Application of Worth of Supply in Distribution Systems' Planning

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Abstract: The paper studies the reliability of distribution networks and the outage cost perceived by customers in these distribution networks. Existing reliability data and outage cost data are used in order to assess and compare the investment cost needed to achieve a certain level of reliability in distribution networks, with the benefits derived from the networks by the users and society. A typical distribution radial system is examined and very useful conclusions were extracted from the comparison between the investment costs that a utility has, and the benefits that the customers derive from these.

Keywords: Reliability, Distribution systems, Customer outage cost, Customer damage function

1. Introduction

The function of an electricity distribution system is to deliver electrical energy from the transmission substations or small generating stations to each customer, transforming it to a suitable voltage where necessary. The distribution system must supply power as economically as possible and with an acceptable level of continuity, reliability and quality [1].

The reliability of supply to customers is judged from many factors such as the frequency of interruptions, the duration of each interruption and the value a customer places on the supply of electricity at the time that the service in not provided. These factors depend on variables such as the reliability of individual items of equipment, circuit length and loading, network configuration, distribution automation, load profile and available transfer capacity [2, 3].

Users, customers and society in general expect that systems are reliable and safe. In other words, they expect that there are no failures and interruptions, something which often causes effects that range from inconvenience and irritation to a severe impact on society and environment. The probability of having a failure and customers being disconnected, however, can be reduced by increased investment either during the planning phase, or during the operating phase or both.

The aim of this paper is to contribute in the significant research effort which has been presented the last years worldwide [4-14], in order a certain level of reliability to be achieved, taking into consideration the required implied cost and the customer outage cost. A typical distribution radial system is examined and very useful conclusions were extracted from the comparison between the investment costs that a utility has, and the benefits that the customers derive from these.

2. Reliability and economics

It is evident, that costs and economics play a major role in the application of reliability. The relation between the reliability of a product or a system and the investment cost is shown clearly in figure 1.

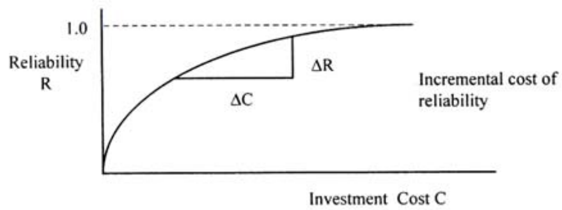

Figure 1: Reliability related to investment cost.

Figure 1 presents the general trend that the incremental cost ΔC to achieve a given increase in reliability ΔR, increases as the reliability level increases, or alternatively, a given increase in investment produces a decreasing increment in reliability as the reliability is increased. In either case, high reliability is expensive to achieve [5].

The incremental cost of reliability, $\Delta C/\Delta R$ (figure 1), is one way of deciding whether an investment in the system is worth it. However, it does not adequately reflect the benefits seen by the manufacturer, the service industry, the customers or the society. The two aspects of reliability and economics can be appraised more consistently by comparing the reliability cost with the reliability worth [6, 7].

3. The radial distribution system

A radial system has a single simultaneous path of power flow to the load. It is used extensively to secure the light and medium density load areas where the primary and secondary circuits are usually carried on overhead poles. The distribution substation or substations can be supplied from the bulk power source over radial or loop sub-transmission circuits or over a sub-transmission grid or network.

The primary feeders radiate from the distribution substation and branch into subfeeders and laterals, which extend into all parts of the area served. The distribution transformers are connected to the primary feeders, subfeeders, and laterals through fused cutouts, and supply the radial secondary circuits to which the customers' services are connected [8].

The main advantages of radial distribution systems are simplicity and low first cost. These result from a straightforward circuit arrangement, where a single or radial path is provided from the distribution substation to the consumers. With such a circuit arrangement, the amount of switching equipment is small and the protective relaying is simple. A simple form of radial type distribution system is shown in figure 2.

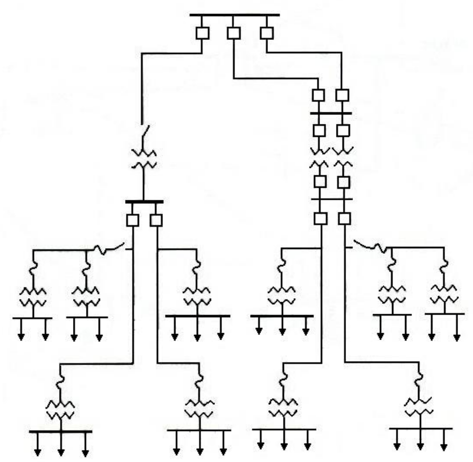

Figure 2: A simple radial distribution system.

