USING A PROBABILISTIC DESIGN PROCESS TO MAXIMIZE RELIABILITY AND MINIMIZE COST IN URBAN CENTRAL BUSINESS DISTRICTS

Lavelle A. FREEMAN, Devin T. VAN ZANDT, Louie J. POWELL
GE Energy – United States
lavelle.freeman@ge.com

INTRODUCTION

The practices currently used by many US utilities in designing urban distribution systems were developed during the early part of the twentieth century. In those days, distribution systems were not as heavily loaded as they are today, assets were not as aged as they now are now, thermal and spatial constraints were less severe, customers were less demanding, and utilities were not faced with the regulatory and competitive pressures that exist in today's market.

In this dynamic market environment, utility managers are starting to search for new approaches to design and operate their systems. Their objectives in this search are to identify approaches and technologies that enable them to deliver an acceptable level of end-customer reliability and satisfaction, at reasonable costs, while managing the political and public relations risks that are an inevitable part of the regulated utility business.

This paper will present the case for a new design process in a modern distribution utility based on probabilistic principles. In the past, it was common practice to ensure reliability and simplify engineering by designing to a deterministic standard such as N-1 or N-2 redundancy, regardless of the application or environment. The paper will examine the impact of deterministic standards on the design of the system, and discuss the potential deficiencies of this design process in a constrained and changing environment. The probabilistic design process will be explained and illustrated on an example sub-system and the cost, reliability and risk implications will be discussed.

DESCRIPTION OF URBAN UTILITY SYSTEMS

Utility systems that serve high population urban centers share unique characteristics that have evolved over time. In the US, they are typically underground systems and are often looped, or configured as secondary grids or spot networks. The primary motivation for the selection of this architecture was the belief that it provided the lowest cost approach to serving high-density, relatively uniform urban loads while satisfying the increased reliability expectations of urban load centers.

Secondary Grids

Figure 1 shows the typical configuration of the distribution network used in the downtown areas of many US cities. Several medium voltage feeders (typically 15-kV-class design), from a nearby distribution substation, are connected at multiple locations to a 120/208 V secondary cable grid through network transformers. The network transformers have a "network protector" in series with their secondary output. This network protector is a circuit interrupter that automatically opens if power attempts to flow from the low-voltage secondary grid through the transformer to the medium-voltage feeder. Customer service drops are connected directly to the secondary cables via manhole splices. Typically, overall transformer capacity in a secondary network system is significantly larger than the peak load, so failure of an individual network transformer does not result in an outage to any customers[1].

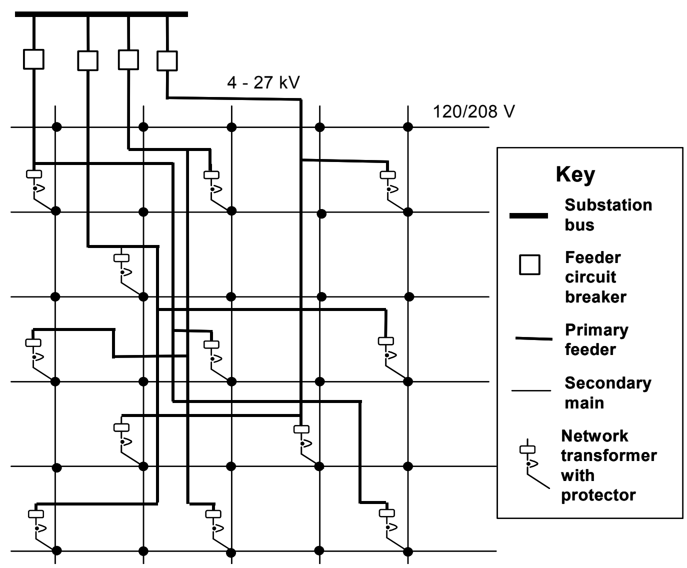


Figure 1. Schematic of a typical secondary grid arrangement

Spot Networks

Spot networks are used to serve large high density loads, and critical loads such as high-rise buildings and hospitals. It is not unusual to find these large loads in downtown areas surrounded by low-rise commercial and residential structures. In a spot network, all the network transformers are connected to a common secondary bus (usually at 480 V) as shown in Figure 2. The protection and control of spot networks is similar in concept to the secondary grid.

