A COST-BENEFIT ANALYSIS OF THE NETWORK AUTOMATION PROGRAMME

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ABSTRACT

This paper presents a proposed cost-benefit analysis of the automation programme targeting the worst performing high-voltage circuits. Performance is measured in terms of customer-interruptions and customer-minutes-lost, where the values are defined by the Regulator. Reliability analysis and optimisation of the individual circuits is the first stage of the methodology. The proposed cost-benefit analysis of the entire programme accounts for financial uncertainties and determines the level of investments based on an economic criterion.

INTRODUCTION

Distribution network business is regulated in the UK by the Regulator and the companies are obliged to provide network services. The services are funded by the Price and Revenue Cap mechanism with the income governed by an RPI-X formula [1], which is reviewed every five years. The income consists of the base revenue and the incentives, where the latter are performance driven. The capital expenditure (capex) allowance and the capex efficiency mechanism are very important parts of the base revenue. The latter allows companies to retain a pre-specified percentage of the *efficient* underspend [2]. On the other hand, performance-driven incentives are designed to either reward companies for their overperformance, or penalise them for underperformance. The quality-of-supply performance metrics are customer-interruptions (CIs) and customer-minutes-lost (CMLs) and the incentive regime is graphically shown in Fig. 1. The regime is company-specific and it is defined by the CI & CML targets and upper & lower limits in all years of the price control period. An integral part are the CI incentive rate in [£/CI] and the CML incentive rate in [£/CML] defined over the individual years. It should be noted that the current regime is symmetric (i.e. reward rate is equal to the penalty rate) with no deadband.

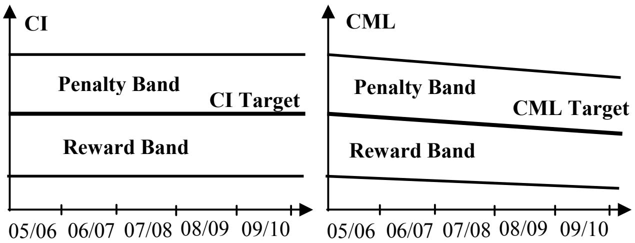

Figure 1 – CI and CML incentive regime

In the United Utilities network area typically more than 70% of CIs and CMLs are caused by the high-voltage (HV) faults and it was decided to initiate a network automation programme targeting the worst performing HV circuits. Automation of the circuits is done in two phases [3]: in the remote control (RC) phase, actuators and communication equipment are installed enabling control engineers to operate devices from the control room. In the automation phase, automatic restoration sequence software is installed in order to realize automatic restoration. Approvals of the initial programme stages were based on a simplified cost-benefit model, where the average costs per circuit together with the average relative CI and CML reductions were used to obtain benefit- cost ratios. This method worked well for the initial stages where a large number of frequently-faulting HV feeders was available. However, in the later phases the problem of diminishing return (i.e. reduced benefits when going down the list of HV circuits) became very pronounced indicating a need for a new cost-benefit model.

A new cost-benefit model for analysis of the network automation programme is presented in this paper. It takes into account uncertainties and determines the level of investments by using the internal rate of return (IRR) method. The model is based on the reliability analysis and optimisation of individual circuits, which are given in the next section. The major steps of the proposed cost-benefit model are calculation of the benefit-cost threshold, application of the incremental cost-benefit approach, modelling of uncertainties and determining the level of investments. Illustrative results and conclusions represent the closing sections of the paper.

STUDY OF INDIVIDUAL CIRCUITS

Analysis of individual HV circuits consists of the following steps: a. Circuit ranking, b. Fault data analysis, c. Reliability analysis and d. Reliability optimisation. They are briefly presented below.

Circuit Ranking

The HV circuits are ranked in order to tackle the worst performing circuits first. A good ranking order is very important because it can save a lot of effort in the later stage when doing the full analysis of individual circuits. Circuit ranking can be done by using one (or a combination) of the following approaches:

1. Ranking by fault history:
    - Average historic CIs.
    - Average historic CMLs.
    - Combination of average historic CIs and CMLs where weighting factors can be regulatory values or pre-defined weights.
2. Ranking by circuit attributes:
    - Number of customers or circuit length.
    - Product of the circuit length and the number of customers.
    - Product as above with the number of protection zones factored in.

It seems appropriate to use different ranking methods for overhead (OH) and underground (UG) circuits. As there are typically many faults on OH lines, the fault statistic is much more reliable and ranking by fault history should be applied. On the other hand, UG circuits can be ranked by using one of the circuit attributes with an additional requirement that at least one fault has occurred in the last *x* years.

