Lightning Risk Assessment Software Design for Photovoltaic Plants in Accordance with IEC 62305-2

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***Abstract* — The lack of an effective protection scheme delays the integration of photovoltaic (PV) plants into distribution networks. Outdoor installation of these systems always exposes them to direct/indirect lightning strikes and consequent overvoltages. If lightning overvoltages are not limited, the PV plant equipment may be damaged. A lightning protection system (LPS) consisting of external and internal sections aims to protect the PV plant against overvoltages of the atmospheric origin. However, the lightning risk assessment for determining the need for the LPS installation and the overvoltage protection system design are complicated tasks. In the past, there was no special software for lightning risk assessment in solar power plants, and only some papers have mentioned the calculation method and software developed according to local standards. This paper develops a software application for lightning protection design of PV plants especially for risk assessment analyses according to IEC62305-2. The designed software has used a comprehensive standard compared to other software, and in addition to considering solar farms, it also covers off-grid and on-grid rooftop systems. The evaluation results show that the proposed software is a useful tool for electrical engineers and renewable energy experts who are active in the PV integration industry. Using this software, specialists will be able to easily perform complex calculations and select the suitable LPS for the projects.**

***Index Terms*: photovoltaic, lightning protection software, risk assessment, surge protective device.**

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I. Introduction

One of the important topics of electrical engineering is the study of different aspects of renewable energies. Accessibility, free primary energy, PV modules advancement, and government incentives contribute to increased attention to the PV systems among other renewable energy sources [1]. According to the international energy agency (IEA) report, despite the COVID-19 crisis, the global PV will increase every year [2]. The safe and accurate performance of the PV systems improves their offered resilience. Therefore, the enhancement of control algorithms and protection systems ensures that the PV systems remain at the forefront of renewable energy technologies.

The design of an effective protection system has always been one of the main challenges of electrical networks. Protection system should be simple and economic and detect any abnormal condition quickly to decrease damage to the network equipment (reliability and speed). It should also isolate only the faulty section (selectivity). Due to outdoor installation, the PV systems are subjected to both overcurrent due to short-circuit faults and overvoltage of atmospheric origin. A short-circuit fault results in overcurrent on the DC/AC side of the PV power plant, which is usually detected and isolated by the miniature circuit breakers (MCBs) or molded case circuit breakers (MCCBs). A ground fault is detected by the ground fault protection device. On the other hand, lightning may result in overvoltages in the PV system equipment. In some research, computer programs for risk calculations in solar power plants have been developed based on local and old standards [3]. Software developed by the world's largest companies does not provide the evaluation of solar power plants separately [4, 5].

Little work has been done as yet to design software to assess the risk of lightning strikes on photovoltaic installations. In [6], a comprehensive review of the superior modeling methods of PV systems during lightning strikes is presented. The paper displays various platforms to simulate the transient effects of lightning strikes on PV systems. This paper also gives some recommendations about the modeling methods and protection of PV systems during lightning strikes. A computer program for lightning strike risk assessment and design of lightning protection system for the photovoltaic system is also proposed in [7].

In this paper, a developed software for risk assessment calculation according to IEC62305-2 and LPS design for PV plants is introduced and investigated. By using this software, an engineer can evaluate various lightning protection system designs in a short time. This software helps to understand the concepts of lightning protection design and to view the result of their design without performing numerous calculations.

II. Fundamentals of Lightning Protection System Design for PV Systems

1.1. Basic Principles

Lightning overvoltage protection is one of the main modules of protection schemes of PV power plants, especially in countries with stormy and cloudy climates [8]. If an overvoltage condition is not detected and isolated, the PV system equipment may be damaged, which will lead to an increase in the return time of investment. PV systems are subjected to both direct and indirect overvoltages. In the former case, the lightning strikes the PV structure while in the latter case, lightning falls near the structure, or signaling/electrical lines entering the structure are affected by the lightning. When lightning strikes near the structure, the resultant variable magnetic field induces the overvoltages on the building circuit (inductive coupling) while when lightning strikes the entering lines, through the line characteristic impedance, the lightning current results in overvoltage (resistive coupling). If an overvoltage exceeds the impulse withstand voltage of equipment, it is damaged and even poses a risk of fire hazard.

An LPS consists of external and internal protection systems. The external protection system protects the PV system against direct strikes by using the air-termination system (ATS), down-conductor system, and earth-termination system for intercepting the lightning, conducting the current to the ground, and distributing the current in the ground, respectively. The internal protection system protects the PV system against sparking inside the structure by implementing equipotential bonding or keeping a separation distance between the LPS components and other conductive elements of the structure.

In the case of direct lightning, there can be three conditions [9]:

1. Rooftop PV plant without LPS: If the PV installation does not change the building outline, the frequency of the threat does not change, and consequently, no measures are required. Otherwise, the risk assessment should be performed.
2. Rooftop PV plant with LPS: If the PV plant does not significantly change the building outline and the minimum distance d between the available LPS and PV system is greater than safety distance s, no measures are required. However, if d is less than s, the LPS should be extended and connected to the PV metal structure. If the PV installation changes the building outline, a new risk assessment is required.
3. Ground PV plant: In this case, there is no fire threat due to direct strike.

In the case of indirect lightning strikes, the circuits are shielded to decrease the magnetic field. In addition, the module conductors are twisted and the live conductors are kept near to protective earth conductor to decrease the induced circuit turn area.

Even for limited overvoltages, surge protective devices (SPDs) are required to discharge them to the ground. An SPD presents a high impedance at the nominal voltage while its impedance significantly decreases in the case of an overvoltage, making a low-impedance path to the ground. Thus, the lightning current is discharged to the ground and the PV plant equipment is protected against overvoltage.

1.2. Risk Assessment Based on IEC 62305-2

According to IEC 62305-2 standard [7], risk assessment requires that source of damage, type of damage, and type of losses be determined. The primary source of damage is the lightning current. There are four damage sources: lightning strike to a structure (S1), lightning strike near a structure (S2), lightning strike to a line (S3), and lightning strike near a line (S4). Depending on the structure characteristic, there are three damage types: electric shock and the resultant injury to living beings (D1), physical damage (D2), and failure of electronic and electrical systems (D3). There are four types of loss in the structure resultant from various types of damage: human life loss, including permanent injury (L1); public service loss (L2); cultural heritage loss (L3), and economic value loss (L4).

The total potential risk in a structure is calculated as [8]

$$R = R_1 + R_2 + R_3 + R_4, \tag{1}$$

where R_1 is the risk of L1 as

$$R_1 = R_A + R_B + R_C + R_M + R_U + R_V + R_W + R_Z, \tag{2}$$

R_2 is the risk of L2 as

$$R_2 = R_B + R_C + R_M + R_V + R_W + R_Z, \tag{3}$$

R_3 is the risk of L3 as

$$R_3 = R_B + R_V, \tag{4}$$

R_4 is the risk of L4 as

$$R_4 = R_A + R_B + R_C + R_M + R_U + R_V + R_W + R_Z, \tag{5}$$

and

- R_A is related to the injury to living beings resulting from step and touch voltages in the case of a direct strike,
- R_B is related to the physical damage resulting from sparking inside the structure, which triggers explosion or fire in the case of a direct strike,
- R_C is related to the internal system's failure resulting from lightning electromagnetic impulse (LEMP) in the case of a direct strike,

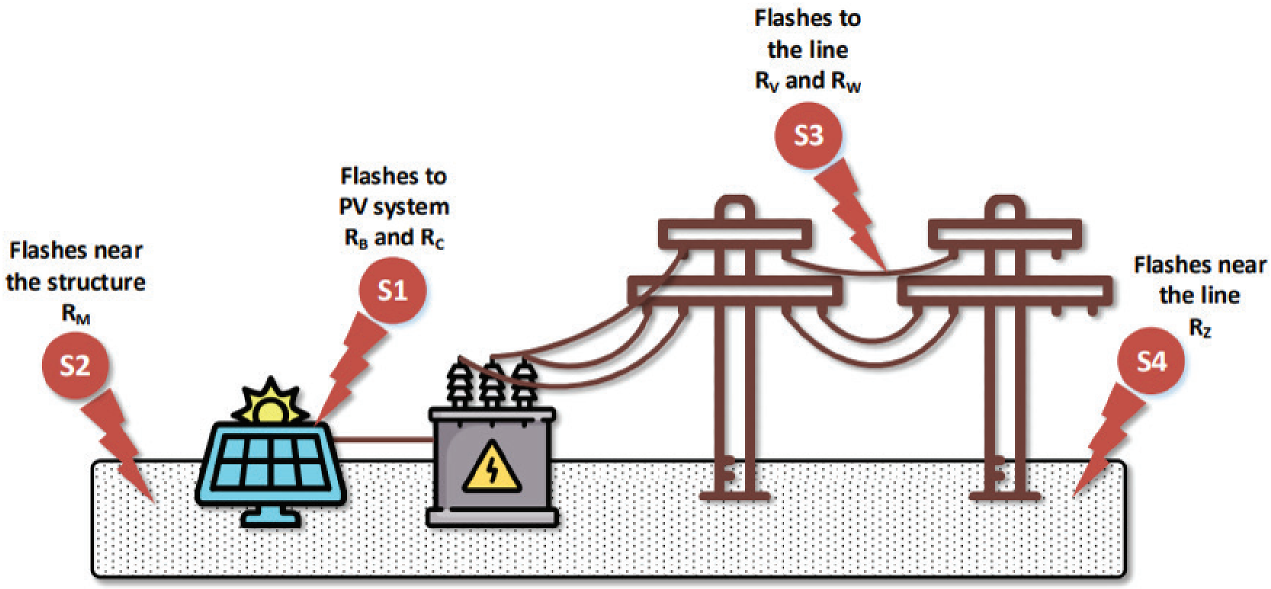

Fig. 1. Risk components of a PV system.

