost 12,000 km of electrified railway lines using the 3 kV DC system, powered by over 500 traction substations. Many of these facilities are either new or have been upgraded in recent years. For this reason, introducing a 2 × 25 kV AC system at this time would only be reasonable for new, separate lines or non-electrified lines over 100 km in length.

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