Fault Data Analysis

All fault data are recorded in the "Nafirs" database [4]. The historic fault data are extracted from the database in order to match the modelled circuit reliability performance to the long-term average historic performance (see below). The following data are required:

1. Fault count in the considered period.
2. Fault durations.
3. Customers interrupted during all fault stages.
4. Customer minutes lost over all fault stages.

Before applying the historic fault data in the reliability analysis, the data need to be analysed and cleansed. The following issues need to be tackled:

1. Fault location: fault grid reference should be checked against the entered circuit number, where discrepancies are likely in the case of OH circuits.
2. Multi-circuit faults: fault data for faults that spread to other feeders (e.g. stuck breaker) should be appropriately modified to account for the actual number of customers and minutes lost on the feeder causing disruption.
3. Fault causes: some types of faults should be excluded from the further analyses because circuit automation cannot contribute to the CI/CML reduction (e.g. operation of stand-by earth protection, etc.).
4. Persistent and transient faults: if an analysis of both the sustained and short-term interruptions is done, faults need to be classified into persistent and transient classes.
5. Significance of fault data: UG faults can be very infrequent but with high consequences, which indicates that company defaults might be more appropriate. Besides, failure rates of short UG circuits can be extremely distorted.
6. Modified circuits: fault data for circuits which were reconfigured, refurbished, rebuild or where protection and switching devices were installed, should be adjusted.

Reliability Analysis

Reliability analysis of the present HV circuit arrangement is done first in order to obtain the modelled CIs and CMLs identical to the long-term historic averages. The impact of network automation is assessed in the optimisation stage.

Prior to the reliability analysis, circuit representation in the reliability software tool [5] is verified by comparison with the control room model. The reliability analysis model is based on long-term averages and analytical techniques suitable for radial distribution networks [6]. This is a three-stage model where the automation, tele-controlled and manual stage are modelled in a consecutive manner. Linkage between the fault data and the types of interruptions is given in Fig. 2. Both the persistent and transient faults give rise to sustained interruptions, which are subjected to the incentive scheme. On the other hand, short-term interruptions, while reported to the Regulator, do not form part of the incentive scheme. An example for each fault-interruption link is also given in Fig 2.

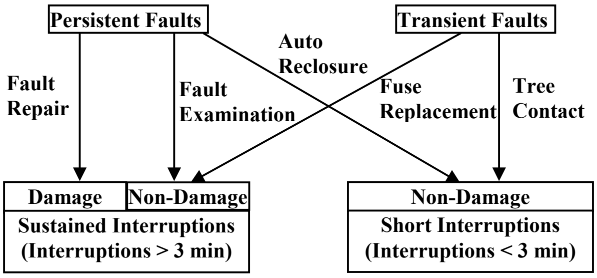

Figure 2 – Structure of fault and interruption data

Results of the reliability analysis are displayed in the CI and CML tables (Fig. 3). Persistent faults are specified by user-defined persistent failure rates and the customers can be restored by auto-reclosure, automation, tele-control, manual switching and repair. Transient faults are defined by transient failure rates and there is no repair phase of restoration. Each row corresponds to a single switching zone, and the customers restored within individual phases together with corresponding times, switching zone lengths and failure rates are presented. Finally, summation over "Reclose" and "Auto" columns gives short interruptions, while "RC", "Manual" and "Repair" columns contribute to the sustained interruptions.

Persistent Faults **Customers Restored*					Transient Faults **Customers Restored**				CIs & CMLs				
									Short Interrup		Sustained Interruption		
Reclo	Auto	RC	Man	Repair	Reclo	Auto	RC	Man	Reclo	Auto	RC	Man	Repair

Figure 3 – Classification of CI and CML results

An iterative adjustment of input data is done to match the sustained interruption CIs and CMLs with the long-term historic averages. The simplest approach is to scale a single persistent failure rate to obtain correct CIs and then to scale manual switching and repair times to get CMLs. Multiple persistent failure rates are often used with OH circuits (typically for light and heavy OH construction), in which case ratios between individual rates should be known. Both the persistent and transient failure rates are used if the short interruption records are available. In this case, an adjustment is done in such a way to match both the sustained-interruption and short-interruption CIs.

Reliability Optimisation

Several types of initiatives on HV feeders are available to improve circuit performance. These initiatives can be classified as interventions on assets, automation of assets and network interventions. Asset interventions are related to addition and removal of circuit breakers, reclosers, sectionalisers, ASLs, fuses, line switches and links. Automation of breakers, reclosers and line switches is a further initiative central to the presented analyses. Finally, feeder reconfiguration and moving of normally open points (NOPs) are the commonly applied network interventions.

Reliability optimisation in the planning stage (i.e. for the programme approval) is done by considering the asset interventions and automation, while all initiatives including network interventions are closely looked at in the design stage. An optimisation problem is set up for each considered

HV feeder in the form:

$$\max z = \{\text{Revenue} - \text{Cost}\}_{PV}$$

s/to:
Incentive Reward/Cost Ratio > Threshold,
Operational Restrictions,
Construction Restrictions.

