Indonesian Journal of Electrical Engineering and Computer Science
Vol. 14, No. 3, June 2019, pp. 1057~1064
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v14.i3.pp1057-1064

Reliability optimization of electrical distribution systems considering expenditures on maintenance and customer interruptions

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Article Info

Article history:

Received Sep 10, 2018
Revised Nov 11, 2018
Accepted Jan 15, 2019

Keywords:

Customer interruption cost
Distribution systems
Flower pollination algorithm
Rbts-2
Reliability indices

ABSTRACT

In this paper, a methodology is proposed which shows enhancement of reliability by optimizing total reliability cost of electrical distribution systems. The total reliability cost consists of cost incurred by utility and customers both. An objective function in terms of failure rates and repair times i.e. primary reliability indices has been formulated which depicts both these costs . Hence, optimization of the objective function will give a balance between these costs with optimized values of primary reliability indices. This optimization has been done considering the constraints of achieving customer and energy based reliability indices below threshold/target values. The methodology has been applied on Roy Billinton Test System- Bus 2 (RBTS-2). The problem has been solved by applying Flower Pollination (FP) algorithm. A comparison has been made with the results obtained by Differential evolution (DE) algorithm also for the system considered

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1. INTRODUCTION

It has been observed that the customers look for value-added service from their utilities. Failures in identifying customer needs may lead to drastic fall in the business of utilities as the electricity selling market has started becoming competitive. It is a challenging task for any utility to provide qualitative service to the customers keeping the cost on its operation and maintenance such as to provide low cost services to them. In this paper a balance between the utility cost and cost incurred to the customers due to interruptions have been found maintaining the required targets of reliability of the system. The optimum value of system reliability with least combined cost thus found may lead towards value based reliability planning of distribution systems [1].

Cossi et al. [2] gave a formulation regarding planning of primary distribution networks considering the reliability costs obtained by calculating the non-supplied energy due to the repairing and switching operations. Kahrobaee and Asgarpoor [3] have determined the optimum standby electricity storage capacity in a smart grid based on reliability indices such as Expected Interruption Cost (EIC) using particle swarm optimization. Beni et al. [4] presented a practical method to estimate customer damage function (CDF) which describes relationship between interruption duration and its customer economic losses due to interruptions. Nelson and Lankutis [5] presented a method to quantify the costs associated with interruptions of service to customers of electric utilities. Schellenberg et al. [6] developed an Interruption Cost Estimate (ICE) calculator, a tool designed for electric reliability planners at utilities, government organizations or other entities that are interested in estimating interruption costs and/or the benefits associated with reliability improvements. Tsao et al. [7] presented a value based reliability assessment considering different topologies for planning a new distribution system based on comparison of the distribution system reliability cost/worth analysis for different planning topologies. Sonvane and Kushare [8] have increased reliability of distribution system by placing capacitors in proper way. An optimized balance between the costs of reliability and capacitor bank has been found in this paper. Narimani et al. [9] have presented an algorithm to reconfigure distribution feeder considering reliability, loss and operational cost by applying Enhanced Gravitational Search Algorithm (EGSA). Bakkiyaraj and Kumarappan [10] have given optimal reliability enhancement model of electrical distribution system based on the trade-off between the investments required for improving reliability and reduction in the costs of power interruptions applying natural computational algorithms. The optimal locations of distributed static series compensator (DSSC) to enhance the power system reliability by reducing expected damage cost (EDC) have been found by Ghamsari et al. [11]. An algorithm for reliability optimization of power distribution systems considering cost minimization has been given by Banerjee et al.[12]. Ghosh and Kumar [13] have given a methodology for feeder reconfiguration considering overall system cost and reliability incorporating both primary and secondary power distribution systems. Küfeoğlu and Lehtonen [14] have given a review summarizing the academic work done in the fields of worth of electric power reliability and customer interruption costs assessment techniques from the year 1990 to 2015. Lei Sun et al. [15] presented a smart substation allocation model to determine the optimal number and allocation of smart substations in a given distribution system with the upgrade costs of substations and the interruption costs of customers taken into account considering reliability criterion. Sridhar and Prakash [16] have found optimal locations of distributed generations (DGs) considering cost of the power tariff and DG. Reddy et al [17] have found the optimal size and placement of DGs by Whale optimization algorithm enhancing the reliability and other parameters of the system. In [18], authors have gained economic benefits alongwith improvement in other required system parameters and indices by optimal placement of DGs using Dragonfly optimization algorithm. In [19] techno-economic evaluation of an off-grid hybrid renewable energy generation system has been made and compared with that of the solar and wind generation in terms of per unit cost of energy generated by it and reliability.

