

# Distribution Grid Future Planning Under Uncertainty Conditions

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**Abstract.** The paper presents an approach for making decisions about the future development of a distribution grid under uncertainty conditions. The levels of a grid hosting capacity and adequacy are examined using probabilistic approach compared to the conventional deterministic fit-and-forget approach. It is shown that the probabilistic approach according to the 99 % confidence probability saves significant costs in comparison with the deterministic approach. The probabilistic calculations prove the use of an equipment rated capacity downsized by 2 points of a typical IEC scale, and in some cases to refuse the construction of a parallel circuit.

The main contribution of the paper is a method for choosing an effective rated voltage of a distribution grid in a probabilistic interpretation based on the conventional formulas of Still, Zalessky and Illarionov. The technique includes obtaining the probability of loads location at different distances from power supply centre and the probability of load power distribution in a given range of values. It is shown that the calculation using the developed method makes possible to prefer grid rated voltage at least 1 point downsized by IEC scale with sufficient savings due to the difference in the equipment price compared with the deterministic fit-and-forget approach.

**Key words.** Distribution grid, distributed energy resources, future planning, decision making, uncertainty conditions.

## 1. Introduction

The issue of distribution grid planning is of great importance nowadays. Due to the development of microgrids and Smart Grids conventional approaches to be revised to ensure proper level of grid adequacy and economy. The main challenge for the planning is a high degree of uncertainty provided by distributed energy sources, including the renewables [1].

The existing design and planning practice for distribution grid future development typically includes a selection of a grid equipment with a significant margin of capacity reserve based on a calculation of peak-load steady state

[2], [3]. This conventional approach is deterministic fit-and-forget approach. The margin of reserve often leads to unreasonably high capital investments to a grid, since corresponding high levels of load and generation imbalances that very seldom occur [4]. Historically, this was due non-smart stage of medium-voltage distribution grids development: unidirectional power flows, lack of proper observability of the distribution network, lack of dispatch control (in fact, only service and maintenance were applied) [5].

A probabilistic approach to the future development of an electrical distribution grid provides avoiding unreasonably high capital investments to a grid during the conditions of increasing load density, increasing length of a grid, and interconnecting distributed generation of all types [6], [7].

The paper presents an approach to making decisions about the future development of a distribution grid under uncertainty conditions. The levels of electrical loads and generation based on renewable energy sources, including photovoltaic and wind generation, are considered as uncertainties. The calculation is performed by a probabilistic method using mathematical distributions describing the relevant influencing factors.

The paper provides the quantitative representation of the economy provided by the choice between some rated voltage of a grid given the variety of state and topology diversity. However, the main contribution of the paper is a rated voltage selection for distribution grid based on the probabilistic approach applied to conventional formulas describing the relations between grid load and its length.

## 2. Theoretical Background

The balances depend upon nodal power injections. The nodal injections are represented by loads and sources, like distributed power generation. The idea of the algorithm is to obtain flows between nodes given the nodal injections with respect to their probability parameters and

to compare the flows values with the capacity of planned equipment [8]. The stages of calculation are represented further.

### A. Obtaining Nodal Power Distribution Probabilities

Load power  $P$  can be represented by Gaussian distribution [9], [10]:

$$f(P) = \frac{1}{\sigma_P \sqrt{2\pi}} \exp\left(-\frac{(P - P_{med})^2}{2\sigma_P^2}\right), \quad (1)$$

$P$  is not a constant here;  $P_{med}$  can be represented as medium estimated load in a node;  $\sigma_P$  can be obtained as the difference between maximum  $P_{max}$  and medium  $P_{med}$  estimated loads from Gaussian distribution properties:

$$\sigma_P = (P_{max} - P_{med})/5 \quad (2)$$

It is well known that  $\pm 2\sigma_P$  confidence interval corresponds to the 95.4 % confidence probability and  $\pm 3\sigma_P$  confidence interval corresponds to the 99.2 % confidence probability.

Wind speed  $V$  distribution is described by Weibull probability distribution [11], [12]:

$$f(V) = \frac{k}{\lambda} \left(\frac{V}{\lambda}\right)^{k-1} \exp\left(-\left(\frac{V}{\lambda}\right)^k\right), \quad (3)$$

where  $k$  and  $\lambda$  are probability distribution parameters obtained from gathered statistics or numerical weather prediction for a given region where the grid is located.