The objective function is a difference between the present values of the revenue and the spend. The revenue consists of two terms, the first being the incentive reward, while the second is a proportion of the cost that goes on the regulatory asset base (so-called RAB cost) and is being remunerated to utilities. The incentive reward is calculated from the CI and CML savings and incentive rates in £/CI and £/CML. The first constraint is used as an eligibility criterion for the circuit to enter the programme. If it is not met, the circuit is discarded from the further analyses. Here, the overall benefit-cost threshold value is calculated in an approximate way shown in the next section. The operational restriction constraints are defined for protection and switching devices which cannot be modified freely. These constraints limit the number of feasible solutions and speed-up the solution process. Similar logic applies to the construction constraints, where the total number of interventions, number of works of a certain type, etc. are typical limitations.

The optimisation problem so defined has discrete variables. We have used an integer map to represent the set of potential solutions. Here, the string of integers is defined by the locations of existing and new protection/switching devices. The individual integer values represent the types of interventions which can be done on a specific location. The solution methodology is a variant of the hill climbing algorithm [7] starting with the existing state of the feeder and using the analytical reliability calculation method to compute system reliability.

STUDY OF THE PROGRAMME

The proposed approach for the analysis of the automation programme consists of the following steps:

1. Finding the "hurdle rate" for individual circuits.
2. Calculation of the no-risk benefit-cost curve.
3. Uncertainty analysis and calculation of the risk curve.
4. Determination of the level of investments.

These steps are briefly elaborated in the sequel.

Hurdle Rate

The fundamental problem we are faced with is: we cannot build an accurate benefit-cost curve for the programme unless we specify the threshold value ("hurdle rate") for individual circuits, but an accurate hurdle rate can only be determined from the already defined benefit-cost curve. We have therefore used an approximate method to calculate the hurdle rate which is graphically shown in Fig. 4. Line 0-B-A and slope tgα define the initial cost, which must be exceeded by the incentive reward. This cost consists of two terms. The first is the opportunity cost based on the "do nothing" alternative, which is in fact the capex efficiency cost equal to *x%* of RAB costs. The second term is equal to 100% of non-RAB costs, so that these two terms give tgα of the overall cost. Assuming that benefit-cost curve is known (no-risk curve), the breakeven point should be at point A. However because different uncertainties need to be accounted for, the breakeven point is at point B on the risk-curve. Given that a deterministic methodology is used for individual feeder analysis, the hurdle rate should be found at point C and it is equal to tgβ. This value is determined assuming a percentage difference between the no-risk and risk curves, which is typically in the range of 20-30%.

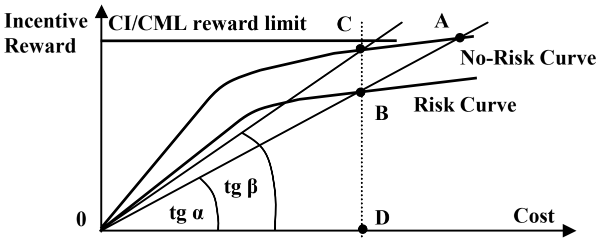

Figure 4 – Calculation of the benefit-cost threshold value

Benefit-Cost Curve

The (no-risk) benefit-cost curve can be obtained either by studying the individual feeders down the prioritised list of HV circuits, or by extrapolating the values of some typical relative indicators from the previous programme blocks. We are presenting here the first approach.

We have applied the incremental cost-benefit analysis [8] to obtain the no-risk benefit-cost curve. The main principle is that each incremental (i.e. additional) monetary unit spent must be justified by the value it adds to the programme. The optimal solution for each individual feeder was therefore reconsidered by decomposing it into a set of interventions. Those interventions, which did not give the satisfactory *incremental* benefit-cost ratio, were discarded giving an improved overall benefit-cost ratio. Finally, all feeder interventions were ranked based on the corresponding benefit-cost slopes. The order of interventions on individual feeders was respected because intervention benefit depends on the starting circuit state which is a function of the previous intervention.

Uncertainty Analysis

The cost-benefit model for the analysis of the feeder automation programme is stochastic in nature since various uncertainties are present. Cost uncertainties are not envisaged because this is short-term planning with less than 6 months lead-time. The main uncertainties are associated with the assessed benefits. Firstly, values of CI and CML savings are well defined in this price control period, while they are completely unknown beyond 2010. Only the cumulative present values of CI and CML savings in this price control period are therefore used. Here, the major source of uncertainty is construction delays, which reduce the cumulative CI and CML values. Secondly, the CI and CML savings were obtained based on assumptions of error-free operation of remote control and automatic restoration software, as well as long-term average failure data. However, automatic and remote control operations are prone to malfunctioning and fault occurrence in future can differ from the past.

