

AN ANALYTICAL APPROACH FOR DETERMINING THE APPROPRIATE MEDIUM VOLTAGE (MV) CABLING LEVEL IN RENEWABLE ENERGY PARKS

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Abstract: Renewable energy parks, primarily solar parks and wind farms are connected to the high voltage PCC by medium voltage (MV) cabling system. Cabling system can have significant impact on CAPEX of renewable park. On the other hand, during exploitation power losses can have significant impact on hidden costs of energy park operation (OPEX). CAPEX and OPEX including hidden costs can contribute to unnecessary costs. MV cabling system in renewable energy parks is specific in terms of MV level. This paper gives an analytical approach for determining the appropriate MV cabling level in renewable energy parks. Voltage levels 20 kV, 30 kV, 33 kV and 35 kV were examined. For each voltage level constraints in terms of voltage drop are given and the minimum cable cross-sections is calculated. Calculations of short-circuit levels and power losses have been made for examined voltage levels. Appropriate MV cable level is voltage level with the minimum costs in 20 years exploitation of MV cable system. Mentioned costs are sum of MV cable system costs (CAPEX) and power losses costs in exploitation period.

Keywords: analytical approach, MV cabling, renewable energy parks, appropriate MV voltage level, costs minimization, power losses

INTRODUCTION

MV cabling system can have significant impact on CAPEX of renewable park. On the other hand, during exploitation power losses can have significant impact on hidden costs of energy park operation (OPEX). MV cabling system in renewable energy parks is specific in terms of MV level. This paper gives an analytical approach for determining the appropriate MV cabling level in renewable energy parks. Voltage levels 20 kV, 30 kV, 33 kV and 35 kV were examined. Appropriate MV cable level is voltage level with the minimum costs in 20 years exploitation of MV cable system. Mentioned costs are sum of MV cable system costs (CAPEX) and power losses costs in exploitation period. Contribution of this paper is in consideration of short-circuit level for appropriate MV cable and switchgear selection regarding voltage level. Additionally, power generation of renewable park (wind farm or PV plant) is considered too in manner of power losses influence on total losses in economic sense. The paper is organized as follows.

In section 1. Literature review is presented. Methodology is explained in section 2. regarding appropriate MV cabling selection in renewable energy parks. Calculation methods flowchart is presented. Economic evaluation of method is introduced in section 3. Selected case study is analysed in section 4. Section 5. gives case study results. Discussion of introduced analysis with economic evaluation of results is presented in section 6.

1. LITERATURE REVIEW

In [1] a new approach for cable routing in onshore wind farms using a Quota Steiner tree problem (QSTP) is introduced. According to [1] current methods for planning onshore wind farms and connecting them to the power network do not always meet minimum cost solutions. Literature [2] presents necessity of considering the active energy losses in the cables of the designed network. Active energy cable losses have a major influence on the final shape of wind farm network and the cross-sections of the cables used. The cable cross-section was analysed by optimization methods. A one-stage method was used which allows simultaneous optimisation of the layout and the selection of cable cross-sections of the wind farm's internal power network.

In [3] a review of electrical cable optimization in offshore wind farms is presented (state-of-the-art review of the optimization of electrical cables in offshore wind farms). Optimization is done in manner of used internal network such as radial, star, looped and other types.

In [4] the MILP algorithm considers system reliability, power transfer capacities and power quality issue in wind farm cable design. The novelty in this optimization algorithm is to simultaneously minimize cable installation cost and the cost of lost energy production and therefore maximize the reliability of the system. The results presented in paper

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show that more cable options contribute to decreasing the total costs.

Paper [5] addresses the wind farm optimization layout considering several substations. It is given a set of wind turbines jointly with a set of substations, and the goal is to obtain the optimal design to minimize the infrastructure cost and the cost of electrical energy losses during the wind farm lifetime. Optimal cable connection layout is goal of optimisation.

In [6] the optimization of cable layout design in wind farm internal networks is presented. Several methods for optimal cable layout were presented. The goal is to find optimal cable length for internal cable networks.

Paper [7] presents novel constraints to enhance a well-known cable type-based COP MILP formulation addressing radial networks. The developed approach leveraged the problem's characteristics regarding power flow interactions related to cable types. This method enables writing equations that tightened the solution region and yielded global solutions.