4. Measuring and evaluating reliability

Every power system has an inbuilt reliability which depends on the reliability of its constituent components, on the standards to which it was planned and designed, and on the operating and environmental conditions to which it is subjected. During operation two sets of indices are used to measure the reliability of distribution systems. These are: (i) the basic load point indices which measure the frequency and duration of interruptions in supply and include the average failure rate in occurrences per year, the average duration of interruption in hours per interruption and the annual outage time in hours per year. They are denoted as λ, r and U, respectively and are related with the expression $U = \lambda \cdot r$, (ii) the system performance indices, which reflect the severity of significance of interruptions. The latter are derivatives of the former and therefore either set may be used to assess the impacts of any factor that affect reliability [9].

For a given service area, the cost model is a series of values $C(r_i)$ referred to as the composite customer damage function (CCDF) and defined as the normalized costs due to supply interruptions expressed as a function of interruption duration for the customer mix supplied. The CCDF has the dimensions of either €/KWh or €/KW. To develop a CCDF the following steps are required [10, 14].

a) Surveys are conducted to derive the customer estimates from the perceived costs of interruption (€) for the various interruption durations,

b) The estimates for each interruption are normalized by dividing the costs by either the annual energy consumed or the peak demand,

c) These normalized costs are grouped according to classes of consumers and the average values for a class obtained.

These are, in turn appropriately weighted to yield a series of sector values referred to as sector customer damage function (SCDF). For each sector y and its load factor LF_y, the value corresponding to an interruption of duration r_i is denoted by $C_y(r_i)$ and is given by eqn 1. The definition of SCDF is similar to the CCDF but refers to a sector rather than the entire customer mix [11].

$$C_y(r_i) = \frac{C_{L,y}(r_i)}{LF_y \cdot 8.76} \quad \text{€/MWh} \qquad (1)$$

where $C_{L,y}(r_i)$ is the SCDF value in €/KW derived from the surveys without giving due regard to the load factor,

d) Finally the SCDF values are appropriately weighted to give CCDF values. Eqn 2 shows the formula for evaluating the CCDF values $C_y(r_i)$ for an interruption duration r_i, with weighting in proportion to the respective sector annual energy consumption [12, 14].

$$C(r_i) = \sum_{y}^{ny} C_y(r_i) \cdot \left(\frac{E_y}{\sum_{y}^{ny} E_y} \right) \quad €/\text{MWh} \qquad (2)$$

where E_y is the annual energy consumed by sector y.

Using the above models, the COC at a load point j supplying ny sectors can be calculated from:

$$COC_j = \left(\sum_{y}^{ny} E_{jy} \right) \cdot C_j(r_i) \cdot \lambda_j \quad € \qquad (3)$$

where the average outage duration r_i is different from those used in the survey questionnaire, linear extrapolation is used to calculate $C_j(r_j)$ otherwise it can be read off a CCDF curve. A summation of the COCs at all the relevant load points yields the costs SCOC, for a service area as shown by eqn 4 [13].

$$SCOC = \sum_{j}^{b} COC_j \quad € \qquad (4)$$

5. Case study: typical radial system

5.1 Examined radial distribution system

The typical radial distribution system of figure 3 is examined. In each load point (A, B, C, D) there are connected, residential, commercial and industrial customers. The arrangement of showing how many of these are connected in each load point and the load model data for the three different types of customers is shown in table 1.

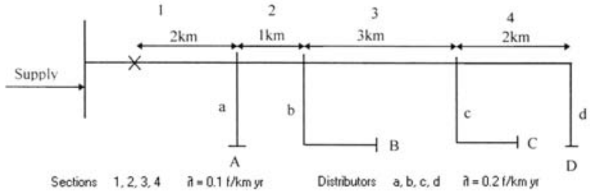

Figure 3: A typical radial distribution system.

Table 2 is constructed, showing the energy, the peak demand and the load factor in each load point. The sector customer function (SCDF) is provided from [15] and concerning Greek electrical power customers. According to the SCDFs values in [15], the load model data and the eqn 5, the composite customer damage function (CCDF) is calculated in each load point, for each type of customer.