In the above mentioned literatures, interruptions cost at the customer end have been focused and also tried for their reduction. In line of the same, this paper aims at reducing the total reliability cost of system by reducing customer interruptions and hence consequently enhancing the reliability of distribution systems.

The paper has been organized as follows. In Section 2 the problem to be solved has been formulated. Section 3 gives brief review of FP. Section 4 gives solution methodology for the problem by FP. Section 5 is regarding discussion of the results obtained in this paper. Section 6 leads to the conclusions evaluated. Section 7 enlists the referred work to make this paper.

2. PROBLEM FORMULATION

Distribution system reliability should be based on proper balance between cost to the utility and benefits received by the customers. If the customer interruptions are less, the benefits in terms of profit to the customers and customer satisfaction are more. Thus to design a reliability planning rationally so as to maintain proper service continuity requires incorporating the utility costs and the costs incurred by the customers associated with service interruptions in the analysis.
In view of this, the objective function is designed as follows.

$$J = \sum_{k=1}^{N_c} \alpha_k/\lambda_k^2 + \sum_{k=1}^{N_c} \beta_k/r_k + \sum_{k=1}^{N_c} CIC \quad (1)$$

where,

$$CIC = \lambda_k \times r_k \times L_i \times C_{p_k} \quad (2)$$

In the relation (1), λ_k is the failure rate of k^{th} section; r_k is the average repair time of k^{th} section; α_k and β_k are the cost coefficients; CIC is customer interruption cost at various load points; L_i is the average connected load at load point i; C_{p_k} is the cost of interruption in rupees per kilowatt for an outage duration of r_k associated with k^{th} section; N_c is the total number sections of the distribution system.

The objective function consists of three terms. The first two terms are related to modification costs related to maintenance activities. The first term reflects cost of modification of failure rates of each section. The failure rates can be reduced by investing in maintenance activities on regular basis. The second term is

related to cost of modifications in average repair time. Lesser are the values of these terms; more are the costs or investments associated with preventive maintenance and corrective repair required by utility to achieve them [20]. Both these terms are based on Duane's reliability growth model [21]. The third part of the relation (1); i.e. cost of interruption depicts the costs incurred at the customers end in terms of loss at the time of power fail. When a utility is engaged in supplying power to industrial and commercial facilities, the high costs associated with power outages of course keep more significance. The total cost of interruptions for any load point i can be determined by adding the cost of all section outages. The total cost of customer interruptions for all customers can then be evaluated. The value of service which is equivalent to the cost of reliability, depicted in terms of cost of customer interruptions can be derived by doing actual surveys of customers regarding their expectations in regard to the level of reliability of supply. By defining specific values in rupees for specific level of service reliability a balance in distribution reliability can be established. The customer cost at a single customer load point depends entirely on the cost characteristics of the customers at that load point. The customer cost associated to any load point due to any interruption is the combination of the costs of all type of customers affected due to that distribution outage [1]. Objective function (1) is minimized based on the following customer and energy based constraints [22].
(i) Constraints on the decision variables

$$\lambda_{k,min} \le \lambda_k \le \lambda_{k,max} \tag{3}$$

$$r_{k,min} \le r_k \le r_{k,max} \tag{4}$$

$$k = 1, \dots\dots\dots\dots\dots, N_c$$

where,
$\lambda_{k,min}$ and $r_{k,min}$ are minimum reachable values of failure rate and repair time of k^{th} section. $\lambda_{k,max}$ and $r_{k,max}$ are maximum allowable failure rate and repair time respectively.
(ii) Inequality constraints on the system average interruption frequency index SAIFI

