PORCELAIN LONG ROD VS CAP & PIN INSULATORS: IMPACT ON OVERHEAD LINE DESIGN

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HIGH VOLTAGE OHL 400kV AC PROJECT STUDY

CONTENT:

ABSTRACT

The project study has brought the result about a potential, way and future ability to optimize and increase efficiency of Overhead Line (OHL) high voltage power electric systems based on a new and tailored porcelain Long Rod design and specific and professional design tool respecting all technical constraints, a particular terrain morphology and proposing upgrade and saving of OHL materials.
Key words: Overhead Line (OHL) porcelain Long Rod and Cap & Pin insulator strings, span, sag, conductor tension, slack, ground clearance, tower types and arms and its dimensions and types, insulator string protections, Insulation Coordination Study (ICS), shielding wires and protection, ROW Right-Of-Way

DESCRIPTION AND OBJECTIVE

The project study was done on existing, in operation, HVAC OHL 400kV T&D PES (Transmission & Distribution Power Electric System).

The OHL are equipped with lattice steel grounded Donau type towers, 2x3xphase electric system, 3xstrands of each phase aluminum (Camel) ACSR conductors, doubled I-type suspension and tension porcelain (original) Long Rod insulator strings in configuration 2x3xLong Rod unit strings with anti-corona rings and arcing horn protections, 2xshielding wires, specific maximum area outdoor conditions (environment) and constraints for the countryside and with the total length (substation to substation) of the OHL is 48km located in Central Europe and the owner is national transmission system operator (TSO) .

The study and analysis objective was a potential improvement, optimization and replacement of the existing original OHL Long Rod insulator strings in the selected 5,5km line segment with new Cap & Pin (Disc) insulator strings and new Long Rod insulator strings. The improvement and optimization of existing insulator strings was done based on worsened and more stringent outdoor conditions (environment) than the original OHL design followed by the optimization based on different insulator string lengths, towers dimensions (height, length of arms, foundations) and position and number of towers (suspension type) respecting all constraints and ICS (Insulation Coordination Study) study for new conditions and insulator strings was completed. There were created 3x new variants of insulator strings (variant 0, A, B), worsened environmental conditions (wind conditions, pollution, icing) and mutually compared and evaluated benefits of the variants comprised optimization criteria.

The engineering tools used in the study (models, calculations and simulations) are PLS-CADD for OHL line 3D design and optimization, TOWER tool for different towers design. Both are from Power Line Systems company.

TECHNOLOGY SPECIFICATIONS
OHL HVAC 400kV

International standards	EN 50341-1, EN 50341-2-23
Nominal system voltage [kV], AC	400
Maximum system voltage [kV], AC	420
BIL Lightning withstand voltage [kV], Dry	min 1425
SIL Switching withstand voltage [kV], Wet	min 950
SPS class – Minimum creepage distance [mm/kV]	E (Extra heavy polluted) 45
Icing zone – Basic unfactored ice load [kg/m]	Zone I3 = 3

Wind zone – Basic unfactored wind speed [m/s]	Zone III = 30
Relative humidity [%]	5 ÷ 95
Maximum altitude range [m]	0 ÷ 1000
Real altitude range (assessed line section) [m]	160 ÷ 260
Ambient temperature range [°C]	-30 ÷ +40
EDT – Everyday temperature [°C]	+10
Maximum operating temperature of conductors [°C]	+80
Minimum distance of conductors from ground [m]	12
Maximum allowable conductor tension [% RTS]	50
Maximum allowable conductor catenary at EDT [m]	2200
Conductor type	476-AL1/62-ST1A (Camel)
Conductor bundle arrangement (strands) [mm]	Triangular, Bundle distance 400

LATTICE STEEL TOWERS

Type of towers - Donau tension (angle, dead-end) and Donau suspension (tangential)
Power electric system - 2xsystem 3xphase 400kV system
Phases of both systems are arranged in equilateral triangles, each system on on side of a common tower body
According to EN 50341-2-23 are required followed clearances

No wind, up to mild wind with speed 10m/s	min. 2 800 mm
Nominal wind, with 3-year return period (V3)	min. 1 960 mm
Extreme wind, with 50-year return period (V50)	min. 750 mm

Minimum shielding (protection) angle of ground / shielding wires set to 16 ° geometric.
Minimum in-span clearances between phases enabling spans up to 500m, in case of longer spans, additional gap between bottom phase conductors needed and additional lengthening of crossarms needed as well. There are used phase spacers with function of dampers.
Optimal tower tops were selected enabling the optimal swing angles of suspension insulator strings.

Towers dimensions respect all conductor stress constraints (tension), sag and minimum ground clearance and morphology of the area terrain.