The reliability indices of each load point (A, B, C, D) of the system are shown in table 3. Using the eqns 3 and 4, table 4 was constructed giving the customer outage costs for the system.

$$C_{r(i)} = \sum_{y}^{ny} \left[\left(\frac{C_{L,y}(r_i)}{LF_y \cdot 8.76} \right) \left(\frac{E_y}{\sum_{y}^{ny} E_y} \right) \right] \quad €/\text{MWh} \; (5)$$

5.2 Reinforcement of the system

The examined network is reinforced with disconnects and fusegear at each one section. Assuming that the switching time for the disconnects is 0.5 hours and that the fusegear operates with a probability of 0.9, the new reliability indices are shown in table 5. Using again eqns 3 and 4, table 6 which gives the customer outage costs for the reinforced system was constructed.

6. Discussion on the results

The reinforcement of the typical radial distribution network presented in paragraph 5 with disconnects and fusegear was carried out for several reasons such as: the improvement of the system, the increase in the security of the system for the society/customers and for the reduction of the COC.

The result was a change in the reliability indices for each one of the four load points. The average failure rate in occurrences per year λ and the average duration of interruption in hours per interruption r, were reduced having as a result the reduction of the annual outage time in hours per year U. After that, the new values for the COC of this system were calculated.

As it was expected, these new values were much lower than these prior the changes in the system. This can be seen in table 7, where ΔCOC is the difference in COC prior and after the changes. According to table 7 the changes in the system gave rise to great advantages, since the annual savings in euros are up to 170,000 euros for the whole system.

However, in order to decide if the examined system has real benefits from the reinforcement another one factor must be considered. This is the investment cost and in the case of this radial distribution system, is: (i) the cost for the disconnects and the fusegear and (ii) the costs for the extra annual operation and maintenance of them. A careful comparison, between the savings in COC and the investment cost can show if this

Table 1: Number of customers in each load point and load model data

	Load Point						
	A	B	C	D	E(MWh)	L(MW)	Load factor
Residential	100	200	200	500	8760	2	50.0%
Commercial	50	50	50	50	15800	4	45.1%
Industrial	20	15	5	0	10510	2	60.0%

Table 2: Energy, peak demand and load factor in each load point

	Load point A			Load point B			Load point C			Load point D		
	E (MWh)	L (MW)	LF (%)	E (MWh)	L (MW)	LF (%)	E (MWh)	L (MW)	LF (%)	E (MWh)	L (MW)	LF (%)
Residential	876	0.2	50	1752	0.4	50	1752	0.4	50	4380	1	50
Commercial	3950	1	45	3950	1	45	3950	1	45	3950	1	45
Industrial	5255	1	60	3940	0.75	60	1315	0.25	60	0	0	0
Total	10081	2.2	52.3	9642	2.15	51.2	7017	1.65	48.5	8330	2	47.5

Table 3: Reliability indices for each load point

	Load point A			Load point B			Load point C			Load point D		
	λ (f/yr)	r (hours)	U (hrs/yr)	λ (f/yr)	r (hours)	U (hrs/yr)	λ (f/yr)	r (hours)	U (hrs/yr)	λ (f/yr)	r (hours)	U (hrs/yr)
Section												
1	0.2	4	0.8	0.2	4	0.8	0.2	4	0.8	0.2	4	0.8
2	0.1	4	0.4	0.1	4	0.4	0.1	4	0.4	0.1	4	0.4
3	0.3	4	1.2	0.3	4	1.2	0.3	4	1.2	0.3	4	1.2
4	0.2	4	0.8	0.2	4	0.8	0.2	4	0.8	0.2	4	0.8
Distributor												
a	0.2	2	0.4	0.2	2	0.4	0.2	2	0.4	0.2	2	0.4
b	0.6	2	1.2	0.6	2	1.2	0.6	2	1.2	0.6	2	1.2
c	0.4	2	0.8	0.4	2	0.8	0.4	2	0.8	0.4	2	0.8
d	0.2	2	0.4	0.2	2	0.4	0.2	2	0.4	0.2	2	0.4
Total	2.2	2.73	6.0	2.2	2.73	6.0	2.2	2.73	6.0	2.2	2.73	6.0

