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An analysis of selected aspects of transmission capacity for replacement of overhead power lines with cable lines

***Abstract**. Construction of new power lines is a complicated and long-term formal and legal process. The duration of the investments is extended by trade arrangements, public consultations in order to delimit line corridor, time required to obtain necessary decisions, permits, analyses and opinions necessary to implement an enterprise. The main goal of this article was to present analyses of variants of possibility of rebuilding of a power network in the aspect of increasing transmission potential of existing 110 kV lines, taking technical and financial aspects into account.*

***Streszczenie.** Budowa nowych linii elektroenergetycznych to skomplikowany i długotrwały proces formalnoprawny. Czas realizacji inwestycji wydłużają prowadzone uzgodnienia branżowe, prowadzone konsultacje społeczne w celu wytyczenia korytarza linii, oczekiwania na pozyskanie koniecznych decyzji, pozwoleń, analiz i opinii niezbędnych do realizacji przedsięwzięcia.Głównym celem publikacji jest przeprowadzenie przedstawienie analiz wariantów możliwości przebudowy sieci elektroenergetycznej w aspekcie zwiększenia zdolności przesyłowych istniejącej linii 110 kV z uwzględnieniem zagadnień technicznych oraz finansowych. (**Analiza wybranych aspektów zdolności przesyłowej dla zastąpienia linii napowietrznej linią kablową**).*

Keywords: High Temperature Cables, Cable Rating, Adaptation works, AFL, ACSR, ACSS/TW.
Słowa kluczowe: Przewody wysokotemperaturowe, Obciążalność przewodu, Prace dostosowawcze, AFL, ACSR, ACSS/TW.

Introduction

Civilizational and economic development leads inevitably to concentrate smaller towns around big cities and to settle areas that are not densely populated. This tendency leads to formation of large population centres with one central city and smaller town surrounding such city and also blurring borders between them. This process is called agglomerization and, in Poland, has led to creation of three large agglomerations, that is, Katowice, Warsaw and Tricity. These agglomerations are characterized by high population and density and like any population require electricity supply. Large population and numerous service and production facilities make it necessary to construct complex supply network and get energy from sources distant from agglomeration [1]. For historical and technological reasons, most of energy is obtained from coal combustion, which makes it impossible to situate a plant in the vicinity of large cities (except for Silesian agglomeration). Transport of energy from producers to agglomeration is connected with construction and use of high-voltage overhead power lines and transformer and switching stations. Most of these power lines were built in the 1970s and their period of use both due to technical condition and insufficient transmission capacity is coming to an end [2, 17]. Therefore, there is necessity of both major renovations of these lines and construction of new connections supplying large cities [4]. Taking numerous procedural, legal and social barriers into account, construction of new lines is a long-term and costly process in comparison with repair and modernization of existing connections [5]. The issue of particular importance is the possibility of increasing transmission capacity of a line, obtained as an effect of additional modernization changes and possibility of modernization to increase transmission capacity using minimum financial outlays. In addition, with growing density of building development, as well as growing value of land in an agglomeration, replacement of overhead power lines with cable lines as a part of modernization and repair works is becoming increasingly important.

The wires of high-voltage overhead power lines

Transmission of electricity using high values of currents results in noticeable impact of phenomenon of skin effect, which was broadly described in literature [6,7] can be briefly described as tendencies to carry energy not through the whole section of a wire, but through their external parts. It can be concluded that the most effective shape of a wire is a pipe empty inside with appropriate section area. Because of mechanical strength and economic costs, it is not possible. Overhead power wires must not only have appropriate electrical properties, but also be resistant to mechanical loads from its own weight, wind and ice forming a deposit. Because strength of pure aluminium is too low to meet these requirements, aluminium wires with a core made of materials more mechanically resistant have been brought into general use. Such wires are the oldest and the most common structure of overhead power wires for high-voltage lines. AFL-8-525 was analysed in details as the most typical one in the Public Power System. It is made of 54 aluminium wires with a diameter of 3 mm, every in three layers. Every layer is turned in a different direction, whereas, direction of turning of the last layer must always be to the right – which is a requirement dictated by structure of equipment and has become a requirement of a system operator. Centre of a wire consists of six steel wires turned to the left and one central simple steel wire. Steel wires are greased before winding aluminium wires to make free movement of aluminium layer on steel core along with temperature lengthening of materials possible. Figure 1 presents a view and schematic section of AFL.

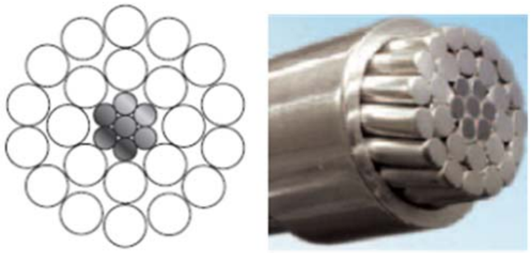

Fig.1. Wire AFL-8-525 [9]

Such wires are characterized by good electric properties, simple structure and affordable price. Disadvantage of AFLs is relatively low permissible working temperature, which, especially in summer months, limits transmission capacity of a high-voltage line. Detailed parameters of basic data of

AFL-8-525 and AFLs-10-525 were published in the articles [8, 9].