Generated electrical energy from the wind farms can be improved in manner of the design of the cable network layout. Paper [8] has addressed the optimal design of the wind farm cable network aiming to minimize the sum of the infrastructure cost and the cost of the power that is lost in the cables over an expected lifetime of 20 years. In order to assess the gains of considering the losses costs in the design goal, it was also considered the problem of minimizing only the infrastructure cost.

In paper [9], a new MILP model for optimal cable routing in wind farms is introduced. A main novelty of this model is its capability of taking both installation costs and power losses into full account.

The study presented in paper [10] showed that optimising the wind farm layout was also optimised by deciding which cable to use for those connections.

A model to solve a cable connection layout considering wind farms with several substations is introduced in [11]. The presented model is fast at finding the optimal solution. A practical model for calculation of the optimal cross sections of cables for connecting wind farms performed independently from the route optimisation is presented in [12].

The main characteristics of the basic components for PV plant have been detailed in [13]. The internal AC collection network for various networks have been described. The right choice of the components affects the area occupied, the efficiency and the reliability of PV plants.

A mathematical model for optimal voltage level of wind farm connection is presented in [14]. Model in this paper

considers the costs of connection to competitive voltage levels of PCC. Selection of the optimal PCC provides the optimal balance between the investment and operating costs and thus reduces the costs for the owner of the wind farm. In [15] optimal cable cross-section selection is introduced regarding cable ampacity. Method is valid for low-voltage direct buried cables.

2. METHODOLOGY

This chapter presents a methodology of presented analysis regarding appropriate MV cabling selection in renewable energy parks. For each voltage level constraints are given

in terms of voltage drop and the minimum cable cross-sections were calculated. Calculations of short-circuit levels and power losses have been made for examined voltage levels.

Voltage drop represents the difference in voltage between the beginning and end of an electrical line through which current flows. When electric current flows through a conductor that has a certain resistance (R) and reactance (X), part of the electrical energy is consumed to overcome these impedances, so the voltage at the end of the line becomes lower than at the beginning.

The voltage drop indicates how much the voltage changes during the transmission of electrical energy through a line due to thermal and reactive losses in the conductor. This loss of voltage reduces supply quality and, if too large, can lead to improper operation of connected devices or generators.

Voltage is defined as a complex phasor. The fundamental equation for the voltage at the receiving end is:

$$\underline{V}_1 = \underline{V}_2 + \underline{I} \underline{Z} \quad (1)$$

Where $\underline{V}_1$ and $\underline{V}_2$ are complex voltage phasors at the sending and receiving nodes, $\underline{I}$ is complex line current and $\underline{Z} = R + jX$ is complex impedance.

Voltage drop magnitude is presented as:

$$\Delta U = |\underline{V}_1| - |\underline{V}_2| \quad (2)$$

The calculation of voltage drop is a key step in the design and analysis of power networks, especially those that connect distributed energy sources. It enables the sizing of cable cross-sections in order to limit the voltage drop to permissible values (typically up to 3%).

For adopted MV cable voltage levels 20 kV, 30 kV, 33 kV and 35 kV minimum cable cross-section must be calculated.

According to IEC 60287 and VDE general cable ampacity can be defined as follows:

$$I_n = \sqrt{\frac{\Delta\theta - W_d [0.5T_1 + n(T_2 + T_3 + T_4)]}{RT_1 + nR(1 + \lambda_1)T_2 + nR(1 + \lambda_1 + \lambda_2)(T_3 + T_4)}} \quad (3)$$

where $\Delta\theta$ is conductor temperature increase above ambient temperature 20 °C; R is electrical resistance [Ω/m]; T_1 , T_2 , T_3 are thermal resistances of conductor layers by unit of length [Km/W]; T_4 is thermal resistance of cable surface against the environment by unit of length [Km/W]; W_d is dielectric losses by unit of length [W/m]; n number of current-flown conductors in one cable; λ_1 is ratio between losses in the metal screen and total losses in the conductors; λ_2 is ratio between losses in the metal armor and total losses in the conductors. It can be defined too that $0.5T_1$ means that only half of conductor thermal resistance is affected by dielectric losses (IEC assumption). Sum $n(T_2 + T_3 + T_4)$ means that dielectric losses heat all surrounding layers and all parallel cables.

The real cable ampacity (I_r) can be obtained by multiplying the cable ampacity equation 3 and all correction factors:

$$I_r = I_n \cdot \sum_{i=1}^n f_i \quad (4)$$

and

$$\sum_{i=1}^n f_i = f_1 \quad (5)$$

where f_i can be:

- f_1 - factor depending on soil temperature, soil thermal resistivity and load level and
- f_2 - factor depending on soil thermal resistivity, load level cable grouping.

