Long term assessment of critical factors affecting the reliability of transmission grids

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I. INTRODUCTION

The critical nature of electricity transmission grids is an established fact that supports requirements of permanent availability and very high reliability. To meet such requirements, investments in reserve capacity and grid redundancy are acknowledged by regulators on each market while maintaining pressure on Transmission System Operators [TSO] to demonstrate the need of such investments.

Improving the availability and reliability of the grid involves investments of two different natures: investments on how to prevent failure (usually line tripping) and investments on how to cope with failure by mitigating its consequences. The paper focuses on a long-term effort to assess technical and economic benefits of the former, so that the latter becomes less important. An alternative reasoning on this approach is that identifying effective measurements to improve reliability will extend grid capacity in the future, thus postponing the need for investment in additional generation capacity, line redundancy and transmission reserve capacity.

Generation from distributed, renewable resources presents a special case since regulations often require TSO to dispatch all available power and, as most of it comes from wind generation and is difficult to schedule, the reliability of the grid is tested on remote locations that are often at the end of transmission grids.

Environmental factors are a major cause for reliability issues as transmission grids spread across the territory, often crossing remote areas to connect to hydro and wind generation, but the interpretation of phenomena that leads to reliability issues is seldom straightforward. The authors participate on a long-term project to optimize maintenance decisions and scheduling according to field findings on the Portuguese electricity transmission grid operated by REN [1].

The grid operated by REN is mature in the sense that most of its assets are beyond half lifetime and quite a significant number of them are near the end of their estimated lifetime.

One of the main challenges found, is that the Portuguese transmission grid already has a high quality record for reliability; therefore it is imperative to learn the maximum from each issue. Also, it is difficult and uncertain to wait for years to test a hypothesis on the explanation of a given set of line failures. Finally, it is deemed unacceptable to degrade the quality of service and reliability to empirically find the optimum balance with decreasing total cost of ownership.

The authors begin with a ten year list of recordings of line faults where each occurrence is tagged with an immediate cause determined by experience or some heuristics. Then they match these occurrences in time and space with many phenomena related to equipment, operation, natural hazards and third-party human interaction (the latter two are considered environmental in the broad sense that people living and working around power overhead lines are part of its environment), to find whether the field data corroborates the immediate explanation.

While the project is still on-going, some interesting cases have been highlighted: how vegetation management affects mean time between failure in individual lines; how reliable is the binding between incidents associated with lightning and lightning referencing in space and time provided by weather services; how storks seem to be near towers with broken insulators; how human activities on the ground may help or hinder grid maintenance and exploitation.

The authors use an information system platform to characterize the environment and land use [2] along transmission lines and massively cross different factors to find plausible explanations to line incidents and how they could relate with the cause mentioned in the incident recordings.

The near goal is to evaluate the effectiveness of maintenance practices implemented to improve the reliability of the existing grid and where and how resources ought to be applied to reach optimum efficiency. The longer term goal is to supply such data to grid planners so that future grids could be more economical and more reliable as well.

II. PORTUGUESE ELECTRICITY TRANSMISSION GRID

a) General information

REN – Rede Eléctrica Nacional S.A. is the concessionaire of the Portuguese National Electricity Transmission Grid (RNT). This concession includes the construction, operation and maintenance of the RNT. It also includes research and development relating to electricity transmission and the technical global management of the electricity system to ensure the coordination of the electricity distribution and electricity transmission infrastructures, thereby assuring the continuity and security of supply and preserving the integrated and efficient operation of the national electricity system. REN strives to maintain and improve its quality of service through appropriate planning for safety and to ensure continuous supply, suitable investment in the renovation of older power lines and substations, appropriate maintenance policies and strategies and efficient use of technical and human resources in the operation and maintenance of the RNT.

By the end of 2011, the transmission lines total length was 8371 km (55.4 km of underground cables), with 2236 km of 400 kV, 3492 km of 220 kV and 2643 km of 150 kV. The transmission grid had 64 substations, 13 switching stations, 189 power transformers and autotransformers and 1297 bays, with a total installed capacity of 33627 MVA.

b) Transmission Grid performance

In the last years, REN has invested massively in the renovation and extension of the transmission grid in Portugal, in order to optimize its transmission capacity, responding to demand and supply dynamics, and improving service quality. Over the last six years, the RNT verified a remarkable evolution. From 2006 to 2011, the number of substations and switching stations has grown by 31% and the circuit length by 20%. Despite the considerable increase on the length of transmission lines, in the same period (2006-2011), the incidents' number had a decrease of 9.5% (Fig.1).

