Distribution Systems' Reliability Increase using a Cost-Benefit Decision-Making Process

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Abstract: It is evident that electric utilities all over world are facing an increasing number of complaints about distribution systems' reliability. High levels of continuity and quality are the two characteristics that customers expect and demand. Therefore distribution systems' reliability increase constitutes one of the most important issues in the studies of distribution power systems' electrical engineers. The purpose of this paper is to study the distribution systems' reliability increase using a decision-making process based on both incremental cost and incremental benefits criteria. The IEEE Reliability Test System has been used as a case study and useful conclusions concerning reliability investment appraisals are stated.

Keywords: Reliability of power systems, Decision-making process, Distribution systems, Customer outage cost, IEEE Reliability test system

1. Introduction

Over the last decades it was widespread accepted the opinion that the distribution systems must supply power as economically as possible and with an acceptable level of continuity, reliability and quality [1]. In recent years this opinion was strengthened and expanded with the increased customers' willingness to pay for a higher level of reliability due to their own particular electricity demand and their more sensitive loads in all sectors (residential, commercial and industrial) [2].

Therefore a pressing need exists to study the reliability investment/reinforcement costs of distribution systems and the benefits received from these reliability upgrades. Although it is evident that the more invested money, the higher level of reliability customers will receive, a threshold value should be selected to control the level of investment [3]. Decision-making processes are addressed in order to support these decisions and to help electrical engineers in their studies.

The aim of this paper is to contribute in the significant research effort which is done the last years worldwide [3-8] in the reliability field, studying the distribution systems' reliability increase. A decision-making process based on both incremental cost and incremental benefits criteria is used, constituted a very useful tool. The IEEE Reliability Test System has been used as a reliability increase case study and very useful conclusions concerning reliability investment appraisals are extracted.

2. Reliability and economics

The two aspects of reliability and economics can be appraised more consistently by comparing reliability cost with reliability worth. The basic concept of reliability cost/worth evaluation is relatively simple and is summarized in figure 1. The curves show that the investment cost will generally increase as consumers are provided with higher reliability. On the other hand, the user/society costs associated with failures will decrease as the reliability increases. The total life cycle costs will therefore be the sum of these two individual costs. This total cost exhibits a minimum, and so an "optimum" or target level of reliability is achieved. This concept is quite valid. Two difficulties arise in its assessment. The first one is that the calculated indices are usually derived only from approximate models. The second one is that there are significant problems in assessing customer perceptions of system failure costs [9].

To sum up, it can be said that reliability analysis can be used to evaluate the reliability of individual system configurations - not only to compare relative levels of reliability but also to assess the costs of providing a particular level of reliability. Cost/benefit studies then enable a decision to be made on whether to adopt a specific configuration to solve an individual problem. They can also be used to formulate policy decisions on the level of reliability to be afforded to groups of customers, or to support a given load level, for example [10].

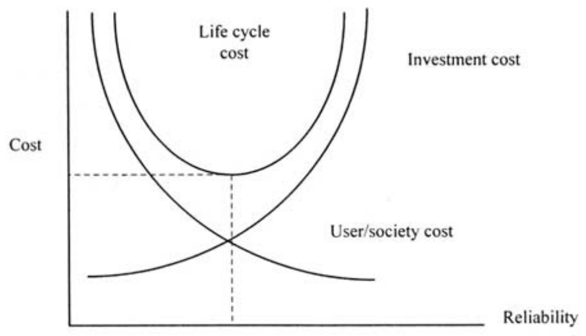

Figure 1: Reliability and total system costs.