$$\text{SAIFI} \le \text{SAIFI}_t \tag{5}$$

where, System average interruption frequency index (SAIFI) is defined as

$$\text{SAIFI} = \frac{\sum \lambda_{sys,i} N_i}{\sum N_i} \tag{6}$$

(iii) Inequality constraints on the system average interruption duration index (SAIDI)

$$\text{SAIDI} \le \text{SAIDI}_t \tag{7}$$

where, System average interruption duration index (SAIDI) is defined as

$$\text{SAIDI} = \frac{\sum U_{sys,i} N_i}{\sum N_i} \tag{8}$$

(iv) Inequality constraints on the customer average interruption duration index (CAIDI)

$$\text{CAIDI} \le \text{CAIDI}_t \tag{9}$$

where, Customer average interruption duration index (CAIDI) is defined as

$$\text{CAIDI} = \frac{\sum U_{sys,i} N_i}{\sum \lambda_{sys,i} N_i} \tag{10}$$

(v) Inequality constraints on the average energy not supplied index (AENS)

$$\text{AENS} \le \text{AENS}_t \tag{11}$$

where, Average energy not supplied index (AENS) is defined as

$$\text{AENS} = \frac{\sum L_i U_{sys,i}}{\sum N_i} \tag{12}$$

$SAIFI_t$, $SAIDI_t$, $CAIDI_t$ and $AENS_t$ are target/threshold values of the respective indices. They depend on the managerial/administrative decisions.

L_i is average load connected at i^{th} load point, which may be obtained from load duration curve. $\lambda_{sys,i}$ is the system failure rate at i^{th} load point, N_i is number of customers at load point i and $U_{sys,i}$ is system annual outage duration at i^{th} load point. $\lambda_{sys,i}$, $U_{sys,i}$ and $r_{sys,i}$ at a specific load point are derived by gradually solving the network by applying series and parallel laws of reliability [23].

In this formulation, an attempt has been made to apply value based reliability planning in which minimum cost solution is ensured. The cost to be minimized is the total reliability cost of the distribution system which combines cost of maintenance incurred on utility plus the customer outage cost keeping in mind the constraints mentioned in the relations (3), (4), (5), (7), (9) and (11). When the combined utility and customer interruption costs are minimized, the utility customers will receive the least cost service. As both these costs incorporated in the objective function are in terms of failure rate and repair time, constrained minimization of the function will give minimized values of these primary indices enhancing the reliability of the system. The cost of reliability enhancement is the benefit, which is the expected reduction in customer damage cost.

In this paper, recently developed metaheuristic, called Flower pollination (FP) optimization [24] is used for the first time to solve the formulated problem for RBTS-2 and a comparison is made with the results obtained by Differential evolution (DE) [25] methods. Thus by minimizing the function achieving the required target values of the reliability indices will give the optimized values of the maintenance and customer expenditure costs with reliability enhancement.

