The stochastic approach for determination of transmission line wire cross section

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***Abstract*—**In this paper two approaches to choosing the optimum cross-section for an overhead line in the market conditions are considered: the deterministic approach and the stochastic one. This paper presents a new approach for implementing stochastic optimization procedure and comparing the results obtained by the two methodologies. The paper proposes a stochastic method of minimizing the annual costs for the construction of the line based on a statistical representation of the electric power prices, ambient temperature and electrical current loads in the electrical networks. The use of the Monte-Carlo method and the mentioned statistical data allow the synthesis of a user-friendly algorithm to solve this problem. As examples of stochastic approach 110 kV and 330 kV line were chosen. The solution tasks are done in MATLAB and “SAPR LEP 2011” softwares.

***Keywords*—** Costs minimization, network development, stochastic approach, transmission lines.

I. Introduction

PLANNING of the development of transmission networks pursues a number of conflicting, in common case, objectives, which include the following minimization tasks: power losses, capital investments, operation and maintenance costs and costs of energy not supplied due to interruptions in the network [1]. The complexity of the set task is caused by multiple objectives, the large number of variables, and random or uncertain character of initial information as well as dynamic nature of the problem.

In recent years, power industries have faced considerable changes including deregulation, open markets, appearance of local generation and renewable generation sources. These factors significantly change the planning task and the solution conditions and inspire a search for a new, more adequate method. Therefore, it is necessary to carry out more adequate technical and economic calculations in order to determine the compromise solution between the construction and exploitation costs [2].

One of the main elements of a rational construction of electric networks is the correct choice of conductor cross-sections at the new overhead power line design stage or in the network reconstruction situation. Therefore the choice of the optimum cross-section of conductors at design stage of networks determines the further costs in the operation of networks.

All the existing methodologies for selection the optimum conductor cross-section can be divided into the following two categories: the deterministic approach and the stochastic approach.

Significant changes in the conditions of power systems operation are leading to the necessity to consider significant fluctuations in the electricity prices. As a result there is a need for modification and verification of suitability of traditional deterministic approach. To test the validity of deterministic approach the stochastic method, which is outlined below, has been developed. However, convenience of employ, simplicity of obtaining additional information can pose the task of its development and use as a basic tool for the choice of the parameters of the wires.

This paper initially is devoted to a stochastic formulation of the problem. The complexity of the problem and two ways to simplify it are shown. The first way is based on the refusal to account dispersion of random variables [3], [4]. The second applies a user-friendly model for modeling of random processes.

II. Substance of Stochastic Approach

The anticipated optimization problem is based on minimization of annual costs, which can be described as:

$$C = \varphi(I, \beta, T_{amb}, \Pi) \tag{1}$$

where I, β, T_{amb} are respectively line power, energy price and the ambient temperature;

Π includes the set of other parameters influencing annual

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costs (such as maintenances cost, investments, interest rate).

Analyzing (1) one can claim that power and temperature are random time dependent parameters [3], which are correlated to each other. Correspondingly also C is a random time function, since it includes random time dependent parameters.

Multidimensional random process *C(t)* can be simplified by discretisation [3] of the function to a number of time periods:

$$t_1, t_2 \ldots t_n < T_{PL}, \tag{2}$$

where T_{PL} is the length of planning period.

Probability distribution function can be assigned for each time period. These distribution functions can be described as [5]:

$$\begin{cases} \Phi_{(1)}(C_1, t_1) \equiv P\{C(t_1) < C_1\}, \\ \Phi_{(2)}(C_1, t_1;\ C_2, t_2) \equiv \\ \equiv P\{C\ (t_1) < C_1;\ C(t_2) < C_2\}, \\ \ldots \end{cases} \tag{3}$$

Probability distribution function is as following:

$$\begin{cases} p_{(1)}(C_{G,1}, t_1) \equiv P\{C_G(t_1) = C_{G,1}\}, \\ p_{(2)}(C_{G,1}, t_1;\ C_{G,2}, t_2) \equiv P\{C_G(t_1) = \\ = C_{G,1};\ C_G(t_2) = C_{G,2}\}, \\ \ldots \\ \varphi_{(1)}(C_{G,1}, t_1) = \dfrac{\partial \Phi_{(1)}}{\partial C_{G,1}}, \\ \varphi_{(2)}(C_{G,1}, t_1; C_{G,2}, t_2) = \dfrac{\partial^2 \Phi_{(2)}}{\partial C_{G,1}\, \partial C_{G,2}} \end{cases} \tag{4}$$

