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Differential evolution based technique for reliability design of meshed electrical distribution systems

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ABSTRACT

This paper describes a methodology for allocating repair times and failure rates to segments of a meshed distribution system using differential evolution (DE) technique. A cost function based on Duane's reliability growth testing model has been proposed. Constraints on basic reliability indices i.e. failure rate, average interruption duration and average interruption duration per year have been accounted. The algorithm has been implemented on a meshed distribution system and results have been compared with those obtained using particle swarm optimization (PSO) and co-ordinated aggregation based PSO (CAPSO).

1. Introduction

Reliability performance assessment and optimization are important components of overall predictive performance studies for electrical distribution systems. Relatively less importance has been given to reliability problems of distribution systems in comparison to generation and transmission systems in past. The importance of distribution system has been realized and now large numbers of research efforts are being made for reliable and economical operation of the distribution network [1–3]. Various analytical and simulation based methodologies have been developed for reliability evaluation of distribution systems [4–8].

Reliability of distribution system may be improved by modifying (i) fault avoidance measures (ii) network configuration and (iii) corrective measures. Reliability may also be enhanced by suitable location of substation and feeder length. Failure rate and repair time modifications may require additional efforts which are associated with additional expenditures. Su and Lii [8] used genetic algorithm for reliability design of a distribution system. The total cost including the apparatus investment cost and the system interruption cost have been selected as objective function. Constraints on system failure rate and average interruption duration at load point have been accounted. Chowdhury and Custer [9] presented a value based probabilistic approach to design urban distribution system for determination of optimal section length for placement on main feeder, number and placement of feeder ties, feeder and transformer loadings. Bhowmik et al. [10] described a three stage method for planning a power distribution system. These three stages include substation optimization, number of feeders with their active route and node reliability optimization. Chang and Wu [11] developed a technique for optimal reliability design for electrical distribution system. Non-linear optimization problem has been solved using a polynomial-time algorithm. Tsao and Chang [12] developed a set of composite distribution system reliability evaluation models that may be applied to non radial type systems. Tsao and Chang [5] performed comparative case studies for value based distribution system reliability planning. Louit et al. [13] developed an algorithm for determination of optimal interval for major maintenance actions in electrical distribution network. Differential evolution (DE) has been established as a powerful optimization technique [16–18]. Zhang et al. [24] used a self-adaptive DE algorithm for reactive power optimization. Arya et al. [25] used DE algorithm for determining optimum load shed with voltage stability consideration. Further Arya et al. [26] applied it for reliability enhancement of distribution system accounting distribution generation in standby mode. Mallipeddi and Suganthan [27] developed ensemble differential algorithm. Das and Suganthan [28] presented a survey of various variants of DE. Piotrowski et al. [29] presented a modified DE algorithm with separated groups for multidimensional optimization. Banerjee and Islam [30] developed an algorithm for optimum location of distributed generation (DG) in a distribution system based on reliability considerations. Moradi and Abedini [31] used genetic

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algorithm in combination with particle swarm optimization for optimal location and sizing of DG in distribution systems. Hemdan and Kurrat [32] developed a technique for efficient integration of DG in distribution systems to meet increased demand. Ferreira and Bretas [33] used a non-linear binary programming model for reliability optimization of distribution systems.

It is observed that selection of cost functions for repair time and failure rate modification is an important issue. In this paper cost functions for failure rate and repair time modifications have been selected based on reliability growth model developed by Duane [14] which is widely used in reliability growth testing. The contribution of this paper is the development of an algorithm for obtaining optimum failure rate and average repair time of each section of a meshed distribution system considering constraints on primary reliability indices i.e. (i) system failure rate (reciprocal of *MTTF*) (ii) average interruption duration and (iii) average interruption duration per year using DE. Another important contribution is the comparison of the population based optimization technique i.e. DE, PSO and CAPSO. Further the objective has been to provide co-relation between direct cost function and Duane's reliability growth model. Next section provides identification of cost functions for modification of failure rate and repair time of a section of the meshed distribution systems.