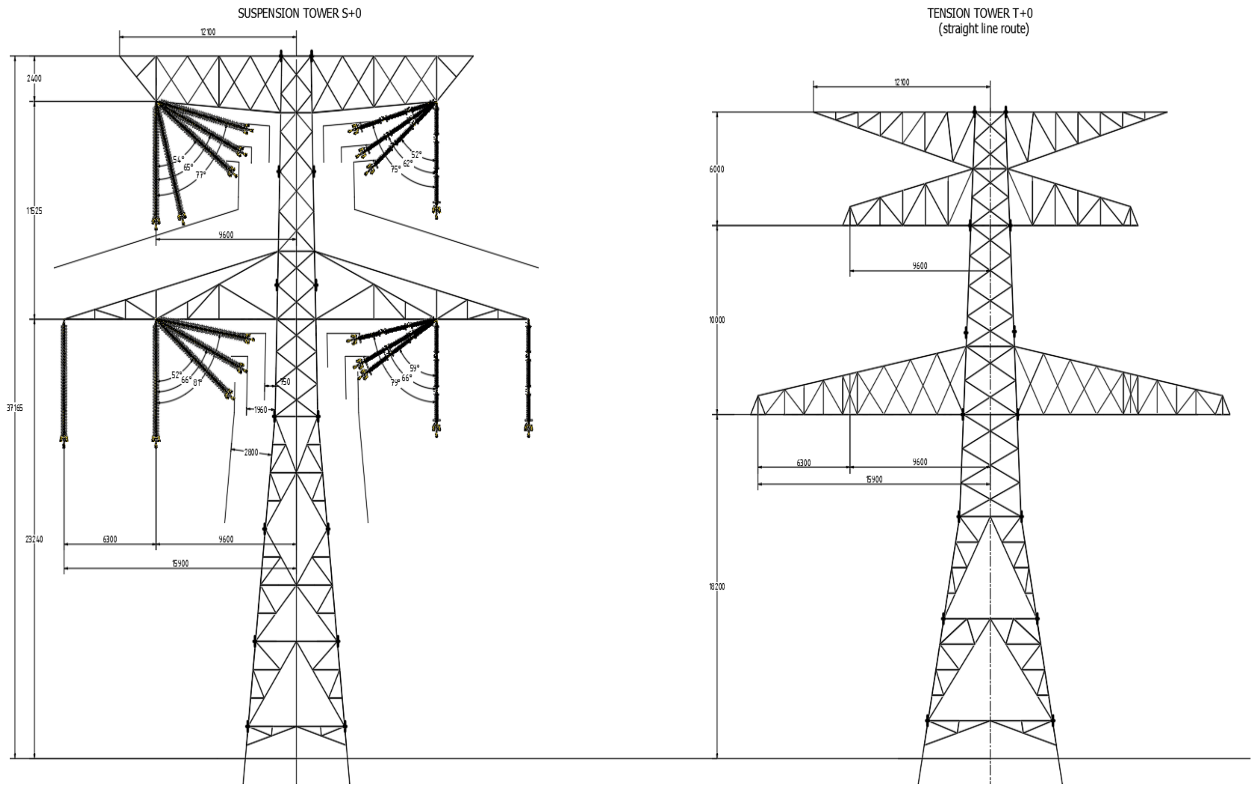


Fig. 1: Donau lattice steel suspension (left) and tension (right) towers for 400kV OHL project

PHASE CONDUCTORS

Wire type	476-AL1/62-ST1A (Camel)
International standards	EN 50182
Type	ACSR (54AL/7ST)
Material and number of wires in the core	7xST1A (3,35 mm)
Core diameter	10,05 mm
Core cross-section area	61,7 mm2
Material and amount of aluminum wires	54xAL1 (3,35 mm)
Aluminum cross-section area	476 mm2
Overall diameter	30,15 mm
Overall cross-section area	537,7 mm2
Wire unit weight	1,7988 [kg/m]
Modulus elasticity	70 [GPa]
Coefficient of linear expansion	0,00001930 [/°K]
Rated tensile strength (RTS)	146,4 [kN]

DC resistance at 20 [°C]	0,0608 [Ω/km]
Current carrying capacity (EN 50341-1] per phase	800/2400 [A]
Bundle arrangement	Triangular / 400 [mm] spacing
Bundle geometry	Equilateral triangle
Aeolian vibration protection	Spacer dampers

