RELIABILITY EVALUATION OF DISTRIBUTION NETWORKS AND PERFORMANCE COMPARISON USING REPRESENTATIVE NETWORKS

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ABSTRACT

The regulation of distribution network monopolies has been shifting from asset-based to performance-based regulation and therefore is becoming more depending on the quality of customer service. Consequently, there has been increasing interest in developing analysis capability and tools that can support quantitative assessments of alternative Distribution Network Operator (DNO) investment plans in terms of costs and benefits involved. Furthermore, it is very important to appreciate the differences in performances across DNO networks and understand the impact that various historical design and operation practices, different topology and population characteristics may have on the network performance. It is also important to understand cost associated with setting individual performance targets to DNOs. Clearly, there is a need for a framework that enables network performances to be objectively compared, the differences to be understood and explained, and cost and benefits of alternative distribution network investment strategies to be evaluated.

INTRODUCTION

Experience has shown that medium voltage networks have the greatest influence on the annual outage costs. Due to the intrinsically monopolistic nature of the distribution business, the revenue recovered by DNOs is closely regulated by OFGEM (UK regulator) in order to protect the customers and to ensure economic efficiency.

Performance Based Regulation

Traditionally considered mainly from the owner's perspective, the network performance of distribution systems is now becoming customer driven. This means that the logic of weighting the investment on the network against the loss of kWhs not supplied has been changed. This leads to the need to include an assessment of the customer's worth of supply and the benefit they derive by system investment. This is the underlying concept of what is called performance-based regulation which is progressively replacing other forms of regulation. Performance-based regulation is centred in the UK on the Information and Incentives Project (IIP). This was set up to strengthen the incentives with respect to delivering the quality of output.

As the IIP is based on financial penalties and rewards, the overall distribution revenue is a function not only of the operating and capital costs incurred by the network owner in providing the service, but also of the quality of customer service [1,2]. Concerning future developments on the present regulation scheme, it should be noticed that there is still to determine whether to base the incentive mechanism on "absolute" or "relative" performance.

Under the absolute-performance based approach, the adjustments to the revenue would be based on assessing the company's performance against their own individual performance targets. It can be questioned whether this approach has the ability to mirror competitive markets, in which companies offering higher quality can charge higher prices. The relative-performance based approach bases the adjustment to the revenue on the relative performance of the company with respect to other companies [3]. The main issues to consider in this case are the credibility of comparing companies' performances and costs on a robust basis and the difficulties associated with the normalisation of the performance indices.

The output measures upon which financial incentives should be applied are described in the initial IIP proposal [1]. The exact implementation of this mechanism is however a major issue to be resolved.

Reference Networks

Whether the incentive mechanism is based on "absolute" or "relative" performance, the adjustments to the revenue would be dependant on some form of reliability indices comparison. If an absolute performance based mechanism would require setting individual company targets, these should be equivalently demanding across competing companies. On the other hand, if a relative performance based mechanism would require a normalization process based on the average performance of all companies, this would have to reflect different customer densities and very different types of network associated with the various companies. The concept of *reference network* was initially and originally developed to provide an absolute approach. Despite this, it can also be used objectively for comparing the performances between different companies, and therefore it is equally suited for the relative approach [3].

The performance-based regulation requires a quantitative understanding of the relationship between cost (input) and performance (output) parameters to be established. This is clearly essential for predicting and quantifying the impact of alternative portfolios of operation and investment strategies on the network performance. The *reference distribution network* is considered to be particularly useful in this context and it offers a viable alternative to the benchmark approach. It is topologically identical to the real one but has optimal network capacities and reliability parameters. Furthermore, the use of *reference networks* is also proposed as a means to compare the optimum improvement and operation policies that any given distribution network operator can achieve [3].

PROBLEM FORMULATION

The enormous diversity of topologies, customer densities and protection levels of the feeders in a real distribution system has been a major obstacle for the strategic planning activity. It would be easier to plan a distribution system if the circuits were identical or if they could be grouped by similar characteristics. *Representative networks (RN)* were defined as typical feeders. Each *RN* is supposed to be the best fit to a specific group of real feeders.

The work described in this paper is one step further towards the implementation of a *reference network* based methodology that enables the reliability evaluation of distribution networks and a network performance comparison framework. It does so by building on the methodologies which were previously proposed [4,5] describing the generation of representative networks capable of replicating the reliability performance of distribution networks.

In this paper, two further questions are addressed. Firstly, *RN*s are used to explain the reasons why distribution networks perform differently and, secondly, these differences are quantified. This generates knowledge that may be employed to identify efficient network investments.

PERFORMANCE COMPARISON

In order to build a network performance comparison framework it is required that *RNs* be built which may replicate with good and known precision the reliability performance of a set of distribution feeders.

To accomplish this, some basic procedures must be considered (Fig.1).

High level feeder database

The database which was built to support the reliability assessment tool described a set of high-level data parameters for each feeder [4, 5]. Structural attributes define the topology of the network and population parameters are then collected from feeders of known structure.