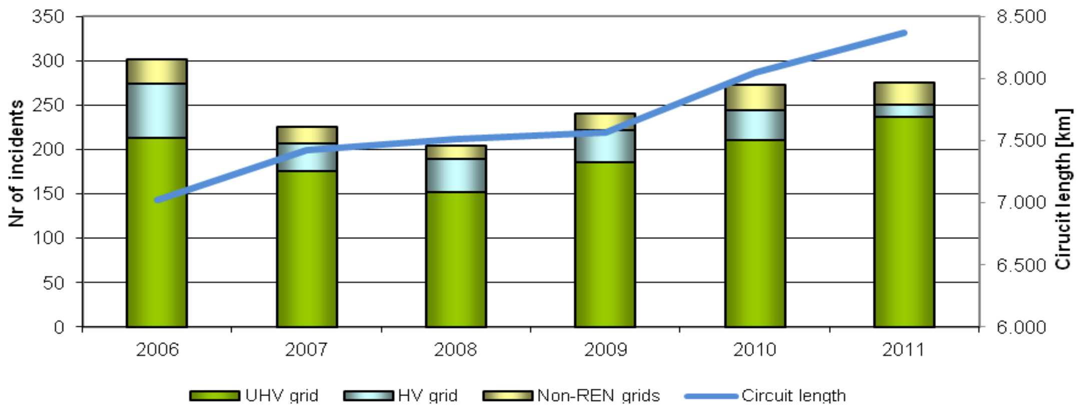

Fig. 1 Evolution of number of incidents and circuit length

From this group of events, 84% had origin in overhead lines (Fig.2). These, due to their dispersion over a wide geographic area and because of the many different ground features where they are deployed, are more exposed to the action of external factors which cause most of the grid incidents.

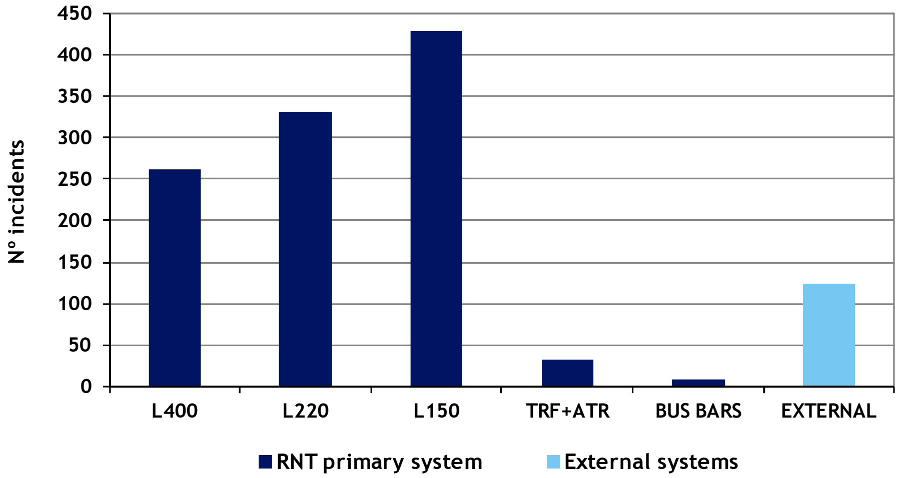

Fig. 2 Number of incidents per equipment type

The most common and frequent causes for incidents in the Portuguese electricity transmission grid are the following: Lightning, storks, forest fires, fog in combination with pollution.

These four main causes represent about 75% of the faults in the Portuguese electricity transmission grid (Fig. 3).