3. Costs and benefits of reliability

When a utility invests to improve the reliability of supply, it aims at the increase of the benefits of customers, and the investment cost is passed on to them as a component of the electricity bill. Therefore, when making any "incremental reliability investment", the aim of the utility should be to match the marginal cost of the supplier of adding a unit of reliability with the consumers' marginal valuation of the benefit of the additional unit of supply reliability. The marginal case, which should also yield the lowest total costs can therefore, represented by eqns 1 and 2.

$$\textit{Total costs} = \textit{utility costs} + \textit{COCs} \qquad (1)$$

$$\frac{\Delta C}{\Delta R} = \frac{\Delta B}{\Delta R} \qquad (2)$$

where ΔC is the costs of investment and includes the capital costs and the resulting maintenance and operation costs, minus the cost of any savings on energy losses achieved, ΔB is the customer benefits resulting from the investment and ΔR is the chance in reliability due to the investment [11].

Despite widespread acknowledgement that customers' valuation of electricity supply is determined by the benefits they derive from using it (e.g. production of goods, entertainment and lighting etc.) and the benefits its quality, (e.g. the avoidance of damage to equipment, materials and products etc.), it is only recently that acceptable methods for evaluating the worth of reliability to consumers have been established. These methods are based on customer surveys [12, 13] assuming that the customers are in the best position to assess their losses as a result of interruptions in their supply. The incremental values of these losses, referred to as customer outage costs (COC), as a result of changes in reliability are construed to be the corresponding worth of reliability, or its proxy.

4. Implied cost

The concept of implied cost per KWh saved was created in the 1970s as a measure of the effectiveness of any specific reinforcement scheme. Associated with this development, it was suggested that the timing of a proposed investment should be such that the marginal costs to the supplier of adding a unit of supply reliability equals the consumers' marginal evaluation of the benefit of the additional unit of supply reliability.

This suggestion adds that the value to consumers of electricity supply is determined by the benefits which they can derive from using it and that the valuation of losses due to failure of supply is based upon this loss of usefulness rather than upon the charges which they pay for a unit of electricity. Despite the apparent importance attached to customers' valuations of losses inferred in these two reports, eqn 3 for calculating the implied cost index does not include these valuations i.e. [14],

$$V = (C_\alpha + C_m - S_l) / E \qquad (3)$$

where
V is the cost per KWh saved (€/KWh),
C_α is the capital component of not deferring expenditure for 1 year,
C_m is the extra annual operation and maintenance costs resulting from the reinforcement and
S_l is the annual savings in the cost of electrical losses resulting from the reinforcement.

In order to decide whether a particular investment should be made, a "threshold" value V_t should be selected to control the level of investment such that, if $V_t > V$, the investment is justified. From the foregoing, the only probable benefit to the consumer which can be discerned is a reduction in the electricity bill. The valuation of the losses due to failures is based upon loss of usefulness of the service rather than upon the charges a consumer pays for electricity [15].

5. The IEEE reliability test system

The IEEE Reliability test system (RTS) was developed in order to provide a common test system which could be used for comparing the results obtained by different methods (figure 2). The transmission network consists of 24 bus locations connected by 38 lines. The transmission lines are at two voltages, 138 kV and 230 kV [14].

Each one of the 24 buses of the RTS, consisted of several substations, and each substation consisted in turn of several busbars.

Four different kinds of customers can be found in each substation. These are residential, commercial, industrial and large user customers.