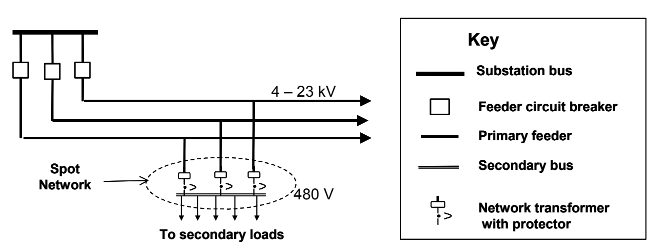


Figure 2. Schematic of a typical spot network arrangement

Challenges and Constraints

Both the secondary network design and the spot network achieve high end-customer reliability by providing multiple paths through which those customers can be supplied. This is the so-called N-x deterministic approach to designing for reliability; substations and spot networks are designed such that a single (N-1) or double (N-2) network transformer and/or primary feeder failure will not cause end-customer interruption. There is no question that this approach provides highly reliable service, but the operating and capital costs and space requirements are higher than conventional radial designs.

Urban underground systems are inherently spatially constrained and this translates into high costs for real estate acquisition. Underground rights-of-way and conduits are crowded by other utilities (telephone, water, gas, etc.) and are sometimes thermally saturated. In some areas, interveners actively try to block construction of new facilities while still demanding the same or better performance from the utility. Solutions that address physical constraints are extremely expensive alternatives.

With the convergence of factors such as aging infrastructure, real spatial limitations, thermal constraints, regulatory issues, risk of bypass, high O&M cost, and customer demands, it is not difficult to imagine a point on the horizon where conventional urban systems are no longer a viable option to serve customers while maintaining the financial strength of a utility. It is imperative that urban utilities begin to look ahead now and plan for a more suitable system architecture. A probabilistic design approach may help utilities to develop the next generation distribution system.

PROBABILISTIC DESIGN PROCESS

The principles of probabilistic design that have been applied in the aerospace and power generation industries for some time are finding new applications in the distribution power planning and engineering. Probabilistic design methodology provides a way to objectively quantify the relative value of different design arrangements and operational practices. Also, the probabilistic approach makes it possible to understand the sensitivity of the design to system variables, thereby giving the system operator knowledge about where system reinforcements are required to improve performance. This is in contrast to the deterministic approach that incorporates "factors of uncertainty" or safety factors to produce a design that may be overly conservative. A good reliability model and a firm grasp on the capital and O&M cost activities are essential to this process.

Reliability Models

The accepted definition of reliability is the probability that a system will survive beyond a certain time. In the world of power distribution engineering, a "system" can be a secondary network, a spot network, a feeder, a distribution network, a substation, or a combination of these elements. For all practical purposes, the reliability of the distribution system is simply its ability to serve the customer load. For an individual customer, this is completely described by the number of outages he or she experiences in a certain time period (a common alternative is the expected interval between outages) and the total time he or she is de-energized for the time period. These customer-level metrics can then be rolled up into any number of the system-level indices that are normally used to characterize distribution reliability[2].

A good distribution system model is the key to reliability analysis. The two components of the model are (1) connectivity and (2) component performance data. Connectivity describes the manner in which distribution components interact to form the system. A distribution system or subsystem can be a complex arrangement of thousands of components. In an urban distribution system, these may include network transformers, cable sections, switches, breakers, network protectors and bus sections. A functionally accurate description of the topographical arrangement is critical to capturing the diversity of supply, equipment redundancies, remedial actions and mitigating measures. The most common sources for connectivity data are system maps, one-line diagrams and GIS databases.

The data component of the model describes the failure, repair and remedial characteristics of the individual components and the system. The most often used parameters are[3]:

- Permanent failure rate – the number of times that a component will experience a permanent fault in a given year
- Temporary failure rate – the number of times that a component will experience a temporary fault (one that can be cleared by de-energizing the line) in a given year
- Mean time to repair – the average time to repair a component once it has failed
- Mean time to switch – the average time to perform switching actions to restore customers after a fault (or isolate the fault) following the action of protective devices

Ideally, each utility should collect component statistics on its own system that reflect its unique operating environment and maintenance practices. Practically, however, it would take many years of operation and diligent record-keeping to gather meaningful performance statistics on a single system. In the mean time, there are a number of alternative sources from organizations such as the IEEE[4], the Reliability Application Center of the US Army Corps of Engineers[5] and the Canadian Electrical Association[6].

