Electrical grid modelling for overhead maintenance cycle optimisation

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Abstract. This paper presents preliminary work introducing a time and space framework for the optimisation of high voltage grid maintenance, combining data from project, asset management, inspection, remedial actions and audits. This framework is based on geo-referenced and time-changing databases, and probabilistic models for asset condition and risk management. The grid topology is naturally modelled as a graph, which we already represented in a database for the Portuguese case, to serve as a basis to solve a number of constraint satisfaction and optimisation problems concerning the grid maintenance cycle. Due to its complexity, and in order to tackle different problems, for generality, the resulting structure is a multi-weighted partially directed graph, with different classes of nodes, which promises interest research questions and challenges for constraint solving.

1 Introduction

Electrical grid operators have been struggling in recent years to deploy new lines to meet demands for more energy and higher quality of service. Regardless of their success in that endeavour, every grid operator is now asked to reevaluate safety provisions to make the best use of the reserve capacity available on their grids while maintaining safe and reliable operations.

Defining grid maintenance as a cycle of processes that keeps the electrical grid running includes inspection, quality and condition audits and remedial actions. The proposed framework to optimise this cycle features an architecture and a tool set to aggregate data and methods from different sources into a consistent model for grid maintenance, where the grid topology is represented by a graph with special characteristics. Figure 1 shows one model of the cycle with twelve main tasks, organised as a clock dial, where green background represents field tasks and sand background represents office tasks, involving planning, scheduling, verification, etc..

Entering the cycle at one o'clock, there is the over-head line (OHL) inspection. Asset management data is used to highlight previous known issues and features of each element that are relevant for inspection while geographic information systems (GIS) help inspectors find the right lines to inspect and plan optimal routes.

At two o'clock, there is data recording with space and time stamps and real time issue detection, as an option. The latter is used to help inspectors optimise the

procedures according to the perceived condition of the line, triggering a thorough review of any candidate issue [1]. Moreover, real time allows for critical issues to be reported just after the inspection (3 o'clock), which is decisive for contingency operations.

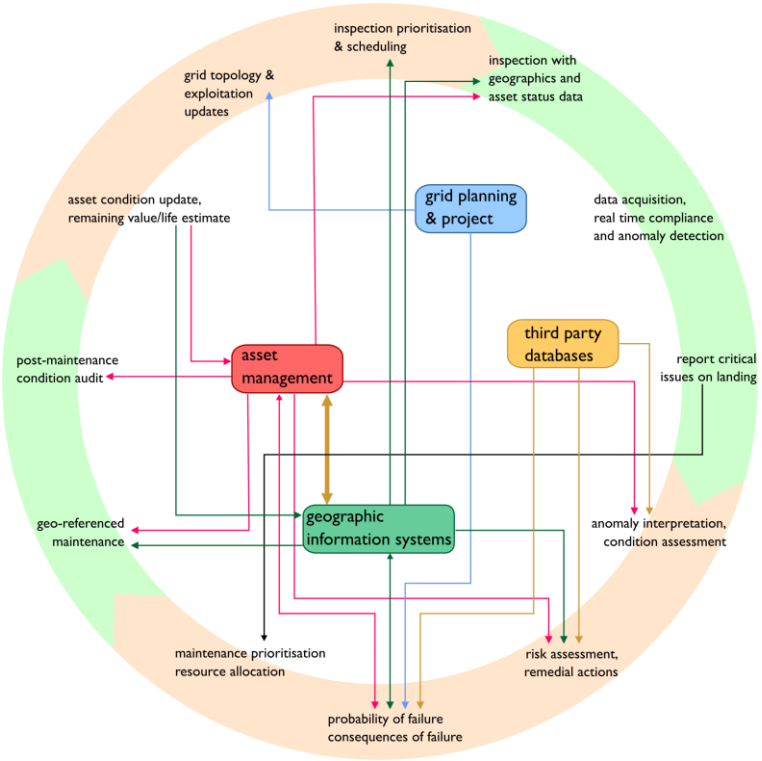

Fig. 1. Maintenance cycle

Back to the office, experts perform a detailed analysis (4 o'clock), comparing faulty elements with similar ones from asset data and third party sources to estimate its current condition. The next step (5 o'clock) is yet to be implemented in many utilities. It involves assessing the risk associated with each issue as a function of the degree of non-compliance. Since risk encompasses many aspects (performance, reputation, safety, sales, ...), for each type of issue there is a function of risk. A human expert based approach, termed Condition Based Risk Management [2] was introduced for mechanical and wear issues, while we favoured an automatic approach to risk vegetation management [3].