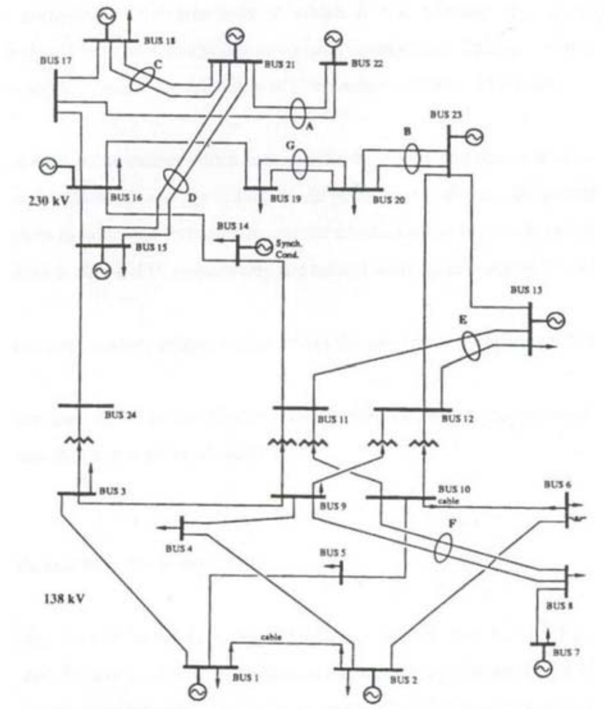

Figure 2: Single line diagram of the IEEE reliability test system.

6. Case study: reliability increase of Bus 9 of IEEE RTS

One of the twenty four load points of the RTS is examined. The reliability and customer outage costs of this bus (Bus 9) are evaluated. Bus 9 consists of 32 substations. Substations 1 to 22 are not shown in the following calculations because they are distribution substations in the Bus 9 system. The energy, the peak demand and the load factor for each kind of customer in each one of the ten remaining substations are shown in table 1.

According to the SCDFs values provided in [11, 14], the load model data and the eqn 4, the composite customer damage function (CCDF) is calculated for each one of the ten analysed substations [14, 16].

$$C_{r(i)} = \sum_{y}^{ny} \left[\left(\frac{C_{L,y}(r_i)}{LF_y \cdot 8.76} \right) \left(\frac{E_y}{\sum_{y}^{ny} E_y} \right) \right] \text{ €/MWh} \quad (4)$$

The reliability indices for each one of the ten analysed substations of the system are shown in table 2. Using eqns 5 and 6 [15], table 4 was constructed giving the customer outage costs for the system [11, 14].

$$COC_j = \left(\sum_{y}^{ny} E_{jy} \right) \cdot C_j(r_i) \cdot \lambda_j \quad € \qquad (5)$$

$$SCOC = \sum_{j}^{b} COC_j \quad € \qquad (6)$$

Observing the results from the previous calculations the substations which need reinforcement were identified. These are the substations 25, 29, 30, 31 and 32, which all present high repair time. Replacement and improvement had to be done in order to reduce the customer outage cost. Performing the necessary improvements, the new reliability indices and the new customer outage costs for these substations are recalculated (table 3).

7. Discussion on the results

Studying the Bus 9 of the IEEE RTS, it was quite easy to identify these substations which increase dramatically the COC of the whole bus. Since IEE RTS is a complex system and it was not in the scope of this work the introduction of ways of reinforcement and improvement of distribution systems but the benefits derived from these according to the cost, the high values of the average duration of interruptions of these substations which increase the COC were reduced.

The result was to have savings in the amount of over 800,000 euros per year since the COC before the changes was 222,425 euros and after the changes 32,436 euros. An amount of up to 189,987 euros can be invested bringing back safe benefits for the consumers for all points of view. This means that: (i) the average failure rate in occurrences per year will be less, reflected in better quality of supply, (ii) the average duration of interruption will be also less, reflected in less inconvenience for the consumers and (iii) the outage cost will be less too.

8. Decision-making process

Reliability investment appraisals based on the cost effectiveness suggested by eqn 3 has provide significant service in the past [14, 17]. However, the availability of acceptable methods for determining the customers' evaluation of the worth of reliability ΔCOC provides the opportunity to apply the economic principle represented in eqn 2 (i.e. substitution of ΔC and ΔB with $C_a + C_m - S_l$

Table 1: Energy, peak demand and load factor in each substation of Bus 9

	Residential			Commercial		
	E (MWh)	L (MW)	LF (%)	E (MWh)	L (MW)	LF (%)
SUB 23	-	-	-	23650	4.5	60
SUB 24	17900	3.4	60	21300	4.05	60
SUB 25	37050	7.05	60	53100	10.1	60
SUB 26	54400	10.35	60	-	-	-
SUB 27	35200	6.7	60	-	-	-
SUB 28	-	-	-	34700	6.6	60
SUB 29	18400	3.5	60	13100	2.5	60
SUB 30	18700	3.55	60	16800	3.2	60
SUB 31	34100	6.5	60	19700	3.75	60
SUB 32	-	-	-	72300	13.75	60

