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Risk Assessment Methodology for Operations applied to the Portuguese Transmission System - the Probabilistic Model

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SUMMARY

Nowadays most of the transmission systems' operating conditions are more stressed due to the introduction of a competitive environment in the power system industry and the regulatory changes causing the unbundling of generation, transmission and distribution, the environmental concerns, which limit the construction of new transmission lines and generation capacity, and the strong incentives to the generation through renewable energy sources. The use of methodologies that take advantage of the actual real-time conditions in combination with past knowledge is extremely interesting in the system operation's environment, because it gives a more accurate overview to the control room operators allowing them to prevent harmful situations. Obviously, this type of methodologies has received even more interest after the large disturbances which occurred in recent years, because they increase the awareness about the risk of unpredictable disturbances. Recent international data show that the frequency of large blackouts has increased and also that simple initiating faults can have very severe consequences. References [1-4] present a few examples of severe disturbances, which occurred in the recent past. Despite all the efforts being done regarding supervisory practices, operation strategies and protection and control systems' improvements, it is technically and economically impossible to eradicate major disturbances and blackouts. They will be a permanent threat to the electrical power systems, making incident analysis a crucial activity. The risk assessment methodology that is being developed is composed of two parts: probability of occurrence and severity for all contingencies under analysis. This paper aims to present the complete probabilistic model used to calculate the probability of occurrence of contingencies, including overhead lines, transformers and busbars. N-2 common cause contingencies are also considered for faults caused by lightning and forest fires.

KEYWORDS

Contingencies, power transmission faults, probability, risk assessment and system operation

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1- Probabilistic approach versus deterministic approach

The deterministic security assessment has been widely used by Transmission System Operators (TSOs) to guarantee a high level of security in system operations, being known as N-1 criterion [5]. This method has provided high reliability levels and is easy to implement because of its simplicity, but it has some weaknesses. The deterministic approach only addresses the severity of contingencies, in terms of thermal loading, voltage violations and loss of load, considering that events are equally likely and therefore it cannot address increased or decreased uncertainty in the operating conditions.

Facing an adverse weather situation, such as lightning occurrence or a high risk of forest fires, the likelihood of contingencies is still the same, although there are TSOs that also include specific N-k events, with K>1, in their "must-run" contingency list. The risk of multiple contingencies cannot be neglected and the analysis needs to include local conditions, such as environmental, geographical and geological, e.g. the presence of pollution or storks' population, but also current conditions, such as adverse weather or risk of forest fires.

The deterministic security assessment does not consider the current conditions (such as lightning occurrence), the effect of longer overhead lines, which are more exposed to the action of external factors due to their dispersion over a wide area than the shorter ones; neither the inherent characteristics of the geographical area where they are deployed nor the actual presence of the fault's cause, which increases significantly its probability of fault. While probabilistic assessment gives the opportunity to include through historical failures rates the seasonality, geographical influence and even current conditions in the probability calculation.

The probabilistic assessment versus deterministic assessment is a broadly discussed topic, which appears in several references, such as [6]-[8].

2- Online Risk Assessment

An integral risk assessment methodology is being developed to support control room operators in their continuous task, aiming to evaluate online the risk of contingencies for the next hour. By combining severity and probability, it is possible to evaluate the risk of contingencies, as in (1).

$$Risk_i = probability_i \times severity_i \tag{1}$$

where i represents the i^{th} contingency under analysis.

For on-line risk assessment short-term failure rates are crucial, considering actual conditions, identifying which are the areas more exposed to risk, as well as historical fault data, including network characteristics, geographical, geological, and environmental and weather data in the calculation. Reference [6] gives a very good insight on the operational risk assessment and discusses the external influencing factors and the concept of short-term failure rate which was developed in this work.

To calculate severity for the next hour, current State Estimator snapshots will be used, including the expected changes in actual conditions such as programmed outages, wind generation forecast, load forecast and expected market-driven generation pattern. For each contingency, the severity calculation has to assess thermal overloads, voltage limit violations, voltage instability, loss of load, loss of generation and the danger of cascading. This part is now under development.

The list of contingencies to be evaluated is composed by single and double common cause contingencies.

3- Fault historical data

The incidents' set of data under analysis is composed by 2337 faults over 8 years, where 2157 are OHL faults, representing 92% of the total number of faults in the Portuguese Transmission system (PTS). The faults in transformers represent about 7% and in busbars 1% of the total. The most frequent causes for faults in the PTS are storks, forest fires, fog in combination with pollution and lightning, as shown in Figure 1.