SHIELDING (PROTECTIVE) WIRES

Wire type	185-AL4/43-ST6C
International standards	EN 50182
Type	ACSR (30AL/7ST)
Material and number of wires in the core	7xST6C (2,8 mm)
Core diameter	8,4 mm
Core cross-section area	43,1 mm2
Material and amount of aluminum wires	30xAL4 (2,8 mm)
Aluminum cross-section area	184,7 mm2
Overall diameter	19,6 mm
Overall cross-section area	227,8 mm2
Wire unit weight	0,8471 [kg/m]
Modulus elasticity	84 [GPa]
Coefficient of linear expansion	0,00001810 [/°K]
Rated tensile strength (RTS)	120,81 [kN]
DC resistance at 20 [°C]	0,1850 [Ω/km]
Aeolian vibration protection	Stockbridge vibration dampers

INSULATOR STRINGS – CAP & PIN (DISC) – SUSPENSION TYPE

Designation (IEC)	U160 BMP (XHP-160)
Dimensions (Height / Diameter / Creepage) [mm]	155 / 330 / 550
Fittings	Ball & Socket, Hot dip galvanized
Specified minimum failing load [kN]	160
Porcelain type	C130
String configuration	Double I-suspension, 2x38 units
Maximum system voltage unit / string	11 / 418 kV (38x11)
Unit weight [kg]	12,7

Withstand voltage BIL Dry / PF 1min Dry / Wet [kV]	125 / 80 / 50
Minimum flashover voltage 50% BIL Dry Positive / Negative [kV]	140 / 160
Minimum flashover voltage PF 1min Dry / Wet [kV]	90 / 55
Puncture power frequency PF 1min voltage [kV]	130

INSULATOR STRINGS – CAP & PIN (DISC) – TENSION TYPE

Designation (IEC)	U420 B (XP-420)
Dimensions (Height / Diameter / Creepage) [mm]	205 / 340 / 550
Fittings	Ball & Socket, Hot dip galvanized
Specified minimum failing load [kN]	420
Porcelain type	C130
String configuration	Double I-tension, 2x38 units
Maximum system voltage unit / string	11 / 418 kV (38x11)
Unit weight [kg]	21,5
Withstand voltage BIL Dry / PF 1min Dry / Wet [kV]	125 / 80 / 50
Minimum flashover voltage 50% BIL Dry Positive / Negative [kV]	140 / 160
Minimum flashover voltage PF 1min Dry / Wet [kV]	90 / 55
Puncture power frequency PF 1min voltage [kV]	130

INSULATOR STRINGS – LONG RODS – SUSPENSION TYPE

Designation (IEC)	LP75 / 22+21 / 1710
Dimensions (Length / Core diameter / Creepage) [mm]	1710 / 75 / 6503
Fittings	Clevis & Tongue, Hot dip galvanized
Specified minimum failing load [kN]	160
Porcelain type	C130
String configuration	Double I-suspension, 2 x 3 units
Maximum system voltage unit / string [kV]	145 / 435 (3 x 145)
Unit weight [kg]	65
Withstand voltage BIL Dry / PF 1min Wet [kV]	750 / 325

INSULATOR STRINGS – LONG RODS – TENSION TYPE

Designation (IEC)	LP105 / 21+21 / 1760
Dimensions (Length / Core diameter / Creepage) [mm]	1760 / 105 / 6503
Fittings	Clevis & Tongue, Hot dip galvanized
Specified minimum failing load [kN]	330
Porcelain type	C130
String configuration	Double I-tension, 2 x 3 units
Maximum system voltage unit / string [kV]	145 / 435 (3 x 145)
Unit weight [kg]	109
Withstand voltage BIL Dry / PF 1min Wet [kV]	810 / 390

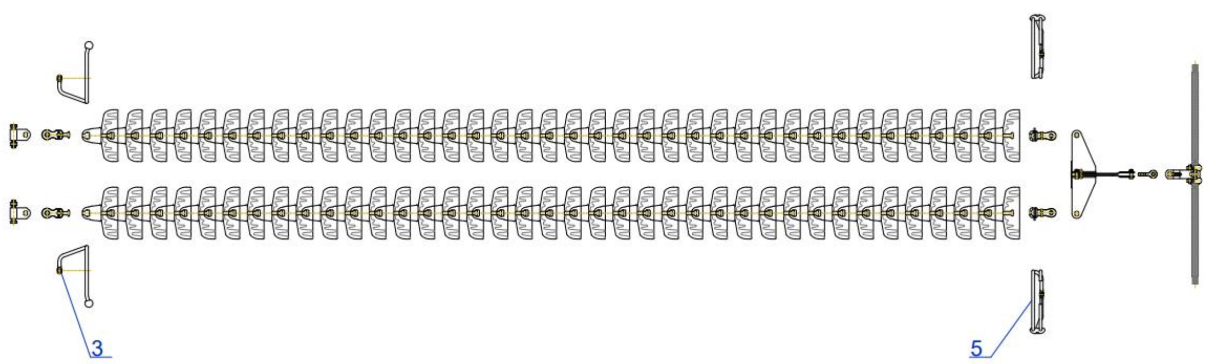


Fig. 2: Cap & Pin porcelain insulator double I-strings with mechanical protection and its equivalency to the original old porcelain Long Rod