To convert wind speed to wind power wind-to-power curve  $P_{urb}=f(V)$  is used according to IEC 61400 [13] for each wind turbine. For on-shore wind farms IIIa and IIIb wind classes are the most common. IEC IIIb class is used in this work for all the wind farms. So, the resulting distribution of a wind power is represented as:

$$P_w(V) = f(V) \cdot P_{urb}(V) \quad (4)$$

PV power is modelled by beta distribution [14]-[16]:

$$f(P) = \frac{P^{\alpha-1}(1-P)^{\beta-1}}{B(\alpha,\beta)}, \quad B(\alpha,\beta) = \int_0^1 P^{\alpha-1}(1-P)^{\beta-1}, \quad (5)$$

where  $\alpha$  and  $\beta$  are probability distribution parameters obtained from gathered statistics for a given region where a distribution grid is located.

After obtaining nodal power distribution probability density functions according to engineering practise it is useful to convert them into numerical integration-friendly format. The idea is to divide the distribution into stepped form graph with the square of rectangle at each step equal to the corresponding integral of the replaced probability function (Fig. 1). Discrete representation of probability values provides more efficient calculations at the next step.

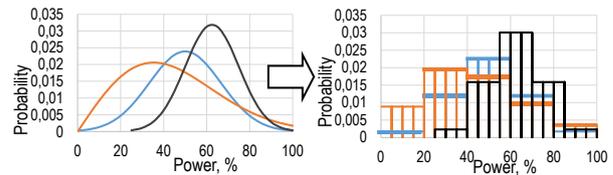


Fig. 1. Probability density graph discretisation. Load is shown in dark grey, wind in orange, and photovoltaic in blue

### B. Calculating Different Combinations of Balances

Calculating of balances (unbalances) is implemented via the calculation of different combinations of nodal power values with respect to their probability. A huge set of literature is devoted to the probabilistic calculation of steady states [17]-[21]. Improving corresponding methods and techniques is out of the scope of this paper. However, the following points to be noted.

One of the main features complicating probabilistic steady state calculation is the covariance (and correlation) between nodal power values leading to the covariance between voltage values. This matters if the calculation is based on voltages [22]. There are two different approaches providing the solution. The first one is the vector space transformation by means of different methods [23]. Taking into account covariance values is an exact approach, although it leads to high computation load, especially in spreading distribution grids.

The second approach is the analysis of the errors arising if the corresponding covariance and correlation between two nodal power values is neglected [22]. A good methodical assumption is the independent voltage control in different nodes that provides smaller error value. For planned future Smart Grids this assumption is close to the reality because inverter-based distributed generation and frequency-driven motors occupying more than 70 % of load that can regulate voltage in the discussed way. Final contribution makes an aggregation of the same-type loads (industrial loads, residential, commercial, etc.). In this case distinguishing loads, as well as distinguishing sources to be supposed low-correlated (independent). During the calculation all the same-type loads are supposed to have the same probability of relative power values.

Both approaches results in an opportunity to use computationally simple and effective combination of nodal power probabilities to calculate the whole set:

$$\Pr\{P_1 \in S_1, P_n \in S_n\} = \prod_{i=1}^N P_i \in S_i, \quad (6)$$

where  $N$  is a number of nodes;  $S$  is an independent set of particular-type power values, including wind power, photovoltaic power, industrial load power, commercial load power, residential load power, etc. Traditional constant coincidence (simultaneity) factors imply strong mutual correlation between the considered power values and can't provide *how often and how long* these cases of the simultaneity arise and the total share of the states to be excluded for prospective planning.

Further calculations can be made using one of the steady-state calculation methods [23]. This work uses current balance-based equations of state parameters. The initial data for the calculation includes power lines conductivity in S, or p.u. along with km if  $R/X$  ratio of a grid is unified. Nodal voltages in current balance form:

$$\mathbf{Y}\mathbf{U} + \mathbf{Y}_B\mathbf{U}_B = \frac{\mathbf{P}}{\mathbf{I}}, \quad (7)$$

where  $\mathbf{Y}$  is a matrix of conductivity;  $\mathbf{U}$ ,  $\mathbf{P}$ ,  $\mathbf{I}$  are vectors of nodal voltages, power values and nodal currents, correspondingly. The results of the calculation are steady-state parameters, including voltages and currents.