General review of major factors affecting cable ampacity is presented in [16].

An electrical disturbance that occurs when conductors of different potentials in an electrical system are connected directly or through very low resistance is called a short circuit. As a result of a short circuit, the current in the circuit increases suddenly, often reaching several hundred times the nominal value. Such large current values can lead to equipment damage and pose a significant safety risk to people. A short circuit is most often caused by mechanical damage, electrical overloads, external influences, improper handling, and aging of insulating material. This paper analyzes three-phase short circuits (basis for equipment selection, and generally, a lower short-circuit current value means more affordable and cost-effective equipment). At the voltage levels addressed, the three-phase short-circuit currents used for equipment selection are usually: 16 kA, 20 kA, 25 kA, 31.5 kA etc. Initial symmetrical three-phase short-circuit current at a specific fault location according to IEC 60909:

$$I_{k3}'' = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_k} \quad (6)$$

where c is coefficient accounts for the difference between the nominal system voltage and the actual voltage at the fault location, as well as variations in transformer taps. Z_k is equivalent short-circuit impedance (positive sequence impedance) looking into the system from the fault point.

The initial short-circuit current can be calculated (IEC 60909):

$$i_p = \sqrt{2} \cdot \gamma \cdot I_{k3}'' \quad (7)$$

where γ is a factor depending on the R/X and can be calculated approximately using the following equation:

$$\gamma = 1.02 + 0.98 \cdot e^{-3 \frac{R}{X}} \quad (8)$$

3. MATERIALS AND METHODS

An analytical approach for determining the appropriate MV cabling level in renewable energy parks (considering voltage levels 20 kV, 30 kV, 33 kV and 35 kV) is introduced. This approach is generalized regarding renewable energy parks with radial feeders. Appropriate MV cable level is voltage level with the minimum costs in 20 years exploitation of MV cable system. Mentioned costs are sum of MV cable system costs including MV switchgear (CAPEX) and power losses costs in exploitation period.

Formula can be written:

$$MV_{costs}(EUR) = CAPEX(EUR) + \sum_{t=0}^{20} \text{Energy losses}(EUR) \quad (9)$$

where $MV_{costs}(EUR)$ are total losses in EUR for exploitation period. $CAPEX(EUR)$ is total cost of MV cabling systems including cables and switchgear regarding short circuit level and sum of Energy losses (EUR) are total energy losses in 20-year exploitation period.

Energy losses on yearly basis in MWh can be easily defined as:

$$\text{Energy losses}(MWh) = P(kW) \cdot t(h) \cdot 1000 \quad (10)$$

$$\sum_{t=0}^{20} \text{Energy losses}(EUR) = \text{Energy losses}(MWh) \cdot c(EUR/MWh) \quad (11)$$

where $t(h)$ present working hours (full load equivalent), $P(kW)$ are power losses in yearly period and $c(EUR/MWh)$ is price of power losses. Price of power losses can vary, and different values can be obtained. Generally, cost of power losses can be easily defined as price of energy not supplied to the network (PCC) due to losses. Regarding that, average price for generated energy of the park can be set as price for power losses on yearly basis. For every energy park type, generated energy can be presumed regarding park modelling (location of park, windspeed, sunny hours, cabling etc.). According to [17] PV plant generated energy can vary 1500-2000 MWh/y. According to [18] windfarm generated energy can be 3000-4000 MWh/y. Regarding

energy prices (EUR/MWh), those values depend on stock exchange. For PV plant energy price (loss price) of 80 EUR/MWh is taken, and for wind farms 140 EUR/MWh. With this method, it is easy to find total MVcosts (EUR) of MV cabling systems including cables and switchgear regarding short circuit level and sum sum of Energy losses (EUR) in 20-year exploitation period. This exploitation period can vary but 20-year period is selected as a minimum lifetime of energy parks windfarms and PV plants.

4. CASE STUDY

Case study will be energy park, in this case PV plant with five radial feeders. The single-line diagram is shown in Figure 1. and details are given in Table I.

Summary of the internal cable network:

- 17 substations (transformer stations),
- 13 3-winding transformers,
- 4 2-winding transformers,
- 33 kilometres of internal cable network,
- 5 feeders,
- 96 MVA installed transformer capacity,
- 58.8 MW rated power of plant.