Due to the fact that energy is transmitted mainly in aluminium layer, it is possible to extend cross-section of this layer by better use of available space, that is, by replacing two external layers of aluminium wires with segment wires. Such wire, with the same outside dimensions, has higher cross-section and also higher transmission capacity. Figure 2 presents a view and schematic section of AFLs. Basic data of AFLs-10-525 in [9]. It must be emphasized that occurrence of AFLs is limited to segments after emergency repairs and modernizations, and actual state of most of the wires is different than the one on the photographs. As a result of flow of time, atmospheric factors and mechanical loads, layers of aluminium are covered with oxides and surfaces of the wires are considerably damaged.

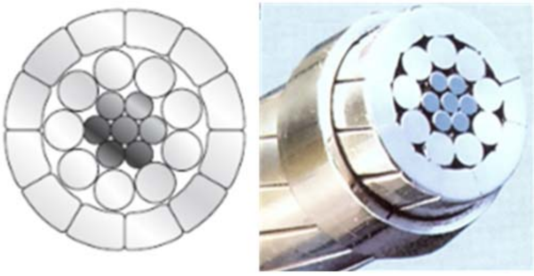

Fig.2. Wire AFLs-10-525 [9]

Due to limitations resulting from maximum permissible working temperature of a wire, the wires of increased heat stability such as ACSS/TW and ACCC can be used. ACSSs are aluminium wires made of fully annealed aluminium with a steel core of increased mechanical and thermal resistance [16]. Their maximum working temperature is 250°C. These wires have reduced values of the sags in comparison with AFLs with the same stress caused by pressure of wind and icing. As a model wire of such type, ACSS/TW Curlew and ACSS Curlew with section corresponding to AFL-8-525 were selected. Figure 3 shows a view and schematic section of ACSS. ACCCs are made of layer of aluminium trapezoidal wires for transmission of electricity and of composite core made of carbon and glass fibre. Composite core is more resistant than steel core and has also slight coefficient of thermal expansion. This last property causes that these wires have very low sag in comparison with traditional solutions and additional applications of composite core causes that with identical outside dimensions and similar mass, ACCCs have between 20% and 30% higher surface conducting electric current. Figure 4 presents a view and schematic section of ACCC.

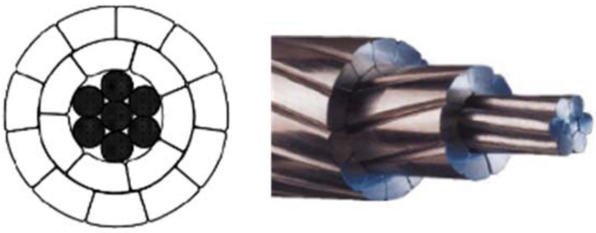

Fig.3. Wire ACSS/TW [10]

An issue of basic importance for efficiency of transmission of energy using high-voltage lines is capacity of the wires in the function of their temperature. In winter, in Poland, temperatures reach between -30°C and +5°C, which makes easier to remove heat from a wire. In the summer, air temperature reaches +30°C and along with sun exposure considerably reduces potential of heat removal from a wire. In order to compare capacity that is possible to achieve, the values of permissible currents for various working temperatures of wires and their types were presented in [8, 11]. Capacity of overhead power wires of AFL, ACSS and ACCC for various working temperatures was presented in [8].

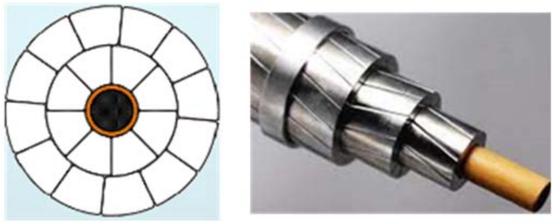

Fig.4. Wire ACCC [10]

High-voltage power cables

High-voltage cables of paper and oil or polymer insulation can be used in power lines. In the event of voltage of 220 kV, they are single-phase cables to be arranged in flat or rarely triangular system.

Due to technological progress, only the possibility of application of the cables with polymer insulation of transmission capacity identical or higher than applied overhead power wires was considered.

In the discussed variant, XRUHKXS 1x1400 mm^2 cable and HXCHBMK 1x1400 mm^2 cable were compared, both with voltage of 127/230 kV. These cables have working conductors made of copper with nominal diameter of 1400 mm^2 and insulation made of cross-linked polyethylene. Technical data of both cables were presented in [3] and [8]. The cables have certificates of conformity with tests contained in IEC 62067 and were approved for use in the lines with voltage of 220 kV with the highest permissible working voltage of 245 kV, which meets the requirements of PSE Operator. HXCHBMK cable was presented on Figure 5, and XRUHKXS cable on Figure 6.