Having the probability distribution functions the average costs can be calculated as:

$$\begin{aligned} & M\{f[C(t_1), \ldots, C(t_n)]\} = \\ & = \int_{-\infty}^{\infty} \ldots \int_{-\infty}^{\infty} f(C_1, \ldots, C_n)\, d\Phi_{(n)}(C_1, t_1, \ldots, C_n, t_n) \end{aligned} \tag{5}$$

Analyzing the equation (5) one can easily state that stochastic approach has lead us to formulation of extremely complicated target function, especially for minimization problems solution. Indeed, use of a stochastic approach requires large-scale statistical data and performance of labour-intensive calculations. Existence of this fact has formed the main barrier for stochastic approach implementation. Therefore, due to the rapid development of technologies, especially in the data communication and computing areas, this drawback of stochastic approach becomes insignificant.

III. Substance of Deterministic Approach

To explain the deterministic approach, we have to go back to (1) and assume that this equation does not include random parameters. In this case the total annual line exploitation costs depending on cross-section and line maximal current can be defined as follows [6, 7]:

$$\begin{aligned} & C_1 = (i + p_{\Sigma}) \cdot K_{L1} + 3 \cdot I_{maks}^2 \cdot R_1 \cdot (\tau \cdot \beta' + \beta'') \cdot 10^{-3} \\ & C_2 = (i + p_{\Sigma}) \cdot K_{L2} + 3 \cdot I_{maks}^2 \cdot R_2 \cdot (\tau \cdot \beta' + \beta'') \cdot 10^{-3} \\ & \ldots \\ & C_i = (i + p_{\Sigma}) \cdot K_{Li} + 3 \cdot I_{maks}^2 \cdot R_i \cdot (\tau \cdot \beta' + \beta'') \cdot 10^{-3} \end{aligned} \tag{6}$$

where i is the market interest rate, r.u.;

p_{Σ} are the total deductions on amortization, running repair and maintenance from the capital investments in the line construction, r.u.;

K_L is capital investments of overhead line, €/km.

τ is the annual utilization period per year, $\tau = f(T_{max})$, h;

T_{max} is the utilization time of maximum load per year, h;

β' is the specific price of electric power losses, €/kWh;

β'' is the specific price of capacity at the maximum time of power system load, €/kW.

R is active resistance of the wire line, Ω/km.

To simplify the choice of the line cross-section one can calculate and outline nomograms by using equation (6). The method of nomograms is also called the method of economical intervals [6]-[9]. This graphical representation has a shape of intersecting parabolic lines. The intersections of these lines indicate the values of the line current $I_{12} \ldots I_{(i-1),i}$ at which the transition from one cross-section to another is economically viable. The segment between two marginal current values corresponds to certain cross-section optimal for this segment. The new set of parameters p_{Σ}, β', β'' in (6) results in a new set of intersecting parabolic lines. The thick bottom line points at calculated minimal costs and the corresponding optimal cross-sections for each segment.

The choice of cross sections can be made knowing the maximal current and the parameters in equation (6). The examples of economic intervals for 110kV and 330 kV overhead lines are presented in Fig.1, Fig.2. Capital investments are calculated by special program “SAPR LEP 2011” and are described in VII part of the paper.

In Fig.1 it is seen that transfer from cross section 1xAS-185mm^2 to 1xAS-240mm^2 is economically profitable at line current value 100A. In Fig.2 transfer from cross section 1xAS-400mm^2 to 1xAS-500mm^2 is profitable at 350A, but from 2xAS-300mm^2 to 2xAS-400 mm^2 – 600A. If curves that don’t have any crossing with other ones, then corresponding cross sections are economically unprofitable and are not used for line construction.