Table I: Technical characteristics of case study network

Name	Power (MW)	Node1	Node2	Length (m)
Feeder 1	11.5	0	A	790
		A	B	900
		B	C	960
Feeder 2	11	0	D	485
		D	E	360
		E	F	240
Feeder 3	13.85	0	G	605
		G	H	700
		H	I	835
		I	J	250
Feeder 4	9.1	0	K	70
		K	L	335
		L	M	710
Feeder 5	13.35	0	N	1350
		N	O	590
		O	P	1200
		P	R	430

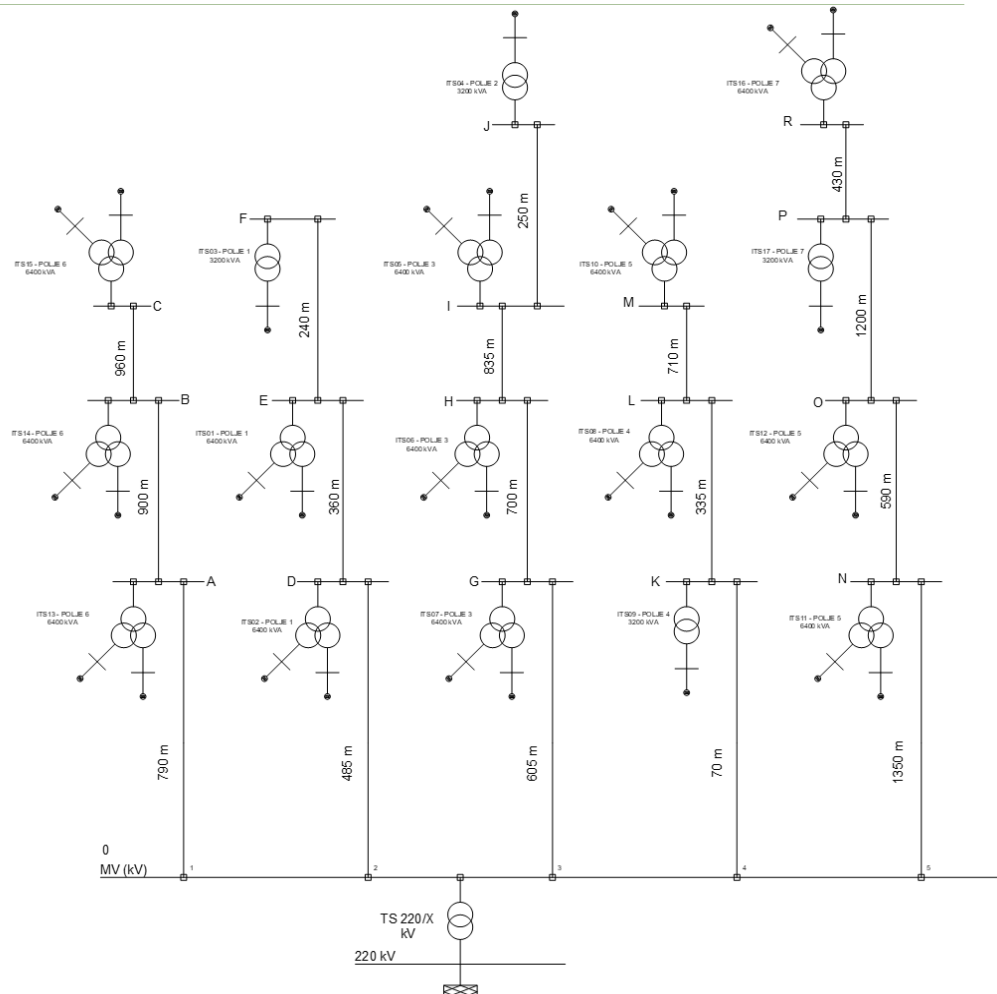


Figure 1: Single-line diagram analysed case study

It is 49 bus system. Even case study is PV plant, same single-line diagram can be adopted for wind farm regarding rated power. Difference can be in generated energy since wind farm in general generates more energy than PV plant.

5. RESULTS

For presented case study load flow and short circuit calculations were performed. Calculations were performed by iterative numerical technique Newton-Raphson approach on previously modelled network.

Regarding cable cross-section, for minimum cable cross-section selection correction factors for cable laying must be considered.