Network disaggregation

Distribution network disaggregation has been proposed [4, 5] as a possibility to allow robust comparisons of companies with diverse performance indices as a result of operating very different networks. A decision-tree approach is used and any feeder being considered is compared against each attribute one-at-a-time and the appropriate branch of the decision-tree taken depending on each outcome. The disaggregation process is intended to create a limited number of *RNs* that can be used to simulate the performance of the real system.

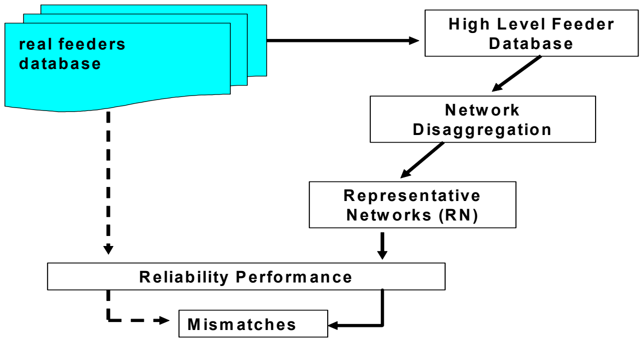

Fig 1 – Calculation of representative networks

Representative networks (*RN*)

In a real distribution system, it is a fact that every feeder is different in some detail to every other feeder, even if only slightly [5]. Typical feeders are defined as *RNs*, with each one being the best fit to a specific group of real feeders. These would translate network inherent attributes such as average number of customers and inherited attributes such as average feeder length and all the major parameters which condition the present reliability performance and establish the grounds (or departure point) from which investment and operational strategies are to be developed.

Reliability calculations

The techniques used are based on the evaluation of load point reliability indices [6] of failure rate and duration, and their translation into customer interruptions (CIs) expressed as "100.interruptions/(customers.yr)" (internationally known as SAIFI) and customer minutes lost (CMLs) expressed as "min/(customer.yr)" (internationally known as SAIDI) as set by OFGEM [7]. Having performed the reliability calculations for the real network and for the *RNs* the following step is to assess any mismatch using a simple calculation which normalizes the comparison for all groups:

$$\frac{CI_{repi} - CI_{gpi}}{CI_{gpi}} \times 100 \ [\%]$$

where:

CI_{repi} is the reliability performance for RN_i;

CI_{gi} is the customer weighted average reliability performance of the feeders of group_i.

Network performance comparison framework

This is based on the actual comparison of the performance of *RNs* which precisely replicate the performance of comparable networks. Considering that *RNs* actually represent average physical parameters, any differences in performance may be associated with differences in particular average physical features between both sets of networks.

CASE STUDY

This methodology has been tested with the network of two UK DNOs. The network of DNO A consists of 1,566 feeders, connecting a total of 2,198,541 customers. The network of DNO B consists of 1,767 feeders supplying 1,377,598 customers.
Among several different sets of disaggregation attributes available, a particular set was chosen to replicate the network disaggregation as performed by the UK regulator [8]. This particular procedure disaggregates distribution networks based on the percentage of overhead (OH) network length, total feeder length and total number of customers connected to the feeder.

Table 1: One of the 22 groups defined by OFGEM's network disaggregation process

Group	OH Length (%)	Number of customers	Feeder Length (Km)
MC1B	[50,80]	> 500	<19

This means that within each group feeders can be found with different number of on-network fault breaking devices (FBDs), number of switches and number of normally open points (NOPs). OFGEM determines that group boundaries were set in such a way to prevent any single DNO from dominating any group for the purpose of setting performance targets.
A basic network comparison underlying assumption considers that only similar networks or similar parts of network should be compared against each other. In the context of this paper, this means that the performance of feeders from both DNOs which belong to the same group will be compared using the resulting *RN* for each DNO on the specified group. In order to exemplify the remaining of the methodology which enables the comparison of the network performance between both DNOs, the following analysis will focus on a particular group only (out of the 22 possible resulting groups).
Feeders which presented the properties shown in table 1 were grouped together. The *RNs* were subsequently calculated from the feeders belonging to group MC1B according to the procedures already described.

Table 2: Characterization of each DNO on a resulting group

Group	No.	Average Customers	Average Feeder	Total
MC1B	feeders	(per feeder)	Length (Km)	Customers
DNO A	23	1241	13.2	28545
DNO B	25	1086	13.9	27152

In table 2 it can be seen that the average feeder length and number of customers is relatively similar as expected given the choice of disaggregation parameters. The total number of feeders placed in this group is also quite similar. The models developed did not consider any network construction practices based on the distinction between domestic, commercial or industrial customers as the reliability incentive mechanisms do not reflect this.
The ability of each representative network to actually represent the performance of the feeders of its group is shown in table 3.