Reliability and Risk Computations

Given that a component has a failure rate, λ, which represents the mean number of failures per year, the probability that the component will fail n times in a given year is given by

$$\text{Prob. of failing } n \text{ times} = \frac{\lambda^n e^{-\lambda}}{n!}$$

Monte Carlo simulation can be used to generate random failure and repair scenarios on a system using this Poisson process. This feature is available today in many commercial software tools. Taking into account the system configuration, the reliability of the system can easily be determined as the probability of supply to the end customers. This can be captured by several metrics, including the mean time to failure or MTTF (where "failure" is the inability to meet the customer demand) and the mean downtime per year. These customer-level metrics can be easily rolled up into the familiar SAIDI, SAIFI and CAIDI indices[3].

Design Trade-offs

The power of the probabilistic design process lies in the fact that it enables one to make intelligent tradeoffs in key features of electrical architecture design and O&M strategies. In urban underground networks, the constraints can generally be expressed as a real economic cost. The need to maintain high reliability may lead to component redundancy (cost), which increases footprint (more cost) and inherently increases operation and maintenance activity (even more cost).

Design Example. Consider a simple spot network with multiple transformers on a single bus. If this system is designed to an N-2 standard, then for a load of 2x (where x is a measure of the maximum allowable transformer load), four transformers are required to meet the deterministic standard of N-2. However, if the reliability requirement were expressed as a probabilistic target instead of a deterministic criterion, a variety of designs with potentially lower costs may emerge to meet the objective. Table 1 shows the results of this simple exercise. The reliability and cost of several alternative designs are expressed on a per-unit basis relative to the reliability and cost of the original four-transformer N-2 spot network. It is clear that a lower (capital) cost, higher utilization design can be obtained, but only at the expense of reliability.

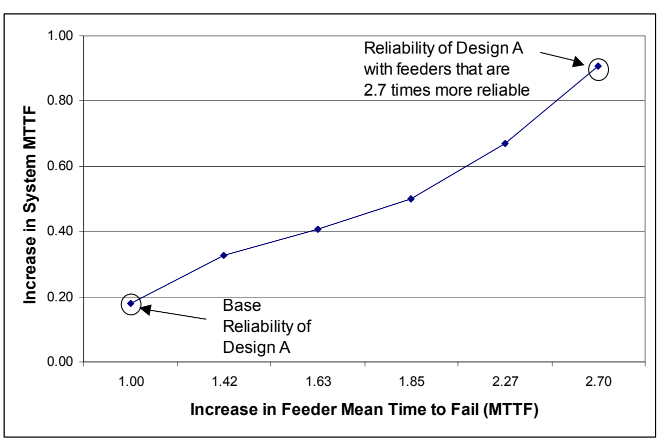
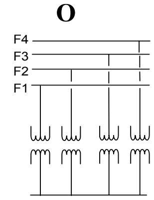
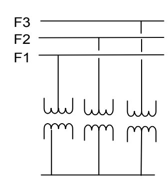
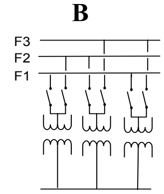
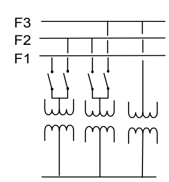
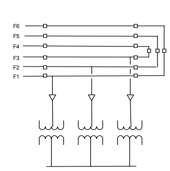


Figure 3. Sensitivity of system MTTF to feeder failures for design A.

The reliability of the supply feeders is a key component of the spot network reliability. An alternative design that may appear to have poor reliability compared with the original design, may actually have comparable reliability if its supply feeders were more reliable. For example, the sensitivity of the MTTF of alternative design A in Table 1 to the feeder failure rate (or conversely, the mean time to feeder fail) is shown in Figure 3. The results shows that the reliability of design A in Table 1, approaches that of the original design (O), when its supply feeders are 2.7 times more reliable (i.e. their failure rate is reduced by 63%).