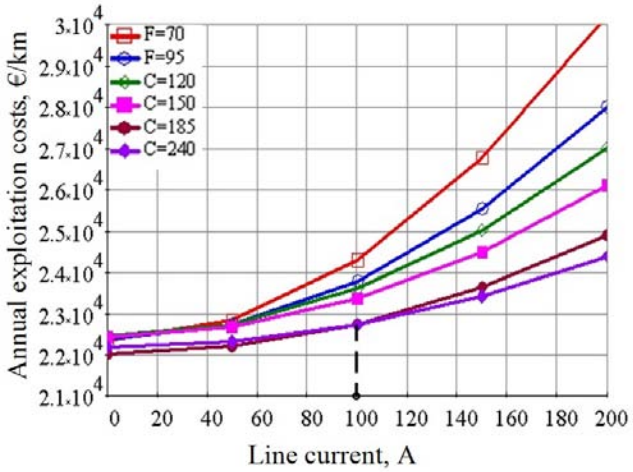

Fig.1. Current economic intervals for 110 kV overhead lines with AS wire

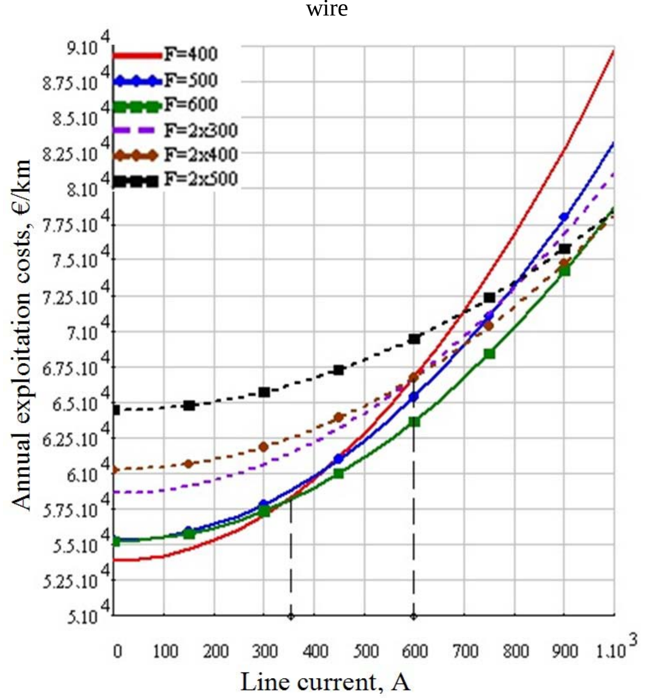

Fig.2. Current economic intervals for 330 kV overhead lines with decomposed AS wires and single AS wire in phase.

IV. Deterministic Approach's Shortcomings

The deterministic approach is simpler; however, it uses a number of assumptions, the validity of which at the new (market) conditions is questionable. By using the deterministic approach, it is difficult to reflect non-linear behavior of the system.

The main drawback of the deterministic method is assumptions leading to disregarding of random parameters in equation (1). In addition, according to the equation (6) the relation between costs and the load current is a nonlinear function. It can be stated that the dispersions of the load current, electricity prices, line resistances (considering temperature dependence) are considerable and influence the final calculation result. Variability of the load current in (6) is taken into account by choosing annual utilization period per year τ, price variation is not taken into account at all.

Thus, there is a need to investigate suitability of deterministic approach or necessity to replace it with a more accurate stochastic approach.

V. Synthesis of Algorithm based on Stochastic Approach

Let us return to the stochastic problem formulation described by equation (5). In order to estimate annual costs according to (5) the complicated multidimensional integral should be calculated. It should be added that for the considered task the dimension of the integral can be huge, since the planning period for the transmission lines is normally 25-40 years at the same time the electricity prices can vary considerably on hourly bases. This means that the number of discrete time periods leading to the dimension of the integral can become hundreds of thousands.

Moreover, in specified task it is necessary to operate with a minimum of three correlated processes. In this case autocorrelation and correlation functions [2], [10] should to be taken into account. It can be confirmed, that in order to avoid labor intensive calculating it is necessary to limit the number of sampling time moment, because each moment should be described by the distribution function. For this purpose it is possible to use detachment of year into few specific days (winter, spring and autumn, summer, work or holidays) [1]. The distribution functions of the parameters for each of such days can be approximated for example by Pearson charts [2]. However, this kind of analysis still demands a lot of efforts. This paper presents the new approach to solve the problem.