Probabilistic decision trees, where the event probabilities are defined either by historic records, or experts' opinions, are used to model the uncertainties. An example of a tree used for UG circuits is shown in Fig. 5. The first two levels deal with technical uncertainties associated with automation and remote-control unavailability. As a result, three modes of operation are to be further analysed, because manual operation gives zero CI and CML benefits. The last two levels describe risks due to reduced number of faults and construction delays. The end result is reduced incentive reward which is used to build the risk benefit-cost curve.

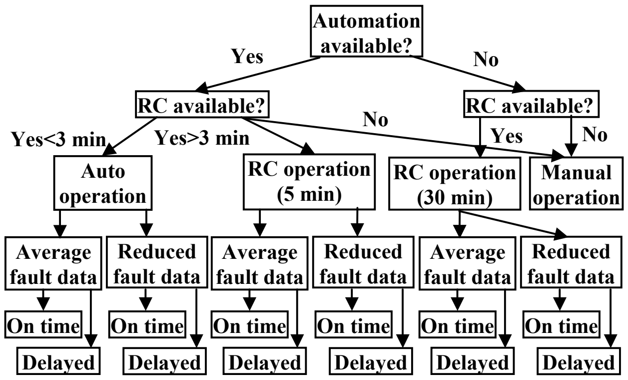

Figure 5 – Modelled uncertainties for UG circuits

Level of Investments

The potential investments for the feeder automation programme lie in the 0-B range on the risk benefit-cost curve (Fig. 4). The pre-tax cash flows are developed for different investment levels and a rate-of-return is calculated for each investment scenario by using the IRR method [8]. The exact level of investments is found by specifying the post-tax rate-of-return of at least *z%*. This rate is converted into an equivalent pre-tax rate-of-return and the level of investments is found from the rate-cost curve. An illustrative example is given in the next section.

ILLUSTRATIVE RESULTS

An example of the optimisation of protection/switching devices with/without automation on an UG circuit is shown in Fig. 6 and Table 1. Symbol *A* denotes switches which need to be put under RC and automation software. An initial investment in the primary vacuum circuit breaker (VCB) and automation of the NOP does not give any benefit. Automation of switches at Aldcliffe West substation (SS) gives large CI and CML savings, while the benefits from the automation at Jackson Close SS are significantly smaller. It is interesting to note that the benefit-cost ratio for the Aldcliffe W SS is 1.38 with the initial investments included, while the incremental benefit-cost ratio for additional works at Jackson Close SS is 1.53. In this way, reduced benefits from the automation of the second SS increase the overall benefit-cost ratio to 1.42 indicating that the whole set of interventions should be taken as a single block.

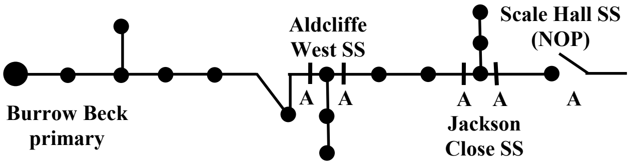

Figure 6 – Automation of an UG feeder

Table 1 – Benefits & costs for interventions on a feeder

Intervention	CI Saved	CML Saved	Budget Cost (£)
1. Burrow Beck: Install VCB	**0**	**0**	
2. Scale Hall SS: RC at NOP	**0**	**0**	
3. Aldcliffe W SS: RC of first switch	**587**	**27,038**	
4.Aldcliffe W SS: RC of second switch	**63**	**2,937**	
5.Jackson Close SS: RC of first switch	**181**	**8,354**	
6.Jackson Cl SS: RC of second switch	**97**	**4,455**	
Total	**928**	**42,784**	

Finding the level of investments for the entire automation programme is illustratively shown in Fig. 7. Internal rates of returns are found for developed cash flows corresponding to different investment levels. The programme investment is then found from the discrete risk curve and the specified IRR^0.

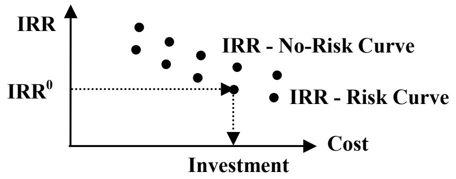

Figure 7 – Calculation of the programme investment level

CONCLUSIONS

A new cost-benefit model for determining the level of investments for the network automation programme is presented in this paper. The benefits from the programme are found by optimising the individual feeder protection and switching devices. Major uncertainties are then modelled giving reduced overall benefits. The investment level is determined from the requirement that the rate-of-return must be at specified level, with the uncertainties taken into account.

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