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Electric Power Systems Research 68 (2004) 208–220

ELECTRIC POWER SYSTEMS RESEARCH

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Optimal allocation of distribution maintenance resources with limited information

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Received 10 February 2003; received in revised form 12 June 2003; accepted 7 July 2003

Abstract

Maintenance of distribution systems plays a central, although often overlooked, role in determining both the reliability and cost of supply. In previous work, an approach was developed that optimizes the effectiveness of distribution protective devices. This paper extends that framework to the optimal use of maintenance resources for reliability. Firstly, a framework is established assuming constant failure rates for the components. Secondly, that framework is extended to optimization given limited information about equipment condition. That is, the failure rates and impact of the reliability are known only approximately. The objective in this framework is to maximize reliability as measured by typical reliability indices. This formulation is demonstrated on a set of numerical examples. Results are analyzed and difficulties that may arise in the proposed approach are investigated. Further, the concept of the value of additional information is introduced. The problems are solved through a two-stage analysis procedure based on linear programming and approximate reasoning using fuzzy sets.

Keywords: Approximate reasoning; Distribution systems; Fuzzy sets; Maintenance; Reliability; Reliability Centered Maintenance (RCM)

1. Introduction

A radial network is the most common and the simplest distribution network used by utilities. A typical radial network consists of a main line and several lateral feeders, distribution transformers, and a secondary network [1]. The main line and lateral feeders can be overhead, underground or a combination of both. Customers served by a distribution network may experience frequent outages for many reasons, including loss of supply from a substation, component failure, a lightning strike, car–pole accident, tree and animal contacts, and insulator flashover due to accumulation of dirt and the presence of moisture. Major components contributing to outages in underground circuits consist of interrupters, fuses, switches, transformers, elbows, splices and cables. The overhead circuit components of concern are transformers, switches, fuses, capacitors, reclosers, sectionalizers, voltage regulators and conductors [2].

A detailed study by Duke Power between 1987 and 1990 indicates that distribution outage causes can be divided into the following different categories with these given failure percentages [3]: equipment 14%, trees 19%, animals 18%, lightning 9%, and others 40%. A study of 85 rural and 95 urban overhead distribution circuits from the Pacific Gas and Electric System [4] indicates that component failures contributed to about 15% of the total permanent outages. For the remaining 85% of the outages, 75% were due to external factors such as lightning strikes, trees, car–pole accidents and third party contacts and 10% were attributed to substation or transmission outages. These two studies are generally consistent and appear representative of distribution outage causes in many locales.

The utility industry takes various preventive actions to minimize those failures that have a direct impact on service reliability. These actions consist of routine maintenance on testable and repairable components, replacement of non-repairable components, tree trimming, installation of animal guards and washing of insulators. Specific device maintenance actions include monitoring, testing, and repairing of components that deteriorate due to aging and contin-

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doi:10.1016/j.epsr.2003.07.001

uous operation. Most utilities traditionally have followed a rigid maintenance schedule based either on a fixed time interval, or on the number operations for the equipment, or on a combination of both. Routine maintenance based on a fixed time schedule depends on the individual utility practices or the manufacturer's recommendations. Non-repairable equipment will be replaced if it fails, or as it ages, if the expected failure rate exceeds an unacceptable value. Tree trimming is performed either after inspection or based on a fixed time interval in order to maintain an acceptable clearance between trees and conductors. When there are more frequent animal caused outages, animal guards are installed. Some utilities wash insulators before the start of the rainy season to prevent flashovers.

Today, due to increased competitive and economic pressures, utilities have been forced to reduce operation and maintenance costs. Thus, there is a need to perform maintenance at minimum cost without jeopardizing system reliability. One of the techniques has been to increase the time interval for routine protective device maintenance and testing. Self-diagnostic capability of new protective devices contributes to the justification for this increase in the maintenance interval [5–7]. Following cost savings achieved in the aircraft industry, utilities have considered the concept of Reliability Centered Maintenance (RCM). RCM views all maintenance from a system reliability point of view, so that, for example, non-critical equipment may receive no preventive maintenance, some equipment is maintained at regular intervals and critical equipment is maintained based on on-line monitoring. In the power industry, most efforts have focused on data gathering and the application of reliability measures has been heuristic [8]. The work here seeks to add rigor to these techniques.

Reliability analyses have been developed that calculate the contribution of each line section, and its associated equipment, to the overall reliability [9]. Such data assists engineers in evaluating the impact of various proposed maintenance schedules. A minimum preventive maintenance model has been built for repairable devices whose condition deteriorates with time in service [10]. Other studies [8] have proposed a probabilistic model for the failure and maintenance processes which predicts the quantitative effect of a given maintenance policy on reliability indices.

In [1,2], various methods have been proposed to optimize effectiveness of protective devices by identifying their type and locations using a binary linear program. In this paper, that formulation is extended in order to optimize maintenance resources. The objective is to focus attention on the more critical components. The method will identify where resources should be allocated in order to achieve the maximum benefit. Maintenance levels for individual component are defined. Actions will be based on the available resources and the impact of the individual component failure rate on the overall service reliability.

In system reliability evaluation, system parameters, i.e., failure and repair rates, are obtained from historical records or typical data (supplied by operators' experience or manufacturer's specification). In practice, one difficult problem in reliability evaluation is the quantification of the reliability parameters [11]. Even if they are available, they are often inaccurate and thus, subject to uncertainty, i.e., historical records can only represent the past behavior but may be unable to predict the future behavior of the equipment. Further, age, adverse operating conditions and the vagaries of manufacturing affect each piece of equipment differently. In the absence of accurate data, it may be necessary to work with rough estimates of probabilities. These estimates, provided by engineers or other experts, are inherently subjective. To establish a rational method for reliability assessment, such subjective uncertainties should be merged with objective statistical randomness in some logically consistent manner. Fuzzy sets were introduced to deal with the subjective uncertainty factors in a quantitative way under the form of possibility distributions. Still these uncertainties must be introduced in a reasonable manner to allow meaningful decisions. In Section 4, this framework is developed.

The given examples focus on the practical numerical issues associated with finding appropriate levels of maintenance. The reliability parameters will be described by an interval of probabilities (e.g., a triangular or trapezoidal fuzzy number) and the binary programming optimization framework is used to determine a maintenance level for each component in a radial distribution network. This is accomplished by assigning a possible range of variation (owing to uncertainty) to the failure rate and solving using a fuzzy programming technique. Guidelines for assigning these uncertainties are given.

The quality and availability of information directly affect engineering decisions. Any additional information, concerning the precision of the values of failure rate of some components in the network (i.e., affecting the range of variation and the expected values of failure rates) should impact these decisions. This information can be acquired from research studies, physical inspection or field tests. Since the acquisition of additional information requires the expense of financial resources, the value of this information is investigated here. The decision-making problem with additional information is solved through a two-stage analysis procedure based on a fuzzy linear programming and ranking scheme. Analysis of this approach is then given.

2. Classification of maintenance

The precise impact of maintenance on a particular component's failure statistics may be difficult and at times nearly impossible to ascertain. To begin, a diagnostic assessment of the condition of a component may be incomplete or unknown until maintenance begins. Hopefully, if component conditions are tracked from year to year, then approximate values for the expected failure rates may be