The algorithm for estimation of cost of power losses described below is based on the following assumptions:

1) Cost of power losses is the random time dependent function;

2) Considerable amount of data from the past is available (databases formed by supervisory control and data acquisition (SCADA) system);

3) The records from the past can be projected into the future processes;

4) Projection of the records from the „past" ($T_{amb}^{P}(t), \beta^{P}(t), I^{P}(t)$) into the „future" processes ($T_{amb}^{F}(t), \beta^{F}(t), I^{F}(t)$) can be performed by using one of the load forecasting parametric or artificial intelligence based methods [11].

In this paper there is a use of the following two algorithms (see Fig. 3):

- using the linear algebraic expressions that describe changes in the characteristics of the random process in time (for example average value and standard deviation of line power changes in the future).
- by summing up the records of past processes with anticipated changes. In this case, to the load of past years can be attached the planned new energy objects load.

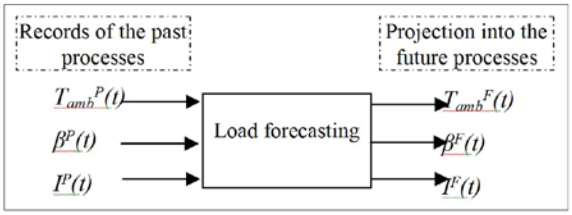

Fig. 3. Load forecasting scheme structure

5) The random process of variations in cost of power losses is egrodic [5]: (the term is used to describe a dynamical system which, broadly speaking, has the same behavior averaged over time as averaged over the space of all the system's states). In this case:

$$M\{C(t)\} \approx \int_{Ti}^{Ti+8760} \varphi\,(P(t), \beta(t), T_{amb}(t), \Pi)dt \qquad (7)$$

where T_i-T_i+8760 is duration year long period.

Adopting (7) instead of (5) allows calculating the average value of annual costs based on multidimensional random process with $I(t)$, $B(t)$, $T_{amb}(t)$.

In this approach due to the implementation of new smart grid technologies realization of (7) became very simple and allows to perform multidimensional registration of parameters (power, air temperature, prices, etc.) and to create an electronic database (library).

The key points of each method for determing annual costs are presented in Fig. 4.

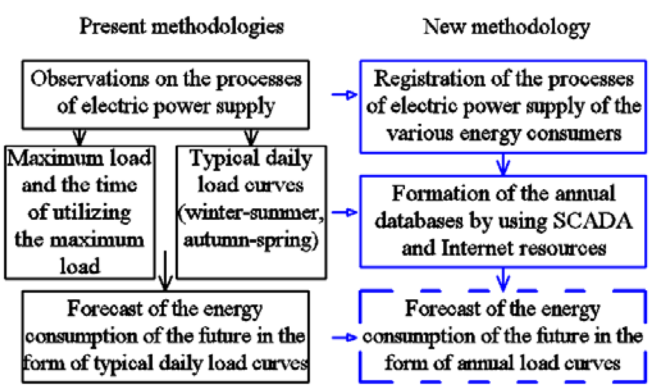

Fig.4. The key points of each method for determing the annual costs

VI. Description of Stochastic Approach's Algorithm

The new approach is based on following stochastic processes realization records application:

-Price change records of market.

-Ambient temperature records.

-Line load records.

The process of price and load changes during the time is expressed as non-stationary process that is why the historical records should be corrected.

The load records for the new line simply do not exist. There are two ways how to solve this problem:

1) select the line, which is analogue to the new one (by consumer type and number)

2) use the individual consumer load records and calculate the total line load by the summing up all the consumer loads.

Ambient temperature change process can be considered as stationary (if not taking into account climate changes). This means that the temperature records can be used without correction.

The structure the proposed algorithm is given in Fig. 5.