A similar analysis can be performed by reducing the component repair times, demonstrating that if equipment could be brought back online faster, the reliability of lower capital cost alternatives can approach the reliability of the original design. However, there is also a capital cost and O&M cost associated with reducing the equipment failure rate and repair time that must also be taken into account.

TABLE 1. Relative Performance of Spot Network Design Alternatives

	Mean Downtime	Mean Time to Fail	Capital Cost	Trasformer Utilization
O 	1.00	1.00	1.00	0.50
A 	1.46	0.18	0.75	0.67
B 	1.03	0.68	0.95	0.67
C 	1.16	0.29	0.88	0.67
D 	1.13	0.55	1.03	0.67

APLICATION EXAMPLE

The principles of probabilistic design described in this paper have been applied to an actual urban underground network typical of the systems found in many central business districts across the United States. Over time, these systems have developed and evolved in response to decisions based on hard rules and deterministic criteria. While they have produced highly reliable and flexible systems, they also have the potential for high capital outlay, low asset utilization and overbuilding. The new design approach uses design decisions based on quantifiable, situational factors such as:

- Distribution feeder reliability
- Equipment utilization
- Customer requirements and expectations
- Load profile
- Life-cycle cost

The result is more efficient spending for specific circumstances and knowledge-based mitigation of the risk of not meeting the load demand.

The underground network chosen for implementation has a mixture of large dense loads, smaller residential type loads and orphan loads (street lights and news stands). These loads are served by a collection of spot networks and a secondary grid, which may have reinforcing street, ties to the spot networks. Several options were explored to supply power to the non-uniform high-density loads and uniform low-density loads.

Non-Uniform High-Density Load

Non-uniform high-density loads are typically supplied from a dedicated spot network. The intrinsic reliability of the spot network is derived from its redundant design configuration and the reliability of its individual components such as the feeders, network transformers, network protectors and secondary bus. The component reliability is mainly characterized by the equipment failure rates and repair times, which are derived from utility data and publicly available industry data. The arrangement of the spot network components was shown earlier in Figure 2.

The level of service experienced by the customer on the spot network also depends on the substation and transmission system supplying the feeder

Starting from the base design, several design options were explored. These included: removing ties between the secondary network on the street and the spot networks within buildings to simplify O&M activities; varying the number of transformers needed to supply the load; including primary selective switching to improve flexibility; and sectionalizing feeders to improve backbone reliability. Figure 4 illustrates the relative reliability and capital cost of the original design and the top four alternatives.

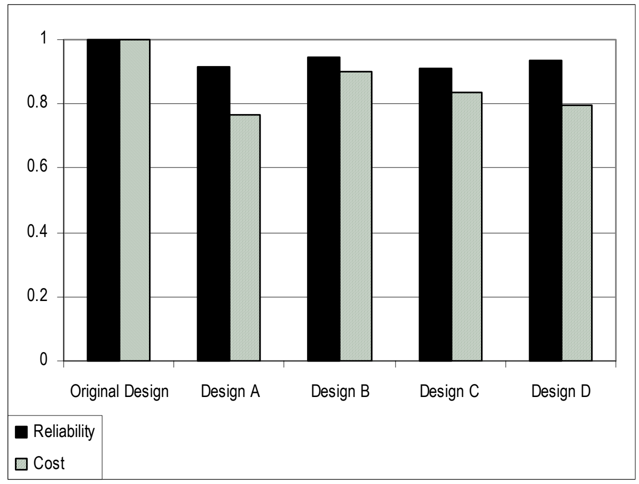


Figure 4. Relative reliability and capital cost of spot network designs.

The solid or dark bars depict one measurement of reliability (mean time to customer interruption) taking into account all known factors – for the present system configuration as well as four potential alternative arrangements. The hashed or light bars show the capital cost of each system design. For the sake of comparison, the reliability and capital cost of the alternatives have been expressed in per unit of the reliability and capital cost of the original design.

By examining the solid or dark bars, the impact of the various design options is readily apparent – design B clearly provides higher reliability than A or C, and design D is reasonably close to design B. While none of the alternatives has better reliability than the original system, the hashed or light bars show that all of the alternatives have a lower capital cost to implement than the original. Option A is the lowest capital cost alternative. But it also has the lowest reliability. Of the alternatives, design B has the highest reliability, but it also has the highest capital cost.