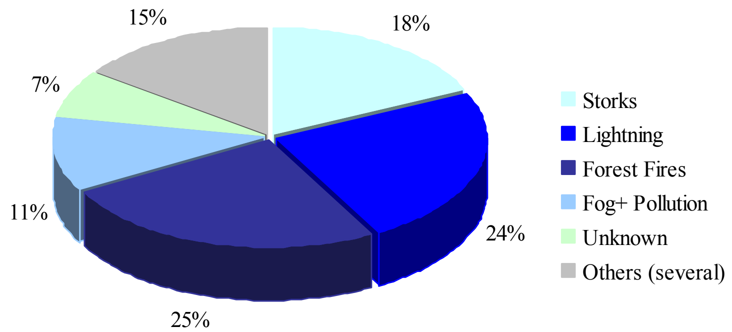

Figure 1 – Percentage of fault causes in the PTS from 2001 to 2008

Overhead lines, due to their dispersion over a wide geographic area and because of the many different ground characteristics where they are deployed, are more exposed to the action of external factors which cause most of the grid incidents. An accurate characterization of the incident's main causes, an analysis of their occurrence and of the intrinsic characteristics of the Portuguese territory is presented in reference [9], including all the mentioned input data, which are crucial for the risk assessment methodology.

4- Fault probability

The probability of fault occurrence on a line can be modelled using the Poisson distribution with a constant fault rate [10]. Therefore, the probability of fault in the time period t is calculated as in (2).

$$Probability_{fault} = 1 - e^{-\lambda \cdot t} \tag{2}$$

Where λ is the average failure rate for the considered period and t the duration. If $\lambda t << 1$, (2) can be approximately defined by $\lambda \cdot t$. The average failure rate can be replaced by the frequency of fault occurrence, obtained from historical data, since the duration of a fault is always extremely short [10].

The probability of fault is calculated independently for each cause that is associated with the circuit-part of overhead lines (OHLs), transformers (TRs), busbars and circuit-ends. Figure 2 presents the OHL scheme for probability calculation, which is explained in [11]. In case of transformers, the two circuit-ends are also considered.

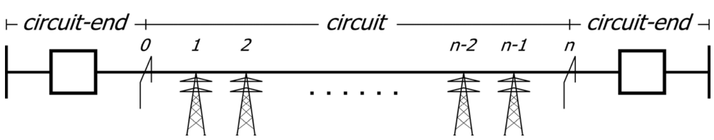

Figure 2 – Overhead line scheme for probability calculation

For each cause dependent on length, namely storks, lightning, forest fires, fog combined with pollution, OHL equipment and others, the probability of fault is calculated taking into account the average failure rates, the actual risk factors based on field characteristics and on current conditions. In the calculation, several types of information is included, such as fault historical data, the physical structure of the network, characteristics of the Portuguese territory (including environmental and geographical data) and weather data (especially lightning data and the risk of forest fires). It is possible to identify the characteristics of each cause (such as time, season and location), their failure rate per length per time of analysis, and the real-time influencing factors.

In the case of transformers, as well as faults caused by the transformer components, e.g. trip caused by Buchholz relay, also the intrinsic characteristics of the location where the transformers are installed and the current conditions influence their performance, such as local fauna. Regarding busbar, the main causes of faults are fog associated with pollution within an identified area and internal origin, like equipment, human errors and protection or control system anomalies, which are causes that affect equally the bays associated with other grid elements.

Generally, the probability of each cause is calculated as in (3) for causes dependent on length or as in (4) for the other causes, with the exception of lightning where the backflash rate is calculated per OHL.

$$probability_{cause_i, OHL_k} = \left[\lambda_{cause_i}(month, day\ period, u) \cdot length\ at\ risk_{cause_i, OHL_k}\right] \cdot t \quad (3)$$

$$probability_{cause_i, element}(u) = \lambda_{cause_i, element}(u) \cdot t \quad (4)$$

where u is the voltage level, t is the analysis duration (for on-line assessment this is typically 1 hour); $\lambda_{cause_i}(month, day\ period, u)$ is the average failure rate for OHLs and $length\ at\ risk_{cause_i, OHL_k}$ is the length at risk of OHL_k, per cause. In (4) element refers to transformers or busbars and $\lambda_{cause_i, element}(u)$ is the failure rate per voltage level per cause. For transformers, the failure rate is selected according to the higher voltage level.