Table 3: Mismatches Table - Reliability performance of real networks, *representative networks* and mismatches

Group	Rep.Net.		Real Network		Mismatch (%)	
MC1B	CI	CML	CI	CML	CI	CML
DNO A	61.25	61.92	61.23	61.94	0,03%	-0.03%
DNO B	72.18	145.15	72.28	145.74	-0.14%	-0.41%

These results show that representative networks are able to replicate group CIs with success. Considering the calculation of group CMLs, similar results are obtained.
It should be added that the impact of a different choice of disaggregation parameters (other than those used by OFGEM) does not impact on the precision of the results. The choice of sensible attributes, cells and their ranges undoubtedly produces similar results to those presented in this paper. That also proves the robustness of a representative network based reliability assessment. However, an inadequate choice of these parameters results in the undesirable situation of having feeders which present very different performance behaviour being represented by the same *RN*.
It has been demonstrated that the methodology is able to generate representative networks that replicate the reliability performance of the networks of both DNOs. These are generated without detailed topological information.
The use of *RNs* to develop a methodology to compare network performance across different DNOs is outlined next.
The characteristic performance of each DNO is represented by a different line (Fig.2). Each line starts at the origin (as if no faults were experienced) and is characterized by its slope. The slope reflects the interaction of network features which are widely regarded as extremely difficult to modify through investment such as network length - would require the construction of substations- and customer connection configuration – would require customers to be moved. For these reasons these are considered to be fixed network parameters.

Table 4: Performance slope as a funcion of average feeder length and average disconnected customers(%)

	Average Length (Km)	Average disconnected customers (%)	Slope = Av. Length x Av.discon. customers
DNO A	13.2	62.90	830.32
DNO B	13.9	67.23	934.49

Table 4 shows the interaction between average feeder length and a customer disconnection index which informs that, in the event of a fault, 62.90% of customers in DNO A will be disconnected on average against 67.23% of customers, on average, for DNO B. This index is related with the distribution of customers on a feeder and is independent from the number of customers connected to a feeder or its length.

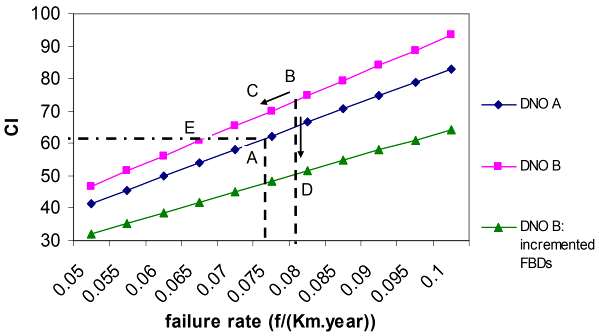

Fig.2 – CI mapping and comparison

The xx axis reflects any average network failure rate and the present operating point can be found by looking back at historical data of DNO A and DNO B (***A*** and ***B***, respectively). The yy axis indicates the performance in terms of CIs.

For the same average failure rate, DNO A performs better in this group than DNO B. It can be seen that an investment effort aimed at decreasing the average failure rate of DNO B (by undergrounding parts of the OH network or by reinforcing its OH network construction) has limited benefits. If the average failure rate of DNO B was improved in such a way that it presented the same value as in DNO A (***C***) there would still be a gap of CI**[*CA*]**= 7.7 CI. This gap could be attributable to differences in average feeder length and/or to a more beneficial average customer distribution with respect to any existing fault breaking devices which are factors that DNO B can hardly control. Additionally, if a further similar investment effort is carried out, it would take a 15.1% reduction of the average failure rate of DNO B to match the performance of DNO A **[*BE*]**.

Another option to improve the average performance of DNO B is to invest on fault breaking devices (FBD) to be deployed on feeders of this group (one per feeder, on average) which mitigate the consequences of a fault in terms of average disconnected customers. A new slope (Fig.2) characterizes the line where the new DNO expected network performance (***D***) could be found and as a result, DNO B would be expected to perform better than DNO A CI[***AD***]=11.56 CI.

It is now possible to weight the benefits and costs of approaching the CIs of both DNOs and to have a better quantitative understanding of why these networks perform differently. A CML performance comparison framework can be developed based on the same procedures.

CONCLUSIONS

This paper validated the techniques which reduce a real system into a limited and manageable number of *representative networks*. These networks are created by choosing relevant disaggregation parameters, which include both fixed network parameters that a company cannot change at least in the short term and variable parameters that can be changed by appropriate investments. They are then useful to predict network performance in terms of CIs and CMLs. It has been shown that *representative networks* can be employed to calculate the associated reference network which has the same set of fixed parameters as the network with which it is paired but with an optimal set of variable parameters. It is therefore possible to establish target networks that a company could be expected to aim for by appropriate investments and against which the company could be compared in an absolute sense. In addition, the methodology demonstrated that it is reliable enough to be used to create or specify benchmark networks both at the system level and at the *RN* level. Benchmark networks are conceptually similar to *reference networks* and can be used to compare companies against a network of known performance. Benchmark networks may be the result of the average set of variables across companies, i.e. a national average, or may be set by the regulator on the basis of some other process.

Finally this work proves that the reference network methodology can be used in an absolute sense to study the predicted performance and it establishes the grounds to prove that the same methodology can be further extended to study reliability performance improvements driven by network investments within a company. It can also be used in a relative sense to compare the performances between companies and to identify the reasons for any differences.

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