General settings for cable ampacity calculation:

- Soil temperature: 25 [°C] – assumed temperature on cable laying depth
- Soil Thermal Resistivity: 1.5 Km/W – regular rain
- Load level: 0.5 – daily full-load maximum period up to 12 hours
- Distance cable to cable: 25 cm
- Maximum number of cables in group: 2

The DIN Standard VDE 0276-1000 provides correction factors f_1 and f_2 . The factor f_1 is defined as follows (Table II.):

Table II: Correction factor f_1 according to VDE 0276-1000

Permissible operating T [°C]	Soil temperature	Soil Thermal Resistivity:
	[°C]	1.5 Km/W
	25	Load level: 0.5
		0.9

In Table II., correction factors are defined with respect to soil temperature, soil thermal resistivity, and load factor.

Factor f_2 is defined for a cable spacing of 25 cm and is presented in Table III.:

Table III: Data of analysed cable

Distance between cables [cm]	Number of circuits	Soil Thermal Resistivity:
		1.5 Km/W
		Load level: 0.5
25	1	1.13
25	2	1.04

Regarding cable details and reduction factors maximum permissible cable current for cable systems in trenches is given in table 1 and 2.

Regarding cable details and reduction factors maximum permissible cable current is for one cable in trench (general I_{cable}):

$$k = f_1 \cdot f_2 = 0.9 \cdot 1.13 = 1$$

$$\begin{aligned} I_{n \text{ uk } 185\text{mm}2120_{\text{kV}}} &= 390 \cdot 1 = 390 \text{ A} \\ I_{n \text{ uk } 120\text{mm}2130_{\text{kV}}} &= 300 \cdot 1 = 300 \text{ A} \\ I_{n \text{ uk } 240\text{mm}2120_{\text{kV}}} &= 443 \cdot 1 = 443 \text{ A} \\ I_{n \text{ uk } 150\text{mm}2130_{\text{kV}}} &= 334 \cdot 1 = 334 \text{ A} \end{aligned}$$

Regarding cable details and reduction factors maximum permissible cable current is for two cables in trench (general I_{cable}):

$$\begin{aligned} k &= f_1 \cdot f_2 = 0.9 \cdot 1.04 = 0.94 \\ I_{n \text{ uk } 240\text{mm}2120_{\text{kV}}} &= 443 \cdot 0.94 = 416 \text{ A} \\ I_{n \text{ uk } 120\text{mm}2130_{\text{kV}}} &= 300 \cdot 0.94 = 282 \text{ A} \\ I_{n \text{ uk } 185\text{mm}2120_{\text{kV}}} &= 390 \cdot 0.94 = 366 \text{ A} \\ I_{n \text{ uk } 150\text{mm}2130_{\text{kV}}} &= 334 \cdot 0.94 = 314 \text{ A} \end{aligned}$$

In this way, the methods of routing and laying cables along all sections have been determined.

The conditions that is satisfied:

- $I_r \geq I_{cable}$ - the rated current of the cable must be greater than the current flowing through the cable at any moment.

For a nominal internal network voltage of 20 kV, a cable with a minimum continuous operating voltage of 20 kV, assuming a maximum network voltage of 24 kV is selected. Therefore, a cable with a rated voltage of 12/20 kV is selected, which corresponds to a maximum permissible voltage of 24 kV [19] – [21].

For a nominal internal network voltage of 30-35 kV, a cable with a minimum continuous operating voltage of 30 kV, assuming a maximum permissible network voltage of 36 kV is selected. Therefore, a cable with a rated voltage of 30 kV is selected, which corresponds to a maximum permissible voltage of 36 kV.

Technical characteristics of adopted power cables are shown in Table IV.

Table IV: Technical characteristics of the MV cables

Cable type	NA2XS(F)2Y XHE 49-A	
Rated voltage U0/U	18/30 kV	
Maximum permanently permissible operating voltage	36 kV	
Permissible cable load current at ground thermal resistance of 100 °C/W (cables laid in a triangle)	334 A	300 A
Conductor material	Al	
Nominal cross-section of the conductor	150 mm ²	120 mm ²
Nominal screen cross-section	25 mm ²	16 mm ²

Cable outer diameter	41 mm	39 mm
Conductor diameter	14,1 mm	12,7 mm
Nominal short-term current at conductor temperature of 90 °C	31,1 kA / 0.2 s	24,8 kA / 0.2 s
Insulation	XLPE	XLPE
Sheath	PE-HD	PE-HD
Cable type	NA2XS(F)2Y XHE 49-A	
Rated voltage U0/U	12/20 kV	
Maximum permanently permissible operating voltage	24 kV	
Permissible cable load current at ground thermal resistance of 100 °C/W (cables laid in a triangle)	336 A	390 A
Conductor material	Al	
Nominal cross-section of the conductor	150 mm ²	185 mm ²
Nominal screen cross-section	25 mm ²	25 mm ²
Cable outer diameter	35 mm	37 mm
Conductor diameter	14,1 mm	15,7 mm
Nominal short-term current at conductor temperature of 90 °C	31,1 kA / 0.2 s	38,3 kA / 0.2 s
Insulation	XLPE	XLPE
Sheath	PE-HD	PE-HD