In case of OHLs, the yearly average failure rate is the number of faults per km per hour, calculated independently for each cause, voltage level, month and day period. For almost all independent causes, geographical, environmental and weather influence are incorporated using weighting factors based on location which will affect the considered length at risk and the current conditions. Reference [11] presents the used weighting factors for storks, fog combined with pollution and forest fire. For forest fire, a frequency analysis of the risk level that causes faults was made and the value of the cumulative probability is used instead of what was presented in [11].

In case of lightning, the backflash rate per OHL is calculated based on the probabilistic method for lightning performance of an overhead line developed by CIGRE [13]. The method uses a large amount of information, such as tower geometry, the tower footing resistance, the insulation level, the conductor diameter, geographical and geological information, lightning monitoring system data, faults' historical data, among others. The critical current, minimum current that causes flashover, is calculated per tower, due to the fact that each tower within an OHL has different characteristics. Afterwards, also per tower, the probability of a flashover (which is the probability that the stroke current I equals or exceeds the critical current IC) is determined through CIGRE reference cumulative distribution for negative lightning current amplitudes, first stroke. The average of the probability of all the towers is calculated per OHL and the backflash rate per OHL is the multiplication of this probability by the number of flashes, NL, that terminate on the ground wire, and a scaling factor that fits the calculated values to the actual historical fault data. In the end, for online evaluation, the backflash rate per OHL is affected by the current conditions and is also calculated per hour [12].

For transformers and busbars, the yearly average failure rate is the number of faults per grid element per hour and it is also calculated independently for each cause and voltage level. There are not enough faults to have a meaningful statistics per month or per period. Reference [12] gives a detailed explanation of the whole probabilistic method.

The different incident causes are assumed to be statistically independent events, which makes it possible to calculate the probability of any part (OHL circuit-part, TR or busbar) using (5).

$$P\left(\bigcup_{i=1}^{n} A_i\right) = \sum_{i=1}^{n} P(A_i) - \sum_{j=1}^{n}\sum_{\substack{i=2\\ j<i}}^{n} P(A_j A_i) + \sum_{j=1}^{n}\sum_{\substack{i=2\\ j<i<k}}^{n}\sum_{k=3}^{n} P(A_j A_i A_k) - \ldots + (-1)^{n-1}\cdot P(A_1 A_2 \ldots A_n) \quad (5)$$

where $A_i, i = 1,2,\ldots,n$ are the probability of occurrence of random events due to $cause_i$.

After combining the causes per part, the final probability of fault occurrence per OHL or TR is calculated as in (6) and, because busbars do not have circuit-ends in their scheme for probability calculation, their probability is simply to apply (5) to all the causes that affect busbars.

$$fault\ probability_j = 1 - \left[(1 - prob_{end}(u)) \times (1 - prob_j) \times (1 - prob_{end}(u))\right] \quad (6)$$

where $prob_j$ is the probability of a specific OHL or TR and $prob_{end}(u)$ is the probability of circuit-end in the voltage level u.

The fault probability value calculated as in (6) is used to assess the risk of single contingencies.

5- Probability final results for single events

For single contingencies, the probability of fault occurrence is hourly calculated. In order to illustrate its results figure 3 presents the probability of fault calculation for a 400kV OHL, from the beginning of June until the end of November 2009. This specific OHL is affected by storks and fog combined with pollution as noticeable from oh to 6h, because of higher probabilities. The small peaks in graph are the effect of lightning occurrence and because the BFR for this 400 kV OHL is relatively low, the lightning occurrence effect also is small.