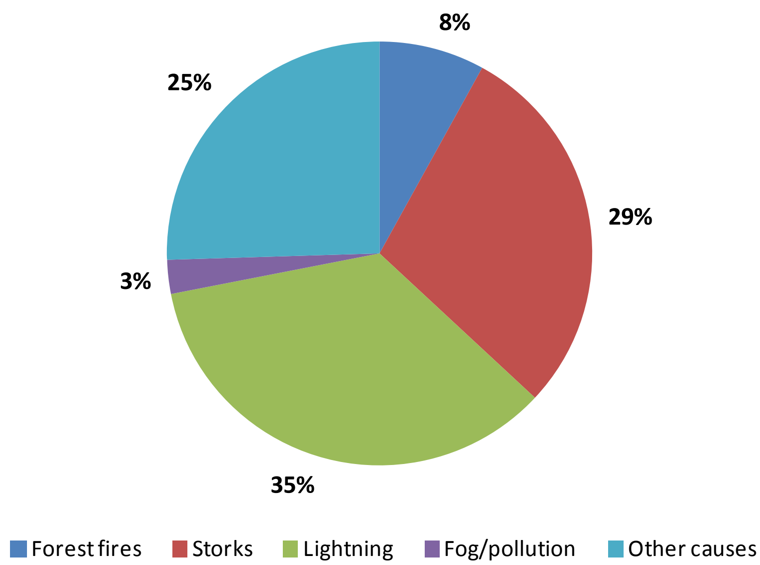

Fig. 3 Fault causes between 2006-2011

III. CRITICAL ENVIRONMENTAL FACTORS

a) Lightning

Overhead lines are especially vulnerable to lightning as they are often located in exposed locations and cover large distances. There is no absolute protection against lightning and it is considered a complex fault cause, although overhead line reliability performance is dependent on adequate insulation coordination. The tower geometry, the soil resistivity, the tower footing resistance, the number of ground wires and the insulation level are aspects that will influence the performance of the grid element in case of lightning.

Over the last years the impact of lightning on the Portuguese transmission grid had gained relative importance compared to other external agents and it is, at the moment, the major cause of faults on overhead lines (Fig. 4). The year 2011 was particularly adverse in what concerns to lightning, having the number of faults per 100km of circuit reached the value of 1.5 which is the maximum limit recommended for a transmission grid. However, 51% of the total number of faults occurred due to lightning, in 2011, took place in six overhead lines only. REN pays particular attention to this development and has already initiated a monitoring analysis of the most critical circuit lines, and is studying, as well, a reassessment of the possible need to review the insulation coordination criteria.