A critical voltage drop is usually above 3% and depends on the project requirements. However, it must be kept in mind that a larger voltage drop also represents increased losses. Since this case study presents renewable energy park (generators), voltage rise for this case study is subjected.

The conditions that must be satisfied for this case study:

- $\Delta u < 3\%$ - the total voltage drop/rise of the MV feeder must be less than 3%.

In table below (Table V.) for analysed voltage levels, highest bus voltage rise is shown.

Table V: Highest bus voltage rise for analysed MV voltage levels

U_{rated} (kV)	U_{max} (kV)	U (p.u.)
20	20.22	1.011
30	30.19	1.006
33	33.16	1.005
35	35.12	1.004

It is visible that voltage rise is negligible for every voltage level.

Regarding short-circuit, calculations for three-phase short circuits were performed. The goal was to find the level of short-circuit currents regarding equipment selection (16 kA, 20 kA, 25 kA or 31.5 kA etc.)

This is important for equipment selection because 25 kA equipment and above is much more expensive than equipment up to 20 kA (standard distribution equipment). For all voltage levels short-circuit calculations, only in case of 20 kV MV cabling short circuit current rises over 20 kA in three buses as presented in Table VI.

Table VI: Buses with short-circuit current over 20 kA in 20 kV network

Bus	U_{rated} (kV)	I_{k3} (kA)
ITS08MV	20	20,10
ITS09MV	20	22,76
Terminal	20	23,19

For all other cases short circuit current are up to 20 kA.

Table VII. shows power losses for different rated voltages of MV cabling systems.

Table VII: Power losses for different rated voltages of MV cabling systems

U_{rated} (kV)	P losses (kW)
20	770
30	620
33	580
35	550

Power losses are sum of transformer losses (iron and cooper losses) and MV cable losses.

As rated voltage is higher, power losses decrease, as presented at Figure 2.

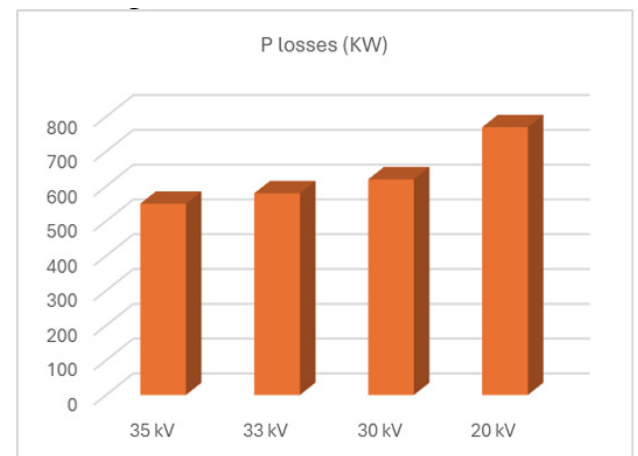


Figure 2: Power losses for analysed case study regarding MV voltage level

6. DISCUSSION

In this chapter, MV costs will be analysed and discussed for four variants of rated MV voltage: 20 kV, 30 kV, 33 kV and 35 kV. In this way, a systematic comparison of multiple internal layout MV cabling variants is enabled. The goal is to select appropriate internal MV cabling rated voltage regarding MV costs.

Table VIII. presents costs for selected cables regarding voltage level. Prices are taken experientially.

Table VIII: Costs for selected cables regarding voltage level

Cable NA2XS(F)2Y XHE 49-A	Length (m)	Price (EUR/m)	Total price (EUR)	CAPEX (EUR)
18/30 kV 120 mm ²	22600	18	406800,00	614700,00
18/30 kV 150 mm ²	9900	21	207900,00	
12/20 kV 150 mm ²	22600	19,5	440700,00	660480,00
12/20 kV 185 mm ²	9900	22,2	219780,00	

Quantity of transformer and line bays is presented in Table IX. For 20 kV system 12 bays are 25 kA rated short-circuit currents.