### C. Selecting a Set of States for Making Decision

After calculating state parameters for the whole set of states different probabilistic criteria can be applied to support decision making. The most common criteria to be applied are confidence probability criteria of 95 and 99 % [6]. According to this criteria, 5 % and 1 % of unlikely states are neglected, correspondingly (Fig. 2.)

## 3. Distribution Grid Capacity Planning

The paper examines levels of a grid hosting capacity and adequacy in terms of steady-state parameters (like voltages and currents) satisfying a grid code with probability of 95% and 99%. The levels are compared to the necessary levels in terms of a deterministic approach of 100 % probability. The set of distribution grids under consideration include 10-35 kV urban and rural grids:

- 1) urban 10 kV grids made of underground cable lines that typically suffers from overcurrents;
- 2) rural 10 kV grids made of self-carrying isolated cable and subject to both overcurrents and voltage deviations;
- 3) rural 35 kV overhead grids made of steel reinforced aluminium wire and subject mostly to voltage deviations.

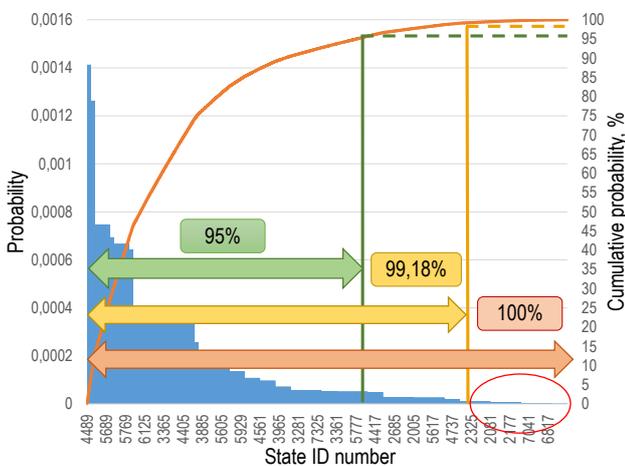


Fig. 2. Selecting a set of states according to confidence probability criteria. Red ellipse circumscribes typical scale of states share that very seldom arise but require additional capacity

Radial-type, loop and trunk topology up to 7 substations in a sequence were considered (Fig. 3). The analysed set includes distinguishing combinations of nodal and generation loads, such as regular, interlaced or consolidated nodal location types. In addition, single-circuit and double-circuit distribution power lines of a grid are considered. Nodal load and distributed generation maximum values vary randomly from 4 MW to 8 MW.

The concept and some results of capacity planning are shown in Fig. 4. Each confidence probability has corresponding confidence interval of power, current and voltage. As it can be seen from the figure, 5 % or 1 % of the most rare states excluded from the set depending upon the confidence probability criteria 95 % and 99 %, correspondingly. These excluded states are always represent the most rare states, like maximum load combined with minimum generation, or, vice versa, maximum generation combined with minimum load. These rare states are completely taken into account by fit-and-forget deterministic approach, but not by a probabilistic approach. The residual less than 1% of cases and states followed by overloads and unacceptable voltage drops are considered as pre-emergency and emergency states to be eliminated by means of relay protection and emergency control automation devices.

The results of the economy that arises for the cases of probabilistic approach-based grid development is shown in Table I. The probabilistic calculations prove the use of an equipment rated capacity downsized by 1 point [24] for 99 % confidence probability and up to 2 cross-section points for 95 % confidence probability. Averaged through case study downsize corresponds to the average economy. In case if the required due to fit-and-forget approach cross-section exceeds maximum available for single-circuit (630, 120 and 150 mm<sup>2</sup>, correspondingly), the probabilistic approach in some cases provides to refuse the construction of a parallel circuit, like for the case of rural 35 kV grid according to 95 % confidence probability criterion. It corresponds to maximum economy value. In should be noted that the reduction of wire-cross section itself for 35 kV overhead lines provides the economy of ~3 % only. but the main share of economy is due to the utilization of more light overhead line towers and tower bases for light wire of low cross-section.