Table 4: Customer outage costs for each one load point of the system

	Load point A		Load point B		Load point C		Load point D	
	COC (€)	SCOC (€)	COC (€)	SCOC (€)	COC (€)	SCOC (€)	COC (€)	SCOC (€)
Section								
1	22420		18940		11730		8570	
2	11210	89620	9470	75760	5865	46920	4285	34280
3	33630		28410		17595		12855	
4	22420		18940		11730		8570	
Distributor								
a	12825		10700		6370		4380	
b	38475	51300	32100	42800	19110	25480	13140	17520
c	25650		21400		12140		8760	
d	12825		10700		6370		4380	
Total		140980		118560		72400		51800

Table 5: New reliability indices for each one load point of the reinforced system

	Load point A			Load point B			Load point C			Load point D		
	λ (f/yr)	r (hours)	U (hrs/yr)	λ (f/yr)	r (hours)	U (hrs/yr)	λ (f/yr)	r (hours)	U (hrs/yr)	λ (f/yr)	r (hours)	U (hrs/yr)
Section												
1	0.2	4	0.8	0.2	4	0.8	0.2	4	0.8	0.2	4	0.8
2	0.1	0.5	0.05	0.1	4	0.4	0.1	4	0.4	0.1	4	0.4
3	0.3	0.5	0.15	0.3	0.5	0.15	0.3	4	1.2	0.3	4	1.2
4	0.2	0.5	0.1	0.2	0.5	0.1	0.2	0.5	0.1	0.2	4	0.8
Distributor												
a	0.2	2	0.4	0.02	0.5	0.01	0.02	0.5	0.01	0.01	0.5	0.01
b	0.06	0.5	0.03	0.6	2	1.2	0.06	0.5	0.03	0.06	0.5	0.03
c	0.04	0.5	0.02	0.04	0.5	0.02	0.4	2	0.8	0.04	0.5	0.02
d	0.02	0.5	0.01	0.02	0.5	0.01	0.02	0.5	0.01	0.2	2	0.4
Total	1.12	1.39	1.56	1.48	1.82	2.69	1.3	2.58	3.35	1.12	3.27	3.66

Table 6: New customer outage costs for each one load point of the reinforced system

	Load point A		Load point B		Load point C		Load point D	
	COC (€)	SCOC (€)	COC (€)	SCOC (€)	COC (€)	SCOC (€)	COC (€)	SCOC (€)
Section								
1	22420		18940		11730		8570	
2	2268	36028	9470	37633	5865	37176	4285	34280
3	6804		5534		17595		12855	
4	4536		3689		1986		8570	
Distributor								
a	12825		369		199		58	
b	1362	15549	32100	33576	596	13734	348	5018
c	908		738		12740		232	
d	454		369		199		4380	
Total		51577		71209		50910		39298

Table 7: Comparison of customer outage costs prior and after the reinforcement

	COC (€)		
	prior changes	after changes	ΔCOC (€)
Load point A	140980	51577	89403
Load point B	118560	71209	47351
Load point C	72400	50910	21490
Load point D	51800	39298	12502

reinforcement and every reinforcement is worth to be done.

Unfortunately in this radial distribution system the investment data (data for the cost of disconnects and fusegear), were not available. However the savings which exist from the improvement of the system are known. These can put a limit, a selected “threshold value” for the investment to be justified.

In the examined case the annual savings are calculated 170,000 euros. So it is concluded that any investment up to this value is acceptable. It must be noticed that this value may be even higher if the benefits are not to be seen from the first year of operation but in ten or fifteen years time let’s say, since these improvements are made to be last, for two, three or even more decades.

7. Conclusions

This paper presents a realistic problem which is being encountered by network planners (i.e. the need to replace obsolete equipment without unduly affecting the quality of supply to connected consumers, while at the same time redressing overinvestment in networks originally designed to very stringent criteria but whose equipment is now obsolete and requiring replacement). An acknowledged weakness in cost-benefit analysis techniques is the lack of an appropriate method for the evaluation of customers' marginal benefits. The procedure for evaluating COC presented in this work corrects this situation. In particular, it is seen from the results that ΔCOC are extremely useful in: (i) highlighting the significance and hence the benefits to consumers associated with network changes resulting from system reinforcement and refurbishment schemes and (ii) in facilitating conclusive judgment on the overall reliability for which other indices may be found wanting or inconclusive.

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