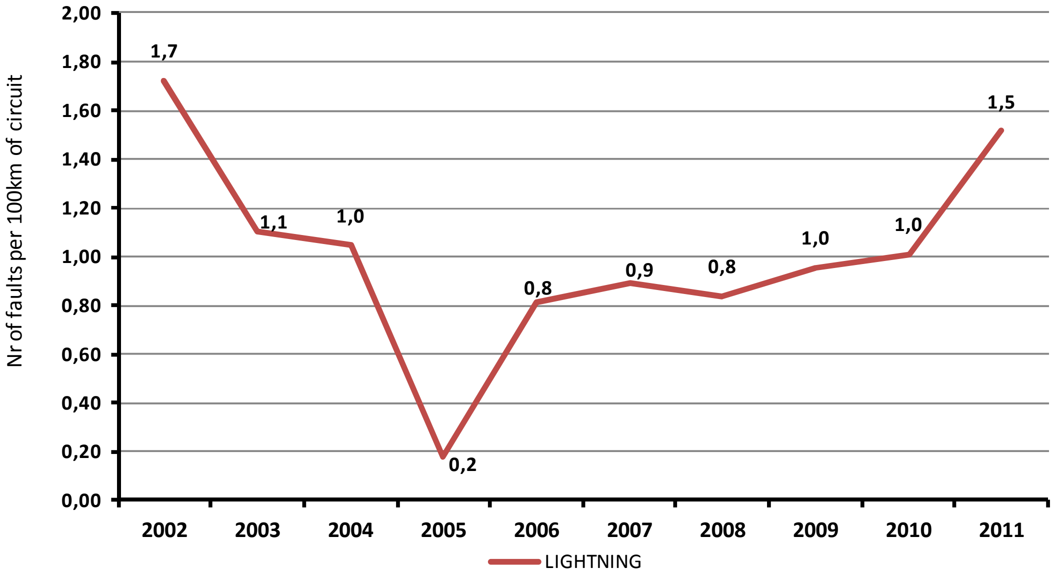

Fig. 4 Number of faults per 100 km per circuit due to lightning

b) Storks

Storks and, to a lesser extent, other birds, are a cause of concern on the Portuguese transmission grid. Storks are the second cause of line tripping, just after lighting, and have been associated with 25% to 30% of incidents. REN has acted accordingly with significant investments in tower accessories: anti-nest devices for hazardous areas and nesting platforms in safe areas. Other birds require bird flight diverters to improve the visibility of the OHL and minimize the likelihood of collision.

Fig. 5 The two top nests are mounted over platforms on "safe" areas. The bottom one was installed on a hazardous location where droppings affect maintenance work. Notice that near the insulator the horizontal mill deters storks from nesting and standing near the insulator chains.

Such equipment is often installed after the OHL has been in service for some years, since there is little knowledge about the number of birds and their behavior before the OHL is installed and mounting such equipment along the whole line would be technically and economically inadequate. In addition to line tripping attributed to birds and loss of wildlife due to collisions with the cables, field inspections have suggested that a correlation exists between the presence of storks and damages to the grid equipment, namely insulators.

It is not yet established whether the storks are the cause of the insulator damage or if the simultaneous occurrence of broken insulators and storks is an evidence of an earlier cause to both issues [3].

REN maintains a record of stork distribution across its grid for more than ten years (Fig. 6) and there is evidence that the stork population is increasing in density while it is extending to new areas. Fig. 7 shows the evolution in the mount of anti-landing devices and nesting platforms.

The investigation of line tripping incidents has also suggested that OHL can be affected by storks even where there are no neighboring nests. Therefore, the current approach of installing supports and constraints to nests might need to be revised or supplemented with other methods to minimize interference to the grid.

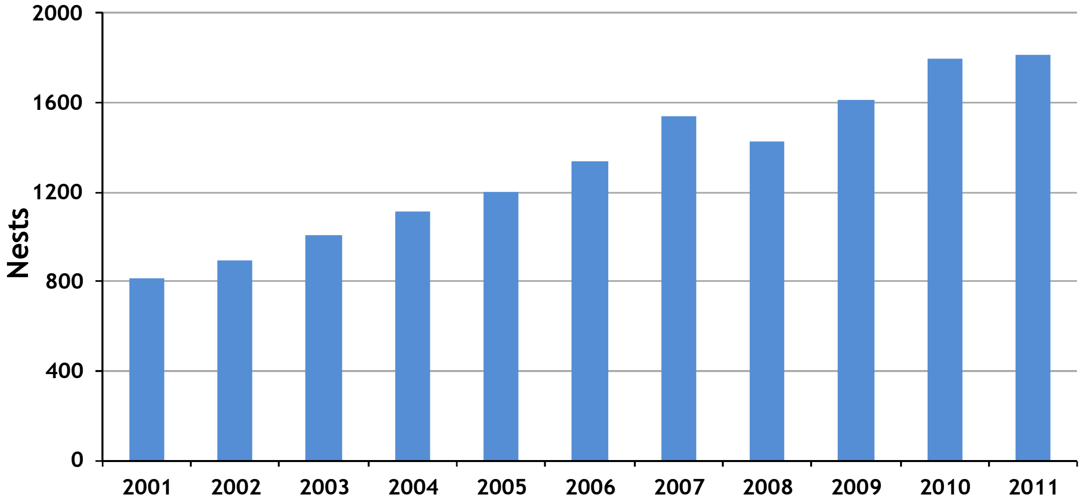

Fig. 6 Evolution of nests in the Portuguese transmission grid.