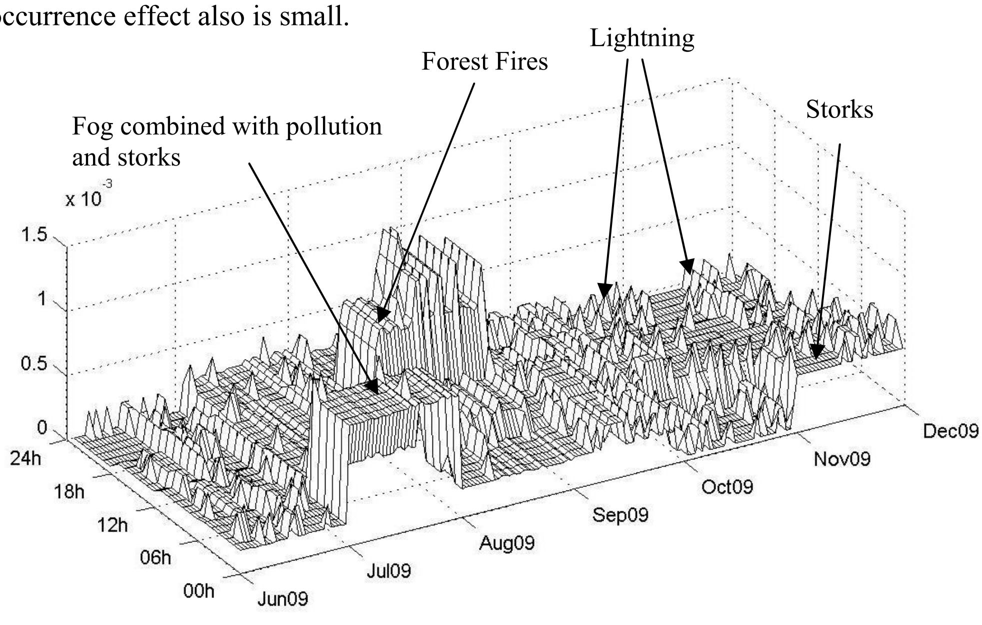

Figure 3 – Probability of fault occurrence for a 400kV OHL

6- Common cause double contingencies

Through historical data analysis, it is possible to conclude that double contingencies caused by a common cause or caused by the combination of an initial fault with a hidden failure cannot be neglected. In this paper, only common cause faults will be addressed. Common cause failures (CCF) mainly happen due to lightning, affecting OHLs that share the same towers during the whole or part of their right-of-way. From 2001 to 2008, the 290 dependent contingencies (about 13% of the total), 137 are common cause, which represents about 47%. About 98.5% of the faults caused by lightning affect OHLs and 30% of those are common cause faults. The length of OHLs sharing the same tower represents on average 15% of the total length.

Beyond lightning also forest fires may cause common cause faults. Based on historical data, it is possible to affirm that the same forest fire may affect OHL corridors that are composed of more than one OHL, but they rarely fail simultaneously (less than 5% of the faults affect more than one OHL in less than 5 seconds). In the same period, forest fires have only affected simultaneously two OHL, which are normally sharing the same towers and right of way, therefore the β-factor model is adequate.

The method used to calculate the CCF rate for both described situations is the β-factor model [14]. With the total failure rate, the number of independent and common faults per each OHL or segment, it is possible to apply the β-factor model for common cause faults in parallel identical OHLs (or segments) that already have CCF in their history. This method is valid for OHLs that share entirely the same right of way, which can be considered identical components having the same failure rate, which is true for the OHL that mainly trip because of faults caused by lightning. For OHLs that only share part of the total right of way, the division into segments is required and the failure rate has to be calculated for each OHL segment independently. Therefore, the location of the faults has to be determined in order to achieve an accurate statistical analysis.

The beta-factor model assumes that: Total component failure frequency (λ_T) = Independent failure frequency (λ_I) + common cause failure frequency (λ_C). The common cause failure probability will be used for risk calculation of N-2 contingencies that are included in the security assessment whenever there is probability of lightning. In case of one of the parallel OHLs, which share the total right of way, with more independent faults than the other, but the same number of CCF, the maximum of the λ_C is used. In case of two OHLs that share only part of the right-of-way, which is normally the length of the shortest OHL, λ_C will be calculated considering the shortest OHL, because it corresponds to the common path.

In case of faults caused by lightning, as already mentioned, the backflash failure rate (BFR) is calculated per OHL based on the probabilistic method for lightning performance of an OHL. Table I presents some of the results for the common cause failure rate for faults caused by lightning, from which is possible to conclude that some OHLs, where β=1, only have CCF faults when affected by lightning. In real-time, λ_C will be affected by the current conditions, i.e., in case of no lightning activity, there is no risk of faults caused by it.

OHL pairs	**U(kV)**	**λ_T (BFR) per year**	**β**	**λ_C per year**
1041+1042	150	0.1978	1	0.1978
1079+1105	150	0.9958	0.89	0.8851
1090+1120	150	0.3986	0.5	0.1993
1108+1107	150	0.1388	1	0.1388
1116+1134	150	0.6505	1	0.6505
2021+2022	220	0.2975	1	0.2975
2044+2045	220	0.1612	1	0.1612
2108+2142	220	0.4246	1	0.4246
2110+2117	220	0.0857	1	0.0857
2121+2123	220	0.0378	0.8	0.0303
2124+2125	220	0.9238	0.86	0.7918
4021+4050	400	0.0202	0.6	0.0121

Table 1 – CCF failure rate per year for N-2 events caused by lightning

Table 2 presents the set of parallel OHLs that were affected simultaneously by the same forest fire and the β value for each pair.

