INTRODUCTION

As lightning surges are considered to be the most dangerous events in power distribution systems, the more we know about them the better we can select and coordinate protection devices. Moreover, a better knowledge of lightning surges gives rise to the accurate positioning of device protection, the reduction of insulation costs at installations and allows operation with well-known risks of failure.

The development of a computer application based on fuzzy logic techniques, which allow the determination of the accurate position of the surge arrester in power systems, controls the risk of failure, thus permitting the selection of appropriate protection schemes for each network. As a consequence, protection costs are reduced in accordance with the costs of the elements actually protected and the continuity of service to be achieved.

LIGHTNING SURGES

Analysis of surge effects in distribution networks has enabled us to assert that lightning surges are generally the most dangerous kind of surges [1].

The selection of an accurate protection scheme against lightning surges for each network should be obtained from a statistical analysis of the surges that can appear in each distribution network, including the aleatory nature of parameters, such as the peak value of the return stroke current or the slope of the wave front [2].

Due to the aleatory nature of lightning surges making them difficult to characterize, a statistical approach is considered the best way to proceed. Withstand voltages against lightning impulses are also defined in a statistical way, since the phenomenon of discharge affects a great number of highly aleatory factors. The statistical analysis of lightning surges allows the determination of the risk of failure of the network components, and the resulting break in service.

Spark gaps and surge arresters are the protective devices used to limit the magnitude of overvoltages in distribution networks. However, spark gaps are replaced by surge arresters, since the latter present a small leak current and they prevent the network from being subjected to a short circuit after the sparkover occurs. Silicon carbide surge arresters are being replaced more and more by metal oxide surge arresters due to the latter’s reliability and greater capacity for surge limitation.

The protection characteristics of surge arresters used in distribution networks in Catalonia are selected by the electric companies based on the voltage level of the networks.

Insulation coordination analysis allows us to attain an acceptable risk of failure of the network components based on economic criteria, such as replacement costs for the components damaged by lightning overvoltages, and service quality criteria, such as the network being off service as a consequence of deficient network protection against overvoltages.

The risk of failure depends on the surge arrester position, since the location of these protection devices determines the maximum value of the lightning overvoltages at the network components. The maximum distance between the surge arrester and the equipment to be protected can be determined from simple network configurations. However, it is extremely complicated to formulate expressions that allow us to establish the maximum distance of protection as the dimension of the net increases or when the random nature of lightning is taken into account.

The maximum voltages at the network components are usually found by resolution of the differential equations of the network using numerical methods, so we do not have a known function that relates the position of the arrester and the risk of failure. However, it is possible to extract a set of rules that relates the change of the risk and the change of the arrester position. This set of rules facilitates the implementation of a fuzzy calculator for the arrester location to determine the protection scheme of the distribution network.

The aim of this work is to establish a method for the selection of power system protection schemes against lightning overvoltages, and the development of a computer application based on fuzzy logic techniques, which allow the determination of the accurate position of the surge arresters in power systems.

RISK OF FAILURE

The risk of failure of a network component due to lightning stroke presents the probability that the lightning surge exceeds the withstand voltage [3].

It can be assumed that a network component is appropriately protected if the risk of failure is lower than an admissible risk. The admissible risk of a network component can be obtained from economical criteria, such as replacement costs for the components damaged by lightning overvoltages, and service quality criteria, such as the network being off service as a consequence of deficient network protection against overvoltages.

The values of maximum lightning overvoltages at the nodes of the network can be found from computing programs for electromagnetic transients.

The program chosen is Matlab, a program using an extremely high calculation power as well as different toolboxes, e.g. Simulink, Powerys and Fuzzy Logic. Simulink and Powersys have made the simulation of electrical power networks possible, and Fuzzy Logic facilitates the construction of the fuzzy inference system.

Simulink and Power System Blockset have libraries that
contain models of typical power equipment. The models used for the overhead line and underground cable have distributed parameters, the surge arrester is simulated as a varistor, and the transformer is simulated as an open circuit. Lightning impulse is simulated as a current source represented by a triangular function.

The statistical distribution of lightning overvoltages at the network nodes depends on independent random variables, such as the peak value of the return stroke current, the impact point of the lightning stroke, etc. The statistical distribution of independent random variables is known. While we do not have a known function in order to obtain the statistical distribution of lightning overvoltages, we do have computing programs for electromagnetic transients which, once the independent variables have been fixed, allow us to determine the values of lightning overvoltages at the network nodes.

In order to generate the statistical distribution of lightning overvoltages in the network nodes, we need to avail of a procedure offering random values of independent variables, of which the statistical distributions are known [4]. The procedure considered most convenient is the Montecarlo method.