Fig.5. Cable HXCHBMK 1x1400 mm^2 [19]

As an additional feature of XRUHKXS cable, applied airbag technology securing cable against accidental crushing or excavating must be considered. Detailed data about this technology can be found in producer's magazine [3].

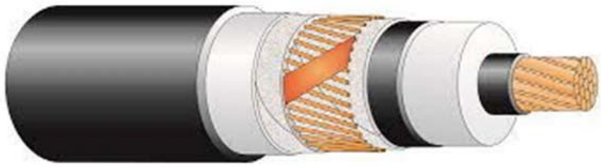

Fig.6. Cable XRUHKXS 1 x 1400 mm^2 [8]

Technical and topographical data of the lines

Transmission line analysed in this article has the following parameters:

- Line is a double-circuit one leading to various types of poles of rated voltage of 220 kV,

– Line runs from station „KK" to station „MM",
– In one track of a line, there is departure to „PP" transformer station,
– Total length of a line is 93,2 km,
– On this length, line is made of ACCC/TW 460 mm^2 Stockholm,
– The second track of a line is divided into segments:
  - „KK" – Pole no. 91 AFL-8 -525 mm^2,
  - Pole no. 91 – Pole no. 37a AFL-8-400 mm^2,
  - Pole no. 37a – „PP" AFL-8-525 mm^2 13 km long,
  - „PP" – Pole no. 37a AFL-8-525 mm^2 13 km long,
  - Pole no. 37a – „MM" AFL-8-525 mm^2.
– Porcelain long rod insulators were used in a line, and in fragment to „PP" station cap glass insulators in accordance with general rules of application of chains of the insulators on contiguous zones and intersections with other objects and on the route of a line.

For safety reasons, it was impossible to obtain other data such as current-carrying capacity or maximum values of current and voltage in a line. However, it is believed that this line was designed to work at a maximum temperature of a wire of 60°C [18]. To fully understand existing potential of increasing transmission capacity, it was assumed that this line is completely worn out and it requires total modernization. In the next chapter, solutions leading to reconstruction of 2 x 220 kV line are presented. The first assumption is application of tubular poles and overhead power wires, the second one is replacement of existing overhead power line with cable line. For both solutions, losses were calculated and costs of rebuilding and potential benefits resulting from changes in exclusions of land etc. were estimated. It was assumed that equipment of the lines was scrapped, which covered the costs of disassembly of an old line.

Calculations of transmission capacity of 220 kV overhead power line

For calculations of transmission capacity and elements of equivalent circuit of overhead power line formulas presented in an article [12, 20] were used, which allow to determine the parameters of equivalent circuit of π type based on knowledge of geometry of the wires and their arrangement in space. Resistivity of the wires was determined using catalogue data. The following calculations were made:
– Resistance of the lines,
– Reactance of the lines,
– Susceptance of the lines,
– Critical phase voltage of the lines,
– Conductance of the lines - if there is necessity to consider it,
– Natural power of the lines,
– Active and reactive losses of the lines.

Figure 7 presents equivalent circuit of π type for transmission line [20].

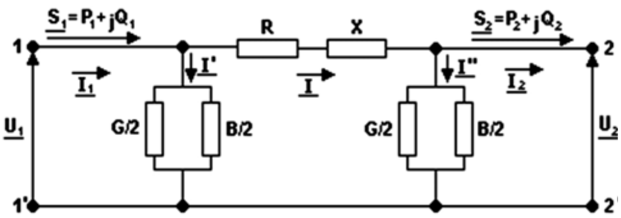

Fig.7. Equivalent circuit of π type for power line

For calculating purposes, the state of a line under normal conditions was assumed, that is, temperature of 20°C and atmospheric pressure of 1013 hPa. While analysing of possibility of occurrence of phenomenon of corona discharge, the worst possible case was assumed, that is, rainy weather (m_a = 0,8) and bad condition of surface of the wires (m_p = 0,87 or 0,83). Such solution guarantees reflection of the worst situation from the point of view of electrical losses. In accordance with theory contained in literature [12, 15], conductance for overhead power lines is necessary with occurrence of phenomenon of corona discharge. This phenomenon depends on structure of a line, weather and working voltage. In the event that working voltage does not exceed critical voltage, it is assumed that corona discharge will not occur, therefore calculation of conductance is pointless. In the calculations lines with wires, the author assumed pole structures of R220P type of segments of the wires b_1 = 580 [cm], b_2 = 580 [cm] and b_3 = 1160 [cm]. Rated voltage of 220 kV line and line works with $U_1 = U_2$ =220 [kV] and with load angle δ =18,2 [°].