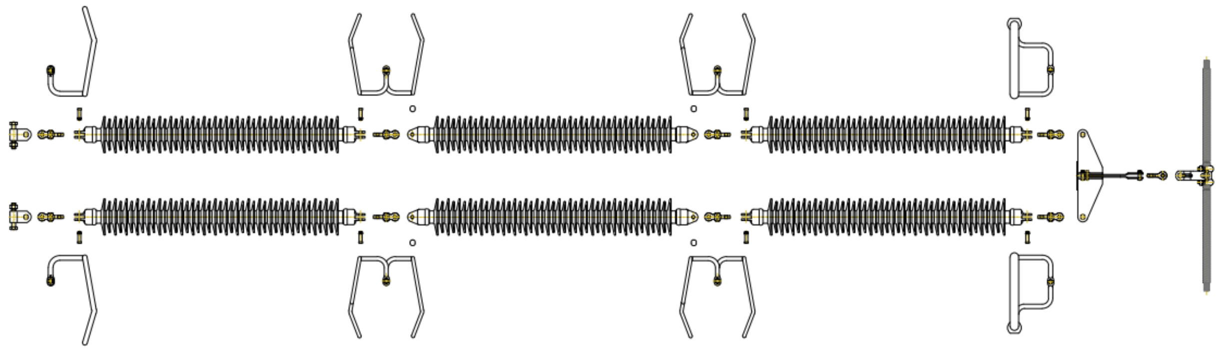


Fig. 3: New porcelain Long Rod insulator double I-strings with mechanical unit protection

PROJECT SOLUTION VARIANTS (0, A, B) AND DIFFERENCES

Variant “0”

Appropriate design of **new porcelain Cap & Pin (Disc)** insulator strings in doubled **I**-type suspension and tension configuration for the selected OHL segment of 5,5km to replace the original OHL porcelain Long Rod insulator strings for more stringent outdoor conditions and the same towers dimensions and their numbers as the original insulator strings.

Variant “A”

Appropriate design of **new porcelain Long Rod** insulator strings in doubled **I**-type suspension and tension configuration for the selected OHL segment of 5,5km to replace the original OHL Long Rod insulator strings for more stringent outdoor conditions and the same number of towers but optimized (decreased) dimensions – height of towers, length of arms and foundations as the original as well as Variant “0” insulators strings.

Variant “B”

Appropriate design of **new porcelain Long Rod** insulator strings in doubled **I**-type suspension and tension configuration for the selected OHL segment of 5,5km to replace the original OHL Long Rod insulator strings for more stringent outdoor conditions and the optimized (decreased) number of towers with different towers dimensions (height, foundations) as the original, Variant “0” as well as Variant “A” insulator strings. The Variant “B” based on appropriate new towers spans, respecting all sag – tension constraints and the terrain morphology and leveling.

All variants (0, A, B) keep minimum mandatory ground and tower clearances (phase conductors to ground distance respecting real morphology of the terrain and conductors to grounded towers) based on ICS (Insulation Coordination Study) calculations and analysis.

The comparison of new Cap & Pin (Disc) insulator strings (Variant 0) with 2xvariants of new Long Rod insulator strings (Variant A, B) was executed in static (steady-state) or semi-static regime.

All the OHL longitudinal profile and ROW is respecting minimum ground clearance 12m (phase line to ground) for 400kV OHL power electric system, maximum temperature of phase conductors +80°C, phase and shielding wires tensions below 55% of their rated tensile strengths at final after creep / load states at -5°C with extreme ice and wind loading (UTS ultimate tension strength - limit state).

Optimization criteria include towers dimensions, arms dimensions, tower foundations and number of towers based on the variant-based insulator strings, real OHL segment, terrain morphology and all electrical, mechanical and environmental constraints respecting the stringent conditions.

Evaluation of differences between variants 0, A, B is based on savings / reduction of materials (towers and arms steel, towers foundations concrete) and number of towers with different insulator strings.

Terrain and its morphology determines position and dimension including foundation of lattice steel 2-system Donau towers. During the optimization it was mandatory to evaluate sag – tension function (dependence) comprising minimum phase conductor to ground clearance (maximum sag) for used OHL stranded conductors.

The process of optimization is connected with a slack in % as well as with the asymmetrical stress (load) of towers combined with OHL weight span S_{PW} [m]. Both are necessary to check and evaluate continuously whenever the towers shift to new positions (inclined / declined span and span changes).