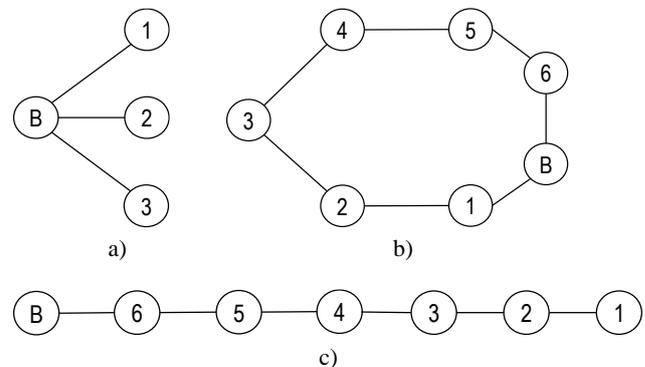


Fig. 3. Considered topologies of a distribution grid: a) radial; b) loop; c) trunk. Sign B (base node) marks power supply centre

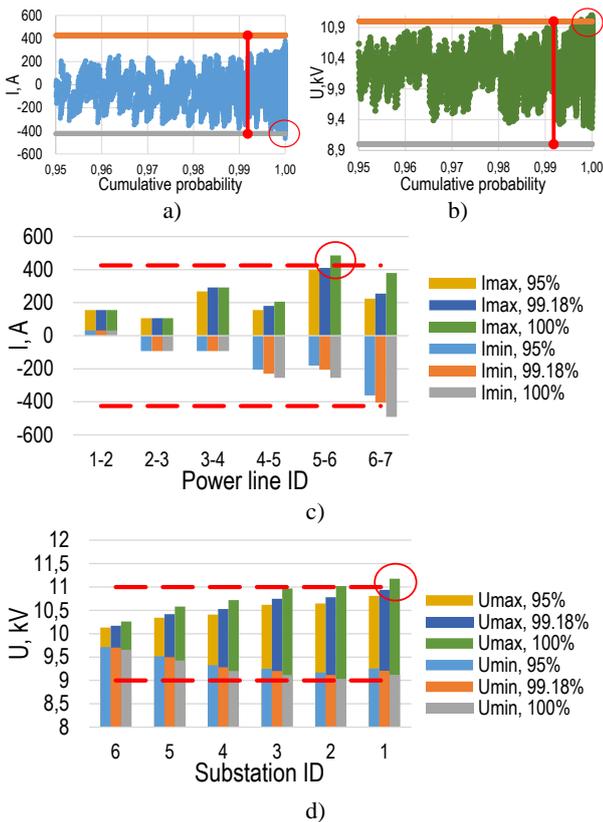


Fig. 4. Probabilistic exclusion of steady states at 10 kV grid shown in Fig. 3, c by means of 95 % and 99 % criteria compared to deterministic approach: a) overcurrent concept for 99 % (minus sign denotes reverse direction of a current); b) overvoltage concept for 99 %; c) overcurrent at the power line between substations No. 5 and No. 6; d) overvoltage at the substations No. 1

Table I. – Costs Economy at Distribution Grid Planning by Means of Necessary Cross-Section Reduction

Grid type	Cross-sections, mm <sup>2</sup>	Confidence probability applied	Cross-section reduction	Costs economy, average/max, %
Urban 10 kV	120, 240, 300, 400, 500, 630	95%	500 to 300	14.4 / 20.6
		99%	500 to 400	11.3 / 15.2
Rural 10 kV	70, 95, 120	95%	120 to 70	10.1 / 16.8
		99%	120 to 95	7.3 / 11.3
Rural 35 kV	70, 95, 120, 150	95%	150 to 95	21.6 / 30.9
		99%	150 to 120	12.1 / 22.7

#### 4. Distribution Grid Rated Voltage Selection

Although probabilistic approach provides some amount of costs economy for a distribution grid during capacity selection, the real potential for costs economy is a rated voltage selection. In real practise there is always a number of power supply centres that are available for a new distribution grid interconnection and development [1], [6]. The question is what rated voltage is more preferable to ensure efficient power distribution.

IEC standard scale assumes rated voltage is a discrete value [25]. Furthermore, in many countries according to grid codes there is a great gap between two adjacent rated voltages, for example, 6-20-110 kV or 10-35-110 kV. In

this case the selection of a proper rated voltage is of great performance, because an overestimation leads to sufficient cost overrun, due to the fact that grid equipment will hardly ever operate at the rated load levels.

There is a number of empirical formulas describing the dependency between power, power line length and required voltage. Well-known formulas that are used in different countries worldwide are Still formula, Illarionov formula and Zalessky formulas [26]. The paper presents a method for choosing an effective rated voltage of a distribution grid in a probabilistic interpretation based on these conventional formulas.