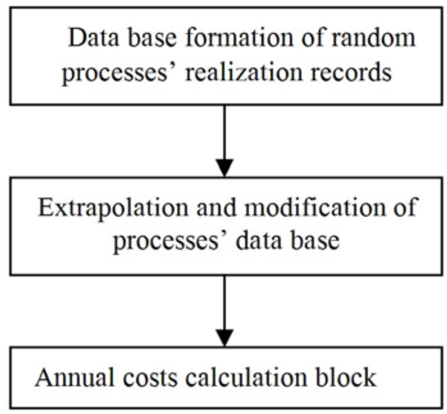

Fig.5. Simplified algorithm for calculation of annual line exploitation costs

Annual costs are calculated using the extrapolated and modified data.

Let's determine two problems, which appear using this algorithm:

1) Calculation of line annual costs demands a huge amount of input data and extensive calculations.

2) Extensive calculations.

The first problem can be solved, using Internet opportunities and public available data bases, besides the load data which is formed and recorded by power utility companies. But extensive calculations can be simplified using Monte-Carlo method.

The method of Monte-Carlo [10], [12] for average costs (7) calculation is very applicable. The new approach is realized in a software and enables quickly and easily to solve the set task. In our case, the solution task is done in MATLAB.

VII. Case Study

In general, the capital investments of transmission line construction are calculated by using simplified formulas, but nowadays due to the constantly changing conditions of the design – the transition from typical model design solutions to an individual approach as well as economic factors and modern energy market conditions directly affect the changes in prices, thus creating significant differences in costs. In consequence, it is necessary to evaluate capital investments in more precise formulation of the posed problem, taking into account the particular transmission line route, its length; the climatic conditions; the choice of the type of mass support, conductor, insulator; the regional perspective of the development of electricity supply; land alienation, etc. [1]

In this paper both 110 kV and 330 kV overhead lines (OHL) were considered for revealing the economic efficiency of power line designing based on the minimization concept of the total annual exploitation cost. The length of each line was conditionally assumed as 100 km.

A number of the competitive variants concerning the selected conductor cross-sections as well as mass tower heights were selected based on the OHL design practice and experience. The comparison was based on two specific cases:

1. There is a 110 kV OHL, which must provide current 160 A. Due to the specific requirements of the load development in a particular region, the tower height to a lower conductor is assumed as 20 m;
2. There is a 330 kV OHL, which must provide current 750 A. Because of the same reason as for the 110 kV circuit, the tower height to a lower conductor – 22 m.

The following cross-sections of aluminium steel (AS) conductor were selected:

- ✓ For 110 kV: AS-120/19, AS-150/19, AS-185/29, AS-240/32.
- ✓ For 330 kV: 2xAS-300/39, AS-400/22, AS-500/27, AS-600/72.

To achieve the posed objective of this paper taking into account a great amount of the necessary informative data about line parameters: the line length, line support types, insulator types, line mounting costs and many others, the modern integrated software designed for automated design of transmission line can be implemented, which will significantly speed up the process of choosing the optimum transmission line design variants and provide the more adequate and cost-effective solution.

Nevertheless, the more adequate estimation of capital investments requires a sufficiently complete possession of the whole database of conductors, towers and line fittings. In view of the above, this paper considers the refined approach, which consists of three steps and the process of an evaluation of the total annual exploitation cost is the following:

1. There is an assessment of the capital investments for the OHL by using a comprehensive software solution, which takes into account previously defined competitive variants of the transmission line design, including selection of the conductor type (in this paper the steel aluminium (AS) conductor was chosen), the cross-sections of this conductor, the number of conductor per phase and the number of circuit in line (to provide the necessary capacity of a particular line); mass tower type and its heights; the insulator type as well as a line route.
2. Using the data on power losses in OHL, depending on the previously adjusted and selected cross-sections of the AS conductor, recalculation of total annual exploitation costs taking into account the cost of power losses was done; Selection of the best variant of transmission line design with the minimum total annual exploitation costs, which corresponds to appropriate cross-section of AS conductor.
3. As far as consider the first step, here the competitive variants were selected by using a special program "SAPR LEP 2011", which allows choosing the most suitable cross-sections of AS conductor, the tower type and its' height to lower conductor according to climate conditions along the OHL route placement and provides the determination of the total number of towers [13].