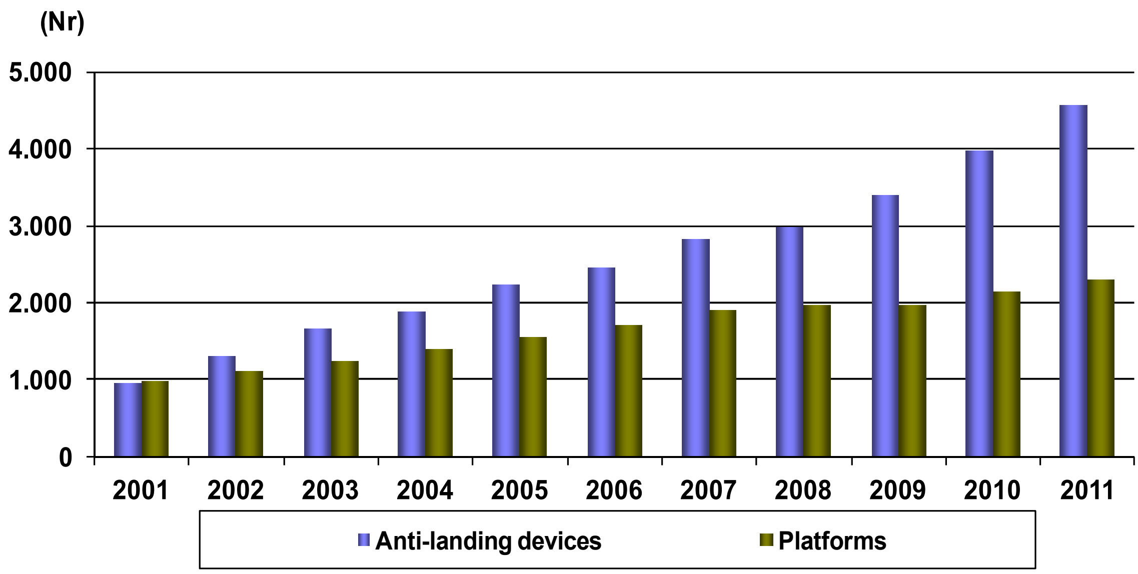

Fig. 7 Evolution of the assembly of anti-landing devices and platforms

c) Vegetation and Clearance

Vegetation has been also a concern to the company over the years. Inspections of overhead lines stopped being performed by all-terrain vehicle and started to be carried out by helicopter, using laser technology. The laser measurement system can measure and plot distances between conductors of overhead lines and obstacles placed in their right of way, identifying and classifying into different categories the different abnormal distances detected, associating this graphical representation to video images and geographically referencing them through GPS equipment.

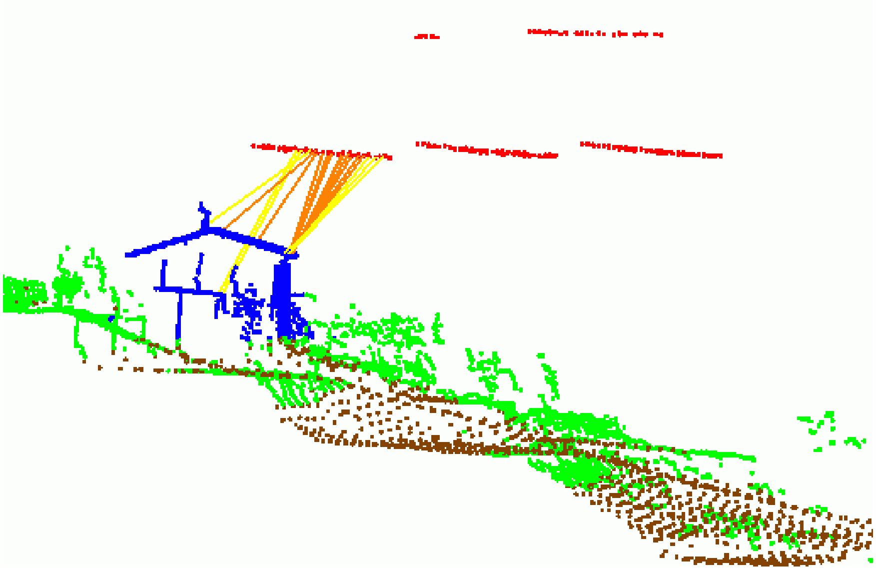

Fig. 8 Warning issued after clearance from the OHL (red) to a house (blue) was measured by laser

The effectiveness of the inspection by ground vehicle was not 100%. On average, about 2 cases per year were registered due to vegetation approach. With the introduction of laser technology, on a period of five years, a single event was recorded. From an economic point of view, there were also benefits using this technology, yielding a 10% reduction in maintenance costs, in a three-year period.