Converting risk into probability of failure and estimating the consequences of failure is the most novel task (6 o'clock). It aggregates data from all information systems to compute the most complex models. The first step is to estimate the effects of single and combined issues in a single OHL; the second step is to compute the aggregated risk across the grid, taking all potential risks into account. All solutions found for this task involve past empirical statistics or educated heuristics. At a later

stage, probability of failure is combined with value/cost of failure and exposition time to assess the overall risk (measured in count or cost units).

The prioritisation of maintenance (7 o'clock) is based on criticality reports, costs of maintenance and distances between neighbouring issues computed from GIS. Some practical approaches are commonly found but a rich framework allows optimal solutions to the multi-variable "travelling salesman problem" (TSP). The field maintenance is the next, universal step (8 o'clock); however, enhancing it with geo-referenced data increases the process efficiency and reporting. The audit to the maintenance action (9 o'clock) is sometimes simultaneous with maintenance, depending on local practices and the nature of issues repaired. Returning to the office, asset managers conclude their role updating the grid condition after maintenance on their information systems as well as on GIS (10 o'clock) and their net asset value and remaining lifetime. This task is homologue to the condition assessment at 4 o'clock. Half the cycle (from 5 to 10 o'clock) was dedicated to optimisation of remedy (=maintenance) while the other half is dedicated to the optimisation of diagnostics (=inspection).

Finally, it is necessary to update the grid topology as new lines enter service and others are renovated (11 o'clock). Defining an optimal route and scheduling for the next round of inspections is the last task (12 o'clock). The information infrastructure supporting this cycle involves other departments (not shown) and it is summarised by the thick gold arrow uniting GIS and asset management.

2 Architecture and Graph Modelling

Our architecture consists of a server with connections to geographical information systems (GIS) and asset management systems, running modular applications, with access to relational databases implemented over PostgreSQL, and with http-based communication.

There should be two databases with information supporting the desired applications and possible future ones: 1) a database containing the electrical grid topology, with all its relevant components and features; 2) a 'lower-level' database containing the raw data produced by line inspections, such as vegetation management, equipment faults, navigation systems data, and so on.

The 'topology' database contains information concerning four categories. Without intending to delve into the details, the current schema is shown in Figure 2, where each of the categories corresponds to a different rectangle region. Some regions overlap and, of course, are related to others:

1. **Graph** (blue & zoom): the grid topology itself, which defines a graph with nodes such as substations, plants, or sectioning posts, and where arcs are the electrical circuits connecting two nodes.
2. **Lines** (yellow): aerial lines carrying the electrical circuits, with their towers and respective numbers. It includes also underground circuit segments, and electrical characteristics.
3. **Assets** (green): towers and wires as grid assets, with their characteristics, their use, and their relations.

4. **Inspections** (pink): general part of inspections already performed, containing identification, and processed data, such as identified towers, wires, environment, and anomalies. Historical data lies mainly in this category.