Still formula is written as:

$$U_{rated} = 4.34\sqrt{D+16P}, \quad (8)$$

where  $D$  is a distribution distance in km;  $P$  is a power in MW to be conducted. There is another one representation of the formula:  $U_{rated} = 5.5\sqrt{(0.62D + 3P/100)} = 4.33\sqrt{(D+48.3P)}$ . The difference is that this formulation calls for a single-phase power value, so rated voltage can be selected for double-phase or single-phase lines too.

Illarionov formula is known as:

$$U_{rated} = \frac{1000}{\sqrt{\frac{500}{D} + \frac{2500}{P}}} \quad (9)$$

Zalessky formula is represented by:

$$U_{rated} = \sqrt{P(100+15\sqrt{D})} \quad (10)$$

Accounting power in the formulas is made in the same way as it described in Chapters 2 and 3 of the paper. The power of load is supposed not to exceed the upper border of the confidence interval corresponding to 95 % or 99 % confidence probability depending on the criterion applied.

Load can be located at the different distance from power supply centre of distribution grid. Furthermore, in general load can exist with a distinguishing probability. The calculation of a distance is a standard square root of 2 coordinates (if height difference is not too large to be neglected). Nevertheless, a matching between distance and probability is required. The method proposed provides for a calculation of a distance by means of a cellular principle. The planed area of future distribution grid is divided to square cells with a power supply center located at the centre of the planned area. All the squares are filled with probability shares that form 1.000 for the area under consideration. The case study illustrates rural area, besides in urban areas all the distances are smaller.

The source values of a distance to be defined by means of a map of planned objects. Probability can be defined by some expert methods [17], but in this work probability is defined as the share of the total base area of the objects that corresponds to  $m$ -th square cellular of a grid area:

$$\sum_{m=1}^M p_m = \sum_{i=m}^M \frac{A_{obj,m}}{A_{obj}} = 1, \quad (8)$$

where  $M$  is a number of square cells,  $A_{obj,m}$  is a summary area of the objects located at  $m$ -th cell and  $A_{obj}$  is a total square of the objects to be supplied by the grid. Calculation of a distance is shown in Fig. 5.

Different combinations of load power probability and location probability can be obtained. They can be interpreted as follows:

- 1) Low probability of load existence, low load power according to 95 % and 99 % criteria. This means that it's unlikely to find a load located in the point. Examples include urban park area;
- 2) Low probability of load existence, high load power according to 95 % and 99 % criteria. This means that exact load location is under consideration due to some environmental restrictions, like new rural industrial plant layout and city office district internal planning;
- 3) High probability of load existence, low load power according to 95 % and 99 % criteria. This corresponds to some minor secondary objects, like industrial auxiliary or commercial buildings;
- 4) High probability of load existence, high load power according to 95 % and 99 % criteria. This corresponds to major primary objects, like industrial core or residential community.

A case study based on the map shown in Fig. 5. Nodal power values varying from 5 MW to 25 MW in a random order were conducted. The results of rated voltage calculation according to formulas are shown in Fig. 6.

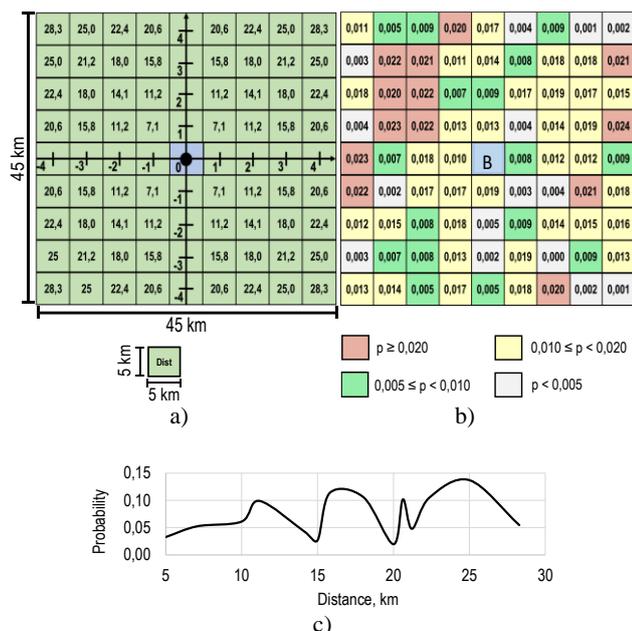


Fig. 5. Probability of load allocation in a distribution grid area using a case study of rural grid with mining, farm and village loads: a) square cellular principle with the values of distances from power supply center; b) probabilities; c) probability as a function of a distance. Sign B denotes power supply center