- R_M is related to the internal system's failure resulting from LEMP in the case of indirect strike,
- R_U is related to the injury to living beings resulting from step and touch voltages in the case of a strike to a line connected to the structure,
- R_V is related to the physical damage resulting from sparking between metallic parts and external installation due to transmitted lightning current through incoming services in the case of a strike to a line connected to the structure,
- R_W is related to the internal systems' failure resulting from induced overvoltage on incoming lines and transmitted to the structure in the case of a strike to a line connected to the structure, and
- R_Z is related to the internal systems' failure resulting from induced overvoltage on incoming lines and transmitted to the structure in the case of a strike near a line connected to the structure.

All risk components of R_A to R_Z are calculated as

$$R_x = N_x \times P_x \times L_x, \tag{6}$$

where N_x is the number of dangerous events (Year^{-1}), P_x is the structure damage probability, and L_x is the consequent loss. Due to space limitation, the detailed procedure of determining R_x is not presented; this procedure is available in [9].

If $R \leq R_T$ where R_T is the tolerable risk, there is no need for lightning protection. While, if $R > R_T$, protection measures should be adopted in such a way that $R \leq R_T$ for all risks threatening the structure. The tolerable risk for human life or permanent injury loss, public service loss, cultural heritage loss, and economic loss are 10^{-5}, 10^{-3}, 10^{-3}, and 10^{-3} (Year^{-1}), respectively.

1.3. Risk Assessment for PV Plants

In the risk assessment of PV systems, there is no need to consider some risks [10]. Since the structure of PV systems is nonflammable, the fire hazard can be neglected. In addition, most of the rooftop PV systems are installed on small buildings; thus, the probability of a direct strike is low. Moreover, there are no people in a large PV power plant. Consequently, human life loss risk (R1) is not considered. On the other hand, due to the small capacity of PV systems, even in the case of PV power plants, the public service is not affected by their failure. Thus, risk R2 can also be neglected. Moreover, the PV systems are not usually installed in historical places; thus, cultural heritage loss risk (R3) can be neglected.

Consequently, economic value loss is the only risk that should be considered in the risk assessment for PV systems. The risk components of R_4, R_A and R_U are related to the cases where animals may be lost. Due to installing PV systems on rooftop or enclosing the PV power plants, these risk components are neglected and only R_B, R_C, R_M, R_V, R_W, and R_Z are considered. According to [8], among these components, R_M, R_W, and R_Z are more relevant than others in the case of rooftop PV systems. Figure 1 shows the risk components of a PV system.

Since there is only one risk in the risk assessment of PV plants, $R = R_4$. The following measures can be implemented to decrease the total risk of a PV system to a tolerable level:

- reduction in R_W and R_Z by installing a coordinated SPD in the low voltage (LV) line entering the building;
- reduction in R_M by installing a coordinated SPD in the DC line of the PV system.

In the case of a PV power plant, in addition to the above-mentioned protections, an external lightning protection system can be installed to reduce R. Figure 2 shows the flowchart of the risk assessment for PV systems.

The above section was aimed at calculating Risk assessment for solar farms. In addition, the developed software can be used to make calculations for off-grid and

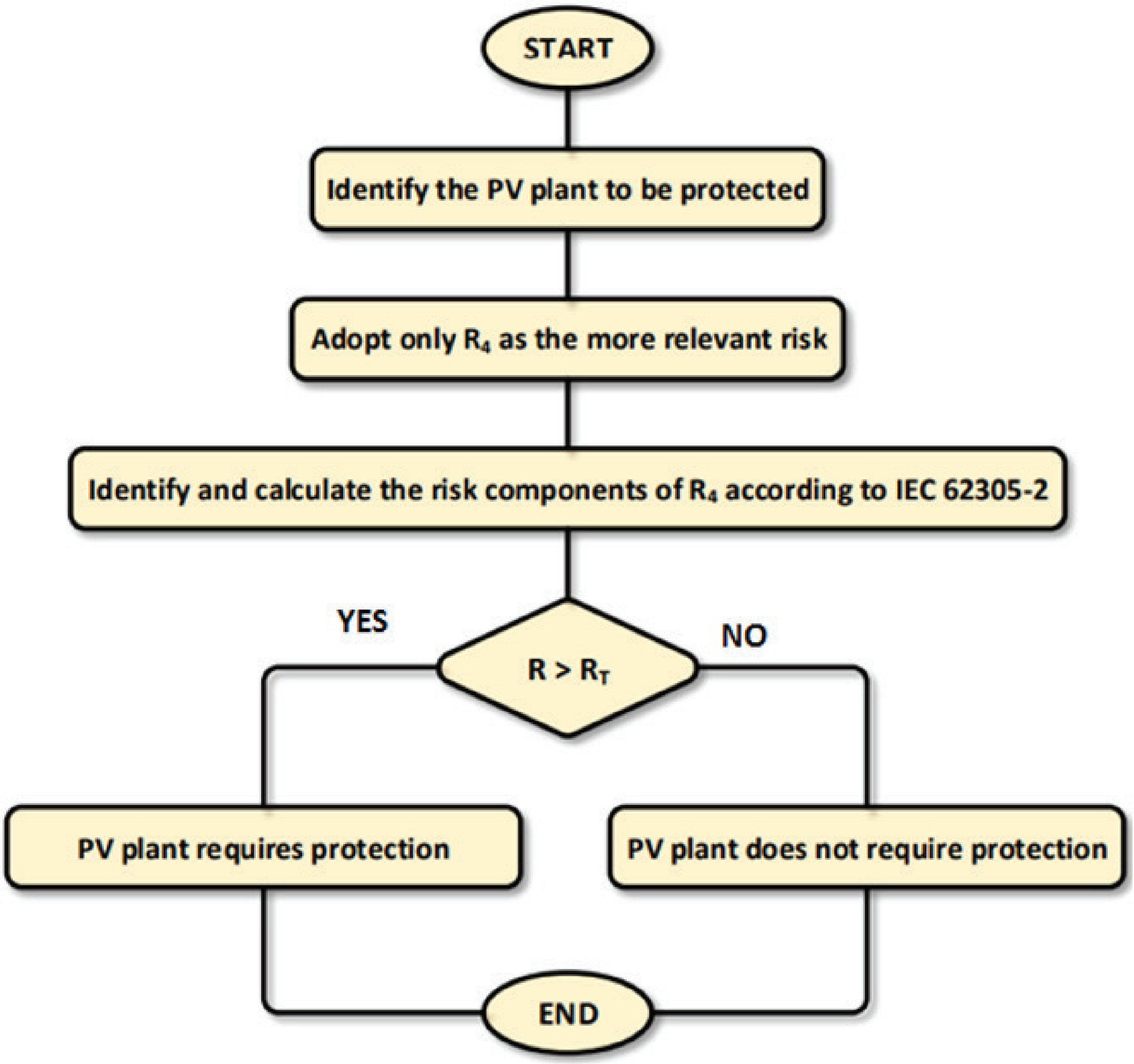

Fig. 2. Flowchart of risk assessment for solar farms.