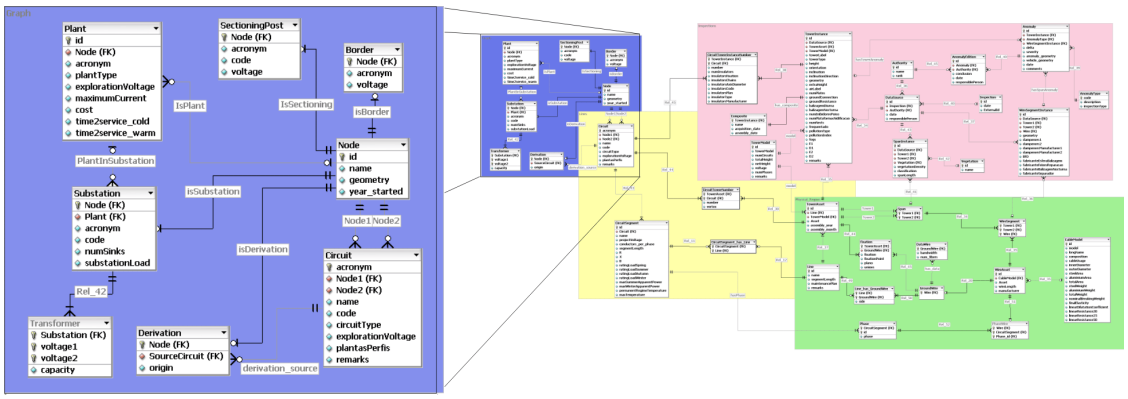

Fig. 2. Database schema

On the left of Figure 2, the 'Graph' region is magnified, as an illustrative example. Electrical circuits are the graph arcs, connecting two nodes, with a given exploitation voltage. Each node has geographical data and can be either a substation, or a plant (if not part of a substation), or a sectioning post. It can also be a simple derivation from some circuit. Border nodes are also considered when lines reach a different country to allow for cross border energy trade. Notice that substations are also modelled with transformation capacities between different voltages, via the Transformer table. This part of the database allows performing global analyses of the grid, calculating critical paths, for instance.

The higher level structure modelling the grid topology defines a graph with special characteristics:

- **Distinct classes of nodes**: in fact, some nodes are just *consumers*, while others are just *producers*, whereas *substations* may receive, transform, and send energy. Energy transformation to a different voltage is constrained by the capacities and types of the available transformers in each substation. Nodes such as *sectioning posts* may simply switch on or off the passing current. Energy flow at *Border* nodes is locally constrained by trade limits, and globally by budget. *Derivation* nodes are simple nodes where a circuit is connected to another, with no control on how much flows towards each arc.
- **Spatially coincident nodes**: sectioning posts work for circuits of some voltage. Thus if, in some location, sectioning is available for circuits of different voltages, e.g. one for 400 kV, and another for 220 kV, this situation is modelled with 2 nodes with the same spatial coordinates: one sectioning post for 400kV, with the corresponding 400kV circuits, and another one for 220kV.
- **Arcs with an interior node**: since a derivation (node) is basically a point in a circuit connected to another node, the circuit (arc) from which the other derives (with wire connections) contains a node between its end nodes. (A

different modelling could be considered to avoid this, but it seems it could complicate, rather than simplify, solving the kind of problems expected.)

- **Partially directed**: in some arcs, energy may only flow in one direction, considering that some nodes may only produce or consume.
- **Multi-weighted**: arcs have a number of attributes, which can be seen as different weights for different problems, and some problems may have to consider more than one kind of weight. Distance between the 2 nodes is the typical weight for TSP. A very important characteristic is the operating voltage (for some applications, this may also be seen as splitting arcs into 3 different classes: 150kV, 220kV, and 400kV), and the line is also constrained by the maximum/project voltage, among others. Another important weight is the *criticality* of each arc, which can be calculated according to its importance to the national grid, its probability of failure, and its consequences.
- **Redundancy**: some arcs may be 'repeated' in the sense that there may be 2 (or more) arcs connecting 2 nodes, and possibly of the same voltage (sometimes such lines may even be supported by the same towers). Redundancy is a usual practice in power transportation, to minimize service disturbances.

In addition, arcs are in fact constituted by conductor wires supported by a sequence of towers and the spans between them, which rarely form a simple line segment. So, a lower level modelling for arcs is also necessary, containing historical data (concerning vegetation underneath, and past failures). Such information can be used stochastically to infer the local probability of failure (due to vegetation proximity), and all spans aggregated to calculate the global probability, p, of line (arc) failure (based on inferred vegetation growth rate), and from there assign a risk index to each line. Risk r may be roughly given by $r = p \times s \times t$, where s is the severity of the failure, and t is the estimated exposition time. We may assume that severity is directly related to unsold energy. Since p also increases with power (line sag is affected by plastic elongation and this contribution is stronger on lines subject to sudden load variations – excessive sag may cause a failure due to vegetation proximity), we conclude that risk is quadratic on the load. Notice that load varies along the day, and its curve is publicly available.