<u>Calculations for a line of K-M relation l = 93,2 [km] long with AFL-8-525 mm²</u>

Unit resistance of a line:

$$R' = 0{,}0564 \ [\Omega/\text{km}]$$

Resistance of the lines:

$$R_l = R' \cdot l = 0{,}0564 \cdot 93{,}2 = 5{,}256 \ [\Omega]$$

Diameter of distance of the wires:

$$b_{śr} = \sqrt[3]{b_1 \cdot b_2 \cdot b_3} = \sqrt[3]{580 \cdot 580 \cdot 1160} = 730{,}75 \ [\text{cm}]$$

Diameter of a wire d = 3,15 cm from a table for AFL-8-525:

Unit inductance of a wire: $r = \frac{d}{2} = \frac{3{,}15}{2} = 1{,}575 \ [\text{cm}]$

$$L' = 4{,}6 \cdot \log\left(\frac{b_{śr}}{0{,}7788 \cdot r}\right) \cdot 10^{-4}$$

$$L' = 4{,}6 \cdot \log\left(\frac{730{,}75}{1{,}226}\right) \cdot 10^{-4}$$

$$L' = 4{,}6 \cdot \log(596{,}04) \cdot 10^{-4}$$

$$L' = 4{,}6 \cdot 2{,}775 \cdot 10^{-4} = 1{,}27 \cdot 10^{-3} \ [\text{H/km}]$$

Unit reactance

$$X' = 2 \cdot \pi \cdot 50 \cdot L' = 100 \cdot \pi \cdot 1{,}27 \cdot 10^{-3} = 0{,}401 \ [\Omega/\text{km}]$$

Reactance and impedance of the lines

$$X_l = X' \cdot l = 0{,}401 \cdot 93{,}2 = 37{,}373 \ [\Omega]$$

$$\underline{Z_l} = R_l + jX_l = (5{,}256 + j37{,}373) \ [\Omega]$$

Capacity and unit susceptance

$$C' = \frac{0{,}02415}{\log\frac{b_{śr}}{r}} \cdot 10^{-6} = \frac{0{,}02415}{\log\left(\frac{730{,}75}{1{,}575}\right)} \cdot 10^{-6}$$

$$C' = \frac{0{,}02415}{2{,}666} \cdot 10^{-6} = 9{,}058 \cdot 10^{-9} \ [\text{F/km}]$$

$$B' = 2 \cdot \pi \cdot 50 \cdot 9{,}085 \cdot 10^{-8} = 2{,}846 \cdot 10^{-6} \ [\text{S/km}]$$

Susceptance of the lines

$$B_l = B' \cdot l = 2{,}843 \cdot 10^{-6} \cdot 93{,}2 = 2{,}652 \cdot 10^{-4} \ [\text{S}]$$

Possibility of occurrence of corona discharge was calculated.

$$U_{fkr} = 48{,}9 \cdot m_a \cdot m_p \cdot \delta_a \cdot r \cdot \log\frac{b_{śr}}{r}$$

where:
r - radius of a wire, m_a - coefficient dependent on atmospheric conditions, m_p - coefficient dependent on

condition of a wire surface, δ - air density, which is a pressure function $\mathbf{p_a}$ [hPa] and temperature **t** [^{o}C].
Assumptions:

p_a - pressure 1013 [hPa],
t - temperature 20 [^{o}C],
m_a = 0,8 - for rain water,
m_p =0,87 - for a link wire.

Calculations:

$$\delta_a = \frac{0{,}302 \cdot p_a}{273+t} = \frac{0{,}302 \cdot 1013}{293} = 1{,}044$$

$$U_{fkr} = 48{,}9 \cdot 0{,}8 \cdot 0{,}87 \cdot 1{,}044 \cdot 1{,}575 \cdot \log\left(\frac{730{,}75}{1{,}575}\right) =$$

$$= 55{,}96 \cdot 2{,}666 = 149{,}21\ [kV]$$

$$U_{kr} = U_{fkr} \cdot \sqrt{3} = 149{,}21 \cdot \sqrt{3} = 258{,}45\ [kV]$$

$$U_n = 220\ [kV] \quad U_{KR} = 258{,}45\ [kV]$$

$$U_n < U_{kr}$$

It was concluded that there will not be a phenomenon of corona discharge, which gives a basis for abandoning calculations of corona discharge losses and conductance of a line. Therefore:

$$R_l = 5{,}256\ [\Omega] \quad G_l = 0\ [S] \quad \Delta P_U = 0\ [MW]$$

$$X_l = 37{,}373\ [\Omega] \quad B_l = 2{,}652 \cdot 10^{-4}\ [S]$$

$$\underline{Z}_l = (5{,}256 + j37{,}373)\ [\Omega] \quad \underline{Y}_l = (0 + j2{,}652) \cdot 10^{-4}\ [S]$$

To calculate the value of transmitted power P_1, P_2, Q_1, Q_2 and power losses ΔP and ΔQ formulas were used [12, 20], typical of modelling of the lines with a four-pole of π: type