In the present analysis, the peak value of the return stroke current is varied random-wise, this current being one of the parameters affecting most influence on the surges values attained. Moreover, following the same procedure, an analysis including the random character of parameters can be made, for example the slope of the wave front, the impact point of the lightning stroke etc.

The lightning overvoltage set for each network node is obtained with a set of the independent variables and an electromagnetic transients program. It is assumed that lightning overvoltage distribution is the Gaussian density function, so this distribution can be obtained in terms of the mean value and the standard deviation.

It is assumed that probability of disruptive discharge of self-restoring insulation is given by a Gaussina cumulative probability function. Therefore, we must specify the mean value and the standard deviation. The standard mean value is found by the maximum system voltage and the standard deviation is of the order of 3%. For non-self-restoring insulations, the statistical nature of the strength cannot usually be found by testing and the assumed voltage deemed to correspond to a withstand probability of 100% is applied.

The risk of failure of a network component is calculated with the distribution of applied overvoltages to the network component and the distribution of its withstand voltages.

**PROTECTION PROCEDURE**

In this section we shall establish the method of calculating the location of surge arresters in order to limit the risk of failure [5-6]. It can be assumed that an electrical network is protected if the risks of failure at its components are lower than the admissible risks.

The admissible risk at the network equipment can be acquired from economic criteria, such as replacement costs for the components damaged by lightning overvoltages, and service quality criteria, such as the network being off service as a consequence of deficient network protection against overvoltages.

The error of failure can be defined as the risk of failure minus the admissible risk. From the error of the risk of failure established for the network components (which can be different), the surge arrester’s location is determined.

The network is protected if all the error of the risk of failure are negative.

The determination of the number of arresters and their ideal location for the protection of a distribution network is initiated by installing a surge arrester at the overhead line node and underground cable connection. This arrester can be installed far from the node line and cable connection to protect other nodes if all nodes between the line/cable connection and this arrester are completely protected.

The arrester can be installed far from the line and cable connection when the greatest risk error of the nodes without allocated protection is negative, resulting in the arrester location that allocates protection to the greatest number of nodes.

Additional arresters can be installed to protect the unprotected nodes. Each additional arrester is installed at the beginning of the unprotected node closest to the line and cable connection. The protective process is suspended when all nodes have allocated protection.

On some occasions, it may be convenient that for underground cables, depending on their length, the risks of failure be evaluated at several points associated to one and the same underground cable, so that the protection is not only guaranteed at their ends, but also at intermediate points where surges may originate that are sufficiently high to perforate the cable.

The error of risk at a network component decreases when the distance between the surge arrester and the protected component is reduced, so that if the surge arrester is connected directly to the protected component, then its maximum overvoltage is closest to the residual voltage of the surge arrester. Therefore the following considerations shall be taken into account in the protection procedure:

a. The protective procedure is initiated by protecting the components closest to the node of the overhead line and underground cable connection.

b. The magnitude of the applied voltage at a network component is decreased if the distance between a surge arrester and the component is reduced.

c. If a surge arrester can be installed far from the protected components if its risk error is negative, and so other vulnerable network components can be protected.

d. The greatest number of surge arresters between two consecutive nodes is two, one at each node.

e. The protective procedure is suspended when all network components are protected, and more precisely, when all analyzed nodes (interesting nodes) are protected.

The arrester is positioned at the furthest point possible without compromising the safety of the protected components.

An arrester is assigned to a node if this node is protected and the arrester position is fixed.

The protection of a node is achieved when this node is completely protected by one or more assigned arresters,
which means that its risk error is negative. Therefore a fully protected node is protected by arresters with fixed positions. The location of additional arresters will be established in order to protect the nodes without full protection.

In the protection procedure of an electrical network there are fully protected nodes, nodes that we intend to protect and non-analyzed nodes that have not yet been considered for the location of arresters.

In figure 1, we aim to protect two underground cables with a surge arrester. Arrester 1 is assigned to node 1 since this node is fully protected (its error of risk is negative) and the arrester position is fixed. Arrester 1 is assigned to node 2 if its error of risk is negative, otherwise it remains without assigned protection. Subsequent nodes are non-analyzed nodes, since they have not been considered in relation to the location of arrester 1.

The location of additional arresters will be established in order to protect the nodes without full protection. To select an arrester with smaller residual voltage, since it is not possible to protect the network with the selected arrester.

If an arrester is located at the current node and it is proven that its error of risk is not positive, it is analyzed to see if it is connected to an arrester at the following node. If it is, the following nodes are analyzed, and the current node is not assigned protection, since there are existing arresters protecting it whose position can vary. However, if there is no arrester connected at the following node, the following non-protected node with a smaller error of risk is located and this is the one that can be protected by the arrester.