$S_{L\%} = (L_C – S_P) / S_P . 100$ [%]

$S_{L\%}$ [%] - Slack (distance ratio)
L_C [m] – Length of OHL conductor (catenary conductor curve length)
S_P [m] – Span (neighboring towers straight distance usually inclined or declined)
S_{PW} [m] – Weight span (distance between 2xneighboring sags)

Regarding the OHL optimization based on new tower positions and their dimensions (height) and arms lengths is calculated a ruling span and new tower positions respect it. New tower positions respecting all constraints have main impact on number of towers.

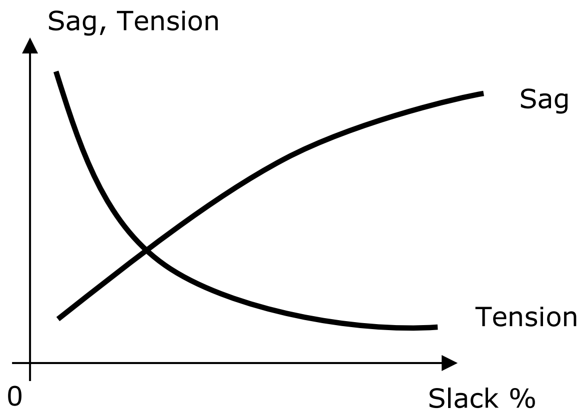


Fig. 4: Functions Sag – Slack and Tension – Slack in OHL conductors

Sag and Tension are substantial but mutually inversed parameters relevant to optimization based on suspension (tangential) and tension (angled) towers respecting a real terrain morphology. These parameters are adjusted and optimized considering all constraints from OHL conductors, insulator strings and towers.

The optimization was done in PLS-CADD and using dependencies and constraints of towers span S_P [m], sag S_G [m] and tension T [kg] and in simplified form it is as follow

$\Delta S_G = |S_{G1} - S_{G2}| = W . |X1 + X2| . |X1 – X2| / (2 . T) = W . S_P . |X1 - X2| / (2 . T)$
$\Delta S_G = |S_{G1} - S_{G2}| = W . S_P . |X1 - X2| / (2 . T)$

S_P [m] – Span (neighboring towers distance usually inclined or declined, it is reason for the absolute value |X1 – X2|)
S_{G1}, S_{G2} [m] – Sags from two neighboring towers

T [kg] – Tension in conductor
W [kg/m] – Conductor unit weight
X1, X2 [m] – Distances of the lowest conductor catenary curve point from both towers
$X1 + X2 = S_P$ [m]

In case when constraints of span, sag, tension (temperature, wind, ice) are not achieved towers dimensions were discretely changed by adding / subtracting (±3m) and adequately changed spans of lattice steel towers

EVALUATION AND CONCLUSION

Suspension and Tension towers equipped with Cap & Pin and new Long Rod insulator strings and their dimensions (tower height, tower arm length - ROW) and material amount of comparison (see charts).