(1) $$P_1 = Y_1 \cdot U_1 \cdot U_2 \cdot \sin\delta - Y_2 \cdot U_1 \cdot U_2 \cdot \cos\delta + Y_3 \cdot U_1^2$$

(2) $$Q_1 = -Y_2 \cdot U_1 \cdot U_2 \cdot \sin\delta - Y_1 \cdot U_1 \cdot U_2 \cdot \cos\delta + Y_4 \cdot U_1^2$$

(3) $$P_2 = Y_1 \cdot U_1 \cdot U_2 \cdot \sin\delta + Y_2 \cdot U_1 \cdot U_2 \cdot \cos\delta - Y_3 \cdot U_2^2$$

(4) $$Q_2 = -Y_2 \cdot U_1 \cdot U_2 \cdot \sin\delta + Y_1 \cdot U_1 \cdot U_2 \cdot \cos\delta - Y_4 \cdot U_2^2$$

(5) $$\Delta P = P_1 - P_2$$

(6) $$\Delta Q = Q_1 - Q_2$$

These calculations require calculating the values Y_1, Y_2, Y_3, Y_4 which was made using the following relationships:

(7) $$Y_1 = \frac{X_l}{R_l^2 + X_l^2}$$

(8) $$Y_2 = \frac{R_l}{R_l^2 + X_l^2}$$

(9) $$Y_3 = \frac{R_l}{R_l^2 + X_l^2}$$

(10) $$Y_1 = \frac{X_l}{R_l^2 + X_l^2} - \frac{B_l}{2}$$

MATLAB was used for calculations. This package has implemented both complex numbers, matrixes and permissible actions [13, 14]. Model listing of software in MATLAB was presented below.

```
%Wire AFL-8 525 for T=60C Relation K-M
format long;
%Setting the current voltage and line impedance
U1=220;          %[kV]
U2=220;          %[kV]
Rl=5.256;        %[Ohm]
Xl=37.373;       %[Ohm]
Bl=2.652e-4;     %[S]
d=18.2;          %[deg]
% Admittance calculation
Y1=Xl/(Rl^2+Xl^2)
Y2=Rl/(Rl^2+Xl^2)
Y3=Rl/(Rl^2+Xl^2)
Y4=Xl/((Rl^2+Xl^2)-Bl/2)
format short;
% Calculation of active power
P1=(Y1*U1*U2*sind(d))-(Y2*U1*U2*cosd(d))+(Y3*U1^2)   %[MW]
P2=(Y1*U1*U2*sind(d))+(Y2*U1*U2*cosd(d))-(Y3*U2^2)   %[MW]
% Reactive power calculation
Q1=(-Y2*U1*U2*sind(d))-(Y1*U1*U2*cosd(d))+(Y4*U1^2) %[MVar]
Q2=(-Y2*U1*U2*sind(d))+(Y1*U1*U2*cosd(d))-(Y4*U2^2) %[MVar]
% Power loss calculation
dP=P1-P2                                             %[MW]
dQ=Q1-Q2                                           %[MVar]
```

The following values were obtained:
Active losses: P_1 = 405,58 [MW]; P_2 = 387,71 [MW];
Reactive losses: Q_1 = 1,33 [MVar]; Q_2 = -112,89 [MVar];
Power losses: ΔP = 17,87 [MW]; ΔQ = 114,23 [MVar].

Calculations for a line of K-M relation l = 93,2 [km] long with ACCC Budapest

Table 1 presents calculations of parameters for a line of K-M relation with ACCC Budapest.

Table 1. Parameters of a line of K-M relation with ACCC Budapest

Line parameters	Unit	Value
Unit resistance	[Ω/km]	0,0416
Resistance of the lines	[Ω]	3,877
Average wire distance	[cm]	730,754
Wire diameter d = 3,15	[cm]	1,575
Unit inductance of a wire	[H/km]	$1{,}275 \cdot 10^{-3}$
Unit reactance	[Ω/km]	0,401
Reactance of the lines	[Ω]	37,373
Impedance of the lines	[Ω]	(3,877+j37,373)
Unit capacity	[F/km]	$9{,}056 \cdot 10^{-9}$
Unit susceptance	[S/km]	$2{,}85 \cdot 10^{-6}$
Susceptance of the lines	[S]	$2{,}65 \cdot 10^{-4}$
Admittance of the lines	[S]	$(0+j2{,}65) \cdot 10^{-3}$
Critical phase voltage for δ_a=1,044	[kV]	142,34
Critical voltage - no corona discharge ΔP_u = 0	[kV]	246,54

Based on relationships (1) to (10) and calculations, the following values of transmitted power and power losses were obtained:

P_1 = 406,93 [MW]; P_2 = 393,63 [MW],
Q_1 = 16,19 [MVar]; Q_2 = -99,24 [MVar],
ΔP = 13,31 [MW]; ΔQ = 115,43 [MVar].