Table 2: Reliability indices and customer outage costs for each substation of Bus 9

Component failure	λ (f/yr)	r (hours)	U (hours/yr)	COC (€)	SCOC (€)
Sub 23	0.249	0.220	0.055	2876	222425
Sub 24	0.249	0.220	0.055	2660	
Sub 25	0.286	0.708	0.202	23485	
Sub 26	0.286	0.708	0.202	1046	
Sub 27	0.313	0.204	0.064	195	
Sub 28	0.313	0.204	0.064	4904	
Sub 29	0.333	0.981	0.326	9262	
Sub 30	0.333	0.981	0.326	11737	
Sub 31	0.286	0.708	0.202	9104	
Sub 32	1.015	1.055	1.071	157156	

Table 3: New reliability indices and new customer outage costs for each reinforced substation of Bus 9

Component failure	λ (f/yr)	r (hours)	U (hours/yr)	COC (€)	SCOC (€)
Sub 25	0.286	0.200	0.057	6906	32436
Sub 29	0.333	0.200	0.067	2179	
Sub 30	0.333	0.200	0.067	2585	
Sub 31	0.286	0.200	0.057	2665	
Sub 32	0.200	0.200	0.040	6420	

and *ΔCOC* respectively, in the marginal case) [18],

$$\frac{C_{\alpha} + C_m - S_l}{\Delta R} = \frac{\Delta COC}{\Delta R} \qquad (7)$$

in € per unit reliability change.

Ideally, as the value on the right-hand side of eqn 7 becomes greater, the better the scheme. This criterion can then be applied to schemes that meet relevant technical and financial requirements under the two main planning stages in order to prioritize tentative proposals under the capital program development and to choose between alternative proposals of a project proposal during the final commitment stage [19]. This decision-making process using both incremental costs and incremental benefits criteria, can be represented by the flow diagram shown in figure 3.

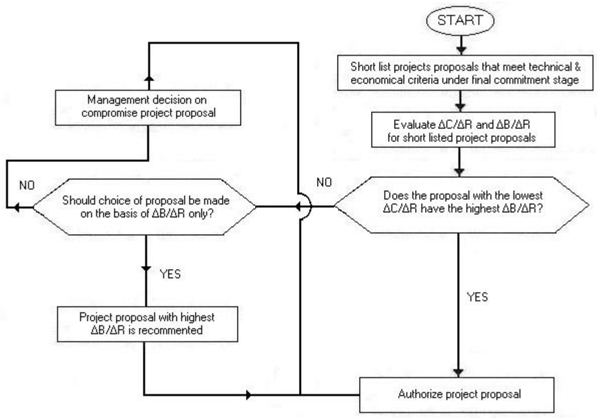

Figure 3: Decision-making process flow diagram.

9. Conclusions

It is known, that utilities usually plan their investment programs a number of years in advance and within this span agree detailed list of investments for the next year or two depending on the financial policy. The planning process, especially for a large scheme, is an extensive procedure and requires a long list of considerations. Reliability investment appraisal is only a part, albeit a vital one, of this process and seeks to justify the costs of improving the reliability of a network or system on the basis that the reliability improvement is cost effective. Cost-benefit analysis can be used as part of this appraisal process.

The application of cost-benefit analysis based on the economic principle represented by eqn 2 is not new. Understandably, due to the unavailability of appropriate methods for evaluating reliability worth, the right hand side of eqn 2 has been largely ignored. Denoting the marginal costs as V_l, (the criteria for investment approval is such that V_l is minimized or, in a specific application to radial high voltage distribution systems with overhead lines), V_l should be less than a selected "threshold value" V_t for the investment to be justified.