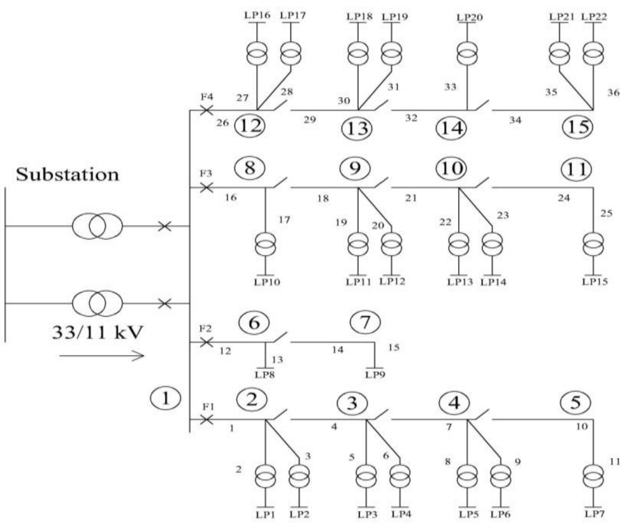

Figure 1. RBTS-2

3. FLOWER POLLINATION ALGORITHM (FP): AN OVERVIEW

The Flower Pollination (FP) algorithm was developed by Xin-She Yang [24] in 2012 and is inspired by the flow pollination process of flowering plants. The certain rules defining the process in brief are: (a) Biotic and cross-pollination are global pollination process and pollen-carrying pollinators travel in a way which obeys Levy flights. (b) A-biotic and self-pollination are local pollination. (c) Pollinators such as insects can develop flower reliability, which is equivalent to a reproduction probability and it is proportional to the similarity of two flowers implicated. (d) A switch probability $p \in [0,1]$ controls local pollination and global pollination.

Local pollination do have a significant fraction p in the overall pollination activities due to the physical proximity and other factors such as wind.

Following are the notations used for describing the FP.

M: Population of flowers /pollen gametes

D: Number of variables

k_{max}: Maximum number of allowable generations

p : switch probability $\in [0,1]$

Step-(a) Initialization: An initial population of size 'M' is generated as follows.

$$S^0 = [X_1^0, X_2^0, \dots\dots, X_M^0] \tag{13}$$

$$X_i^0 = [X_{i1}^0, X_{i2}^0, \dots., X_{iD}^0]^T \tag{14}$$

X_{ij}^0 i.e. j^{th} parameter of X_i vector is obtained from uniform distribution as follows.

$$X_{ij}^0 = X_{j,min} + (X_{j,max} - X_{j,min})rand_j \tag{15}$$

$X_{j,min}$ and $X_{j,max}$ are lower and upper bounds on variable X_j. $rand_j$ is a random digit in the range [0,1].
Step-(b) Updating vectors by global and local pollination

$$X_i^{(k+1)} = \begin{cases} X_i^k + \propto \times L\,(X_{best}^{(k)} - X_i^k),\ if\ rand < p \\ X_i^{(k)} + \in (X_j^{(k)} - X_k^{(k)})\ otherwise. where, X_j^{(k)} \neq X_k^{(k)} \end{cases} \tag{16}$$

$X_{best}^{(k)}$ is the current best solution found among all solutions at the current generation/iteration. $\in$ is drawn from uniform distribution [0,1]. $X_i^{(k)}$ and $X_i^{(k+1)}$ are the current and the updated sulutions at k^{th} generation.

$\propto > 0$ is a scaling factor to control the step size. The parameter L is the strength of the pollination, which essentially is a step size. Since insects may move over a long distance with various distance steps, a L´evy flight can be used to represent this characteristic efficiently [26,27]. Lévy distribution:

$$L = v \times \frac{\sigma_x(\beta)}{\sigma_y(\beta)} \tag{17}$$

$$v = \frac{rand_x}{|rand_y|^{1/\beta}} \tag{18}$$

Where $rand_x$ and $rand_y$ are two normally distributed stochastic variables with standard deviation $\sigma_x(\beta)$ and $\sigma_y(\beta)$ given by:

$$\sigma_x(\beta) = \left[\frac{\Gamma(1+\beta)\times\left(\frac{\pi\beta}{2}\right)}{\Gamma\left(\frac{1+\beta}{2}\right)\times 2^{\left(\frac{\beta-1}{2}\right)}}\right]^{1/\beta} \tag{19}$$

$$\sigma_y(\beta) = 1 \tag{20}$$

Where β is the distribution factor ($0.3 \leq \beta \leq 1.99$) and Γ (.) is the gamma distribution function.
Step-(c) Comparing the fitness of the updated vectors with the initial vectors

$$X_i^{(k+1)} = \begin{cases} X_i^{k+1}, if\ f(X_i^{k+1}) < f(X_i^{(k)}) \\ X_i^{(k)}\ otherwise \end{cases} \tag{21}$$

The current best solution $X_{best}^{(k)}$ and its fitness is then found.This process is executed for all target vector index i and a new population is created till the optimal solution is obtained or the pre-specified generations(k_{max}) have been executed.