Calculations of transmission capacity of 220 kV cable line

Calculations of transmission capacity and elements of equivalent circuit of 220 kV cable line were made for an equivalent circuit of π type presented on Figure 7. Technical data of the cables from [3] end [8] were used for calculations. It was assumed that cable line works with U_1 = U_2 = 220 [kV] and with load angle of δ = 18,2 [°].

Calculations for a line of K-M relation l = 93,2 [km] long with XRUHAKS cable with a diameter of 1400 mm^2 and unit parameters:

R' = 0,0174 [Ω/km], L' = 0,549 [mH/km], C' = 0,204 [μF/km]

Table 2 presents calculations of parameters for a line of K-M relation with XRUHAKS cable

Table 2. Parameters of for a line of K-M relation with XRUHAKS cable

Line parameters	Unit	Value
Resistance of the lines	[Ω]	1,621
Unit reactance	[Ω/km]	0,172
Reactance of the lines	[Ω]	16,030
Impedance of the lines	[Ω]	(1,621+j16,030)
Unit susceptance	[S/km]	$6,408 \cdot 10^{-5}$
Susceptance of the lines	[S]	$5,973 \cdot 10^{-3}$
Admittance of the lines	[S]	$(0+j5,973 \cdot 10^{-3})$

Based on relationships (1) to (10) and computer calculations the following values of transmitted power and power losses were obtained:

P_1 = 948,61 [MW]; P_2 = 918,37 [MW],

Q_1 = -89,42 [MVar]; Q_2 = -99,37 [MVar],

ΔP = 30,24 [MW]; ΔQ = 9,95 [MVar].

Calculations for a line of K-M relation l = 93,2 [km] long with HXCHBMK cable with a diameter of 1400 mm² and unit parameters

R' = 0,0175 [Ω/km], L' = 0,680 [mH/km], C' = 0,220 [μF/km]

Table 3 presents calculations of parameters for a line of K-M relation z HXCHBMK cable

Table 3. Parameters of a line of K-M relation with HXCHBMK cable

Line parameters	Unit	Value
Resistance of the lines	[Ω]	1,631
Unit reactance	[Ω/km]	0,214
Reactance of the lines	[Ω]	19,901
Impedance of the lines	[Ω]	(1,631+j19,901)
Unit susceptance	[S/km]	$6,911 \cdot 10^{-5}$
Susceptance of the lines	[S]	$6,441 \cdot 10^{-3}$
Admittance of the lines	[S]	$(0+j6,441) \cdot 10^{-3}$

Based on relationships (1) to (10) and computer calculations the following values of transmitted power and power losses were obtained:

P_1 = 764,10 [MW]; P_2 = 744,30 [MW],

Q_1 = -96,85 [MVar]; Q_2 = -26,71 [MVar],

ΔP = 19,79 [MW]; ΔQ = -70,13 [MVar].

Calculations under conditions of compensation of 220 kV line

Previously conducted analysis allows to determine which of the wires/cables has higher transmission capacity, assuming identical values of the voltage modules and angles of their flaring. In practice, the value of voltage in a plant hub can be regulated within range of ±10%. To determine the highest possible transmission capacity of a line, we must determine flare angle of the vectors U_1 and U_2 so as to have minimum losses of reactive power. In accordance with formulas described in literature [12], reactive and active power were calculated using MATLAB and flare angle, which losses of reactive power amount to 10^{-6} [MVar] for, which practically means compensation of a line.

Calculations for a line of K-M relation with AFL-8-525 mm² with the parameters:

$$\underline{Z_l} = (5,256 + j37,373)\,[\Omega], \quad \underline{Y_l} = (0 + j2,652) \cdot 10^{-4}\,[S]$$

For a line with rated voltage of 220 kV and work with U_1 = U_2 = 220 kV from relationship (11), condition defining an angle with which line is fully compensated from is obtained [12].

$$\cos\delta = \frac{Y_4}{Y_1} \cdot \frac{U_1^2 + U_2^2}{2 \cdot U_1 \cdot U_2} \qquad (11)$$

After conversion, the following relationship was obtained (12):

$$\delta = \arccos\left(\frac{Y_4}{Y_1} \cdot \frac{U_1^2 + U_2^2}{2 \cdot U_1 \cdot U_2}\right) \qquad (12)$$

Further in this article, MATLAB was used for automated calculating of Y_1, Y_2, Y_3, Y_4 values, as well as values of power and power losses with calculated δ. The following values were obtained from these calculations:

P_1 = 128,41 [MW]; P_2 = 126,60 [MW]; ΔP = 1,81 [MW],

Q_1 = -17,93 [MVar]; Q_2 = -17,93 [MVar]; ΔQ =$7,28 \cdot 10^{-6}$ [MVar],

δ = 5,76267836°.