When the greater error of risk of the nodes without assigned protection is not zero and the position of the arrester is not the end of the cable, it is proven that the smallest error of risk of the subsequent nodes and the biggest error of risk of the nodes without assigned protection are positive. If they are not positive, the fuzzy calculator finds the new position of the arrester and the errors of risk are calculated.

At the iterative process, if the greatest error of risk of the nodes without assigned protection is zero, then it is checked if the smallest error of risk of the following nodes is positive. If this error is positive, the arrester is located at the current node. If not, the arrester is located at the calculated position. Then the subsequent nodes are analyzed.

At the iterative process, if the position of the arrester is the end of the cable and the greatest error of risk of the nodes without assigned protection is negative, the subsequent nodes are analyzed, taking into account that the arrester position can be located at the following cable.

At the iterative process, if the smallest error of risk of the subsequent nodes and the greatest error of risk of the nodes without assigned protection are both positive, the arrester is located at the current node, since other nodes cannot be protected with the arrester. Then the subsequent nodes are analyzed.

**FUZZY CALCULATING SYSTEM**

The fuzzy calculating system is built using the Fuzzy Logic Toolbox, which allows the representation of existing knowledge of power network protection using surge arresters. This, in turn, leads to the location of the arresters, resulting in an admissible risk of failure at the network components.

We do not have an explicit function that can relate the risk of failure of network components to the position of surge arresters, we only have evaluations of the function obtained after running a transients simulation program. Therefore fuzzy logic is an effective technique in the calculation of the location of arresters.

The inputs of the fuzzy calculating system are: the risk error at the present iteration ($e_i$) and the output of the fuzzy inference system at the previous iteration ($s_{i-1}$), the latter being the change of arrester position ($\Delta L_{i-1}$) normalized in relation to the limit distance between the arrester and the protected component, Fig. 2. The output of the fuzzy calculating system is the change of arrester position ($\Delta L_i$). In the developed system, fuzzy values are given a linguistic value when they fall within a certain range. In the current implementation, the terms «negative», «zero», and «positive» are used for the normalized error of the risk of failure.
The terms «negative», «zero negative», «zero positive» and «positive» are used for the output of the fuzzy inference system at the previous iteration, which is an input variable. The linguistic values used for the output variable of the fuzzy inference system are «negative high», «negative low», «zero», «positive low» and «positive high».

In table 1, the array of rules of the fuzzy inference system is shown. The inputs to the array are two fuzzy linguistic sets: the normalized risk error (row) and the output of the fuzzy inference system at the previous iteration (column). The output of the array is one fuzzy linguistic set, which is the output of the fuzzy inference system at the present iteration.

**TABLE 1 – Array of rules of the fuzzy inference system.**

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**COMPUTER APPLICATION**

The application implemented calculates the surge arrester positions so that the network component risks are lower than the values specified by the user. This application has been implemented using Matlab, since it is a powerful calculation tool which also allows easy communication between the fuzzy logic algorithms (Fuzzy Logic Toolbox) and the transients simulation program (Simulink and Powersys Toolbox). The block diagram of the application is shown in Figure 3.

The electrical network model is built from the network component models implemented in the blockset Powersys.

**EXAMPLE**

In this section we perform the analysis of the protection of an underground network connected to an overhead line. The rated voltage used for this distribution system is 25 kV (the value used by electrical companies in Catalonia).

The underground network has a 30 m cable connected to the MV/LV transformer, Figure 4.

It is given that the impact of the lightning stroke is on the last span of the overhead line and the flashover on the insulator chain does not occur.

The surge arrester must be placed in a position where a risk of failure lower than 0.1 at node 1 and 0.12 at node 2 can be obtained.

The protection process is initiated by installing a surge arrester at node 1, which is the overhead line and underground cable connection node. At its current position, the risk error at node 1 is negative, therefore the arrester can be installed further from node 1 in order to increase protection of node 2. The result regarding the surge arrester position is 13.28 m.

The result obtained with the program have been verified by evaluating the risks of failure of the node, taking into consideration the arrester position.
Fig. 4. Scheme of the analyzed network.
Figure 5 shows how the risks of failure at the network nodes are lower than the specified values for the arrester position calculated, therefore the protection of the network is established.

CONCLUSION

The aim of this work is to establish a method for the selection of power system protection schemes against lightning overvoltages. The proposed method is based on statistical analysis of surges and fuzzy logic techniques with the objective of establishing the arrester locations that provide risks of failure at network nodes that are lower than the admissible risks. The implemented algorithms optimize the surge arrester location, working with known risks of failure. The method developed in order to establish the surge arrester’s location is an alternative to the optimization method, which is based on mathematical techniques for calculating the minimum risk of failure. The running time of the fuzzy program is lower than the one in an optimization program.

REFERENCES


Fig. 5 Risk of failure at network nodes versus surge arrester position.