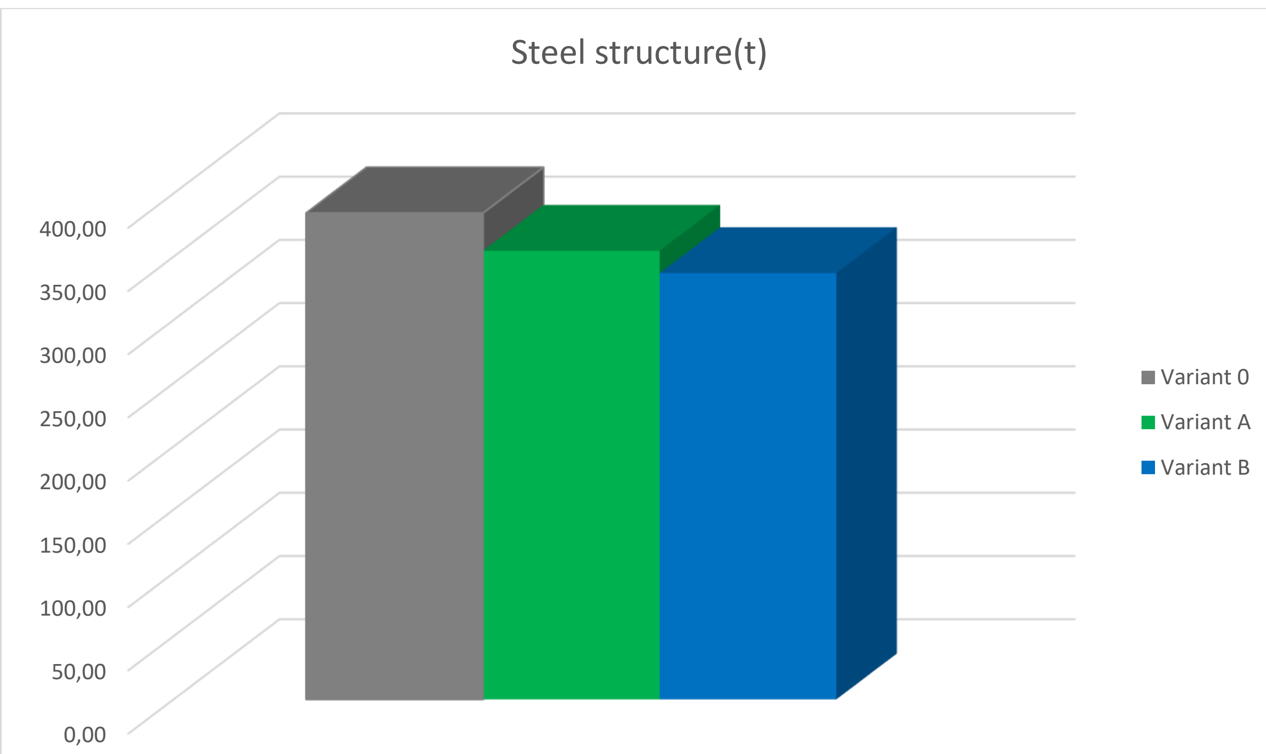


Fig. 5: Evaluation of towers steel used in all 3xvariants

Steel used in different variants comprises optimization criteria of each variant and different

towers dimensions based on the optimization variant.
Suspension and Tension towers foundations (concrete) optimization

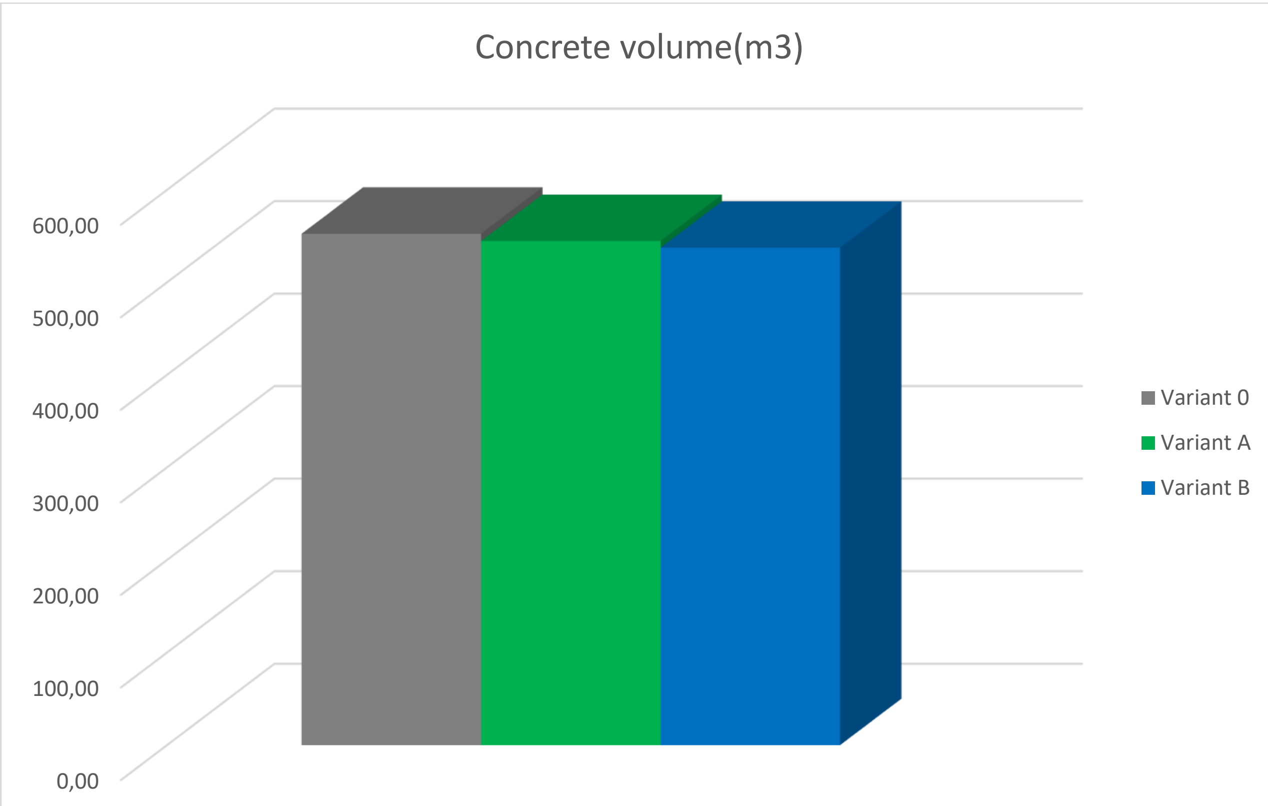


Fig. 6: Evaluation of towers concrete used in all 3xvariants

Rough relative percentages in savings of material variants A and B compared to variant 0 are following