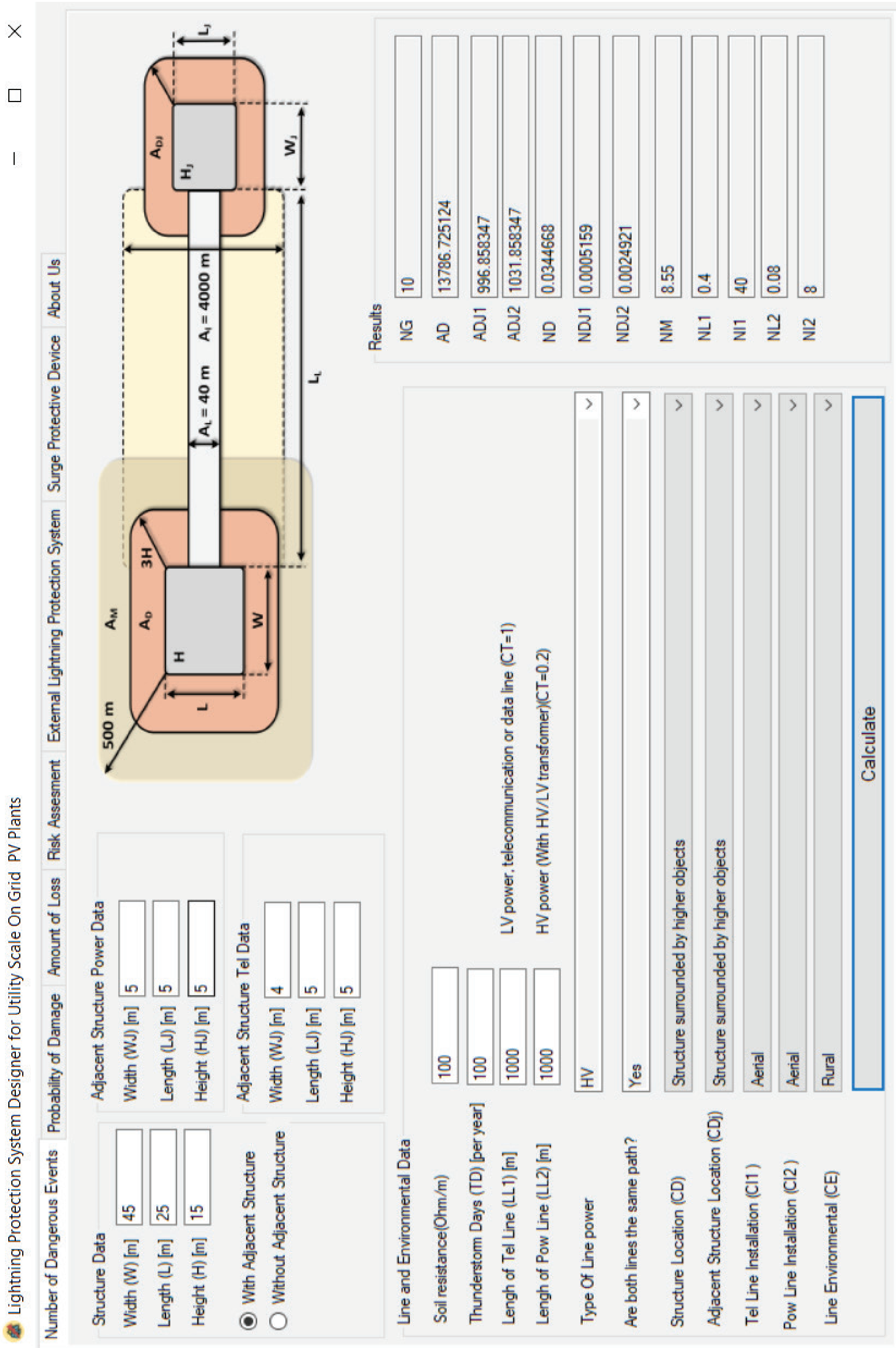

Fig. 3. The main page of the developed overvoltage protection software design.

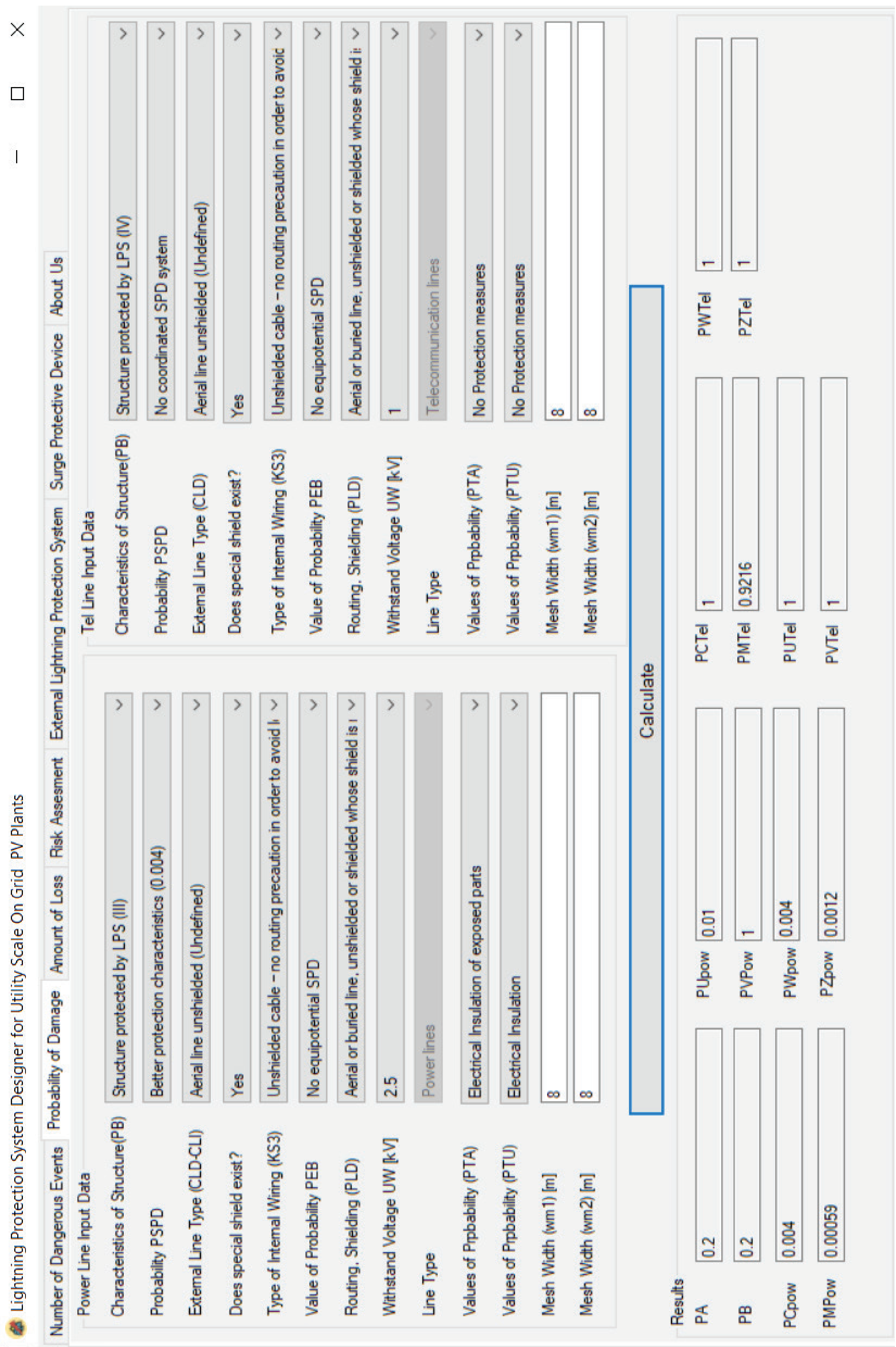

Fig. 4. The Probability of Damage Menu of the developed overvoltage protection design software.

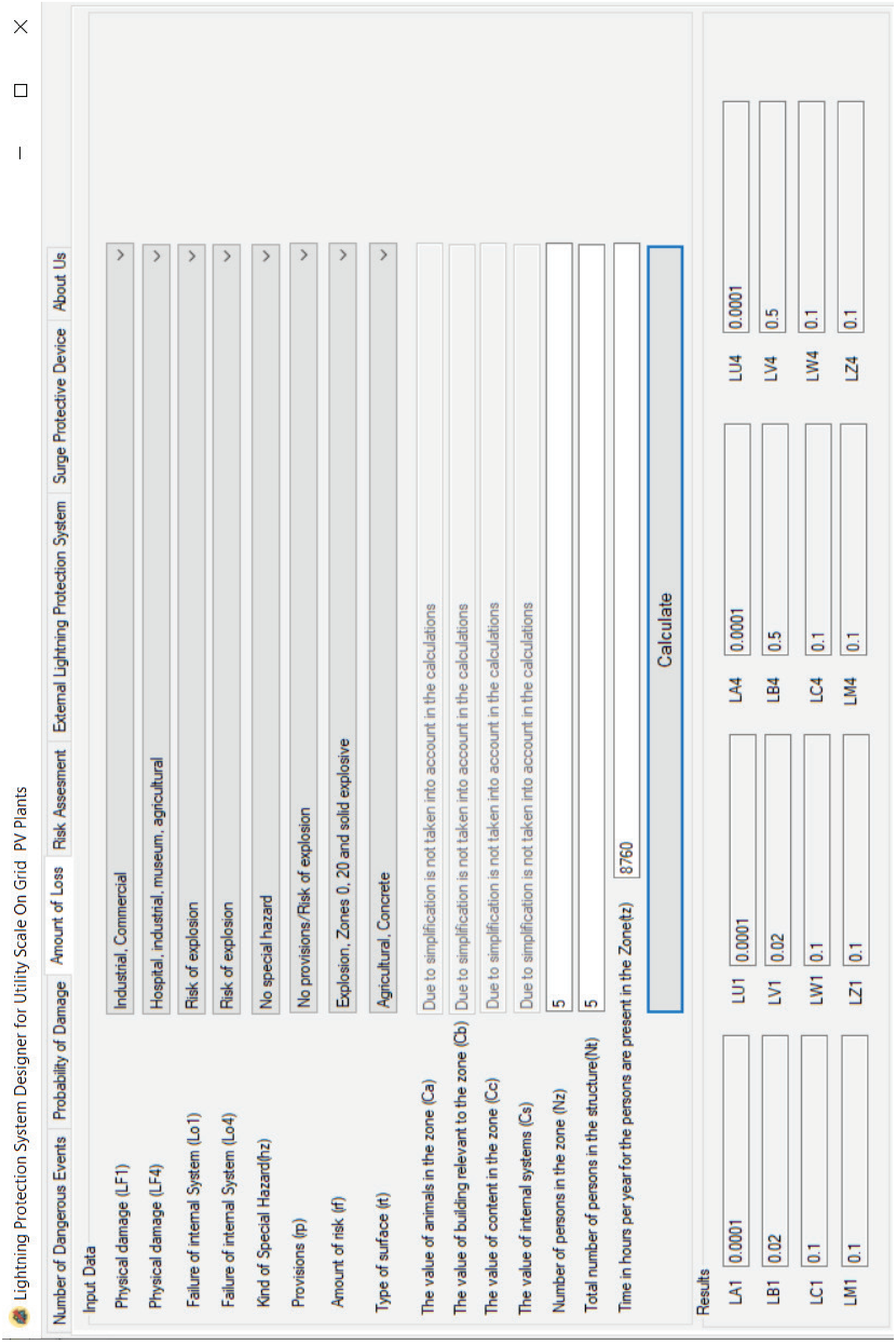

Fig. 5. The Amount of Loss Menu of the developed overvoltage protection design software.