2. Cost function identification using reliability growth model

The purpose of reliability growth testing is to improve reliability over time via change in product design, selecting better quality of spare parts and procedures. Reliability growth testing identifies product deficiencies and areas of improvement. An idealized reliability growth curve is shown in Fig. 1. This reliability curve exhibits that as time passes *MTTF* increases or failure rate decreases. *MTTF* approaches to final value (M_f). This is associated with a cost per unit time. Most frequently used reliability growth model was proposed by Duane [14]. The model is based on the observation that plot of the logarithm of cumulative number of failure per test time versus the logarithm of test time during growth testing is approximately linear. This aspect is expressed mathematically as follows:

$$\ln\left(\frac{t}{n(t)}\right) = a + b\ln t \tag{1}$$

where t is the total test time; $n(t)$ is the accumulated number of failure up to t; a, b are constants of straight line. Constants a and b are estimated using the method of least squares and coefficient of determination is calculated to test the accuracy of fit [15]. $\frac{n(t)}{t}$ is cumulative failure rate and reciprocal of it is cumulative *MTTF*. Relation (1) is written as follows:

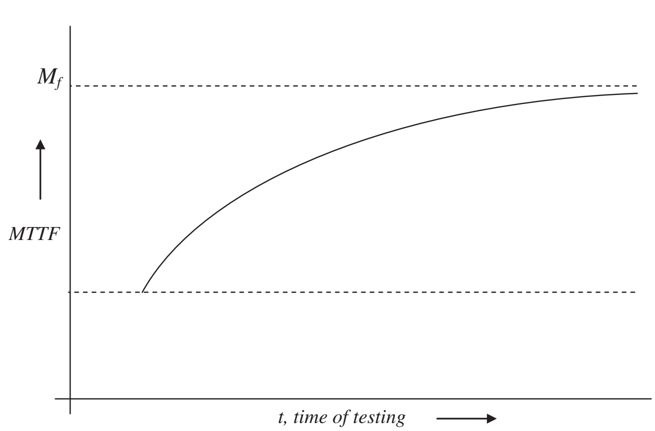

Fig. 1. A typical reliability growth plot.

$$\frac{t}{n(t)} = MTTF_c = p \cdot t^b \tag{2}$$

where $MTTF_c$ is cumulative *MTTF* and p is a constant equals to e^a.

Accumulated failure is written from relation (2) as follows:

$$n(t) = \frac{1}{p}t^{1-b} \tag{3}$$

Typical value of constants 'b' lies in the range from 0.3 to 0.6. The constant 'b' represents rate of growth. Instantaneous failure rate is evaluated from (3) as follows:

$$\frac{dn(t)}{dt} = \lambda(t) = \frac{(1-b)}{p}t^{-b} \tag{4}$$

The reciprocal of $\lambda(t)$ is instantaneous *MTTF*

$$MTTF_i = \frac{pt^b}{1-b} \tag{5}$$

The above equation is solved for t as follows:

$$t = \left[\frac{(1-b)MTTF_i}{p}\right]^{1/b} \tag{6}$$

In term of failure rate above relation is written as

$$t = \left[\frac{(1-b)}{p}\frac{1}{\lambda}\right]^{1/b} \tag{7}$$

In above λ simply denotes failure rate at the end of test time 't'.

In fact a section of distribution system may be considered under reliability growth test with variable value of failure rate so as to achieve a desired value of failure rate (as decided by solution of optimization problem). Each time the situation is assessed and measures are taken to reduce failure rate. It is expected that more the time more will be the cost. The cost may be assumed to be proportional to the length of test time. In view of this cost of failure rate modification may be written from (7) as follows:

$$C(\lambda) = CF\left[\frac{1-b}{p}\frac{1}{\lambda}\right]^{1/b} \tag{8}$$

CF is proportionality constant.

The above cost function is written as follows:

$$C(\lambda) = \frac{\alpha}{\lambda^{1/b}} \tag{9}$$

where

$$\alpha = CF\left[\frac{1-b}{p}\right]^{1/b}$$

Eq. (9) gives a convex cost function since the value of 'b' is positive and less than unity. At times it is appropriate to select $b = 0.5$ [15]. This results a quadratic cost curve as shown in Fig. 2.

A similar approach is used for developing cost functions for average repair time (*MTTR*) modification. As is observed in many engineering applications log-log curve may be approximated as straight line. Plot of $\ln\left(\frac{t_r}{n(t_r)}\right)$ v/s $\ln t_r$ is plotted and assumed to be straight line as shown in Fig. 3. Hence following relation can be written between cumulative mean repair time and total time to repair

$$MTTR_c = \frac{t_r}{n(t_r)} = a' t_r^{-b'} \tag{10}$$

a', b' are positive constants and may be evaluated using graphical plot of data or least square estimation.

$n(t_r)$, Total number of repairs carried out in time t_r.

t_r, Total time required for repairs.