Variant “A to 0”	Tower Steel 7.75%	Foundation Concrete 1.42%
Variant “B to 0”	Tower Steel 12.34%	Foundation Concrete 2.74%
Variant “B to A”	Reduction of 2xsuspension (tangential) towers	

variant 0				variant A				variant B			
No.	Type	Steel (t)	Concrete (m3)	No.	type	steel (t)	Concrete (m3)	No.	type	steel (t)	Concrete (m3)
1	T+3	31,63	49,94	A1	Q+3	29,55	51,65	B1	Q+3	29,55	51,65
2	S+6	17,57	23,79	A2	P+6	16,89	24,83	B2	P+6	16,89	25,90
3	S+6	17,57	23,79	A3	P+3	15,45	24,13	B3	P+6	16,89	25,90
4	S+3	16,19	23,08	A4	P+0	14,07	19,48	B4	P+9	18,72	27,78
5	S+6	17,57	23,79	A5	P+6	16,89	24,83	B5	P+9	18,72	27,78
6	S+9	19,51	26,70	A6	P+6	16,89	24,83	B6	P+9	18,72	27,78
7	S+9	19,51	26,70	A7	P+9	18,72	22,56	B7	P+6	16,89	25,90
8	S+3	16,19	23,08	A8	P+3	15,45	24,13	B8	P+0	14,07	22,45
9	S+6	17,57	23,79	A9	P+6	16,89	24,83	B9	P+6	16,89	25,90
10	T+6	33,49	55,87	A10	Q+3	29,55	51,65	B10	P+9	18,72	27,78
11	S+6	17,57	23,79	A11	P+3	15,45	24,13	B11	P+9	18,72	27,78
12	S+0	14,84	18,55	A12	P+0	14,07	19,48	B12	Q+6	31,43	57,67
13	S+9	19,51	26,70	A13	P+12	20,04	28,63	B13	P+9	18,72	27,78
14	S+12	20,81	27,53	A14	P+12	20,04	28,63	B14	P+6	16,89	25,90
15	S+3	16,19	23,08	A15	P+0	14,07	19,48	B15	P+6	16,89	25,90
16	S+3	16,19	23,08	A16	P+3	15,45	24,13	B16	P+6	16,89	25,90
17	S+9	19,51	26,70	A17	P+6	16,89	24,83	B17	Q+6	31,43	57,67
18	S+9	19,51	26,70	A18	P+6	16,89	24,83				
19	T+6	33,49	55,87	A19	Q+6	31,43	57,67				
Sum		384,46	552,53	Sum		354,68	544,73	Sum		337,02	537,42

Fig. 7: Evaluation of towers concrete used in all 3xvariants

Variant 0

Total number of towers = 19 (various tower heights), S & T tower types

T – Number of Tension towers = 3

S – Number of Suspension towers =16

Variant A

Total number of towers = 19 (various tower heights), A1 ÷ A19 tower types

Q – Number of Tension towers = 3

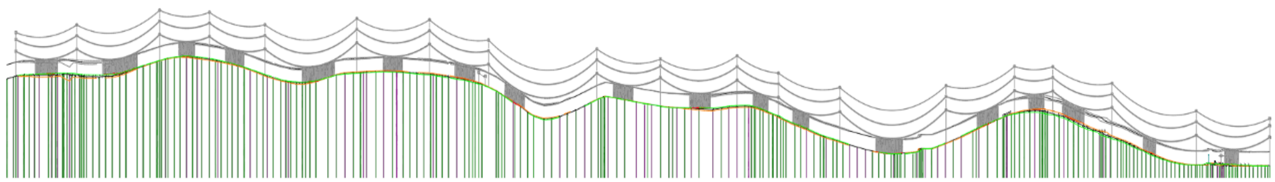
P – Number of Suspension towers =16

Variant B

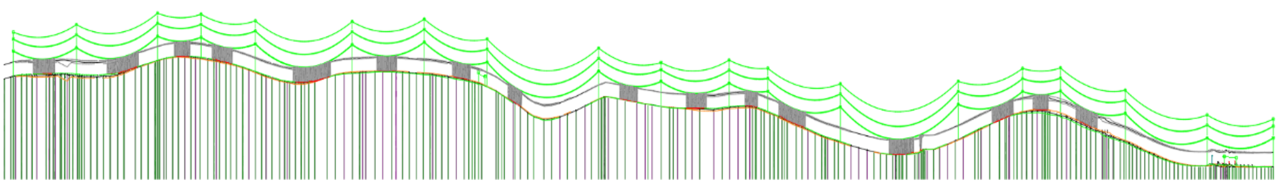
Total number of towers = 17 (various heights), B1 ÷ B17 tower types
Q – Number of Tension towers = 3
P – Number of Suspension towers =14