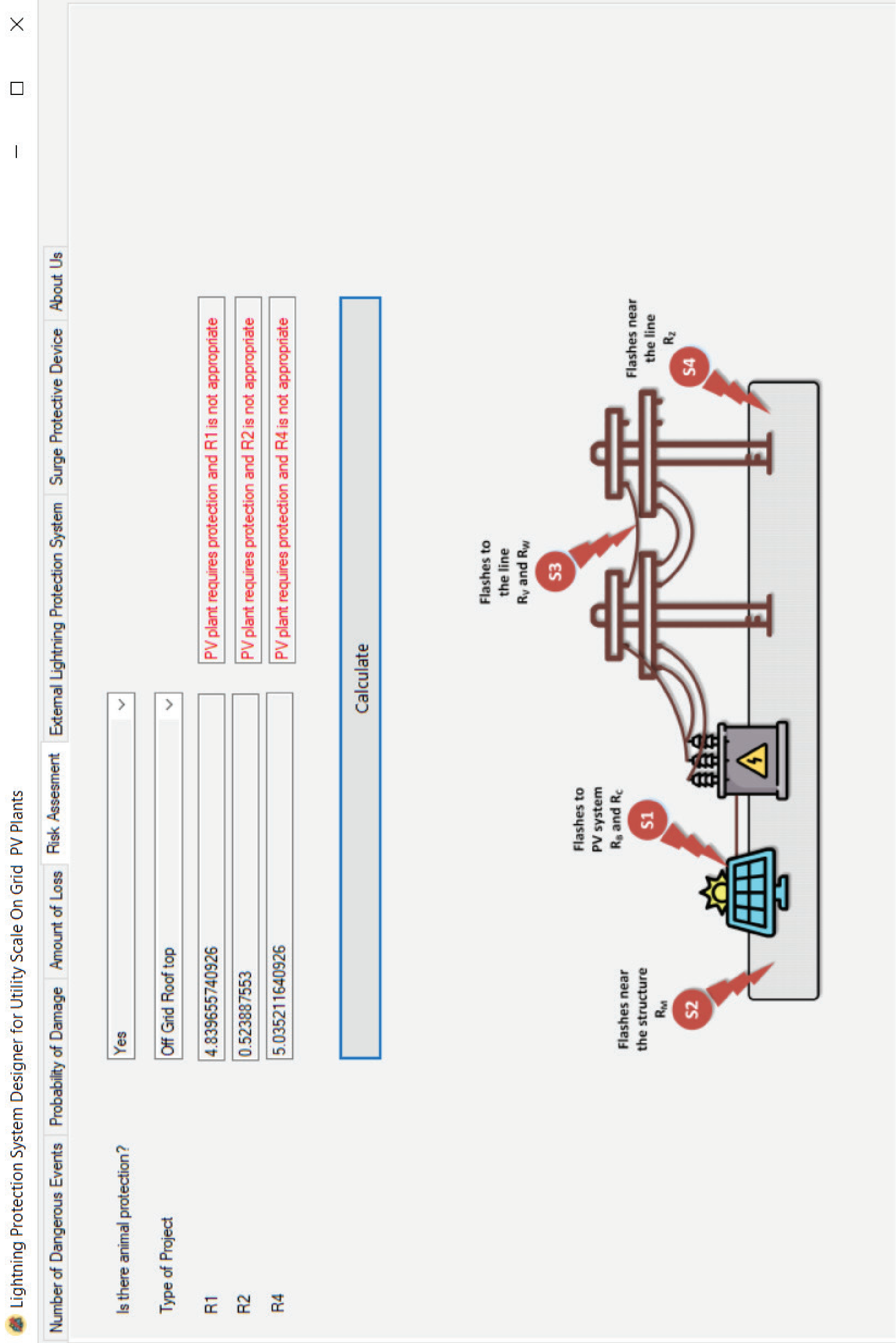

Fig. 6. The Risk Assessment Menu of the developed overvoltage protection design software.

Fig. 7. The External Lightning Protection System section.

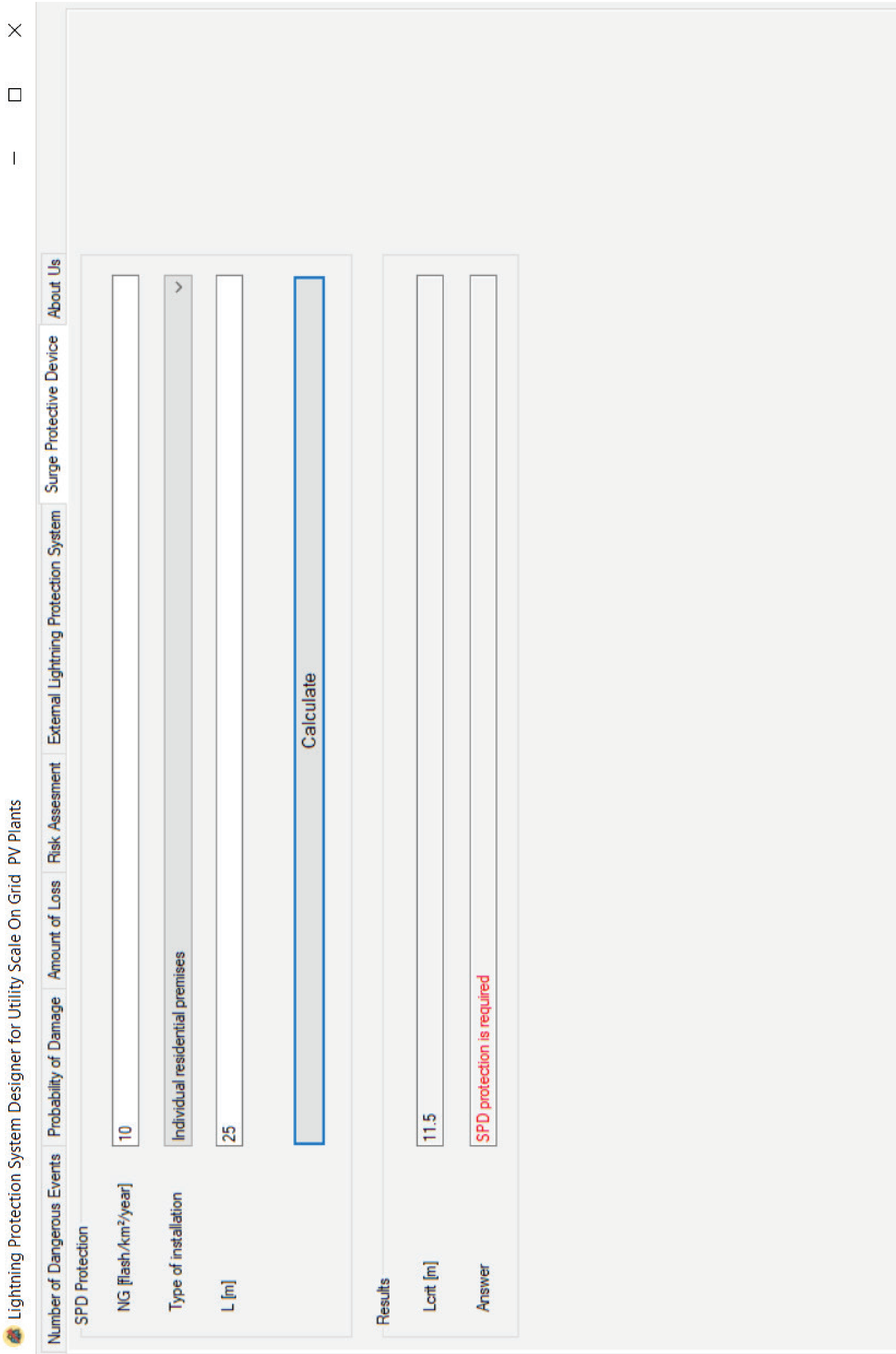

Fig. 8. The Surge Protective Device Menu.