Price of losses, line current and ambient temperature for the period of time determined on the basis of sustainable statistical data [14], [15].

Fig. 6 presents the obtained results of the calculations of the total capital investments for both particular 110 kV and 330 kV OHL cases from a minimization point of view.

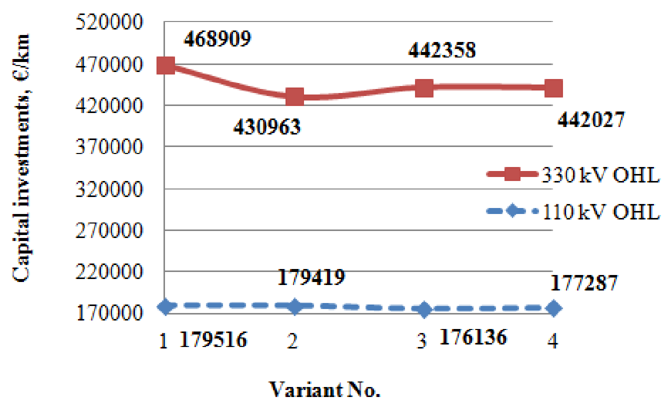

Fig.6 The diagram of total capital investments for designing OHL

Fig. 6 reveals the following:

1) Variant No. 1 – for 110 kV OHL: the load is 160 A, 1xAS-120/19 conductor; for 330 kV OHL: the load is 750 A, 2xAS-300/39 conductor;
2) Variant No. 2 – for 110 kV OHL: the load is 160 A, 1xAS-150/19 conductor; for 330 kV OHL: the load is 750 A, 1xAS-400/22 conductor;
3) Variant No. 3 – for 110 kV OHL: the load is 160 A, 1xAS-185/19 conductor; for 330 kV OHL: the load is 750 A, 1xAS-500/27 conductor;
4) Variant No. 4 – for 110 kV OHL: the load is 160 A, 1xAS-240/32 conductor; for 330 kV OHL: the load is 750 A, 1xAS-600/72 conductor.

The analysis shows the following:

A. The amount of capital investments for 110 kV OHL is approximately 2.5 times smaller as compared with the 330 kV OHL;
B. If there is a 110 kV OHL, the line with 1xAS-150/19 conductor has the lowest capital investments (the tower height to a lower conductor is 20 m) – 176136 €/km;
C. If there is a 330 kV OHL, the line with 1xAS-400/22 conductor has the lowest capital investments (the tower height to a lower conductor is 22 m) – 430963 €/km.

As a result, the total capital investments must be calculated taking into account whole initial data concerning the main designing components of the OHL, which relates to the determination of the optimum solution already at the stage of feasibility study and the obtained results of capital investment, will greatly impact the final result of the calculations of the annual total cost.

The second step presents the obtained results of the possible competitive variants after the first step realization, which in this case takes into account power losses. The total deductions on amortization, running repair and maintenance are assumed as 7.6 %, and market interest rate – 5 %.

Taking into account all factors and values of parameters, overhead line cross- section under open market conditions is estimated by two methods: economic intervals method and Monte Carlo method.

The method of Monte Carlo is applied as following: for each cross-section annual average cost is calculated by using the past records data base and certain number of trials (N=1000). From all obtained average costs the minimal cost and the corresponding optimal cross-section is chosen. Fig. 7 and Fig. 8 illustrate the results of calculations by the Monte Carlo method.

Accordingly to Fig. 1 and Fig. 2, optimal cross-sections were chosen by economic intervals method. Two variants are offered: single AS wire and decomposed AS wire.

Finally, the variants with minimum total annual exploitation costs of OHL design and appropriate the optimum cross-section of AS conductor based on the two specific cases, which were formulated previously, can be founded (see Table I and Table II).