Table IX: Quantity of transformer and line bays

	Quantity	
	12/20 kV	18/30 kV
Transformer Bay	30	30
Line Bay	35	35
	65*	65

Unit prices for transformer and line bays are presented in Table X. Prices are taken experientially.

Table X: Unit prices for transformer and line bays

	Price	
	18/30 kV	12/20 kV
Transformer Bay (EUR)	25000	12000
Line Bay (EUR)	20000	8000
Bay 25 kA		40000

Total CAPEX (EUR) is calculated as mathematical sum of cable and switchgear costs in EUR. It is presented in Table XI.

Table XI: CAPEX (cable and switchgear)

	CAPEX (EUR)	
	35 kV	20 kV
CABLE	614700,00	660480,00
SWITCHGEAR	1450000,00	1004000,00
SUM	2064700,00	1664480,00

Energy losses in MWh for voltage levels 20-30-33-35 kV are calculated on yearly basis (Eq 10). It is presented in Table XII.

Table XII: Energy losses in MWh for voltage levels 20-30-33-35 kV

	Working hours (full load equivalent)			
	1500 h	2000 h	3000 h	4000 h
35 kV	825	1100	1650	2200
33 kV	870	1160	1740	2320
30 kV	930	1240	1860	2480
20 kV	1155	1540	2310	3080

Working hours (as full load equivalent) are 1500 - 2000 hours for PV plants and 3000 – 4000 hours for wind farms. Energy losses on yearly basis are calculated with Eq.11. It is presented in Table XIII.

Table XIII: Energy losses on yearly basis in MWh

	Energy losses (EUR)			
	Working hours (full load equivalent)			
kV	1500 h	2000 h	3000 h	4000 h
35	66000,00	88000,00	231000,00	308000,00
33	69600,00	92800,00	243600,00	324800,00
30	74400,00	99200,00	260400,00	347200,00
20	92400,00	123200,00	323400,00	431200,00

For PV plant energy price (loss price) of 80 EUR/MWh is taken, and for wind farms 140 EUR/MWh.

On Figure 3 MV_{costs} (EUR) on yearly basis for 20-year period are presented (1500 full working hours equivalent energy park). MV cabling level 20 kV and 35 kV are compared.

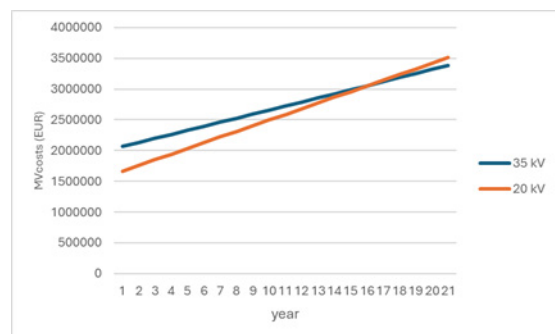


Figure 3: Comparison of MV_{costs} (EUR) on yearly basis for 20-year period (1500 full working hours equivalent energy park) 20 kV – 35 kV

It can be concluded that in this case 20 kV MV costs are higher regarding 35 kV costs in 20-year period. These 20 kV MV costs become higher after 15 years of system exploitation regarding 35 kV MV costs.

On Figure 4 MV_{costs} (EUR) on yearly basis for 20-year period are presented (4000 full working hours equivalent energy park). MV cabling level 20 kV and 35 kV are compared.

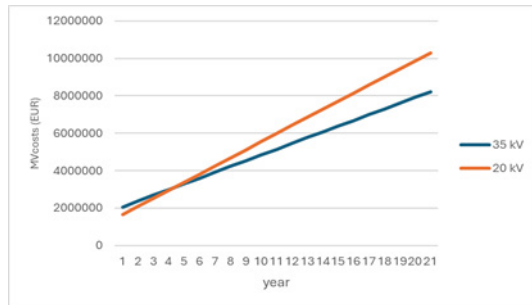


Figure 4: Comparison of MV_{costs} (EUR) on yearly basis for 20-year period (4000 full working hours equivalent energy park) 20 kV – 35 kV

It can be concluded that in this case 20 kV MV costs are higher regarding 35 kV costs in 20-year period. These 20 kV MV costs become higher after 3 years of system exploitation regarding 35 kV MV costs.

If short-circuit currents were for each case study below 20 kA (hypothetical) total CAPEX (EUR) are presented in Table XIV.