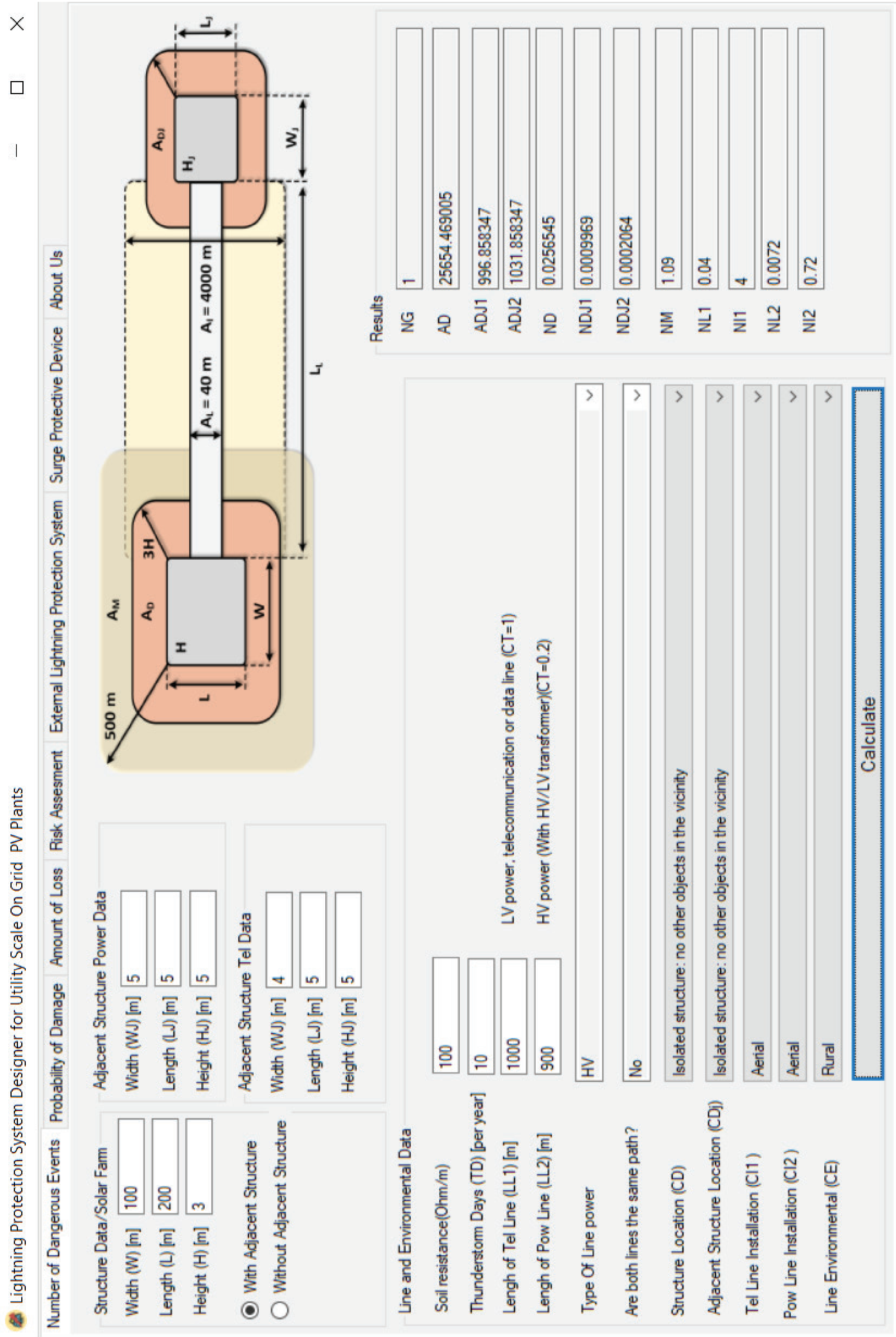

Fig. 9. The Number of Dangerous Events Menu.

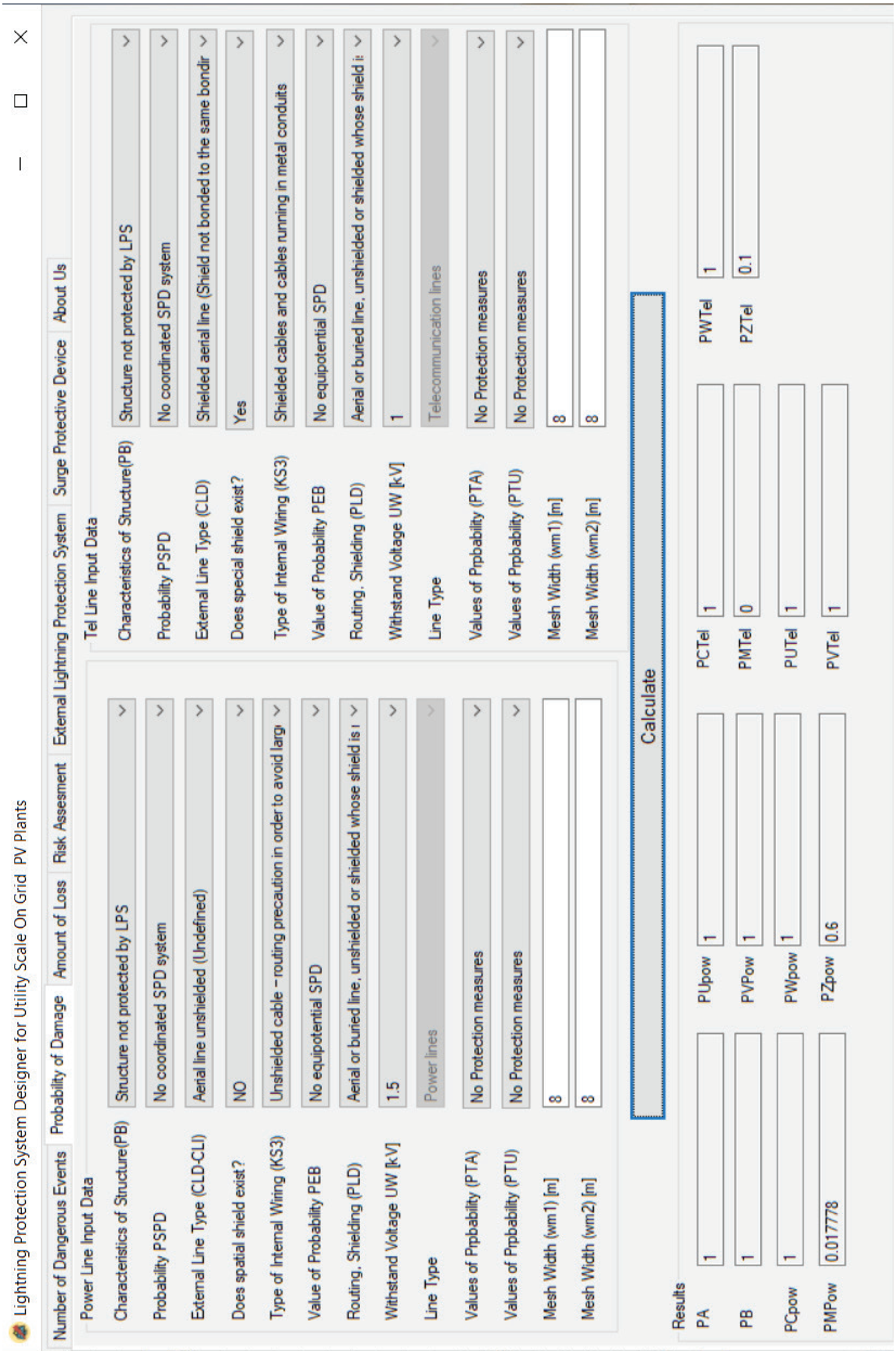

Fig. 10. The Probability of Damage Menu.

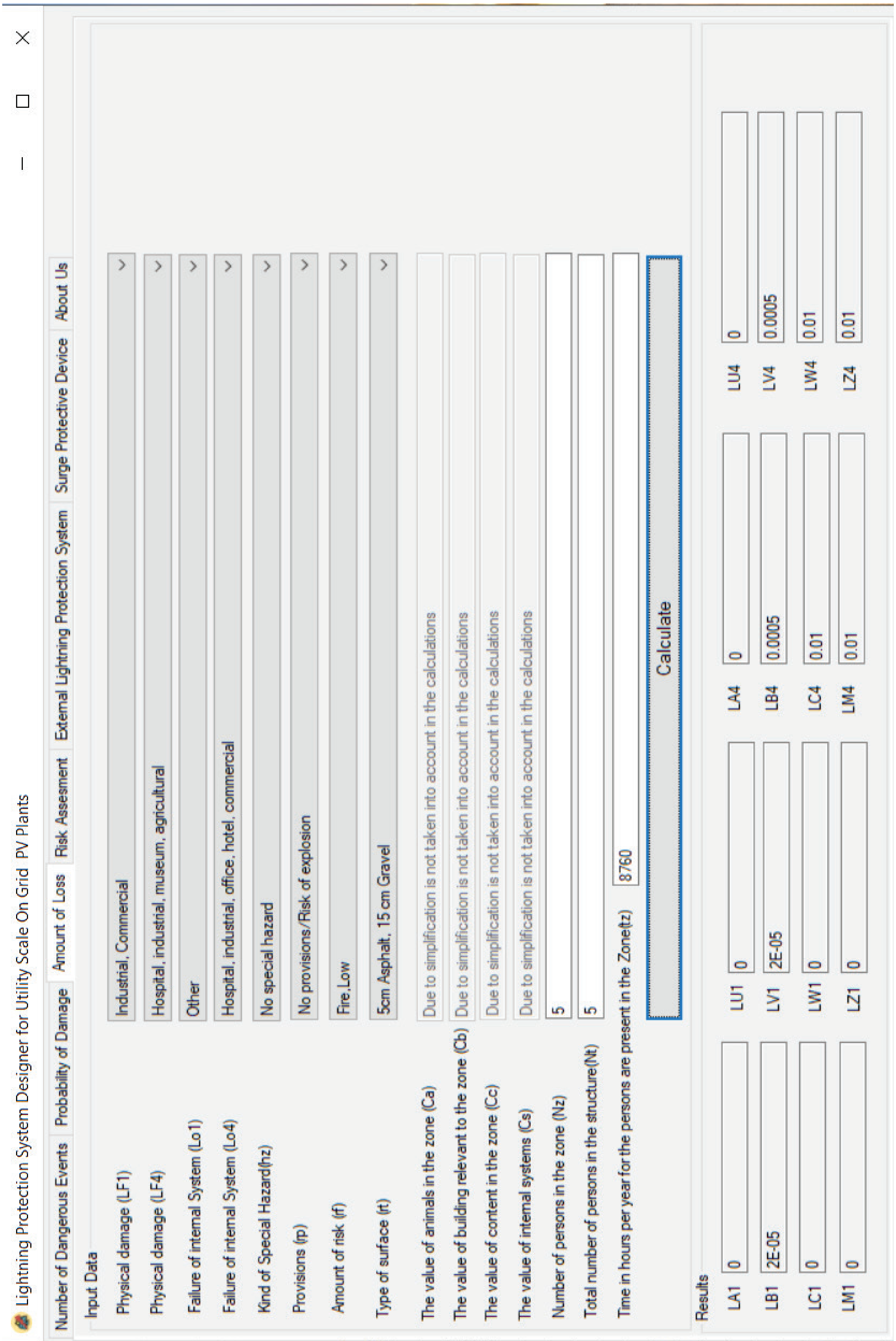

Fig. 11. The Amount of Loss Menu.