With such risk indexes, together with the grid topology, with its power sources and sinks (consumer nodes), we want to calculate the criticality (an arc weight), which is a constraint satisfaction problem by itself.

Note that time issues have also to be considered, as different types of power plants take longer than others to achieve full power while others have limited capacity or seasonal variations.

3 Examples

Once the architecture has been deployed, tools that address every issue are required. Given the wide span of issues found on OHL, in this section we introduce some of the desired applications, showing the adequacy of the constraint solving paradigm [4]. Although many of the available inputs and desired outputs are tacit or qualitative, an effort should be made to express all of these in numerical forms, using stochastic

variables where appropriate, so that different modules can be compared and merged or grafted on different sections of the grid model.

Time and space analysis was introduced in [5], where examples of various faults. The examples herein focus on time and space analysis aspects of the framework.

Let us consider a section in a transmission grid with one voltage level, a total line distance of 350km with a main power source at A (S≤800MVA) and reserve power source at D (S ≤ 160MVA) and sinks at C (S≤240MVA) and E (S≤240MVA) (see Figure 3 (left)). Each arc has two numbers: the first is one solution to the power flow (black) while the second is the upper limit (red).

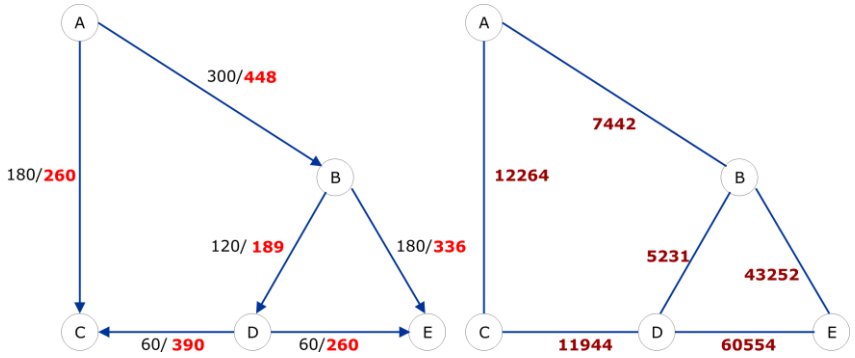

Fig. 3. Simple partial grid with line loads (left) and risk factor (right)

Using condition based risk estimator methods, example normalised aggregated risk factors for each line are shown in Figure 3 (right); a higher number represents higher risk. The probability of failure on each arc is proportional to the risk factor. Assuming the maintenance cost is proportional to the arc physical length (which is known) and independent of the risk factor, it is possible to draw the chart in Figure 4 where the horizontal axis depicts the target probability of failure to deliver energy to the sinks in Figure 3 (nodes C and E), and the vertical axis the total length that needs to be maintained to meet the goal on each arc and in the whole system.

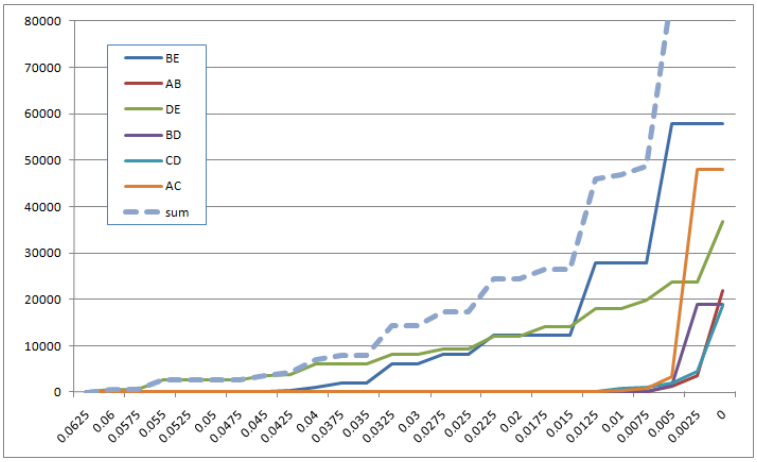

Fig. 4. Length [m] to maintain on each line as a function of maximum probability of failure

If management sets a ceiling on the individual probability of failure, the total extension to maintain (depending on the risk assessment for each span) is the dashed curve in Figure 4. Setting the ceiling at 0.005 requires 86.3 km to oversee, which is only 25% of the overall length. However, if the redundancy in BDE triangle and the spare capacity at BE are considered, the maintenance effort in the highest risk line, DE, can be reduced, thus lowering the overall cost. The determination of the optimal point involves the value of customers on each injection point, the cost of energy at each source, the cost of emergency remedy against programmed maintenance, among other lesser factors.