OHL pairs	U(kV)	β
1090+1120	150	0.50
1108/1616+1107/1615	150	1.00
1125+1113	150	0.50
2021+2022	220	0.67
2108+2142	220	0.25
2124/2612+2125/2613	220	0.80
2135+2136	220	0.31

Table 2 – OHL pairs and respective β
for N-2 events caused by the same forest fire

The common cause failure rate is not presented in Table 2, because the failure rate will change according to the current risk level or the presence of forest fires in the municipalities where the towers of each OHL are located. This will be hourly updated in real-time. Figure 4 shows the probability of occurrence of an N-2 contingency, where is possible to distinguish the effect of lightning activity through the peaks in the graph and the effect of forest fires through the higher surfaces mainly noticeable in August. When none of these causes are present the probability of CCF is not considered and in the figure 4 is presented as zero.

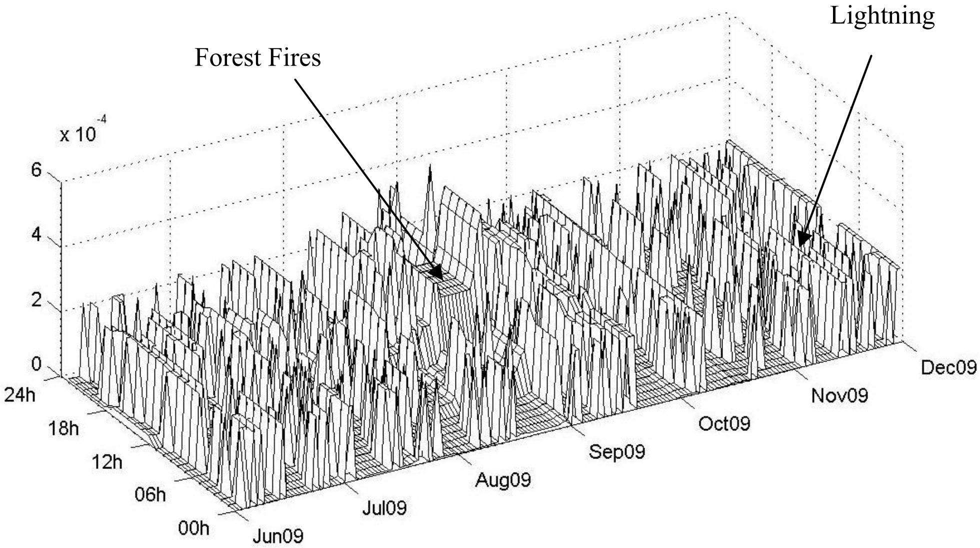

Figure 4 – N-2 contingency composed by two 220 kV OHLs

7- Conclusions

In this paper, the probabilistic method of an integral risk assessment methodology is presented. In order to develop it, information gathering was crucial; therefore having a TSO structure (where the system operator and the asset owner part of the same organisational entity) facilitates this process. It is also important to make this methodology flexible and easily updated, i.e., to be valid for now and for the future. In terms of risk assessment, the relevant variables should be added, changed or removed from the probability of occurrence when needed and according to the evolution of the physical network, terrain and meteorological conditions and system's security requirements.

The risk of single and multiple contingencies cannot be neglected. Common cause faults occur in electrical power systems under specific circumstances, such as lightning and forest fires. The β-factor model has proven to be adequate to address the N-2 contingencies for parallel OHLs.

A risk assessment methodology with a probabilistic analysis will also allow a more efficient use of the network capacity, considering different probabilities related to different contingencies, mainly N-1 and N-2 events. It is being developed to be used on-line as a decision support tool for control room operators in the security evaluation, providing them with risk-based security indices for the subsequent time period (such as 1 hour).

8- Future Developments

Protection system hidden failures together with common cause faults are the most frequent causes for double contingencies. These contingencies are considered also dependent as common cause ones, but the causes that affect the involved elements are different. While common cause failures are only present under specific conditions, such as adverse weather and forest fires, hidden failure events are always present in the system because they do not depend on external factors. For future developments the integration of these faults in the presented methodology is proposed.

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