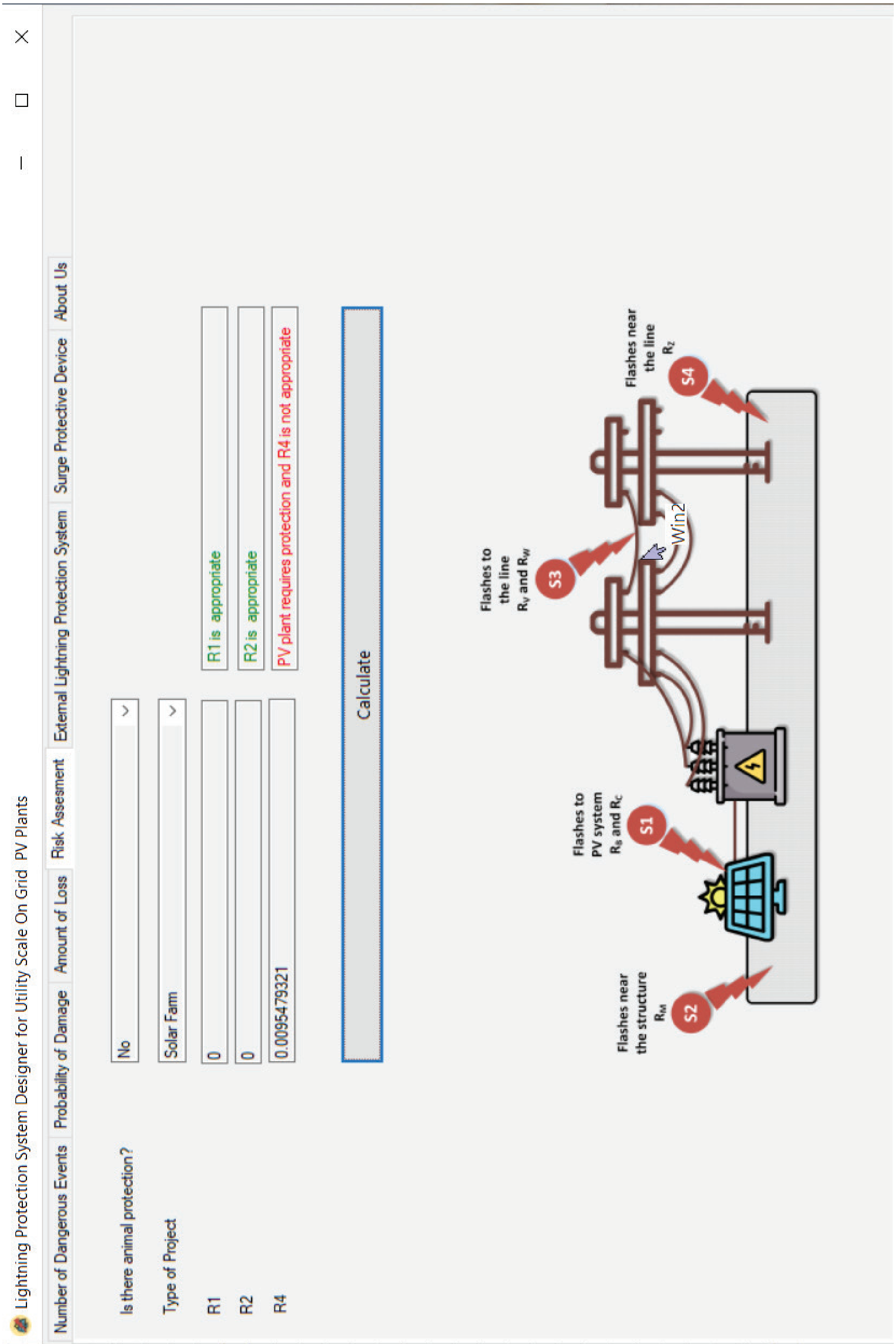

Fig. 12. The Risk Assessment Menu.

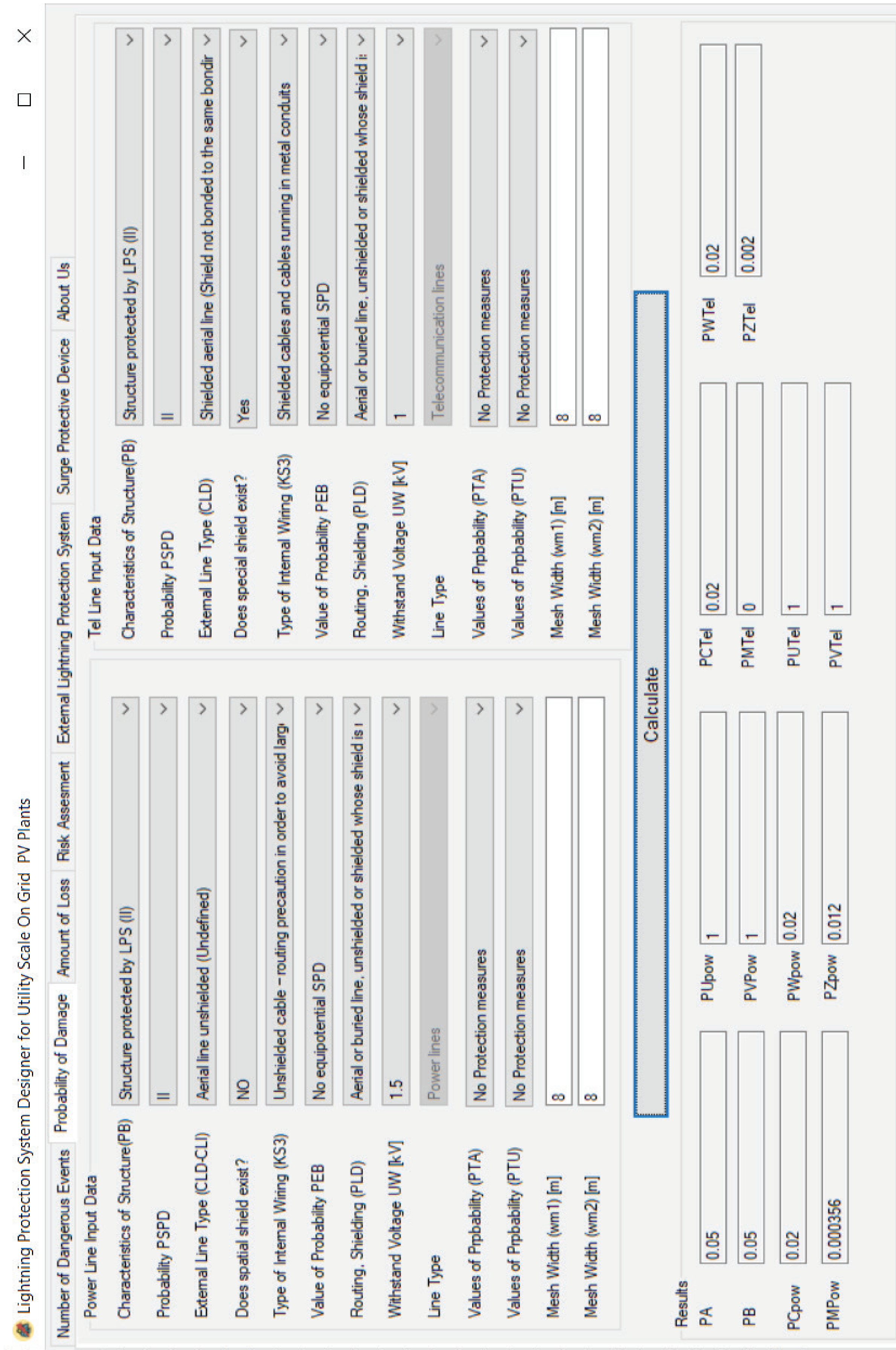

Fig. 13. The Probability of Damage Menu with new settings.