Figure 5 shows part of the condition assessment related to vegetation management for a 79-span OHL. The top row defines the span as rural (green), mixed (cyan) or urban (blue). The middle row shows the growth rate of the dominant species: growth speed increases from green to red. The bottom row shows the density of vegetation increasing from green to red.

The first choice criterion is span classification since maintenance in urban and mixed area calls for different methods than rural ones. The second choice focuses on fast growth trees first (in some cases, clearances are inferior to the growth expected during the maintenance cycle period) ; in this example, fast growth trees depicted in red coincide with high density (it is a region with eucalyptus), while medium growth trees depicted in orange (pines) occur both in sparse and dense woods. The optimal schedule should balance the work load between short period and long period cycles and seasonal variations.

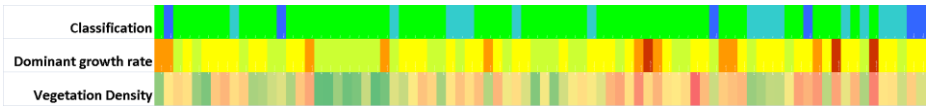

Fig. 5. Right of way classification along a 79-span line

As other examples, the most innovative tools being developed focus on tasks depicted at 4 to 7 and 12 o'clock in Figure 1. We briefly outline some of them to show the practical aspects of the framework:

Condition based risk estimation (advance from 4 o'clock to 5 o'clock)

Most companies are seasoned in condition estimation of all their assets. However, estimating the risk associated to each condition issue is a rarer task. Extending this knowledge to a whole grid involves wrapping each asset subject to each sort of fault with a model of the environment as rich and detailed as possible.

Maintenance resource allocation (7 o'clock)

Maintenance targets are often set as "how to maximise quality of service (or minimise the probability of failure) with a given budget or, symmetrically, minimise the budget that meets a specified quality of service (or risk factor, or probability of failure). The nature of issues determines the maintenance methods; whenever these are independent, the optimisation strategy may be restricted to a single issue analysis with moderate losses. One typical example is vegetation management, which is independent of repairs on line equipment.

Vegetation management is a major resource-consuming activity which has evolved significantly over the last decade. Traditional optimisation strategies were based on

incremental improvements over established practices. Instead, computational methods are used to determine the optimal maintenance schedule. The result may be a sequence of small sections requiring maintenance separated by large swathes with minor risks. If geographic rules are used, even remedies for low risk spans become worth doing, if they are performed while maintenance is done on a line nearby.

Inspection scheduling (12 o'clock)

This task is homologue to the previous one, substituting maintenance for inspection. The purpose is to replace full line inspection at fixed intervals with sections of different lines inspected at optimal intervals and connected to minimise travelling between inspections. However, this task is more complex since each type of inspection requires its own frequency, and decoupling is rarely efficient.

4 Conclusions and Future Work

The proposed framework offers a consistent environment to support a better insight into the relevant variables for maintenance optimisation. Its ability to combine disparate data, to tag observations with time and date references, the expandable database architecture and traceability of operations makes it an ideal candidate for research and development of the best tools for tomorrow's grid managers.

The graph modelling of the grid topology, with all its specific features makes it an especially interesting challenge for constraint solving. Among the problems we intend to solve, in addition to the ones we briefly described, are:

- finding critical paths in the current grid, and also when removing 1 or more arcs;
- calculating demand sensibility, and offer/production sensibility;
- where to optimally place new nodes (substations)?
- Developing contingency models: isolated and islanding systems (i.e. with no borders, or isolated by regions)

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