TABLE I. RESULTS COMPARISON OF METHODS (110 KV)

	MC method	Economic intervals method
Maximum line current, A	160	160
Annual exploitation costs, €/km	2.3082e+004	2.358 e+004
Corresponding cross-section, mm²	240	240

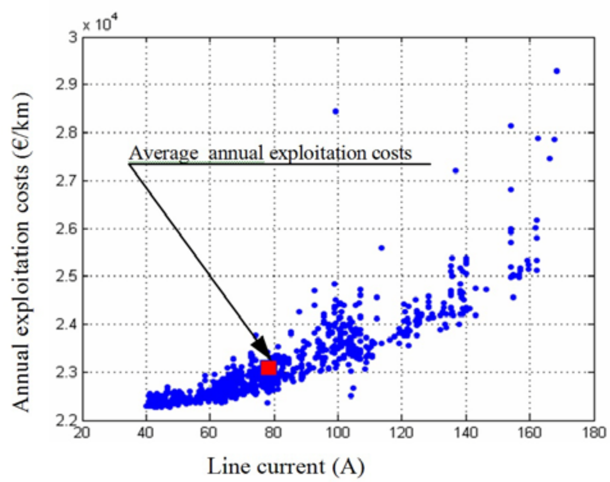

Fig.7. Calculated annual exploitation costs' of 1xAS-240 depending on line current (Monte Carlo method, 110 kV).

Let us consider the second case, when there is a 330 kV OHL, which shows the other obtained results of the annual costs.

TABLE II. RESULTS COMPARISON OF METHODS (330 KV)

	MC method	Economic intervals method
Maximum line current, A	750	750
Annual exploitation costs, €/km	6.2323e+004	6.837e+004/ 7.029e+004
Corresponding cross-section, mm²	1xAS-600	1xAS-600/ 2xAS-400

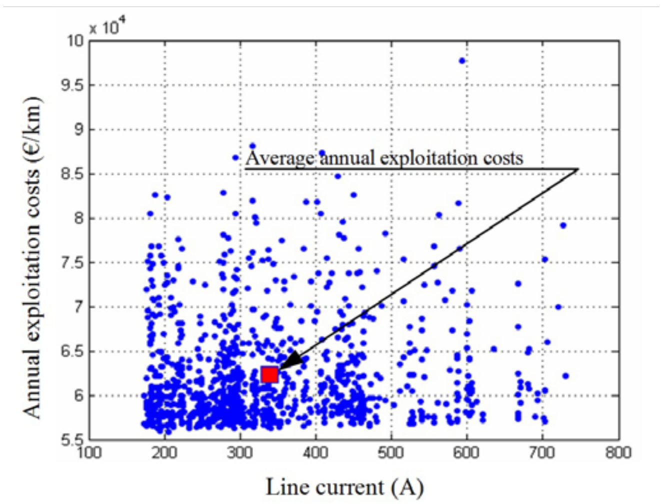

Fig.8. Calculated total annual exploitation costs' of 1xAS-600 depending on line current (Monte Carlo method, 330 kV).

As a result, the following can be concluded:

- If there is a first case (110 kV OHL), then preferable AS conductor cross-section is 1xAS-240/32.
- If there is a second case (330 kV OHL), here AS conductor cross-section by using the Monte Carlo method is 1xAS-600/72, but by using economic

interval method there are two possible variants: 1xAS-600/72 or 2xAS-400/22.

- ➢ If there is first case (110kV, 160 A), then it can be concluded that there is insignificant difference in values of the total annual exploitation costs for Monte Carlo method – 23082 €/km, for economic interval method – 23580 €/km (2,11%).
- ➢ If there is second case (330kV, 750 A), then it can be concluded that there is quite closed values of the total annual exploitation costs. For first variant the difference is 8%, but for second variant it is 11%.

After all estimations it can be resulted that chosen optimal cross-sections by two approaches differ. Given calculations prove that two methods are suitable for optimal cross section choice. However, stochastic approach is more accurate and reliable one.

VIII. Conclusion

1) New tendencies and conditions in organization of electric power supply (deregulation, open market and appearance of local generation) increase level of uncertainty in planning tasks and inspire the search for new accurate methods, based on stochastic positions and Monte-Carlo method application.

2) The developed algorithm takes into consideration the stochastic nature of energy prices, ambient temperature and load lines.

3) The proposed algorithm allows finding the minimum overhead line annual cost and the choice of wires optimal cross-section.

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