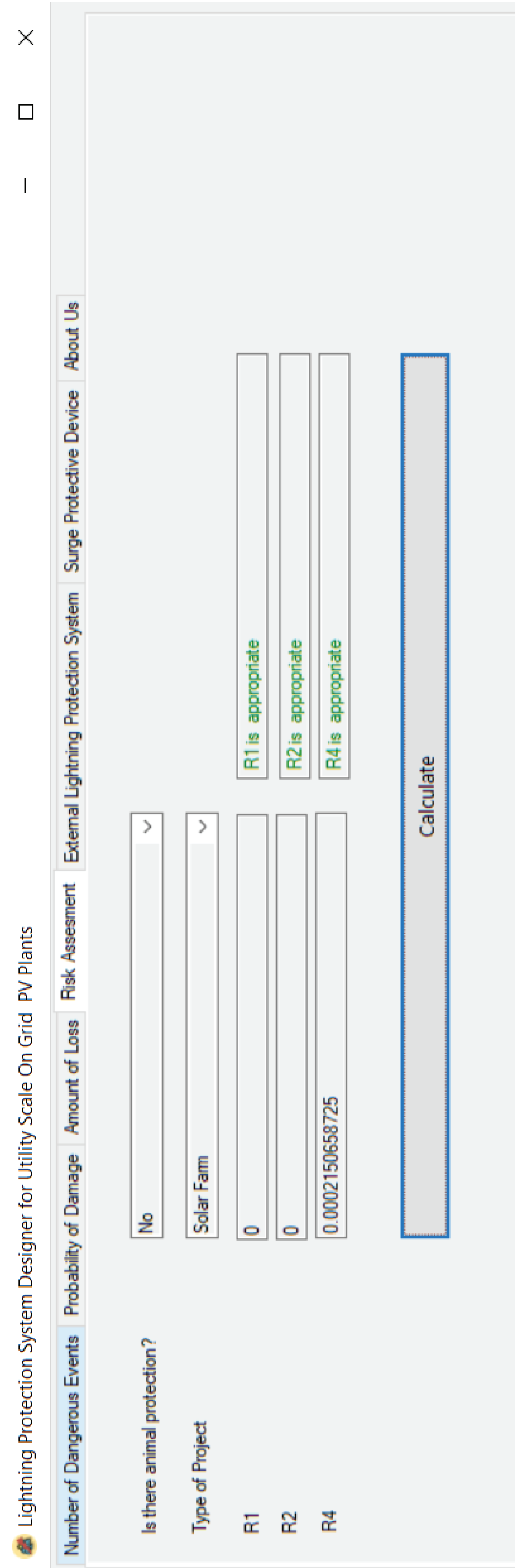

Fig. 14. The Risk Assessment Menu with new calculation.

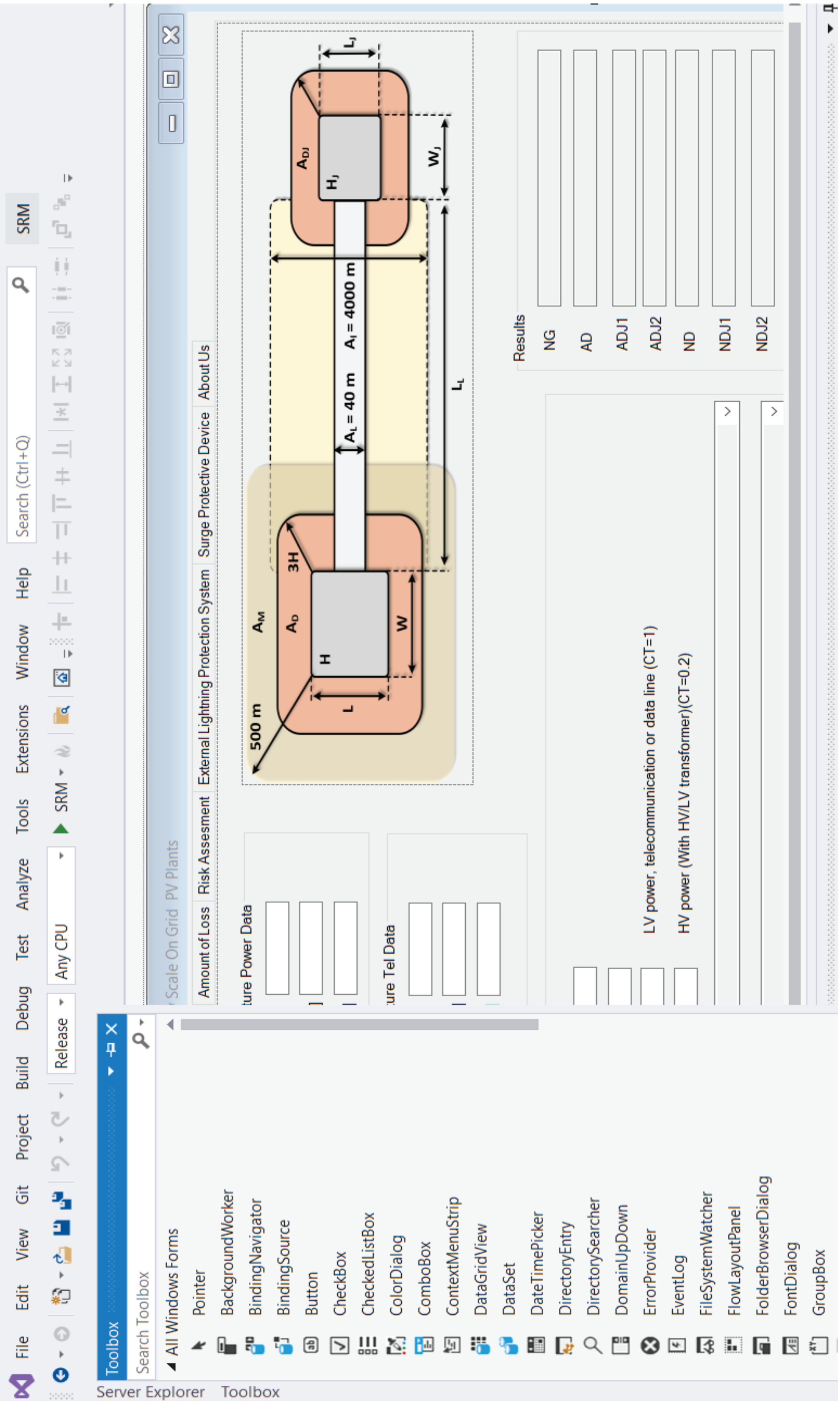

Fig. 15. Designed Software Window by Visual Studio.

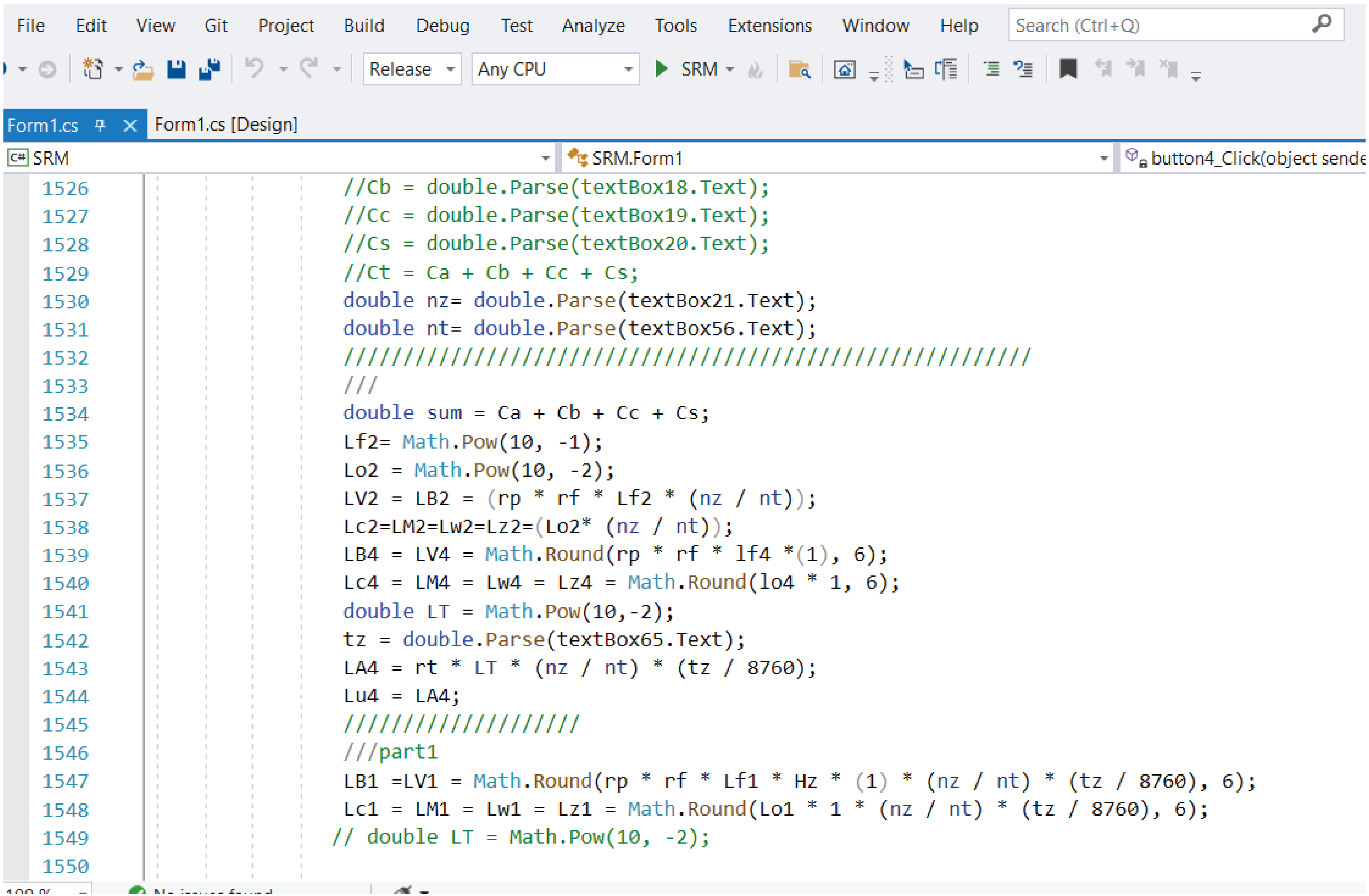

Fig. 16. Part of the Software Codes.

on-grid rooftop projects. In off-grid solar systems, risk R3 can be excluded because they are rarely used in heritage buildings. In systems connected to the solar network, we can eliminate the risk of public services and heritage buildings (R2, R3). Briefly, the following parameters have been considered for various solar power plants:
1. Solar Farms: R4.
2. Off-grid projects: R1+R2+R4.
3. On-grid rooftop projects: R1+R4.