Table XIV: CAPEX (cable and switchgear) for 20 kA switchgear

	CAPEX (EUR)	
	35 kV	20 kV
CABLE	614700,00	660480,00
SWITCHGEAR	1450000,00	1004000,00
SUM	2064700,00	1664480,00

On Figure 5 MV_{costs} (EUR) on yearly basis for 20-year period are presented (1500 full working hours equivalent energy park). MV cabling level 20 kV and 35 kV are compared. This is valid for 20 kA switchgear.

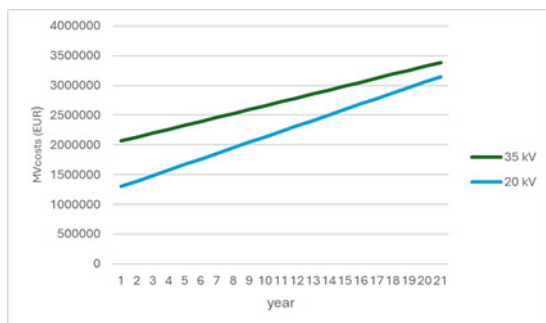


Figure 5: Comparison of MV_{costs} (EUR) on yearly basis for 20-year period (1500 full working hours equivalent energy park) 20 kV – 35 kV (up to 20 kA switchgear)

It can be concluded that in this case 35 kV MV costs are higher regarding 20 kV costs in 20-year period.

On Figure 6 MV_{costs} (EUR) on yearly basis for 20-year period are presented (4000 full working hours equivalent energy park). MV cabling level 20 kV and 35 kV are compared. This is valid for 20 kA switchgear.

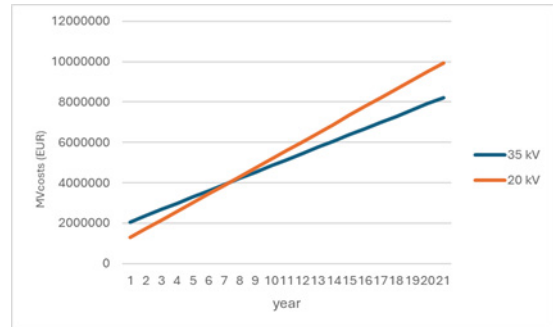


Figure 6: Comparison of MV_{costs} (EUR) on yearly basis for 20-year period (4000 full working hours equivalent energy park) 20 kV – 35 kV (up to 20 kA switchgear)

It can be concluded that in this case 20 kV MV costs are higher regarding 35 kV costs in 20-year period. These 20 kV MV costs become higher after 6 years of system exploitation regarding 35 kV MV costs.

7. CONCLUSION

This paper gives an analytical approach for determining the appropriate MV cabling level in renewable energy parks. Voltage levels 20 kV, 30 kV, 33 kV and 35 kV were examined. Appropriate MV cable level is voltage level with the minimum costs in 20 years exploitation of MV cable system. Mentioned MV costs (EUR) are sum of MV cable system costs (CAPEX) and power losses costs in exploitation period.

Obviously, higher nominal MV voltage level decreases power losses. Lower nominal MV voltage level generally increases short-circuit level.

In presented case study for various short-circuit switchgear currents regarding short-circuit calculations:

- It can be concluded that in this case 20 kV MV costs are higher regarding 35 kV costs in 20-year period. These 20 kV MV costs become higher after 15 years of system exploitation. This is valid for renewable energy parks with 1500 h - 2000 h full working hours equivalent (PV plants).
- It can be concluded that in this case 20 kV MV costs are higher regarding 35 kV costs in 20-year period. These 20 kV MV costs become higher after 3 years of system exploitation. This is valid for renewable energy parks with 3000 h - 4000 h full working hours equivalent (wind farms).

Generally, it can be concluded regarding analysis performed in this case study for 20 kA switchgear (standard switchgear):

- For renewable energy parks with 1500 h - 2000 h full working hours equivalent (PV plants) can be concluded that 35 kV MV costs are higher regarding 20 kV costs.
- For presented case study 35 kV MV costs are higher throughout the total exploitative period regarding 20 kV MV costs.
- For renewable energy parks with 3000 h - 4000 h full working hours equivalent (wind farms) can be concluded that 20 kV MV costs are higher regarding 35 kV costs. These 20 kV MV costs become higher after 6 years of system exploitation.

Switchgear nominal current depends on a short-circuit calculations. Those calculations must be performed before switchgear selection.

Presented model is uniform and can be easily implemented in design of appropriate radial MV cabling systems for various types of renewable energy parks.

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