The positive effects on the reliability depend on adjusting the maintenance period with the growth rate of the trees because, as they grow, they'll come closer to OHL cables raising the probability of failures through phase-to-ground faults. The next step will be to optimize inspection and maintenance combined with the special regulations related to forest fires introduced next.

d) Forest fires

Forest fires are a severe natural hazard in mainland Portugal. As a side effect to the injury to the environment and the local economy, they also interfere with the operation of the transmission grid in two manners: the occurrence of fires under the OHL causes line tripping or the line is mandatorily disconnected to protect firefighters on the ground.

The approach followed by REN and recently put into the legislation with the New Forest Defense Law is to ensure that OHL corridors act as way out routes for biomass during regular forestry activities and as open corridors to slow the progress of fire during wildfires.

In addition to regular vegetation management, the new procedures require that a corridor – usually narrower than the full right-of-way - is kept clear at all times. This is carried by subcontractors under REN supervision with the cooperation of local authorities that define the extent of areas to clear. Selective bush clearing occurs in about three year cycles. In the aftermath of a forest fire, the OHL track is clean for about two to five years, depending on the region and this should affect any reliability models for OHL near burnt areas.

Different from lightning and storks, forest fires often affect more than one OHL in the same region and the traditional N-1 approach (one reserve line per each active line is less effective: if one line is removed from operation due to a forest fire, the likelihood of failure of the reserve line running parallel a few hundred meters away increases. Thus all reliability studies should investigate the cross-correlation of OHL failure in N-1 lines due to forest fires and search for alternate energy routing through distant channels, less likely to be affected by the same wildfire.

REN assesses the efficiency of vegetation management through the ITOMS methodology [4] and the input data used combines previous knowledge of the grid with field data from laser measurements, right-of-way reports, and selective bush clearing to provide a more accurate estimate of the grid characteristics.

e) Fog and Pollution

Fog and pollution act together to cause OHL tripping. It is a mixture of humidity in the air and dust containing conductive particles that causes a conduction route to be established in the periphery of insulators. REN has mitigated this issue by thoroughly replacing the glass and porcelain insulator chains with polymeric insulators.

This has effectively reduced the number of incidents related to fog and pollution but it is a costly intervention and one that needs planning years ahead for the refurbishment of a OHL. The reliability of polymeric insulators as they age is yet to be characterized.

IV. THE INFORMATION INFRASTRUCTURE

The key features of the information infrastructure required to connect data from such disparate sources are open interfaces, time and geo-references, layering, reversibility and auditing. Open interfaces are necessary to read and combine information from many sources. The system can read spreadsheet files, geographic information files, multimedia files, databases and can connect automatically to sources of information for timely updates. The main data repository is a geographic and time referenced database in PostgreSQL. This allows the user to compare data at the same instant in different locations and at the same location across time. The numerical operators that match data, accumulate effects (a form of addition), detect differences (a form of subtraction), look for repetitive patterns, etc., establish a kind of algebra that can be used through systematic number crunching to blindly establish correlations among multiple disparate factors and, eventually, nexus of causes between environmental factors, asset ageing characteristics, operation variables and the observed incidents.

A later goal is to try to modify conditions to hamper or inhibit the nexus of causality that leads to the incident, reducing the number of events and wear to the equipment.

The whole system is organized in layers similar to geographic information systems with the addition of time and technical information. Moreover, the system is reversible and auditable in the sense that all changes are authored and preserve previous information. As a consequence, any debate about a method, about the quality of input data, can be audited and reversed, in the sense that one can make an alternative procedure from a previous state of variables or modifying the data layers.

The system integrates with REN's Geographic Information System and asset management platform in addition to its own web based toolset to offer engineers a computer lab on OHL exploitation and ageing.

The layers of data already stored include land use, temperature, humidity, pollution maps, keraunic (lightning) maps, stork nest distribution, line inspection reports and asset information (type, part numbers, age). This spreads across a variable period of time (two years to eleven years) and geographic coverage is complete in most layers. However, the detail and quality of the data changes across samples. More data is expected, such as wind speed and directions, dispatch data (loads, lines removed from service, generation constraints).