4. SOLUTION METHODOLOGY USING FP ALGORITHM

Step 1. Data input $\lambda_{k,max}$, $r_{k,max}$,$\lambda_{k,min}$, $r_{k,min}$ and cost of interruption (C_{p_k}). $SAIFI_t$, $SAIDI_t$, $CAIDI_t$ and $AENS_t$.

Step 2. Initialization: Generate a population of size 'M' (flowers) for failure rate λ and repair time r each by relation (15), where each vector of respective population consists of failure rate and repair time of each component respectively. These values are obtained by sampling uniformly between lower and upper limits as given by relation (3) and (4).

Step 3. Evaluate $\lambda_{sys,i}$, $r_{sys,i}$ and $U_{sys,i}$ at each load point.

Step 4. Evaluate SAIFI, SAIDI, CAIDI and AENS as mentioned in the relations (6), (8), (10) and (12) respectively for vectors of the population.

Step 5. Calculate value of objective function J for all vectors in the population i.e.$J\left(X_i^{(k)}\right)$, $i = 1, \ldots \ldots \ldots \ldots \ldots, 'M'$ as given by relation (1) and (2).

Step 6. Evaluate inequality constraints from the relations (5), (7), (9) and (11) for each vector of the population. Vectors satisfying these constraints will be feasible otherwise not feasible vectors. From among the feasible vectors, based on the value of objective function, identify the best solution vector $X_{best}^{(k)}$.

Step 7. Set generation counter $= 1$.

Step 8. Select target vector, $= 1$.

Step 9. Find the updated value of the vector by relation (16).

Step 10. Compare the fitness of the updated vectors with that of the initial vectors and retain the best ones using relation (21).

Step 11. Repeat from Step 3.to Step 6. for the updated vector.

Step 12. Increase target vector $i = i + 1$. If $i \leq M$, repeat from Step 9 otherwise increase generation count $k = k + 1$.

Step 13. Repeat from step 8 if the desired optimum value is not found or $\leq k_{max}$.

In the same way, solution may be obtained by DE method also.

5. RESULTS AND DISCUSSIONS

The developed algorithm in this paper has been implemented on distribution system RBTS-2 as follows. The problem has been solved by FP algorithm and comparison has been made with the results obtained by DE. The algorithms used have been coded in MATLAB-13. Roy Billinton Test System-Bus 2 (RBTS-2) [28, 29]:

The test system which has been used in this paper is Roy Billinton Test System-Bus 2 as shown in Figure 1. The required basic data have been taken from [28, 29]. The control parameters for the two optimization methods; FP and DE are as given in Table 1. Table 2 gives the optimized values of maintenance cost, customer interruption cost and objective function (J) for RBTS-2. Table 3 shows the current and optimized values of customer and energy based reliability indices. The convergence of minimum value of objective function (J) over the number of generations for both the optimization methods are shown in Figure 2. The frequency distribution plots of minimum values of (J) due to DE and FP are shown in Figure 3 and Figure 4 respectively. The cost and expenditures currency taken here is Indian Rupees (Rs.).

5.1. Comparative Study

A comparison of the results obtained by FP has been made with those obtained by other optimization method i.e. DE for the distribution system in consideration to authenticate the results obtained by FP. The value of objective function (J) obtained by FP is better than that obtained by DE for RBTS-2. The results by both the methods have very less margin. In the same way the customer and energy based reliability indices obtained by the two methods are also compared. For RBTS-2, the results by both the methods don’t have much difference. Frequency distribution plots for minimum values of objective function (J) for both the optimization methods used for RBTS-2 in this paper have been shown. From the plots obtained, the convergence frequencies of (J) seem to be better by FP.