In this paper, the distribution systems' reliability increase using a decision-making process based on both incremental cost and incremental benefits criteria, was studied. The Bus 9 of the IEEE Reliability Test System has been used as a case study and useful conclusions concerning reliability investment appraisals were stated.

References:

[1] E. Lakervi, E.J. Holves, "Electricity distribution network design", Peter Peregrinous Ltd, London, 1989

[2] R. Billinton, R.N. Allan, "Evaluation assessment of large electric power systems", Kluwer Press, 1988

[3] R. Billinton, R.N. Allan, "Reliability evaluation of engineering systems", Plenum Press, 1992

[4] P. Wang, R. Billinton, "Reliability cost/worth assessment of distribution systems incorporating time-varying weather conditions and restoration resources", IEEE Trans on Power Delivery, vol. 17, no. 1, 2002, pp. 260-265

[5] J.G. Tine, D.A. Walder, "Improved distribution system reliability at Northeast uutilities: a case history", IEEE Trans on Power Delivery, vol. 8, no. 2, 1993, pp. 689-696

[6] S. Gheorghe, V. Branescu, "Power quality and improvement of the performance in electricity distribution system", IEEE PES International Symposium Quality and Security of Electric Power Delivery Systems, CIGRE/PES 2003, 2003, pp. 109-114

[7] M. Tanrioven, "Reliability and cost-benefits of adding alternate power sources to an independent micro-grid community", Journal of Power Sources, vol. 150, 2005, pp. 136-149

[8] T.F. Tsao, H.C. Chang, "Comparative case studies for value-based distribution system reliability planning", Electric Power Systems Research, vol. 68, 2004, pp. 229-237

[9] D.F. Bins, "Economics of electrical power engineering", Electrical Logic Power Ltd., Manchester, 1986

[10] R.F. Ghajar, R. Billinton, "Economic costs of power interruptions: a consistent model and methodology", Electrical Power and Energy Systems, vol. 28, 2006, pp. 29-35

[11] K.K. Kariuki, R.N. Allan, "Applications of customer outage costs in system planning design and operation", IEE Generation, Transmission and Distribution, vol. 143, no. 2, 1996, pp. 305-312

[12] S.M. Megalokonomos, E.N. Dialynas, V.C. Dali, "Interruption cost analysis for the agricultural electrical power customers in Greece", MedPower 2002, Athens, 2002

[13] G. Tollefson, R. Billinton, G. Wacker, E. Chan, J. Aweya, "Canadian customer survey to assess power system reliability worth", IEEE Trans on PWRS, vol. 9, pp. 443-450

[14] I. Sjarief, "Reliability evaluation of distribution systems", MSc. Thesis, UMIST, Manchester, 1990

[15] K.K. Kariuki, R.N. Allan, "Evaluation of reliability worth and value of lost load", IEE Generation, Transmission and Distribution, vol. 143, no. 2, 1996, pp. 171-180

[16] R. Billinton, S. Ali, G. Wacker, "Rural distribution system reliability worth evaluation using individual customer outage cost characteristics", Electrical Power and Energy Systems, vol. 26, 2004, pp. 235-240

[17] L. Goel, R. Billinton, "Impacts of pertinent factors on reliability worth indices in an

electric power system", Electric Power Systems Research, vol. 41, 1997, pp. 151-158

[18]R. Billinton, P. Wang, "Reliability worth of distribution system network reinforcement considering dispersed customer cost data", IEE Proc Generation, Transmission and Distribution, vol. 146, no. 3, 1999, pp. 318-324

[19]G. Cartina, C. Bonciu, E. Birladeanu, M. Moshe, "Optimization of the decisions for the renewal/reinforcements on distribution networks", 10th Mediterranean Electro technical Conference, MELECON 2000, vol. 3, 2000, pp. 911-914