Calculations for a line of K-M relation with ACCC Budapest with the parameters

$$\underline{Z_l} = (3,877 + j37,373)\,[\Omega], \quad \underline{Y_l} = (0 + j2,65) \cdot 10^{-4}\,[S]$$

As a result of calculations using MATLAB:

P_1 = 128,70 [MW]; P_2 = 127,37 [MW]; ΔP = 1,33 [MW],

Q_1 = -13,28 [MVar]; Q_2 = -13,28 [MVar]; ΔQ = $1,17 \cdot 10^{-6}$ [MVar],

δ = 5,73495773°.

Calculations for a line of K-M relation with XRUHAKS cable with the parameters

$$\underline{Z_l} = (1,621 + j16,030)\,[\Omega], \quad \underline{Y_l} = (0 + j5,973) \cdot 10^{-3}\,[S]$$

As a result of calculations using MATLAB:

P_1 = 932,84 [MW]; P_2 = 903,61 [MW]; ΔP = 29,23 [MW]

Q_1 = -92,85 [MVar]; Q_2 = -92,85 [MVar]; ΔQ = $1,61 \cdot 10^{-6}$ [MVar]

δ = 17,89208436°.

Calculations for a line of K-M relation with HXCHBMK cable with the parameters

$$\underline{Z_l} = (1,631 + j19,901)\,[\Omega], \quad \underline{Y_l} = (0 + j6,441) \cdot 10^{-3}\,[S]$$

As a result of calculations using MATLAB:

P_1 = 866,28 [MW]; P_2 = 840,74 [MW]; ΔP= 25,54 [MW],

Q_1 = -69,92 [MVar]; Q_2 = -69,92 [MVar]; ΔQ = $1,62 \cdot 10^{-6}$ [MVar],

δ = 20,69910434°.

Determination of impact area of 220 kV overhead power line

To determine the costs of transmission easement and compensations and cutting of trees, it is necessary to determine the width of strip of land, in which line has impact on the surroundings. Impact area for overhead power lines can be estimated using a formula (13):

$$S = B + 2 \cdot \left(\frac{U_N}{150}\right) \qquad (13)$$

where: S - width of impact area, B - width of supporting structure, U_N - rated voltage of a line.

After adding numeric data, we obtained:

- for single-circuit line

$$S = B + 2 \cdot \left(\frac{U_N}{150}\right) = 6 + 2 \cdot \frac{220}{150} = = 6 + 2,93 = 8,93\,[m] \approx 9\,[m]$$

- for double-circuit line

$$S = B + 2 \cdot \left(\frac{U_N}{150}\right) = 10 + 2 \cdot \frac{220}{150} = = 10 + 2,93 = 12,93\,[m] \approx 13\,[m]$$

Width of impact area for cable lines is connected with the width of cable excavation. It was assumed that this zone is double the width of excavation.

- for single-circuit line 3,2 [m],
- for double-circuit lines 6,4 [m].

Total land surface that is subject to transmission easement and compensations can be larger than calculated one in the event that route of a line makes it completely impossible to use a plot in accordance with its character. Calculations of costs for proposed solutions were presented in chapter 7 with prices of land between PLN 100 and 250 for 1 m^2, whereas, it must be observed that the price of PLN 100 is the price for reduction of potential of the use of land, and the price of PLN 250 is the total price of buyout of the land.

Precise calculations of the values of compensations and transmission easement must be made individually with reference to a specific plot, which is not possible and purposeful in this article.

Calculations of costs of 220 kV line for overhead power and cable lines

Total costs of construction and use of a line for the period of at least 30 years depend on the following factors:

– costs of construction of a line,
– the lie of the land,
– number of contiguous zones and intersections of a line,
– atmospheric conditions – microclimate,
– catastrophic atmospheric conditions,
– density of forestation of an area that line runs through.

Due to considerable diversity of factors mentioned above, precise economic calculations must be made every time in any individual case. It is one of necessary stages of designing power lines.

Because data received from an operator of K-M line do not contain detailed data about factors described above, calculations of costs will be made using similar method based on unit costs of construction of a line and percentage costs of repairs, cutting trees and accidental repairs. The costs of repairs and accidental repairs were estimated at 10% of costs of of construction for overhead power lines and 5% for cable lines within 30 years. The following unit costs of construction of a line were assumed:

– 220 kV single-circuit overhead power line - 900 000 PLN for 1km,
– 220 kV double-circuit overhead power line - 1 300 000 PLN for 1km,
– 220 kV cable single-circuit - 4 000 000 PLN for 1km.

For repairs resulting from the use of a line, the following costs were assumed:

– 220 kV single-circuit overhead power line - 90 000 PLN for 1km,
– 220 kV double-circuit overhead power line - 130 000 PLN for 1km,
– 220 kV single-circuit cable line - 200 000 PLN for 1km.

For transmission easement and compensations, unit costs were assumed:

– 220 kV single-circuit overhead power line - 900 000 PLN for 1km,
– 220 kV double-circuit overhead power line - 1 300 000 PLN for 1km,
– 220 kV single-circuit overhead power line - 800 000 PLN for 1km
– 220 kV double-circuit cable line – 1 600 000 PLN for 1km.