Table 1. Control Parameters for FP and DE for RBTS-2

Sr No.	Parameters	Values of parameters
1	Population size(FP,DE)	20
2	Max generation specified(k_{max}) (FP, DE)	1000
3	Updated step size ($\propto$) (FP)	0.01
4	Distribution factor (β) (FP)	1.5
5	Switch probability (FP)	0.8
6	Step size (F) (DE)	0.8
7	Cross over rate (C_r) (DE)	0.7

Table 2. Current and Optimized Values of Objective Function (J) Obtained by FP and DE for RBTS-2

Sr. No.		Current Values (Rs.)	Optimized Values(Rs.)	
			FP	DE
1	Maintenance cost ($\sum_{k=1}^{N_c} \alpha_k/\lambda_k^2 + \sum_{k=1}^{N_c} \beta_k/r_k$)	232680.49	251359.559	251322.049
2	Customer interruption cost ($\sum_{k=1}^{N_c} CIC$)	575134.93	206345.713	206429.19
3	Objective function (J)	807815.43	457575.464	457632.56

Table 3. Current and Optimized Reliability Indices for RBTS-2

Sr. No.	Index	Current Values	Optimized Values		Threshold Values
			FP	DE	
1	SAIFI(interruptions/customer)	0.098578	0.08442103	0.08467967	0.086
2	SAIDI(h/customer)	0.58817	0.24793783	0.25711545	0.4
3	CAIDI(h/customer interruption)	5.9665	3.33862018	3.03836874	4.0
4	AENS(kW/customer)	4.664	1.86786221	1.91072114	2.2

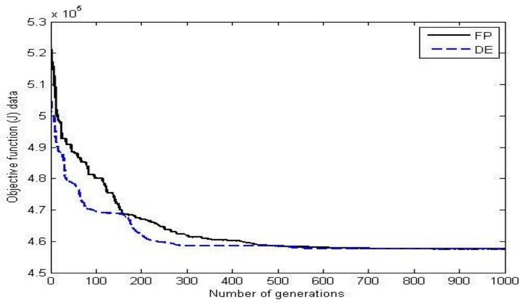

Figure 2. Variation of objective function (J) over number of generations for RBTS-2

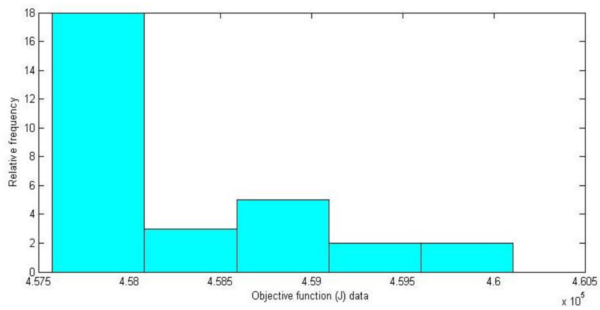

Figure 3. Frequency distribution of the minimum values of objective function (J) using DE for RBTS-2

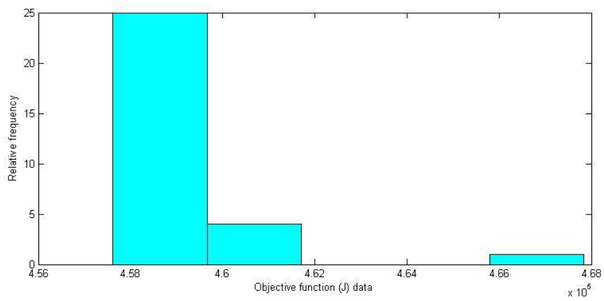

Figure 4. Frequency distribution of the minimum values of objective function (J) using FP for RBTS-2

6. CONCLUSIONS

The aim of this paper has been to improve reliability of a distribution system by finding out a balance between costs of maintenance and customer interruptions. When these combined costs become minimum, customers will get service with least costs leading to enhanced customer satisfaction level. In this paper, this has been achieved by optimizing the objective function formulated subject to achieving the desired reliability level with reduction in the customer interruption costs. It has been applied on RBTS-2 finding the results by FP and DE. It has been found that for the test system in consideration, FP has shown better performance in terms of quality and robustness.

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