Different metrics and estimations could be applied for the selection of rated voltage. First, reference value to compare with that can be determined as:

- 1) simple average between rated voltages (72.5 kV in the case study between 35 kV and 110 kV);
- 2) taking into account voltage against power nonlinearity, root mean square between rated voltages (81.6 kV);
- 3) equal costs value for the rated voltages (depends upon the country).

Secondly, the metrics for estimating the obtained dataset may vary. Essential metrics include weighted by probability rated voltage  $\sum p_i U_{rated,i}$  (used further in the work), averaged via the dataset or median value. Furthermore, for the deterministic fit-and-forget approach rated voltage to be defined by means of the maximum value of the dataset regardless of the uncertainty either in load value or in load distance allocation. The results of rated voltage selection is shown in Table II. Based on the majority of estimations, 35 kV rated voltage can be selected for the distribution grid.

Specific costs for 35 kV grid construction and operation compared to 110 kV ones depend upon the region, but for this work they are 41 % lower. That states a great potential for costs economy using the proposed approach and methods.

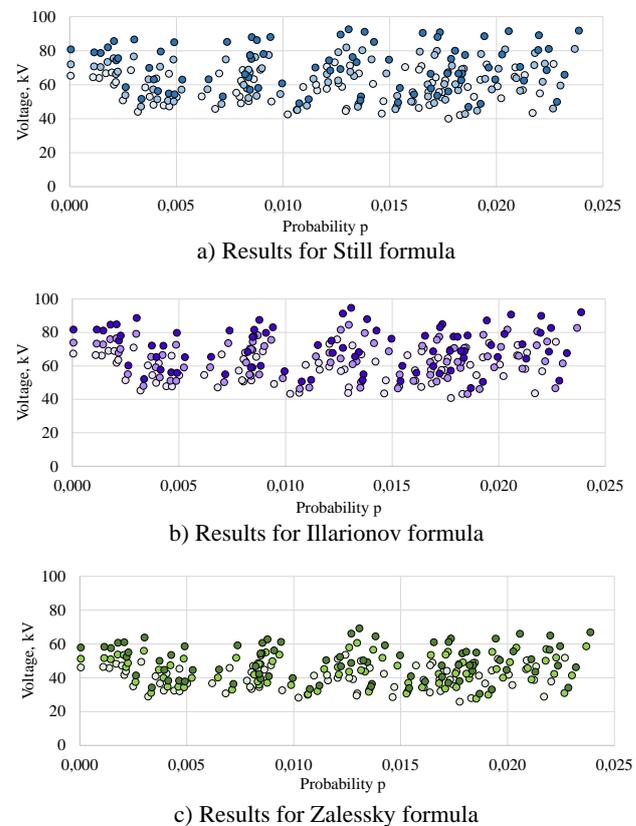


Fig. 6. Appropriate rated voltage according to the formulas. Vertical axis denotes recommended voltage in a variety of steady states. Horizontal axis denotes the probability of each state (the sum is 1.000). Light coloured dots denote 95 % confidence interval, medium coloured dots denote 99 % confidence interval and dark saturated dots denote deterministic approach

Table II. – Rated Voltage Selection

Load power confidential probability	Rated voltage selection by formula, kV		
	Still	Illarionov	Zalesky
95 %	52.6 → 35	56.4 → 35	35.9 → 35
99 %	63.3 → 35	65.2 → 35	42.6 → 35
100 %	92.6 → 110	94.8 → 110	73.2 → 110

## 5. Conclusion

The proposed methods provide the following possibilities:

- 1) To carry out the selection of probable grid operation steady states according to the given confidential probability criteria.
- 2) To select hosting capacity providing costs economy of 7.3-30.9 % for 10-35 kV distribution grids compared to deterministic approach;
- 3) To select rated voltage of a distribution grid based on the probabilistic approach to conventional formulas, that provides an economy up to 41 % (depends upon world region).

Further investigations to be concentrated on uncertainty analysis and on metrics for rated voltage estimations.

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