1.4. External Lightning Protection System

As mentioned in the previous subsection, an external LPS may be required to reduce the total risk of a PV power plant. One of the most important parts of the external LPS is the air-termination system (ATS), which can consist of catenary wires (horizontal conductors), rods, and meshed conductors (Faraday cage) [11]. The ATS prevents direct flashes on the PV structure. The proper design of ATS reduces damage to the area to be protected. There are three methods to determine an ATS protection area [12]:

- Rolling sphere method: It is a universal technique, especially for complicated applications.
- Protective angle method: It is proper for simple-shaped buildings, but it has a limitation of the ATS height.
- Mesh method: It is suitable to protect the plane surfaces (for buildings).

The rolling sphere technique is an acceptable method for designing ATS. In this method, given the lightning rod height and highest piece of rooftop power plant project, the protective radius r_p of each rod is calculated as follows [13]:

$$r_p = \begin{cases} r_s + \sqrt{2h_e r_s - h_e^2}, & h_r \ge r_s, \\ \sqrt{2r_s h_r - h_r^2} - \sqrt{2h_e r_s - h_e^2}, & h_r \le r_s, \end{cases} \quad (7)$$

where r_s is the rolling sphere radius, and h_e and h_r are the maximum height of the equipment and rod height, respectively.

1.5. Surge Protective Device on DC Side Based on IEC 60364-7-712

IEC 60364-7-712 standard [14] determines whether the DC side of a PV plant requires SPD or not. According to this standard, the critical length L_{crit} is calculated as

$$L_{\text{crit}} = \begin{cases} \dfrac{115}{N_G}, & \text{for rooftop PV system,} \\ \dfrac{120}{N_G}, & \text{for PV power plant,} \end{cases} \quad (8)$$

where N_G is the density of lightning ground flash (flash/km^2/year) which depends on the location of the structures and power lines. L_{crit} is compared with maximum route length between the connection points of PV modules of the different strings and the plant inverter L. If $L < L_{\text{crit}}$, there is no need for installing SPDs on the DC side; otherwise, the overvoltage protection system should be equipped with SPDs on the DC side.

III. Developed PV Lightning Protection System Design Software

In the studies, the standard IEC62305-2 was thoroughly analyzed, the effect of various parameters in solar power plants was studied, and software was designed based on solar power plants' features. In addition, other standards [15, 16] were examined and compared to other sources. The major purpose of developers has been the simplicity of calculations for fast and accurate design. Sometimes, the complexity of the calculations forces the experts to overlook the design of the lightning protection, which can cause irreparable damage in the event of a lightning strike and delay the return on investment of projects that have been supported by the off-taker.

The lightning protection design for a PV system, including risk assessment, is a challenging task due to numerous variables. There are also many tables in the IEC-62305-2 for the calculation of R_xs. To address this problem, a software application is developed using C# environment. It provides a user-friendly graphical interface to simplify LPS calculations. Figure 3 shows the main page of the "Lightning Overvoltage Protection Designer for PV Plants" software. It consists of the following six sections:

1. The number of dangerous events calculations;
2. The probability of damage calculations;
3. The amount of loss calculations;
4. The risk assessment;
5. The external lightning protection system calculations; and
6. The surge protective device calculations.

Upon opening the software, the "Number of Dangerous Events" section appears. The user enters the dimensions of the structure and solar farm to be protected. In addition, if available, the dimensions of the adjacent structure are specified. Finally, the user enters the line and environmental data. By clicking on the "calculate" button, the numbers of various dangerous events due to flashes are calculated according to IEC 62305-2. The second section is dedicated to calculating the probability of damage resulting from the lightning strike, as shown in Fig. 4. In this section, after entering the required data such as structure characteristic, line type, and whether a coordinated SPD is provided, the results are shown.

Figure 5 shows the "Amount of Loss" section of the software. In this section, the user specifies the input data such as the amount of risk and various values to calculate the consequent losses. The fourth section of the developed software is dedicated to assessing the risk of the PV plant, as shown in Figure 6. Using the data entered in the previous tabs, the total risk R is calculated. Then, based on Fig. 2, it is determined whether the PV plant requires protection or not.

As mentioned in subsection 2.3, it may be required to equip a PV power plant with the external LPS. The "External Lightning Protection System" section of the software calculates the number and coverage area of ATS rods based on the rolling sphere method. In this section, the user enters the dimension of plant and protection overlap percentage. Figure 7 shows the fifth section of the developed software. Finally, the sixth section is dedicated to determining whether SPD is required on the DC side or not, as shown in Fig. 8. In this section, the density of lightning ground flash is transferred from the first tab or the user enters it; also, the installation type and L are entered. By clicking on the "calculate" button, the critical length is calculated and the answer is shown according to Subsection 2.5.

IV. Performance Evaluation

This section is dedicated to investigating the performance of the developed software in both 1 MW power plant systems. The main data of 1 MW PV power plant project implemented in the north-west of Iran are presented as follows:

- Length = 200 m, Width = 100 m, Height = 3 m;
- Adjacent structure power data information: Length = 5 m, Width = 5 m, H = 5 m;
- Adjacent structure telecom data information: Length = 4 m, Width = 5 m, H = 5 m;
- Thunderstorm Days (TD) = 10;
- Complete length of power line = 1000 m;
- Complete length of data line = 900 m;

Other input information is shown in Fig. 8, 9, 10, and 11

Figure 10 indicates the risk parameters with little consideration at first.

- According to the input information in the previous menus, the results can be viewed. Figure 12 shows the Risk Assessment menu with the selection of solar farm option first and then calculation. As it turned out, the risk of R4 was identified with red color, which is not acceptable. For this reason, according to Fig. 13, we have used class 2 LPS and SPD. After the new calculation, the results have been shown in green color (Fig. 14), which indicates that the solar farm is protected with this design. In the same way, one can see the effect of different parameters using the software and do the best design.

When selecting lightning protection measures, one must examine whether the risk R determined for the relevant types of loss exceeds a tolerable value (R_T). According to the IEC 62305-2, the acceptable values are programmed in the software and compared to the desired values.

According to the simulation results (Fig. 12), 0.0095479321 is obtained for the first time, which indicates that this solar farm is not protected. The designer may need to reconsider the calculations to check various parameters to find the appropriate protection according to Fig. 13 and 14, which may take a lot of time but this software has increased the accuracy and speed of calculations and reached the desired result of 0.00021506.

V. Overview of the methods

The developed software is programmed in the C# language. In order to develop such software, at first comprehensive studies must be done to prepare computational and optimization algorithms. After the algorithms are developed, according to the Visual Studio product, we can design the software and reach the desired results by using C# codes. As mentioned in the paper, there are applications in this field that do not have the features of the designed software.

About 4000 lines of code were written for the development of this software in 9 months. Figures 15 and 16 show a designed software window with some codes.

VI. Conclusion

This paper was motivated by the complicated procedure of risk assessment and lightning protection of PV plants for engineers. The developed software provides risk assessment for PV plants to determine the necessity of the LPS. The number of ATS rods and the necessity to install SPD on the DC side are also determined. By adopting various combinations of inputs, the users can evaluate various LPS designs. The developed software can be used as a helpful tool to increase the LPS design understanding. In addition, compared to previous research, this study presents software designed based on a comprehensive standard and considers three different categories of solar farms, off-grid systems and on-grid rooftop systems. In addition, compared to other software designed, this software determines the number of air terminals and provides risk calculations for SPD, especially for solar power plants. By using this software, simplifying calculations and designing protection against lightning, the power plant will be safe in the event of a lightning accident. If the owner sells the electricity to the network and off-taker, the return period of its investment will be reduced.

This software can be used in countries with many lightning strikes such as East Asian countries and some European countries.

Declarations

Ethical Approval and Consent to participate

I morally accept the rules of the journal and Ethical conditions.

Consent for Publication

I express my consent to the publication of the full paper by the journal and state that I will not submit this paper to any other journal.

Availability of Supporting Data

Paper information is available and can be provided if needed.

Competing Interests

I have done this project as free research and this problem existed in the past. The only solution for fast computing has been provided. The owner and developer of this software is Mohammad Parhamfar. Thus, there are no Competing interests.

Funding

There was no special funding for this project. I have requested that the cost of publishing the paper be waived due to the Iran conditions.

Authors' Contributions

Mohammad Parhamfar has proposed the idea and developed the software using C# language. The paper has been written by him.

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