For assumed computational data, total costs of K-M line for overhead power and cable lines were determined and results of calculations were presented in Table 4.

Table 4. Total cost of K-M overhead power and cable lines

Line type	Line construction [mln PLN]	Renovations and repairs [mln PLN]	Servitude and compensation [mln PLN]	Totality [mln PLN]
Overhead	121,160	12,161	121,160	254,481
Cable	372,800	18,640	74,560	466

Economic calculations were based on average price of square meter in the vicinity of place where lines are constructed. The prices of land as we approach to M station will be higher, even a few times due to large urban agglomeration. While approaching in the direction of K, the prices of land will be dropping mainly due to their agricultural character. While determining precise compensations, the main criterion is permissible way of use (agricultural, building, wooded). In this article, method of calculating excluded surface characteristic of woodland was assumed, where the whole strip of impact is limited by forestation (permissible forest nurseries). Assuming such method resulted from inability to determine the character of every plot on the route of a line, for example, on agricultural land is excluded from use only surface of base of supporting structure and in built-up areas, often the whole plot can't be developed because of exceeding permissible level of electric and/or magnetic field strength - 1 kV/m or 60 A/m^2. The calculations presented in this article are aimed at comparison of costs of technical potential of rebuilding of 220 kV lines. Percentage method of calculating costs of repairs and failures was made analogically as method of estimating the values of compensations described above. Assumed period of 30 years is a typical period of amortization of devices in heavy current engineering and does not reflect possible working time of a line, especially cable line.

Conclusions

As it was shown in the calculations, it is possible and appropriate to replace worn out 220 kV lines with modern solutions and allowing to satisfy still growing needs of agglomerations. Out of possible technologies, all of them have advantages and disadvantages and their application depends on field conditions that line runs through. Generally, it must be said that cable lines are few times more expensive and harder to compensate. However, these disadvantages are balanced by their higher transmission capacity caused mainly by very large cross-section of the cables and possibility of carrying the route of a cable line in such a way that can run along existing road and railway routes, which reduces the costs of compensations and land easement. It is correct to say that with the price of land exceeding PLN 300/m^2, application of cable lines is cost-effective due to the costs of the land and protests of inhabitants against overhead power lines. As a result of calculations and analysis of their results, the following conclusions were drawn:

- 220 kV lines, although not developed in the Public Power System, are still useful as power connection to the Main Power Supply Point on the outskirts of large cities. It is mainly caused by their lower size than 400 kV lines and the fact of their relatively easy revitalization,
- Under conditions of full compensation, there is no

significant difference between AFLs and ACCCs, however, due to thermal capacity, ACCCs should be used in new structures,

- Costs of overhead power line are few times lower than those of cable lines, except for in the areas of intense suburban buildings where prices of building plots increase such costs to the costs similar to those of cable lines,
- Cable lines are fully compensated with δ of 20÷26° which is hard to achieve under working conditions of the Public Power System, however, it is not impossible,
- Cable lines are expensive at the stage of investments, however, duration of their use is few times higher than overhead power lines, that is, 30 years. If cable, as a result of actions of third parties (an effect of earthworks), are not destroyed, such lines can work even 60 years,
- For economic reasons, it is sensible to apply combined solutions, that is, cable and overhead power line ones. Such line is constructed similar to overhead power one and ends with very cable pole. Road to Main Power Supply Point and further route of a line in the agglomeration is through cable line. Such solution allows to reduce investment costs and make transmission of power between Main Power Supply Points during work easier,
- For economic reasons, cable and overhead power lines are the best solution to supply Main Power Supply Points of large cities. Cost of overhead power solution is about PLN 300 million, only cable one is more than million 1 billion, and cable and overhead power is PLN 600 million. Whereas, completely overhead power one is impossible for the reasons described above,
- Provided economic calculations do not consider such factors as compensations for not providing energy to the consumer, which can be crucial if specific Main Power Supply Point supplies power to the consumers requiring constant power supply (e.g. coking plants, chemical plants etc.). Potential losses resulting from lack of energy are so serious that make it justifiable to make line as completely cable line. It is connected with total resistance of cable lines to atmospheric conditions, that is, to failures of catastrophic character,
- In the suburban areas, large number of roads and railway lines makes arrangements concerning cable line route quick and easy that those with hundreds of inhabitants by the route of overhead power lines. In the event of carrying line route along roads and railway routes, costs of buying the land are much lower than costs of buying the plots and paying compensations,
- To sum up, replacement of totally worn out 220 kV cable line is technically possible and leads to increasing transmission capacity of such line, and moreover, reduces exposing of such connection to atmospheric catastrophe, increasing certainty of power supply,
- Increasing transmission capacity is connected mainly with the use of a cable with section of 1400 mm^2, which is equivalent when we consider thermal conductivity that amounts to 0,5 ÷ 0,7, lines with a bundle conductor with two wires in a bundle.

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