V. THE RELIABILITY ASSESSMENT METHOD

The computation of the reliability functions is based on the assumption that failure causes are independent and sufficiently small as to be able to neglect the probability of multiple simultaneous failures.

The first step of the method is to compute the probability of failure of an element of the grid (a felled conductor, a worn union that overheats, a damaged insulator chain). To this end, the possible causes are listed. If the cause is associated to an equipment part the results from previous inspections can provide quantities or, in other cases observations on how the characteristics of the equipment relate to the probability of failure. Depending on the equipment this could be a statistics (mean time between failures), a theoretic model or a heuristic. If the cause is an environmental factor, then the measured quantity or observed phenomenon can be loaded from the data layers stored in the information system. Statistics and heuristics are then used to estimate a hazard probability associated to the equipment part.

The probability of failure of a circuit in the grid is the key event for the dispatch. While in some cases the failure of the circuit results from the failure of a single element (if the phase conductor falls on the ground then the circuit fails), in most cases the probability of failure of the circuit is a composition of probabilities of failures of individual components, that could be independent or not, and environmental conditions, recalling the need for multi-variable correlation. In such cases, operators rely on heuristics to create a transfer function from the failure of individual components to the failure of the circuit.

The third step is to establish the reliability of the grid to serve every energy delivery point – the fact that actually matters to the client. Topology, economic and generation constraints play a major role in establishing the overall reliability. Artificial intelligence algorithms or, in some cases, exhaustive simulation of all grid configurations, are used to obtain estimates that can be compared to results from the past.

As variables are independent and incidents are rare, the methodology is suited to iterative approaches that involve more refined models of equipment failure and environmental hazards to yield improved reliability functions.

Currently, the most advanced reliability function is phase to ground incidents due to vegetation since its evolution over time is based on tree growth models and the changes in spatial distribution are monitored with regular inspections.

VI. CONCLUSIONS AND FUTURE STEPS

The ongoing project is a complex endeavor with yet many steps to take before conclusions can be reached. The approach assumes that the cross influence of many factors is unnoticed as people only grasp the last phenomenon that leads to a line tripping and that earlier causes or contributing factors should be detected to effectively improve the reliability of the grid.

The progress of the project will follow parallel routes:

1. Improve the input data by incorporating new layers of data or by obtaining higher quality and consistency for existing layers.

2. Compare equipment reliability functions with state of the art solutions in the literature (that typically involve fewer variables) and improve reliability functions as needed.

3. Compare circuit reliability with past data and implicit knowledge of utility experts.

4. Create toolsets and visualization tools to let interested people interact with the information stored and devise new ways of using it.

One of the main challenges is that modern grids are already very efficient and incidents are rare. However, the need to maintain or improve reliability with diminishing maintenance resources is widespread as well as the awareness of rare and major incidents ("the black swans") that could cripple transmission grids at national or super-national levels (refer to US coast blackout in 14 August 2003, another one in Italy on 28 September or the Elme river incident on November 2006). More is to be learned and prepared to comfort clients and regulators that utilities are delivering the best quality of service that electricity prices could buy.

VII. REFERENCES

[1] L. Campos Pinto, J. Casaca, "Criticality indices for lines and substations", International Conference on Condition Monitoring, Diagnosis and Maintenance, CMDM2011, Bucharest, Romania,19th-23rd September 2011.

[2] F. Azevedo, J. Gomes-Mota, L. Campos-Pinto, J. Casaca "Environmental characterization of the Portuguese transmission grid from line inspection data", Iberian-American regional meeting of CIGRÉ, Ciudad del Este, 22nd-26th May, Paraguay (paper in Portuguese).

[3] J. Gomes-Mota, A. Brantes, L. Campos-Pinto, F. Azevedo, "How environment factors impact line performance - Field results from Southwest Europe", Environment and Electrical Engineering International Conference, EEEIC, 18-25 May, 2012, Italy

[4] ITOMS International Transmission Operations and Maintenance Study http://www.umsgroup.com/ums_static/itoms.asp