Optimization criteria – Height and arm lengths of towers, tower concrete foundations, position and number of towers

Variant "0" Longitudinal profile



Variant "A" Longitudinal profile



Variant "B" Longitudinal profile

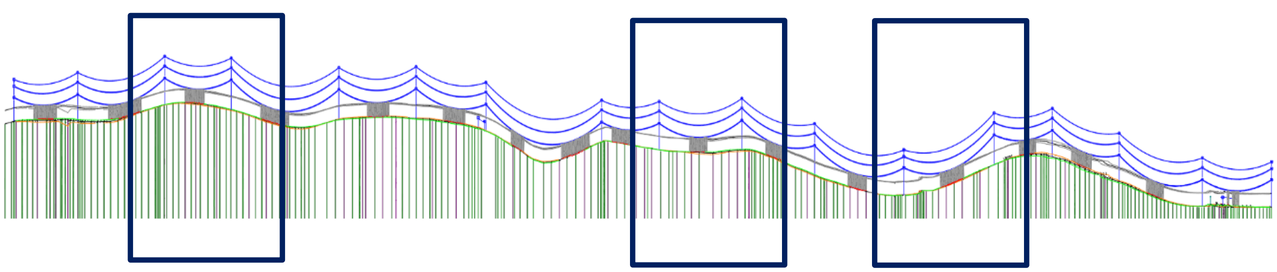


Fig. 8: OHL and terrain profile for all variants with marked places of towers missing and reconfiguration

Towers and their positions influenced by the optimization are marked.

Study and particular solution variants summary, benefits and results of the variants. The original older Long Rod insulator strings designed and implemented for local environment conditions were, in the study, replaced by new Cap & Pin and later by new Long Rod insulator strings for stringent environmental conditions with 2xdifferent criteria of optimization. First, new Long Rod insulator strings optimized against the Cap & Pin based on dimensions of towers and second, new Long Rod insulator strings optimized against Cap & Pin based on towers position and dimensions respecting all insulator string electrical, mechanical and environmental constraints as well as sag vs tension OHL stranded conductors constraints. The original environmental conditions were worsened because of higher wind level occurs as well as higher icing level during winter time and more industrial and traffic pollution in the area.

Variant "0"

OHL HVAC equipped with **Cap & Pin insulator strings** is a base of comparison as 100% of materials (steel and concrete) and number of suspension and tension towers is 19pcs as originally designed. The variant completely proposed a potential equivalent replacement of the original older Long Rod insulator strings (2x3xunits). The Cap & Pin (Disc) design of the potential replacement was based on experience and evaluation of existing older Long Rod insulator strings and respects new and worsened environmental conditions.

Variant "A"

OHL HVAC equipped with **new Long Rod insulator strings** results in 92,25% (steel) and 98,58% (concrete) of Variant "0" materials and number of suspension and tension towers is 19, optimized towers dimensions and foundations. It has a positive impact (diminishing) to the OHL segment ROW (Right – Of – Way) it means a reduction of the line width.

Variant "B"

OHL HVAC equipped with **new Long Rod insulator strings** results in 87,66% (steel) and 97,26% (concrete) of Variant "0" materials and number of suspension and tension towers is 17, savings of 2xsuspension type towers. It has a positive impact to the OHL material requirement – saved material because of smaller number of towers (2xtowers less).

It was shown and confirmed that it is possible to optimize existing OHL and its insulator strings design based on different technical criteria and save tower materials as well as keep all line constraints and existing phase conductors and shielding wires.

Such length benefits are then translated into more effective design of span lengths, using of lower tower types while keeping similar span lengths or possibly skipping some towers, if using longer spans which eventually, by summing those extra lengths, enable for such optimization.
All outputs and results from this study are based on and depending very much on the parameters on the inputs from the particular OHL application and could not be taken as a general rule in terms of comparison of Long Rod and Cap & Pin insulators. For different voltage levels, different insulator unit and strings, different environmental conditions (mainly creepage distance requirements), different terrain morphology, the results may vary but in general exist a way to improve OHL design based on insulator strings and towers dimensions and positions.

A significant assistance in the optimization and the upgrade was made on the professional OHL design tool PLS – CADD and its SW add-on called Tower.

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