Deciding which design is the "best" may not be obvious because it depends on several soft factors, including the competitive and regulatory structure within a utility is operating. The operating environment heavily influences the value of reliability to the utility, i.e. how much the utility is willing to spend on a unit of reliability. Knowing this, the benefit of each design can be quantified, and the marginal utility (additional satisfaction or benefit) derived in moving from one design to another can be easily computed. The marginal utility derived in moving from design A (the lowest cost design) to design B is more than that of moving from design A to any other design (including the original design). Therefore, if option B also presents opportunities for O&M cost savings or risk avoidance to the utility, it may be a clear winner.

Uniform Low-Density Load

Uniform low density loads such as residences and light commercial are typically supplied from the secondary grid. The intrinsic reliability of the secondary grid is determined almost exclusively by its highly interconnected nature. To a lesser extent, the reliability (failure rate and repair time) of the secondary grid components such as secondary mains cable, manhole splices, service drops and limiters also affect the level of service experienced by the customer. However, the main contributor to the customer perception of reliability is events outside the grid such as network collapse due to simultaneous feeder outages, substation events and transmission events. Therefore a comprehensive model for the secondary grid reliability must include these components as well.

Starting from the base low-density supply design, several alternative design options were explored. In this case, because the area has a mix of high-density loads supplied by spot networks and uniform low-density loads, a natural design option would be to serve the low-density loads with extensions off the spot networks. Depending on the spot network design and its distance from the low-density load, this option may provide adequate reliability. Given another network dominated by uniform low-density loads, other designs would naturally evolve – such as subdividing the grid into smaller grids to serve blocks of customers or creating small spot networks with radial and looped extensions along streets to serve the low-density loads. Figure 5 displays the relative reliability and capital cost of the original design and the top four alternatives.

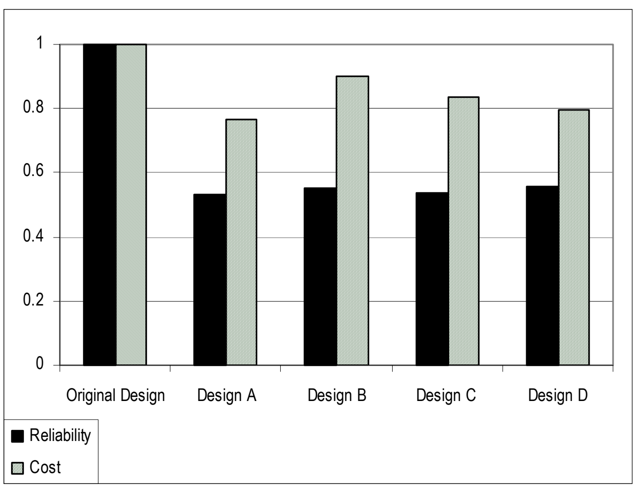


Figure 5. Relative reliability and capital cost of low-density supply alternatives

In this instance, the difference between the original customer reliability and the reliability under the most optimistic option is noticeably different. The cost of the alternative designs are also significantly less than the original design. If the level of reliability presented by the alternative designs is acceptable (i.e. the reliability of the original design was so high that a reduction produces no appreciable impact on customer service), and cost reduction is a priority for the utility, then a decision might now be made to select the alternative that reflects the lowest rate of capital and operational expenditure, or that presents the greatest opportunity for risk management.

CONCLUSIONS

This paper has outlined and discussed the application of a probabilistic design process in a modern distribution utility serving a central business district. Utilities that serve such high population urban centers are faced with unique challenges brought about by aging infrastructure, spatial and thermal constraints, potential for bypass, heightened socio-political sensitivity, fiscal pressure and the demand for better performance. In order to bring their legacy design practices inline with today's demand, utilities may consider moving away from purely deterministic design criteria (such as N-x) and instead incorporate probabilistic principles into their system design practices. A good reliability model and a firm grasp on the capital and O&M cost activities are essential to this process. With this knowledge, utilities can effectively trade off reliability, risk and cost in developing the most suitable design and operating strategies for present conditions.

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